HL-LHC Operational scenarios

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Chairs' questions

Discuss for HL-LHC:

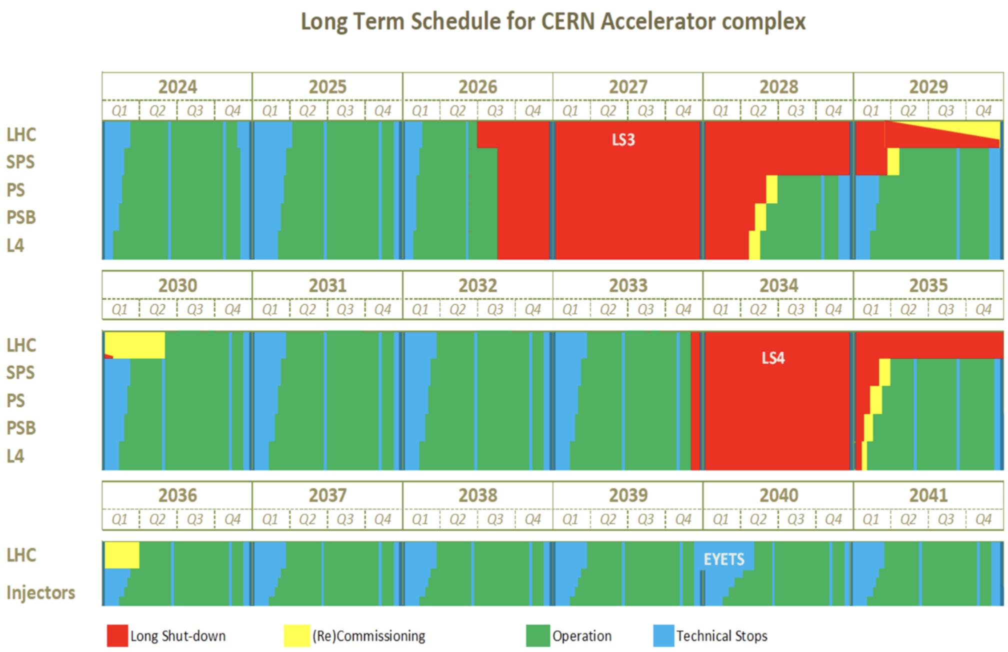
- beam parameters and configurations
- optics options and related performance impact
- impact of different beam production types
- Impact of collimator settings
- RF configurations

Slides in a very draft state!!!

Run 3 to Run 4 for ATLAS/CMS

Domain and teams	Constraints, limiting factors	Parameters	2024	2025	HL-LHC baseline	HL-LHC ultimate
Injectors, RF	Injector performances, bellows, RF power, surface treatments and cooling	Num. Colliding bunches	2340	2340 (2484)	2748	2748
		Protons per bunch SB 10^{11}	1.6	1.6 (1.8)	2.2	2.2
		Emittance INJ	1.3	1.3	2.1	2.1
Optics, incoherent effects	Aperture, magnet field quality, e-cloud	Beta* EOL [urad]	30	60/18	15	15 (18/7.5)
	Beam-beam effects	½ Crossing angle EOL [urad]	150	110	250-190(CC)	220-190(CC)
Optics, coherent effects	Field quality, beam-beam effects, impedance, PC FB noise	Beam losses [mb]	100	100	110	110
		Emittance SB [um]	1.8	1.8	2.5	2.5
		Emittance EOL [um]	2.2	2.2	2.9	2.9
		Virtual luminosity [10^{34} $cm^{-2}s^{-1}$]	3.7	4.3(5.3,)	16.9	16.9(20.7)
Experiment	Detector, cooling	Pile-up / Lev Lumi [$10^{34}cm^{-2}s^{-1}$]	65 / 2.2	65 / 2.2	132 / 5	200 / 7.5
Operation	Reliability, robustess	Turn around time [h]	2.5	2.5	2.5	2.5
		Operational efficiency [%]	0.5	0.6	0.5	0.5
		Days	?	?	198	198
		Lumi	130?		275	340(360)

Schedule

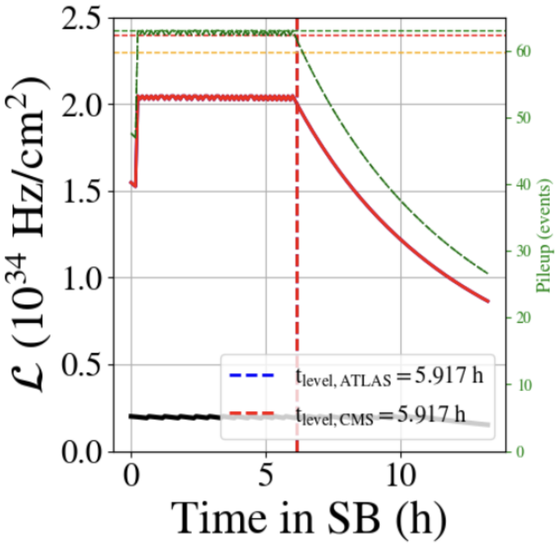


Run	Year	Efficiency	Days Intensity ramp-up	Days Proton physics	Days Ion Physics
4	2030	0.5	20	35	0
	2031	0.5	15	136	29
	2032	0.5	10	154	29
	2033	0.5	10	152	29
5	2036	0.5	15	152	29
	2037	0.5	10	195	29
	2038	0.5	10	198	29
	2039	0.5	10	198	29
	2040	0.5	15	165	29
	2041	0.5	10	203	29

Ions operations in 2031-2041

Luminosity and beam parameters

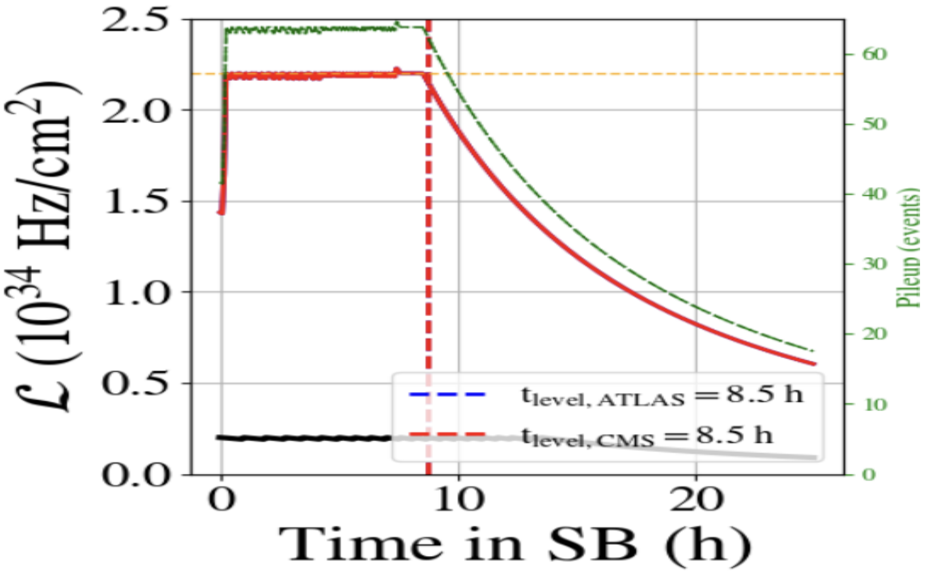
2024



Parameters	HL-LHC baseline	2024
Num. Colliding bunches	2748	2340
Protons per bunch SB 10^{11}	2.2	1.6
Emittance INJ	2.1	1.3
Beta* EOL [cm]	15	30
½ Crossing angle EOL [urad]	250-190(CC)	150
Beam losses [mb]	110	100
Emittance SB [um]	2.5	1.8
Emittance EOL [um]	2.9	2.2
Virtual luminosity [10^{34} cm^{-2}s^{-1}]	16.9	3.7
Pile-up / Lev Lumi [10^{34}cm^{-2}s^{-1}]	132 / 5	65 / 2.2
Turn around time [h]	2.5	2.5
Operational efficiency [%]	0.5	0.6
Daily Lumi		

Luminosity and beam parameters

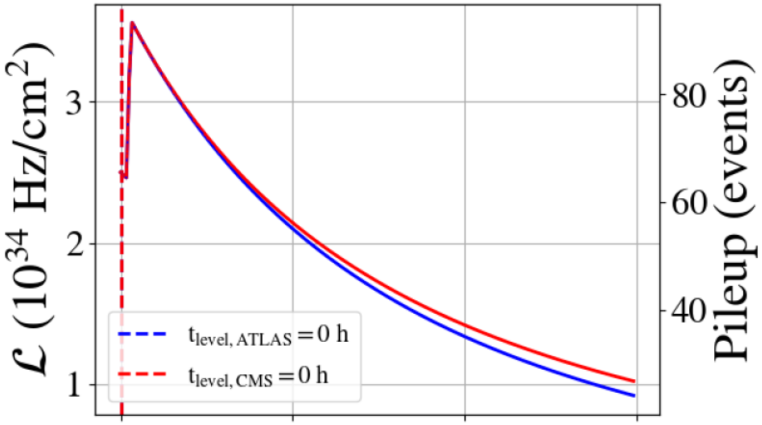
2025



Parameters	HL-LHC baseline	2025
Num. Colliding bunches	2748	2340-2484?
Protons per bunch SB 10^{11}	2.2	1.6-1.8?
Emittance INJ	2.1	1.3
Beta* EOL [cm]	15	60/18
½ Crossing angle EOL [urad]	250-190(CC)	110
Beam losses [mb]	110	100
Emittance SB [um]	2.5	1.8
Emittance EOL [um]	2.9	2.2
Virtual luminosity [10^{34} cm^{-2}s^{-1}]	16.9	4.3(5.3)
Pile-up / Lev Lumi [10^{34}cm^{-2}s^{-1}]	132 / 5	65 / 2.2
Turn around time [h]	2.5	2.5
Operational efficiency [%]	0.5	0.6
Daily Lumi		

Luminosity and beam parameters

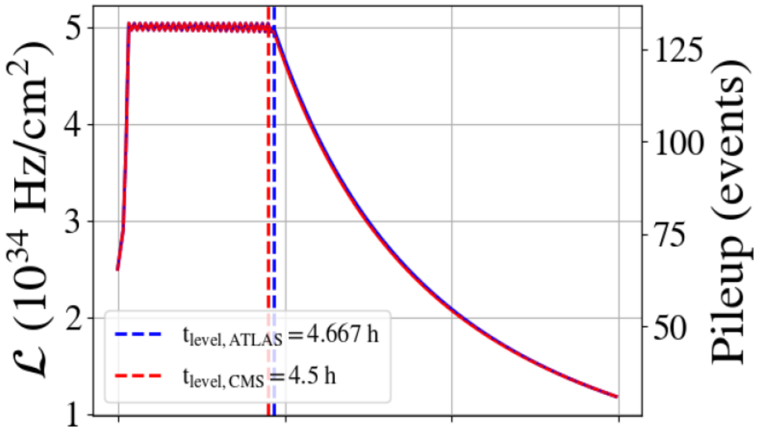
2030



Parameters	**HL-LHC baseline**	**2030**
Num. Colliding bunches	2748	2748
Protons per bunch SB 10^{11}	2.2	1.8 (1.6)
Emittance INJ	2.1	2.1
Beta* EOL [cm]	15	30 (60/18)
½ Crossing angle EOL [urad]	250-190(CC)	250
Beam losses [mb]	110	110
Emittance SB [um]	2.5	2.5
Emittance EOL [um]	2.9	2.9
Virtual luminosity [10^{34} cm^{-2}s^{-1}]	16.9	4.3 ()
Pile-up / Lev Lumi [10^{34}cm^{-2}s^{-1}]	132 / 5	
Turn around time [h]	2.5	2.5
Operational efficiency [%]	0.5	0.6
Daily Lumi		

Luminosity and beam parameters

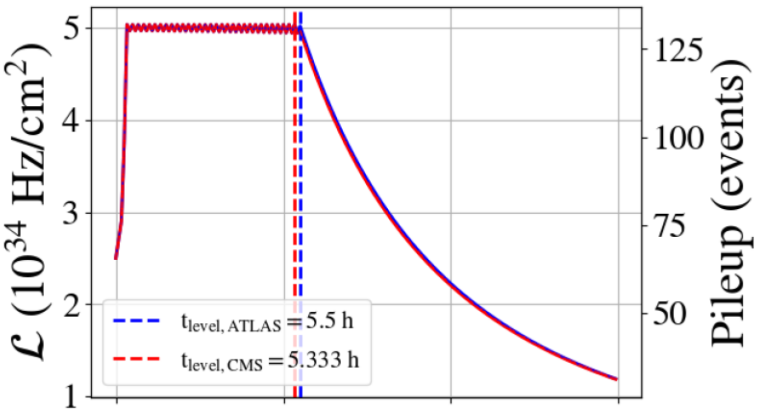
2031



Parameters	HL-LHC baseline	2031
Num. Colliding bunches	2748	2748
Protons per bunch SB 10^{11}	2.2	2.2
Emittance INJ	2.1	2.1
Beta* EOL [cm]	15	25
½ Crossing angle EOL [urad]	250-190(CC)	250 -190(CC)
Beam losses [mb]	110	110
Emittance SB [um]	2.5	2.5
Emittance EOL [um]	2.9	2.9
Virtual luminosity [10^{34} cm^{-2}s^{-1}]	16.9	4.3
Pile-up / Lev Lumi [10^{34}cm^{-2}s^{-1}]	132 / 5	
Turn around time [h]	2.5	2.5
Operational efficiency [%]	0.5	0.6
Daily Lumi		

Luminosity and beam parameters

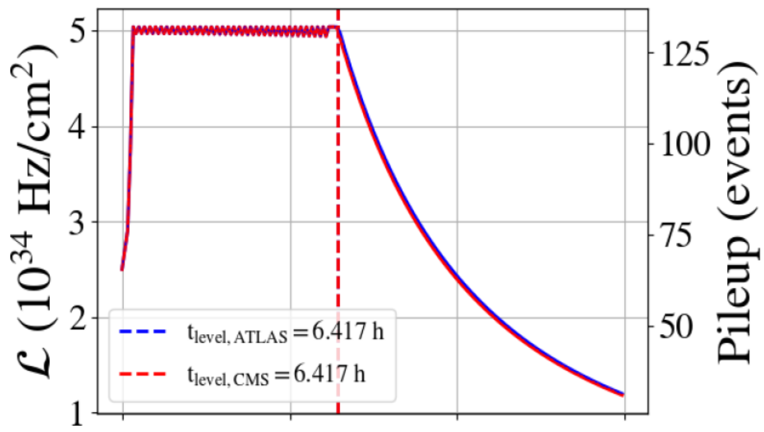
2032-3



Parameters	HL-LHC baseline	2032-3
Num. Colliding bunches	2748	2748
Protons per bunch SB 10^{11}	2.2	2.2
Emittance INJ	2.1	2.1
Beta* EOL [cm]	15	20
½ Crossing angle EOL [urad]	250-190(CC)	250 -190(CC)
Beam losses [mb]	110	110
Emittance SB [um]	2.5	2.5
Emittance EOL [um]	2.9	2.9
Virtual luminosity [10^{34} cm^{-2}s^{-1}]	16.9	4.3
Pile-up / Lev Lumi [10^{34}cm^{-2}s^{-1}]	132 / 5	
Turn around time [h]	2.5	2.5
Operational efficiency [%]	0.5	0.6
Daily Lumi		

Luminosity and beam parameters

2036-41



Parameters	**HL-LHC baseline**	**2032**
Num. Colliding bunches	2748	2748
Protons per bunch SB 10^{11}	2.2	2.2
Emittance INJ	2.1	2.1
Beta* EOL [cm]	15	20
½ Crossing angle EOL [urad]	250-190(CC)	250 -190(CC)
Beam losses [mb]	110	110
Emittance SB [um]	2.5	2.5
Emittance EOL [um]	2.9	2.9
Virtual luminosity [10^{34} cm^{-2}s^{-1}]	16.9	4.3
Pile-up / Lev Lumi [10^{34}cm^{-2}s^{-1}]	132 / 5	
Turn around time [h]	2.5	2.5
Operational efficiency [%]	0.5	0.6
Daily Lumi		

Nominal performance

Run	Year	Efficiency	Bunch intensity (1e11 ppb)	$\beta_{//}^*$ (cm)	β_x^* (cm)	CC	PU_{max}	Days Intensity ramp-up	Days Proton physics	Emit start of SB (µm)	IP1/5 crossing plane	IP1/5 $\varphi/2$ (µrad)	LHCb L_{peak} (1e33 Hz/cm^2) [4]
4	2030	0.5	1.8 (1.6)	30	30	off	101	20	35	2.5	H/V	250	2
	2031	0.5	2.2	25	25	on	132	15	136	2.5	H/V	250	2
	2032	0.5	2.2	20	20	on	132	10	154	2.5	H/V	250	2
	2033	0.5	2.2	20	20	on	132	10	152	2.5	H/V	250	2
5	2036	0.5	2.2	15	15	on	132	15	152	2.5	H/V	250	2
	2037	0.5	2.2	15	15	on	132	10	195	2.5	H/V	250	2
	2038	0.5	2.2	15	15	on	132	10	198	2.5	H/V	250	2
	2039	0.5	2.2	15	15	on	132	10	198	2.5	H/V	250	2
	2040	0.5	2.2	15	15	on	132	15	165	2.5	H/V	250	2
	2041	0.5	2.2	15	15	on	132	10	203	2.5	H/V	250	2

Run	Year	Reference (fb-^{1})
4	2030	31.99
	2031	205.54
	2032	236.85
	2033	233.82
5	2036	208.12
	2037	271
	2038	275.72
	2039	275.72
	2040	228.54
	2041	283.57
Run 4+5		2250.89
All	+520	2770.9

Filling schemes

Type	# Inj.	# bunches	# collising bunches ATLAS/CMS Alice LHCb	E-cloud degradation
4x72 STD	13	2760	2748 2492 2574	
5x48 BCMS	13	2748	2740 2250 2376	
5x36 BCMS	16	2484	2484 2121 2260	
Hybrid	13	2604	2592 2224 2313	
Hybrid	13	~2250	~2250	
8b+4e	12	1972	1960 1886 1178	

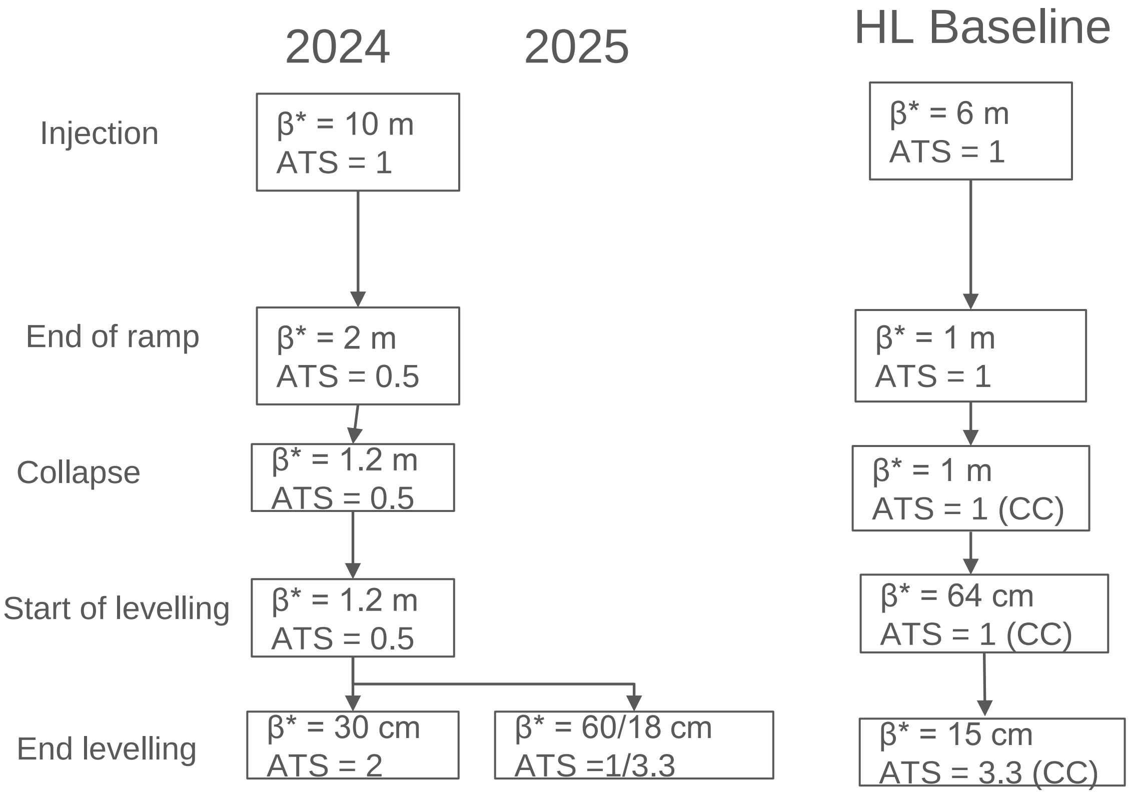
Goal: largest number of colliding bunches at 2.3 10^{11}, while keeping small bunch-by-bunch variations, low tails, small emittance.

Std 72b scheme more bunches, short injection time, better for luminosity compared to BCMS, at the same time

BCMS 48b scheme being better for e-cloud, emittance, tails, losses, was a more optimal choice so far.

Hybrid, gives more bunches compared to pure schemes in the presence of e-cloud issues, but due to complex operation, large bunch-by-bunch variations. Less effective unless severe e-cloud limitations.

Baseline optics cycle



Main features established in 2010:

- ATS paper
- HL-LHCV1.0 layout and further

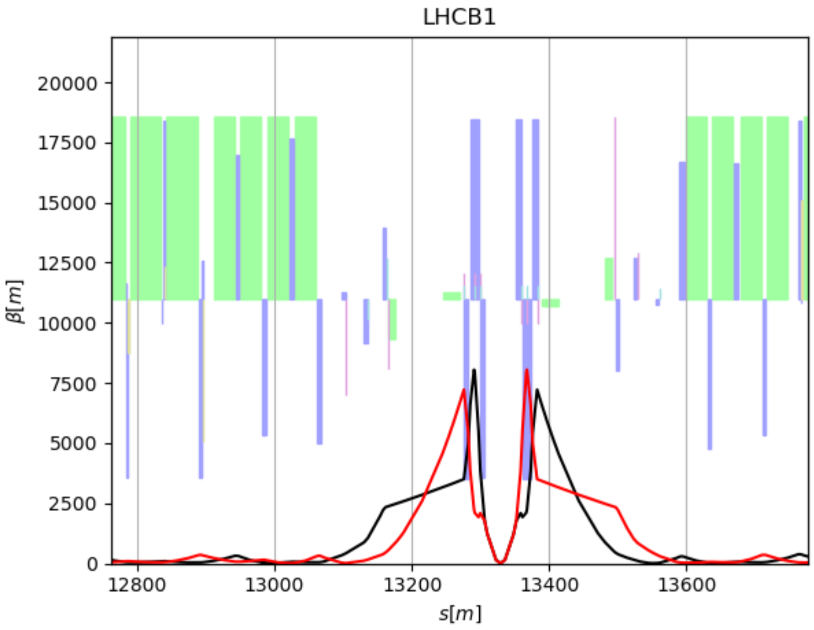
HL-LHC baseline further updated to

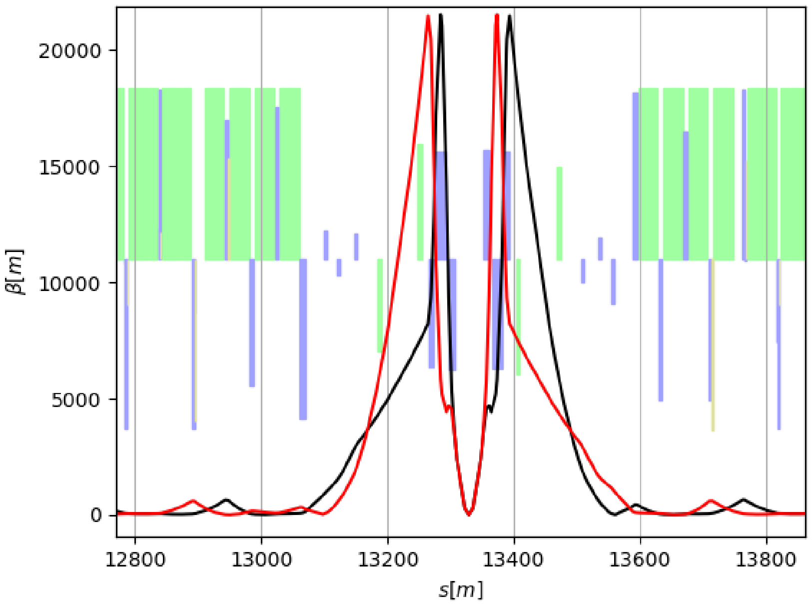
- follow layout changes
- study options and improvements

Crab cavity voltage at 1MV dephased until adjust

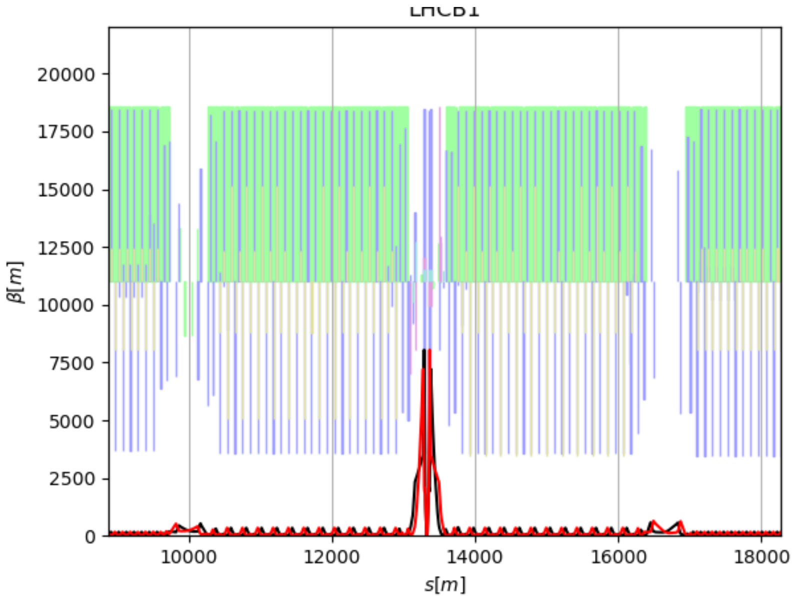
IR1/5 only: Q change, LHCb rotation not shown

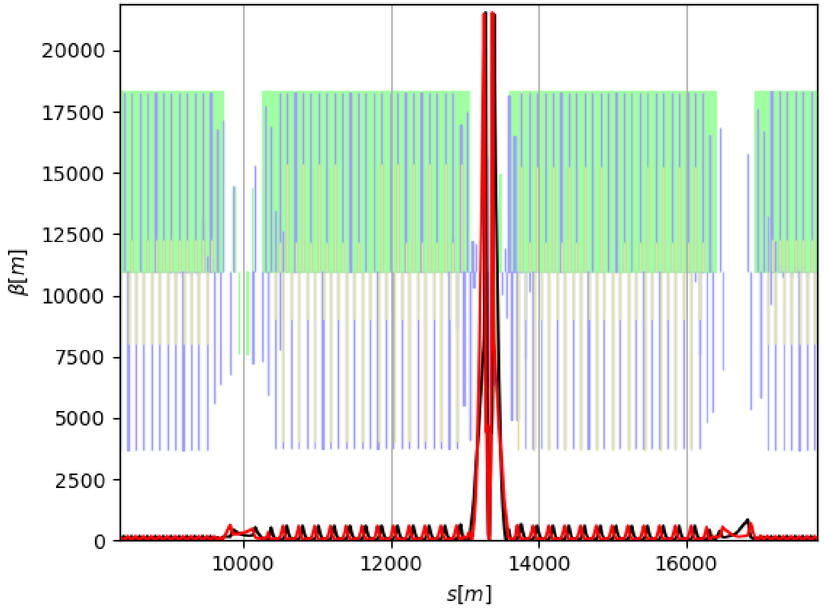
Run 3 -> HL-LHC Optics





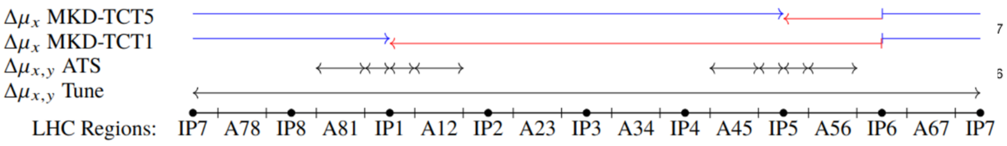
Run 3 -> HL-LHC Optics: Large ATS factor

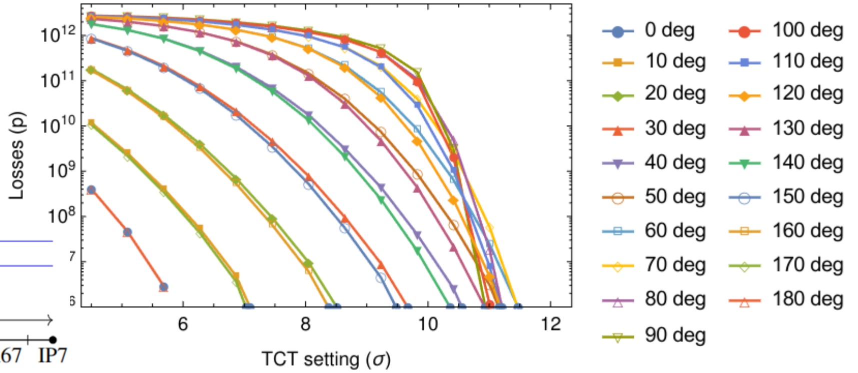




Protected aperture

Protected aperture depends on MKD-TCT phase advance a
flat top in the horizontal plane.
MKD-TCT are difficult in P5 because very few quadrupoles
available (due to ATS) and many constraints. BETS upgrad
and optics developments to improve beta* reach!





Collimator [σ@2.5μm]	2023 Injection	HL Injection	2023 end-of-level settings	HL end-of-level tight settings [1]	HL end-of-level relaxed settings [3]
TCP IR7	6.7	6.7	5.9	6.7	8.5
TCS IR7	7.9	7.9	7.7	9.1	10.1
TCDQ IR6	9.5	9.5	8.6	10.1	11.1
TCT	15.4	15.4	10.1	10.2-13.3*	11.2-14.6*
TCL	parking	parking	17	[21.3 mm]+	[21.3 mm]+
TCLA	11.8	11.8	11.8	13.7	13.7
Aperture	14.2 (meas)	12.6	11.2(meas)	11.2-14.3*	12.2-15.6*

Tight collimator settings have better cleaning and beta* reach.

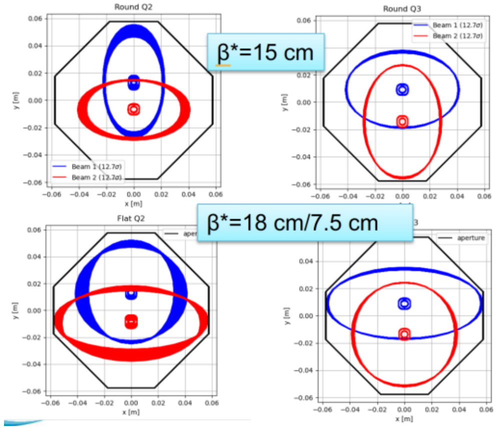
Relaxed settings have less impedance and reduce sensitivity to MP issues, potentially improving intensity reach.

Trade off between cleaning and intensity to be found operationally.

References:
[1] R. Bruce et al. CERN-ACC-2017-0051
[2] R. Bruce ColUSM 115
[3] R. Tomas et al. CERN-ACC-2022-0001

β* reach, flat optics and crossing planes

Flat and round have approximately the same beam size at the triplets.



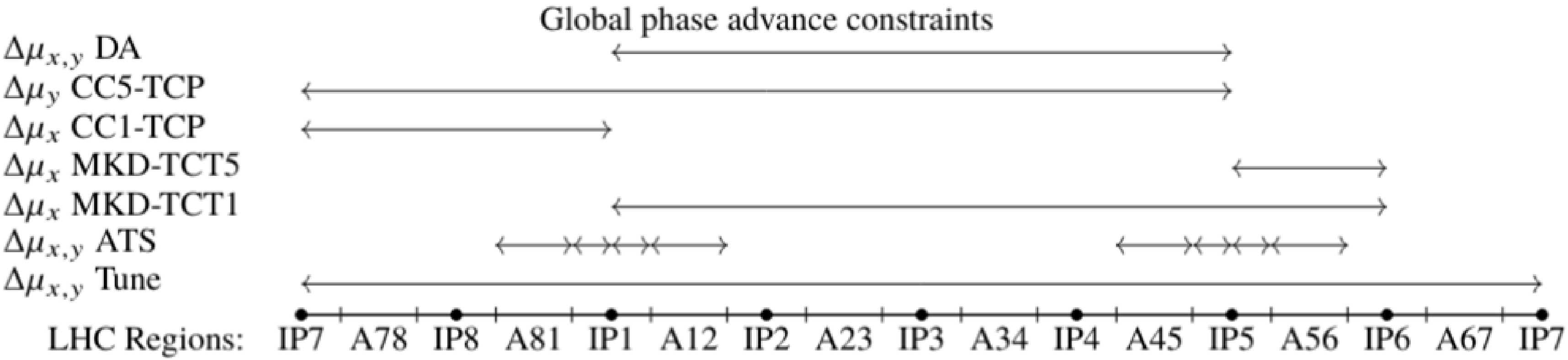
β* reach depends on MKD-TCT phase advance and (new finding) TCL gaps. Crossing plane, triplet polarity, crabbing angle matters, IP1 or IP5!

1) MKD-TCT difficult to achieve when squeezing β^*_X in IP5. Vertical crossing angle (that is small β^*_x in P5) is the worst, well known, choice in this respect.
2) Present triplet polarity $\beta_X > \beta_Y$ at the TCL: large gaps needed (good for PPS2), -> small H radius in pass-through pipe -> large power deposited in D2 and TCLMB for vertical crossing.
3) CLIQ system failure scenarios more critical compared to round optics. Phase advance mitigation under study.

Mitigations:

1) Exchange crab cavities for Run 5 (extend reach 5600 fb-1 lifetime)
2) Improve MKD-TCT also for V crossing in P5: relax dispersion or ATS matching.
3) RP optics could help on TCL settings, but not optimal on current design.

HL-LHC Optics Phase optimization



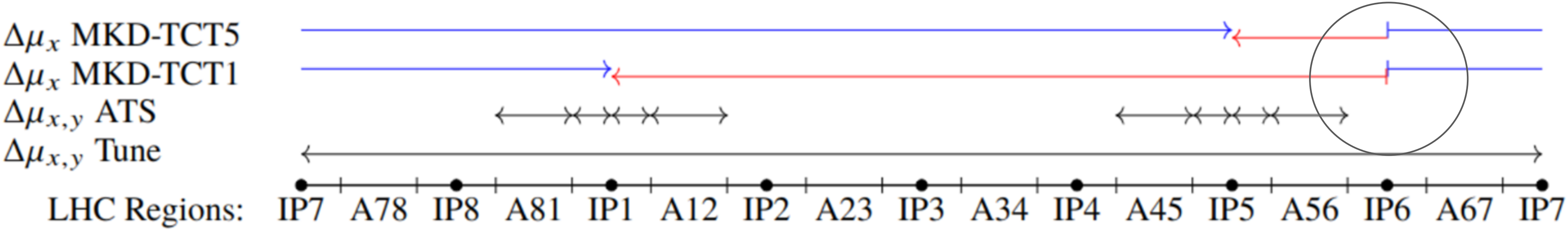
Machine protection issue could limit intensity and beta* reach.
CC-TCP phase is important for crab and CLIQ failure scenarios.
TCP-TCT important for background.
IP1-IP5 phase important for DA.
Phase advances are also important for FA
HL-LHC optics are designed to find a global solutions.

Efforts to find a global optimum for the different phases of the cycle that have different compromises. Work ongoing, iterative work.

Step in the cycle	β^* [cm]	Optimisation criteria
Injection	600	aperture in the arcs, octupole Resonance Driving Terms (RDT)
Flat top	200-50	β_{crab}, octupole RDT
Separation collapse	200-50	octupole RDT
Start of levelling	200-50	octupole RDT, $\Delta\mu_{x,CC1-TCPH}$, $\Delta\mu_{y,CC5-TCPV}$
End of levelling	20-7.5	aperture in the triplets, field quality, $\Delta\mu_{x,MKD-TCT1,5}$, $\Delta\mu_{x,CC1-TCPH}$, $\Delta\mu_{y,CC5-TCPV}$

MKD-TCT optimizations

MKD-TCT are difficult in P5 because very few quadrupoles available (due to ATS) and many constraints



Horizontal matching more difficult because of the dispersion constraints. Options:

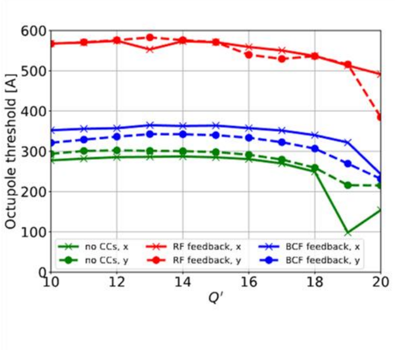
1) Relax dispersion matching -> dispersion beating in the arc 56 (next slide)
2) Relax ATS matching -> limit spurious dispersion correction and off-momentum beta-beating and Q' (next step)

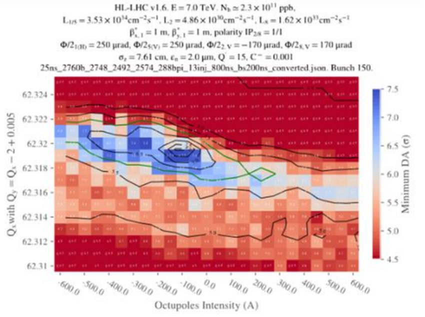
Beyond Nominal: Impedance mitigation

Impedance is stabilized by Landau octupole and chromaticity at the cost of beam lifetime, thus luminosity.

New IR7 and IR3 optics (on top of potential gains by collimators gap), as well as increasing cleaning efficiencies.

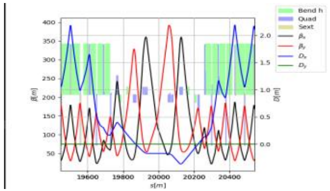
First test in MDs shows no issues, but high intensity needed for assessment.



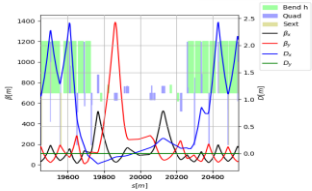


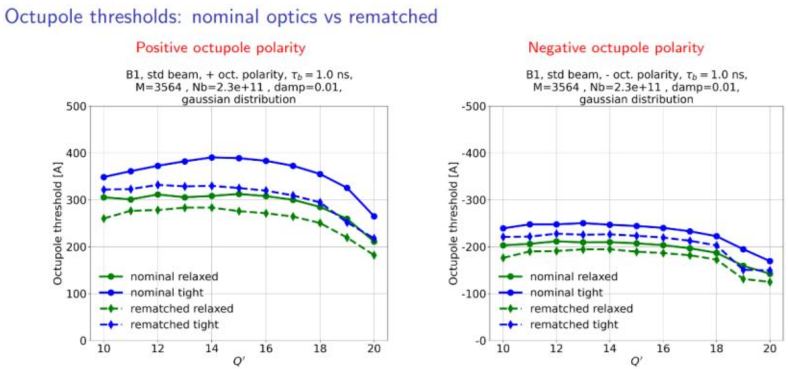
courtesy of C. Droin, S. Kostoglou, G. Sterbini

IR7 injection



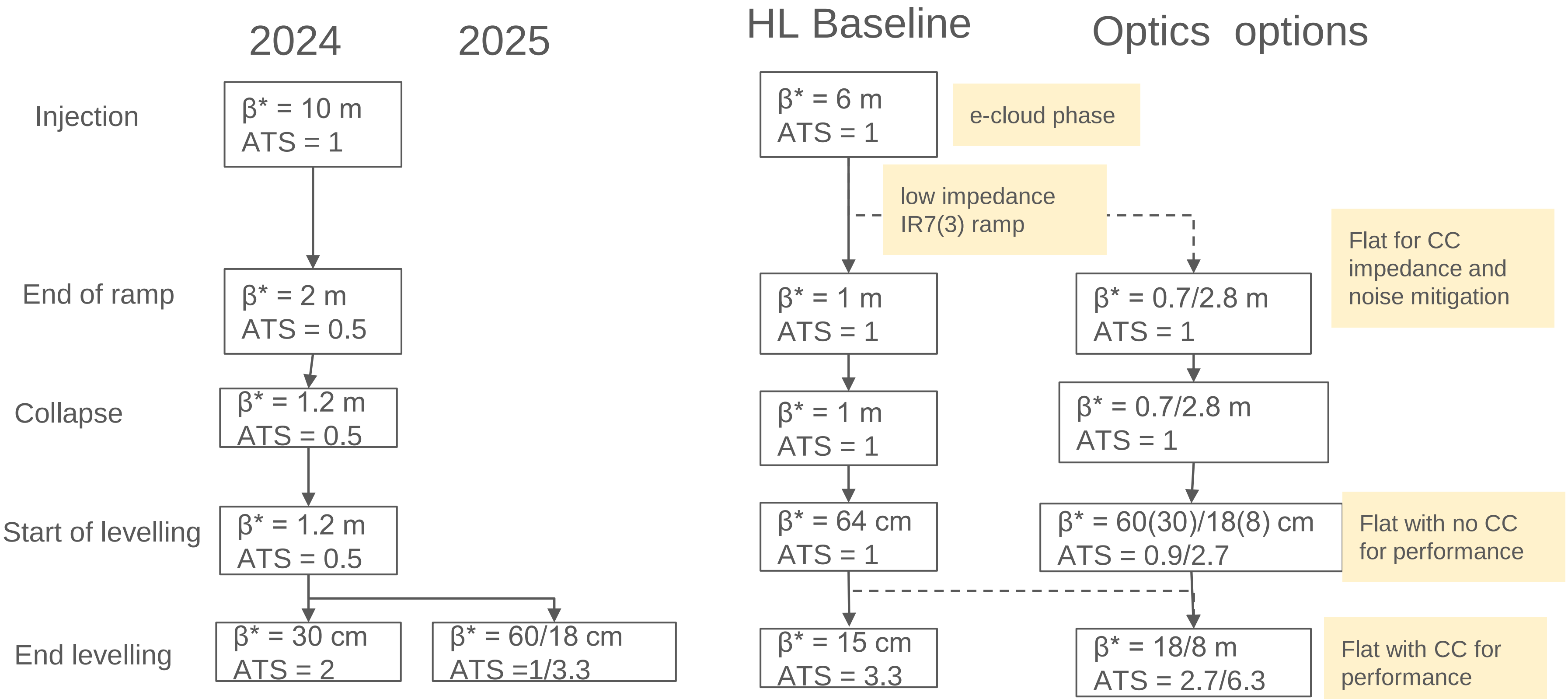
IR7 flat top





Ideally to be tested or put in operation in 2026 or to be assumed baseline from Run 4 and step back during intensity ramp-up in 2023 at marginal cost compared to be limited in high production years.

Optics options cycle



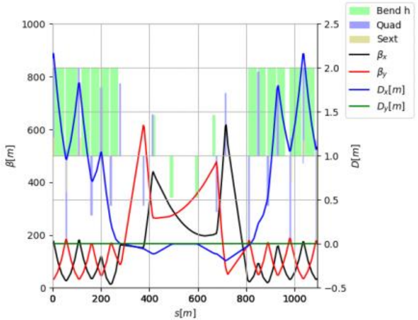
IR1/5 only: Q change, LHCb rotation not shown

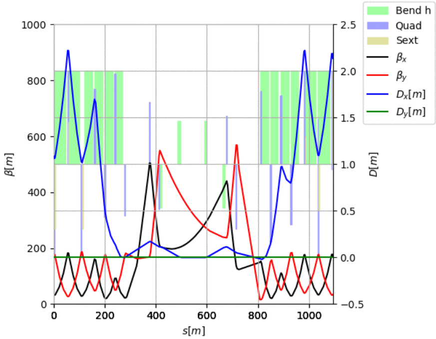
Beyond nominal: IR4 Optics

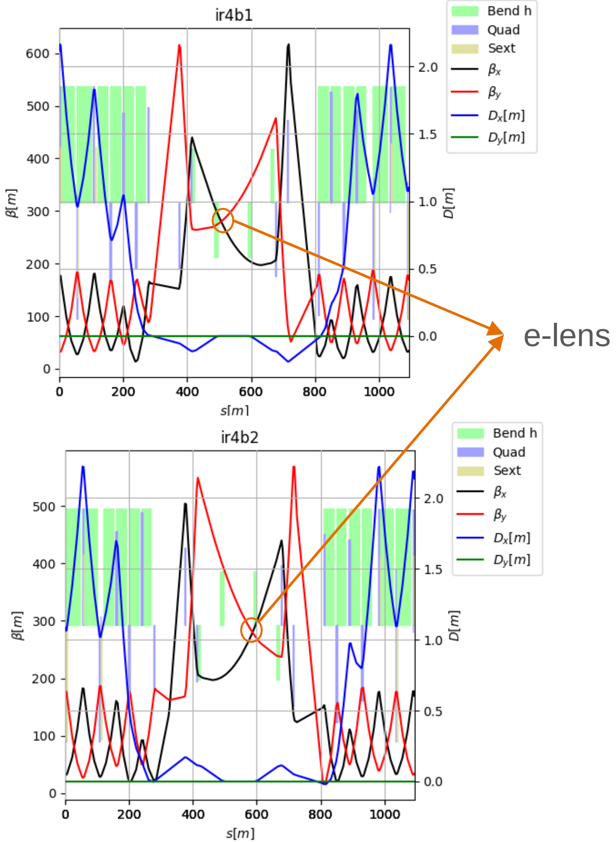
IR4 optics for HL was studied and optimized for e-lens and BI around 2019.

There is still additional optics flexibility.
Currently, is used to control the long-range phase advance constraints, in combinations with the MQTs in the arcs.

However, could also be used to further optimize the optics, in particular, if we allow changes of optics conditions at the IP to increase beta function at to improve SNR (e.g. BSRT, coronagraph)







Principle tested in MD in 2024 showed no issues.

What to optimise beyond the RF?

BLM thresholds for start-of-ramp losses being reviewed (2024-2026)

- **Potentially** a x2-4 that could be gained
  - For BCMS, a x2 represents a decrease in bunch length from 1.42 ns to 1.35 ns
  - Maintaining the same working point in terms of losses and bunch length, this corresponds to a decrease from 5.5 MV to 4.5 MV, i.e. **-18 %** in voltage

Improve the cleaning of debunched beam

- Optimise the present cleaning to have less losses at the start of the ramp?

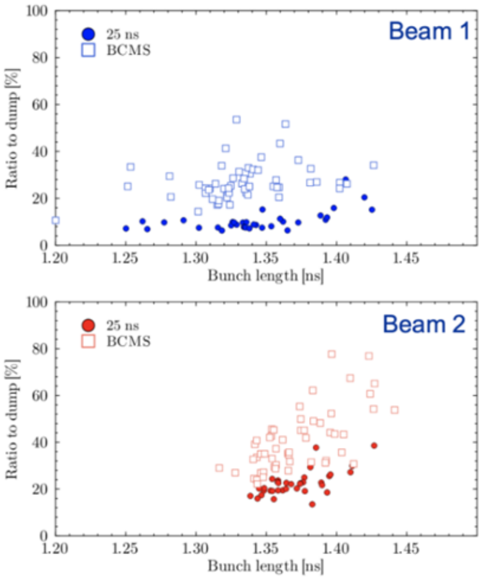
Minimise the time spent at flat bottom

- Favour filling schemes with less injections
- Dedicated LHC filling using improved magnetic hysteresis in the injectors

	N_b	Collisions IP1/5	IP2	IP8	Heat load [W/hc] 1.6e11	1.8e11	N_{bpi}	N_{inj}	SPS flat bottom [s]
5x36b	2496	2484	2121	2260	170	184	180	16	14.4
4x36b	2460	2448	2005	2146	167	180	144	20	10.8
3x36b	2352	2340	2004	2133	158	171	108	24	7.2
Hybrid-48b	2452	2440	1952	2240	153	166	248	12	14.4
Hybrid-36b	2464	2452	1842	1821	142	154	236	12	18

Filling scheme options for 2025

L. Mether and K. Paraschou at LBOC #171 meeting



Losses vs bunch length for BCMS and standard beam

See talk by B. Karlsen-Baeck

Updated projections for HL-LHC

From capture to flat bottom losses

- Estimates based on dp/p are simple, but describe mainly capture losses
- Reality is a mix of capture losses and debunching along the flat bottom
  - What is the ratio of the two? We don't have exact numbers so far…
  - Attempt to disentangle the two with IR3 collimator scraping was not conclusive
- BCMS calls for increased capture voltage, but reviewed BLM thresholds could help to be more comfortable

Scenario	Bunch parameters		SPS parameters			LHC parameters					
	Bunch intensity	Bunch emittance	Main RF voltage	4th harm. voltage	Momentum spread	Main RF voltage	Bunch length	Optimum detuning	Optimum Q_L	Average power	Peak power
2023 (std)	2.0×10^{11} p/b	0.55 eVs	9.4 MV	1.7 MV	5.09×10^{-4}	7 MV	1.25 ns	-9.7 kHz	20.6k	206 kW	230-310 kW
2024 (BCMS)	2.0×10^{11} p/b	0.46 eVs	8.5 MV	1.53 MV	4.58×10^{-4}	7 MV	1.12 ns	-10.3 kHz	19.5k	218 kW	230-310 kW
HL-LHC (std)	2.3×10^{11} p/b	0.58 eVs	10 MV	2 MV	5.32×10^{-4}	7.9 MV	1.25 ns	-9.9 kHz	17.3 k	267 kW	320±15 kW
HL-LHC (BCMS)*	2.3×10^{11} p/b	0.58 eVs	10 MV	2 MV	5.32×10^{-4}	7.1 MV	1.29 ns	-10.8 kHz	18.6k	236 kW	280±15 kW

HL-LHC projections based on MD experience in the LHC

** hypothetical: assuming BCMS beam and a x2 increase in IR3 start-of-ramp BLM thresholds*

Conclusion

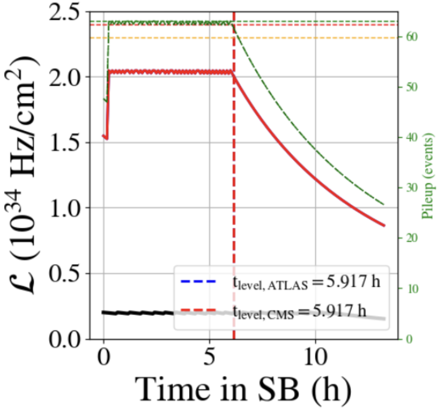
HL-LHC performance is enabled by increased level-luminosity, bunch population, larger beam density (beta*) and overlap (CC).

LHC has not yet demonstrated 2.2 1011 ppb with 2760 bunches: key to make steps to this parameters in 2024.

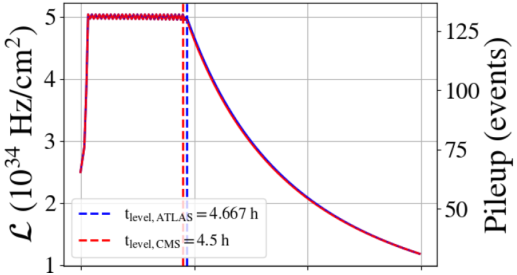
Back-up

Luminosity and beam parameters

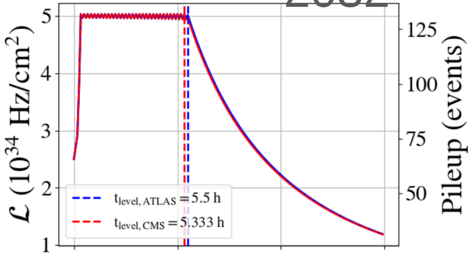
2024



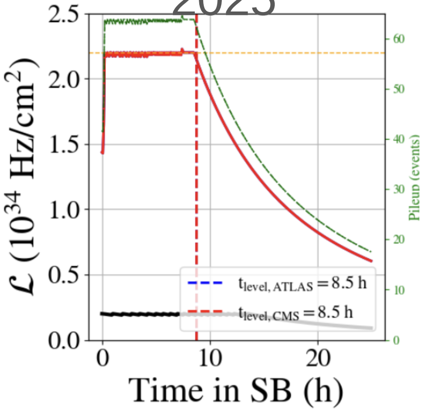
2031



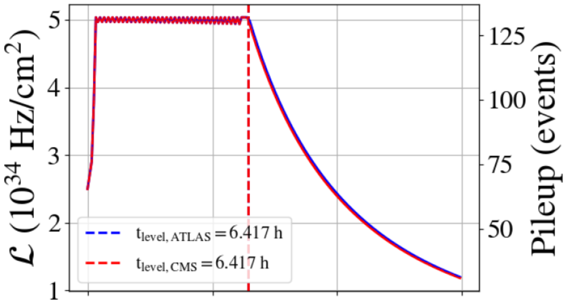
2032



2025



2041



Protected aperture

Parameters	7 TeV	0.45 TeV
Min Ap. no TCT [σ]	19.4	12.6
Min H. Ap. with TCT [σ]	11.2-15.6	12.6
Min V. Ap. with TCT [σ]	11.2-12.2	12.6

Protected aperture depends on MKD-TCT phase advance at flat top in the horizontal plane.

$\Delta\mu_x$ MKD-TCT [°]	H. Ap. W [1] [σ@2.5μm]	H. Ap. CuCD [2] [σ@2.5μm]	H. Ap. W Relaxed [σ@2.5μm]
0-20	11.2	11.2	12.2
30	11.9	11.2	12.9
40	12.9	11.9	13.9
50	13.8	12.8	14.8
60	14.5	13.6	15.5
70	14.6	14.0	15.6
80-90	14.6	14.3	15.6

Collimator [σ@2.5μm]	2023 Injection	HL Injection	2023 end-of-level settings	HL end-of-level tight settings [1]	HL end-of-level relaxed settings [3]
TCP IR7	6.7	6.7	5.9	6.7	8.5
TCS IR7	7.9	7.9	7.7	9.1	10.1
TCDQ IR6	9.5	9.5	8.6	10.1	11.1
TCT	15.4	15.4	10.1	10.2-13.3*	11.2-14.6*
TCL	parking	parking	17	[21.3 mm]+	[21.3 mm]+
TCLA	11.8	11.8	11.8	13.7	13.7
Aperture	14.2 (meas)	12.6	11.2(meas)	11.2-14.3*	12.2-15.6*

* Collimation settings and protected aperture need to be validated with collimation simulations of specific optics.
+ Minimum setting in mm validated by radiation simulations (38W in D2)

References:
[1] R. Bruce et al. CERN-ACC-2017-0051
[2] R. Bruce ColUSM 115
[3] R. Tomas et al. CERN-ACC-2022-0001

TCL, TCT settings estimates

	MKD-TCT5	IP5			IP1		
		β*	TCTH(2)	TCL(2)	β*	TCTH(2)	TCL(2)
Round	30/31	15/15	10.9σ	14.2σ 21.3 mm	15/15	10.2σ	14.2σ 21.3 mm
Flat HV	40/45	9/18	12.3σ	12.3σ 23.8 mm	18/9	10.2σ(1)	15.5σ 21.3 mm
Flat HV	51/54	7.5/18	13.1σ	13.1σ 27.8 mm	18/7.5	10.2σ(1)	15.5σ 21.3 mm
Flat VH	27/25	18/7.5	11.7σ	15.5σ 21.3 mm	7.5/18	10.2σ	10.2σ 21.6 mm

Assuming TCL can be as low as TCTs as they see the same MKD -TCT phase.

1) MKD-TCT is also responsible for limiting beta* reach due to power deposition in D2 and TCLMB
2) Reversing triplet polarity could help here! But, it requires a redesign of TCTPHX, TCLPX, reverse of MCBY orientation in Q4, demonstrate optics solutions in P1/5 for β* 0.5-30 m and crabbing angle >380 murad.
3) Switching crossing planes solves the problem should be the baseline for Run 5 and 6!
4) Exploring complications of improving MKD-TCT (next slide)

(1) achievable but not demonstrated yet, (2) tight collimator setting

RF

Cases for flat optics

There are 3 different cases for preferring flat optics that are logically separated and can be implemented independently.

At collapse: Reduce β function in the crossing plane at the crab cavities to reduce impedance. A reduction of β at the crab cavities can also be done for round optics (25% at β*=1.1m) or without ATS.

β*	1.1 m high	1.1 low	0.9/1.8 low no ats	1.8/0.9 no ats
Avg beta crab	680	466	327	280

During luminosity levelling: Integrate more luminosity at reduced pile-up density. Increase allowed intensity of non-colliding bunches due to lower impedance at the cavities.

Towards the end of luminosity levelling: Increase levelling time and therefore increase luminosity. Sizeable gain when levelling time is in the order of 4-5 hours (e.g. 200 pile-up with 2.2 10^{11} or 140 pile-up at 1.8 10^{11}). Still compelling gain 3-4% for nominal conditions.

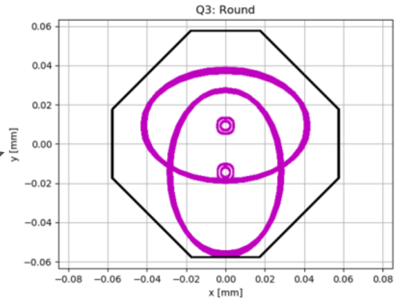
Flat optics opportunities

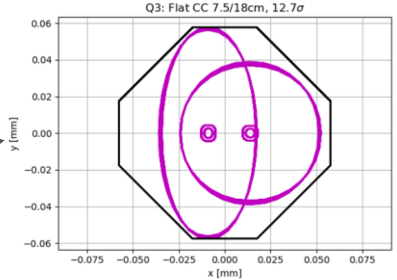
Flat optics: larger beta* in the crossing plane and lower beta* in the separation plane.

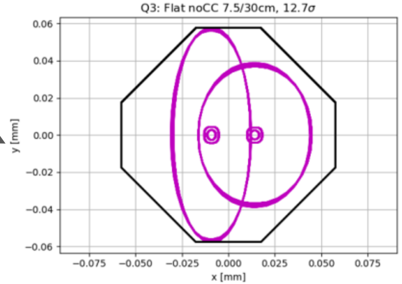
Flat optics at the end of the levelling increases virtual luminosity (for high pile-up, low ppb scenarios) for similar aperture in the triplets.

Flat optics throughout the cycle reduces emittance growth, impedance, failure induced losses from crab cavities.

Virtual lumi 2.2 10^{11} ppb	Round β*=15 cm	Flat β*=8 cm X-plane
CC On	16.9 10^{34} $cm^{-2}s^{-1}$ (250 μrad)	20.6 10^{34} $cm^{-2}s^{-1}$ (18 cm //-plane, 250 urad)
CC Off	8.31 10^{34} $cm^{-2}s^{-1}$ (250 μrad)	16.5 10^{34} $cm^{-2}s^{-1}$ (40 cm //-plane, 200 urad)







Flat optics are more sensitive than round to non-linear imperfections. Simulations have shown that flat with CC is viable at low chromaticity and negative octupoles is still viable.

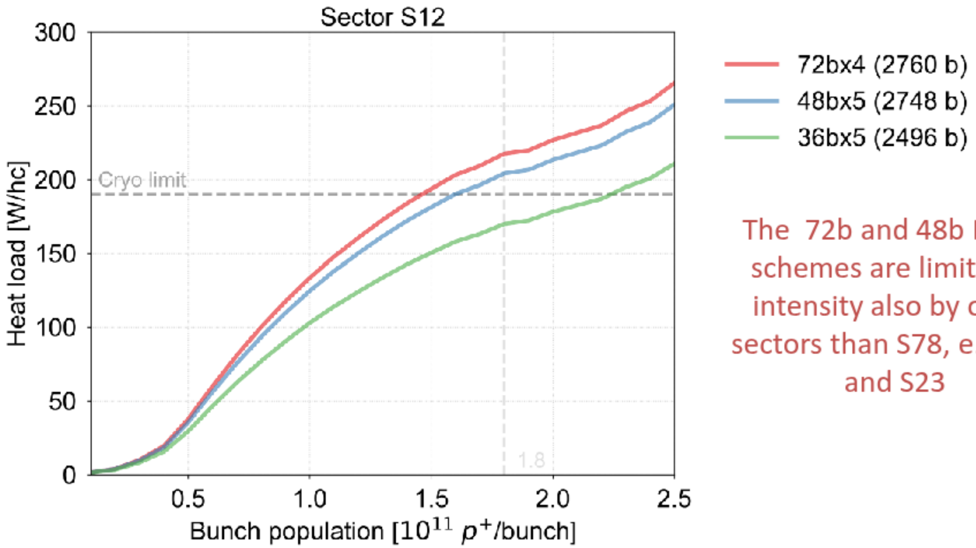
Experience expected in 2025 will provide insights on these scenarios.

Intensity reach for 2023 & Run 3

The intensity reach for different filling schemes is determined by the limitation in S78

	4x72b	5x48b	5x36b	hybrid-48b (*)	hybrid-36b (*)	8x24b	6x24b	8b+4e
N bunches	2760	2748	2496	2452	2464	2316	2220	1972
Intensity	1.1e11	1.2e11	1.5e11	1.75e11	2e11	2.1e11	2.3e11	2.3e11+

(*) Filling scheme candidates for 2023 by LPC



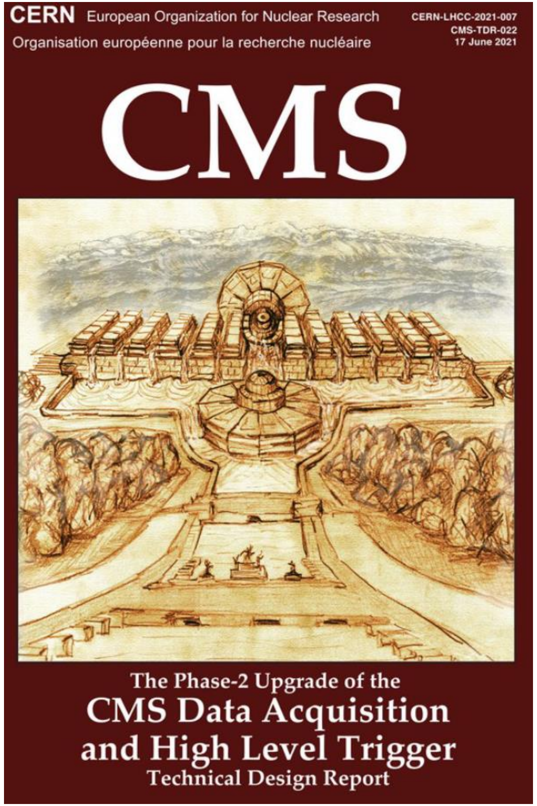
The 72b and 48b BCMS schemes are limited in intensity also by other sectors than S78, e.g. S12 and S23

Filling scheme options for 2025

	N_b	Collisions IP1/5	IP2	IP8	S78 heat load [W/hc] 1.6e11	1.8e11	Heat load per bunch	N_{bpi}	N_{inj}	SPS flat bottom [s]
6x36b	**2604**	2592	2097	2059	177	191	+1.1%	216	13	18
Hybrid-7+47x48b	**2604**	2592	2224	2313	174	187	-1.0%	240	13	14.4
5x36b	**2496**	2484	2121	2260	168	181	1	180	16	14.4
4x36b	**2460**	2448	2005	2146	164	177	-0.8%	144	20	10.8
3x36b	**2352**	2340	2004	2133	156	168	-1.5%	108	24	7.2

- Heat load differences between Nx36b-schemes comes mainly from the number of bunches, while the difference in heat load per bunch is around 1% ≈ 2 W/hc
  - → It makes sense to choose a filling scheme that allows adjusting the heat load to the cryo capacity by adapting the number of bunches (considering that neither heat load measurements nor predictions are 100% precise)
  - → Also gives more flexibility for optimising heat load & performance as a function of the bunch intensity

See presentation by X. Buffat this afternoon for further performance considerations



Chapter 1

Introduction: HL-LHC and the CMS Phase-2 Upgrades

The High Luminosity LHC (HL-LHC), will start operating after the third Long Shutdown (LS3), and is designed to provide an ultimate instantaneous luminosity of 7.5×10^{34} cm^{-2}s^{-1}, at the price of extreme pileup of up to 200 interactions per crossing. In LS3, the CMS detector will also undergo a major upgrade to prepare for the Phase-2 of the LHC physics program, starting in the second half of 2027 (Fig. 1.1).

Performance reach

It is important for the discussion to appreciate some counterintuitive aspects of HL-LHC integrated luminosity estimates.

$$L_{\text{average}} = L_{\text{levelling}} \frac{t_{\text{levelling}}}{t_{\text{leveling}} + t_{\text{turnaround}}}$$

$$t_{\text{levelling}} = \frac{N_i}{n_{\text{ip}} \sigma L_{\text{levelling}}} \left(1 - \sqrt{\frac{L_{\text{leveling}}}{L_{\text{virt}}}}\right)$$

Increase L_levelling
Increase N_i and L_virt

Performance reach

It is important for the discussion to appreciate some counterintuitive aspects of HL-LHC integrated luminosity estimates.

$$L_{\text{average}} = L_{\text{levelling}} \frac{t_{\text{levelling}} + \frac{t_{\text{decay}}\tau}{t_{\text{decay}}+\tau}}{t_{\text{leveling}} + t_{\text{decay}} + t_{\text{turnaround}}}$$

$$t_{\text{levelling}} = \frac{N_i}{n_{\text{ip}}\sigma L_{\text{levelling}}} \left(1 - \sqrt{\frac{L_{\text{leveling}}}{L_{\text{virt}}}}\right)$$

$$L_{\text{average}} = \frac{N_i}{n_{\text{ip}}\sigma} \left(1 - \sqrt{\frac{L_{\text{leveling}}}{L_{\text{virt}}}}\right) \left(1 + \frac{\frac{t_{\text{decay}}\tau}{t_{\text{levelling}}\left(t_{\text{decay}}+\tau\right)}}{1 + \frac{t_{\text{turnaround}}}{t_{\text{leveling}}} + \frac{t_{\text{decay}}}{t_{\text{leveling}}}}\right)$$

‡ The equations used are [15]: $\frac{dN}{dt} = -\frac{N}{\tau} = -n_{\mathrm{IP}}\sigma L_{\mathrm{lev}}$; $\tau = \frac{N}{n_{\mathrm{IP}}\sigma L_{\mathrm{lev}}}$; $L_{\mathrm{virt}} = k\, L_{\mathrm{lev}}$; $t_{\mathrm{lev}} = \tau\left(1 - \frac{1}{\sqrt{k}}\right)$; $t_{\mathrm{decay}} = \frac{\tau}{2-\frac{1}{\sqrt{k}}}\left(-1 + \frac{1}{\sqrt{k}} + \sqrt{\left(1-\frac{1}{\sqrt{k}}\right)^2 + \left(2-\frac{1}{\sqrt{k}}\right)\frac{t_{\mathrm{turnaround}}}{\tau}}\right)$;

$L_{\mathrm{average}} = L_{\mathrm{lev}} \frac{t_{\mathrm{lev}} + \frac{t_{\mathrm{decay}}\tau}{t_{\mathrm{decay}}+\tau}}{t_{\mathrm{lev}} + t_{\mathrm{decay}} + t_{\mathrm{turnaround}}}$; .

Reference

Run	Year	Efficiency	Bunch intensity (1e11 ppb)	$\beta_{//}^*$ (cm)	β_x^* (cm)	CC	PU_{max}	Days Intensity ramp-up	Days Proton physics [2]	# colliding IP1/5 bunches [3]	# colliding IP8 bunches	Emit start of SB (μm)	IP1/5 crossing plane	IP1/5 φ/2 (μrad)	LHCb L_{peak} (1e33 Hz/cm²) [4]	Losses (mb)	Emittance growth (um/h)
4	2030	0.5	1.8 (1.6)	30	30	off	101	20	6 **[1]**	2748	2574	2.5	H/V	250	2	110	Extra V 0.04
	2031	0.5	2.2	25	25	on	132	15	136	2748	2574	2.5	H/V	250	2	110	Extra V 0.04 + CC noise
	2032	0.5	2.2	20	20	on	132	10	154	2748	2574	2.5	H/V	250	2	110	Extra V 0.04 + CC noise
	2033	0.5	2.2	20	20	on	132	10	152	2748	2574	2.5	H/V	250	2	110	Extra V 0.04 + CC noise
5	2036	0.5	2.2	15	15	on	132	15	152	2748	2574	2.5	H/V	250	2	110	Extra V 0.04 + CC noise
	2037	0.5	2.2	15	15	on	132	10	195	2748	2574	2.5	H/V	250	2	110	Extra V 0.04 + CC noise
	2038	0.5	2.2	15	15	on	132	10	198	2748	2574	2.5	H/V	250	2	110	Extra V 0.04 + CC noise
	2039	0.5	2.2	15	15	on	132	10	198	2748	2574	2.5	H/V	250	2	110	Extra V 0.04 + CC noise
	2040	0.5	2.2	15	15	on	132	15	165	2748	2574	2.5	H/V	250	2	110	Extra V 0.04 + CC noise
	2041	0.5	2.2	15	15	on	132	10	203	2748	2574	2.5	H/V	250	2	110	Extra V 0.04 + CC noise

[1]: Reaching 1.6e11 ppb and not 1.8e11 ppb at the end of 2030.
[2]: Same numbers of days as DMR M. Zerlauth, 29 days of ions per year in Run4 and 25 days/year in Run5.
[3]: 25ns_2760b_2748_2492_2574_288bpi_13inj_800ns_bs200ns
[4]: Not considering LHCb upgrade after LS4, up to 3% loss of integrated lumi for ATLAS/CMS.

Relative yearly & total integrated luminosity

Run	Year	Reference (fb^{-1})	Round, 90 mb	Flat optics	Flat optics, 200 urad	Flat optics, 90 mb	Reference, 200 PU	Round, 90 mb, 200 PU	Flat optics, 200 PU	Flat optics, 90 mb, 200 PU
4	2030	31.99	33.7	35.33	38.24	37.31	31.99	33.71	35.33	37.31
	2031	205.54	216.38	210.85	214.89	221.8	237.35	253.13	247.72	264.29
	2032	236.85	248.73	252.76	256.5	263.97	283	301.39	318.88	338.27
	2033	233.82	245.55	249.54	253.23	260.61	279.4	297.52	314.8	333.95
5	2036	208.12	218	214.33	217.68	223.93	256.37	272.5	269.8	286.36
	2037	271	283.75	278.55	282.64	290.88	334.56	355.51	351.53	372.9
	2038	275.72	288.68	283.38	287.54	295.92	340.39	361.71	357.65	379.39
	2039	275.72	288.68	283.38	287.54	295.92	340.39	361.71	357.65	379.39
	2040	228.54	239.37	235.28	238.92	245.8	281.67	299.38	296.38	314.49
	2041	283.57	296.9	291.44	295.71	304.34	350.13	372.1	367.86	390.21
		2250.89	2359.77	2334.86	2372.88	2440.5	2735.3	2908.62	2917.64	3096.54
	+ 520	2770.9	2879.8	2854.9	2892.9	2960.5	3255.3	3482.6	3437.6	3616.5

1. Flat means 18/60 cm for 2030, 14/40 cm for 2031 and 8/18 for the rest
2. 2030 leveling time is 0 with round, but there is some leveling time (0.8 h) with flat
3. 200 PU means 101 max PU for 2030 and 200 for the rest
4. Flat and 200 urad means that crossing angle is reduced to 200, based on DA this is extreme, only 220 possible.

Relative yearly & total integrated luminosity

Run	Year	Reference (fb^{-1})	Round, 90 mb	Flat optics	Flat optics, 200 urad	Flat optics, 90 mb	Reference, 200 PU	Round, 90 mb, 200 PU	Flat optics, 200 PU	Flat optics, 90 mb, 200 PU
4	2030	31.99	5.4	10.4	19.5	16.6	0	5.4	10.4	16.6
	2031	205.54	5.3	2.6	4.6	7.9	15.5	23.2	20.5	28.6
	2032	236.85	5	6.7	8.3	11.5	19.5	27.2	34.6	42.8
	2033	233.82	5	6.7	8.3	11.5	19.5	27.2	34.6	42.8
5	2036	208.12	4.8	3	4.3	7.6	23.2	31	29.7	37.6
	2037	271	4.7	2.8	4.3	7.3	23.4	31.12	29.7	37.6
	2038	275.72	4.7	2.8	4.3	7.3	23.5	31.12	29.7	37.6
	2039	275.72	4.7	2.8	4.3	7.3	23.5	31.2	29.7	37.6
	2040	228.54	4.7	2.9	4.5	7.5	23.2	31	29.7	37.6
	2041	283.57	4.7	2.8	4.3	7.3	23.5	31.2	29.7	37.6
		2250.89	4.8	3.7	5.4	8.4	21.5	29.2	29.6	37.6