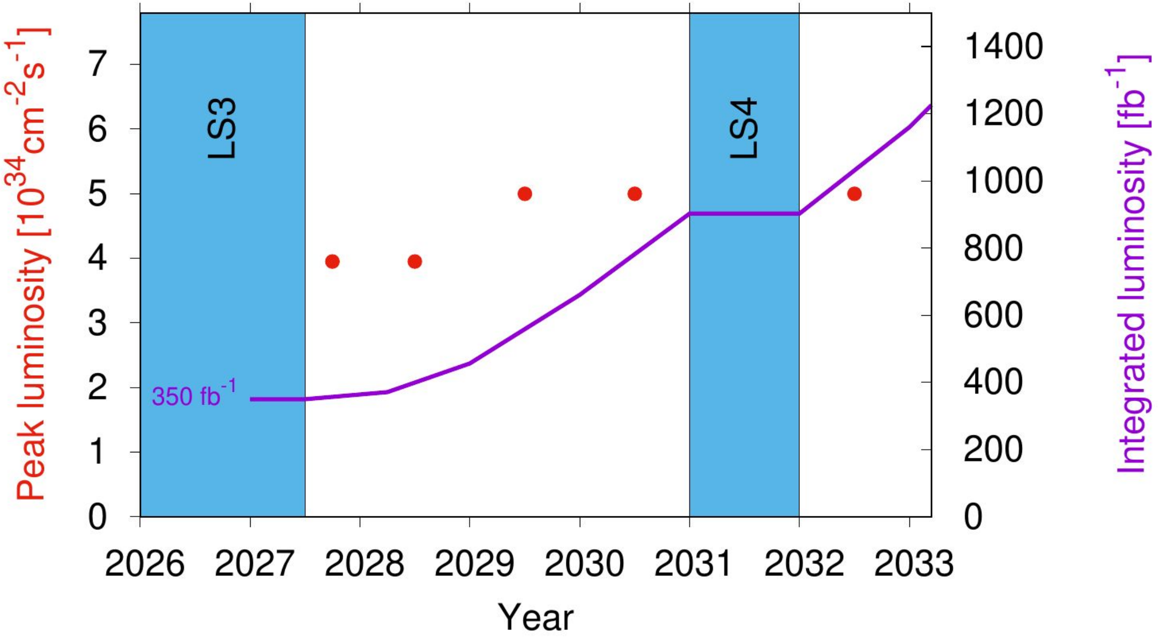
Towards a new Run 4 baseline

WP2 and friends

Contents

- Why a new baseline?
  - Latest fully documented baseline in CERN-ACC-2022-0001
  - New additions to the baseline: MS10 & BETS upgrade
  - Removal of the 11T dipoles and HEL from the baseline
  - Newly found CC main mode instabilities
  - Newly found e-cloud limitations in Run 3
  - Evolving schedule
  - LIU beams arrived in 2023 *(almost)*
- Options under consideration
- First validations: DA and power deposition studies
- Summary & Outlook

Latest Run 4 baseline CERN-ACC-2022-0001



Run length of 3.5 years, β^*=20 cm, with HEL, no MS10, primary coll. at 8.5σ, integrated luminosity: 550 fb^{-1} = **21 + 85 + 205 + 242 fb^{-1}** (3% below HL target: 250)

R. Tomas in HL-LHC collaboration meeting, Sept. 2023

EDMS NO.	REV.	VALIDITY
2796793	0.1	DRAFT

REFERENCE : LHC-M-EC-0007

HL – LHC Engineering Change Request
Installation of Lattice Sextupole in Q10 in Points 1 and 5 during LS3

ECR DESCRIPTION			
WP Originator	WP1, WP2, WP3	***Process***	HL-LHC Cryomagnet installation and refurbishment
Equipment	Additional MS in Q10 in Points 1 and 5	***Baseline affected***	Scope, Cost, Schedule
Drawing	Layout drawings for Points 1 and 5	***Date of Issue***	2022-11-01
Document	None	***CI responsible***	E. Todesco, R. Tomas, P. Fessia

EDMS NO.	REV.	VALIDITY
2924690	0.1	DRAFT

REFERENCE : LHC-MKBC-EC-0001

HL – LHC Engineering Change Request
TCDQ BETS UPGRADE

ECR DESCRIPTION			
WP Originator	WP14	***Process***	Engineering
Equipment	TCDQ	***Baseline affected***	Scope, Cost
Drawing	None	***Date of Issue***	2023-09-12
Document	None	***CI responsible***	C. Bracco

New additions: MS10 and BETS upgrade

Both MS10 and BETS upgrade increase the flexibility in the optics design allowing to reduce β^* below 20 cm down to 15 cm (round optics) and further down to 7.5 cm in one plane (flat optics).

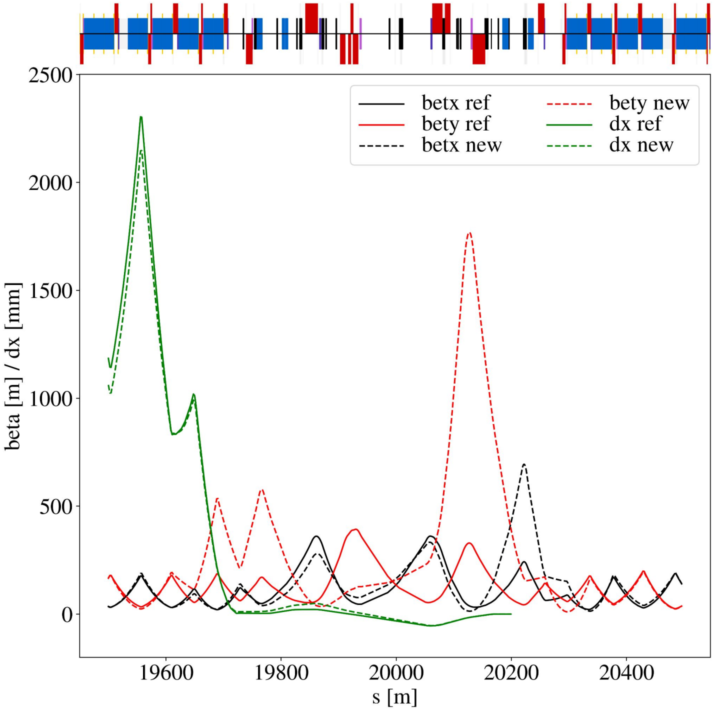
Thanks Chiara, Ezio, Oliver, Markus, Paolo, etc.!

EDMS NO.	REV.	VALIDITY
2938368	**0.1**	**DRAFT**

REFERENCE: LHC-LBH-EC-0002

HL – LHC Engineering Change Request
Descoping of 11T from HL-LHC project (installation during LS3)

ECR DESCRIPTION



Implication for protons: degraded collimation performance in IR7, but still ok.

Mitigation for protons: a **new IR7 optics** for improving both impedance and collimation efficiency, as proposed by WP5, see [B. Lindstrom in WP2/5 meeting]

More by S. Redaelli in **Collimation status**

CERN HiLumi HL-LHC PROJECT

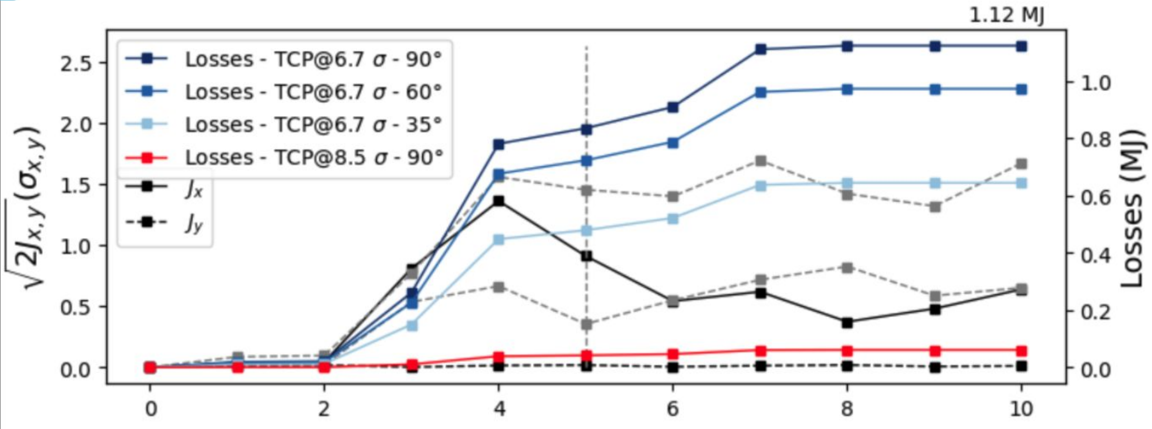
EDMS NO.	REV.	VALIDITY
2780816	1.0	VALID

REFERENCE : LHC-THE-ED-0004

HL-LHC: Decision Management Report
Descoping of Hollow-electron Lens from HL-LHC project

Decision Description			
WP5.3	Production hollow e-lens WP5.3	***Date of Issue***	2022-11-04

Simulations of CC phase slip failure from D. Wollmann et al. chamonix 2023, losses vs. turn-number:



More by D. Wollmann in **Machine Protection status and plans**

Implication: Risk of collimator damage from halo population in fast failures

First mitigation: Keep collimators at larger aperture (e.g. 8.5σ vs. 6.7σ).

Second mitigation: Optimize phase advance between crab cavities and collimators (TCPs)

→**New optics needed**

Third mitigation: Flat optics (lower β @ CCs) - to be analyzed

→New phase of 35° decreases losses by about a factor 2.

→Larger gap (8.5σ) decreases losses by about factor 10.

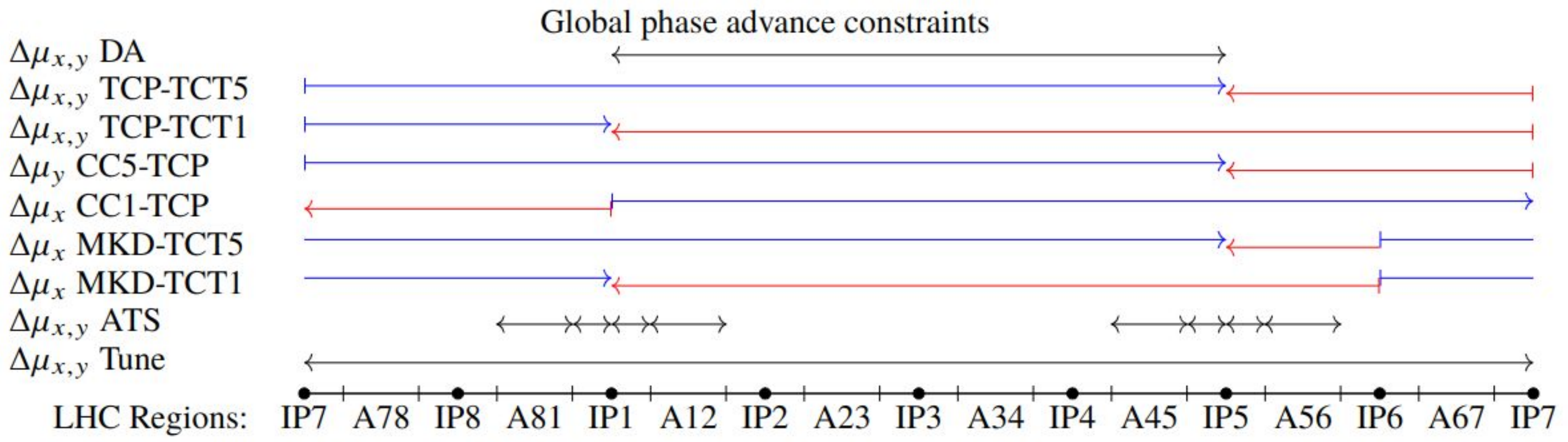
HEL could come in Run 5!!!

S. Redaelli, C. Hernalsteens, D. Wollmann, **Machine protection challenges for Run 4** , LHC Chamonix workshop 2023:

Conclusions

- Crab cavity failures (phase slip) and spurious CLIQ discharges will be the **most critical fast failures** in the HL-LHC era requiring
  - **fast, dedicated interlocks,**
  - **phase advance conditions** CC-TCP.
- The most critical crab cavity failures **need to be studied with beam** in the SPS.
- **Halo depletion reduces the criticality** of the failure cases with dedicated interlocks. Where protection depends on beam losses (BLM / BCCM) the **criticality is increased**.
- **Relaxed collimator** settings can **reduce the criticality** of all discussed failure cases.
- **Halo models** for **relaxed** collimator settings **need to be validated** by halo measurements.
- Reliable and interlock-able **halo monitoring is essential** to profit from the margins provided by the reduced criticality of most failure cases due to lower halo population.

Illustration of phase advance constraints used in optics design



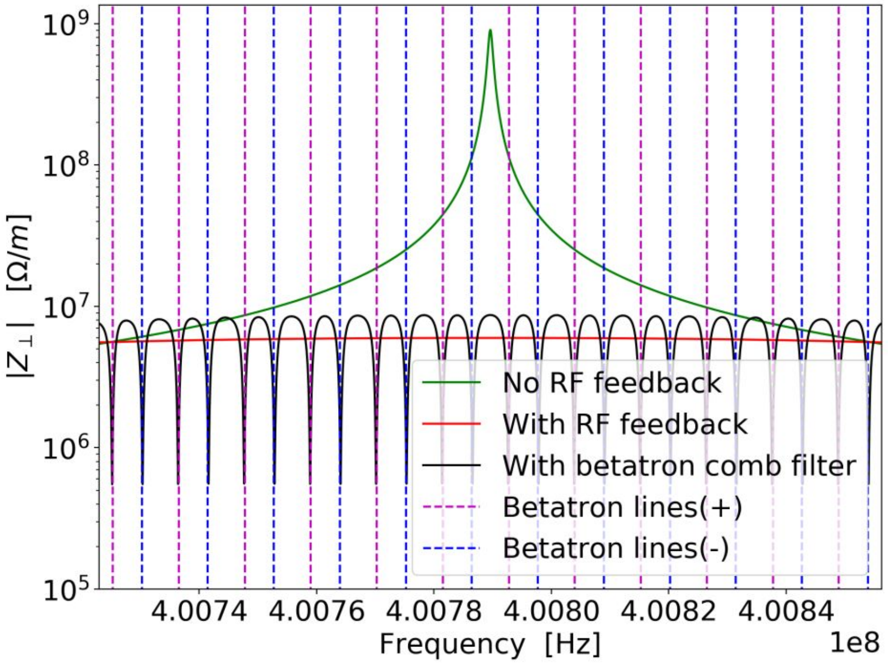
R. De Maria, *Increasing High Luminosity LHC dynamic aperture using optics optimizations,* HB2023

Newly found Crab cavity main mode instability

Implication: Beam stability needs extra 280 Amps in Landau octs. (with RF feedback)→ *Increased losses!!*

First mitigation: Implementation of a new RF comb filter. Performance to be demonstrated and betatron tune variations limited to 0.005.

Second mitigation: Flat optics and the new IR7 optics* (and now IR3**) at flattop could also mitigate the instability.



See L. Giacomel *et al.* in WP2/4 meeting

More by N. Mounet in Wednesday PM - WP2/WP3/WP5/WP10/WP15
and R. Calaga et al in Thursday AM - WP2/WP4/WP13

*see slide 5

**Optics/coll. changes in IR3 can further reduce impedance

Newly found e-cloud limitations from SEY degradation

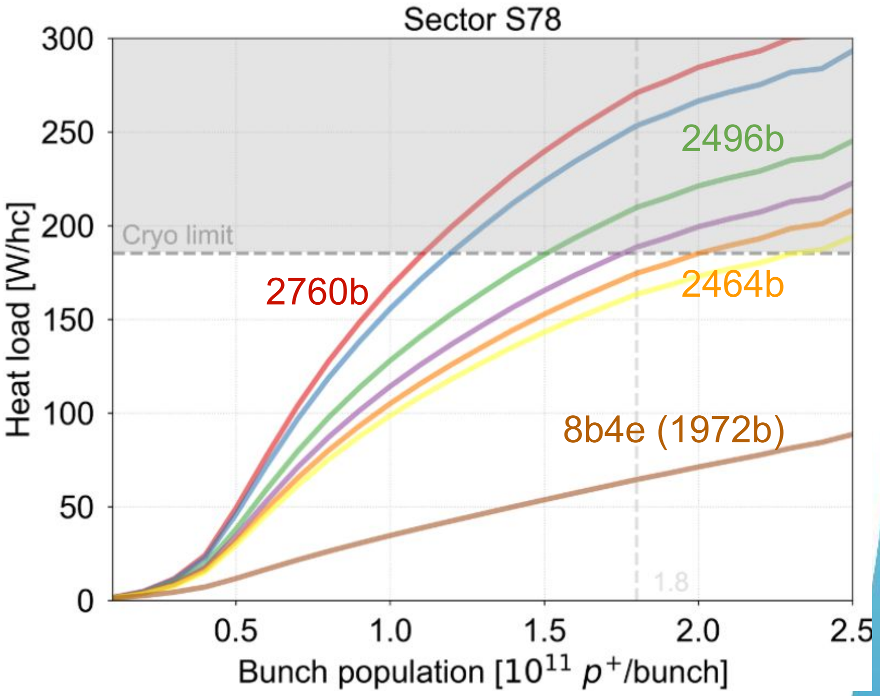
Implication: Stronger e-cloud increases heat-load and related instabilities and incoherent effects.

First mitigation: Reduce SEY by in-situ treatment, see [LMC Sep. 20th 2023]() and

V. Baglan, Electron cloud: potential mitigation strategies

Second mitigation: reduce number of bunches, increase bunch charge (Pile-up?)

Third mitigation: Optics optimization to reduce emittance growth from e-cloud at injection*. Implemented new optics in 2023 operation** to be tested in MDs (2024).



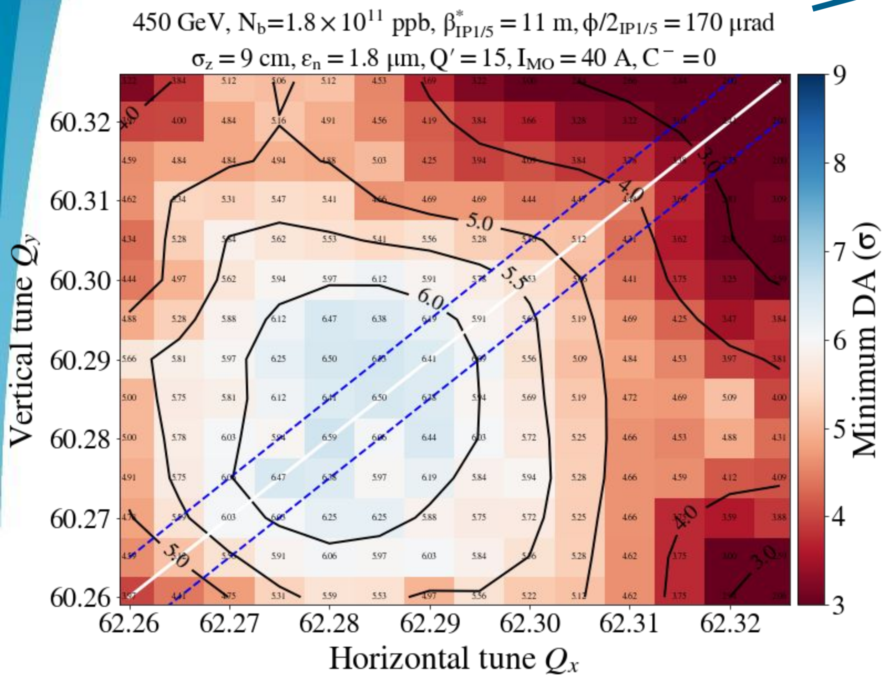
See L. Mether, Chamonix 2023

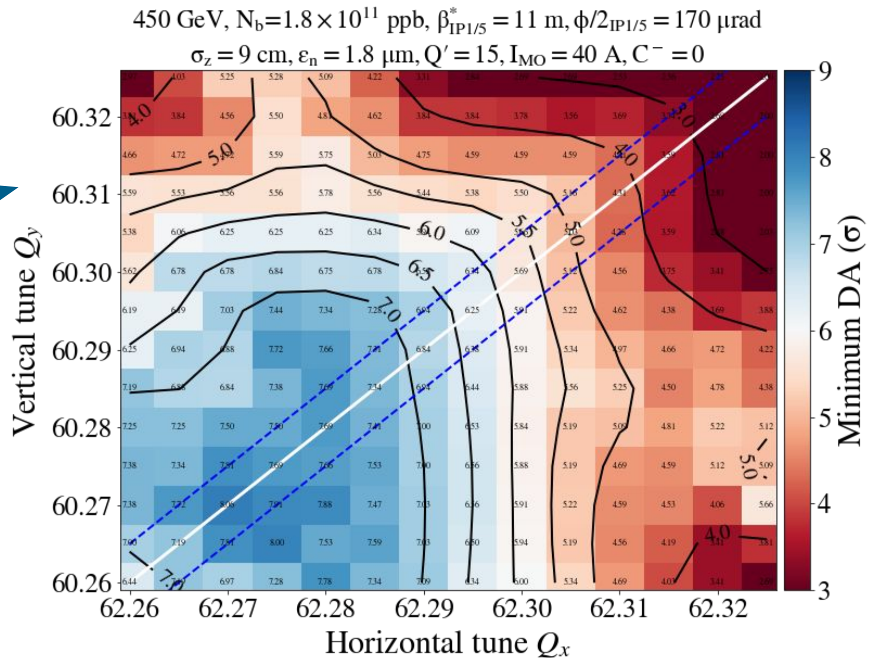
More by L. Mether in Wednesday PM - WP2/WP3/WP5/WP10/WP15

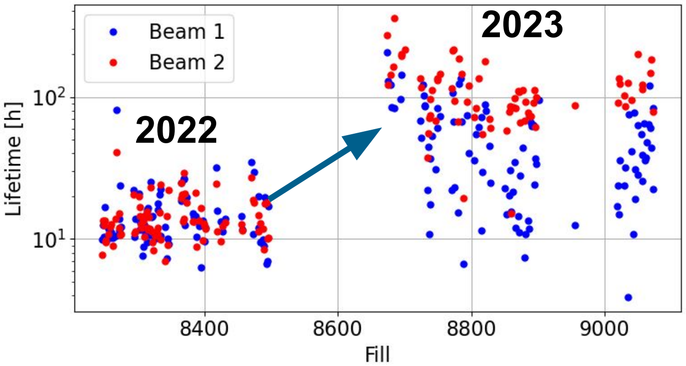
*K. Paraschou et al. *Emittance growth from electron clouds forming in the LHC arc quadrupoles*, HB2023.

**R. Tomás et al., *Optics for Landau damping with minimized octupolar resonances in the LHC*, HB2023

Improvement in DA and lifetime from the new injection optics in LHC





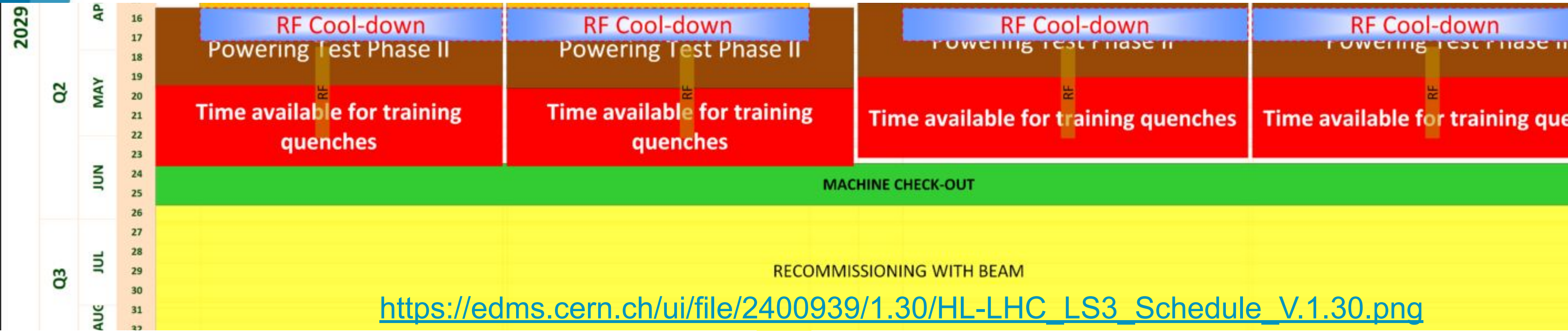


This new optics opens the door to negative octupole polarity

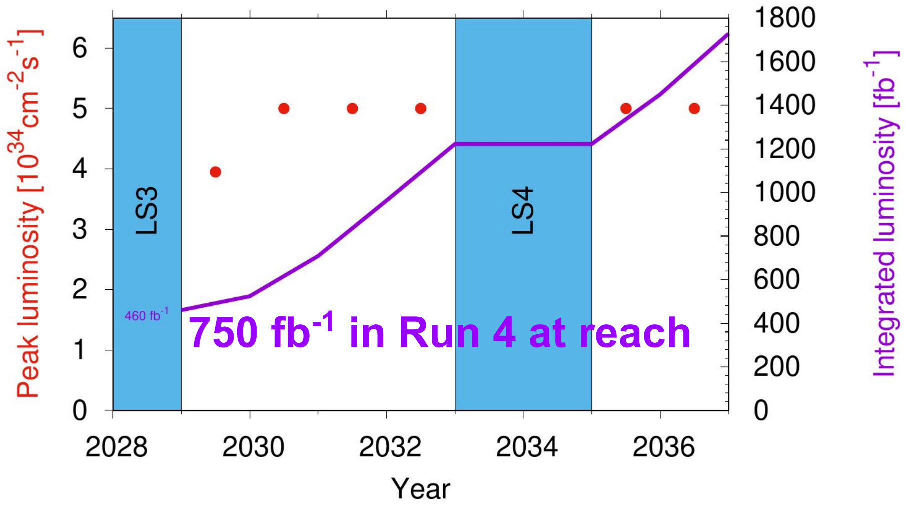
More in Wednesday PM - WP2/WP3/WP5/WP10/WP15

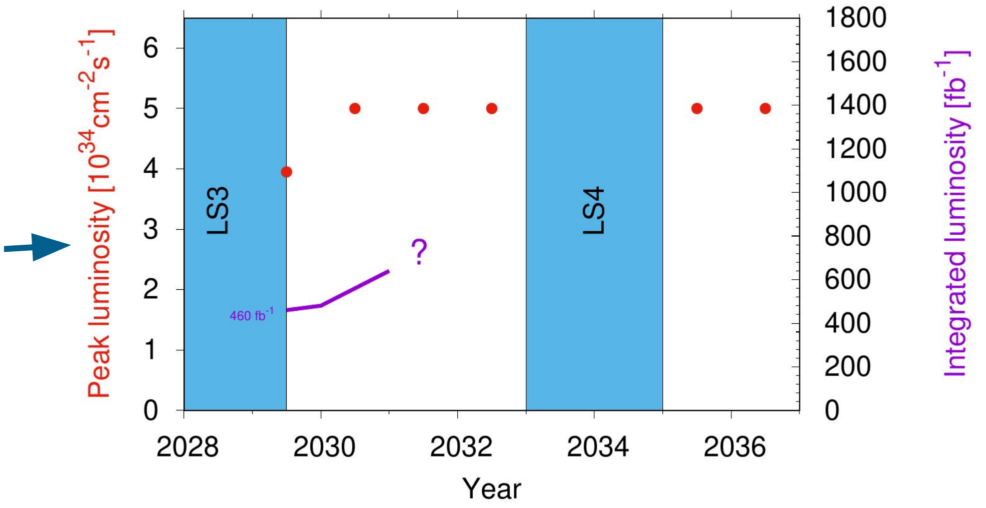
Evolving schedule

More by M. Modena in HL and LS3 installation plans



https://edms.cern.ch/ui/file/2400939/1.30/HL-LHC_LS3_Schedule_V.1.30.png





Evolving operation schedule - pp physics days

https://edms.cern.ch/document/2902691/0.1

Initial project assumption for pp physics days: reaching 160 days in Run 4, 200 days in Run 5 and 220 days in Run 6 (stopping ion physics, special runs and MDs from Run 5).

Now: Time to revise assumptions considering more MDs, scrubbing, intensity ramp-up, etc. Including new options as keeping ion physics or the 19 weeks YETS for reduced electricity bill → **Reduction of pp days**

Ongoing discussions

LIU beams arrived in 2023!!!! *(almost)*

See H. Bartosik's slides in [216th HL WP2 meeting]

year	Intensity at FT [p/b]	# of bunches	Batch spacing [ns]	Bunch length [ns]	Beam type	Date
2023	2.2e11	4 x 72	200	1.6	Standard	13.06.
2023	2.0e11	2 x 56	250	1.6	8b4e	05.04.
2023	1.8e11	56 + 5 x 36	200	1.6	hybrid	19.05.

Also very important for HL-LHC is that LIU beams have tails, at least Gaussian, which helps reducing the strength of the Landau octupoles (see **N. Mounet in Wednesday PM - WP2/WP3/WP5/WP10/WP15**).

Optics options end of leveling, Nominal scenario

For all cases: $L_{lev.}$= **5×10^{34} cm^{-2}/s**, crossing angle = 500 μm, crab cavity noise without feedback, Cryo step at 2.5×10^{34}cm^{-2}/s for 10min and linear ramp*, IBS emittance growth and SR damping, 160 days and 50% efficiency.

# of bunches	**β*x,y [cm]**	**L_{int} [fb^{-1}] (Δ [%])**	**ppb_{endLev} ppb_{end} [10^{11}]**	**Pile-up**	**Fill length [h]**
2748	15, 15	250	1.30-1.10	131	7.9
2748	18, 7.5	259 (+3.6)	1.10-0.96	131	8.7
2748	18, 9	257 (+2.8)	1.15-1.0	131	8.4

Flat optics improves the performance of the nominal scenario by **2.8%** or **3.6%** for β*=18,9cm and β*=18,7.5cm respectively.

*Cryo step (lumi & length) is under review

Optics options end of leveling, Ultimate

For all cases: $L_{lev.}$= **7.5×10^{34}cm^{-2}/s** (+same points as in previous slide)

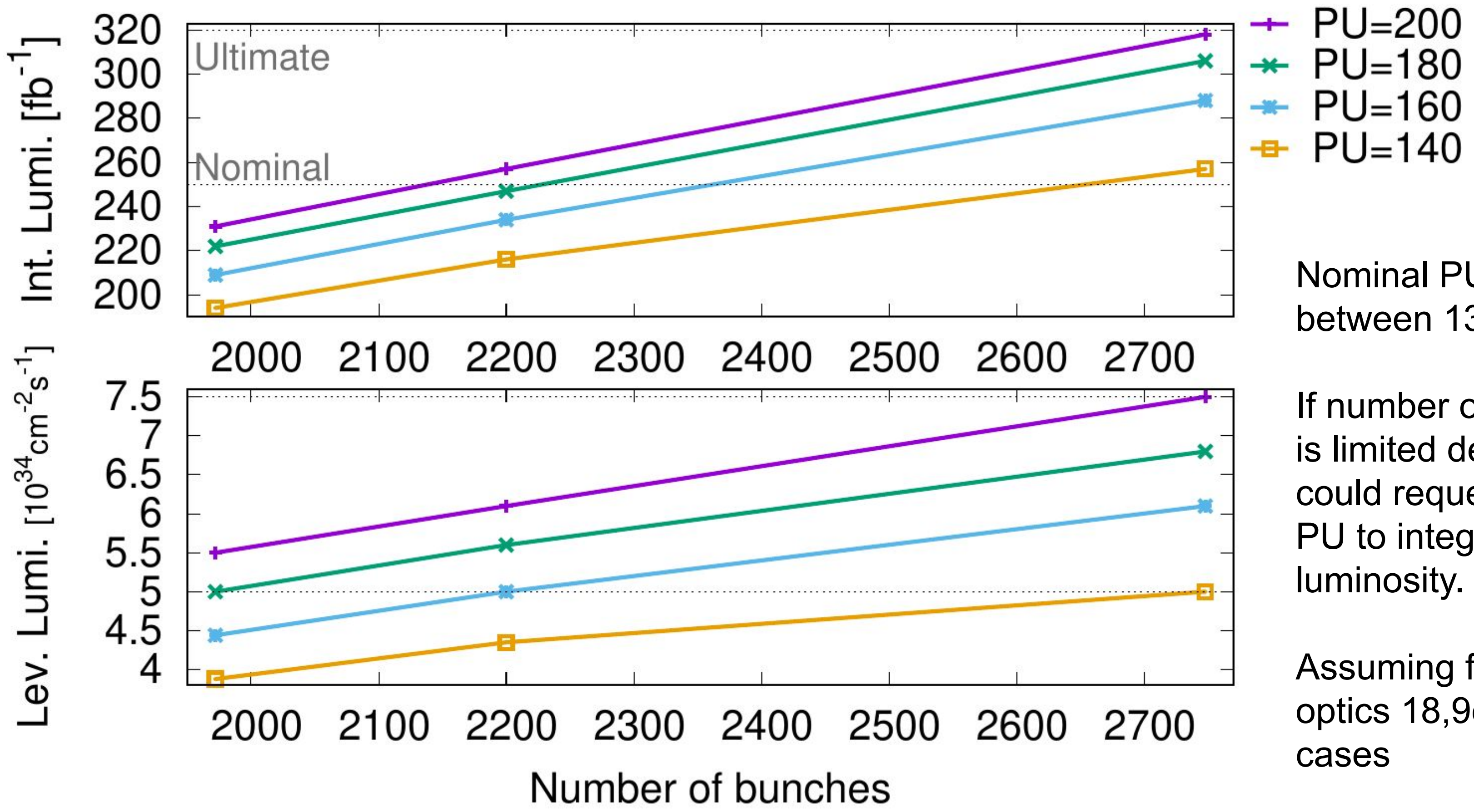
# of bunches	**β*x,y [cm]**	**L_{int} [fb^{-1}] (Δ [%])**	**ppb_{endLev} ppb_{end} [10^{11}]**	**Pile-up**	**Fill length [h]**
2748	15, 15	303	1.60-1.2	197	5.2
2748	18,7.5	323 (+6.6)	1.40-1.11	197	5.5
2748	18, 9	318 (+4.9)	1.40-1.13	197	5.4

Flat optics improves the performance of the Ultimate scenario by **4.9%** or **6.6%** for β*=18,9cm and β*=18,7.5cm, respectively.

Filling schemes for Run 4 under consideration

1. **2760 bunches**: Nominal, but not fully guaranteed even by fixing 100 half cells
2. **2X00 bunches**: Alternative in case of further degradation of SEY (under study).
3. **1972 bunches**: Pure 8b4e, very robust.

Integrated and leveled luminosity versus # of bunches & PU



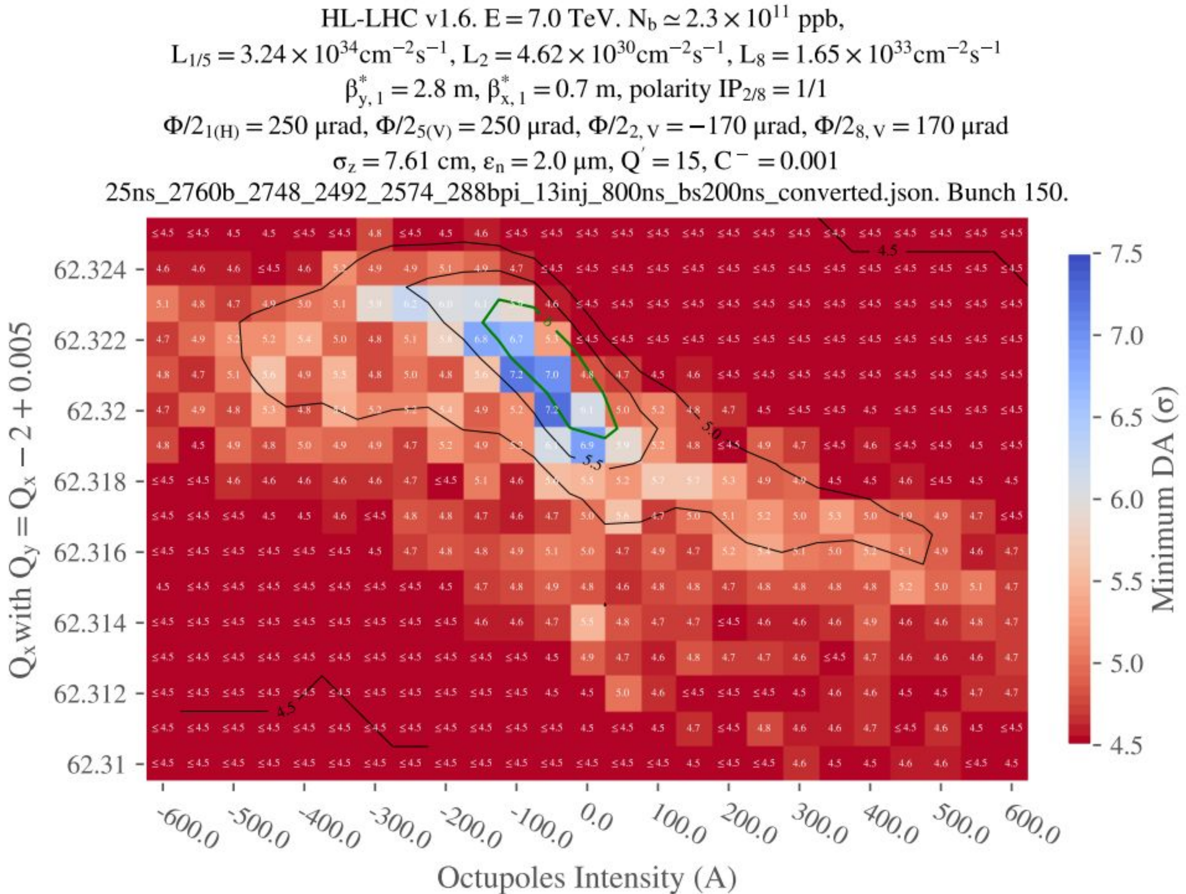
Nominal PU is between 131-140.

If number of bunches is limited detectors could request larger PU to integrate more luminosity.

Assuming for now Flat optics 18,9cm for all cases

First Dynamic Aperture validations

More by G. Sterbini in Wednesday PM - WP2/WP3/WP5/WP10/WP15



Both round and flat optics show promising DA results.

Optics are not yet final.

Hardest configuration is hybrid.

Power deposition studies for flat optics

More by M. Sabate in Wednesday PM - WP2/WP3/WP5/WP10/WP15

For IR5 with V crossing angle and small horizontal β^* (7.5-9cm):

Optics	Luminosity	D2 [W] (%)	TCLMB [W] (%)
Ref. design	Ultimate	28.3	35.7
Flat 18/9cm	Nominal	21.2	29.8
	Ultimate	31.8 (+12%)	44.7 (+25%)
Flat 18/7.5cm	Nominal	36.0 (+27%)	34.6
	Ultimate	54 (+90%)	51.9 (+45%)

"Ref. design" values are not hardware limits but estimates at Ult. lumi. We have asked corresponding WPs for the actual limits.

In IR1 there is no issue as small β^* is in V.

In Run 4 it is OK to use flat optics with a β^* somewhere in between 7.5-9cm. In the more pushed scenarios we could explore to optimize settings after hardware limits are known.

Summary & outlook

- ***For every obstacle, 2 or 3 mitigations are found!***
- Need further beam dynamics studies to converge on a more performant baseline(s) than in CERN-ACC-2022-0001
- Schedule concerns: Starting in the middle of the year, updated OP needs, 19 vs 15 weeks YETS, ion runs…

- Further performance push: the BBLR wire, see **Wednesday PM - WP2/WP13**
- HL could increase its integrated lumi lifetime above 4000fb^{-1} by swapping crossing angle planes and/or implementing the triplet reserved polarity optics, see **M. Sabate in Wednesday PM - WP2/WP3/WP5/WP10/WP15**

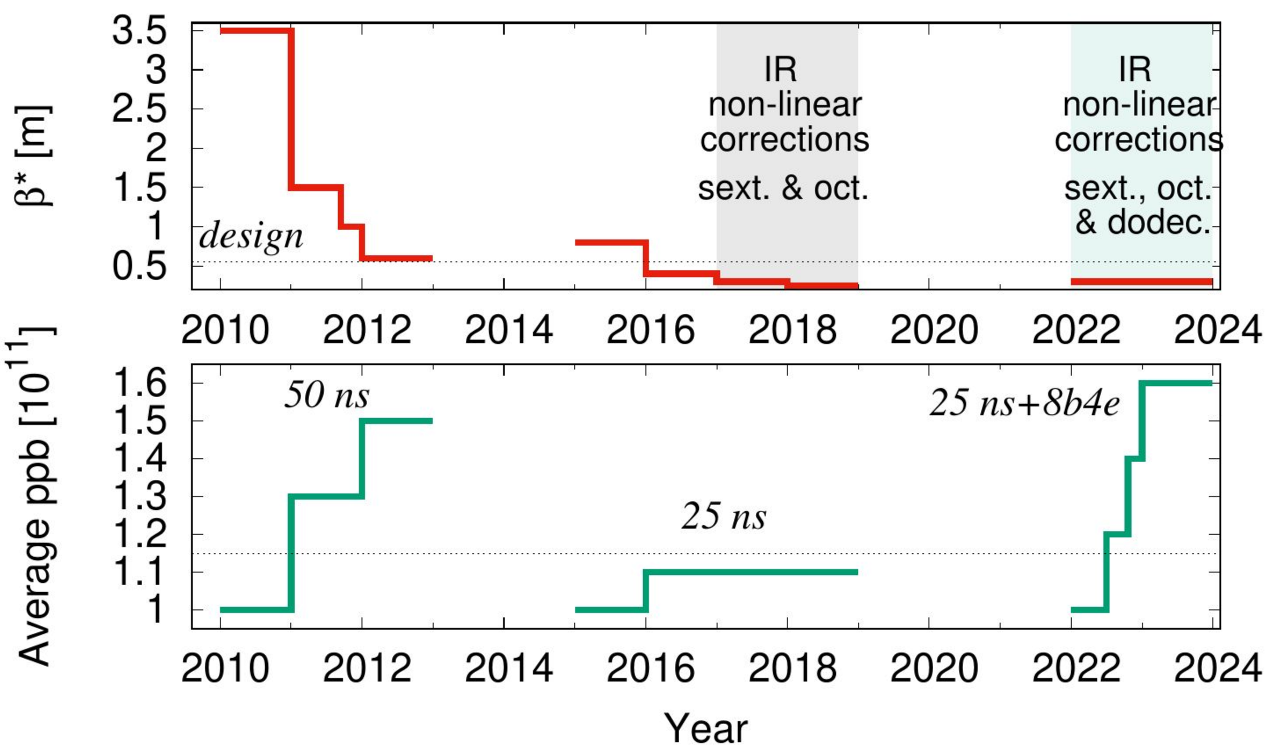
More about the baseline in M. Zerlauth's presentation: HL-LHC Baseline and TCC summary

HiLumi
HL-LHC PROJECT

Thank you for your attention

CERN

History: recalling LHC ramp-up



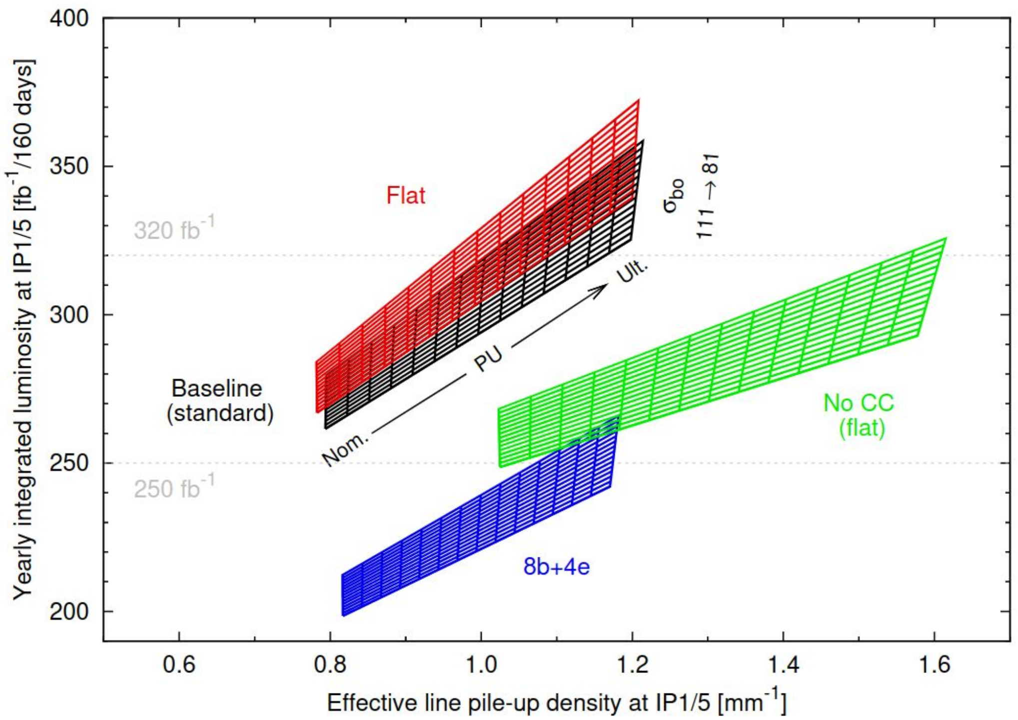
Prudent start and progress with β^*.
IR non-linear corrections took several years.

Steps of 10-30% in bunch charge.

Why moving to Flat optics now? HL-LHC book Chap. 5

Flat optics has always provided better performance than round.
However:
DA had not been fully validated.
BETS upgrade was not baseline.
MS10 was not Run 4 baseline.

Now we are in a much better situation! Also there were MDs in LHC with flat optics:
CERN-ACC-2019-052



Plus flat optics helps to mitigate CC impedance and emittance growth.

Luminosity ramp-up (previous schedule)

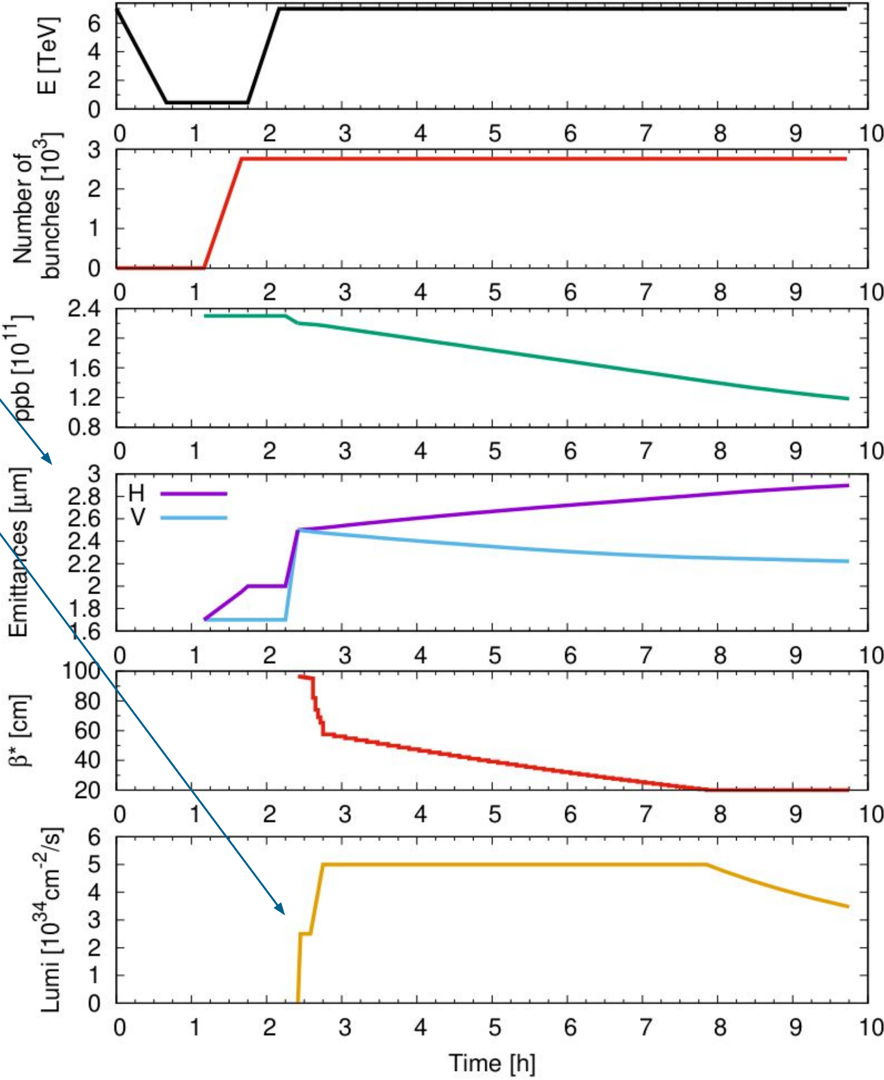
*under review

	Year	ppb $[10^{11}]$	Virtual lumi. $[10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	Days in physics	θ $[\mu\mathrm{rad}]$	β^*_{start} [cm]	β^*_{end} [cm]	HEL and CC	Max. PU
½ year	2027	1.7	3.95	30	380*	58	30	exp	104
	2028	1.7	3.95	120	380*	58	30	exp	104
	2029	2.2	10.3	140	500	100	25	on	132
	2030	2.2	13.5	160	500	100	20	on	132
	2031				Long shutdown 4				
	2032	2.2	13.5	170	500	100	20	on	132
	2033	2.2	16.9	200	500	100	15	on	132
	2033	2.2	16.9	200	500	100	15	on	200

- Minimum □* in Run 4 is 20cm
- Initial bunch intensity of 1.7×10^{11} ppb as placeholder to match Run 3 intensity
- HEL and CC to be thoroughly tested in 2027/28 before becoming operational in 2029

The Run 4 physics fill

- Emittance growth now includes the effect from the Crab cavity noise
- The crab cavity voltage is ramped up after the luminosity plateau for cryo
- In a year of 160 days of proton physics and assuming 50% efficiency 242 fb^{-1} are integrated.
- The luminosity model is being refined by I. Efthymiopoulos



Collimation settings

- Previous collimator settings with TCP at 6.7σ generated too high impedance making the beam unstable
- In new settings TCP increases gap to 8.5 σ, assuming the baseline collimator impedance upgrade
- These settings are being validated by WP5. Currently larger gaps introduce a mild increase of 7% in losses in DS, but not an obstacle for Run 4 scenario.

B. Lindstrom in [Special Joint HiLumi WP2/WP5 Meeting](#) - Tuesday, 24 August 2021

Some of the new collimation settings at 7 TeV end of leveling, for emittance of 2.5 μm and β*=20cm:

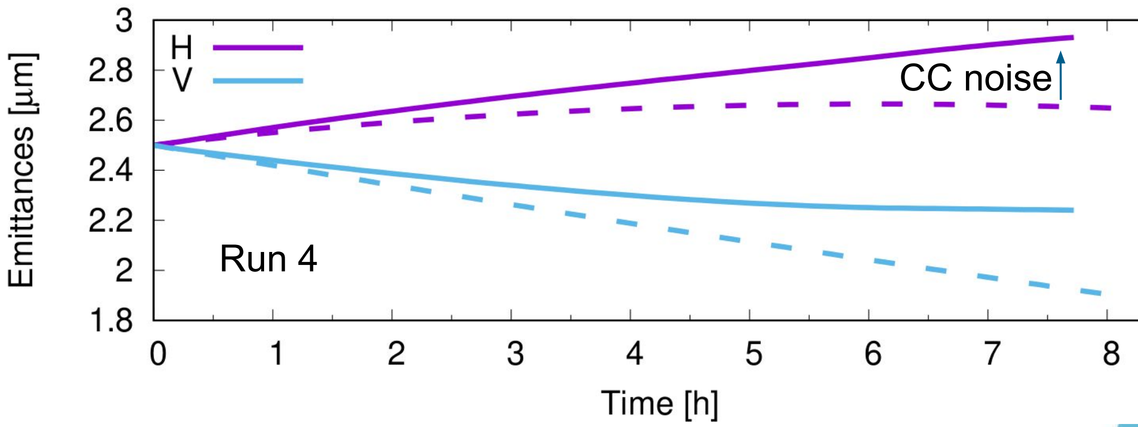
TCP/TCPM IR7 [σ]	8.5
TCSPM/TCSG IR7 [σ]	10.1
TCLA IR7 [σ]	13.7
TCP IR3 [σ]	17.7
TCSG IR3 [σ]	21.3
TCSP IR6 [σ]	11.1
TCT H4-V4-H6-V6 IR1&5 [σ]	13.2
TCDQ IR6 [σ]	11.1
TCL 4-5-6 IR1&5 [σ]	16.4

HiLumi HL-LHC PROJECT CERN

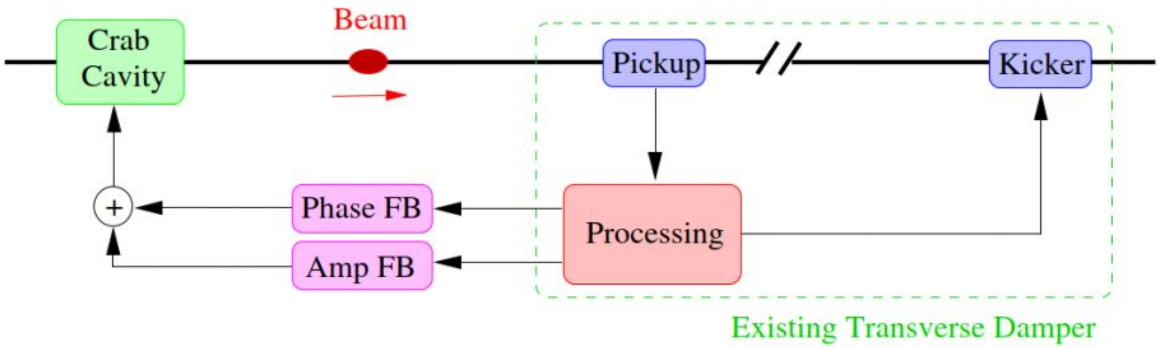
Crab cavity noise & a dedicated feedback

CC noise is now estimated larger than in CDR, still with acceptable luminosity loss in Run 4 of about 1%.

Progress understanding SPS results by N. Triantafyllou, 187th WP2



For Run 5 or new Run 4 situation is more critical and a dedicated feedback with new BPM is being explored (not in baseline). See WP2/WP4/WP13 joint meeting, June 2021



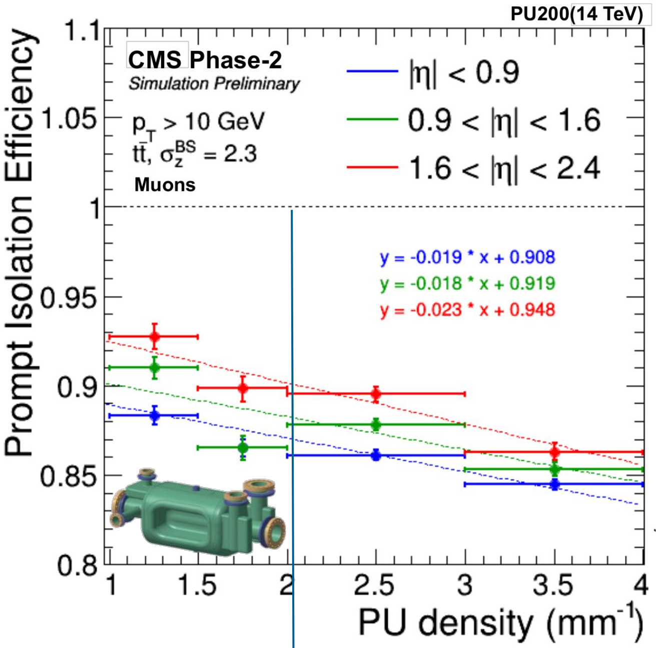
Benefit of crab cavities on detector performance

ATLAS publication:

ATL-PHYS-PUB-2021-023

In absence of CCs, to achieve the same significance of the data as with CCs, for $HH \rightarrow 4b$, experiments need to collect extra 340 fb^{-1} beyond the 3000 fb^{-1}.

This is in addition to the increase of geometric luminosity from CCs



with CCs ← | →without CCs

HL-LHC Experiment Data Quality WG report almost finished**:**

HL-LHC Experiment Data Quality Working Group

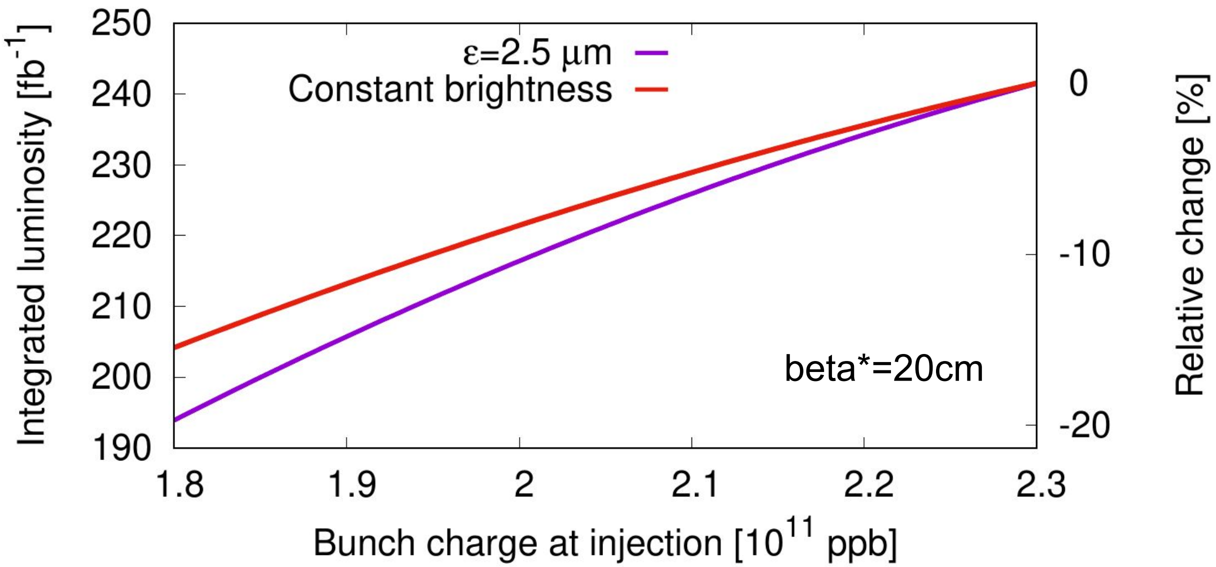
Summary Report

Working Group Members

I. Efthymiopoulos, L. Medina, R. Tomás,
CERN ATS Sector
S.M. Demers Konezny, K. Einsweiler, C. Ohm, B. Petersen, A. Polini, A. Sfyrla,
S. Pagan Griso, T. Strebler
(ATLAS Collaboration)
J. Bendavid, D.C. Gotardo, A. Dabrowski, F. Hartmann, J. Kieseler, L. Malgeri,
M. Narain, G. Pasztor, A. Savin, S. Sekmen, D. Stickland,
(CMS Collaboration)
L. Dufour, E. Thomas, M.R.J. Williams
(LHCb Collaboration)

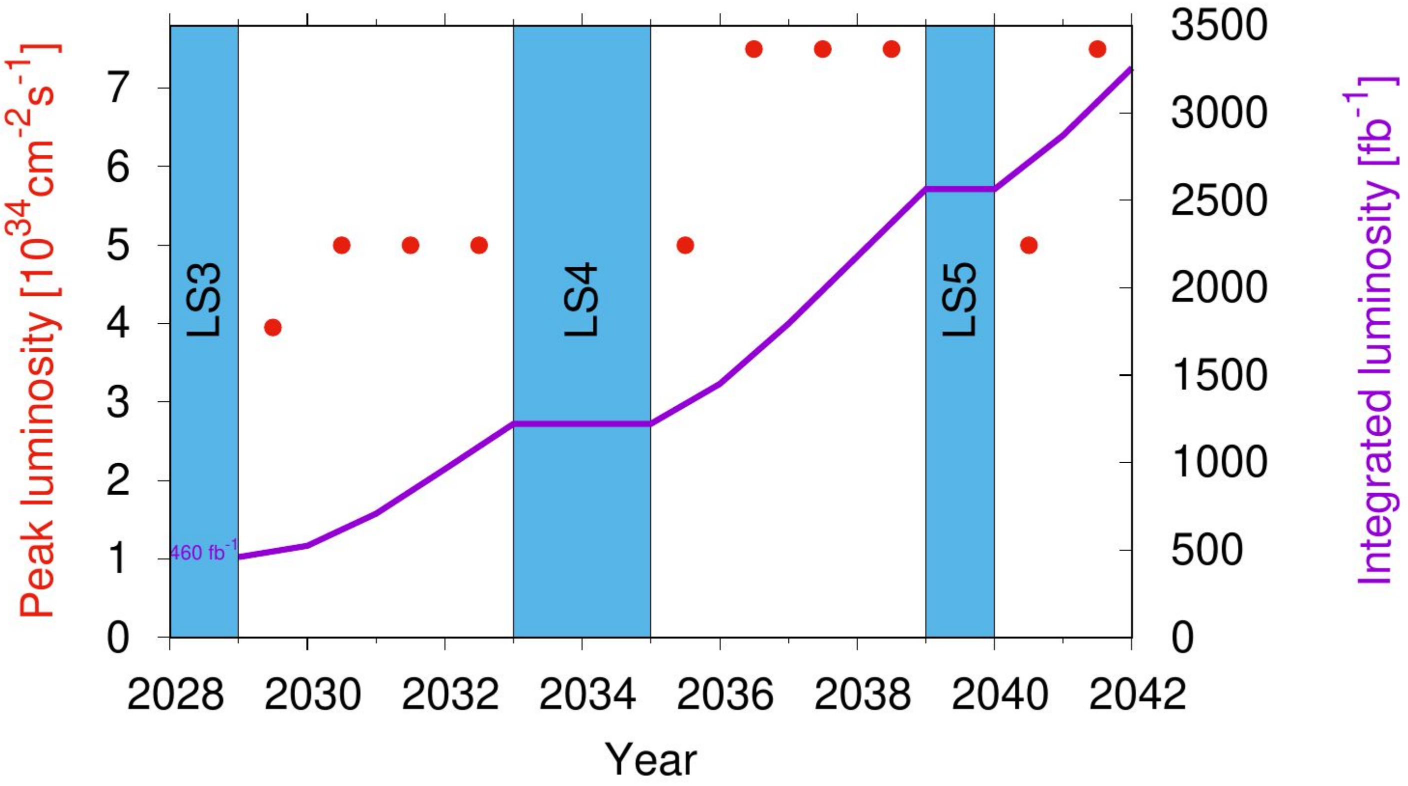
Performance with intensity limitation

Assuming emittance preservation

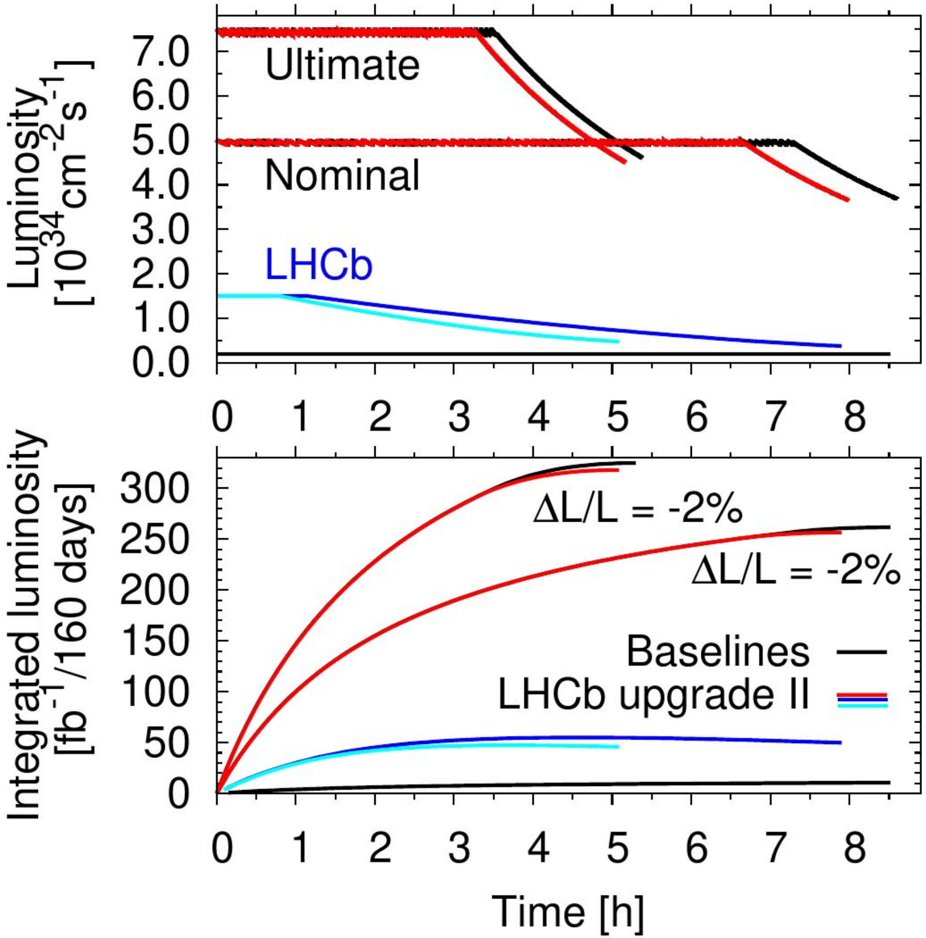


Performance loss up to 15-20%.
Pushing beta* during all Run 4 and enabling 15 cm could allow to still reach 650 fb^{-1} at 1.8×10^{11} ppb (MS10 & BETS and scenario to be validated).
However, reaching nominal intensity as soon as possible is a high priority for HL-LHC!

HL-LHC preliminary optimistic schedule
DG, 13/1/2022



LHCb upgrade II (in Run 5)



LHCb upgrade II, L lev = 1.5×10^{34} cm^{-2} s^{-1} would reduce ATLAS/CMS integrated luminosity by 2% for both Nominal and Ultimate.

Reduced lifetime from increased beam-beam not included here →**Need to develop a fully new operational scenario with LHCb II.**

Increased burn-off in IP8 casues bunch-by-bunch variations, under study.

R. Tomas in LHC performance workshop, January 2022