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Dynamic Aperture of the new HL-LHC baseline

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We thank Y. Angelis, H. Bartosik, R. De Maria, I. Efthymiopoulos, M. Giovannozzi, G. Iadarola, L. Mether, E. Métral, N. Mounet, Y. Papaphilippou, R. Tomás.

DA as main observable

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- HL-LHC performance strongly depends on the **orchestration of several beam and machine parameters during the cycle**.
- For the beam-beam and incoherent effects, the selection/validation of the operational scenario is based on numerical simulations supported by the experience of the past runs: previous studies demonstrated the **correlation between beam lifetime in operation and DA from simulations** [1].

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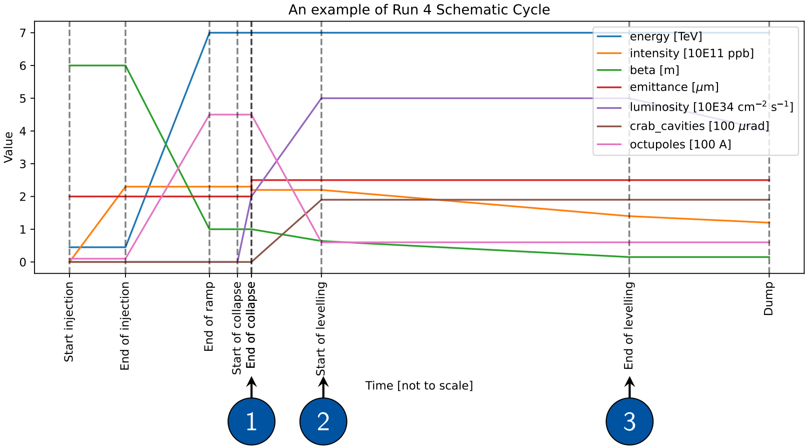
- Goal is to converge to the **best combination of optics, chromaticity, octupole current, crossing angle for stability, DA and overall performance** during various stages of HL-LHC cycle.
- Considering both round and flat optics ($\frac{\beta^*_x}{\beta^*_{//}} = 2$), positive and negative octupole polarity, option to reduce chromaticity (similar to 2024 Run) and crossing angle at the end of leveling.

Schematic of the Run 4 Cycle



Focusing on phases of cycle where beam-beam effects are dominating (courtesy of R. De Maria).

Filling scheme

The e-cloud problem being *a priori* resolved, only the baseline filling scheme is considered (25 ns standard beams, 4x72 bunches per injection):

- **baseline** (**2760** bunches):
  25ns_2760b_2748_2492_2574_288bpi_13inj_800ns_bs200ns

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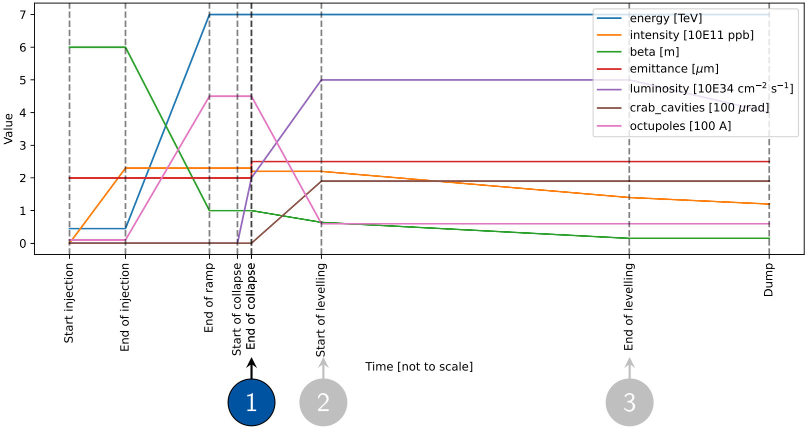
- **baseline** (**2760** bunches): **25ns_2760b_2748_2492_2574_288bpi_13inj_800ns_bs200ns**
- Simulating worst bunch in terms of head-on and long-range interactions in all IPs, not necessarily worst bunch in terms of DA. Similarly to bunch-by-bunch lifetime fluctuations, there are bunch-by-bunch DA variations not illustrated in the DA scans.

End of Collapse

An example of Run 4 Schematic Cycle

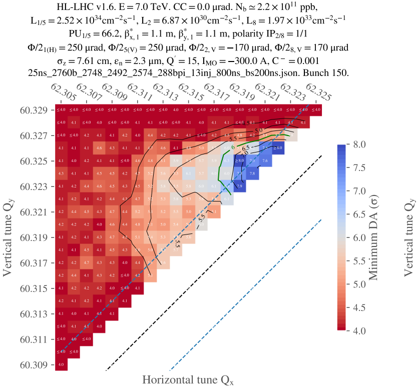


End of Collapse

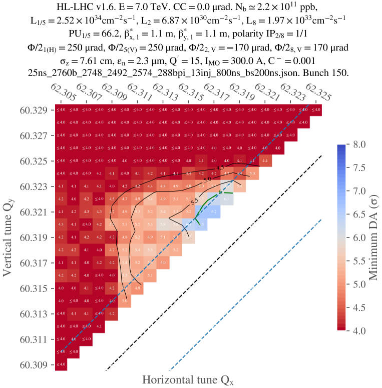
Parameters (unit)	HL-LHC (values)
Beam energy (TeV)	7
Luminosity (10^{34} Hz/cm^2)	**≈2.5**
Bunch population (protons)	2.2×10^{11}
Filling scheme	baseline
Normalised emittance (μm rad)	**2.3**
Nominal working point (Q_x, Q_y)	(62.31, 60.32)
Chromaticity $Q'_{x,y}$	15
IP1/5 half crossing angle (μrad)	250(H) / 250(V)
IP2/8 half crossing angle (μrad)	-170(V) / 170(V)
IP1/5 β^* (m)	**1.1** (round) or **0.9/1.8**
IP2/8 β^* (m)	10/1.5
Half crab-cavity angle (μrad)	0

Round optics: sensitivity to octupole polarity

I=-300A



I=300A

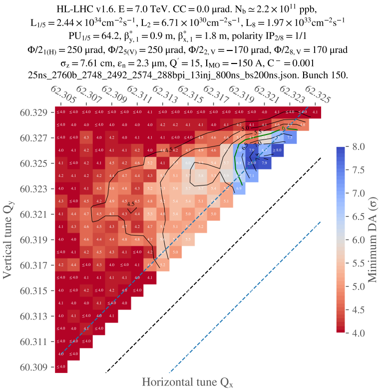


Baseline configuration marginally OK with $I_{OCT} = 300$ A.

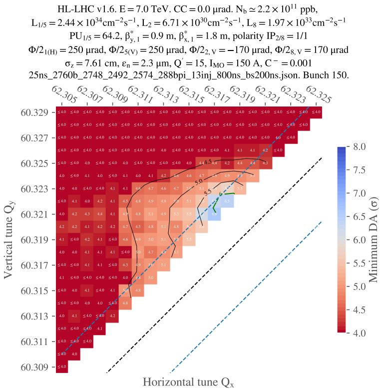
Negative octupoles option yields better results.

Flat optics: sensitivity to octupole polarity

I=-150 A



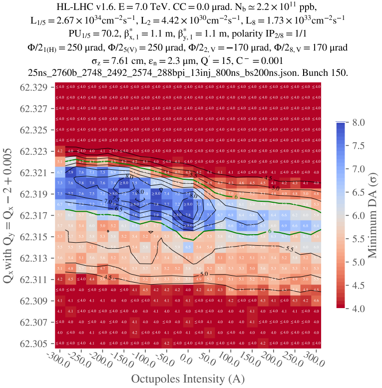
I=150 A



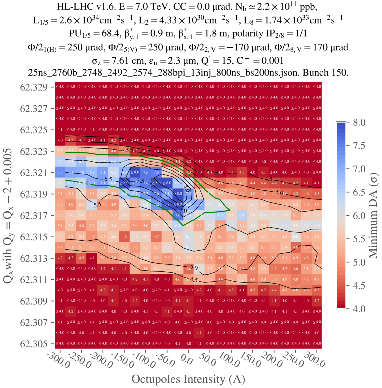
Negative octupoles option yields better results also with flat optics.

I_{MO} scan along the upper diagonal

Round optics

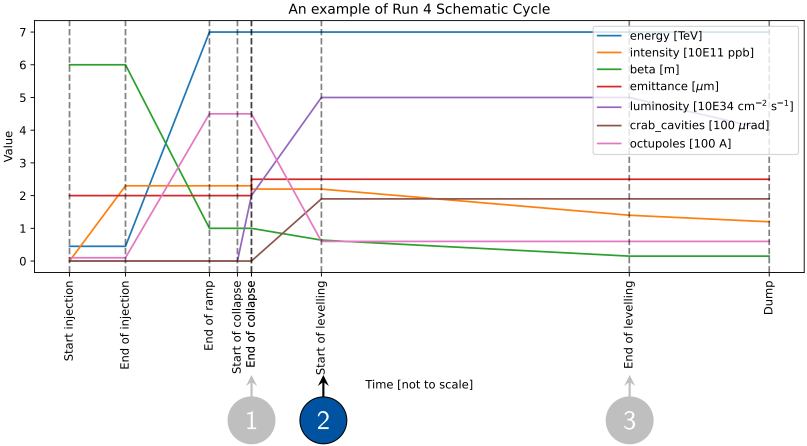


Flat optics



Flat optics could alleviate the impedance of the CC and increase integrated luminosity (current projections at +3%).

Start of $\mathcal{L}$-Levelling

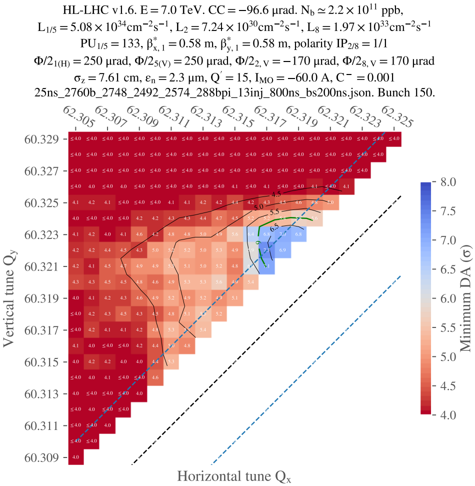


Start of the $\mathcal{L}$-levelling

Parameters (unit)	HL-LHC (values)
Beam energy (TeV)	7
Luminosity (10^{34} Hz/cm^2)	**5**
Bunch population (protons)	2.2×10^{11}
Filling scheme	baseline
Normalized emittance (μm rad)	2.3
Nominal working point (Q_x, Q_y)	(62.31, 60.32)
Chromaticity $Q'_{x,y}$	15
IP1/5 half crossing angle (μrad)	250(H) / 250(V)
IP2/8 half crossing angle (μrad)	-170(V) / 170(V)
IP1/5 β^* (m)	0.58 (**round**)
IP2/8 β^* (m)	10/1.5
Landau octupoles' current (A)	**-60A**
Half crab-cavity angle (μrad)	**-97**[1]

[1] This small value allows not to exceed target lumi as the current SoL optics not adapted for the baseline filling scheme.

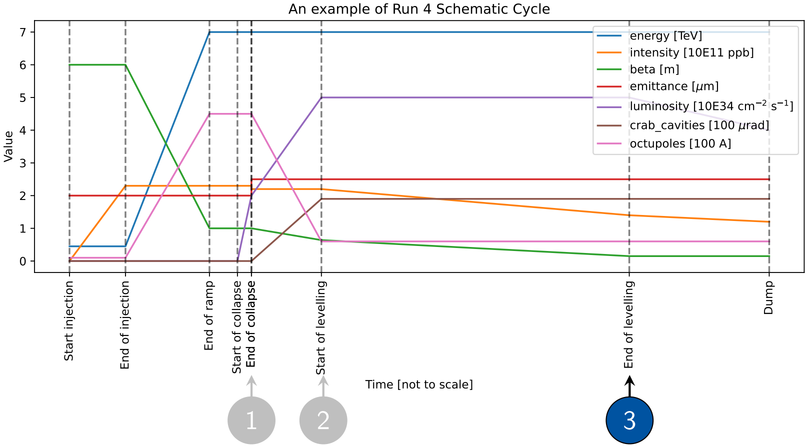
Tune scan



Reaching the DA target with Q'=15 and -60 A

Based on Run3 experience, important to reach 6σ target at end of adjust and start of leveling

End of $\mathcal{L}$-Levelling

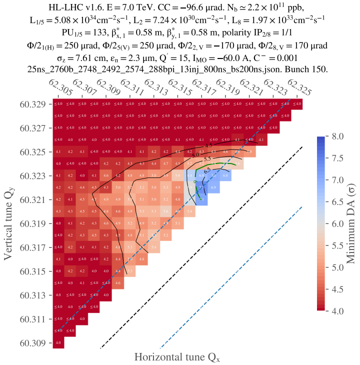


End of the $\mathcal{L}$-levelling

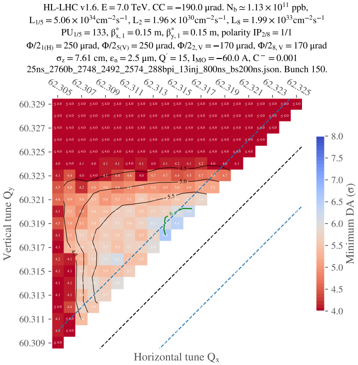
Parameters (unit)	**HL-LHC (values)**
Beam energy (TeV)	7
Luminosity (10^{34} Hz/cm^2)	**5**
Bunch population (protons)	1-1.2$\times 10^{11}$
Filling scheme	baseline
Normalized emittance (μm rad)	2.5
Nominal working point (Q_x, Q_y)	(62.31, 60.32)
Chromaticity $Q'_{x,y}$	5 or 15
IP1/5 half crossing angle (μrad)	250(H) / 250(V)
IP2/8 half crossing angle (μrad)	170(V) / 170(V)
IP1/5 β^* (m)	**7.5/18** (flat) or **15** (round)
IP2/8 β^* (m)	10/1.5
Landau octupoles' current (A)	**$\pm$ 60**
Half crab-cavity angle (μrad)	**-190**

Round optics: tune trims from SOL to EOL

SOL

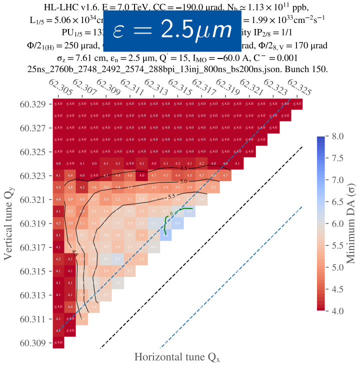


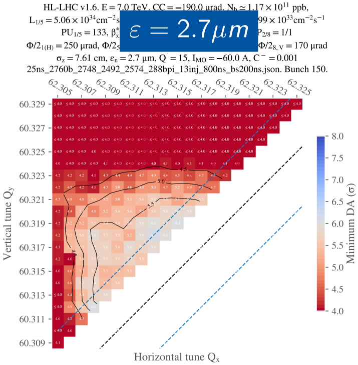
EOL



Optimal working point shifted downward along the diagonal from SOL to EOL

Round optics: sensitivity to emittance



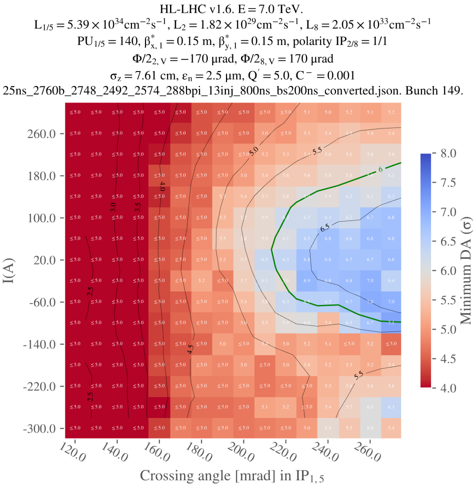


Similar results with round optics and positive/negative octupoles

The DA target is barely met with Q'=15.

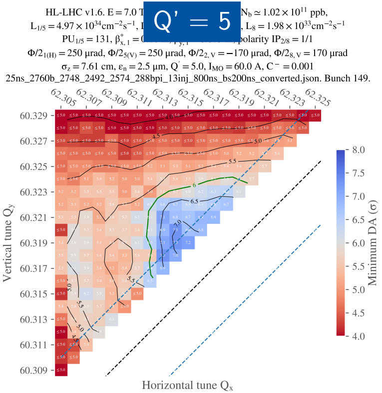
In case of emittance blow-up, the DA target is not met with Q'=15.

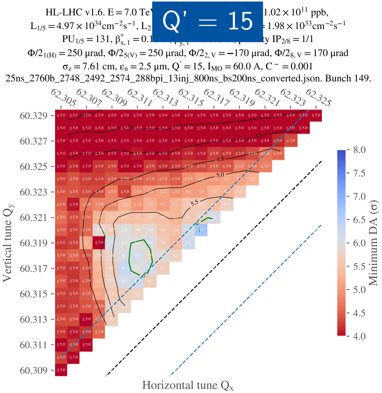
Round optics: varying Q' & $\phi_{IP1/5}$



Reducing Q'=5 is beneficial for DA, crossing angle can be reduced to 220 μrad.

Flat optics: sensitivity to chromaticity

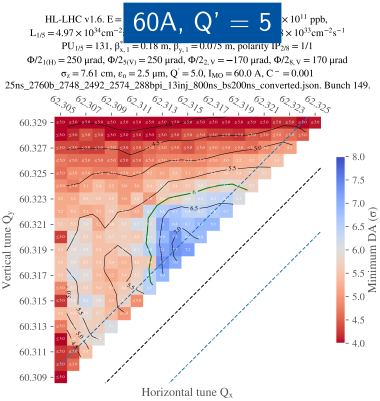


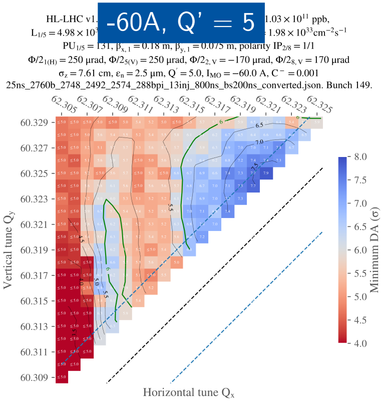


The DA target is met with Q'=5.

The DA target is barely met with Q'=15.

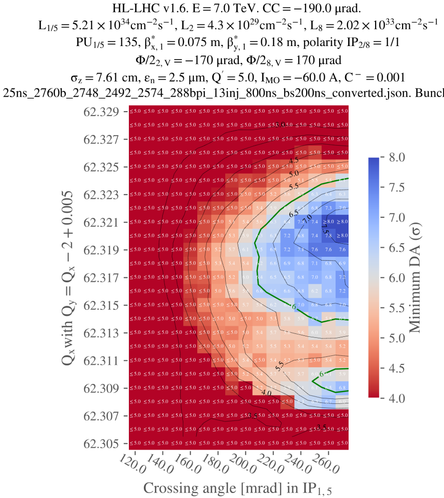
Flat optics: sensitivity to octupole





Improved DA with negative octupole polarity and flat optics

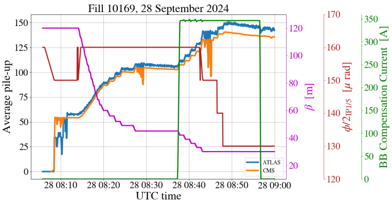
Flat optics: sensitivity to $\phi_{IP1/5}$

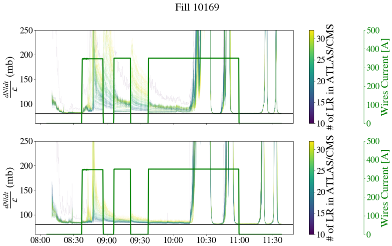


With Q'=5 and -60 A, crossing angle can be reduced to 210 μrad for flat optics at EOL

MD towards HL-LHC beam-beam conditions

- Tested 1 train of 36b per beam with 1.8e11 ppb in beam-beam wire compensation MD.
- β^* was quickly reduced to 30 cm and crossing angle from 160 (12 σ) to 130 μrad (8 σ) to simulate aggressive beam-beam scenario (HL-LHC flat optics 11 σ at EOL).
- 40 h beam lifetime at end of collapse.





Conclusions

IP1/5 luminosity (10^{34} Hz/cm^2)	Chromaticity	Optics	Octupoles (A)	Crossing angle (μrad)	DA
End of collapse	15	Round	+300/-300	250	marginally ok/ok
		Flat	+150/-150	250	marginally ok/ok
Start of leveling	15	Round	-60	250	ok
End of leveling	15	Round	+60/-60	250	marginally ok (not ok if > 2.5 μm)/ok
	5	Round	+60/-60	250/220	ok/ok
End of leveling	15	Flat	+60/-60	250	marginally ok (not ok if > 2.5 μm)/ok
	5	Flat	+60/-60	250/210	ok/ok

- Negative octupole polarity beneficial for all stages of collisions for both round and flat optics. However, operational experience with negative polarity is limited at the moment.
- Flat optics have several advantages and are a viable option based on DA, though limited operational experience at the moment.
- Currently gaining experience with lower chromaticity at EOL in Run3.
- Combining lower chromaticity and negative octupole polarity could allow a crossing angle reduction at EOL that can result in increased integrated luminosity.

Thank you for your attention.

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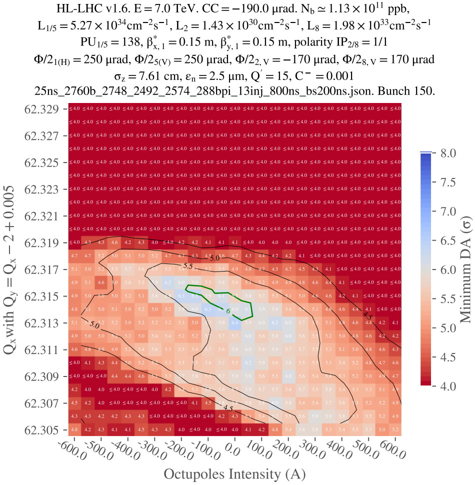
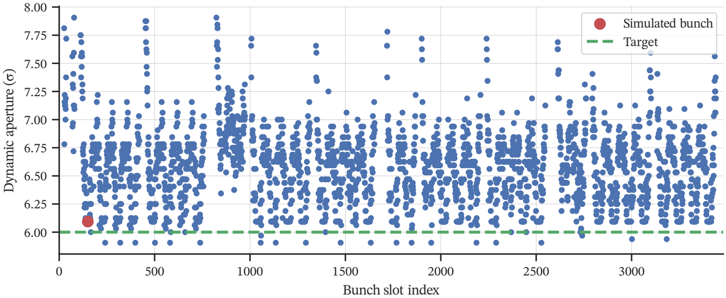
Round optics (octupole scan, Q'=15)



Target can be reached for both positive and negative octupoles

Round optics, bunch scan at Q'=15



Almost all bunches are above target

References (I)

D. Pellegrini, G. Arduini, S. Fartoukh, G. Iadarola, N. Karastathis, Y. Papaphilippou, and G. Sterbini.
Incoherent beam-beam effects and lifetime optimization.
In *Proceedings, 7th Evian Workshop on LHC beam operation: Evian Les Bains, France, December 13-15, 2016*, Geneva, 2017. CERN.