CERN

Dynamic Aperture of the new HL-LHC baseline

C. Droin, S. Kostoglou, G. Sterbini on behalf of WP2 team

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

- HL-LHC performance strongly depends on the **orchestration of several beam and machine parameters during the cycle**.

DA as main observable

- 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].

HL-LHC DA requirements

- Based on this experience, an operational scenario is characterized as feasible when there are working points that satisfy the following criteria in the simulations:

HL-LHC DA requirements

- Based on this experience, an operational scenario is characterized as feasible when there are working points that satisfy the following criteria in the simulations:
  1. A minimum **DA of at least 6** σ.

HL-LHC DA requirements

- Based on this experience, an operational scenario is characterized as feasible when there are working points that satisfy the following criteria in the simulations:
  1. A minimum **DA of at least 6 σ**.
  2. Working point condition $\mathbf{q_x + 5 \times 10^{-3} < q_y}$: no experience operating below the diagonal and tune split of $+5 \times 10^{-3}$ to prevent possible instabilities.

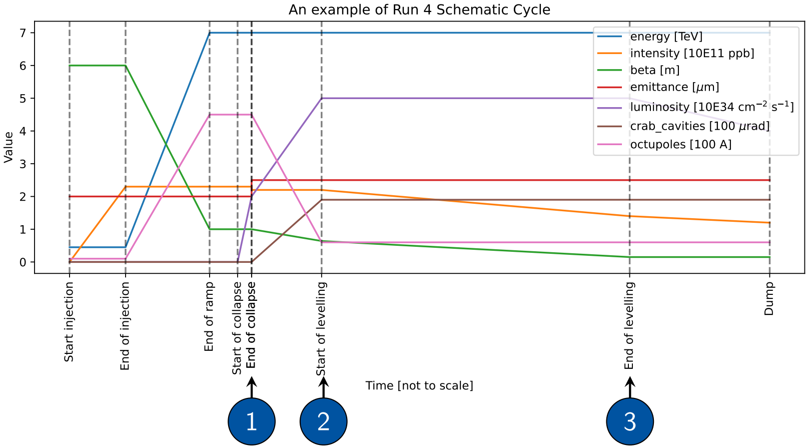
HL-LHC DA requirements

- Based on this experience, an operational scenario is characterized as feasible when there are working points that satisfy the following criteria in the simulations:
  1. A minimum **DA of at least 6 σ**.
  2. Working point condition $\mathbf{q_x + 5 \times 10^{-3} < q_y}$: no experience operating below the diagonal and tune split of $+5 \times 10^{-3}$ to prevent possible instabilities.
- 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.

HL-LHC DA requirements

- Based on this experience, an operational scenario is characterized as feasible when there are working points that satisfy the following criteria in the simulations:
  1. A minimum **DA of at least 6 σ**.
  2. Working point condition $\mathbf{q_x + 5 \times 10^{-3} < q_y}$: no experience operating below the diagonal and tune split of $+5 \times 10^{-3}$ to prevent possible instabilities.
- 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):

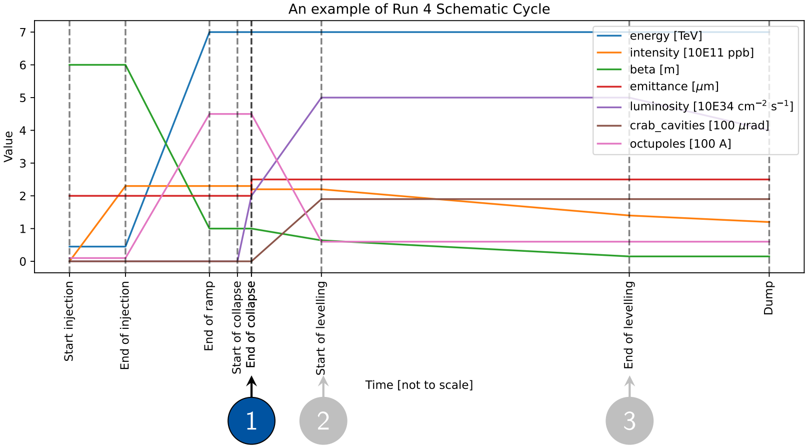
- **baseline** (**2760** bunches):
  25ns_2760b_2748_2492_2574_288bpi_13inj_800ns_bs200ns

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
- 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

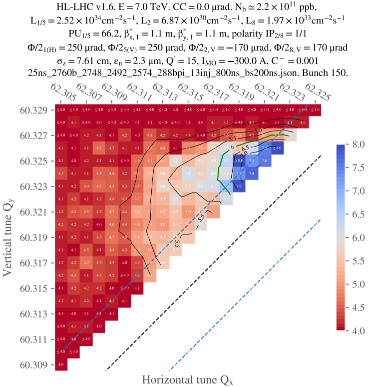


End of Collapse

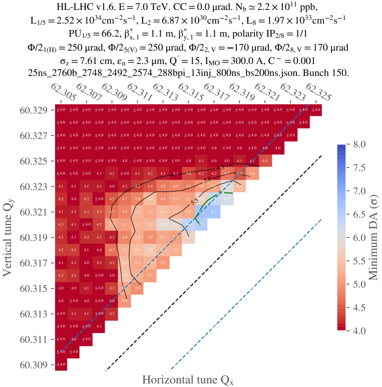
Parameters (unit)	**HL-LHC (values)**
Beam energy (TeV)	7
Luminosity (10^{34} Hz/cm^2)	**≈2.5**
Bunch population (protons)	2.2×10^{11}
Filling scheme	baseline
Normalised emittance (μm rad)	**2.3**
Nominal working point (Q_x, Q_y)	(62.31, 60.32)
Chromaticity $Q'_{x,y}$	15
IP1/5 half crossing angle (μrad)	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



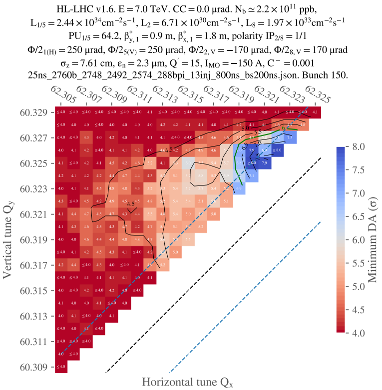
I=300A



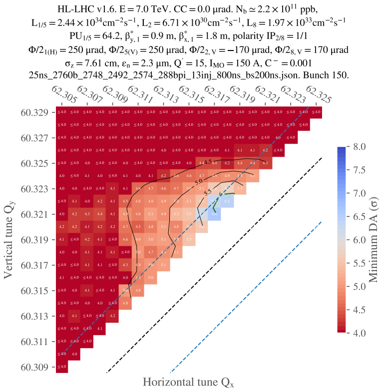
Baseline configuration marginally OK with $I_{OCT} = 300$ A.
Negative octupoles option yields better results.

Flat optics: sensitivity to octupole polarity

I=-150 A



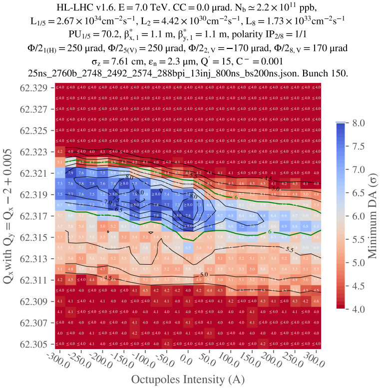
I=150 A



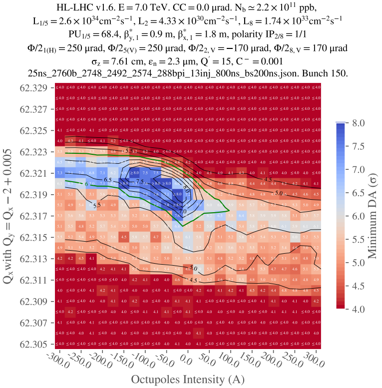
Negative octupoles option yields better results also with flat optics.

I_{MO} scan along the upper diagonal

Round optics

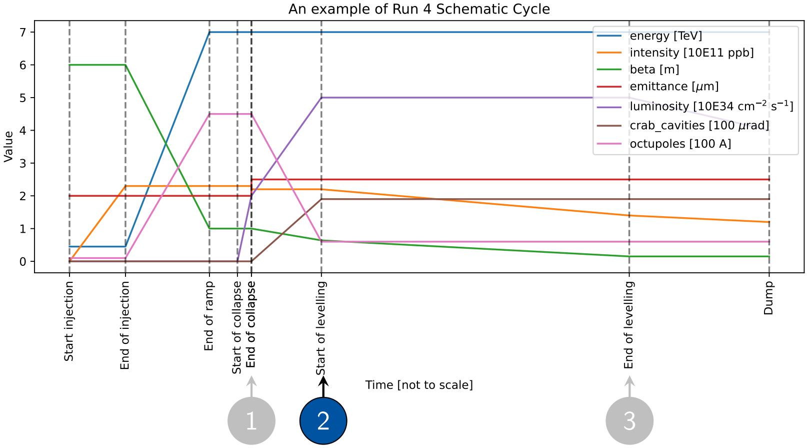


Flat optics



Smaller good DA region with flat optics but could alleviate the impedance of the CC and increase integrated luminosity.

Start of $\mathcal{L}$-Levelling

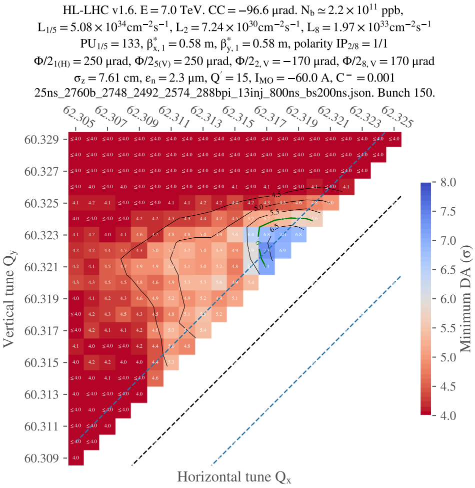


Start of the $\mathcal{L}$-levelling

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]

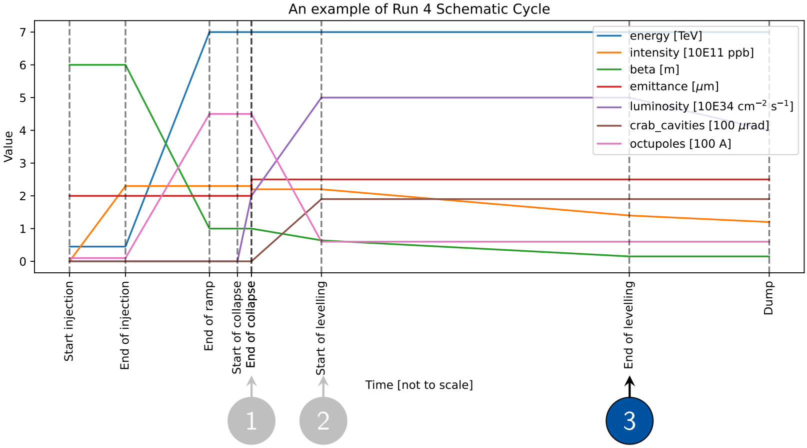
[1]This small value allows not to exceed target lumi as the current SoL optics not adapted for the baseline filling scheme.

Tune scan



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

End of $\mathcal{L}$-Levelling

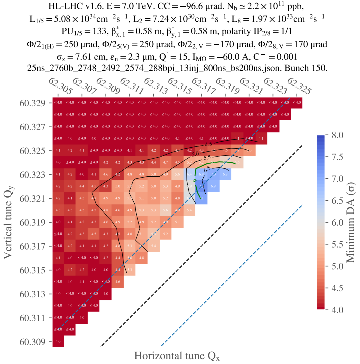


End of the $\mathcal{L}$-levelling

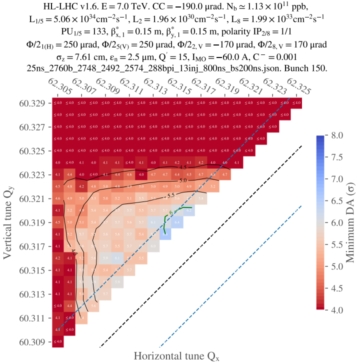
Parameters (unit)	**HL-LHC (values)**
Beam energy (TeV)	7
Luminosity (10^{34} Hz/cm^2)	**5**
Bunch population (protons)	1-1.2$\times10^{11}$
Filling scheme	baseline
Normalized emittance (μm rad)	2.5
Nominal working point (Q_x, Q_y)	(62.31, 60.32)
Chromaticity $Q'_{x,y}$	5 or 15
IP1/5 half crossing angle (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

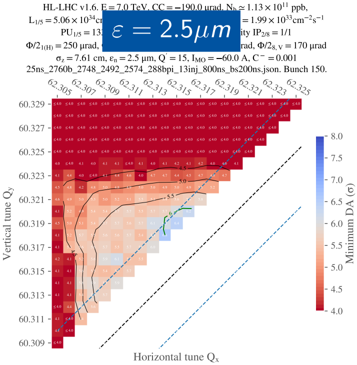


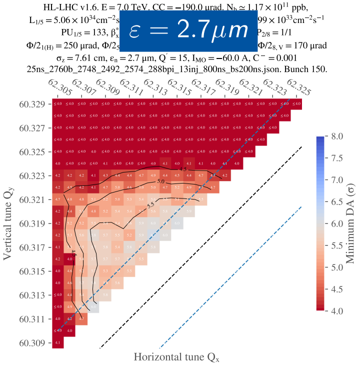
EOL



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

Round optics: sensitivity to emittance



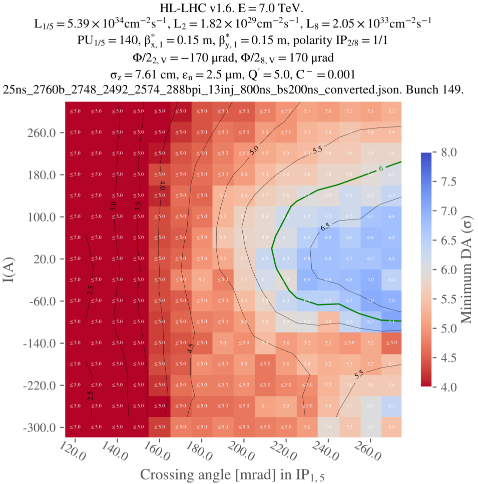


Similar results with round optics and positive/negative octupoles

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

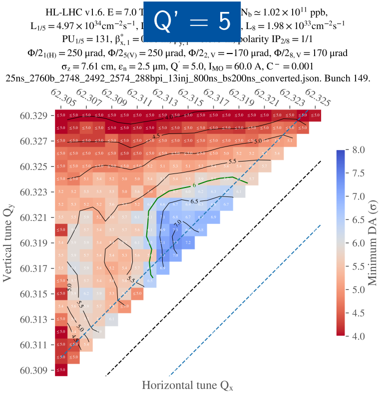
In case of emittance blow-up, the DA target is not met with Q'=15.

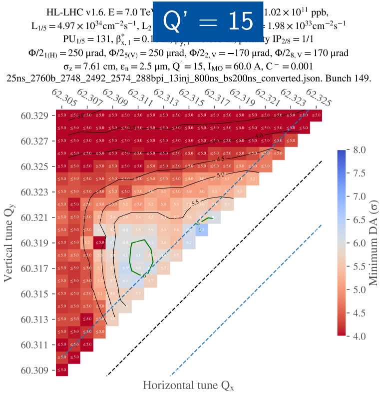
Round optics: varying Q' & $\phi_{IP1/5}$



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

Flat optics: sensitivity to chromaticity

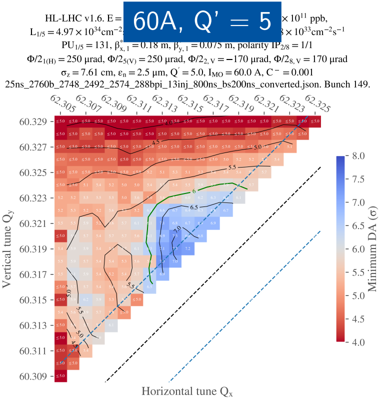


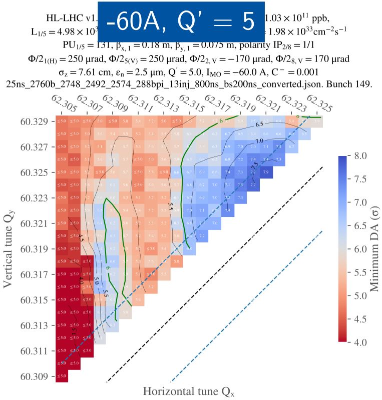


The DA target is met with Q'=5.

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

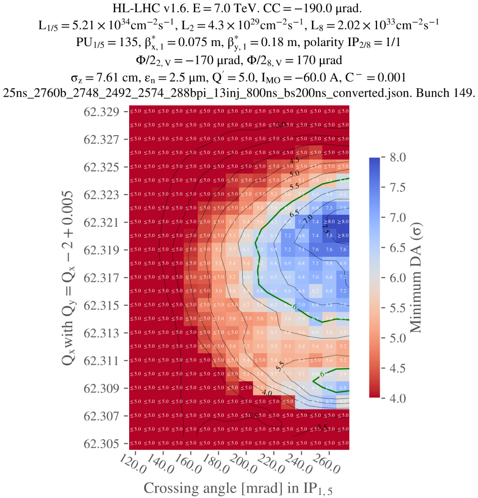
Flat optics: sensitivity to octupole





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

Conclusions

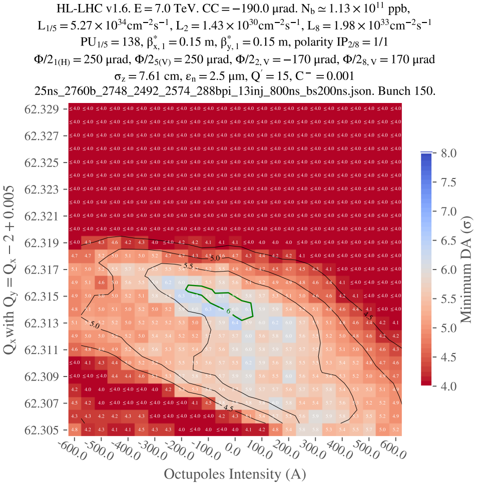
IP1/5 luminosity (10^{34} Hz/cm^2)	Chromaticity	Optics	Octupoles (A)	Crossing angle (μrad)	DA
End of collapse	15	Round	+300/-300	250	marginally ok/ok
		Flat	+150/-150	250	marginally ok/ok
Start of leveling	15	Round	-60	250	ok
End of leveling	15	Round	+60/-60	250	marginally ok (not ok if $>$ 2.5 μm)/ok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

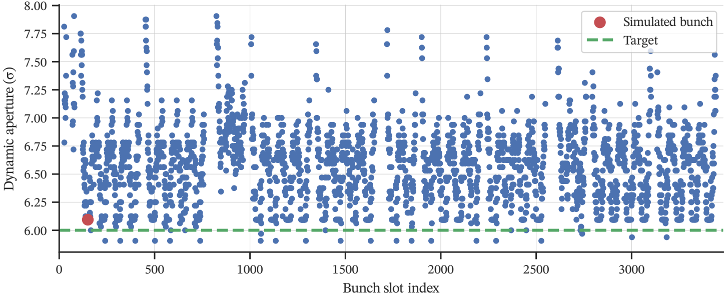
home.cern

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.