



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.

1. Introduction
2. Beam-Beam Studies Results
3. Conclusions

Introduction

Beam-beam Studies Results

End of Collapse

Start of \mathcal{L} -Levelling

End of \mathcal{L} -Levelling

Conclusions

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

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 1. A minimum **DA of at least 6σ** .

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 1. A minimum **DA of at least 6σ** .
 2. Working point condition **$q_x + 5 \times 10^{-3} < q_y$** : no experience operating below the diagonal and tune split of $+5 \times 10^{-3}$ to prevent possible instabilities.

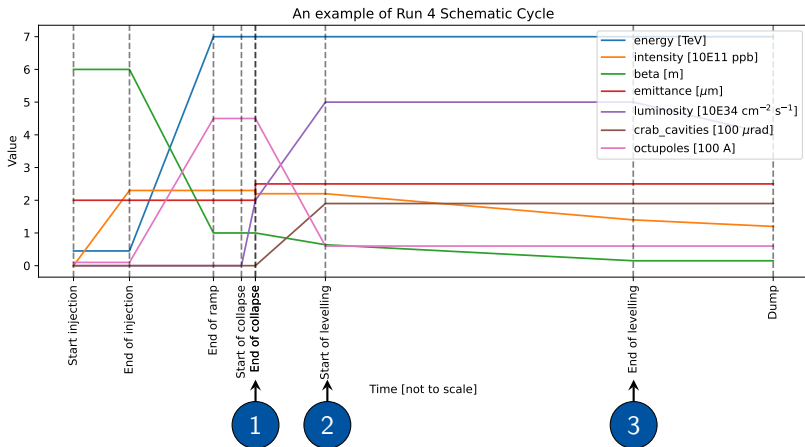
HL-LHC DA requirements

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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.

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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 ($\frac{\beta_x^*}{\beta_y^*} = 2$), 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.

Introduction

Beam-beam Studies Results

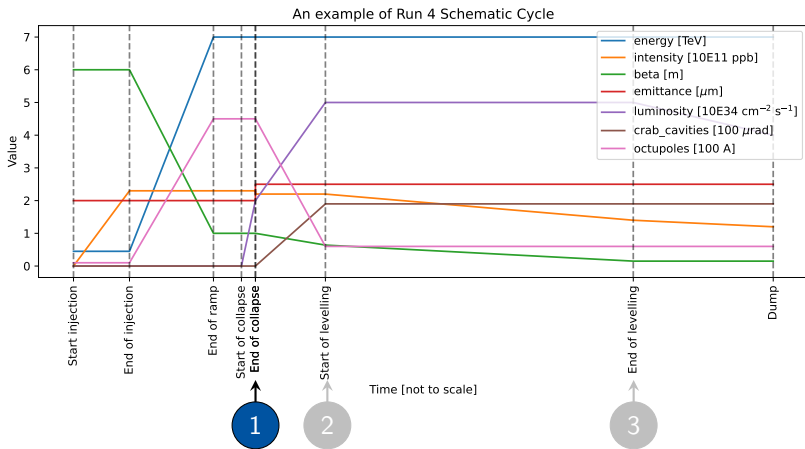
End of Collapse

Start of \mathcal{L} -Levelling

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Conclusions

End of Collapse



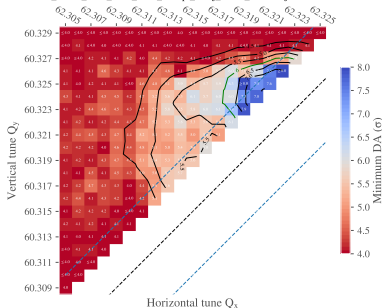
End of Collapse

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 ($\mu\text{m rad}$)	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

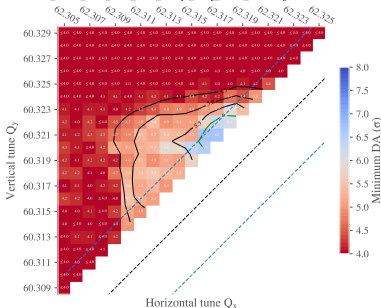
$I = -300A$

HL-LHC v1.6. $E = 7.0$ TeV. $CC = 0.0$ μrad . $N_b \approx 2.2 \times 10^{11}$ ppb,
 $L_{1,5} = 2.52 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$, $L_2 = 6.87 \times 10^{30} \text{cm}^{-2}\text{s}^{-1}$, $L_8 = 1.97 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$
 $PU_{1,5} = 66.2$, $\beta_{x,1}^* = 1.1$ m, $\beta_{y,1}^* = 1.1$ m, polarity $IP_{2,8} = 1/1$
 $\Phi/2_{1(0)} = 250$ μrad , $\Phi/2_{5(V)} = 250$ μrad , $\Phi/2_{2,v} = -170$ μrad , $\Phi/2_{k,v} = 170$ μrad
 $\sigma_x = 7.61$ cm, $e_x = 2.3$ μm , $Q' = 15$, $I_{M0} = -300.0$ A, $C^- = 0.001$
 25ns_2760b_2748_2492_2574_2888bpi_13inj_800ns_bs200ns.json. Bunch 150.



$I = 300A$

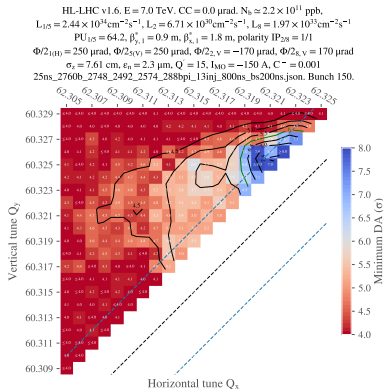
HL-LHC v1.6. $E = 7.0$ TeV. $CC = 0.0$ μrad . $N_b \approx 2.2 \times 10^{11}$ ppb,
 $L_{1,5} = 2.52 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$, $L_2 = 6.87 \times 10^{30} \text{cm}^{-2}\text{s}^{-1}$, $L_8 = 1.97 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$
 $PU_{1,5} = 66.2$, $\beta_{x,1}^* = 1.1$ m, $\beta_{y,1}^* = 1.1$ m, polarity $IP_{2,8} = 1/1$
 $\Phi/2_{1(0)} = 250$ μrad , $\Phi/2_{5(V)} = 250$ μrad , $\Phi/2_{2,v} = -170$ μrad , $\Phi/2_{k,v} = 170$ μrad
 $\sigma_x = 7.61$ cm, $e_x = 2.3$ μm , $Q' = 15$, $I_{M0} = 300.0$ A, $C^- = 0.001$
 25ns_2760b_2748_2492_2574_2888bpi_13inj_800ns_bs200ns.json. Bunch 150.



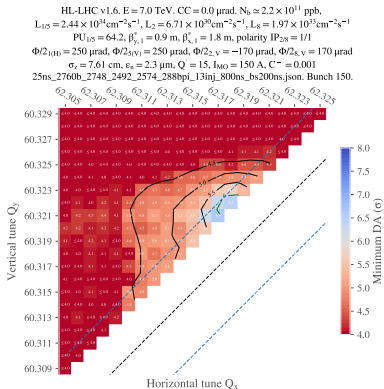
Baseline configuration marginally OK with $I_{OCT} = 300$ A.
Negative octupoles option yields better results.

Flat optics: sensitivity to octupole polarity

I=-150 A



I=150 A

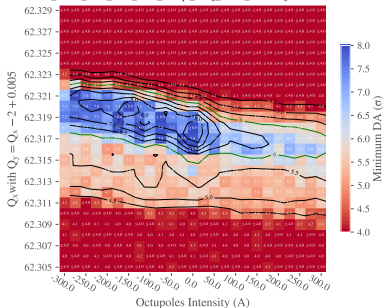


Negative octupoles option yields better results also with flat optics.

I_{MO} scan along the upper diagonal

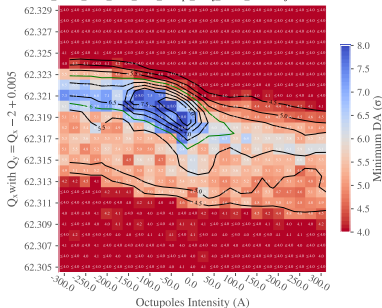
Round optics

HL-LHC v1.6. E = 7.0 TeV. CC = 0.0 μrad . $N_b \approx 2.2 \times 10^{11}$ ppb,
 $L_{105} = 2.67 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$, $L_2 = 4.42 \times 10^{36} \text{cm}^{-2}\text{s}^{-1}$, $L_8 = 1.73 \times 10^{35} \text{cm}^{-2}\text{s}^{-1}$
 PU₁₀₅ = 70.2, $\beta_{y,1}^* = 1.1$ m, $\beta_{x,1}^* = 1.1$ m, polarity IP₂₀₈ = 1/1
 $\Phi/2_{(H)} = 250$ μrad , $\Phi/2_{(V)} = 250$ μrad , $\Phi/2_{z,V} = -170$ μrad , $\Phi/2_{z,H} = 170$ μrad
 $\sigma_x = 7.61$ cm, $\sigma_y = 2.3$ μm , Q = 15, C* = 0.001
 25ns_2760b_2748_2492_2574_2888bpi_13inj_800ns_bs200ns.json. Bunch 150.



Flat optics

HL-LHC v1.6. E = 7.0 TeV. CC = 0.0 μrad . $N_b \approx 2.2 \times 10^{11}$ ppb,
 $L_{105} = 2.6 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$, $L_2 = 4.33 \times 10^{36} \text{cm}^{-2}\text{s}^{-1}$, $L_8 = 1.74 \times 10^{35} \text{cm}^{-2}\text{s}^{-1}$
 PU₁₀₅ = 68.4, $\beta_{y,1}^* = 0.9$ m, $\beta_{x,1}^* = 1.8$ m, polarity IP₂₀₈ = 1/1
 $\Phi/2_{(H)} = 250$ μrad , $\Phi/2_{(V)} = 250$ μrad , $\Phi/2_{z,V} = -170$ μrad , $\Phi/2_{z,H} = 170$ μrad
 $\sigma_x = 7.61$ cm, $\sigma_y = 2.3$ μm , Q = 15, C* = 0.001
 25ns_2760b_2748_2492_2574_2888bpi_13inj_800ns_bs200ns.json. Bunch 150.



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

Introduction

Beam-beam Studies Results

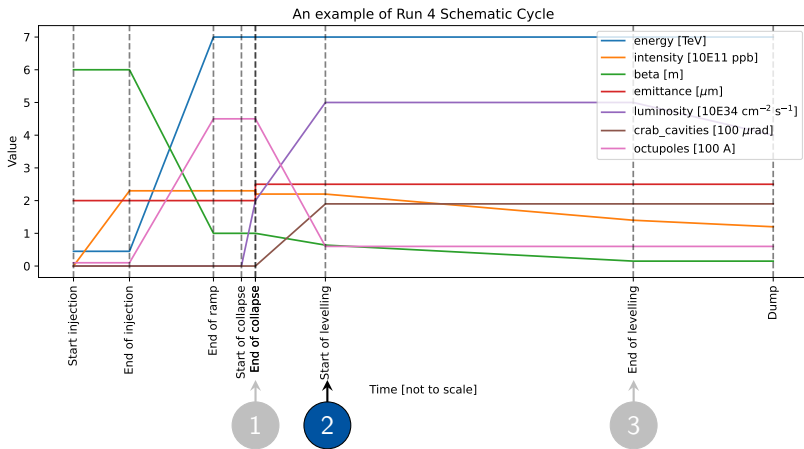
End of Collapse

Start of \mathcal{L} -Levelling

End of \mathcal{L} -Levelling

Conclusions

Start of \mathcal{L} -Levelling



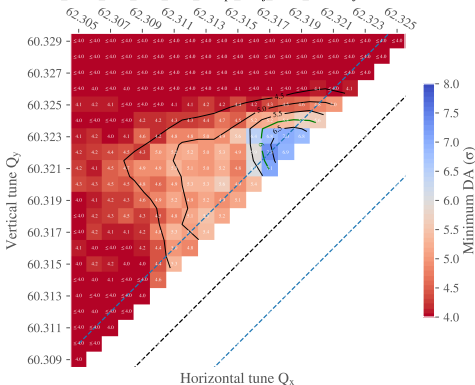
Start of the \mathcal{L} -levelling

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 ($\mu\text{m rad}$)	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)	-97¹

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

Tune scan

HL-LHC v1.6. E = 7.0 TeV. CC = -96.6 μrad . $N_b \approx 2.2 \times 10^{11}$ ppb,
 $L_{1/5} = 5.08 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$, $L_2 = 7.24 \times 10^{30} \text{cm}^{-2} \text{s}^{-1}$, $L_8 = 1.97 \times 10^{33} \text{cm}^{-2} \text{s}^{-1}$
 $\text{PU}_{1/5} = 133$, $\beta_{x,1}^* = 0.58 \text{ m}$, $\beta_{y,1}^* = 0.58 \text{ m}$, polarity $\text{IP}_{2/8} = 1/1$
 $\Phi/2_{(H)} = 250 \mu\text{rad}$, $\Phi/2_{S(V)} = 250 \mu\text{rad}$, $\Phi/2_{z,V} = -170 \mu\text{rad}$, $\Phi/2_{8,V} = 170 \mu\text{rad}$
 $\sigma_y = 7.61 \text{ cm}$, $e_n = 2.3 \mu\text{m}$, $Q' = 15$, $I_{MO} = -60.0 \text{ A}$, $C^- = 0.001$
 25ns_2760b_2748_2492_2574_288bpi_13inj_800ns_bs200ns.json. Bunch 150.



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

Introduction

Beam-beam Studies Results

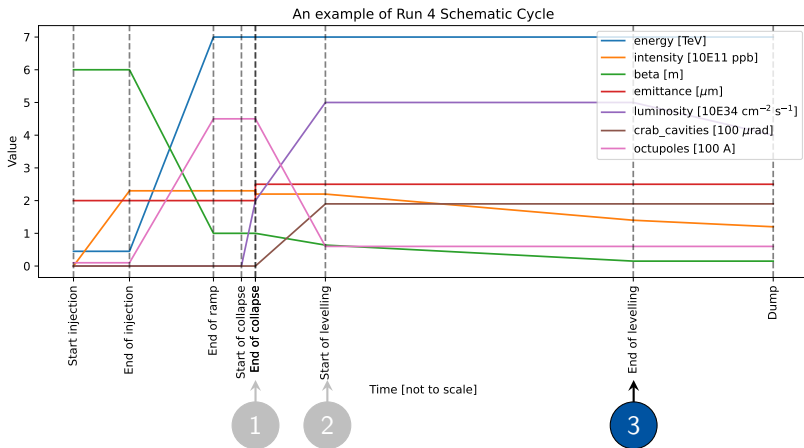
End of Collapse

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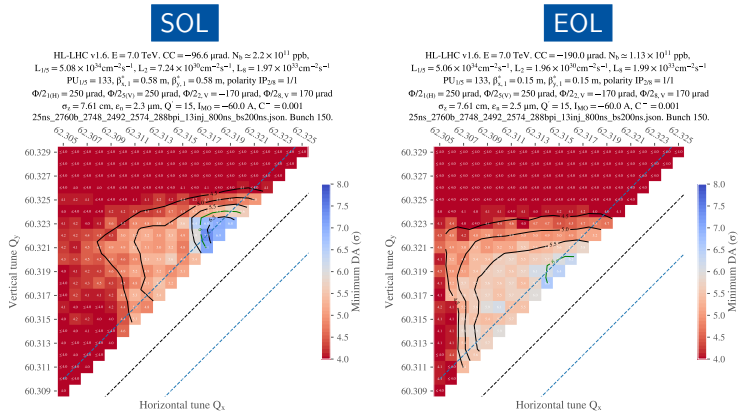
End of \mathcal{L} -Levelling



End of the \mathcal{L} -levelling

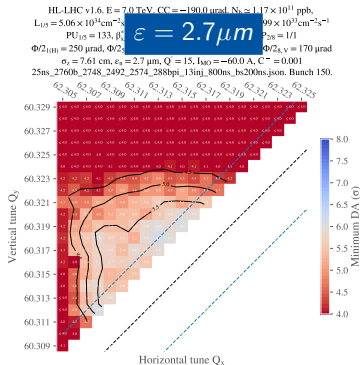
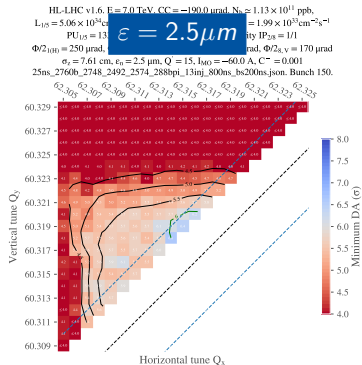
Parameters (unit)	HL-LHC (values)
Beam energy (TeV)	7
Luminosity (10^{34} Hz/cm ²)	5
Bunch population (protons)	$1-1.2 \times 10^{11}$
Filling scheme	baseline
Normalized emittance ($\mu\text{m rad}$)	2.5
Nominal working point (Q_x, Q_y)	(62.31, 60.32)
Chromaticity $Q'_{x,y}$	5 or 15
IP1/5 half crossing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



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

Round optics: sensitivity to emittance



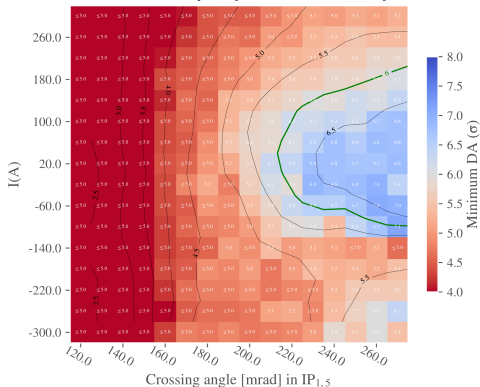
Similar results with round optics and positive/negative octupoles

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' & $\phi_{IP1/5}$

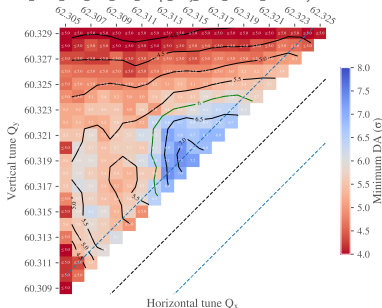
HL-LHC v1.6. $E = 7.0$ TeV.
 $L_{1/5} = 5.39 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$, $L_2 = 1.82 \times 10^{30} \text{cm}^{-2}\text{s}^{-1}$, $L_8 = 2.05 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$
 $\text{PU}_{1/5} = 140$, $\beta_{x,1}^* = 0.15$ m, $\beta_{y,1}^* = 0.15$ m, polarity $\text{IP}_{2/8} = 1/1$
 $\Phi/2_{2,v} = -170$ μrad , $\Phi/2_{8,v} = 170$ μrad
 $\sigma_x = 7.61$ cm, $e_n = 2.5$ μm , $Q' = 5.0$, $C^- = 0.001$
 25ns_2760b_2748_2492_2574_288bpi_13inj_800ns_bs200ns_converted.json. Bunch 149.



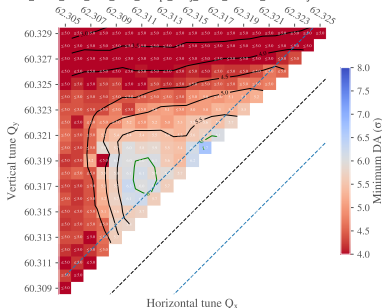
Reducing $Q'=5$ is beneficial for DA, crossing angle can be reduced to 220 μrad .

Flat optics: sensitivity to chromaticity

HL-LHC v1.6, E = 7.0 TeV, $Q' = 5$, $N_b \approx 1.02 \times 10^{11}$ ppb,
 $L_{105} = 4.97 \times 10^{14} \text{cm}^{-2}\text{s}^{-1}$, $L_{108} = 1.98 \times 10^{15} \text{cm}^{-2}\text{s}^{-1}$,
 $PU_{105} = 131$, $\beta_{x1}^* = 0$, $\beta_{y1}^* = 0$, $\beta_{x2}^* = 0$, $\beta_{y2}^* = 0$, $\beta_{x3}^* = 0$, $\beta_{y3}^* = 0$,
 $\Phi/2_{(10)} = 250 \mu\text{rad}$, $\Phi/2_{3(V)} = 250 \mu\text{rad}$, $\Phi/2_{2,V} = -170 \mu\text{rad}$, $\Phi/2_{8,V} = 170 \mu\text{rad}$
 $\sigma_x = 7.61 \text{ cm}$, $e_n = 2.5 \mu\text{m}$, $Q = 5.0$, $I_{800} = 60.0 \text{ A}$, $C^- = 0.001$
 25ns_2760b_2748_2492_2574_2888bpi_13inj_800ns_bs200ns_converted.json. Bunch 149.

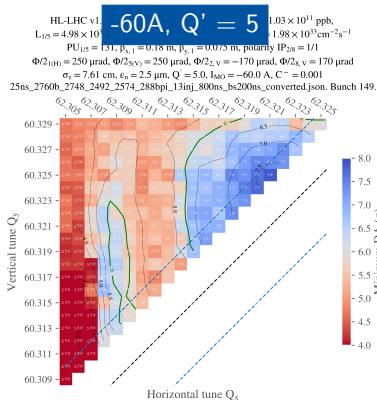
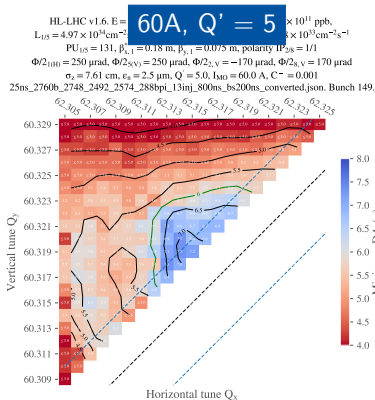


HL-LHC v1.6, E = 7.0 TeV, $Q' = 15$, $N_b \approx 1.02 \times 10^{11}$ ppb,
 $L_{105} = 4.97 \times 10^{14} \text{cm}^{-2}\text{s}^{-1}$, $L_{108} = 1.98 \times 10^{15} \text{cm}^{-2}\text{s}^{-1}$,
 $PU_{105} = 131$, $\beta_{x1}^* = 0$, $\beta_{y1}^* = 0$, $\beta_{x2}^* = 0$, $\beta_{y2}^* = 0$, $\beta_{x3}^* = 0$, $\beta_{y3}^* = 0$,
 $\Phi/2_{(10)} = 250 \mu\text{rad}$, $\Phi/2_{3(V)} = 250 \mu\text{rad}$, $\Phi/2_{2,V} = -170 \mu\text{rad}$, $\Phi/2_{8,V} = 170 \mu\text{rad}$
 $\sigma_x = 7.61 \text{ cm}$, $e_n = 2.5 \mu\text{m}$, $Q = 15$, $I_{800} = 60.0 \text{ A}$, $C^- = 0.001$
 25ns_2760b_2748_2492_2574_2888bpi_13inj_800ns_bs200ns_converted.json. Bunch 149.



The DA target is met with $Q'=5$.
 The DA target is barely met with $Q'=15$.

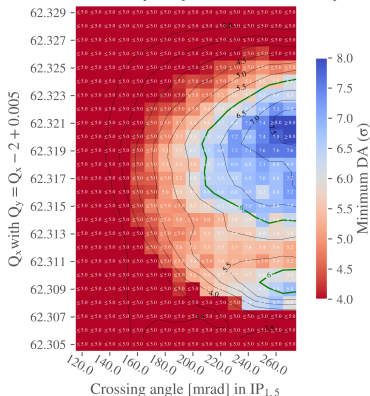
Flat optics: sensitivity to octupole



Improved DA with negative octupole polarity and flat optics

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

HL-LHC v1.6. E = 7.0 TeV. CC = -190.0 μ rad.
 $L_{1/5} = 5.21 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$, $L_2 = 4.3 \times 10^{29} \text{cm}^{-2}\text{s}^{-1}$, $L_8 = 2.02 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$
 $PU_{1/5} = 135$, $\beta_{x,1}^* = 0.075 \text{ m}$, $\beta_{y,1}^* = 0.18 \text{ m}$, polarity $IP_{2/8} = 1/1$
 $\Phi/2_{2,v} = -170 \mu\text{rad}$, $\Phi/2_{8,v} = 170 \mu\text{rad}$
 $\sigma_x = 7.61 \text{ cm}$, $\sigma_n = 2.5 \mu\text{m}$, $Q' = 5.0$, $I_{MO} = -60.0 \text{ A}$, $C^- = 0.001$
 25ns_2760b_2748_2492_2574_288bpi_13inj_800ns_bs200ns_converted.json. Bunch 149.



With $Q' = 5$ and -60 A , crossing angle can be reduced to $210 \mu\text{rad}$ for flat optics at EOL

Introduction

Beam-beam Studies Results

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Conclusions

Conclusions

IP1/5 (10^{34} Hz/cm ²)	luminosity	Chromaticity	Optics	Octupoles (A)	Crossing angle (μ rad)	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 μ m)/ok
	5		Round	+60/-60	250/220	ok/ok
End of leveling	15		Flat	+60/-60	250	marginally ok (not ok if > 2.5 μ m)/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.

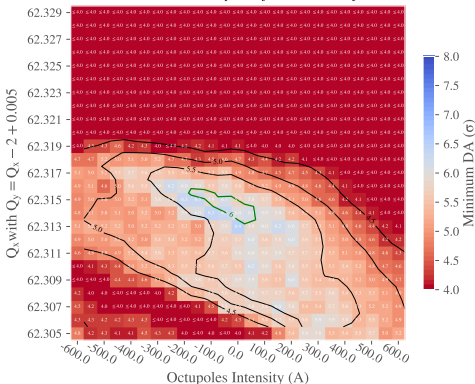
Thank you for your attention.



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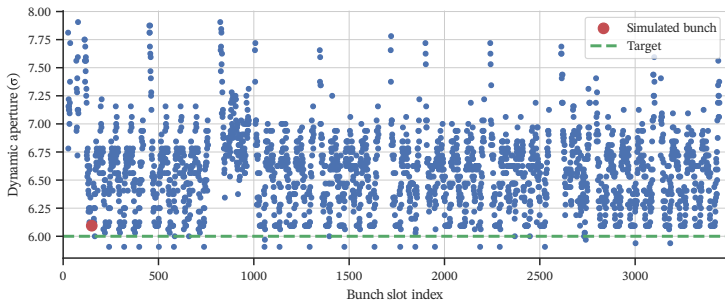
Round optics (octupole scan, $Q' = 15$)

HL-LHC v1.6. $E = 7.0$ TeV. $CC = -190.0$ μrad . $N_b \approx 1.13 \times 10^{11}$ ppb,
 $L_{1/5} = 5.27 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$, $L_2 = 1.43 \times 10^{30} \text{cm}^{-2} \text{s}^{-1}$, $L_8 = 1.98 \times 10^{33} \text{cm}^{-2} \text{s}^{-1}$
 $PU_{1/5} = 138$, $\beta_{x,1}^* = 0.15$ m, $\beta_{y,1}^* = 0.15$ m, polarity $IP_{2/8} = 1/1$
 $\Phi/2_{(H)} = 250$ μrad , $\Phi/2_{(V)} = 250$ μrad , $\Phi/2_{2,V} = -170$ μrad , $\Phi/2_{8,V} = 170$ μrad
 $\sigma_z = 7.61$ cm, $\epsilon_n = 2.5$ μm , $Q' = 15$, $C^- = 0.001$
 25ns_2760b_2748_2492_2574_288bpi_13inj_800ns_bs200ns.json. Bunch 150.



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.

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