



Field quality to achieve the required lifetime goals (with beam-beam)

G. Arduini, S. Fartoukh, N. Karastathis, R.de Maria, E. Metral,
Y. Papaphilippou, D. Pellegrini, R. Tomàs Garcia



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Outline

- **Working Point Optimization**
 - Start of Collisions
 - End of levelling to achieve Dynamic Aperture (DA) targets
 - During the course of the levelling
- **Operational Scenarios**
 - Adaptive crossing angle levelling scenario
 - Baseline
- **Effect of field imperfections on DA**
- **Summary**

Simulation Setup

- **Optics and Collisions**
- HL-LHC v1.3 optics, baseline (MS10 included) (*see Riccardo's talk*)
- $I_{MO} = -300A$, $Q' = 15 \rightarrow$ WP optimization required
- Collisions: IP1/5/8 head-on, IP2 halo at 5σ
- 2 CC per IP per side, max crab angle (full) $380\mu\text{rad}$ (6.8MV)
- Assuming constant round beams $2.5\mu\text{m}$ emittance (*see Stefania's talk*)

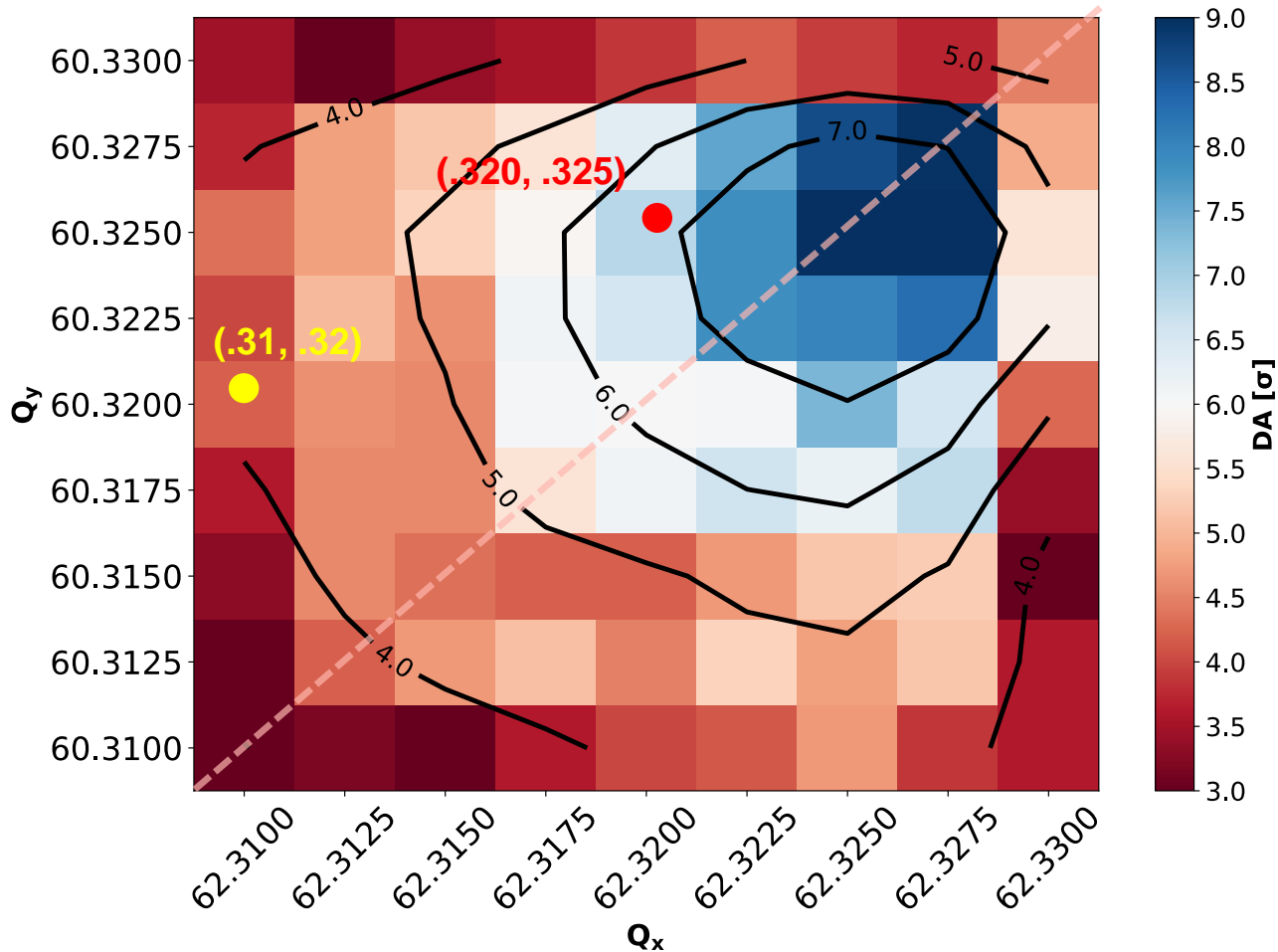
- **LHCb**
- Negative dipole polarity \rightarrow subtract from the external crossing angle
- Luminosity is levelled at $2 \cdot 10^{33} \text{Hz}/\text{cm}^2$

- **Tracking with SixTrack**
- 1M turns
- 5 angles in the (x,y) space
- Amplitudes in the range 0σ - 10σ
- Estimator: minimum Dynamic Aperture over the angles and amplitudes

- **Targets** (*see Dario's talk*)
- $6\sigma \rightarrow$ "Relaxed"
- $5\sigma \rightarrow$ "Aggressive"

Working Point Optimization: Start of Collisions

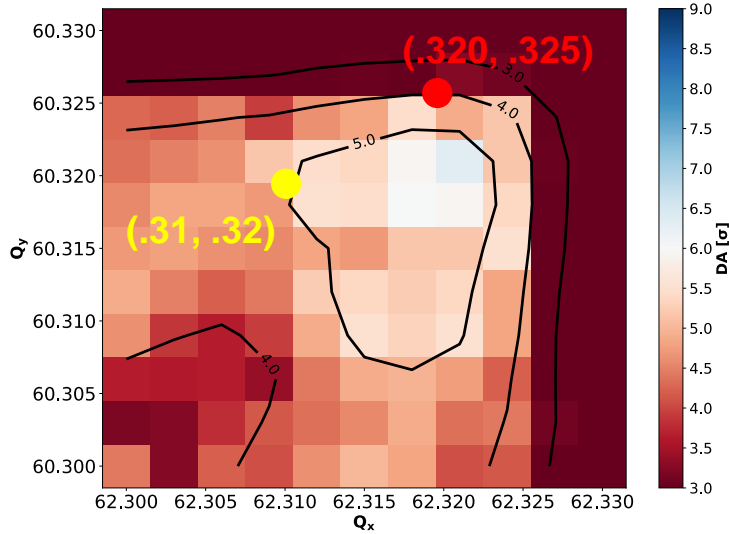
Min DA HL-LHC v1.3, $I = 2.2 \times 10^{11}$ ppb, $\beta^* = 64$ cm, $\phi = 250$ μ rad
 $\epsilon = 2.5$ μ m, $Q' = 15$, $I_{M0} = -570$ A



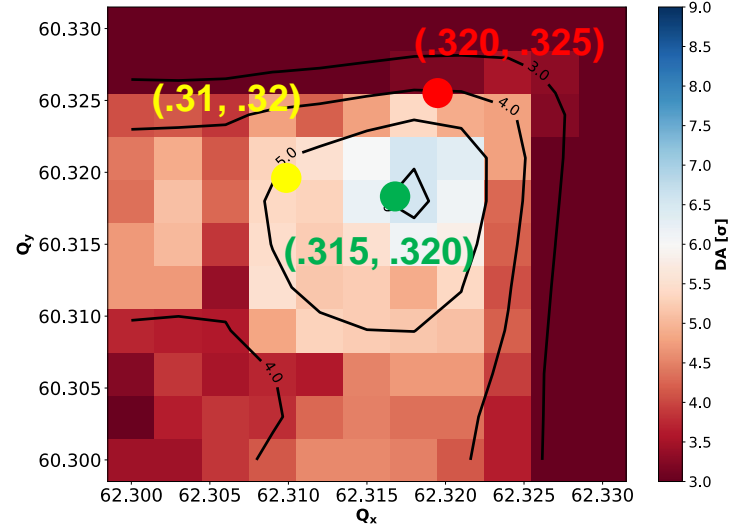
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Working Point Optimization: $\beta^*=15\text{cm}$

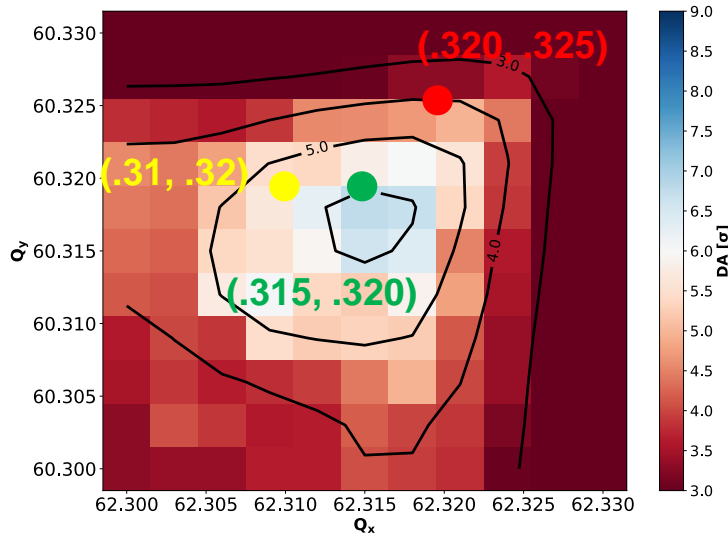
Min DA HL-LHC v1.3, $I = 1.2 \times 10^{11}$ ppb, $\beta^* = 15\text{cm}$
 $\epsilon = 2.5\mu\text{m}$, $Q' = 15$, $I_{M0} = -570\text{A}$



Min DA HL-LHC v1.3, $I = 1.2 \times 10^{11}$ ppb, $\beta^* = 15\text{cm}$
 $\epsilon = 2.5\mu\text{m}$, $Q' = 15$, $I_{M0} = -300\text{A}$



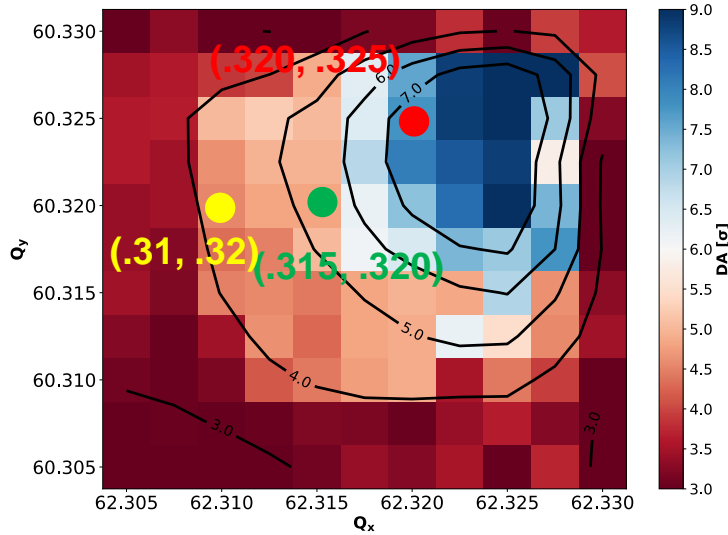
Min DA HL-LHC v1.3, $I = 1.2 \times 10^{11}$ ppb, $\beta^* = 15\text{cm}$
 $\epsilon = 2.5\mu\text{m}$, $Q' = 15$, $I_{M0} = 0\text{A}$



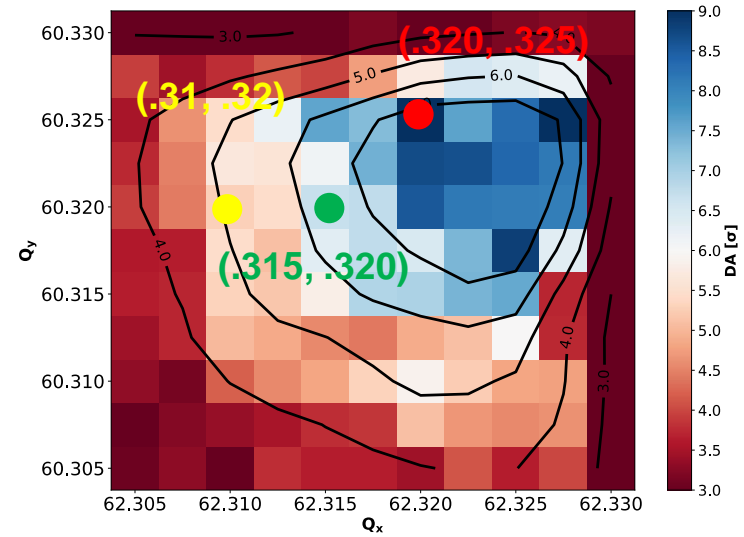
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Working Point Optimization: During Fill

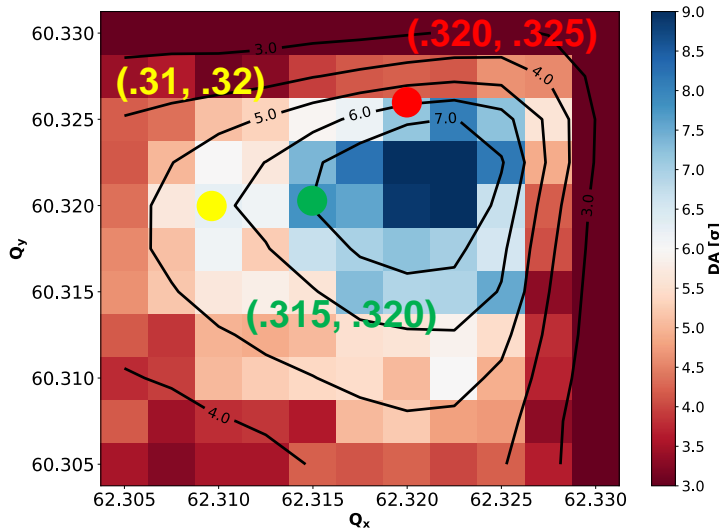
Min DA HL-LHC v1.3, $I = 2.2 \times 10^{11}$ ppb, $\beta^* = 64\text{cm}$, $\phi = 250\mu\text{rad}$
 $\epsilon = 2.5\mu\text{m}$, $Q = 15$, $I_{M0} = -300\text{A}$



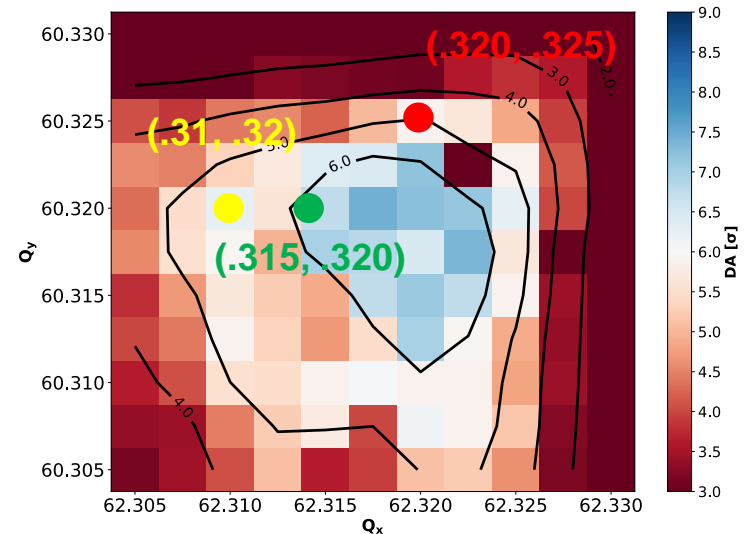
Min DA HL-LHC v1.3, $I = 1.9 \times 10^{11}$ ppb, $\beta^* = 45\text{cm}$, $\phi = 250\mu\text{rad}$
 $\epsilon = 2.5\mu\text{m}$, $Q = 15$, $I_{M0} = -300\text{A}$



Min DA HL-LHC v1.3, $I = 1.6 \times 10^{11}$ ppb, $\beta^* = 30\text{cm}$, $\phi = 250\mu\text{rad}$
 $\epsilon = 2.5\mu\text{m}$, $Q = 15$, $I_{M0} = -300\text{A}$



Min DA HL-LHC v1.3, $I = 1.4 \times 10^{11}$ ppb, $\beta^* = 20\text{cm}$, $\phi = 250\mu\text{rad}$
 $\epsilon = 2.5\mu\text{m}$, $Q = 15$, $I_{M0} = -300\text{A}$

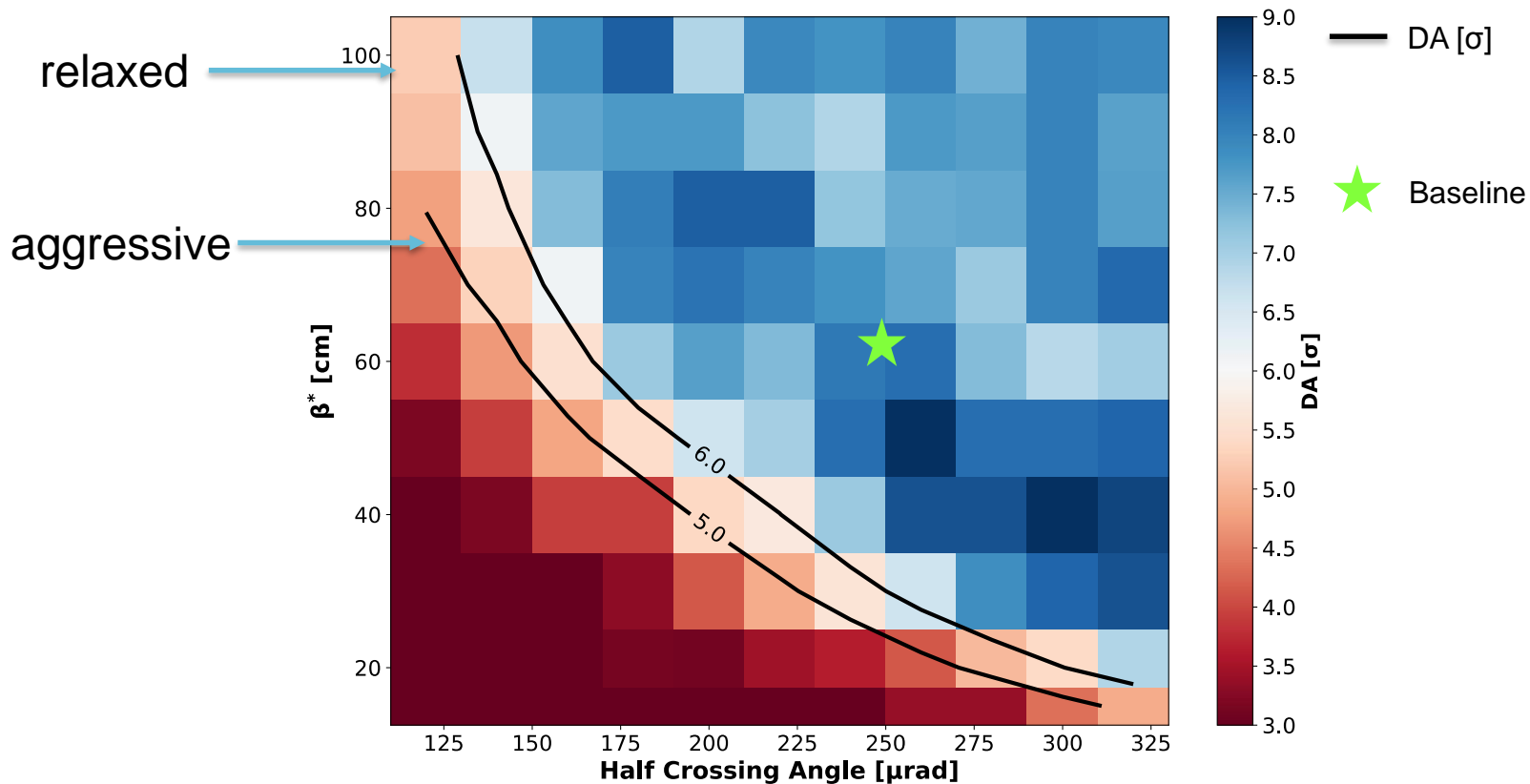


Adaptive Crossing Angle Levelling Scenario

- **HL-LHC baseline operational scenarios presented by Rogelio**
 - Fixed crossing angle at $250\mu\text{rad}$
 - Adapting β^* during the intensity decay to level luminosity at $5 \cdot 10^{34} \text{Hz}/\text{cm}^2$ (nominal) or $7.5 \cdot 10^{34} \text{Hz}/\text{cm}^2$ (ultimate)
- In terms of Dynamic Aperture, the baseline scenario leaves **some margin** to enhance performance by adapting the crossing angle as β^* evolves.
- Adaptive Crossing Angle Levelling Scenario:
 - As **bunch intensity decays** and **β^* is reduced** gradually, draw an alternative levelling path, keeping
 - the **Dynamic Aperture constant** at a target to ensure lifetime
 - **Luminosity constant** at the target scenario
 - This is possible by adapting also the **crossing angle**.

Start of Collisions: $N_b = 2.2 \cdot 10^{11} ppb$

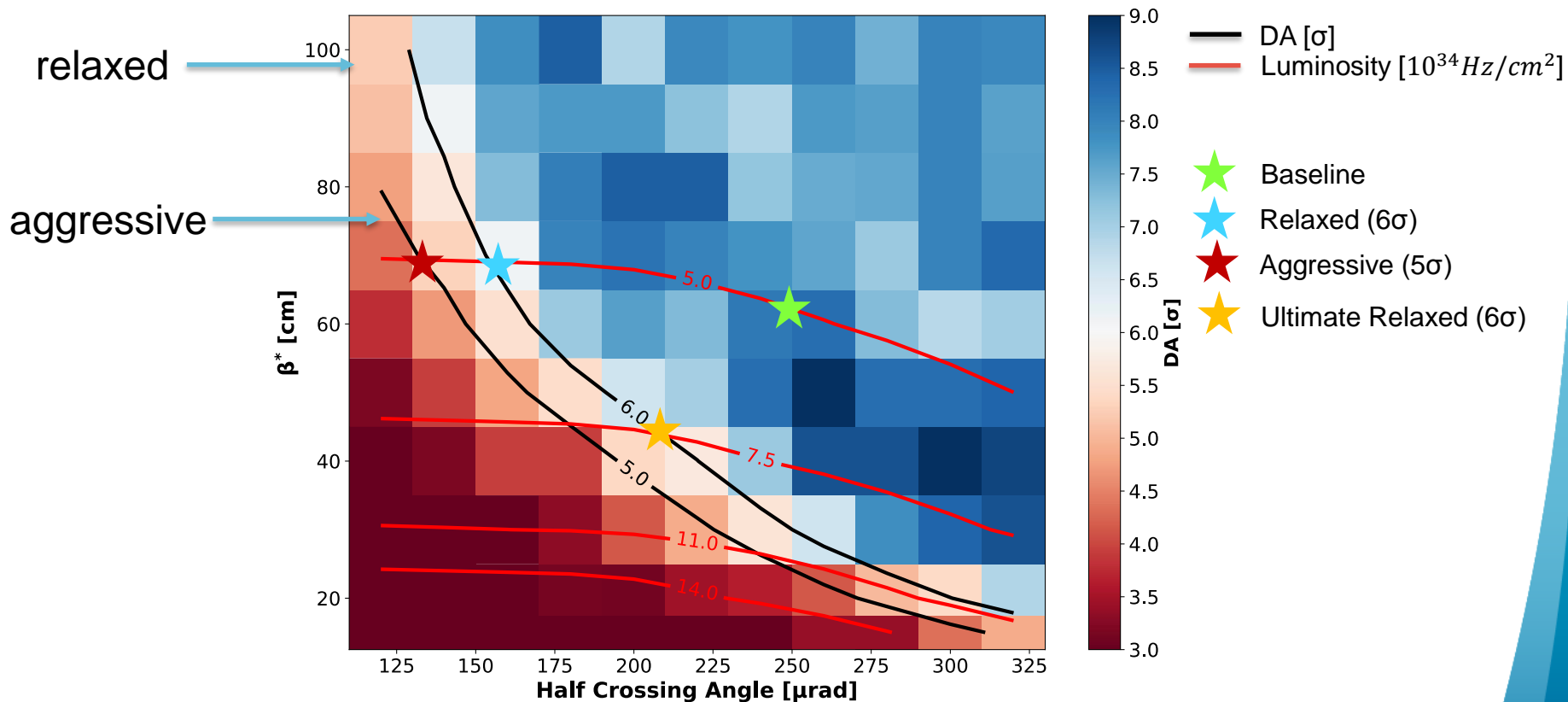
Min DA HL-LHC v1.3, $I=2.2 \times 10^{11}$ ppb, $(Q_x, Q_y)=(62.320, 60.325)$
 $\epsilon=2.5\mu\text{m}$, $Q'=15$, $I_{M0}=-300\text{A}$



Start of Collisions: $N_b = 2.2 \cdot 10^{11} ppb$

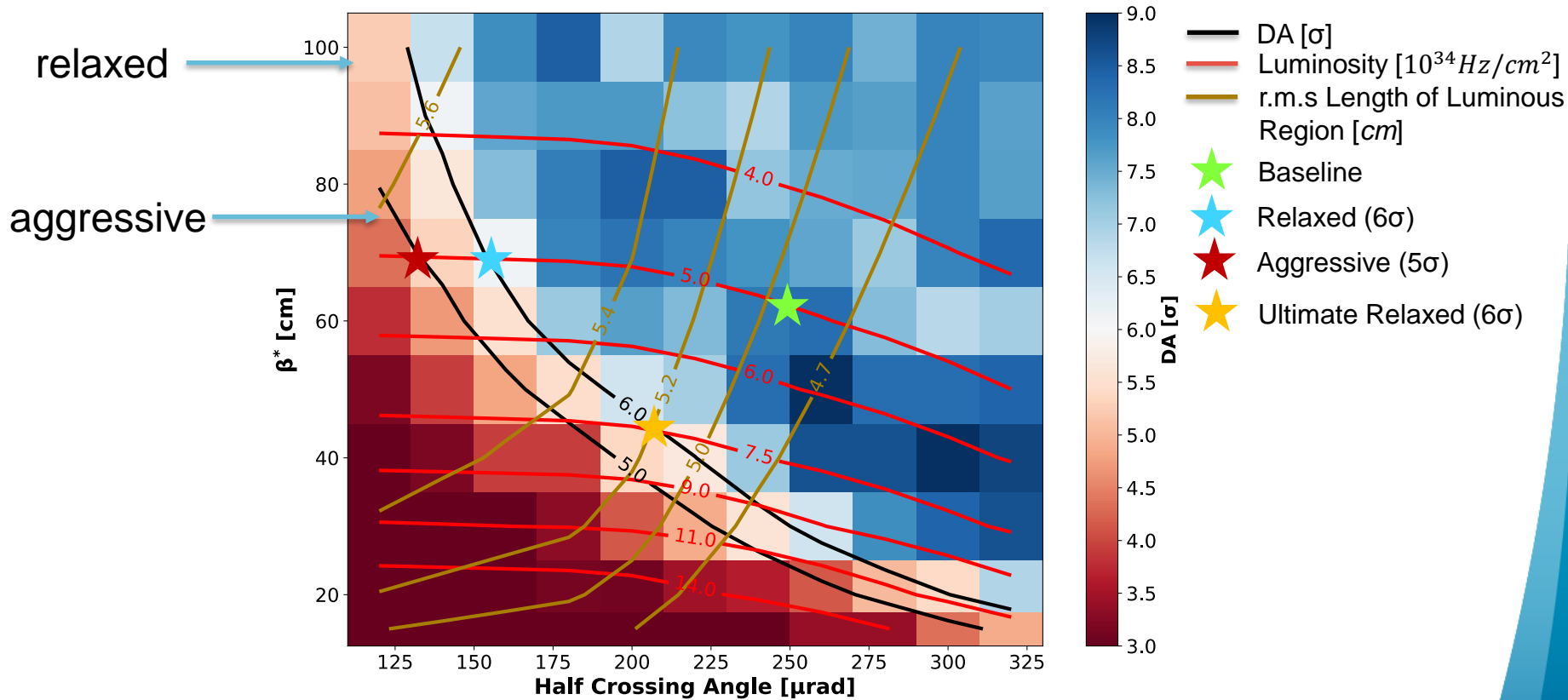
- Disregarding lifetime concerns, peak **luminosity** at 15cm: $\sim 1.4 \cdot 10^{35} Hz/cm^2 \rightarrow$ Pileup > 300 evts

Min DA HL-LHC v1.3, $I=2.2 \times 10^{11}$ ppb, $(Q_x, Q_y)=(62.320, 60.325)$
 $\epsilon=2.5\mu m, Q'=15, I_{M0}=-300A$



Start of Collisions: $N_b = 2.2 \cdot 10^{11} ppb$

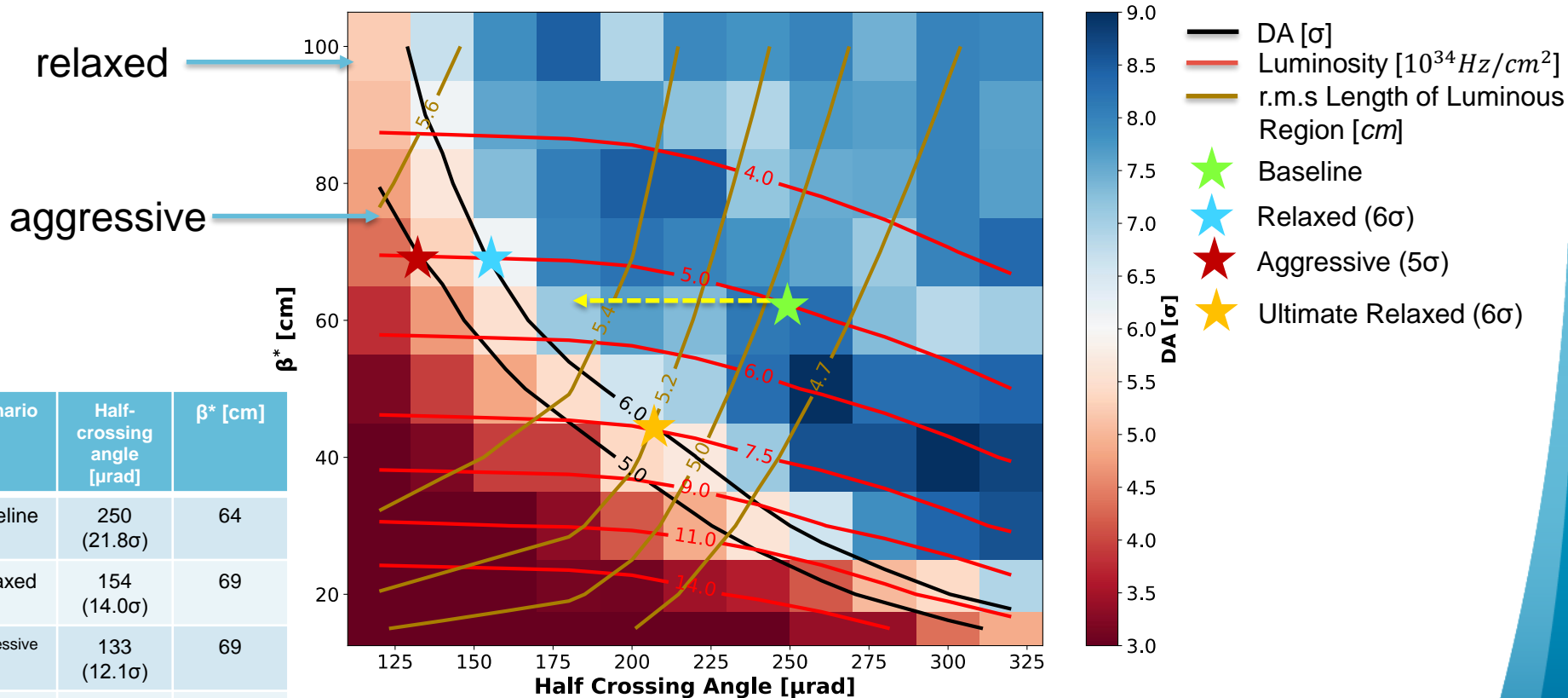
Min DA HL-LHC v1.3, $I=2.2 \times 10^{11} ppb$, $(Q_x, Q_y)=(62.320, 60.325)$
 $\epsilon=2.5 \mu m$, $Q'=15$, $I_{M0}=-300A$



Start of Collisions: $N_b = 2.2 \cdot 10^{11} \text{ ppb}$

- Reduction of **crossing angle** at **constant luminosity**, reduces **pileup** (by elongating the luminous region) and **triplet irradiation**.

Min DA HL-LHC v1.3, $I=2.2 \times 10^{11} \text{ ppb}$, $(Q_x, Q_y)=(62.320, 60.325)$
 $\epsilon=2.5 \mu\text{m}$, $Q'=15$, $I_{M0}=-300\text{A}$

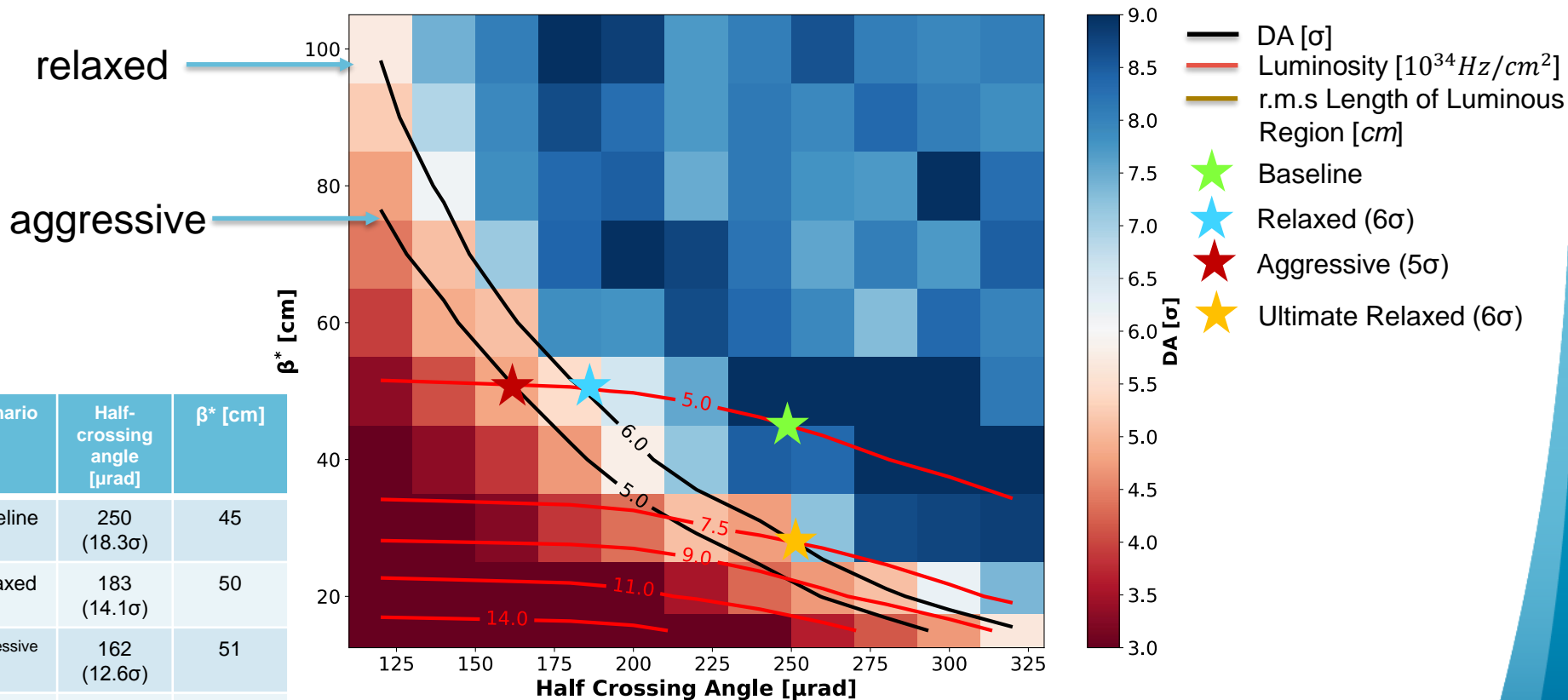


Scenario	Half-crossing angle [μrad]	β^* [cm]
Baseline	250 (21.8 σ)	64
Relaxed	154 (14.0 σ)	69
Aggressive	133 (12.1 σ)	69
Ultimate Relaxed	209 (15.1 σ)	44

Start of Collisions: $N_b = 1.9 \cdot 10^{11} ppb$

- Draw the levelling path by following **iso-DA** and **iso-Luminosity** configurations when bunch intensity decays

Min DA HL-LHC v1.3, $I=1.9 \times 10^{11}$ ppb, $(Q_x, Q_y)=(62.320, 60.325)$
 $\epsilon=2.5\mu\text{m}$, $Q'=15$, $I_{M0}=-300A$

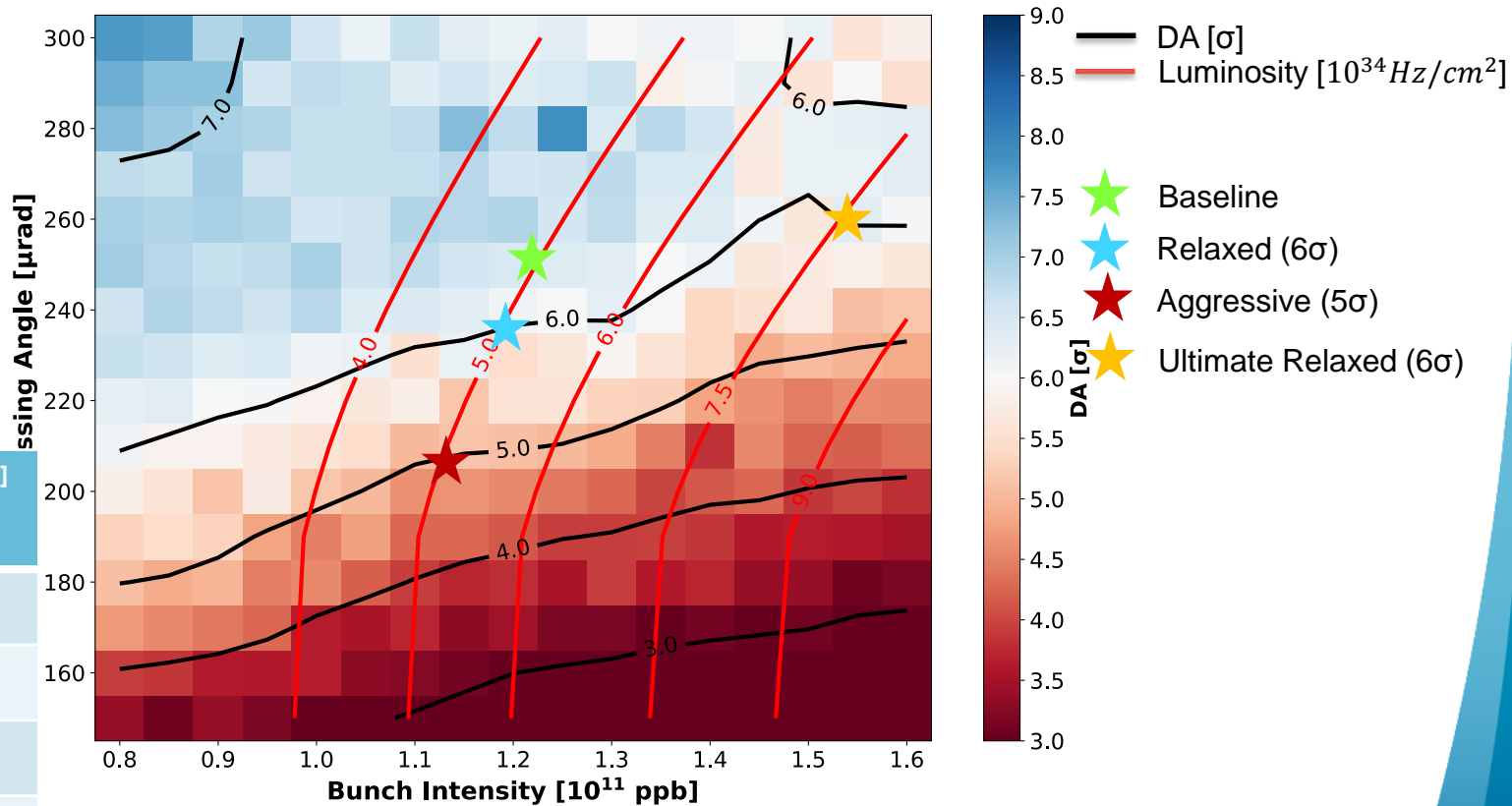


Scenario	Half-crossing angle [μrad]	β* [cm]
Baseline	250 (18.3σ)	45
Relaxed	183 (14.1σ)	50
Aggressive	162 (12.6σ)	51
Ultimate Relaxed	251 (14.5σ)	28

End of Levelling

- To determine the exact point in which we exit the levelling we search for which **intensity** and **crossing angle** we reach $\beta^* = 15cm$

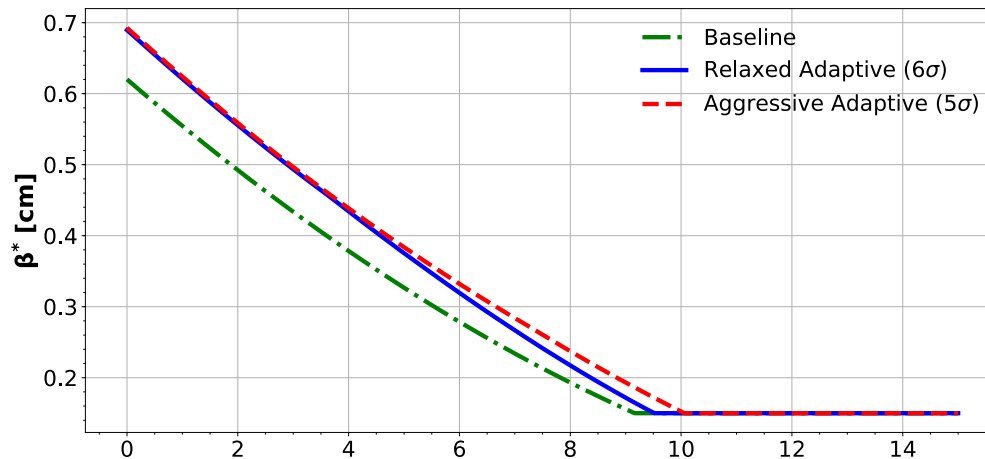
Min DA HL-LHC v1.3, $\beta^* = 15cm$, $(Q_x, Q_y) = (62.315, 60.320)$
 $\epsilon = 2.5\mu m$, $Q' = 15$, $I_{MO} = -300A$



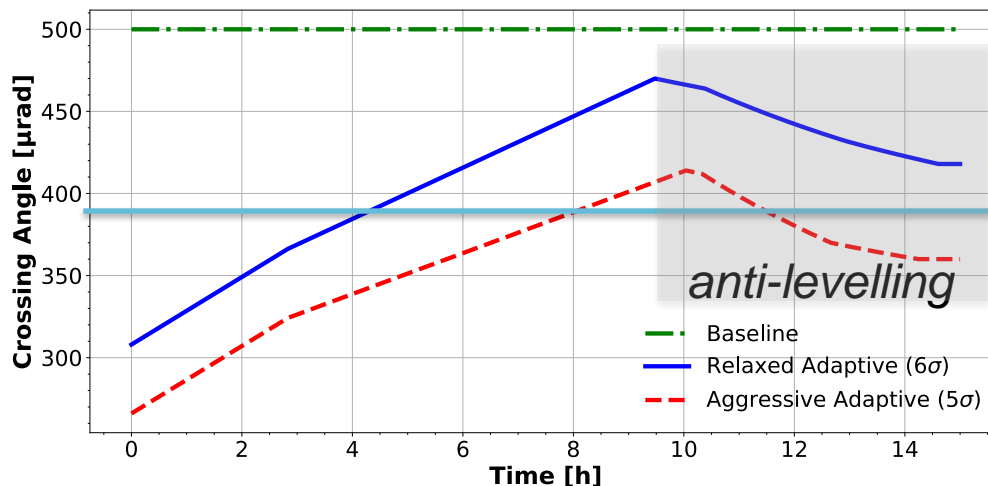
Scenario	Half-crossing angle [μrad]	I [ppb]
Baseline	250 (10.5σ)	1.22
Relaxed	235 (9.9σ)	1.19
Aggressive	207 (8.8σ)	1.13
Ultimate Relaxed	260 (11σ)	1.53

Evolution of Parameters

- For the adaptive scenarios, include **crossing angle “anti-levelling”** à la LHC after the end of levelling



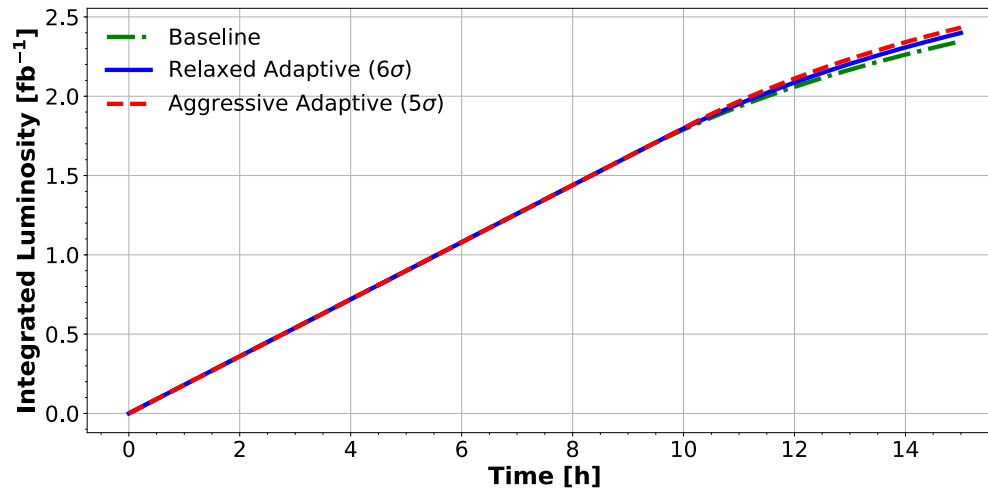
Slightly delay the end of levelling



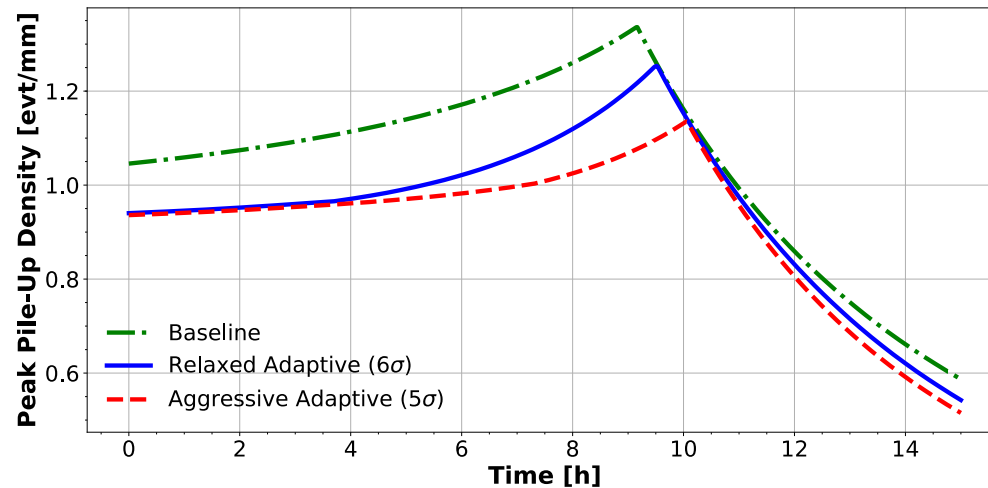
max crabbing angle: 380μrad

anti-levelling

Evolution of Parameters



*Integrated luminosity
 $\approx 2\text{fb}^{-1}$ for 12h fill*



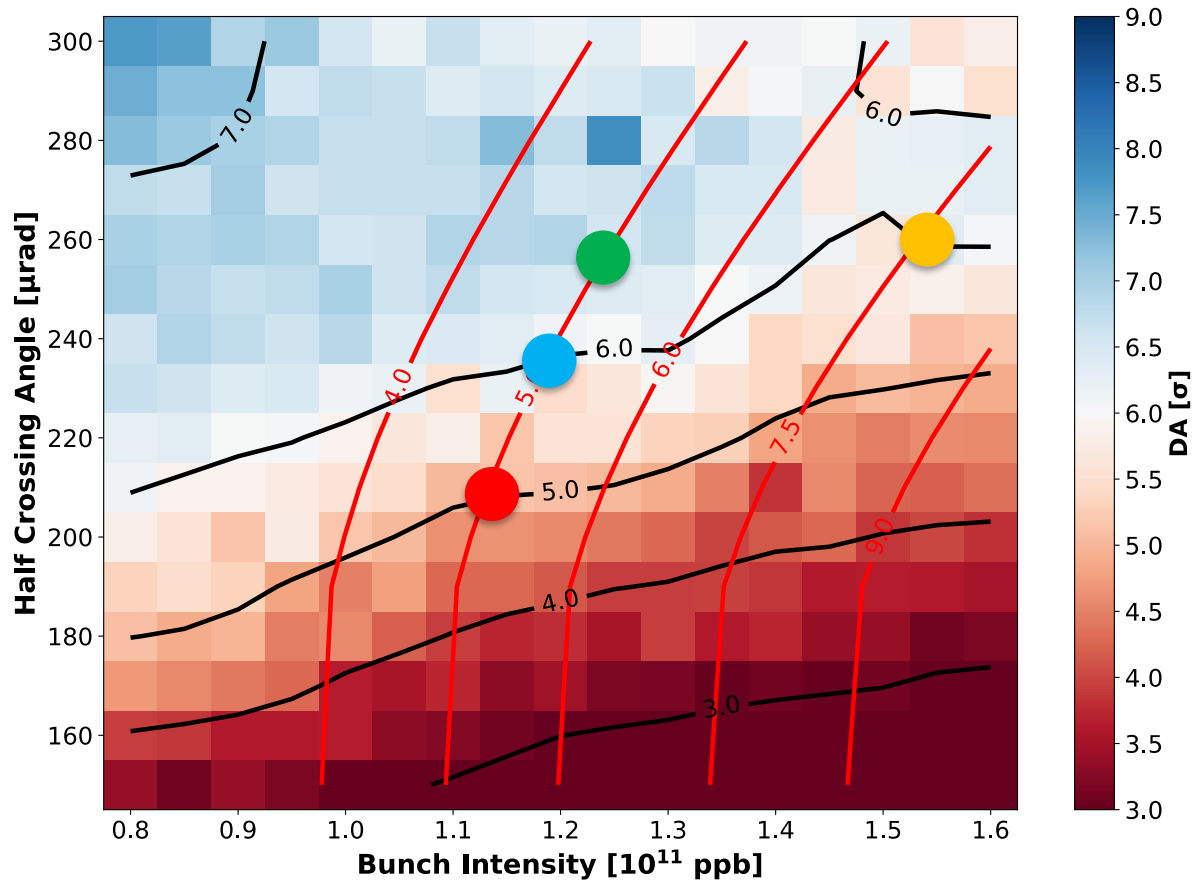
*Elongating luminous
region by $\sim 15\%$
 \rightarrow reducing the peak
pileup density by 7%*

Effect of Field Multipole Errors

- Estimate the effect of the multipolar errors on the DA with beam-beam.
- Track particles using 60 realizations of the machine (seeds)
- Apply field errors from table “errortable_v5”.
- Not correcting for D2 and MCBXF → under study (*Massimo et al*)
- We focus on a few interesting configurations at the start and at the end of the levelling:
 - Aggressive, Relaxed adaptive Scenarios
 - Baseline Nominal Scenario
 - Ultimate Scenario
- We perform a statistical analysis in terms of minimum and average DA of the results over the 5 angles and 5 amplitude ranges.

Field Errors at the End of Levelling

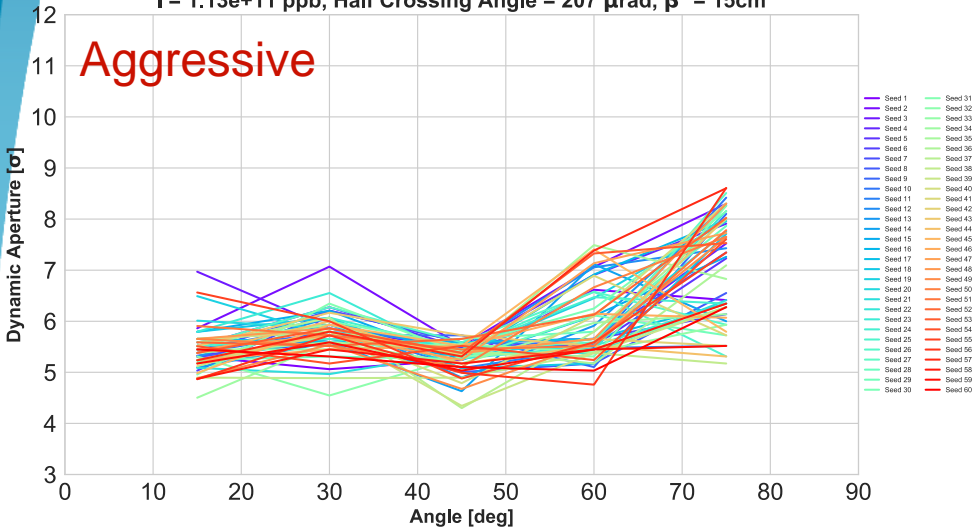
Min DA HL-LHC v1.3, $\beta^*=15\text{cm}$, $(Q_X, Q_Y)=(62.315, 60.320)$
 $\epsilon=2.5\mu\text{m}$, $Q'=15$, $I_{M0}=-300\text{A}$



Field Errors at the End of Levelling

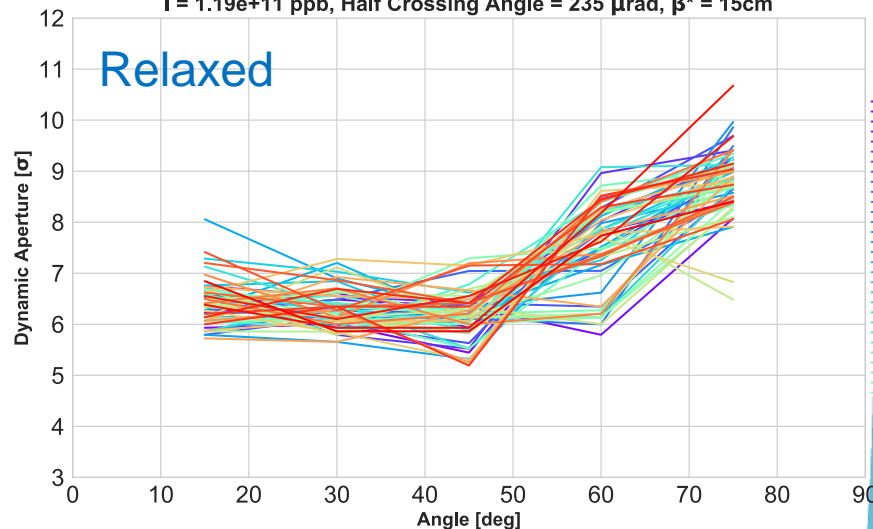
$I = 1.13e+11$ ppb, Half Crossing Angle = 207 μ rad, $\beta^* = 15$ cm

Aggressive



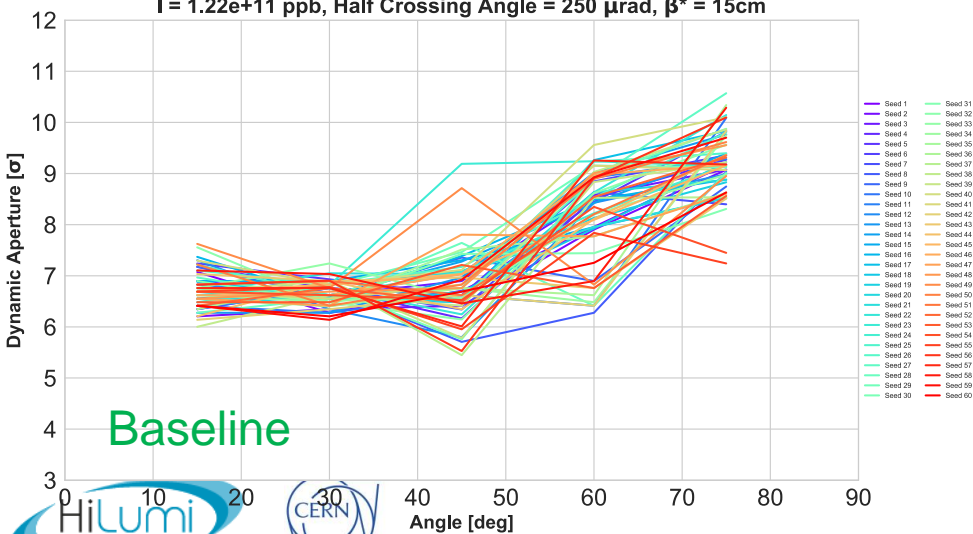
$I = 1.19e+11$ ppb, Half Crossing Angle = 235 μ rad, $\beta^* = 15$ cm

Relaxed



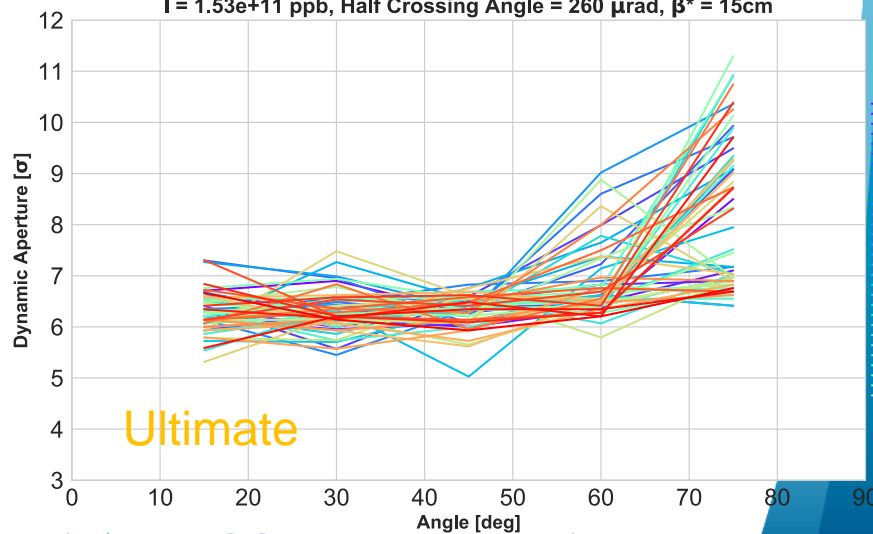
$I = 1.22e+11$ ppb, Half Crossing Angle = 250 μ rad, $\beta^* = 15$ cm

Baseline

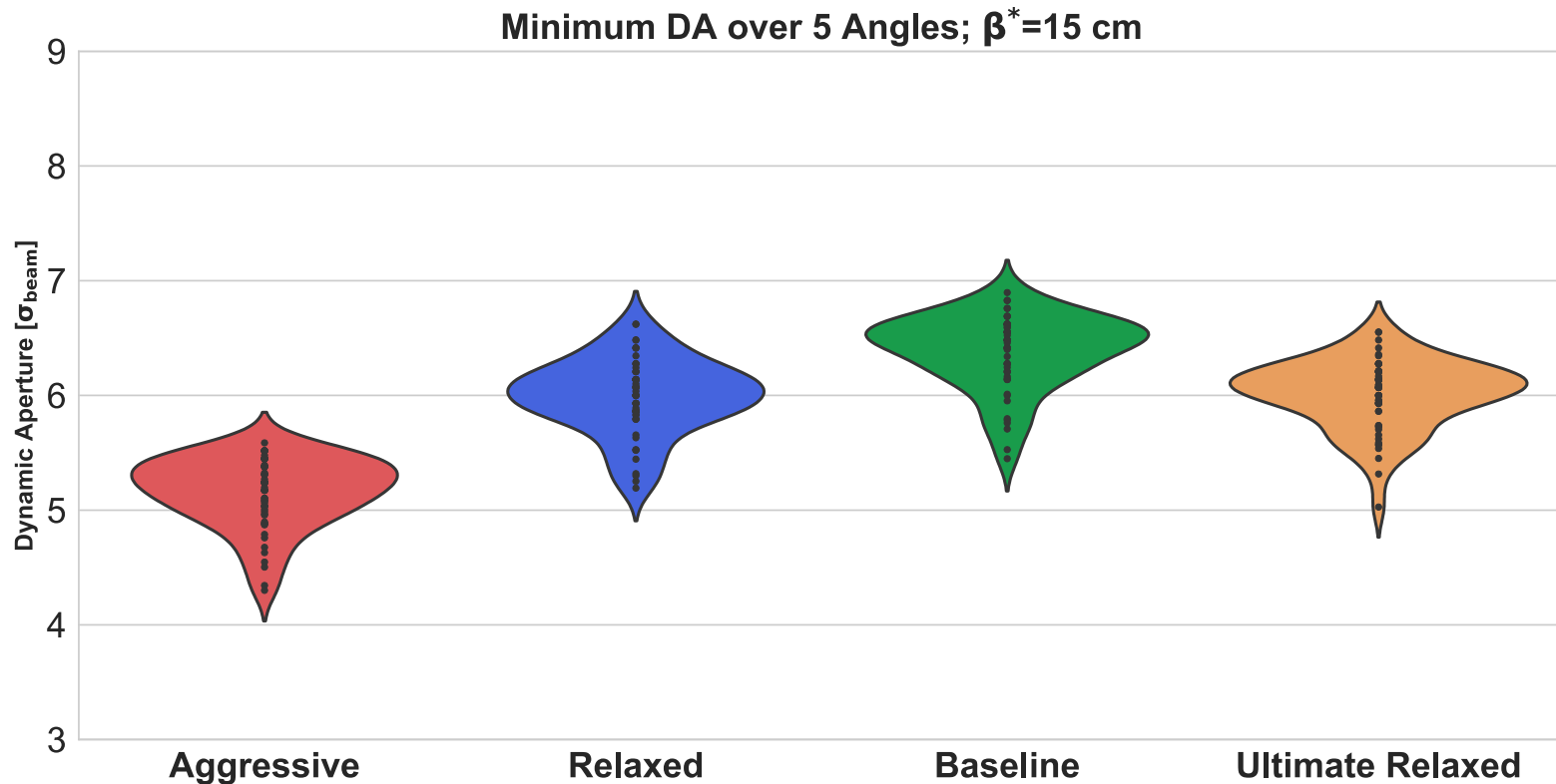


$I = 1.53e+11$ ppb, Half Crossing Angle = 260 μ rad, $\beta^* = 15$ cm

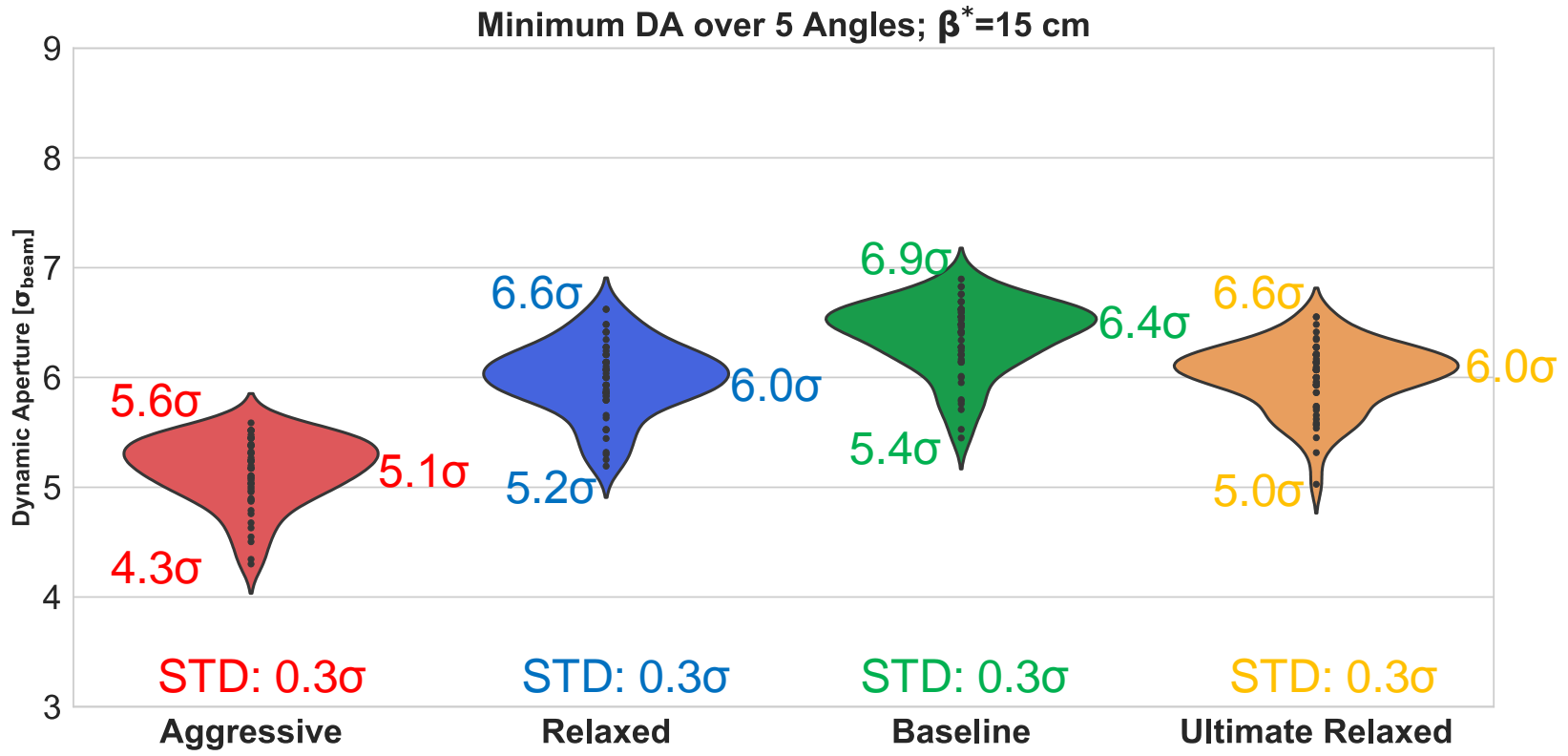
Ultimate



Field Errors at the End of Levelling

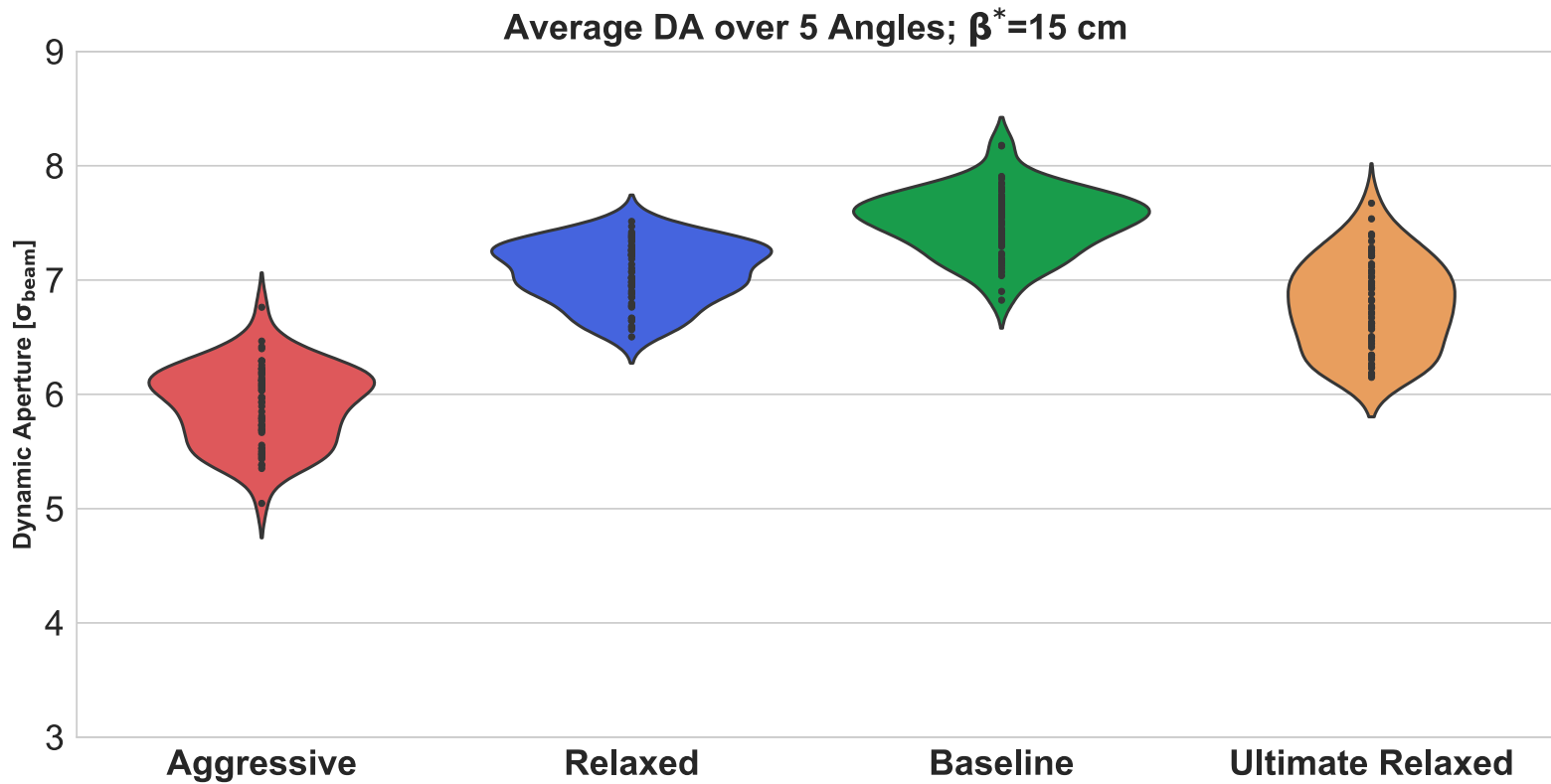


Field Errors at the End of Levelling

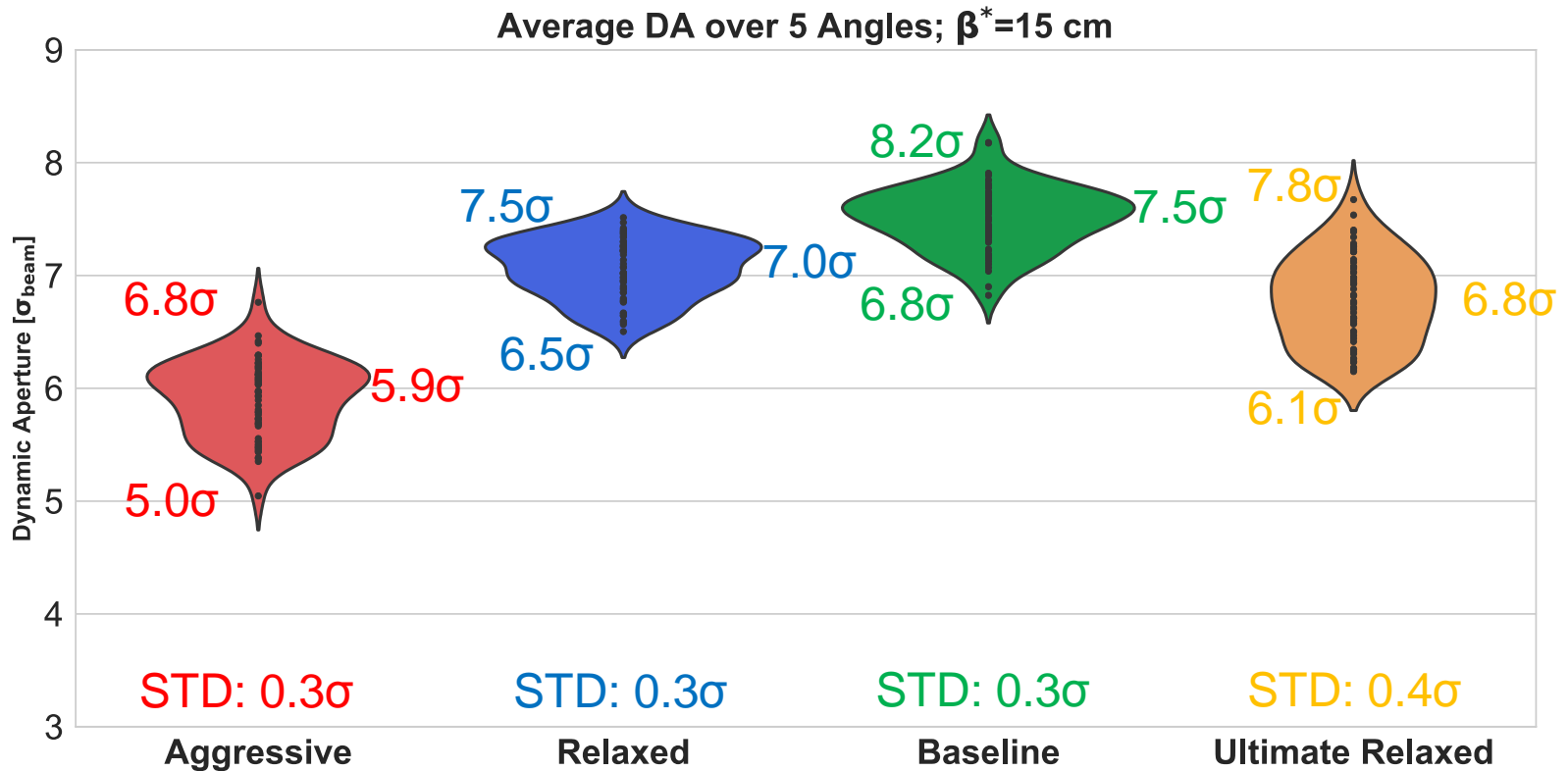


- Average spread of the various realizations of 0.3σ

Field Errors at the End of Levelling



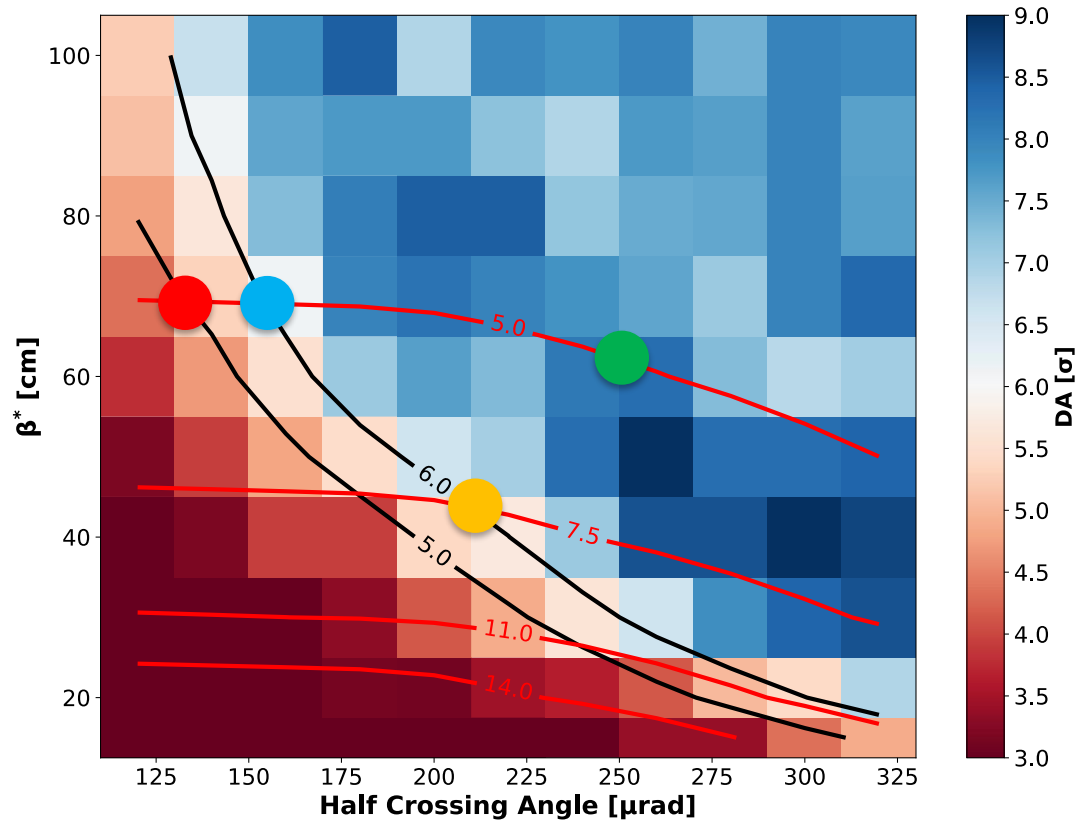
Field Errors at the End of Levelling



- Average spread of the various realizations of 0.3σ (0.4σ for ultimate)

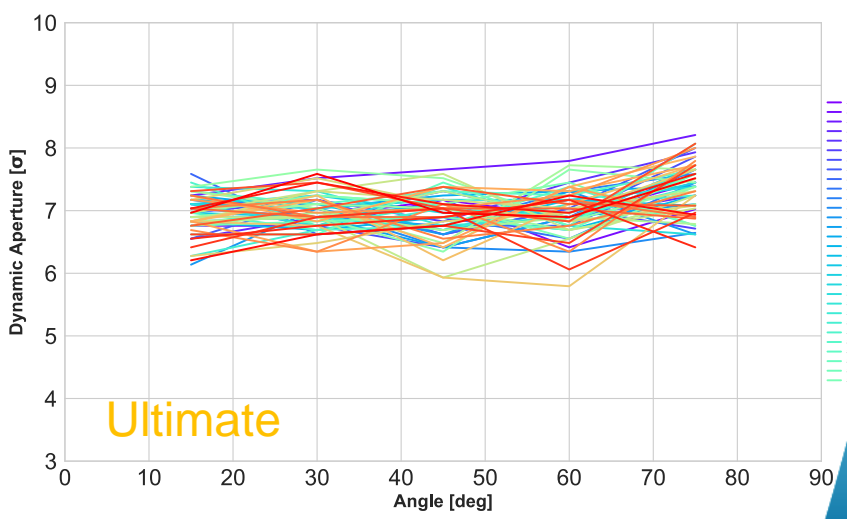
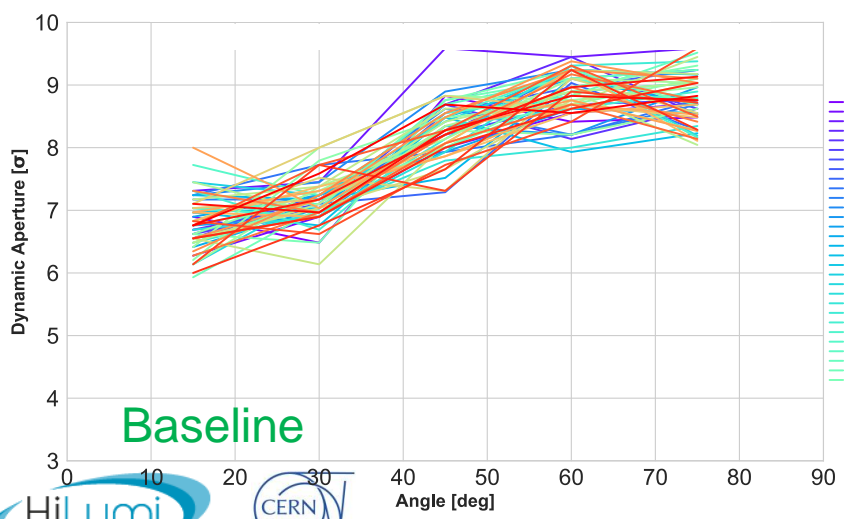
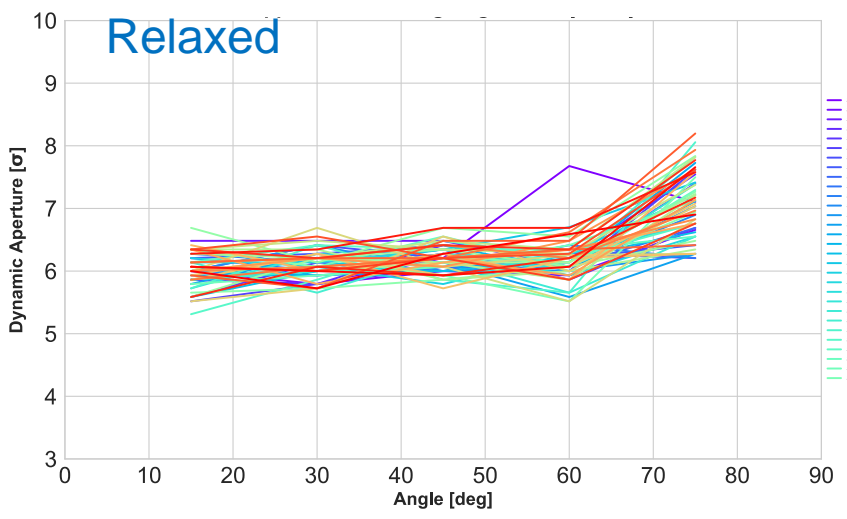
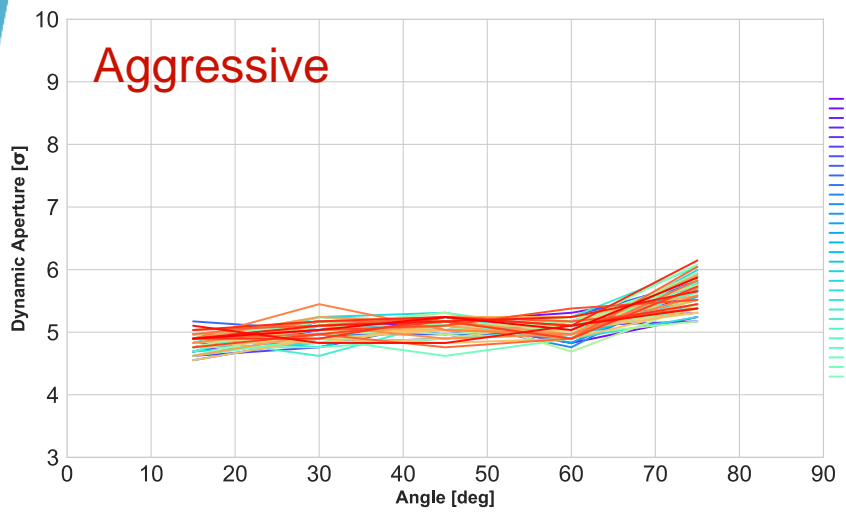
Field Errors at the Start of Levelling

Min DA HL-LHC v1.3, $I=2.2 \times 10^{11}$ ppb, $(Q_x, Q_y)=(62.320, 60.325)$
 $\epsilon=2.5 \mu\text{m}$, $Q'=15$, $I_{M0}=-300\text{A}$

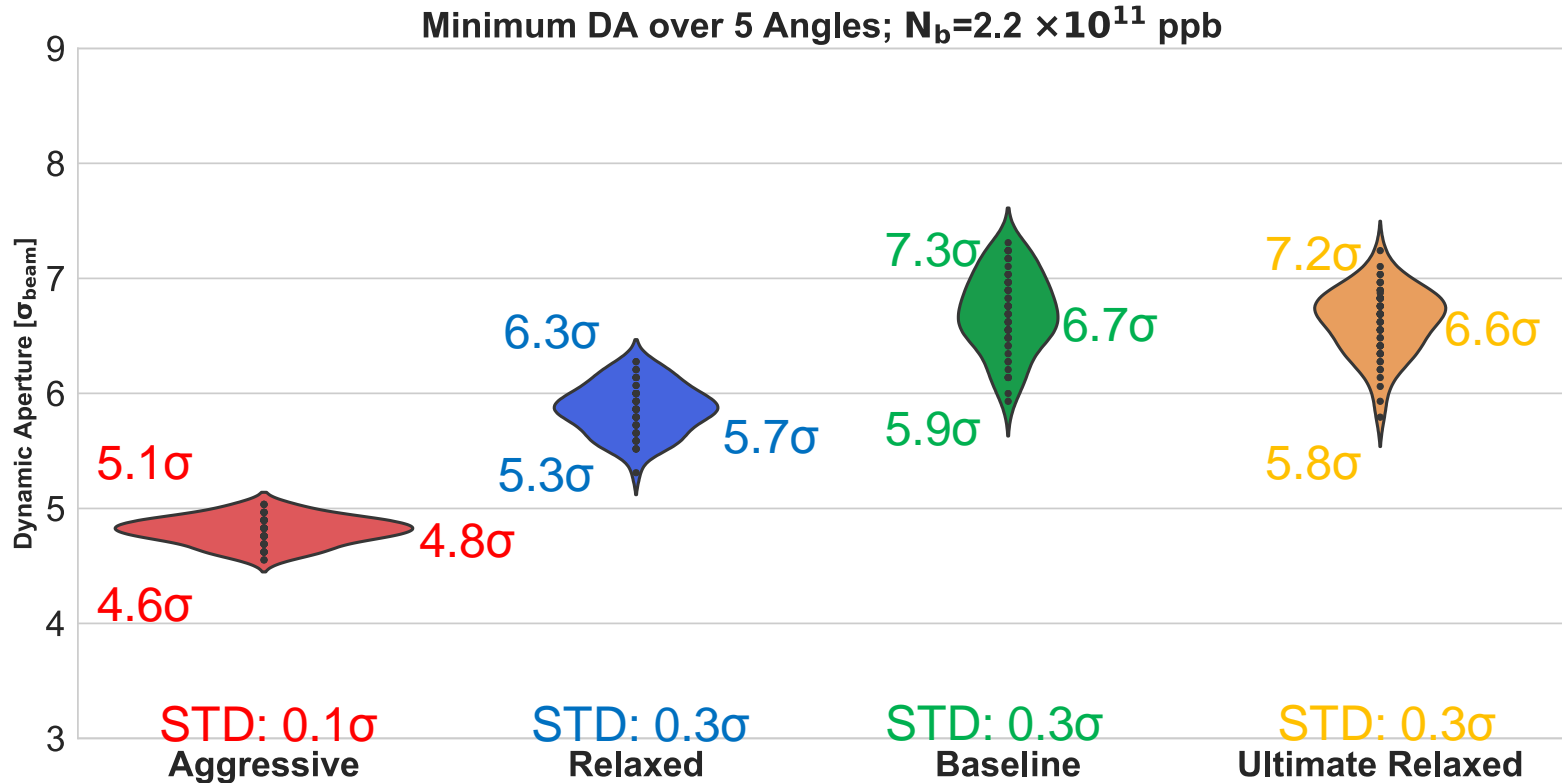


Preliminary

Field Errors at the Start of Levelling

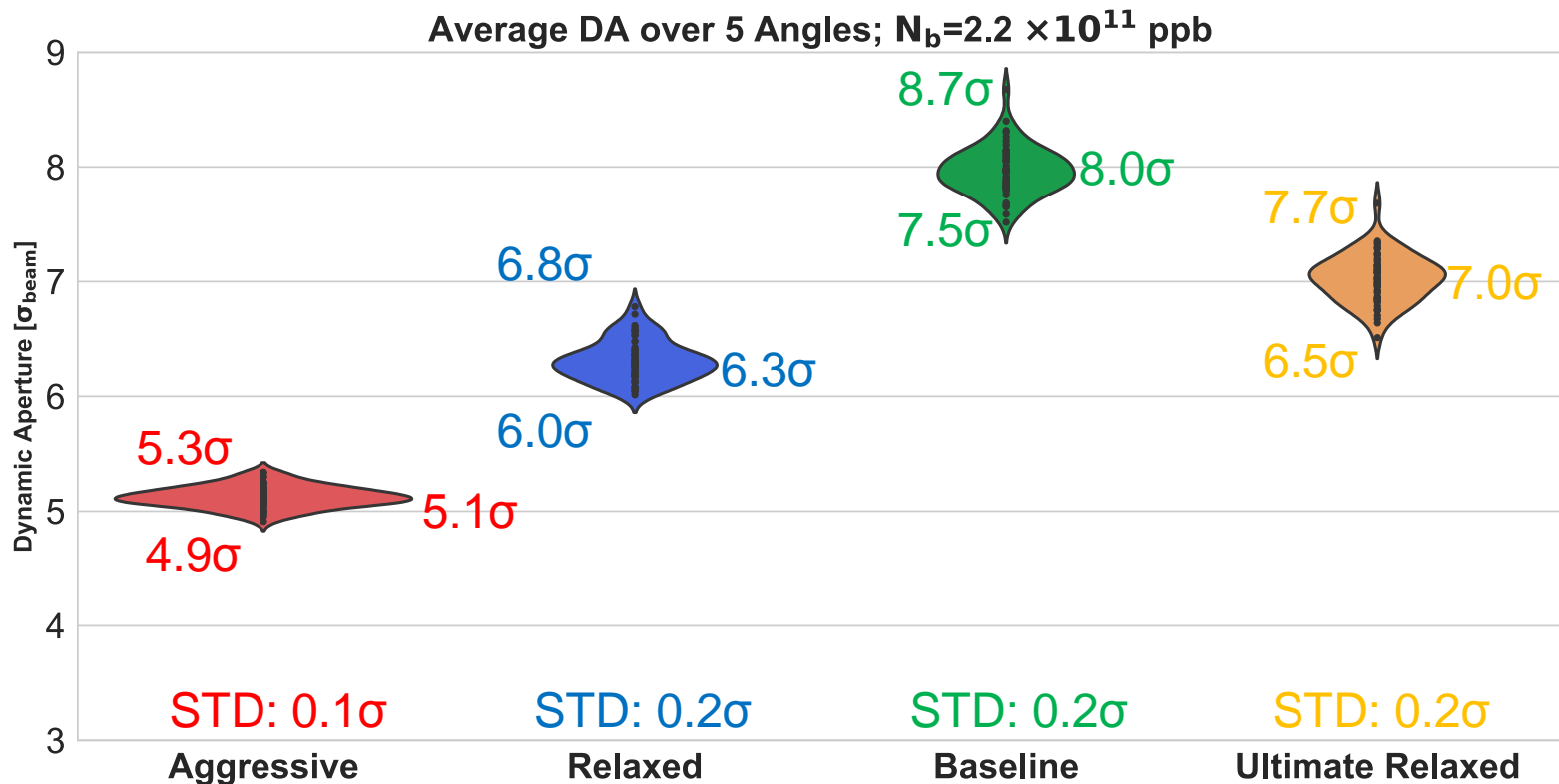


Field Errors at the Start of Levelling



- Spread of 0.3σ , with the exception of the aggressive at $\sim 0.1\sigma$

Field Errors at the Start of Levelling



- Spread of 0.2σ , with the exception of the aggressive at $\sim 0.1\sigma$

Summary and Overview

Operational Scenario

- Operational *long-term stability* with a scenario with **high chromaticity** and **octupole current** requires **mitigation through WP optimization**
 - Suggested WP at the start of levelling: $(Q_x, Q_y) = (62.320, 60.325)$
 - Suggested WP at the end of levelling : $(Q_x, Q_y) = (62.315, 60.320)$
- For $\beta^* = 15\text{cm}$, DA of 6σ cannot be reached with **maximum octupole current** (-570A) and **high chromaticity**
 - Here used -300A, possibility to slightly increase it for **stability margin** (*see Elias' talk*)
 - We have extracted all the available margin in terms of DA, given the restrictions and the requirements
 - Studying scenarios that provide more margin, either by trading in operational complexity, or by adopting mitigation methods (e.g. BBLR compensation (*see Guido's talk*))
- The **ultimate scenario** at $\beta^* = 15\text{cm}$ requires larger crossing angle than allowed by aperture → need additional mitigation techniques to be feasible
- Adaptive crossing angle levelling scenario has the advantage of reduced **pile-up density** and potential reduction of **triplet irradiation** (*see Francesco's talk*).
- The details of bringing the beams to collision have to be refined with respect to the crossing angle and DA at the regime of high octupole current and chromaticity.

Field Quality

- The specified field quality (*see Yuri's talk*) seems **adequate**: *field errors remain in the shadow of the beam-beam effects*
- Average spread** at the crucial points of levelling DA **0.3σ** .



Thank you for your attention



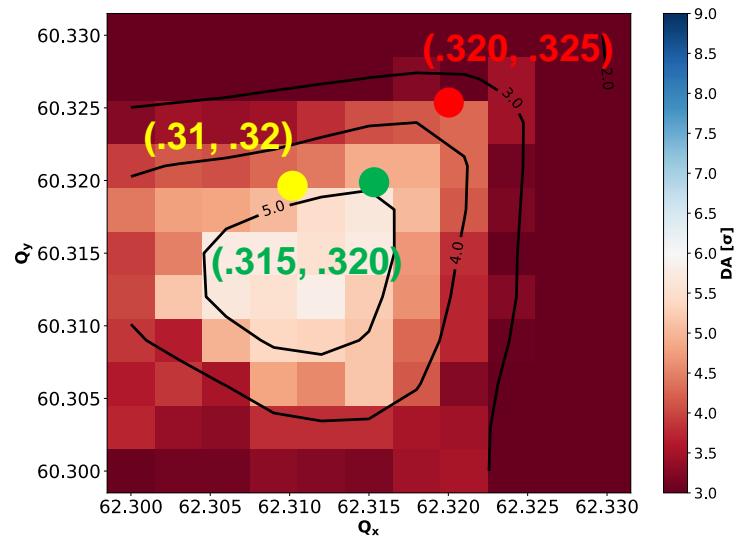
*and many thanks to all the **LHC@home** volunteers!*
SixTrack



SPARE SLIDES

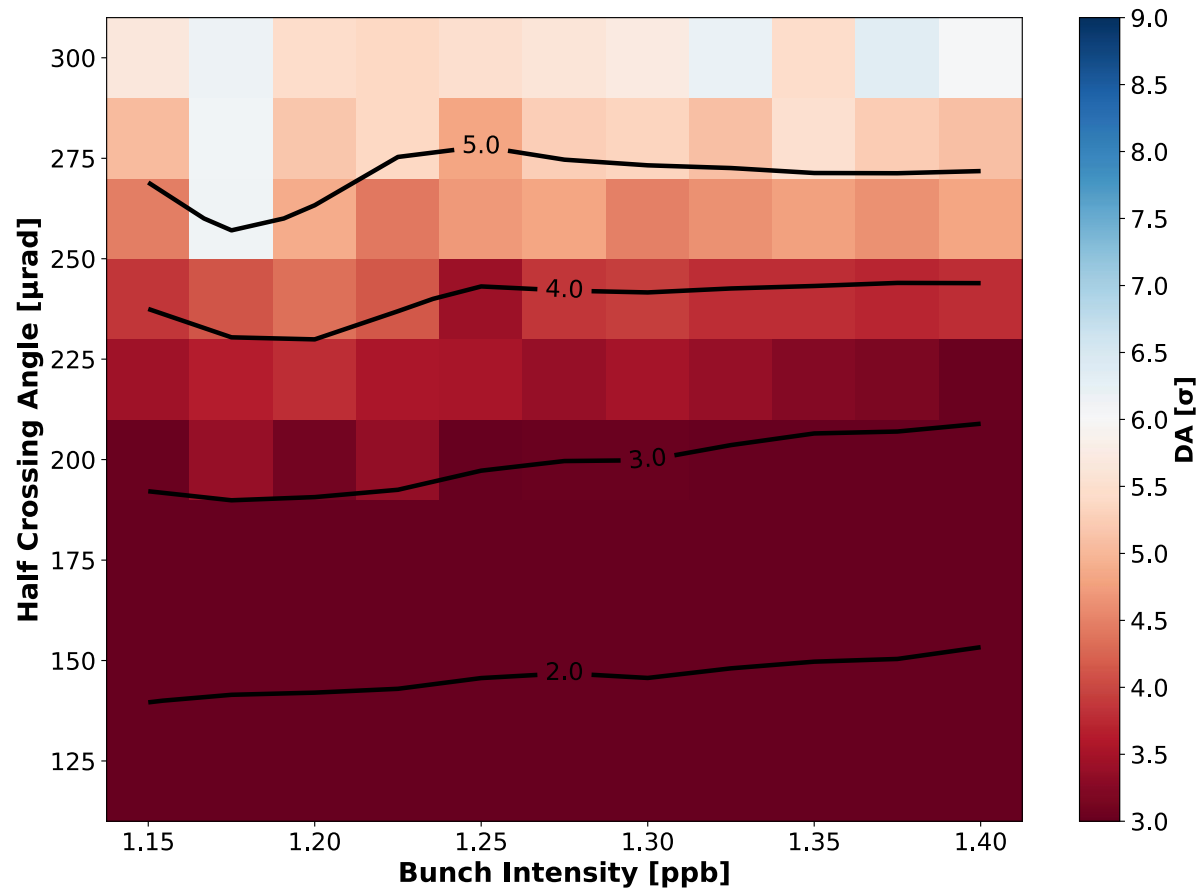
Positive Octupoles

Min DA HL-LHC v1.3, $I = 1.2 \times 10^{11}$ ppb, $\beta^* = 15$ cm
 $\epsilon = 2.5 \mu\text{m}$, $Q = 15$, $I_{M0} = 300$ A

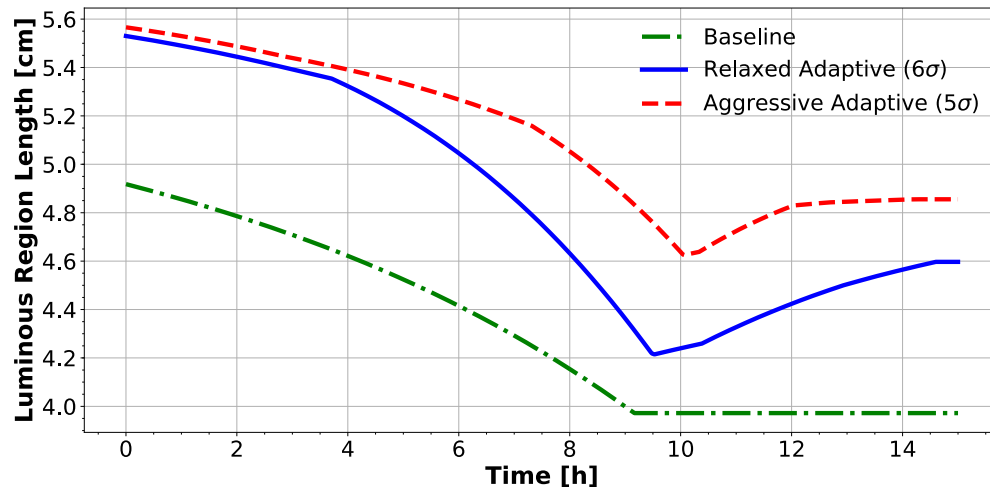
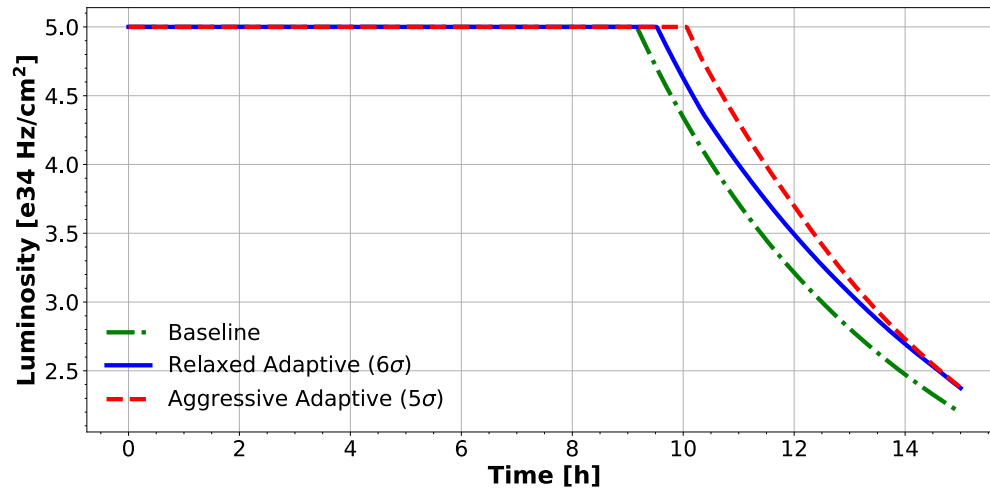


End of Levelling with WP of start of levelling

Min DA HL-LHC v1.3, $\beta^*=15\text{cm}$, $(Q_x, Q_y)=(62.320, 60.325)$
 $\epsilon=2.5\mu\text{m}$, $Q'=15$, $I_{MO}=-570\text{A}$

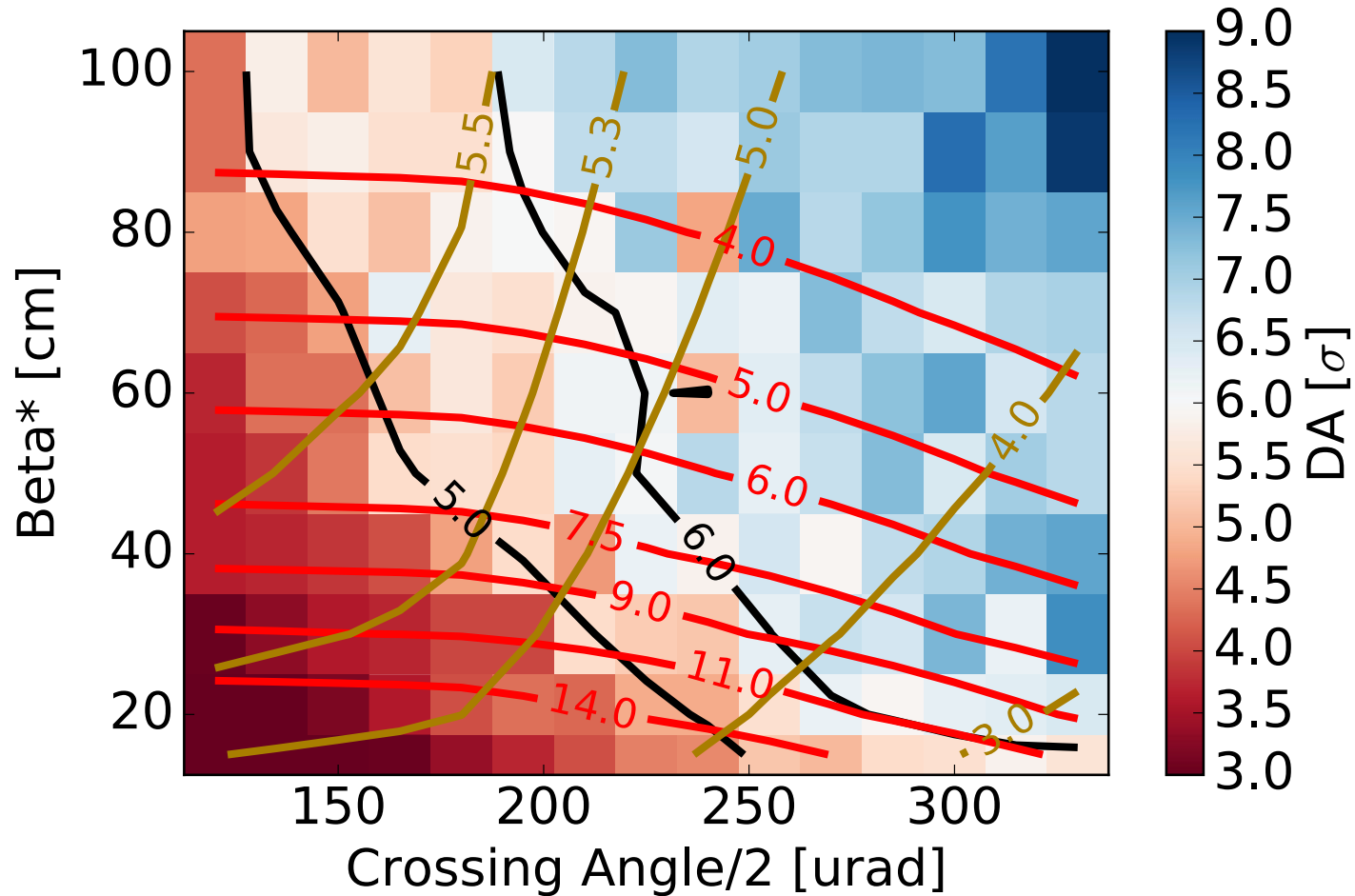


Parameter Evolution



Low Chroma / Octupoles

Min DA; $I = 2.2e11$; $I_{MO} = 0$ A; $Q' = 3$ #



High Chroma / Octupoles

Min DA; $I = 2.2e11$; $I_{MO} = -570$ A; $Q' = 15$ #

