CERN

# Long Range Beam-Beam effects for HL-LHC

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with contributions of G. Arduini, O. Brüning, R. de Maria, **S. Fartoukh**, G. Iadarola, **N. Karastathis**, **D. Pellegrini**, A. Poyet, L. Rossi, K. Skoufaris, **G. Sterbini**, R. Tomas

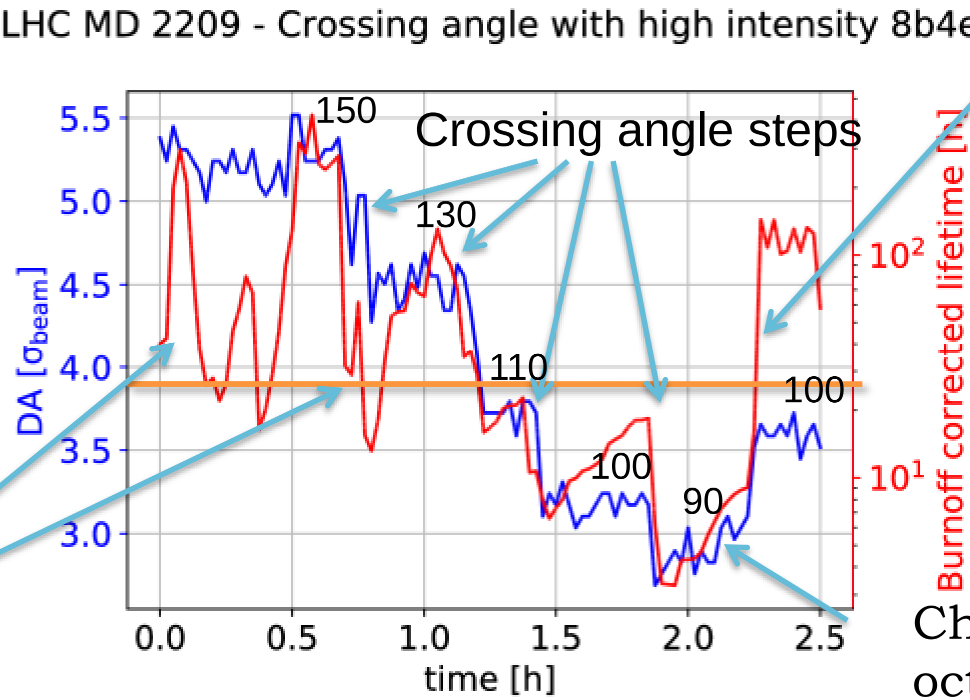
LHC Performance Workshop, Chamonix, 29/01-01/02/2018

# Motivation and Outline

- **Goal** of the presentation:
  - Robustness of HL-LHC **baseline** and **operational scenario** during luminosity production (**levelling**) wrt **Beam-Beam Long-Range (BBLR)** effects
    - Correlation of **Dynamic Aperture** (DA) versus **beam-lifetime** from **LHC experience** -> HL-LHC **DA target**
    - Impact of WP, octupole and chromaticity on DA during levelling
    - Minimum crossing angle (x-angle) for adequate DA through levelling
    - Impact of multi-pole errors during collisions
  - Experimental results of possible (non-baseline) BBLR mitigation measures
    - BBLR compensation with wires and octupoles

# Lifetime vs DA with 8b4e

- Linear scale for DA, logarithmic for lifetime
- In agreement with: $\frac{I(t)}{I_0} = 1 - e^{-\frac{DA^2(t)}{2}}$ (M. Giovannozzi, PRST-AB, 2012)



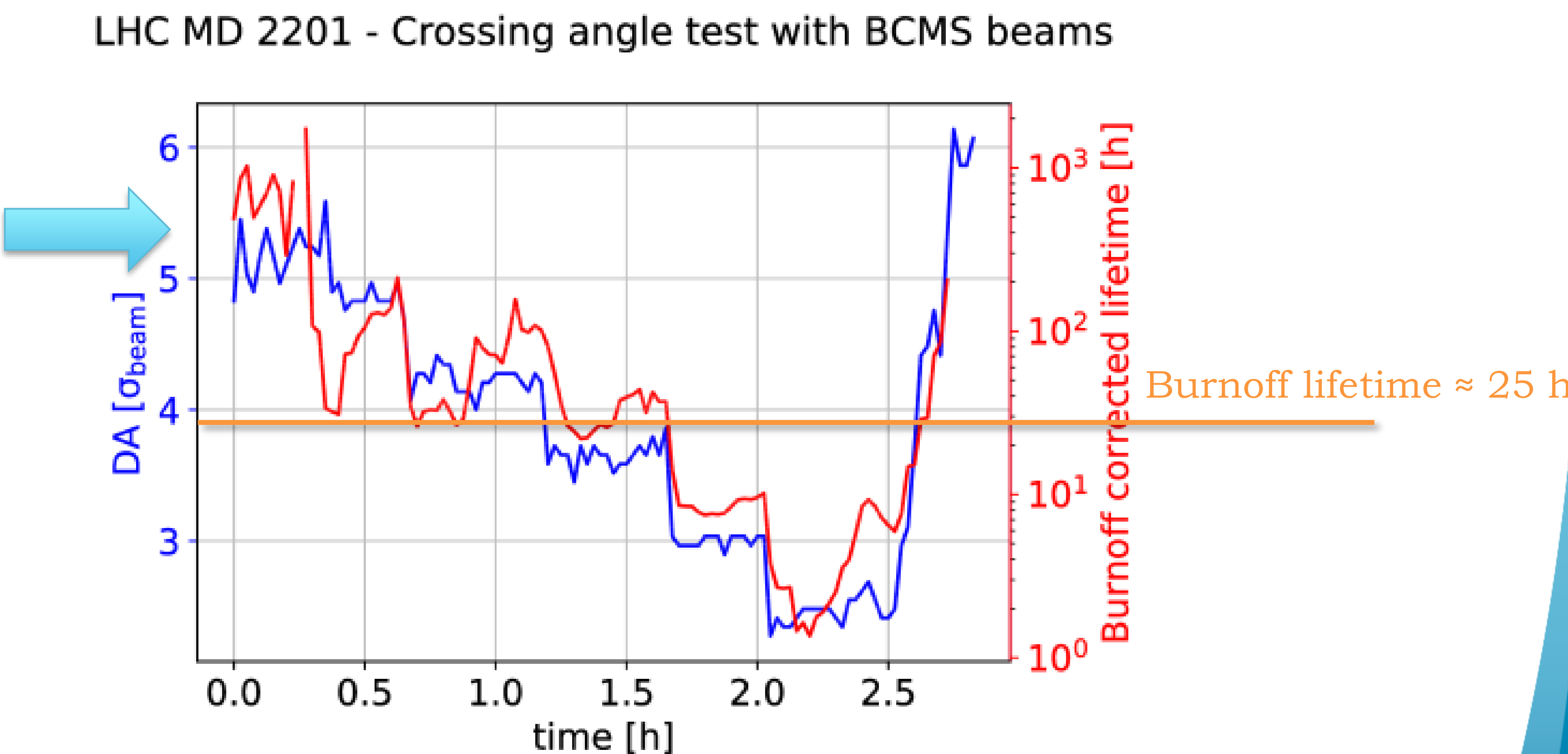

Burnoff lifetime ≈ 25

Tune and Luminosity optimisation

Chromaticity and octupoles reduction

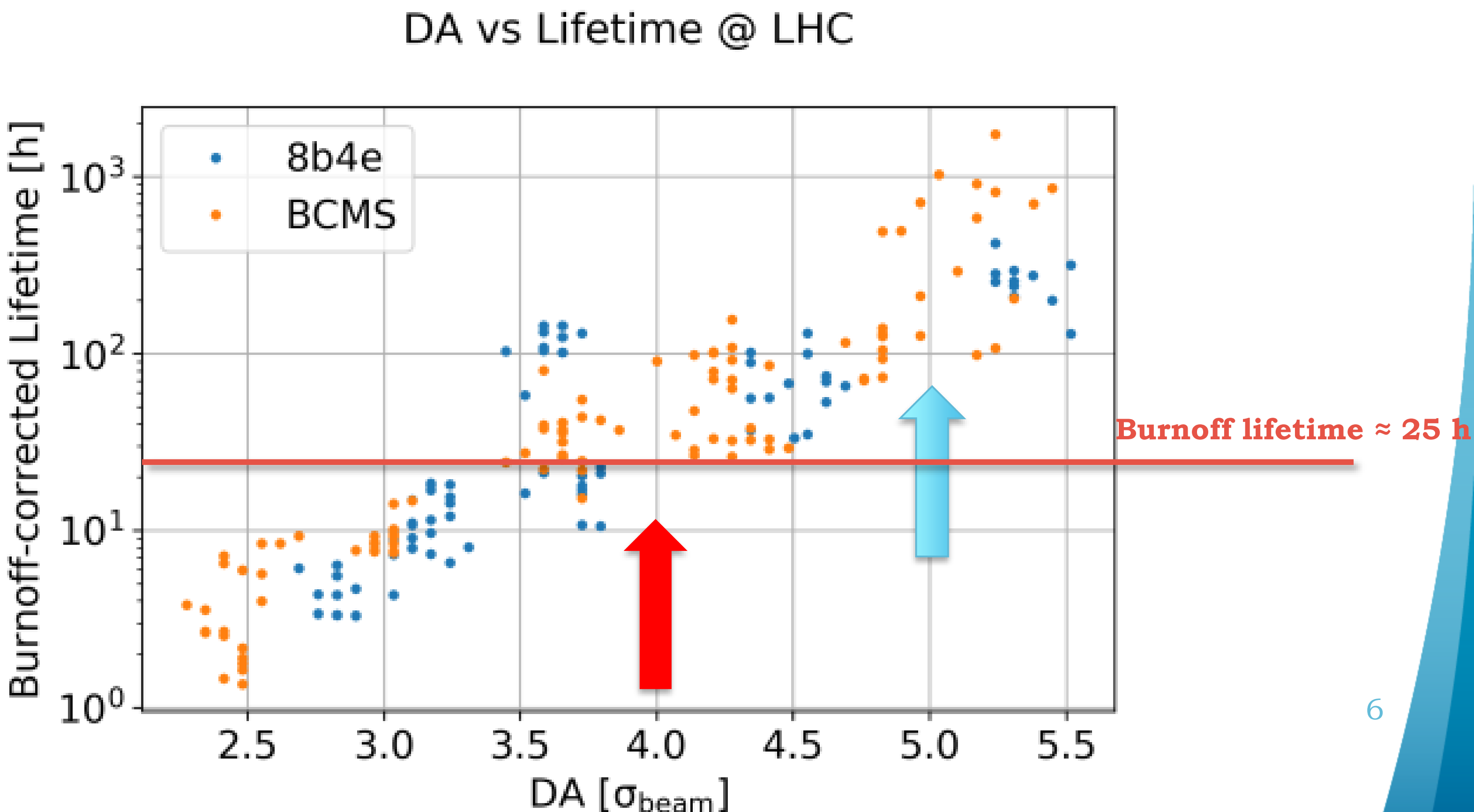
# Lifetime vs DA with BCMS

- Exercise repeated for MD 2201, observing BCMS beams.
- Confirmed the strategy of DA target in the area of **5-6 σ** to allow lifetimes in the complete **shadow** of **burn-off**



# DA vs Lifetime

- Good agreement between **8b4e** and **BCMS** (non-pacman):
  - **4 σ:** provides lifetime close to burn-off lifetime
  - **5 σ:** grants lifetimes of ~100 h: Strict **minimum target** for **LHC operation**
  - **6 σ: target** for **studies** (HL-LHC) in presence of larger uncertainties (e.g. multi-pole errors)

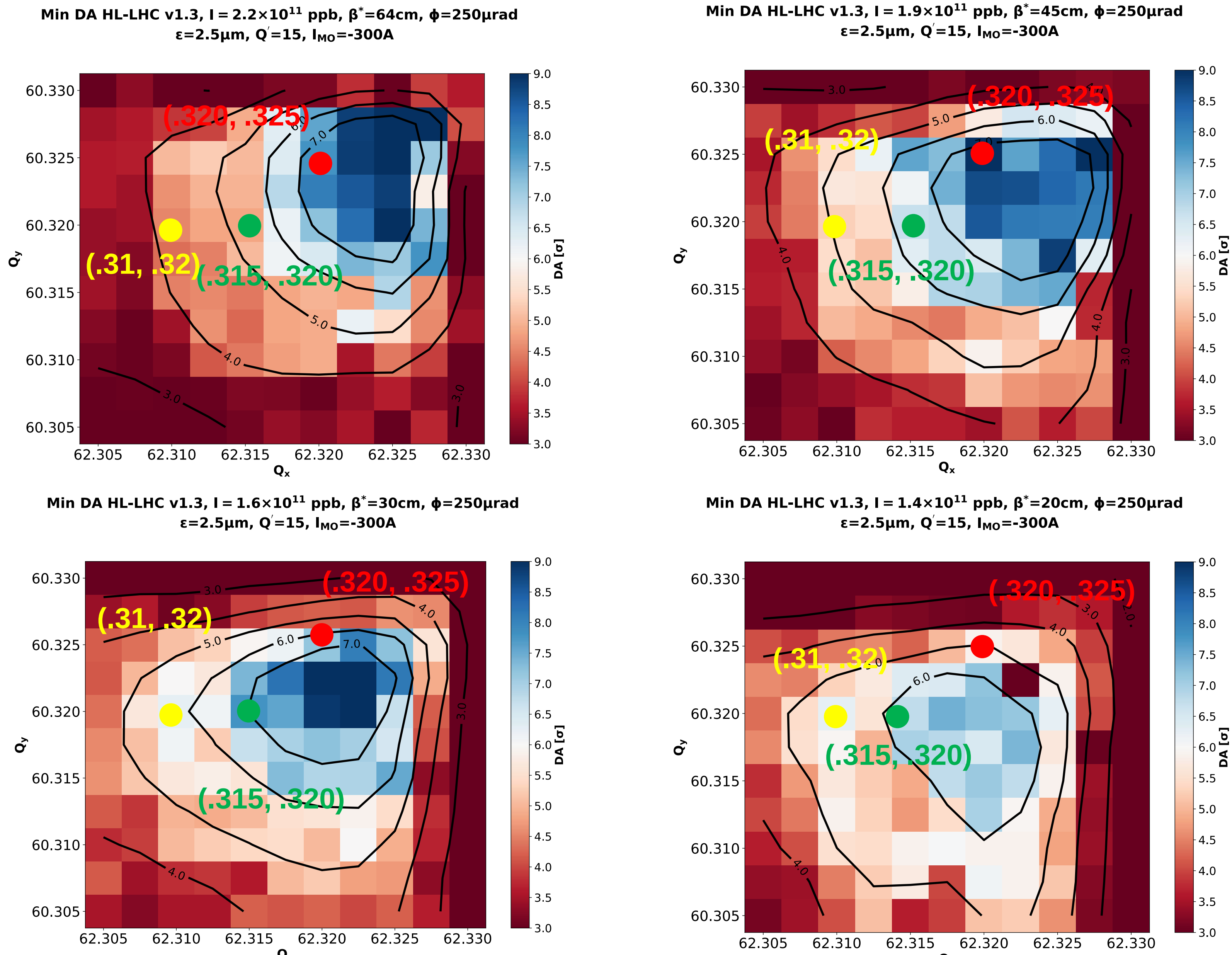


# Parameter optimization during levelling

- **Simulation set-up:**
  - HL-LHC optics v1.3, baseline (MS10 included)
  - half number of crab cavities
  - $I_{MO} = -300$ A, $Q' = 15$ ➔ WP optimization required
  - Collisions: IP1/5 head-on, IP2 halo at 5 σ
  - 2 CC per IP per side, max crab angle (full) 380 μrad (6.8 MV)
  - Assuming **constant** (round) **emittance** of 2.5 μm during collisions
  - **LHCb**
  - Negative dipole polarity ➔ subtract from the external crossing angle
  - Luminosity is levelled at $2 \cdot 10^{33} Hz/cm^2$
- **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
  - **Aggressive** DA of **5 σ** (provided mitigation through WP or BBLR compensation) or to **6 σ** (**relaxed**)

**S.Fartoukh, N. Karastathis, D. Pellegrini**

# Working Point Optimization during levelling



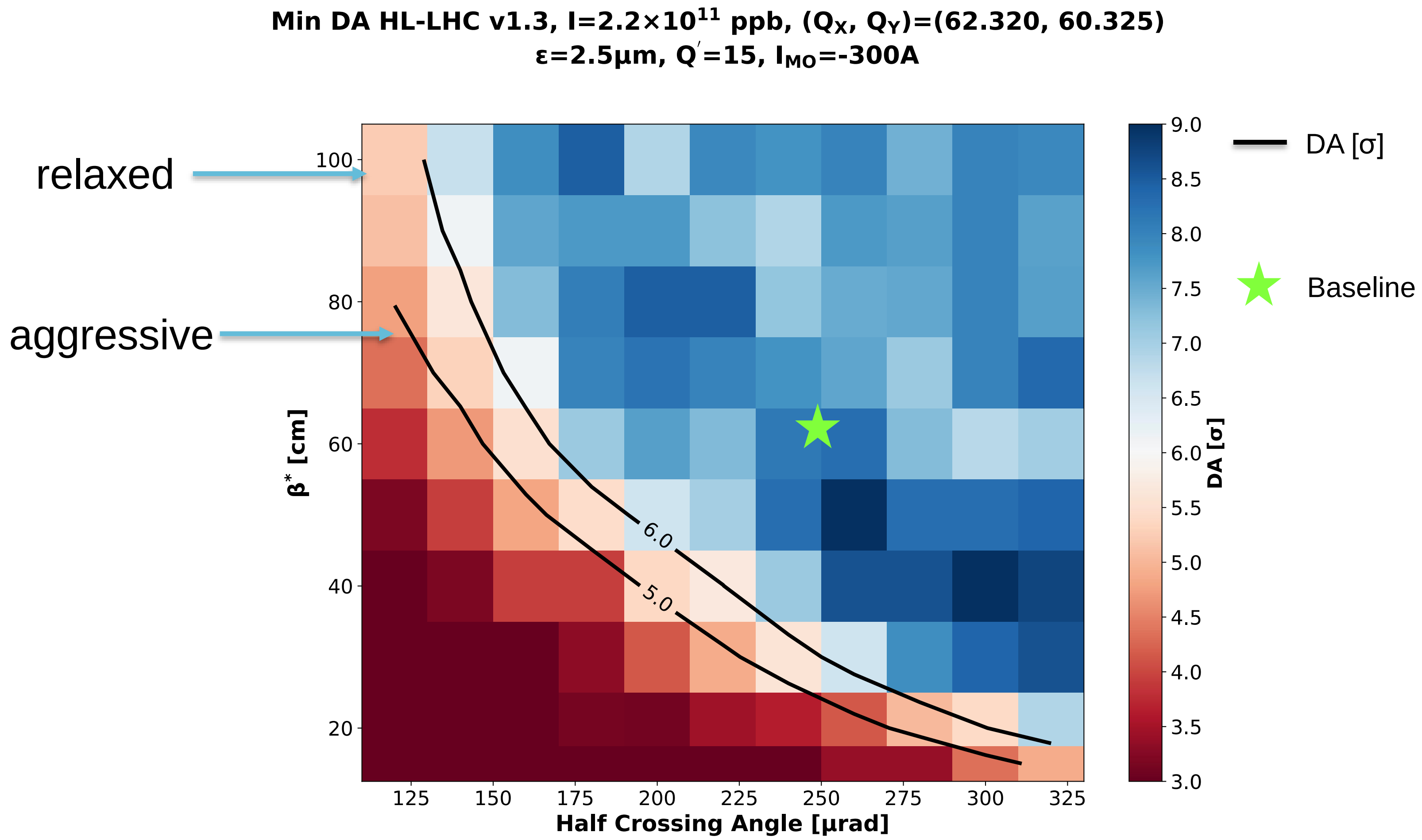
# Adaptive Crossing Angle Levelling Scenario

- **HL-LHC baseline operational scenarios**
  - Fixed crossing angle at 250 μrad
  - Adapting β* during the intensity decay to level luminosity at $5 \cdot 10^{34}$ Hz/cm$^2$ (nominal) or $7.5 \cdot 10^{34}$ Hz/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**.

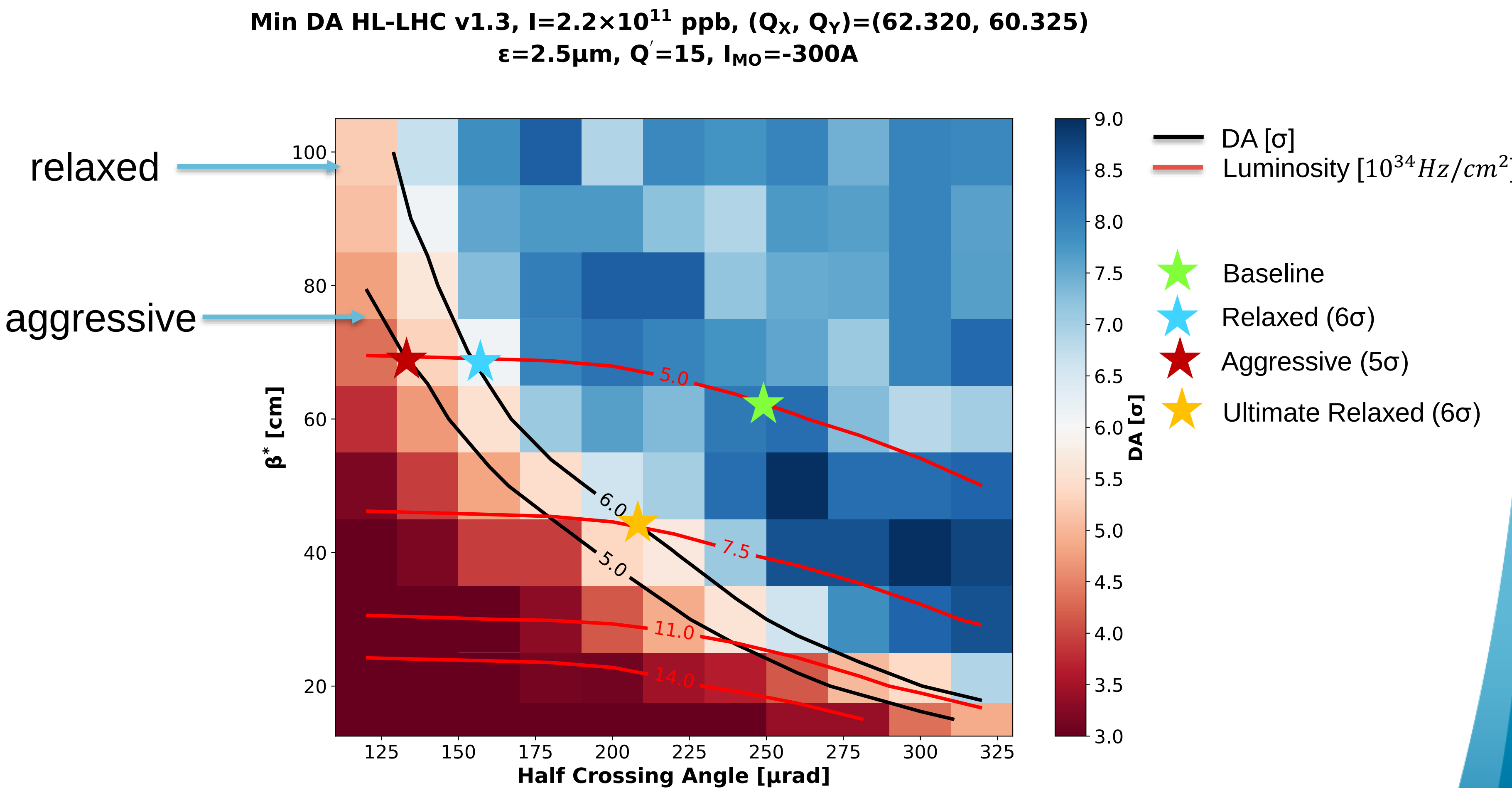
HiLumi HL-LHC PROJECT CERN

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

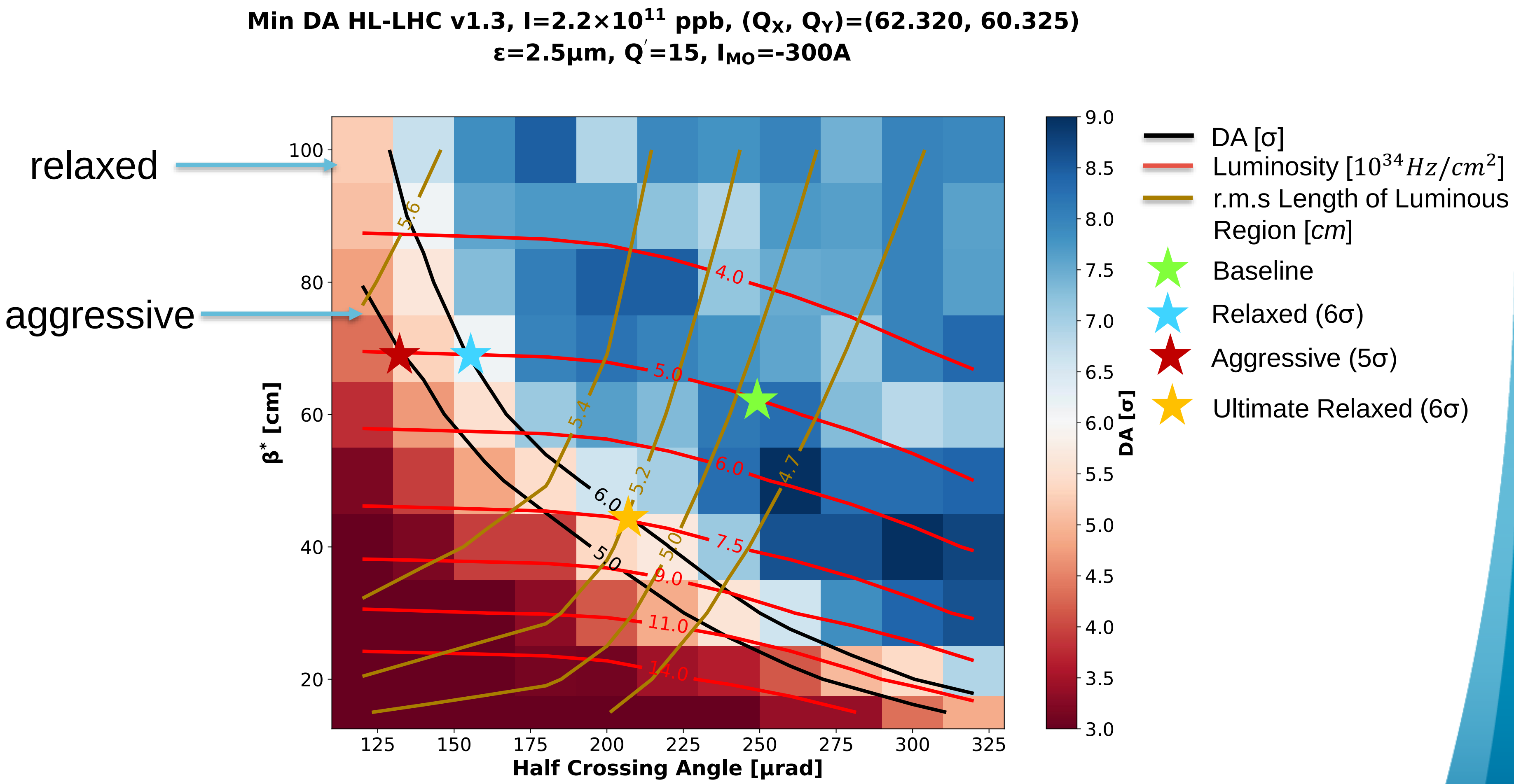


# Start of Collisions: $N_b = 2.2 \cdot 10^{11} ppb$

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

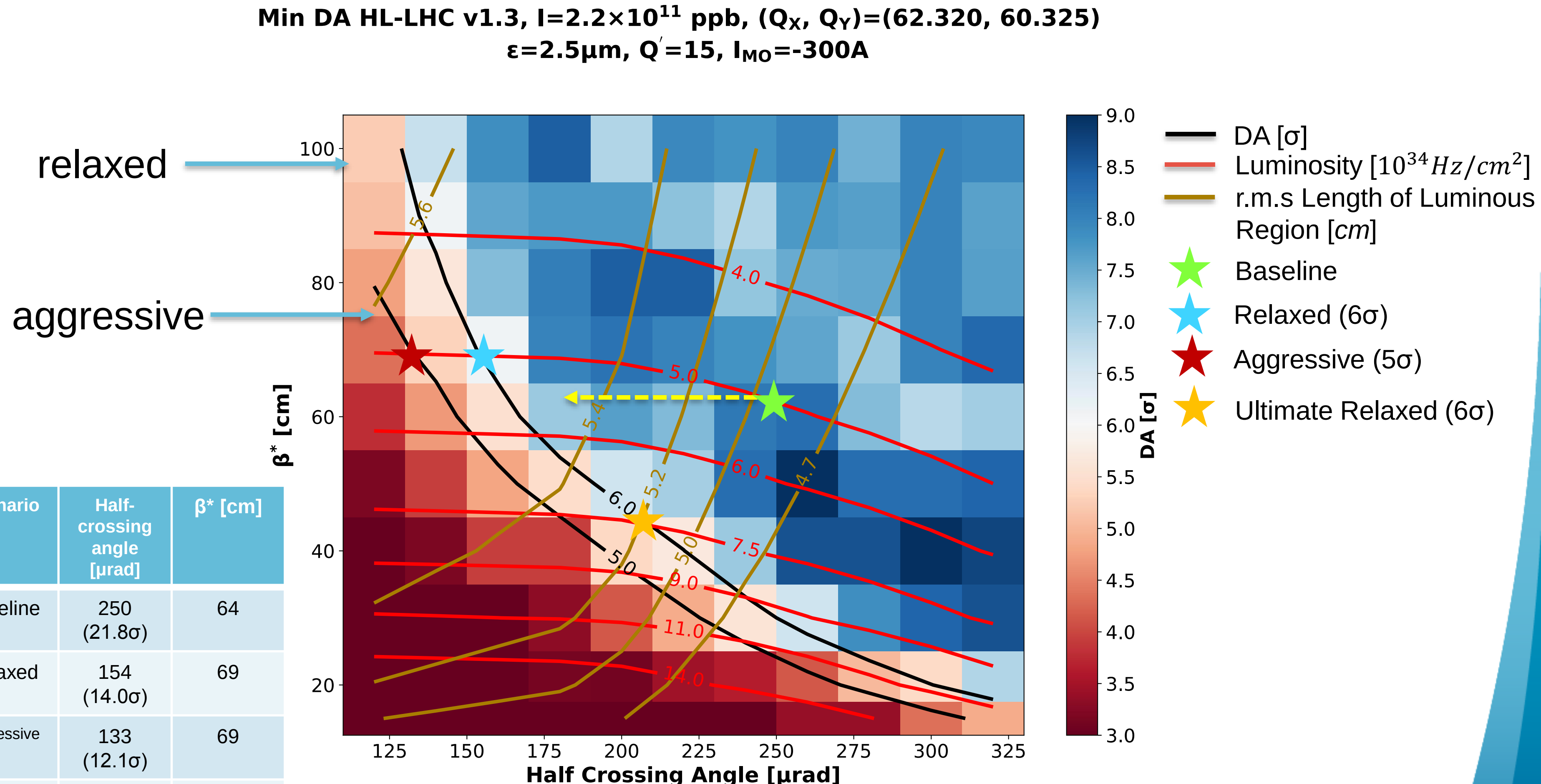


# Start of Collisions: $N_b = 2.2 \cdot 10^{11} ppb$



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

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




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

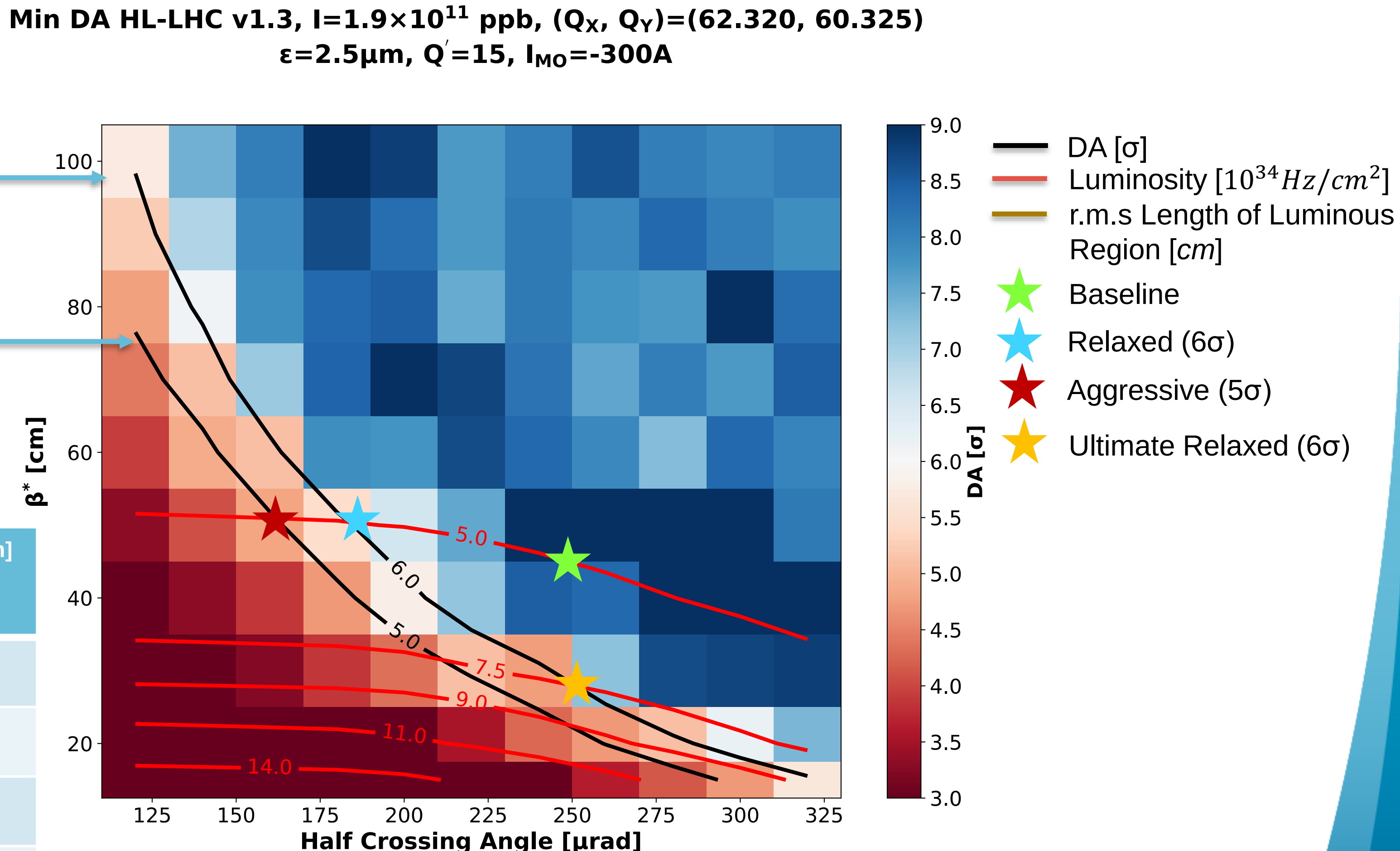
N. Karastathis, D. Pellegrini et al., HL-LHC collaboration meeting 2017

# 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

relaxed

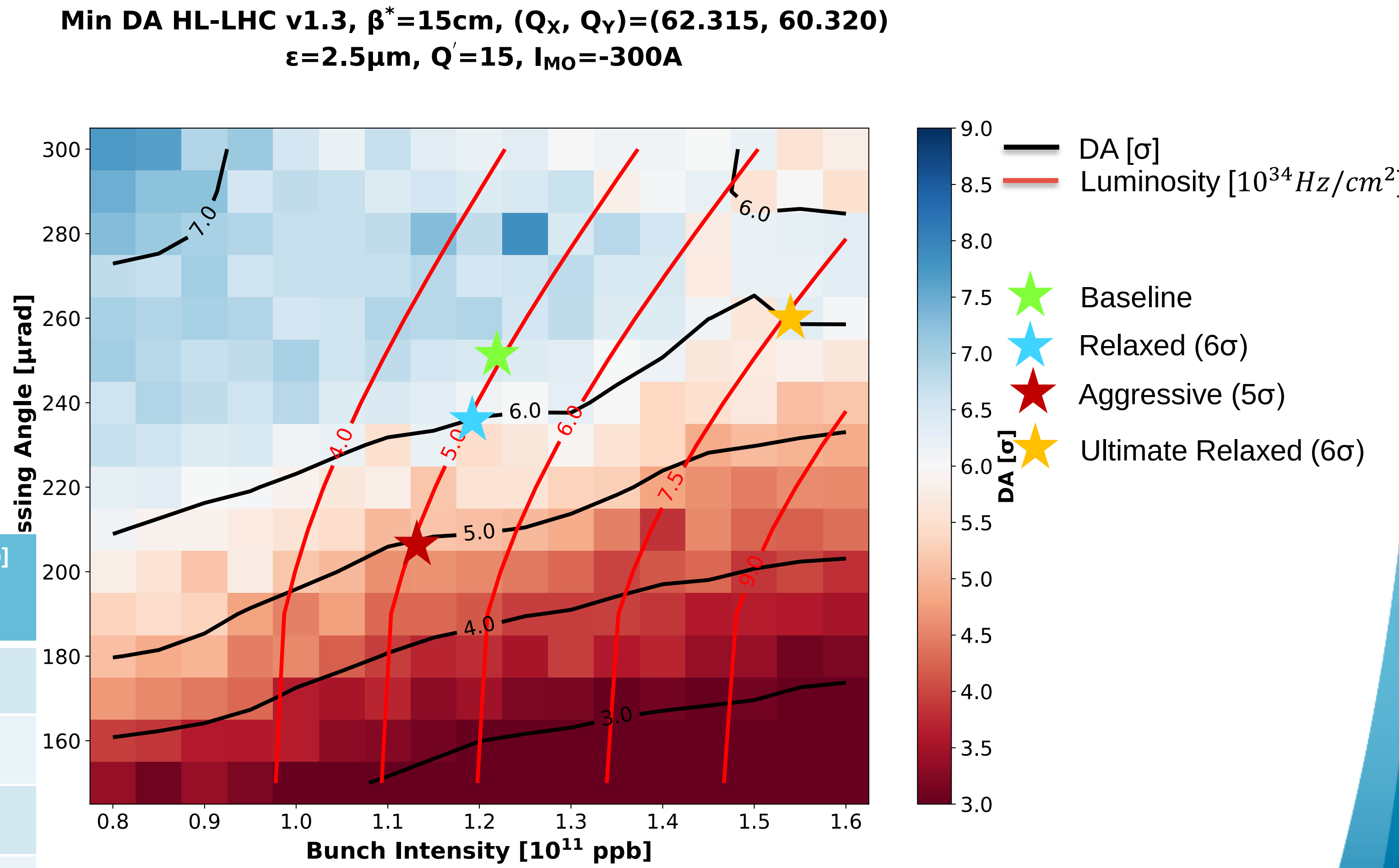
aggressive




| 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 $\beta^* = 15cm$




| 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 |

HL-LHC PROJECT

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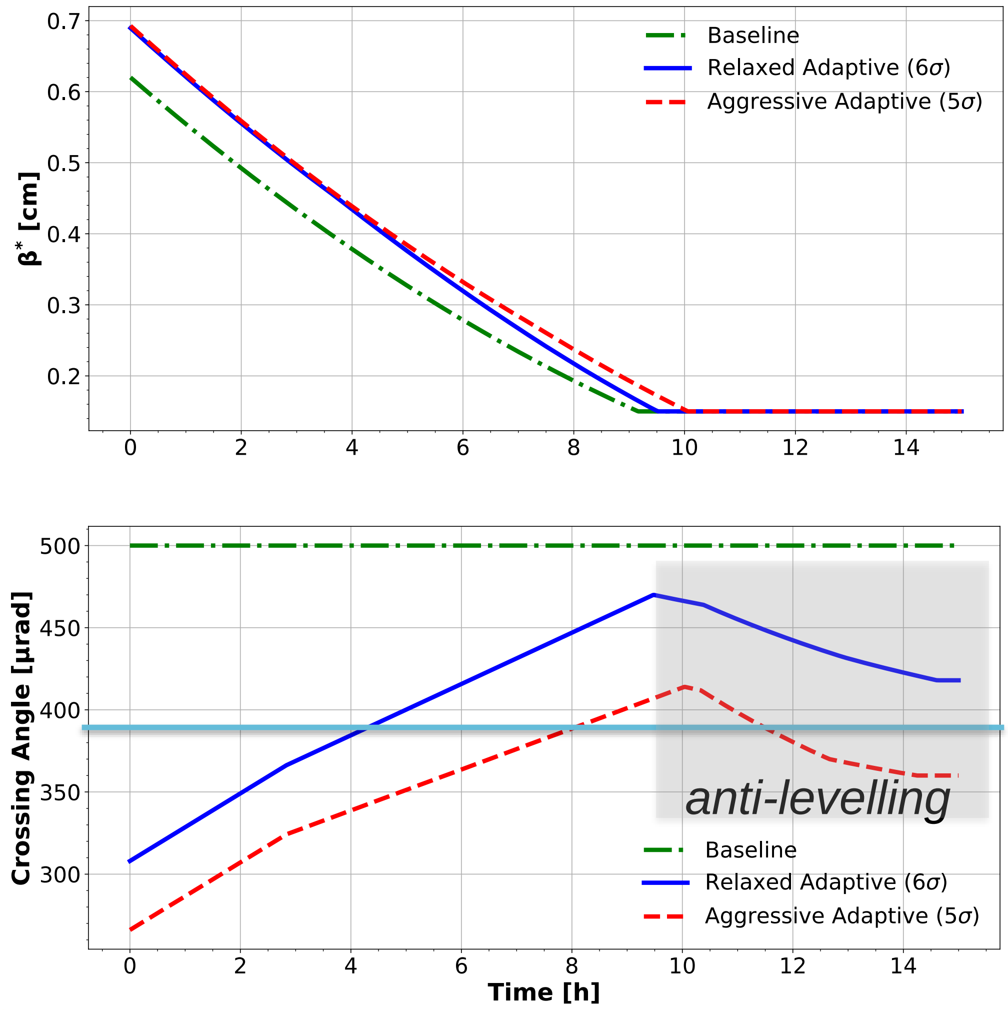
# Evolution of Parameters

- 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

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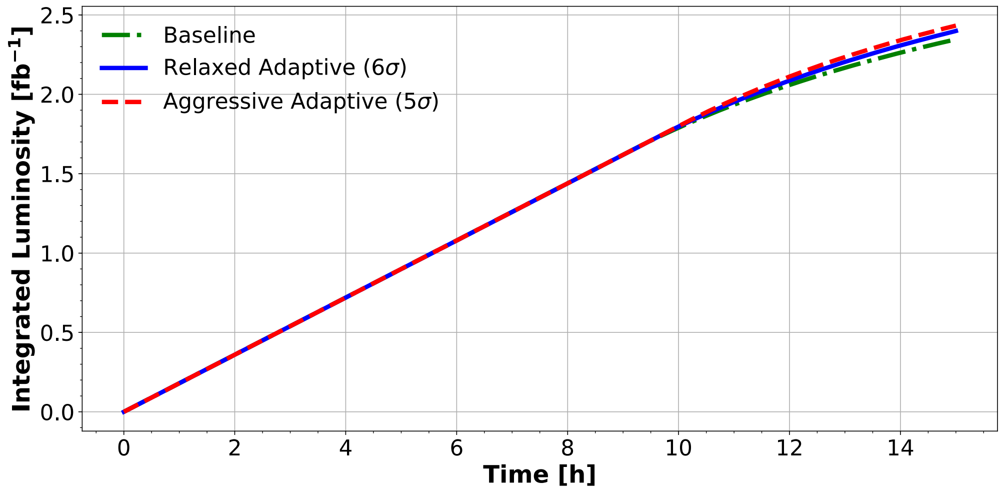
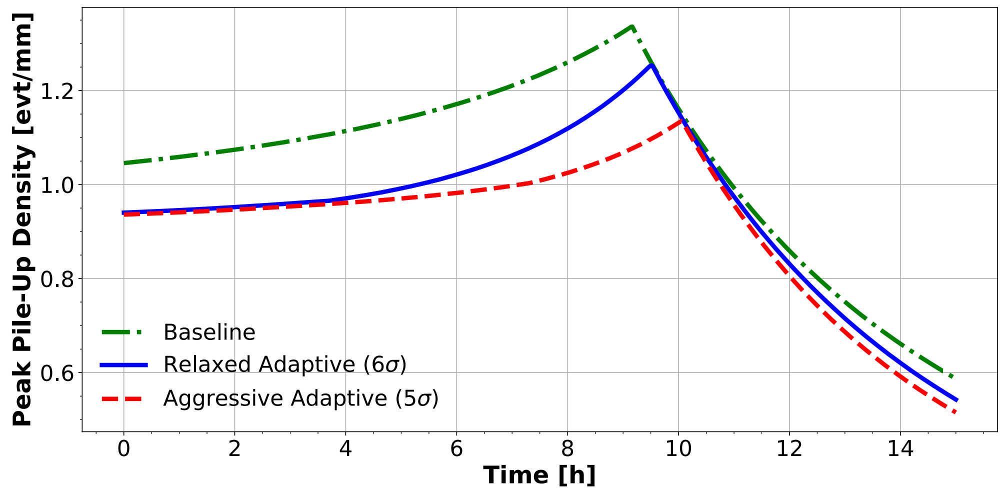
# Evolution of Parameters




*Integrated luminosity ≈ $2fb^{-1}$ for 12h fill*




*Elongating luminous region by ~15% ➔ reducing the peak pileup density by 7%*

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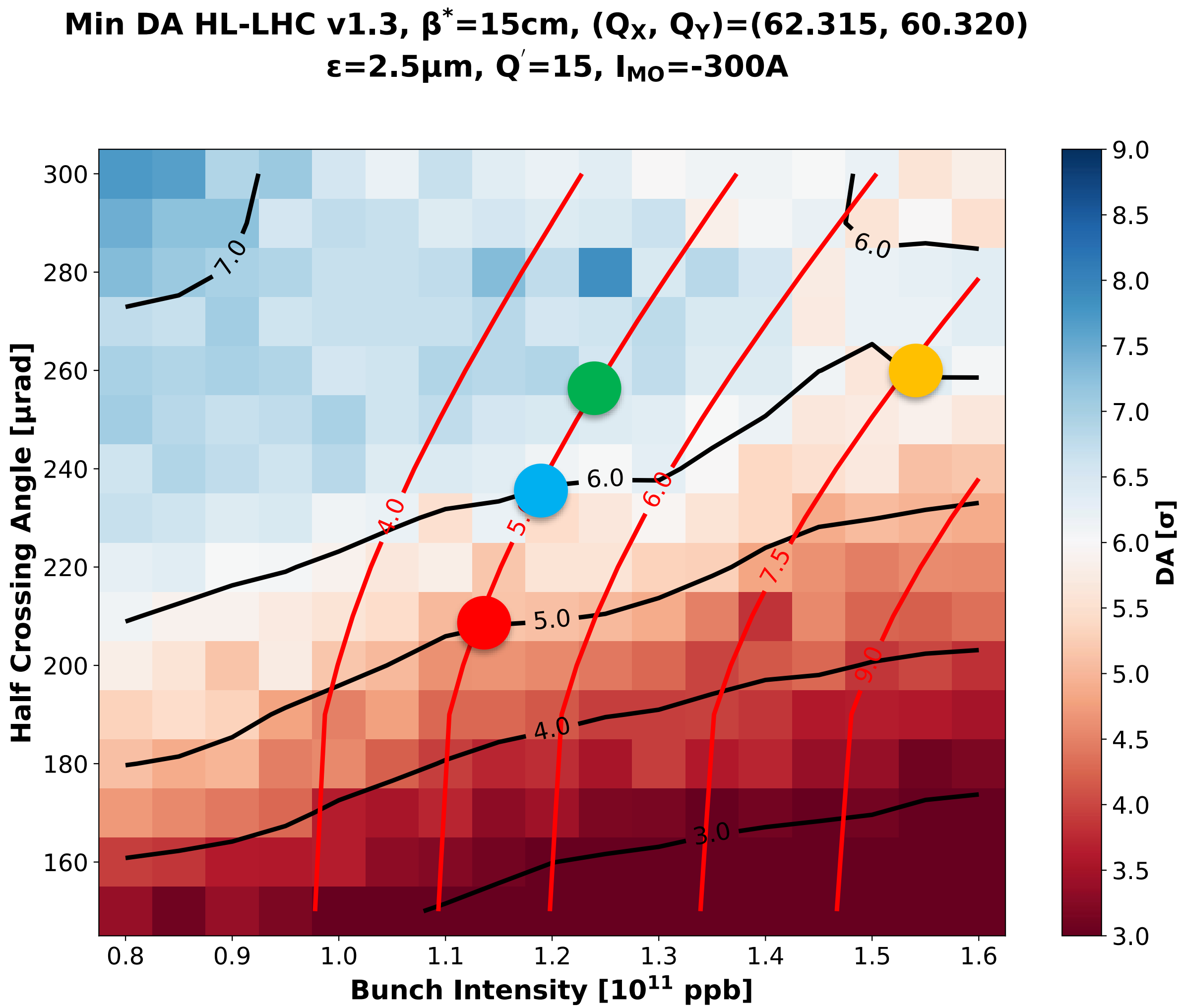
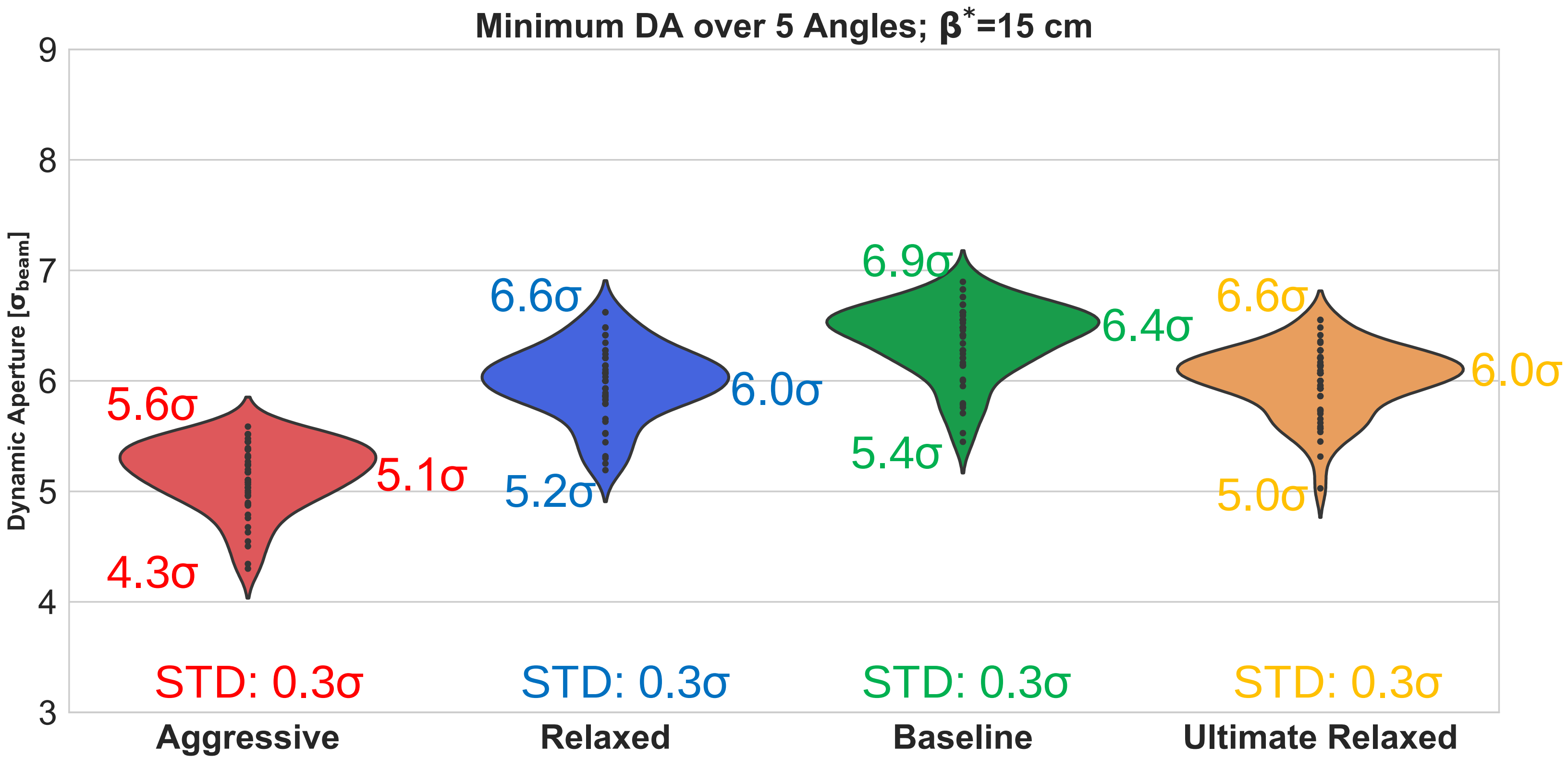
# Effect of Field Multipole Errors

- 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
- 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
- Perform 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

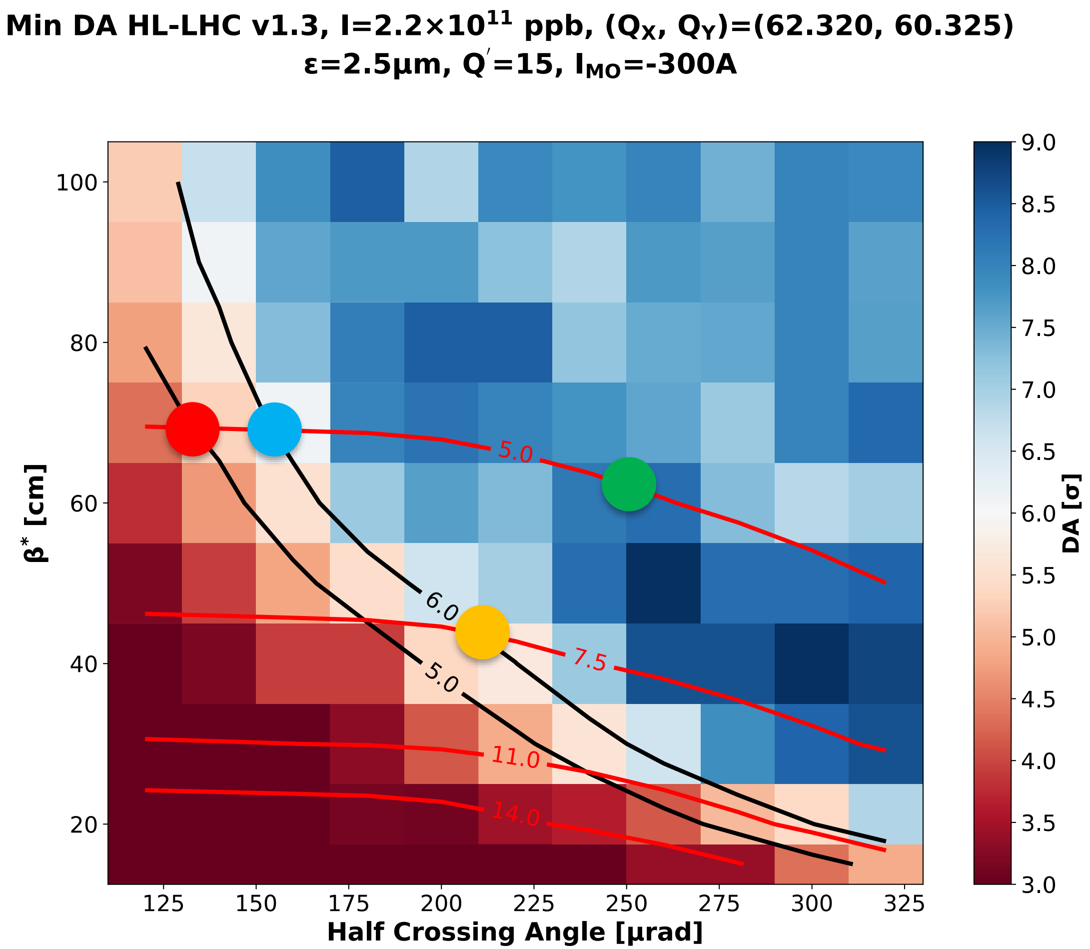


# Field Errors at the End of Levelling

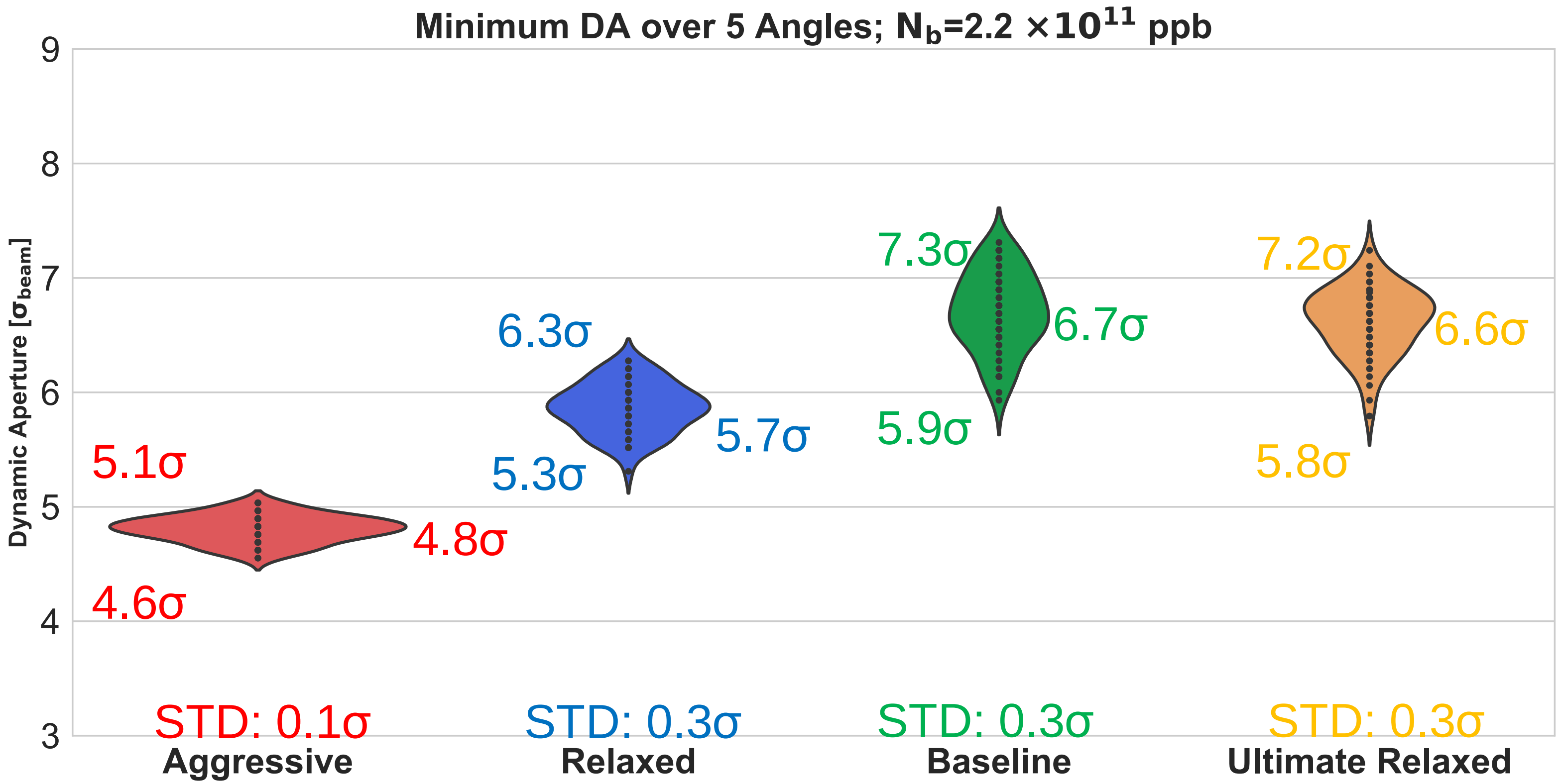



- Average spread of the various realizations of 0.3σ

# Field Errors at the Start of Levelling



# Field Errors at the Start of Levelling



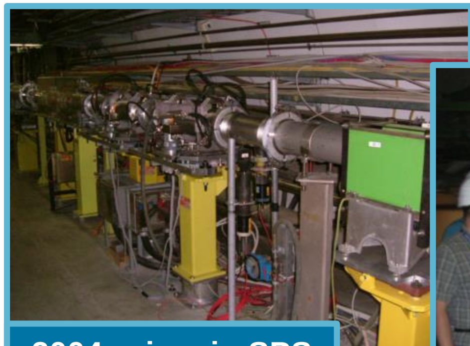

- Spread of 0.3σ, with the exception of the aggressive at ~0.1σ

# Summary HL-LHC beam-beam DA studies

- Operational scenario with high chromaticity and octupole current requires **mitigation through WP optimization**
  - WP at the start of levelling: $(Qx, Qy) = (62.320, 60.325)$
  - WP at the end of levelling : $(Qx, Qy) = (62.315, 60.320)$
- For $\beta^* = 15$ cm, DA of 6 σ cannot be reached with **maximum octupole current** (-570 A) and **high chromaticity**
  - Here used -300A, possibility to slightly increase it for **stability margin**
- The **ultimate scenario** at $\beta^* = 15cm$ requires larger crossing angle than allowed by aperture
- Adaptive crossing angle levelling scenario has the advantage of reduced **pile-up density** and potential reduction of **triplet irradiation (10%,** according to **F. Cerrutti)**
- The **specified field quality** seems **adequate**, as field errors remain in the shadow of the beam-beam effects
- Used **all available DA margin**, given the various restrictions/requirements
- Studying **alternative scenarios** that provide more margin, either by trading in operational complexity, or by adopting mitigation methods (e.g. BBLR compensation, see below)

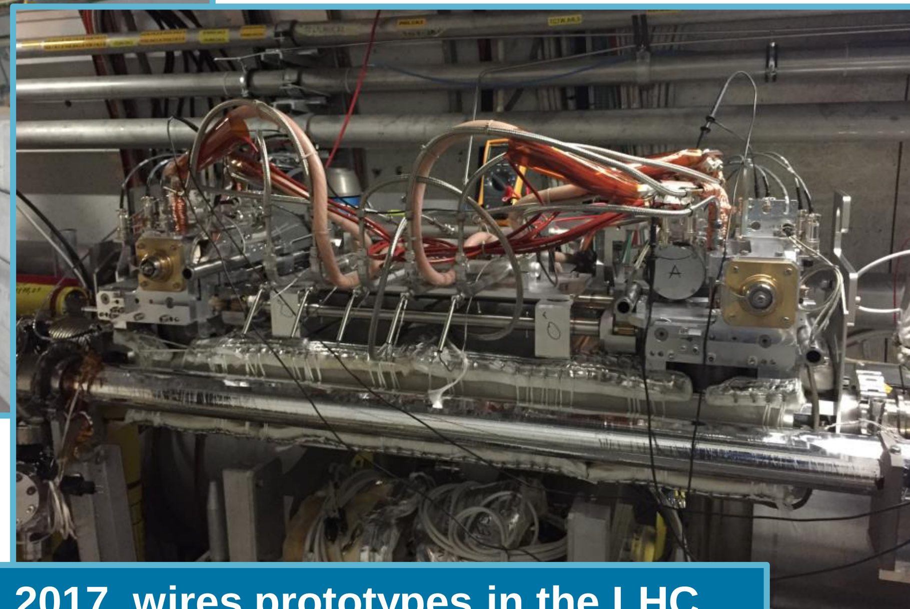
# Beam-Beam Long-Range compensation, the journey

- **1997** – V. Shilsev et al. – e⁻ Q-compression
- J.-P. Koutchouk et al. – Wires in the **SPS** – Since 2004
- **2000** – J.-P. Koutchouk – DC wires for LHC
- W. Fischer et al. – Wires in **RHIC** – 2006
- C. Milardi et al, – Wires in **DAΦNE** – Since 2006
- **2008** – U. Dorda – PhD Thesis
- **2012** – T. Rijoff – M.Sc.Thesis
- F. Zimmermann et al. – Specification of the LHC prototypes – 2013
- **2015** – S. Fartoukh et al. – PRST-AB 18, 121001
- 1st Workshop on (HL-)LHC Wire Compensation – December 2015
- **March 2017** – 2nd Workshop on (HL-)LHC Wire Compensation
- Experiment in the **LHC** – July 2017



2004, wires in SPS

2008, technical investigation in LHC



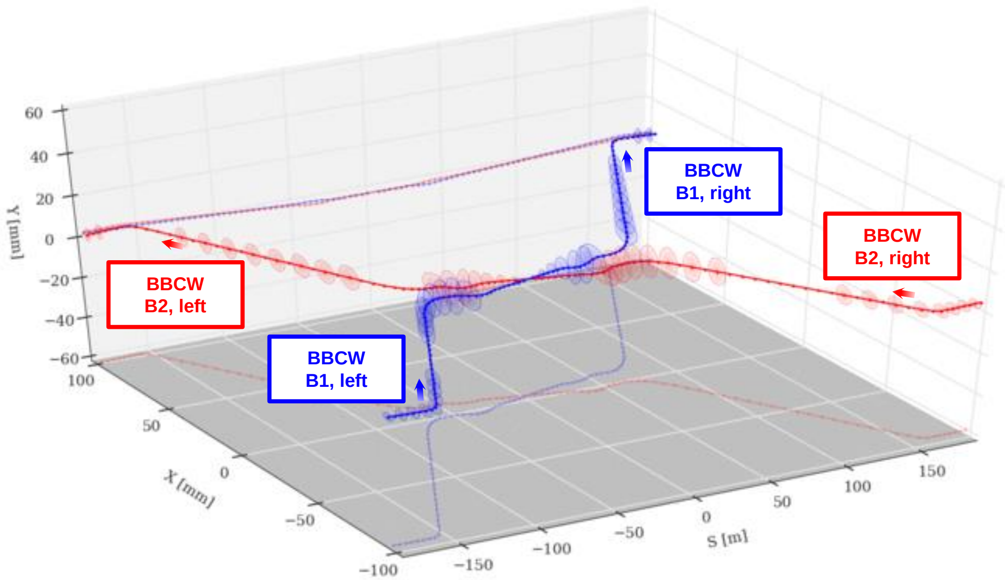
2017, wires prototypes in the LHC

G. Sterbini et al., HL-LHC collaboration meeting 2017

Collaboration between BE-BI, Collimation Team, EN-STI, EN-MME, TE-EPC and HL-LHC collaborators to transform an idea into a prototype.

# The wire compensation principle

- The long-range kick (BBLR effect) can be **compensated by using a DC wire**.
- The wire compensation is **not** in the HL-LHC baseline
- Its **potential for HL-LHC with flat optics or in combination with crab-crossing** was shown by S. Fartoukh et al., PRST-AB 18, 121001, 2015.

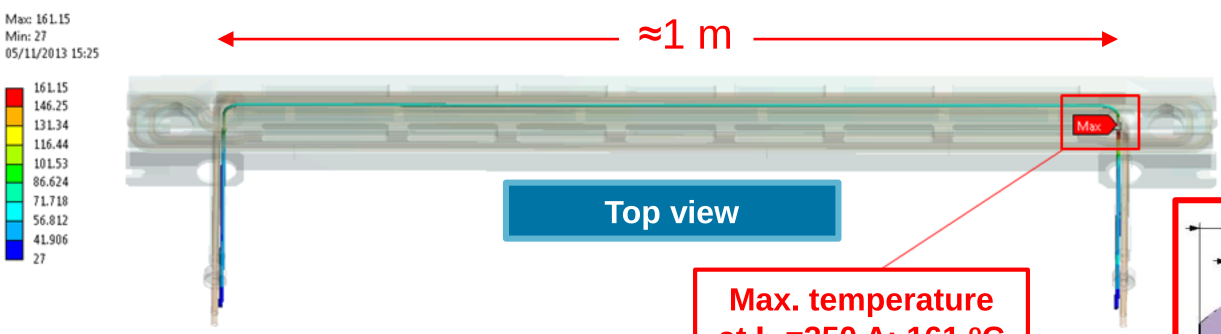



The BBCW principle

- **Since 2017 two wire prototypes (BBCW) are installed in LHC.**

# Integration of the wire in the collimator jaws

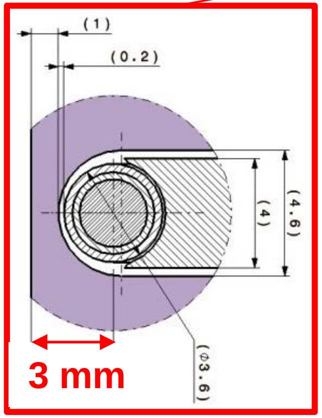
- The **wire-beam distance has to be of the order of few mm** (function of $\theta_c$ and s-position): LHC wires prototypes are embedded in the jaw of two operational tertiary collimators.

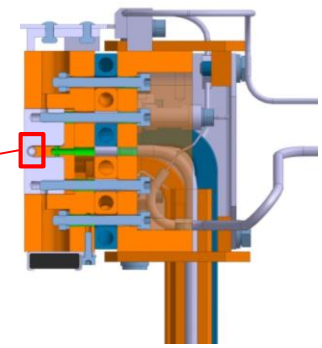



**Top view**

**Max. temperature at $I_W$=350 A: 161 ºC**

Courtesy of F. Carra



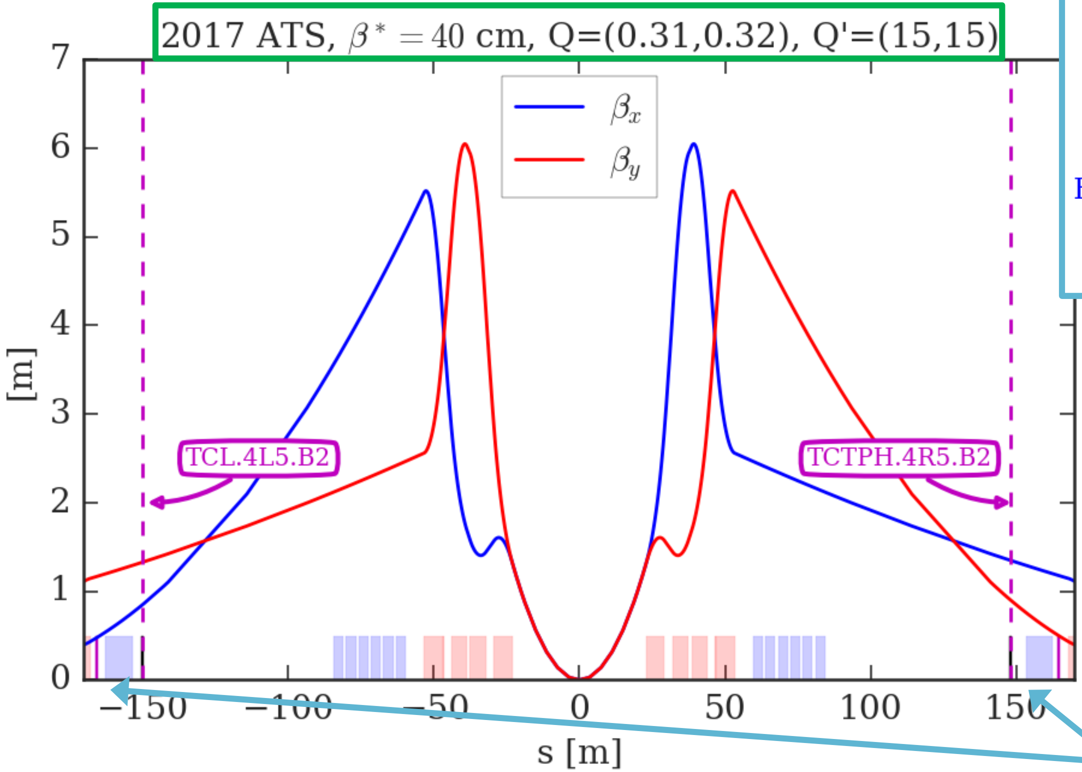



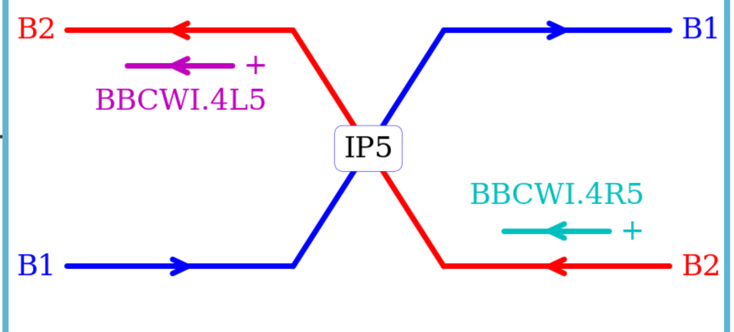
**Side view**

# The BBCW position in LHC

The 2 BBCWs were installed in two **H-collimators of B2 in IR5** (TCTPH.4R5.B2 and TCL.4L5.B2), close to the D2 separation dipoles.

**Longitudinal position of the BBCW and optics used in the experiment**

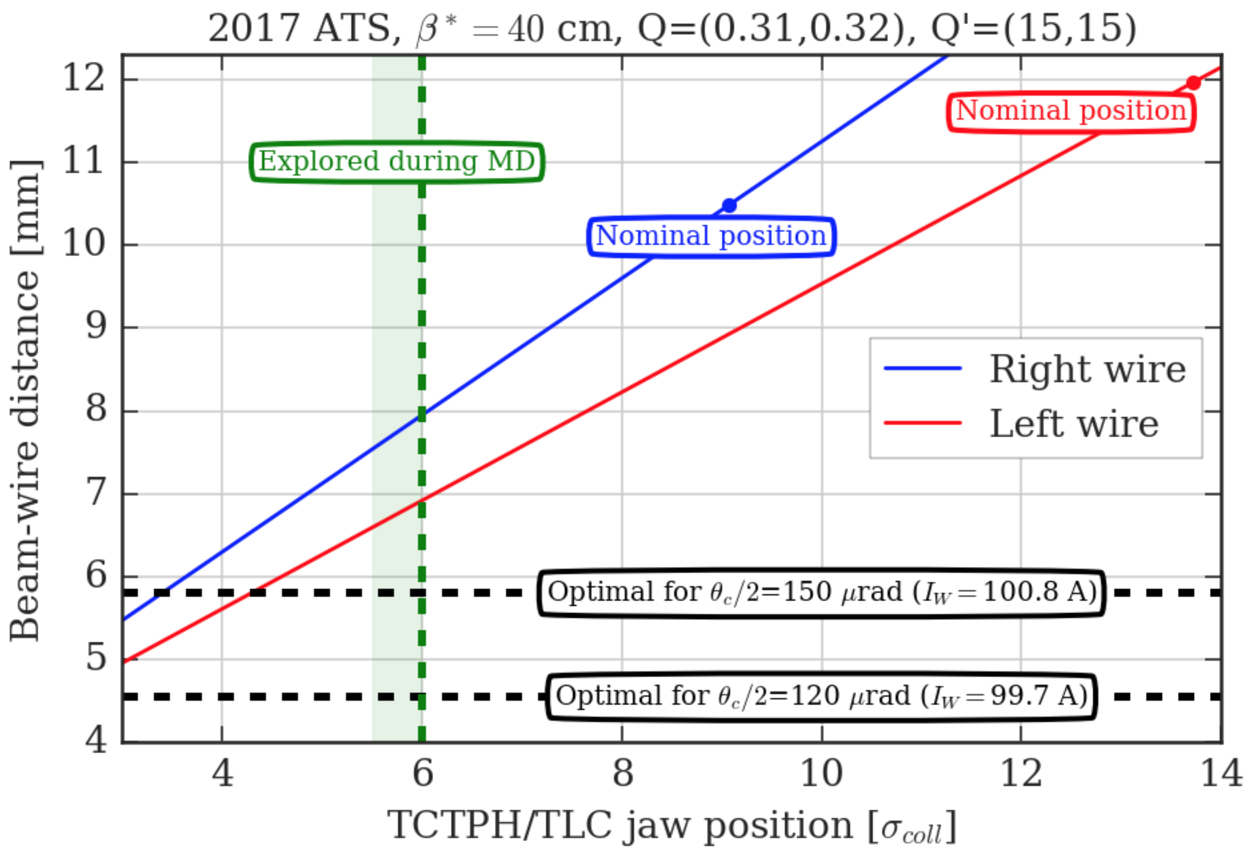



**H-plane position of the BBCW**

**The ideal s-position of the BBCW is ±159 m from the IP5. The actual s-position are -150.03 and +147.94 m.**

# Approaching the wires to the beam




- Practical **limits** in the **positioning** of the **wire** with respect to the beams even for low intensity MD beams.
- Given this constraint, **wire current** used as a knob to cancel the effect of one specific magnetic multipole **(octupole)**

# Two machine experiments

**1 July '17 (MD1)**

- Wire collimators jaws at 6 $s_{coll}$
- Max current in the wires (350/350 A in R/L wires)
- $\beta^*$ = 40 cm
- half-Xing angle = 120 μrad
- 1 train in B1, 3 bunches in B2
- Global tune correction
- Nominal octupoles.

**29 November '17 (MD4)**

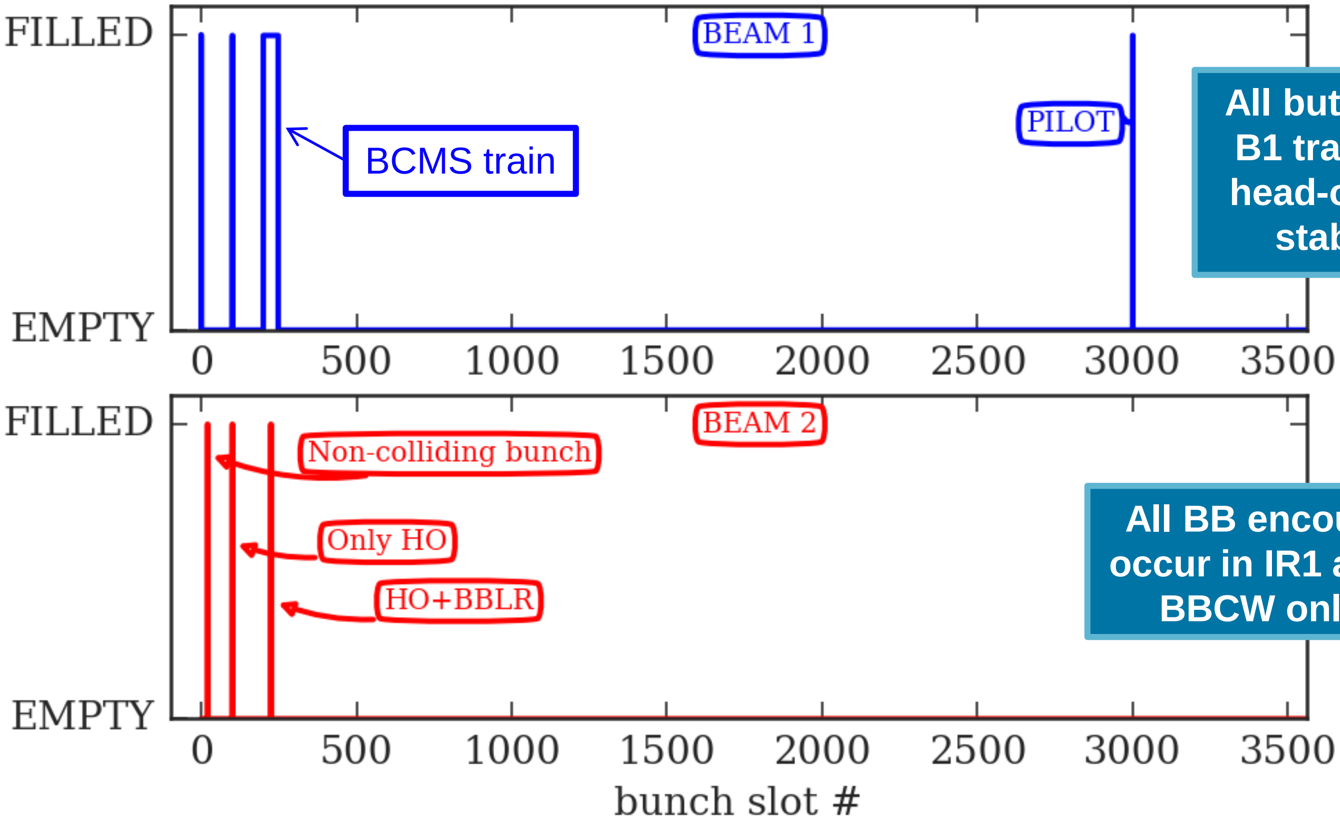
- Wire collimators jaws at 5.5 $\sigma_{coll}$
- Current in the wires (340/190 A in R/L wires)
- $\beta^*$ = 30 cm
- half-Xing angle = 150 mrad
- 3 trains in B1, 2 bunches in B2
- Orchestrated Q4/5 tune correction
- Octupoles at the maximum in B1 and 0 A in B2.
- Coronagraph (G. Trad et al).

# BBLR compensation MD team

*D. Amorim, H. Bartosik, R. Bruce, X. Buffat, L. Carver, G. Cattenoz, E. Effinger, S. Fartoukh, M. Fitterer, N. Fuster, M. Gasior, M. Gonzales, A. Gorzawski, G.-H. Hemelsoet, M. Hostettler, G. Iadarola, R. Jones, D. Kaltchev, K. Karastatis, S. Kostoglou, I. Lamas Garcia, T. Levens, A. Levichev, L. E. Medina, D. Mirarchi, J. Olexa, S. Papadopoulou, Y. Papaphilippou, D. Pellegrini, M. Pojer, L. Poncet, A. Poyet, S. Redaelli, A. Rossi, B. Salvachua, H. Schmickler, F. Schmidt, K. Skoufaris, M. Solfaroli, G. Sterbini, R. Tomas, G. Trad, A. Valishev, D. Valuch, C. Xu, C. Zamantzas, P. Zisopoulos*

# Asymmetric filling scheme

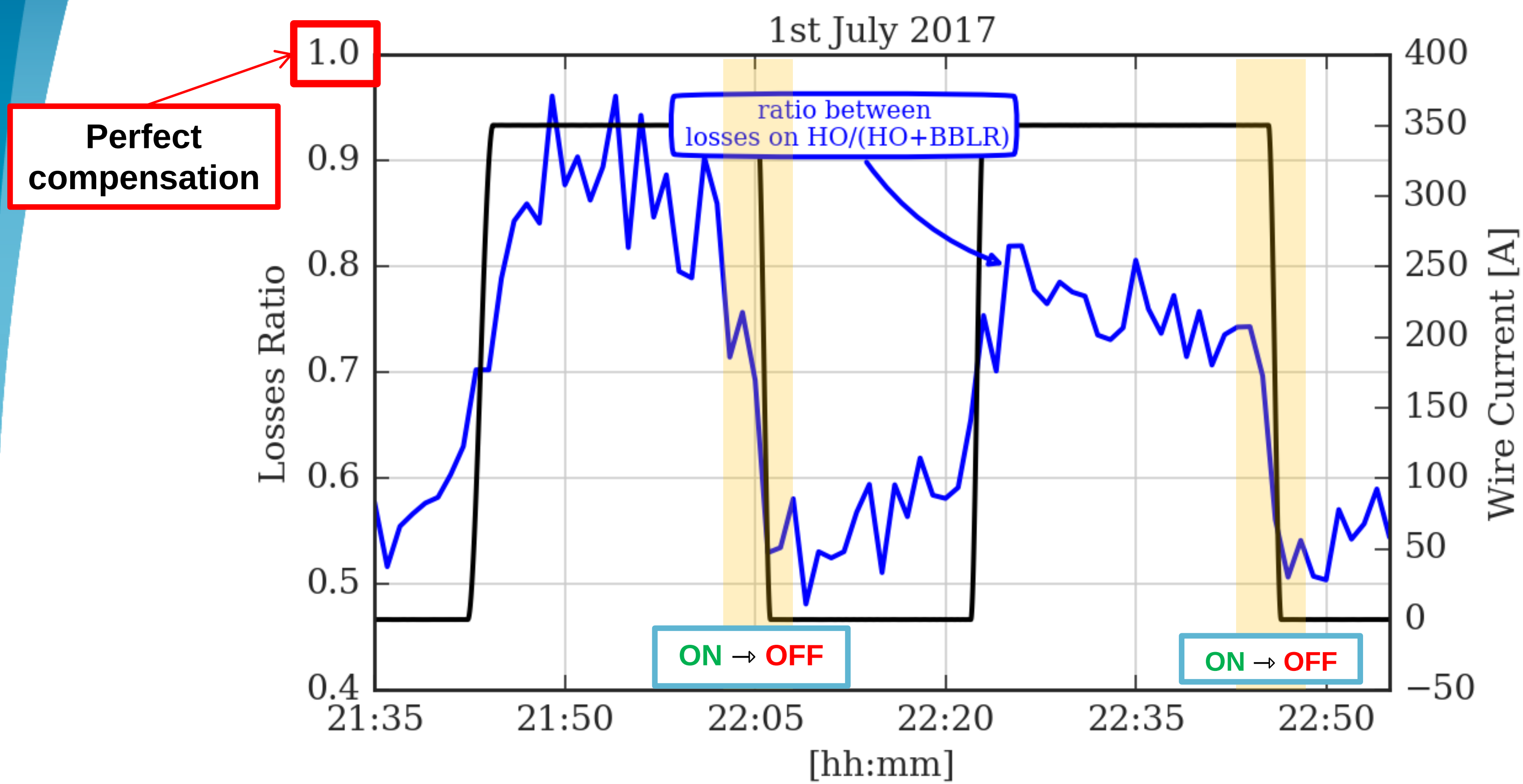
- To approach the wire to the beam the B2 has to be <3e11 p ("safe" limit).
- We will mainly concentrate on the two bunches of B2 (Only HO and HO+BBLR).




All but 1 bunch in the B1 train do not have head-on encounters: stability issues.

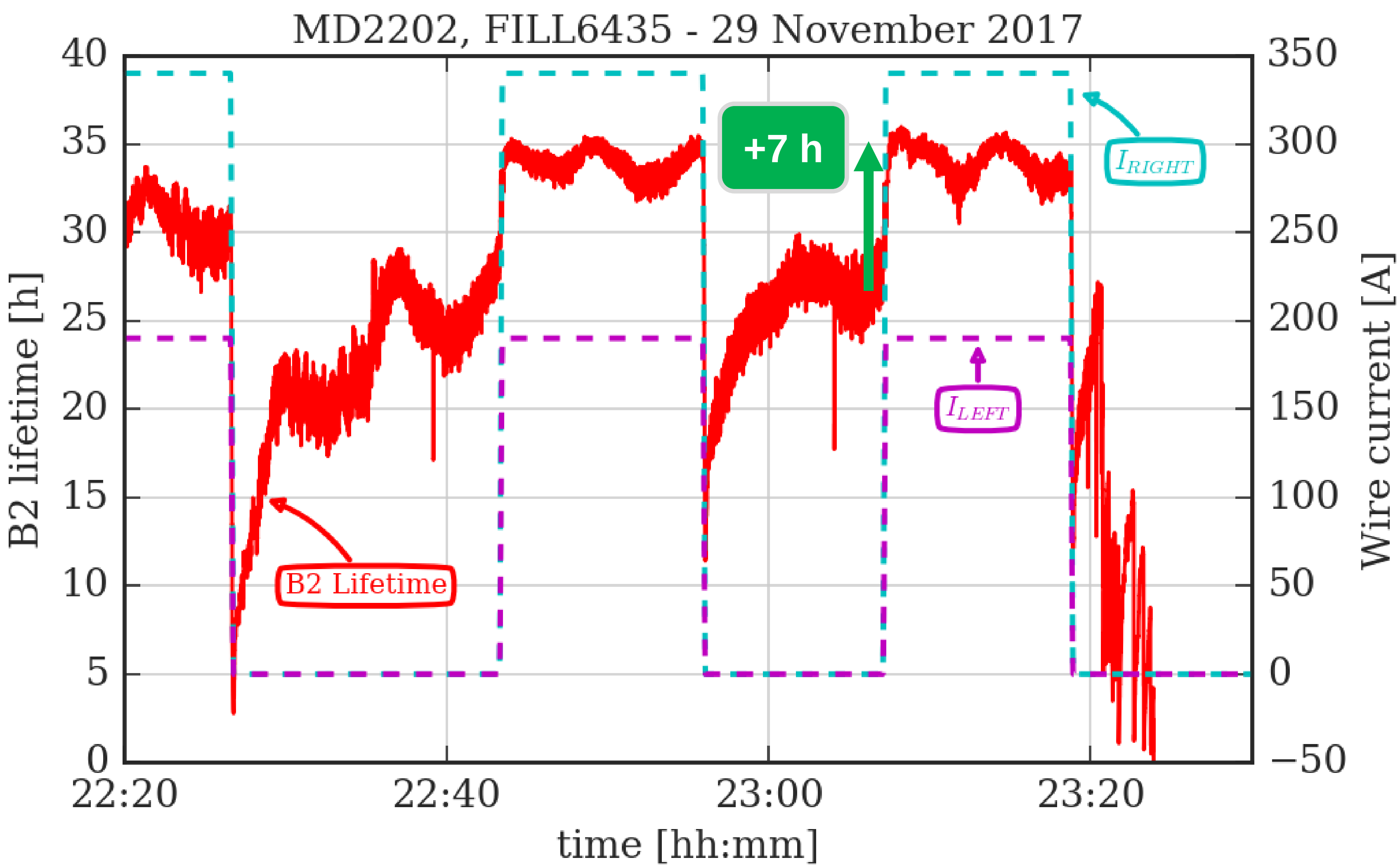
All BB encounters will occur in IR1 and IR5 but BBCW only in IR5.

# MD1 Results on the compensation




- From the bunch-by-bunch intensity signals we can measure the effectiveness of the compensation on the losses
- **Clear effect of the BBCW.**

# MD4 results at 340/190 A and jaw at 5.5 $\sigma_{coll}$




**Positive effect of the wires visible on beam lifetime.**

G. Sterbini et al., HL-LHC TCC 2017

# From lifetime to effective cross-section

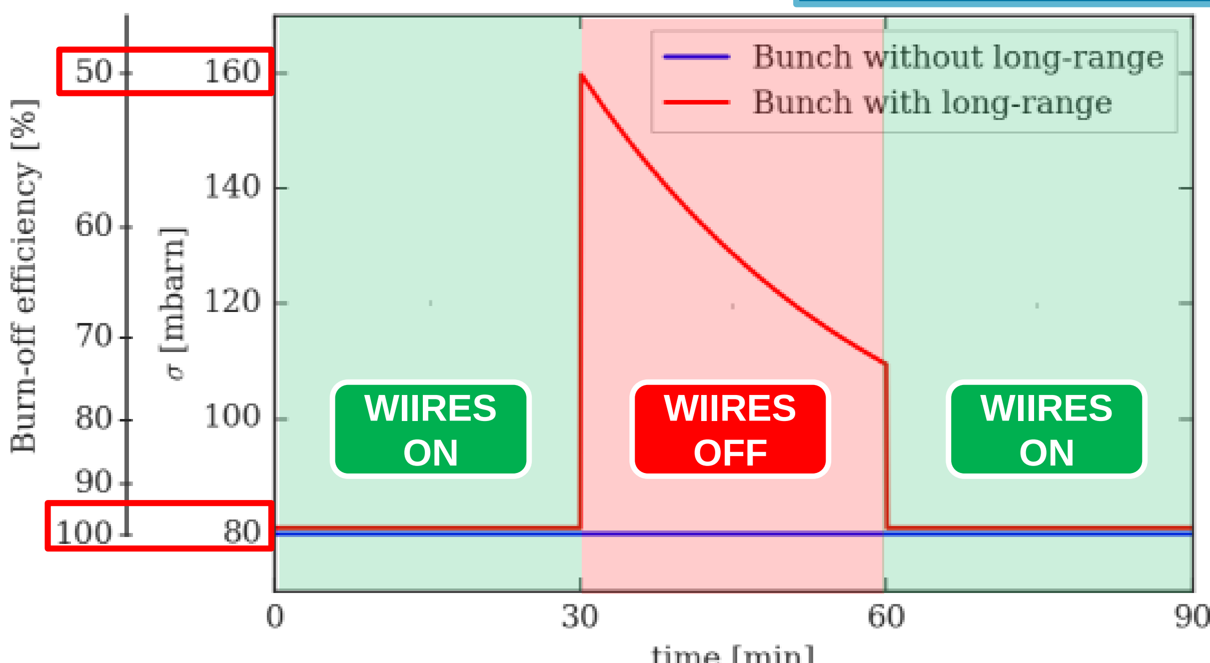
- The previous plot is (1) not bunch-by-bunch and (2) the comparison ON/OFF compensation is fair only assuming constant luminosity.
- Both limits can be overcome by considering the bunch “**effective cross-section**”:

$$\sigma_{EFF} = -\frac{1}{\sum_{IP} L_{IP}} \frac{dN}{dt}$$

Intensity loss-rate

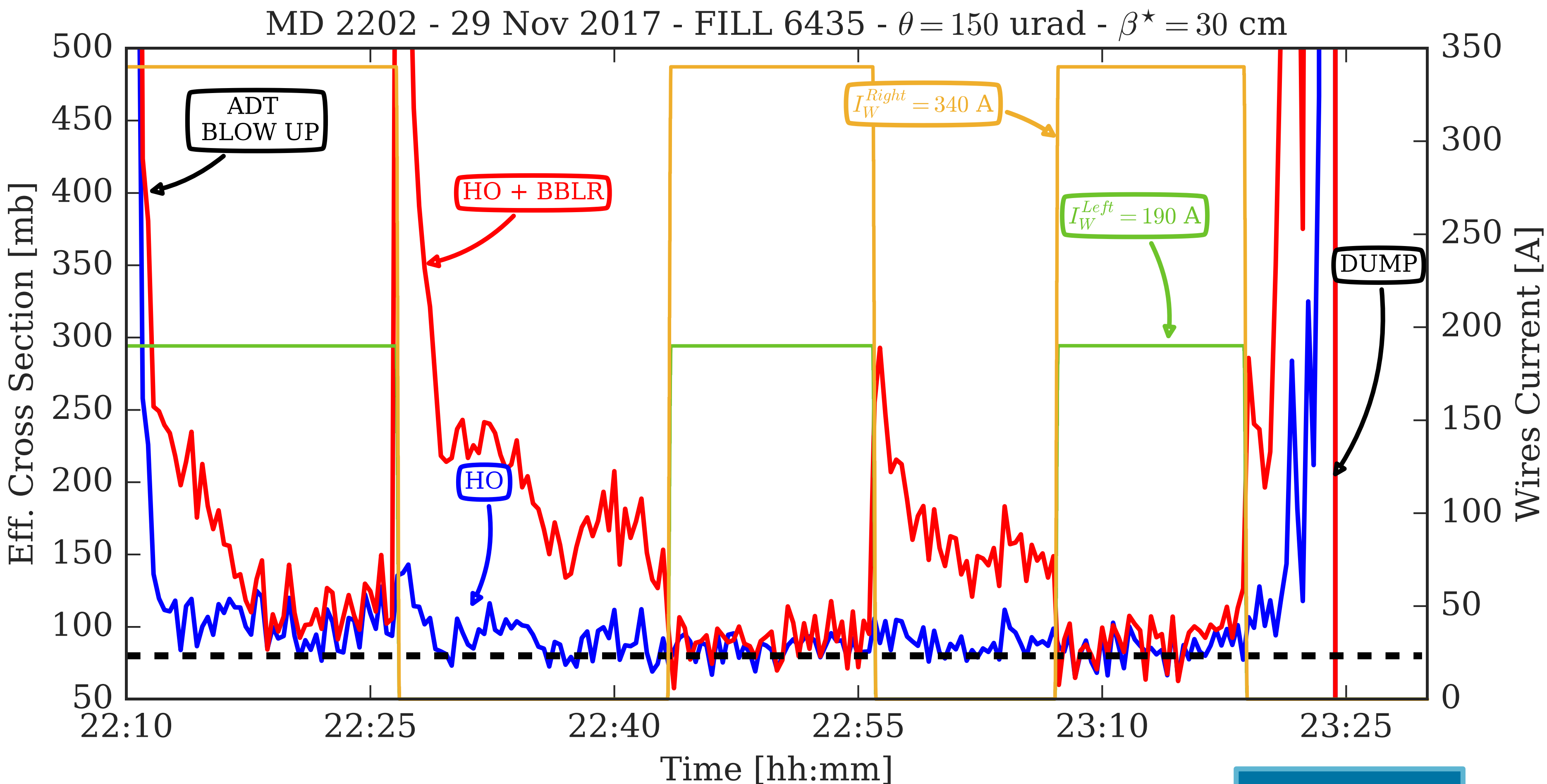
Instantaneous luminosity

**The IDEAL compensation, 2 bunches in B2**




G. Sterbini et al., HL-LHC TCC 2017

# Result at 340/190 A and jaw at 5.5 $\sigma_{coll}$

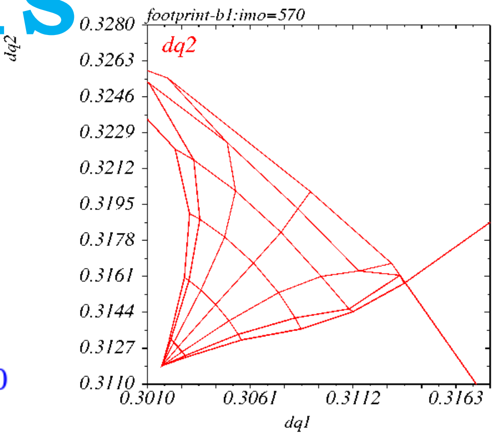



A. Poyet

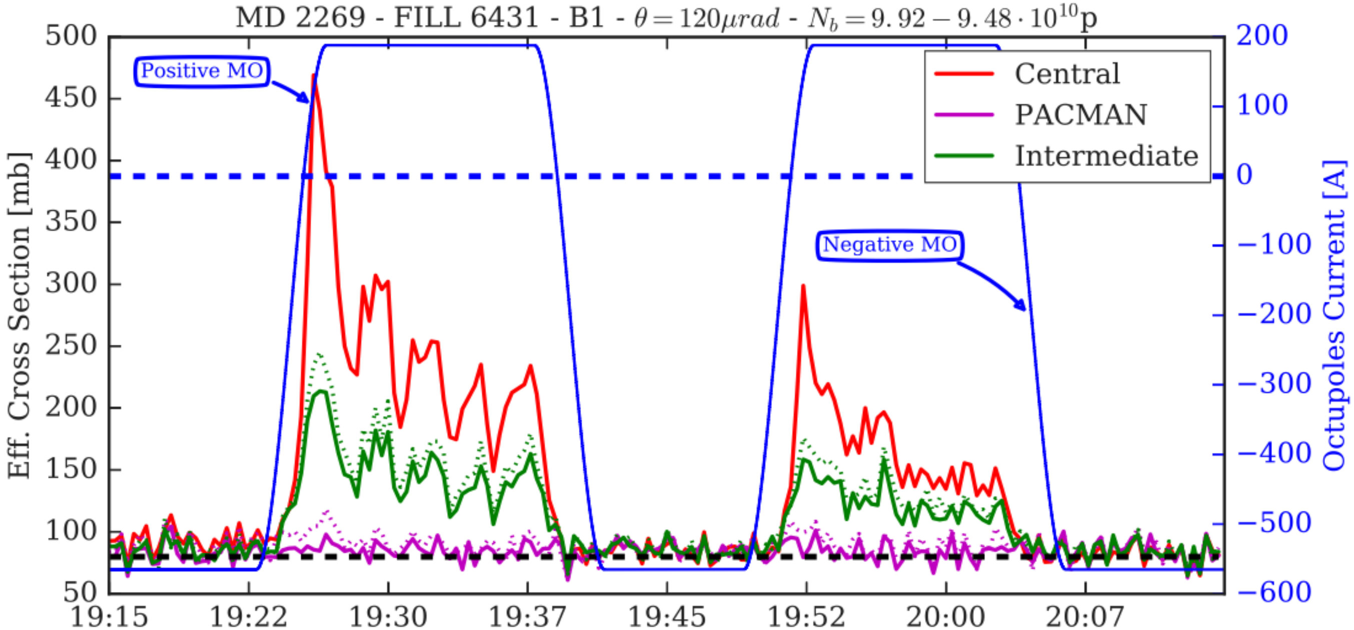
- **Positive effect of the wires visible on the bunch affected by the beam-beam long-range.**

G. Sterbini et al., HL-LHC TCC 2017

# MD for compensation alternative using octupoles and ATS




$$\sigma_{\mathrm{eff}_i} \stackrel{\mathrm{def}}{=} \frac{|dN_i/dt|}{\mathcal{L}_i}$$

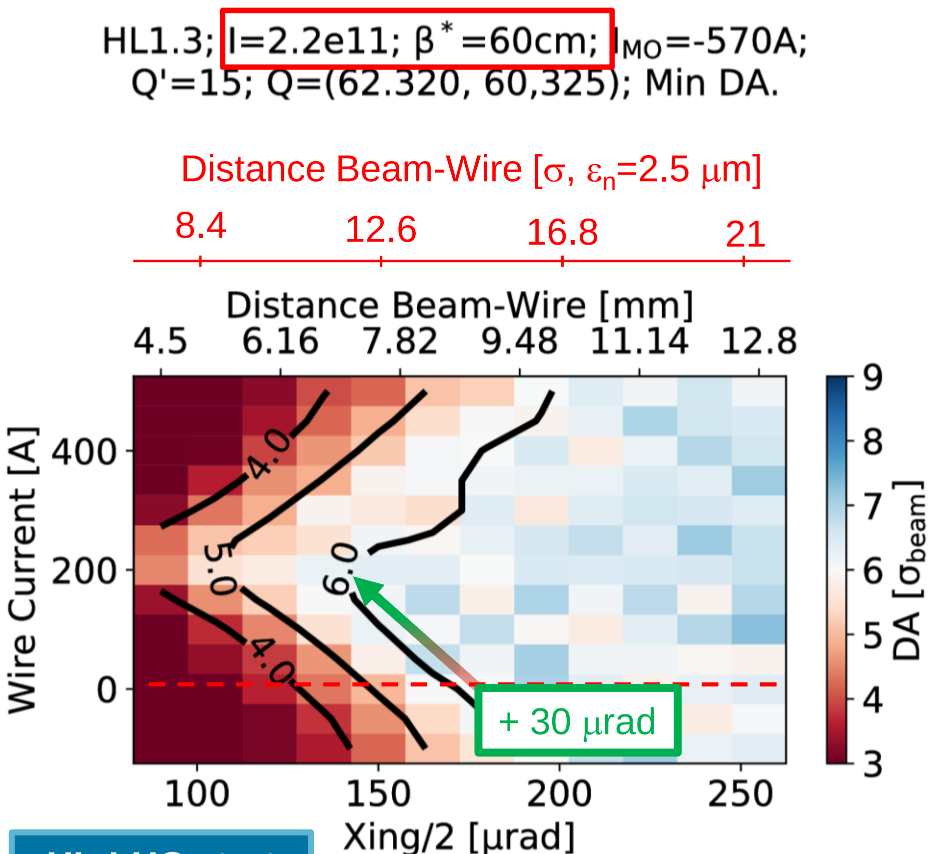



Courtesy of A. Poyet, G. Sterbini, and Beam-Beam team

# Compensation simulation studies

- **Wire compensation tracking studies** initiated with the two-fold aim to benchmark the LHC results and optimize the HL-LHC scenario with the wires.

- For HL-LHC, **preliminary results** (without full optimization) of the longitudinal and transverse wire position, are showing an additional gain of the order of **30 µrad** for the half-crossing angle.




HL-LHC start of the levelling

Courtesy of D. Pellegrini

# Summary for BBLR compensation and plans

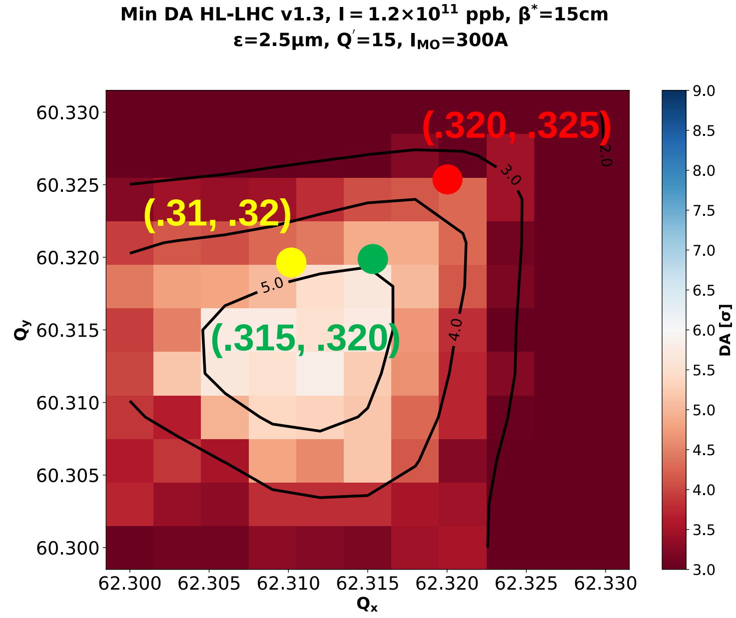
- First observations in LHC of a direct compensation of the BBLR with a DC wire
- **In YETS17/18:** two vertical wires installed in IR1 (s-position of the wires less favorable than in IR5 for the compensation).
- **In 2018:** compensation experiment in IR1 and IR5.
- Significant efforts put in simulation studies to benchmarking the LHC results and study wire potential for the HL-LHC
- Reflect HW solutions for BBLR compensation in the HL-LHC era

# Summary

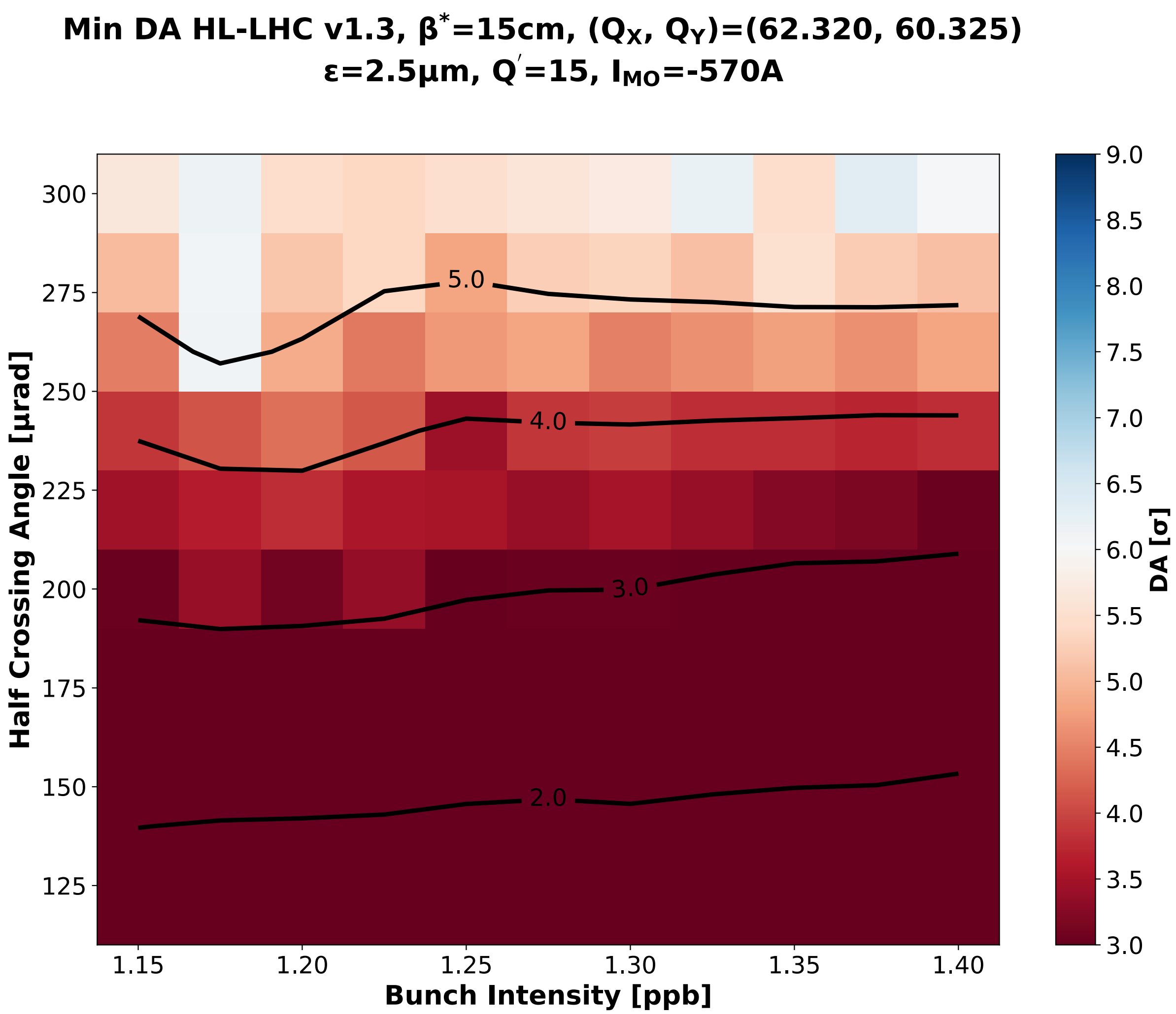
***Thanks for your attention***

# SPARE SLIDES

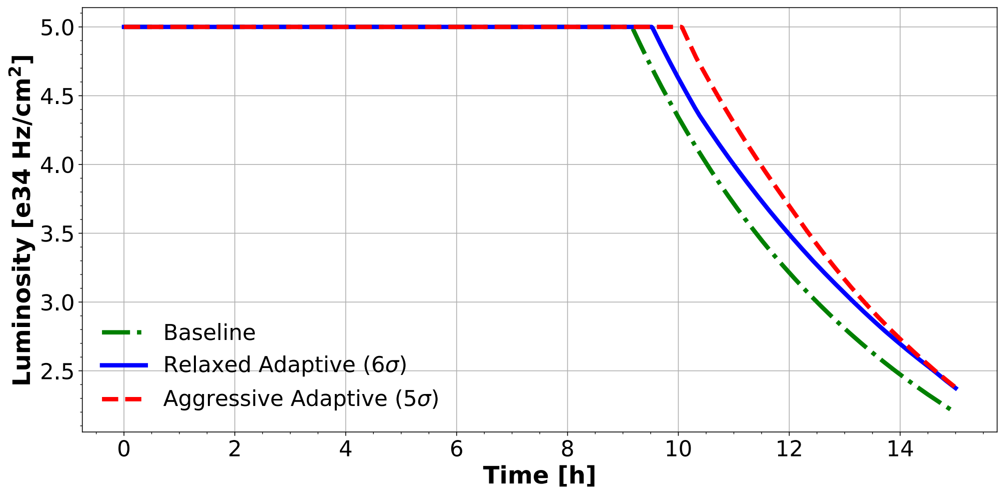
# Positive Octupoles

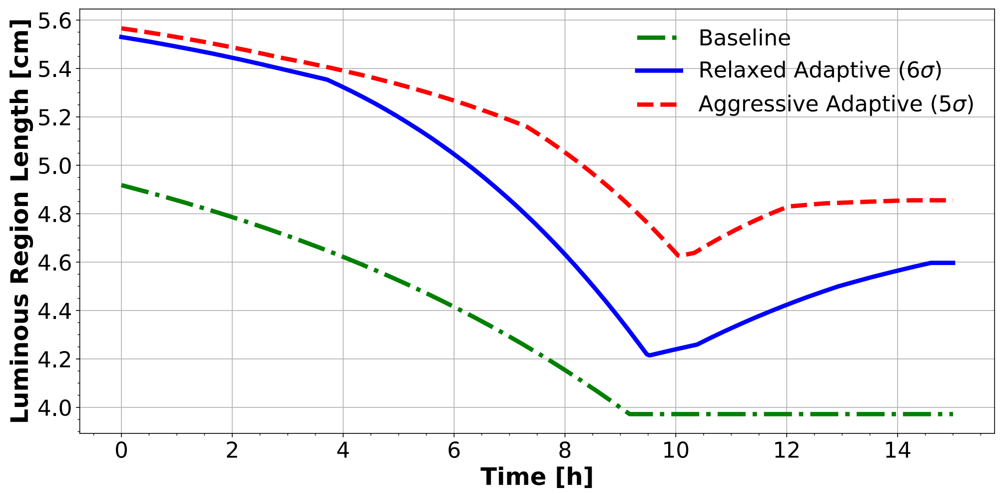


# End of Levelling with WP of start of levelling

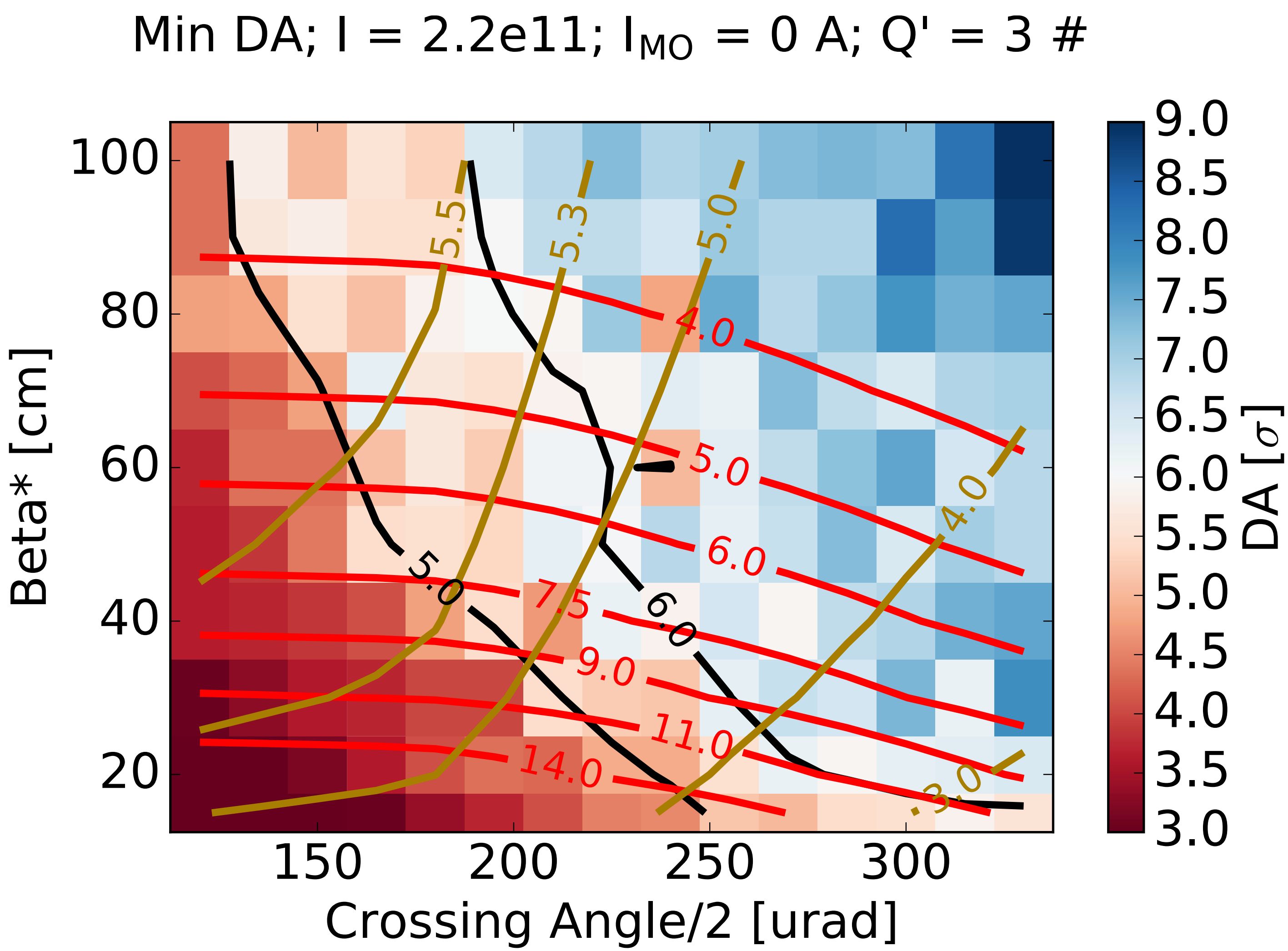


# Parameter Evolution

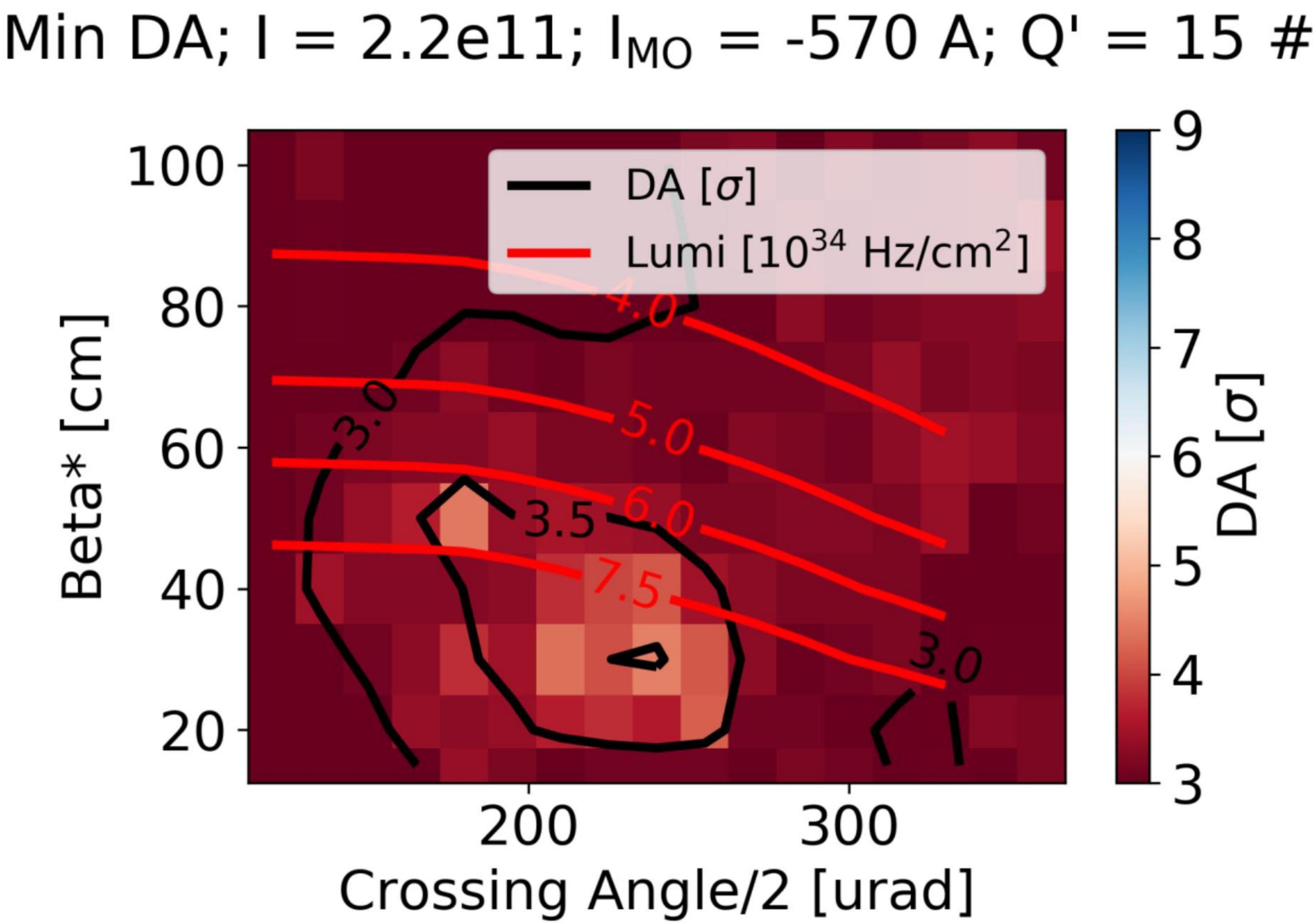


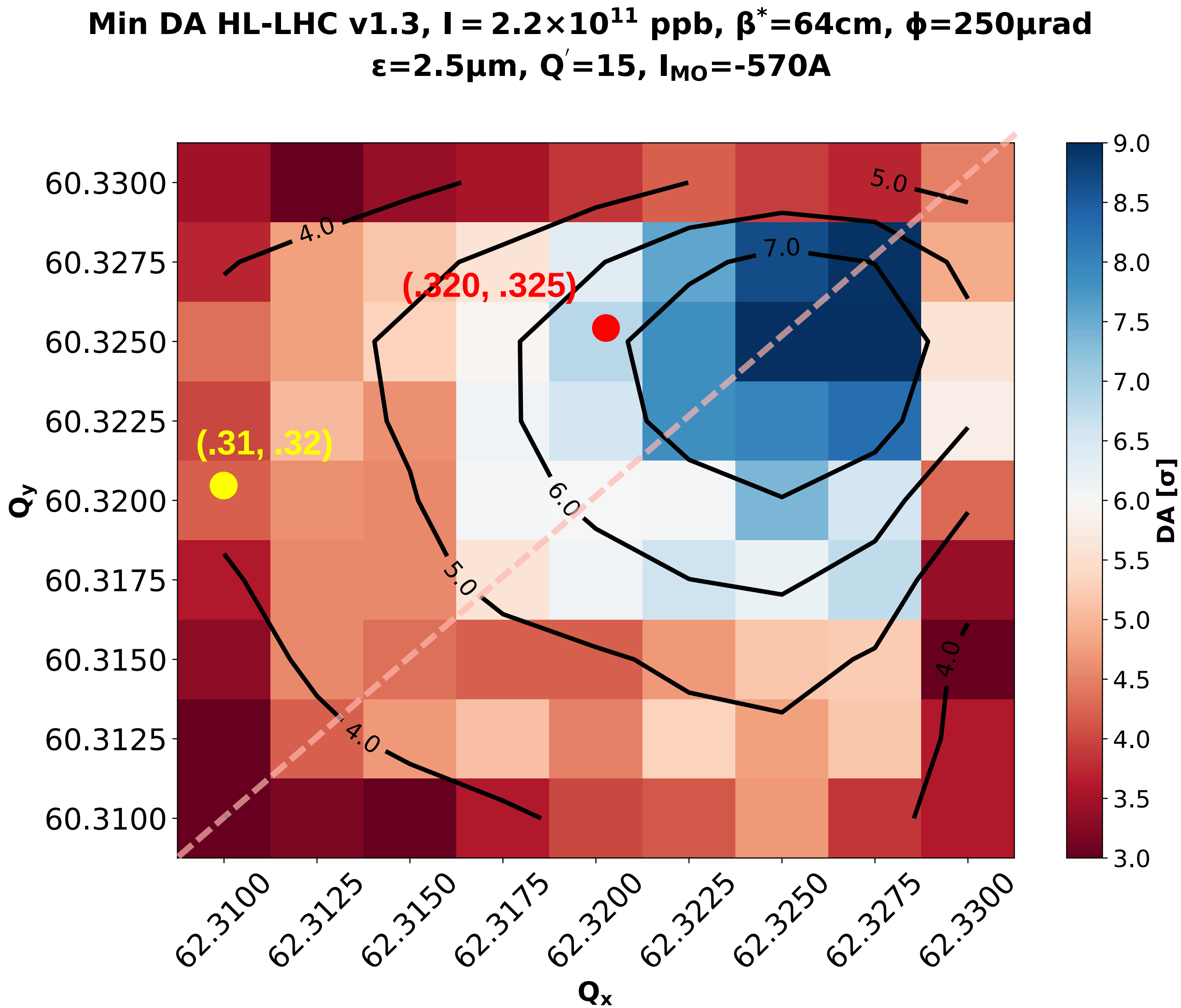
# Low Chroma / Octupoles



# High Chroma / Octupoles

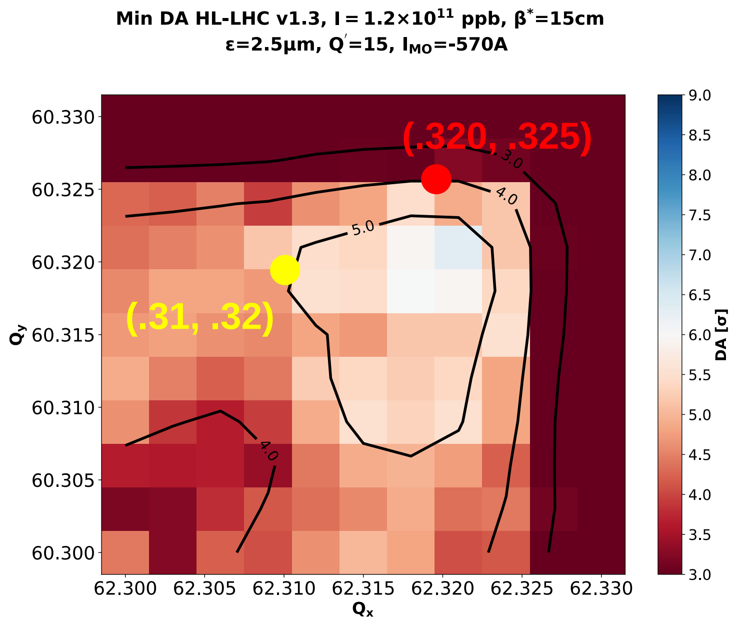


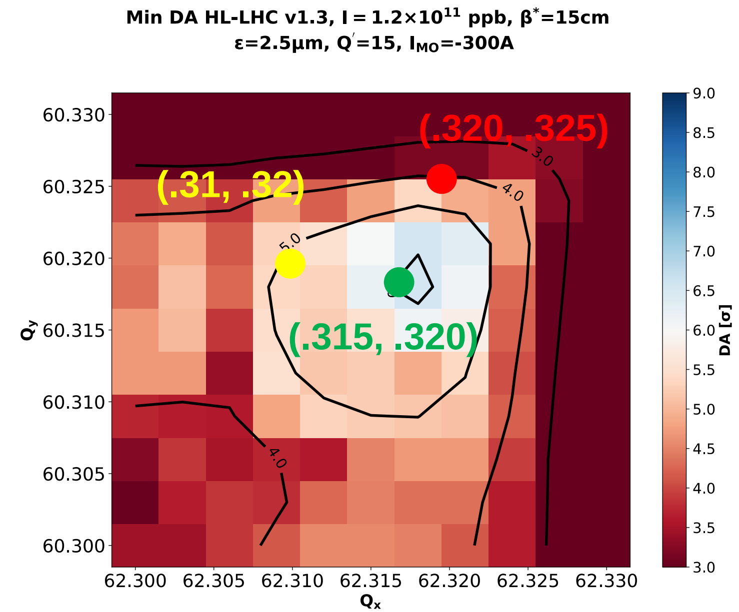
# Working Point Optimization: Start of Collisions

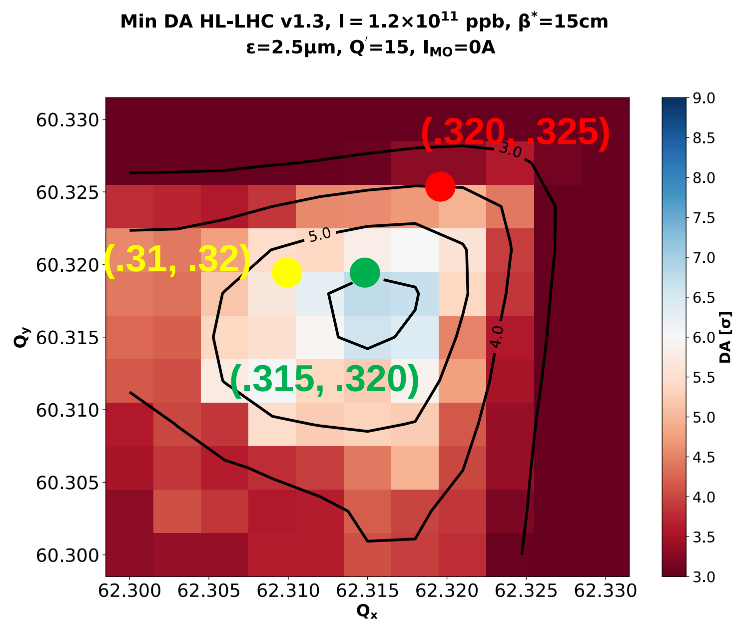



N. Karastathis, D. Pellegrini et al., HL-LHC collaboration meeting 2017

# Working Point Optimization: β*=15cm




HiLumi HL-LHC PROJECT

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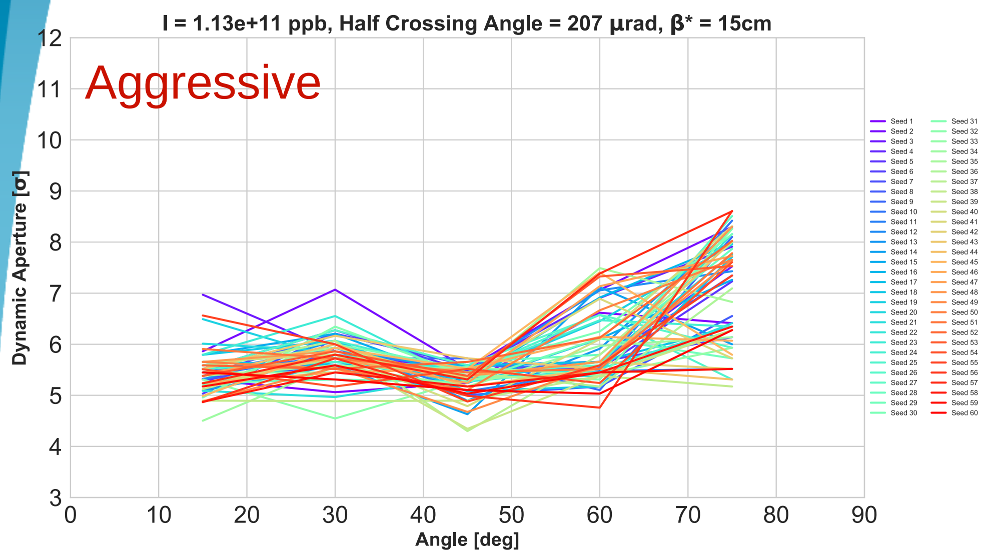
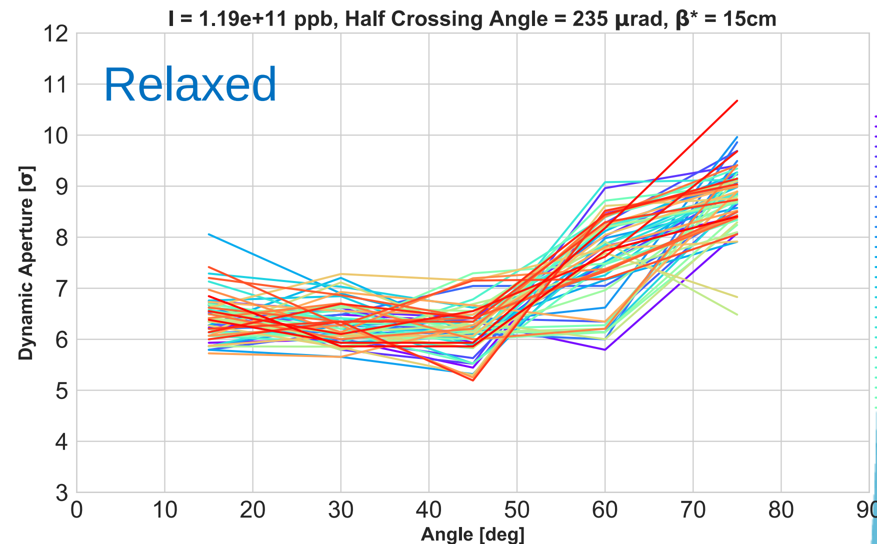
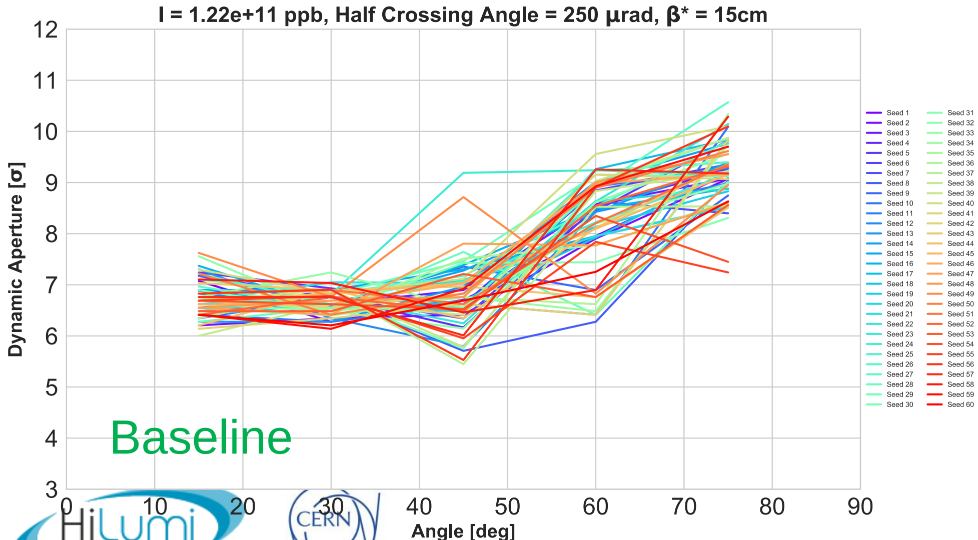
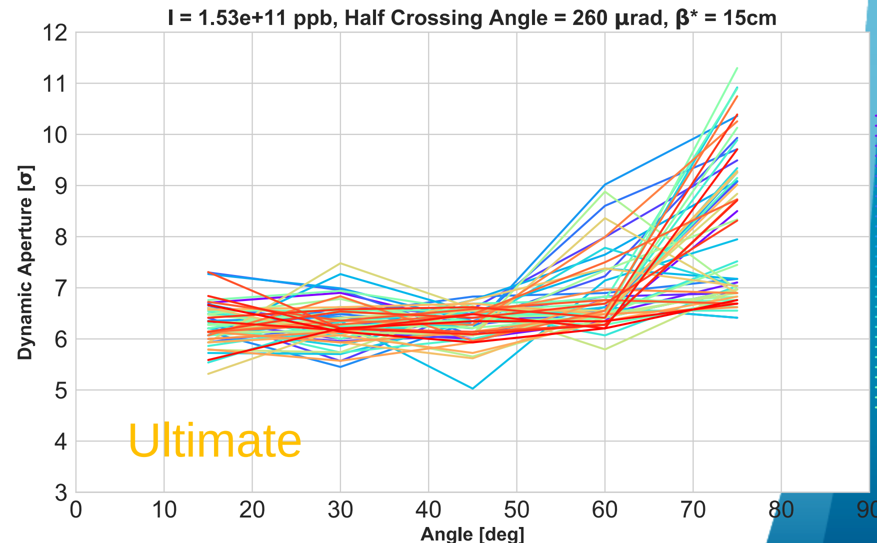
# Field Errors at the End of Levelling

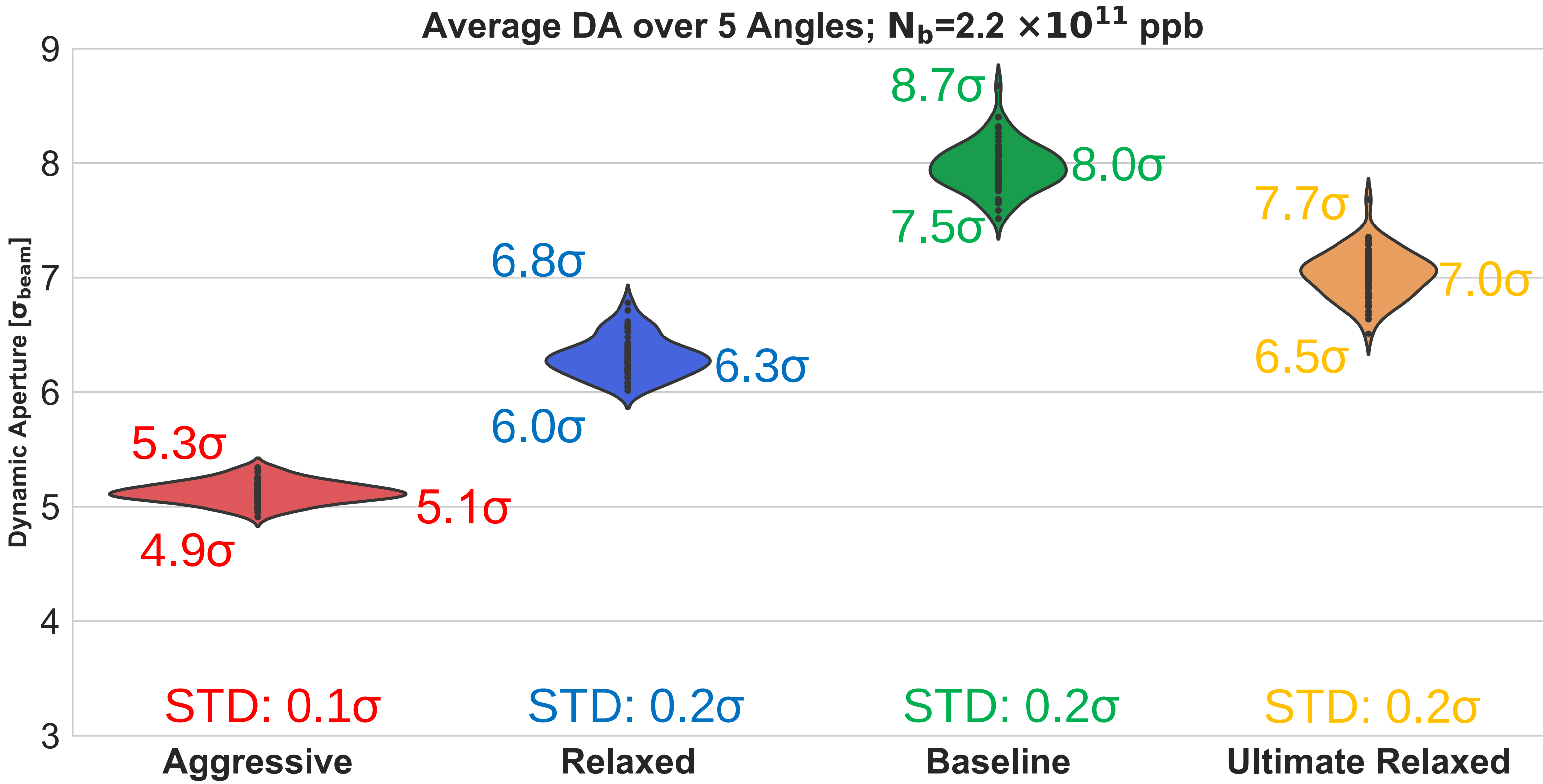


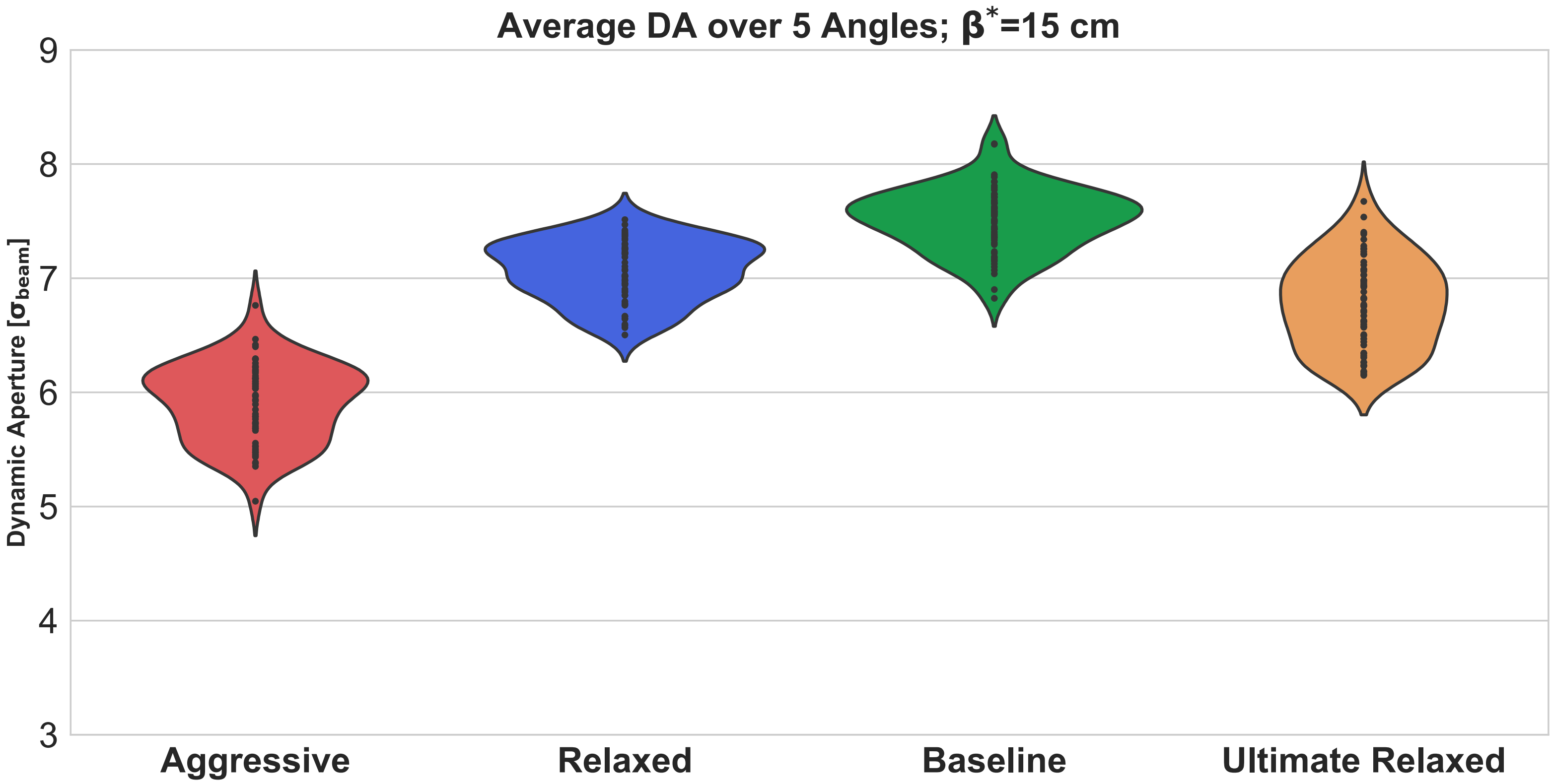



# Field Errors at the Start of Levelling

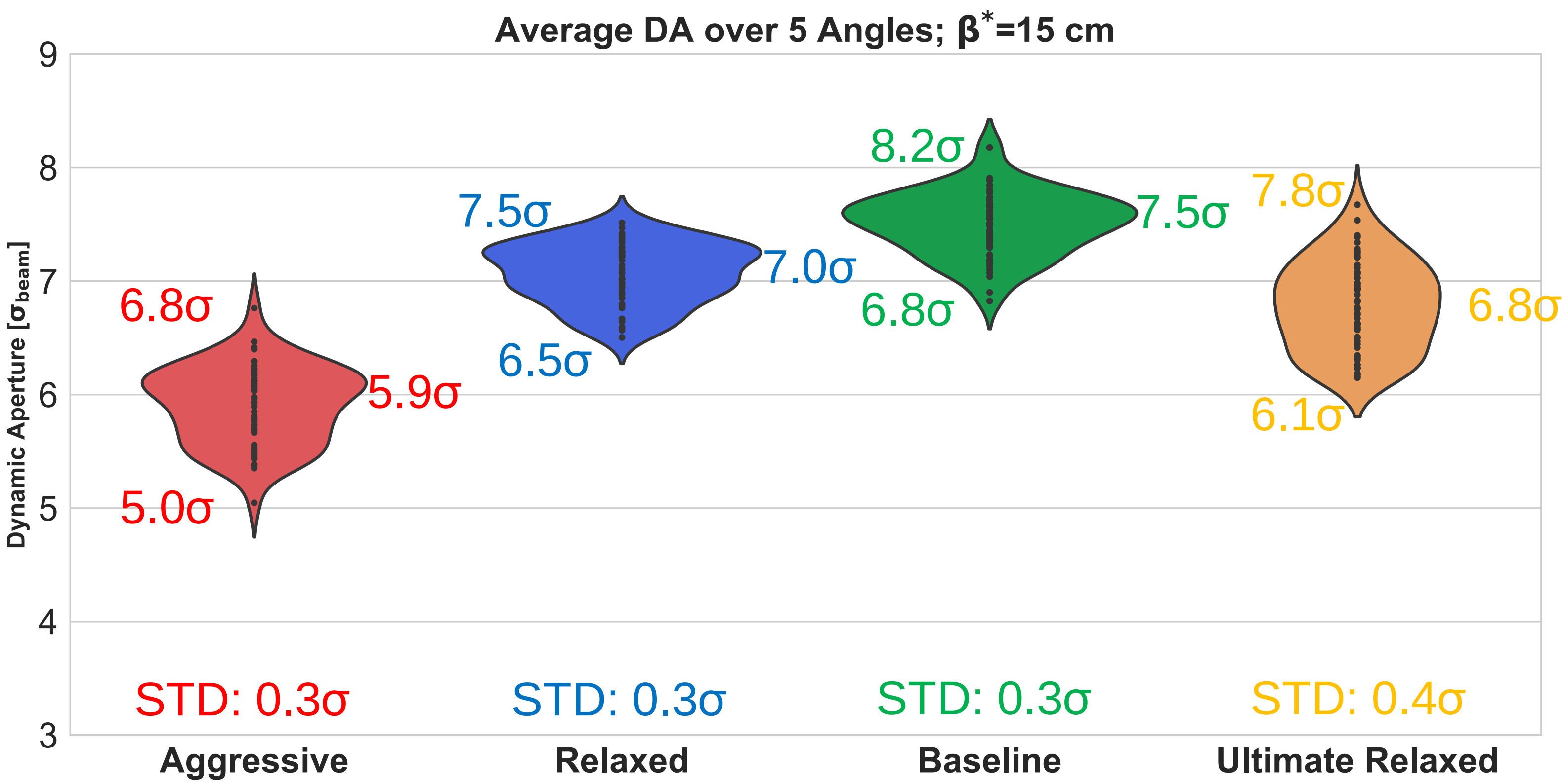



- Spread of 0.2σ, with the exception of the aggressive at ~0.1σ

# 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)

# Analysis of the BBCW compensation

S. Fartoukh et al.
PRST-AB 18, 121001

- Given the constraint on the minimal beam-wire distance, it was not possible to compensate all the resonances excited by the B1.
- We used the maximum current of the wires (350 A) to attack as much as possible the BBLR octupolar term.
- The octupolar terms induced by the BBLR in IR5 was reduced by **75%**.

**Strong-beam driven resonance**

$$c_{pq}^{\mathrm{LR}} \equiv \sum_{k\in \mathrm{LR}} \frac{\beta_x^{p/2}(s_k)\beta_y^{q/2}(s_k)}{d_{bb}^{p+q}(s_k)}$$

**BBCW driven resonance**

$$\begin{cases} c_{pq}^{w.\mathrm{L}} \equiv N_{w.\mathrm{L}} \times \frac{(\beta_x^{w.\mathrm{L}})^{p/2}(\beta_y^{w.\mathrm{L}})^{q/2}}{(d_{w.\mathrm{L}})^{p+q}} \\ c_{pq}^{w.\mathrm{R}} \equiv N_{w.\mathrm{R}} \times \frac{(\beta_x^{w.\mathrm{R}})^{p/2}(\beta_y^{w.\mathrm{R}})^{q/2}}{(d_{w.\mathrm{R}})^{p+q}} \end{cases}$$