Beam-beam simulations and operational scenarios

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  - Single particle stability
  - Coherent stability
  - Baseline scenario
- Reduced / Adaptive crossing angle
- Passive compensation with flat beams (w/o wires)
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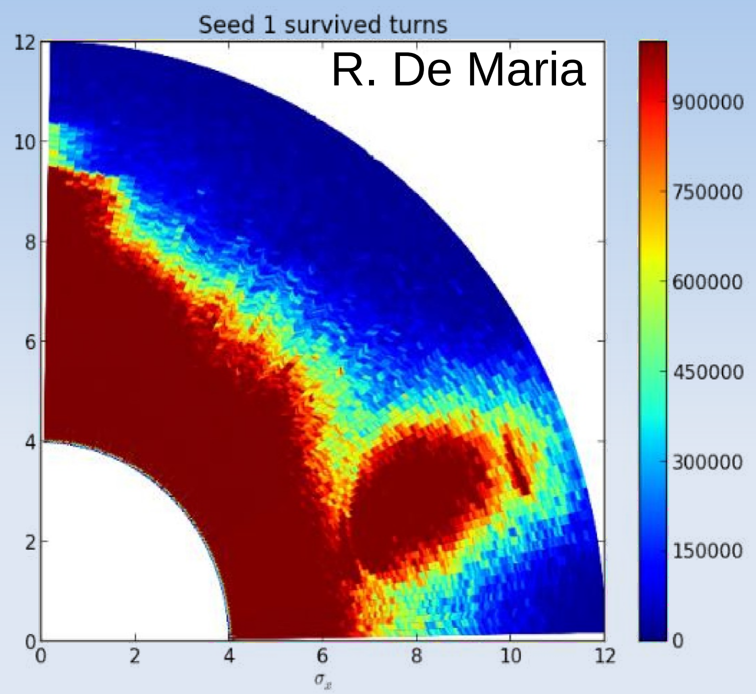
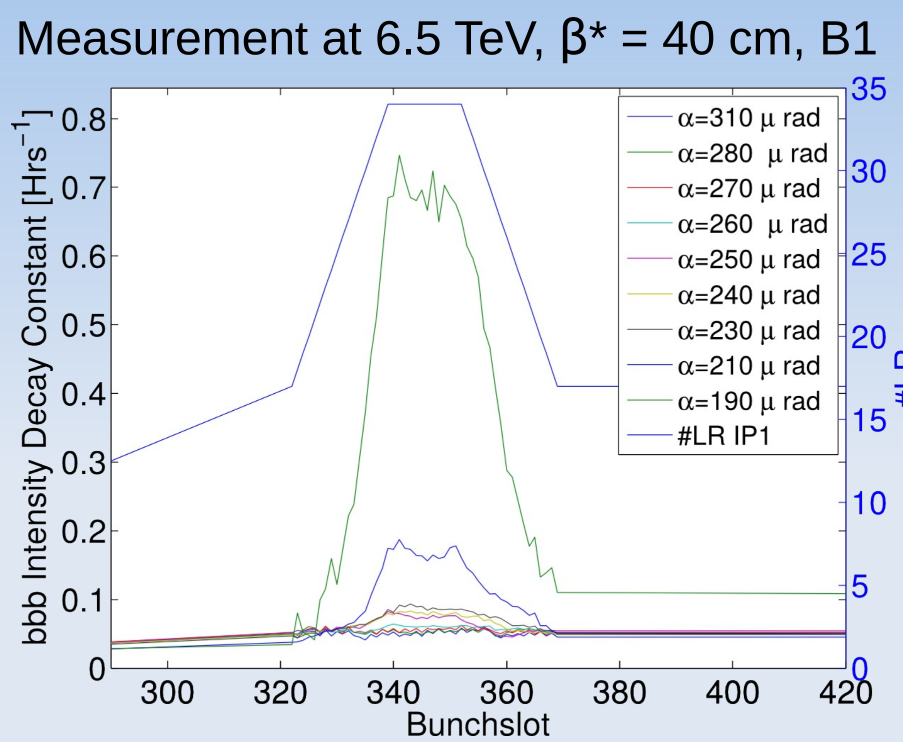
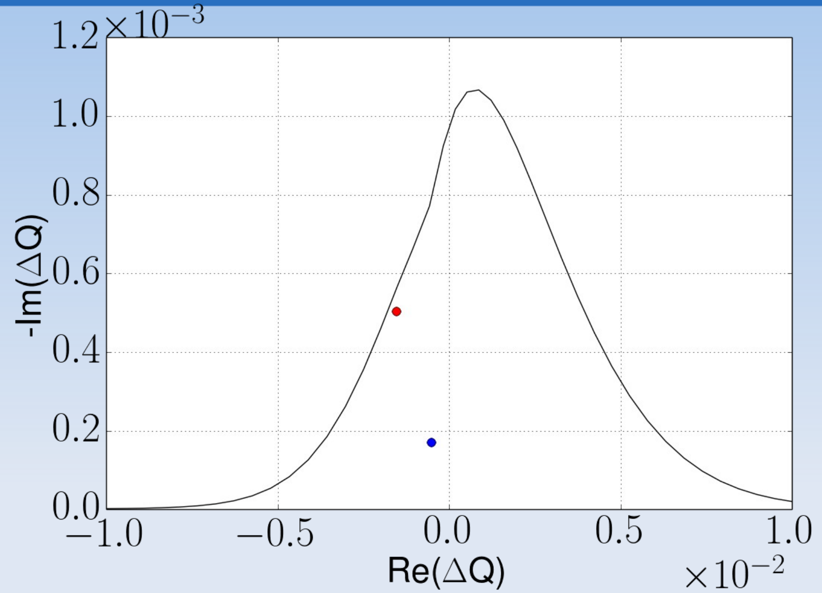
Single particle stability





- Single particle tracking in the weak-strong regime (SIXTRACK)
  - Smallest amplitude of the particles lost after 10^6 turns defines the dynamical aperture
  - Direct correlation between DA and beam lifetime is not trivial
    see M. Crouch @ Beam-beam meeting 14-10-2016
- LHC and HL-LHC are designed with a DA > 6 σ, in dedicated experiments it seems that DA ~ 3-4 σ leads to unacceptably low lifetimes

Stability diagrams, coherent tune shifts and the coherent stability factor



- Landau damping is quantified via the dispersion integral, represented by the stability diagram
  - It is defined by the tune spread (lattice non-linearities, beam-beam and others) (MAD-X and PySSD)
- The coherent tune shifts are defined here by the impedance (DELPHI)

→ The ratio b/a (≡ the coherent stability factor) describes the stability of a mode

→ We define the stability margin of a given machine and beam configuration by the maximum CSF of all the modes

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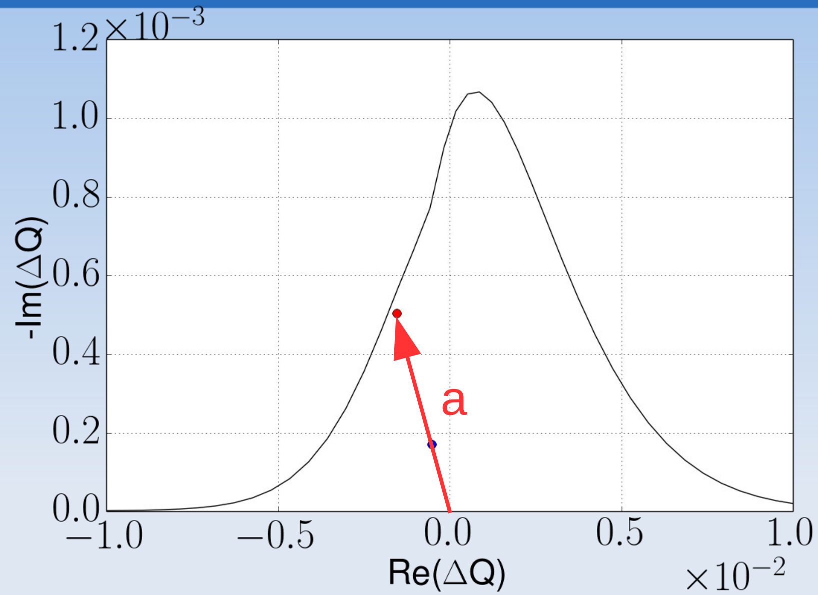

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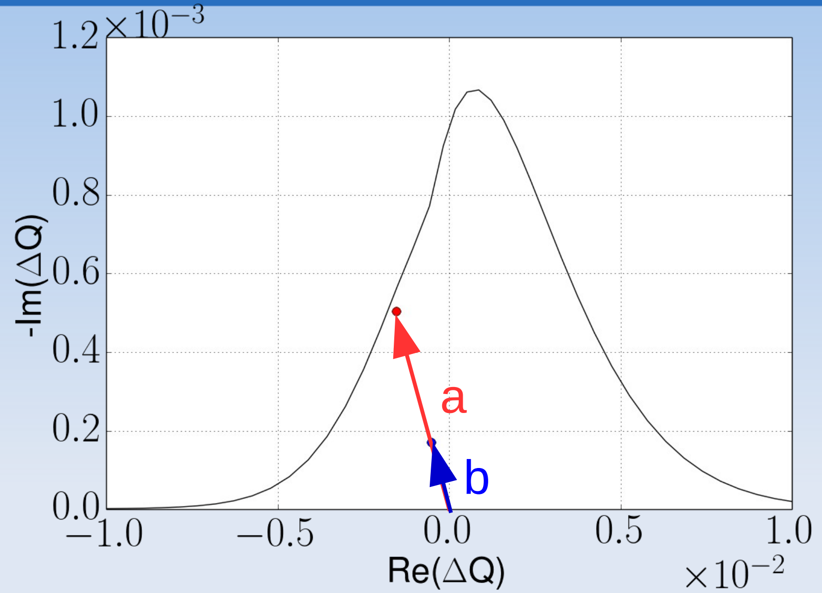

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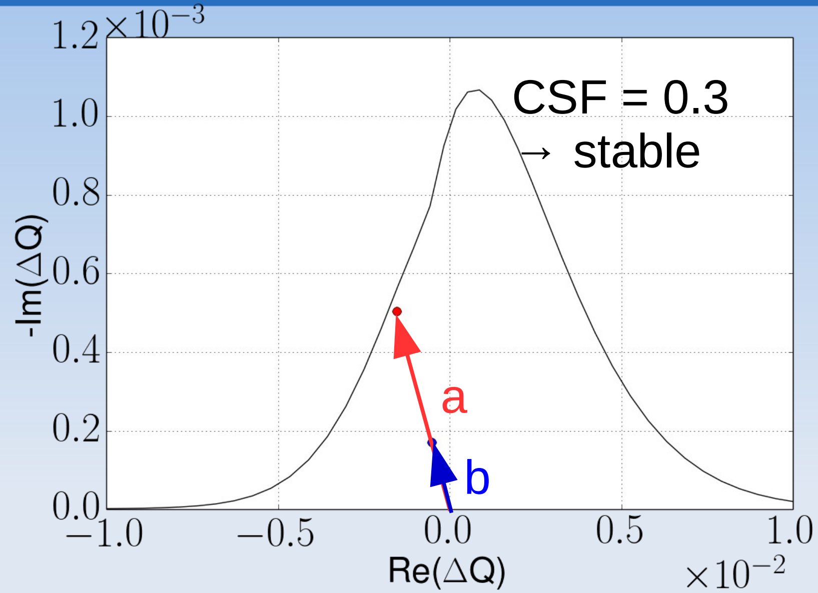

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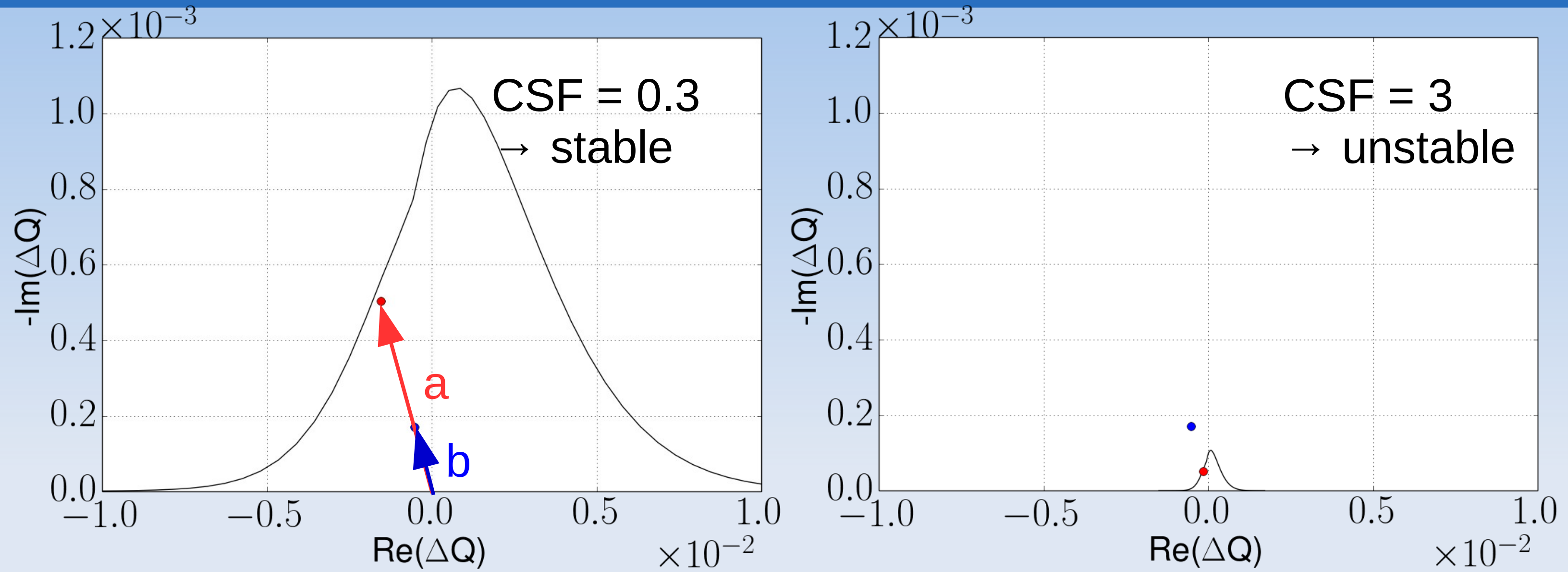

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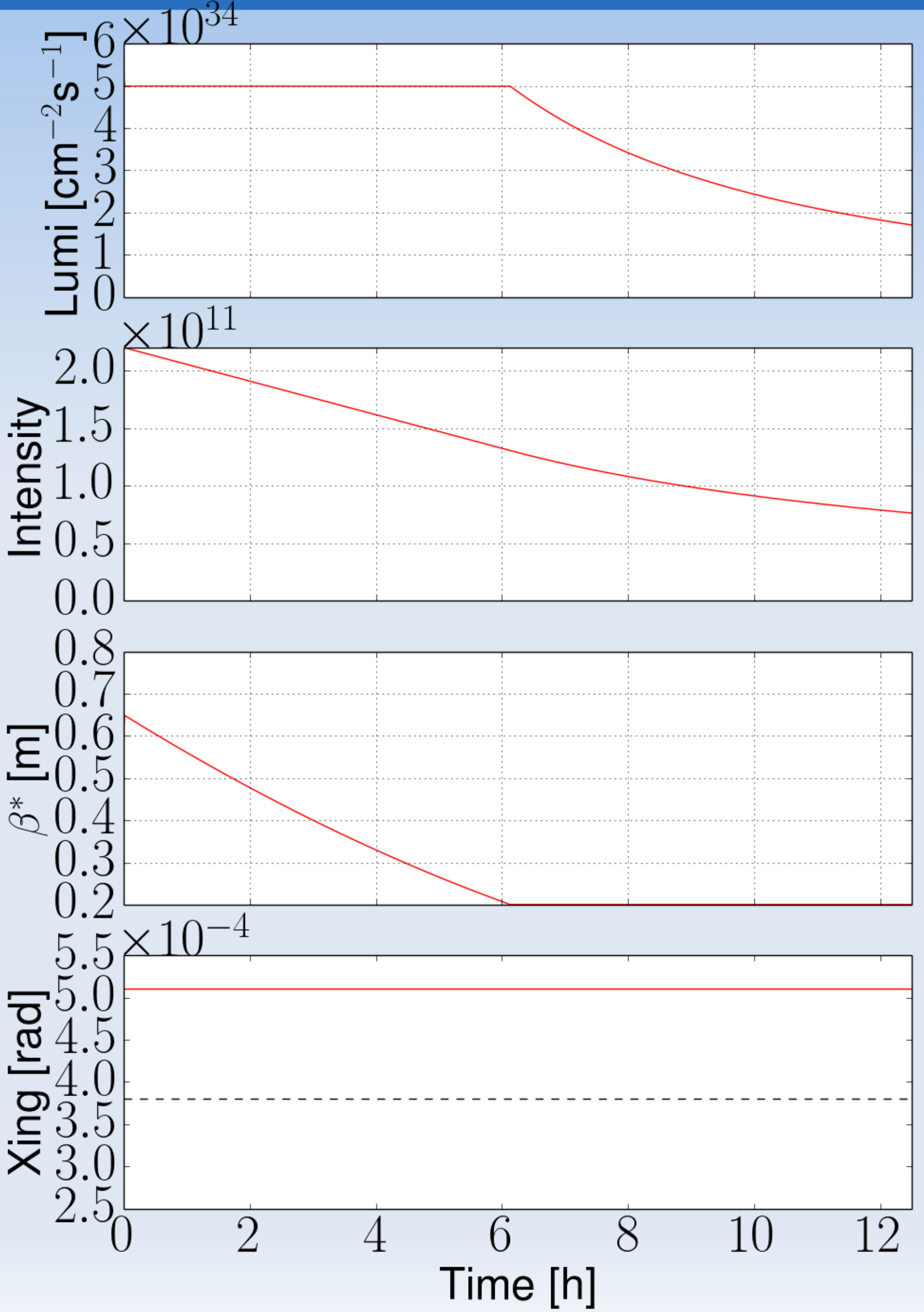
Baseline scenario

- Assumed a constant emittance (2.5 μm)
- About 6 hours of leveling, for an optimal fill length of 8 h (3h of turn around time)
- Crossing angle fixed to have a minimum separation of 12.5 σ with the smallest β*
- Maximum crab angle 380 μrad

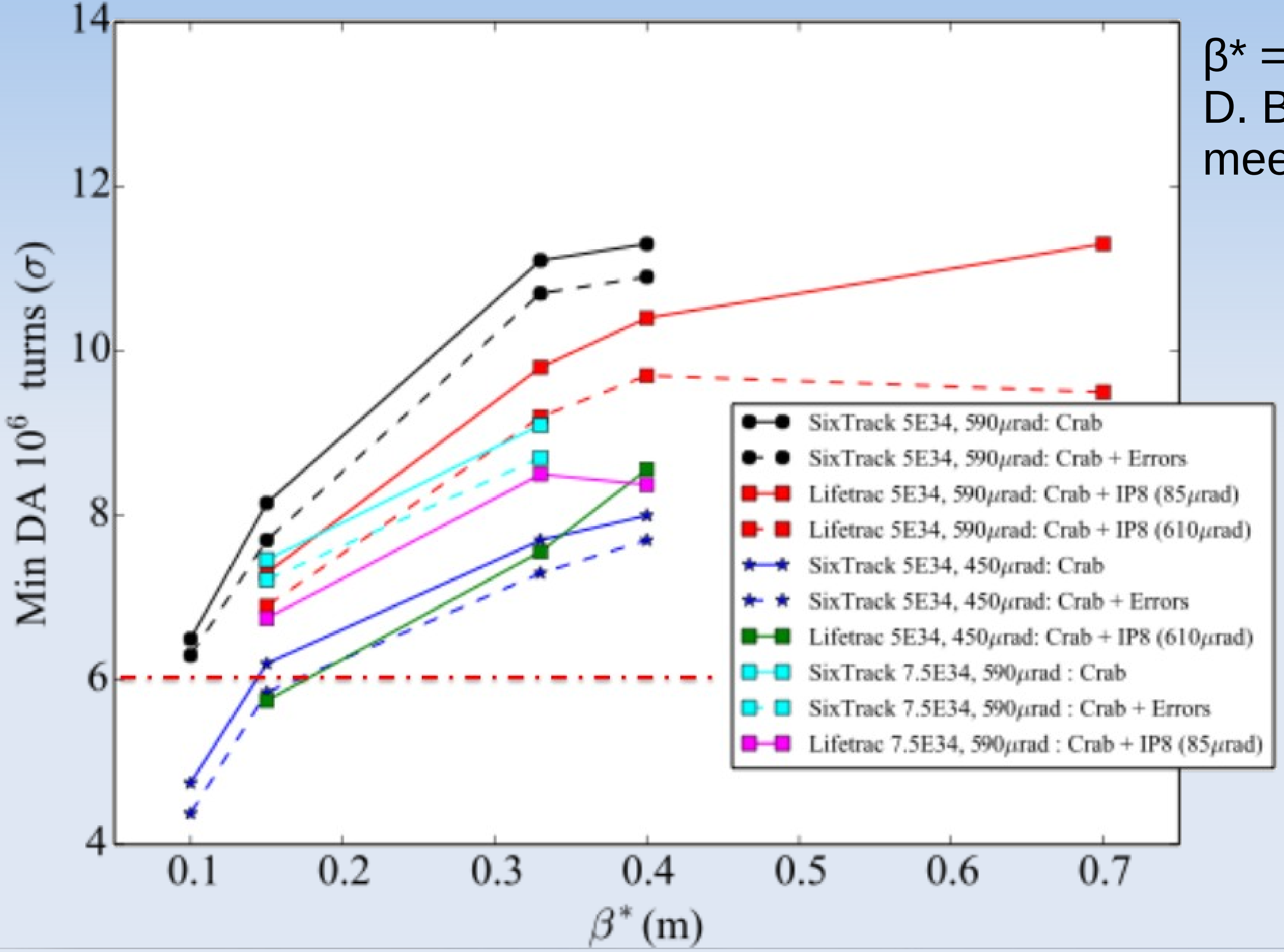
  → Maximum pile up density is increased for large crossing angle and small β*

$$\sigma_{\mathcal{L}} = \frac{\sigma_s}{\sqrt{2\left(1+\phi_p^2\right)}} \qquad \phi_p = \frac{\theta\sigma_s}{2\sigma}$$

- Low crossing angles are favourable for energy deposition in the triplet (A. Tsinganis @ HiLumi-LARP meeting 2015)



Dynamic aperture during β* levelling

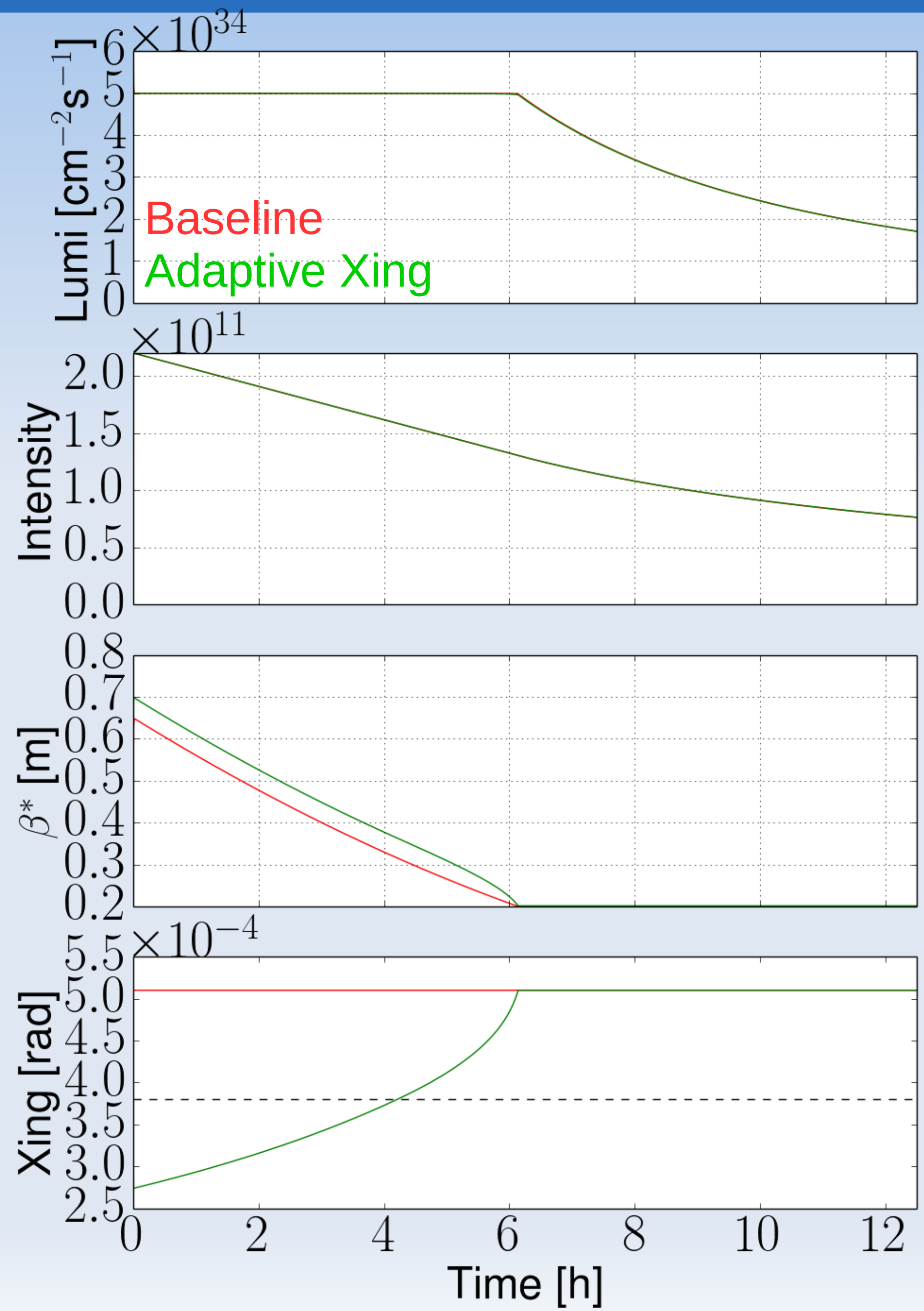


β* = 0.15 m, Fully crabbed
D. Banfi @ HiLumi-LARP meeting 2014

- The normalised long-range beam-beam separation is large at the beginning of the levelling, leading to additional dynamic aperture margins

Adaptive crossing angle

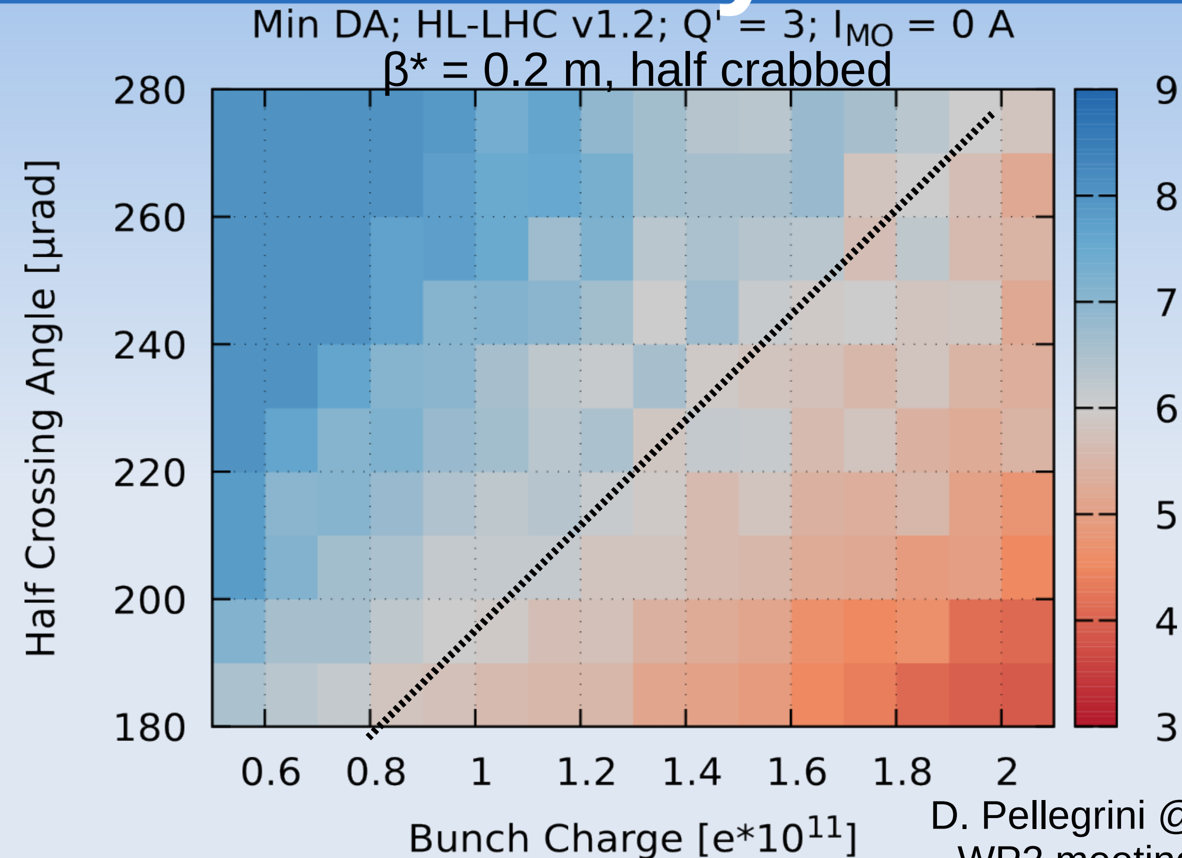
- Adapting the crossing angle, keeping the normalised separation at 12.5 σ has a beneficial impact on the pile up density (~10%)
  - No reduction of dynamic aperture margins
  - No impact on total performance (unless the reduction of the pile up density allows for an increase of the leveled luminosity → +5%)
- The initial crossing angle has an impact on the coherent stability during the squeeze → see later



Dynamic aperture with reduced intensity

- The dynamic aperture scales close to linearly with the bunch intensity
- At the end of the leveling the intensity is about $1.3 \cdot 10^{11}$

  → Scaling from results obtained with previous optics* 400 μrad (9.8 σ) is sufficient to ensure single particle stability (510 μrad, i.e. 12.5 σ, are needed with $2.2 \cdot 10^{11}$)



D. Pellegrini @ WP2 meeting 11.10.2016

- Impact of IP8 with offset levelling needs to be evaluated (~1σ)
  - The crossing angles were chosen assuming that IPs 2 and 8 have a negligible impact on the dynamics → Important impact on the margins
- The impact of magnet errors are usually <1σ for a lower crossing angle (neglected here)

*D. Banfi @ HiLumi-LARP meeting 2014

Adaptive crossing angle

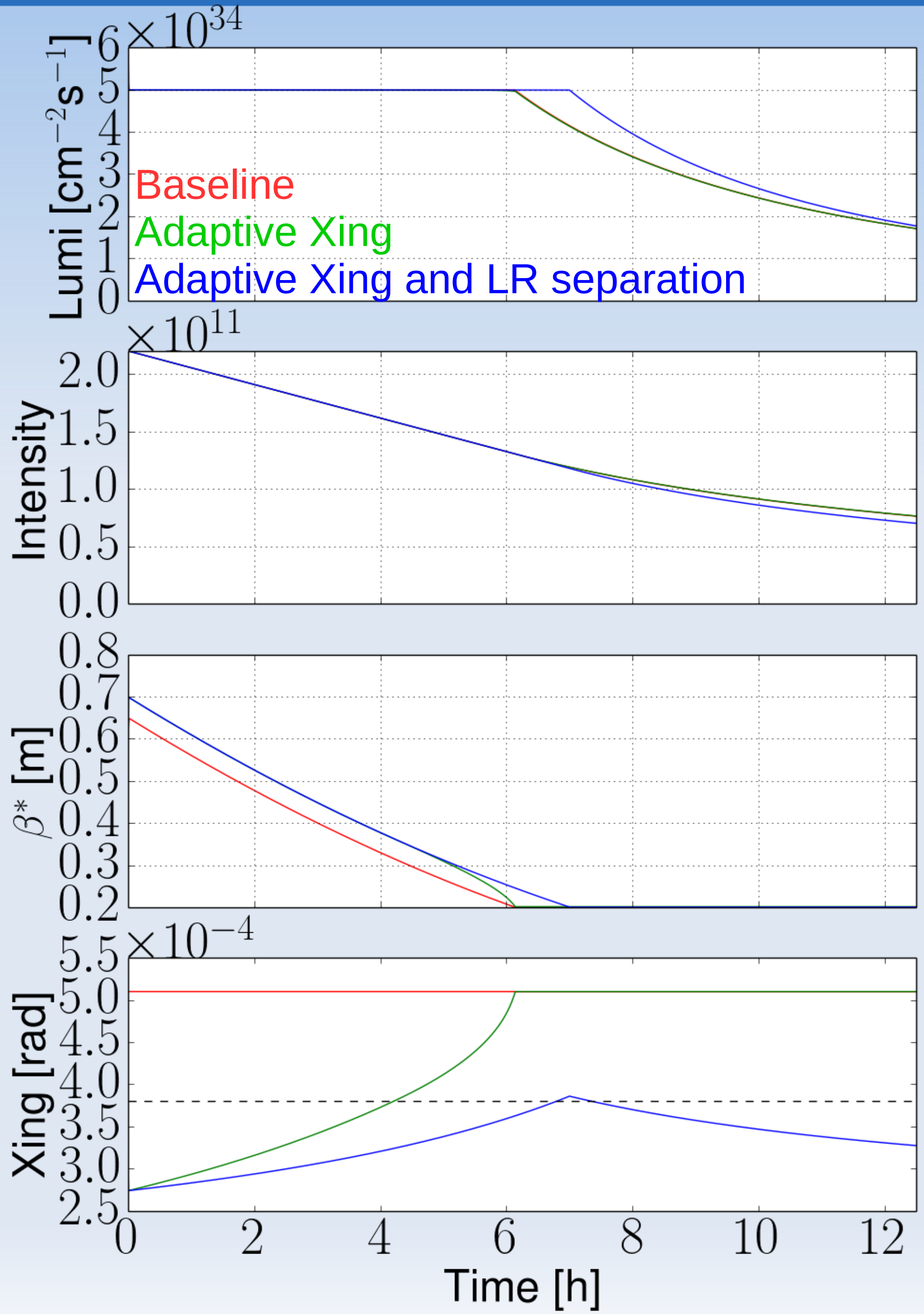
- Adjusting the normalised long-range separation to the bunch intensity leads to a maximum angle of about 400 μrad at the end of the levelling

  → Full crab crossing with two cavities can be achieved for almost the full fill

  → +3% Average luminosity

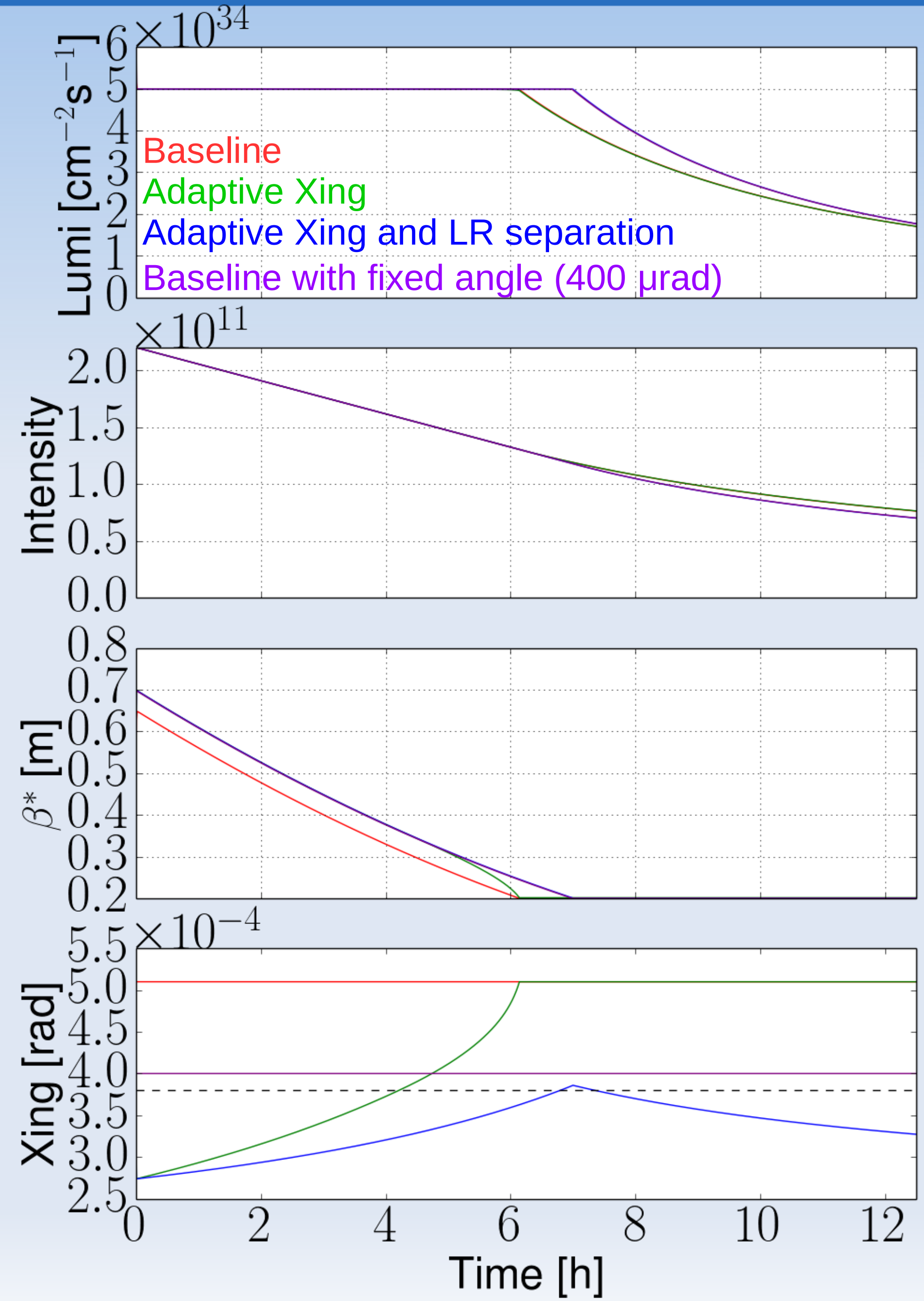
  - While the performance gain in terms of integrated luminosity is marginal, the pile up density is reduced

- With β^*_{min} = 15 cm, the performance is improved by +5% wrt the baseline (R. Tomas, et al)

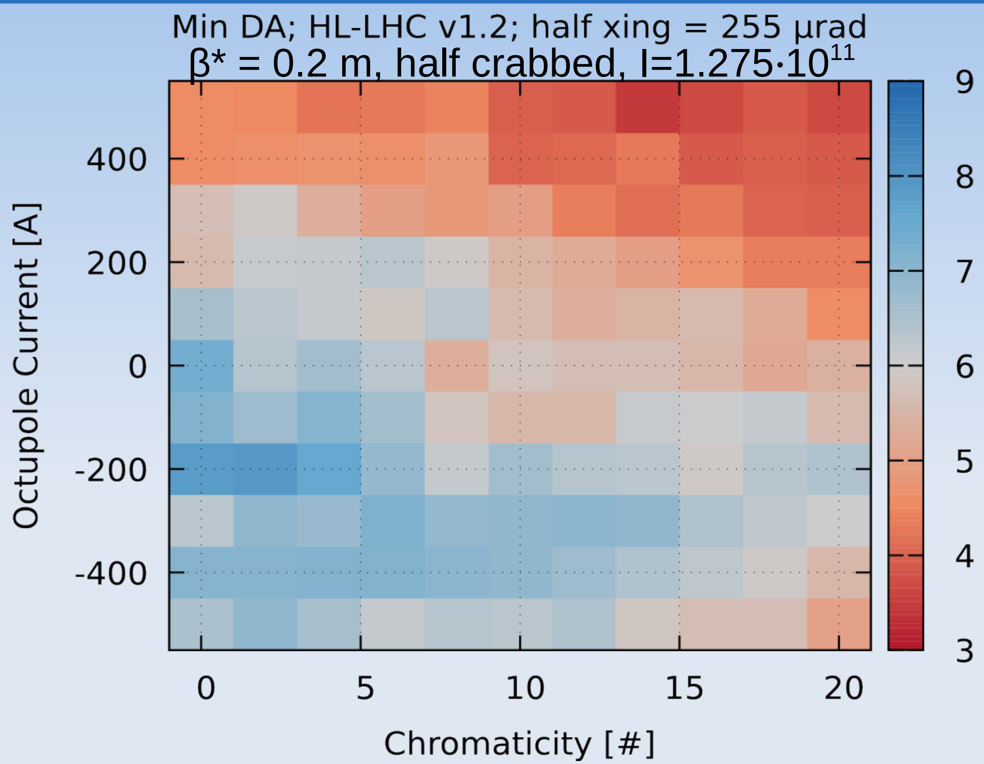


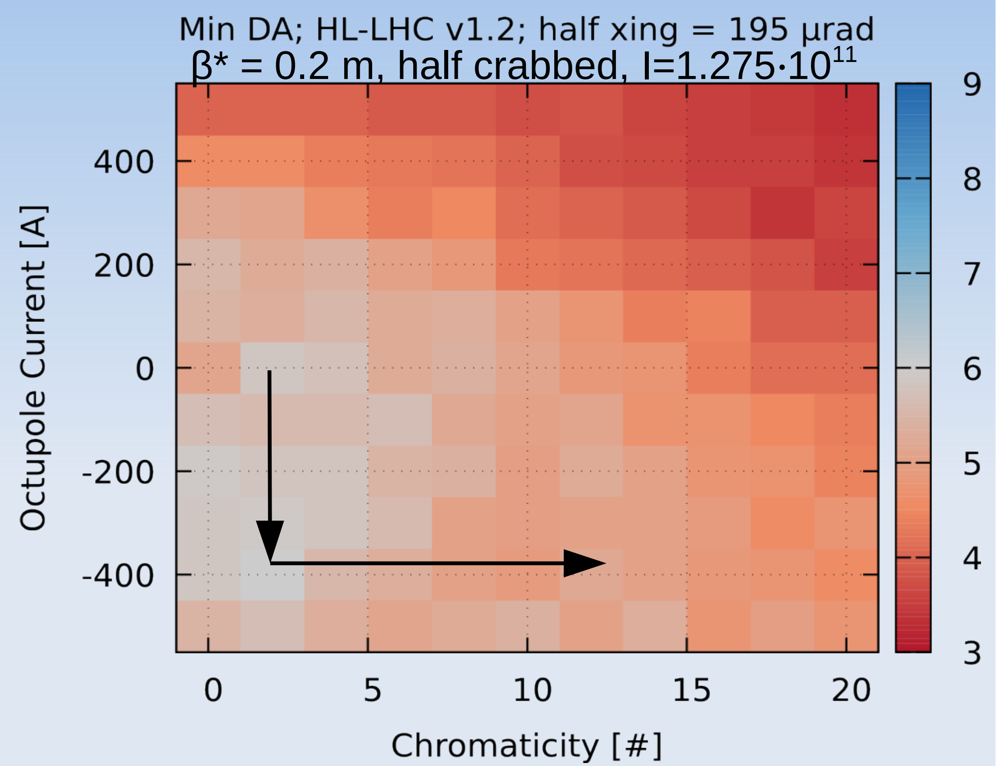
Baseline with a fixed reduced crossing angle

- An identical performance can be achieved with a fixed crossing angle
  - The Piwinski angle remain small → reduced impact on pile up density
  - Less efficient mitigation of the losses on the triplet (to be quantified)



Dynamic aperture at the end of levelling

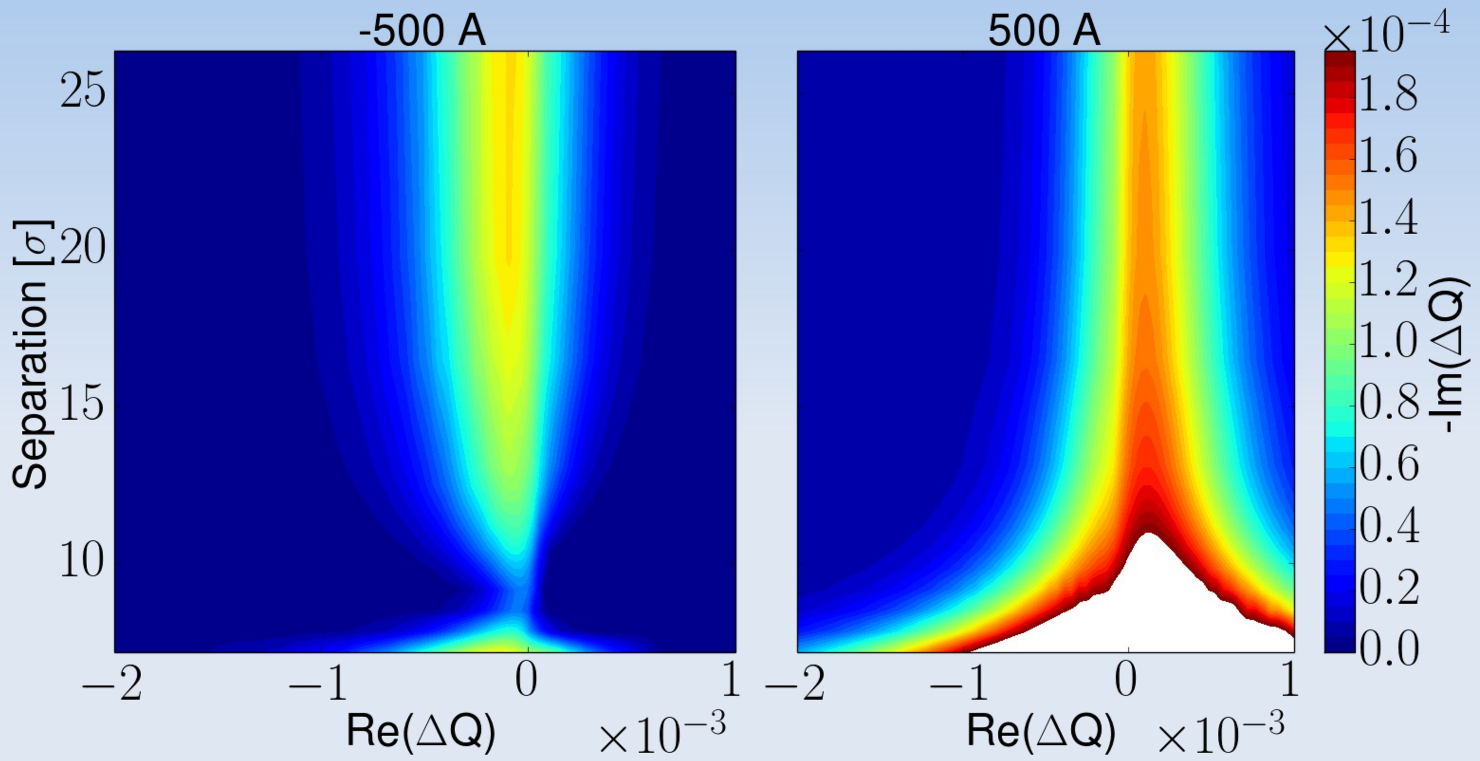




- The smaller normalised separation at the end of levelling provides a sufficient dynamic aperture
  - An optimisation of the octupole strength offers extra margins
  - An larger angle might be required in case a large chromaticity is needed to mitigate coherent instabilities in collision

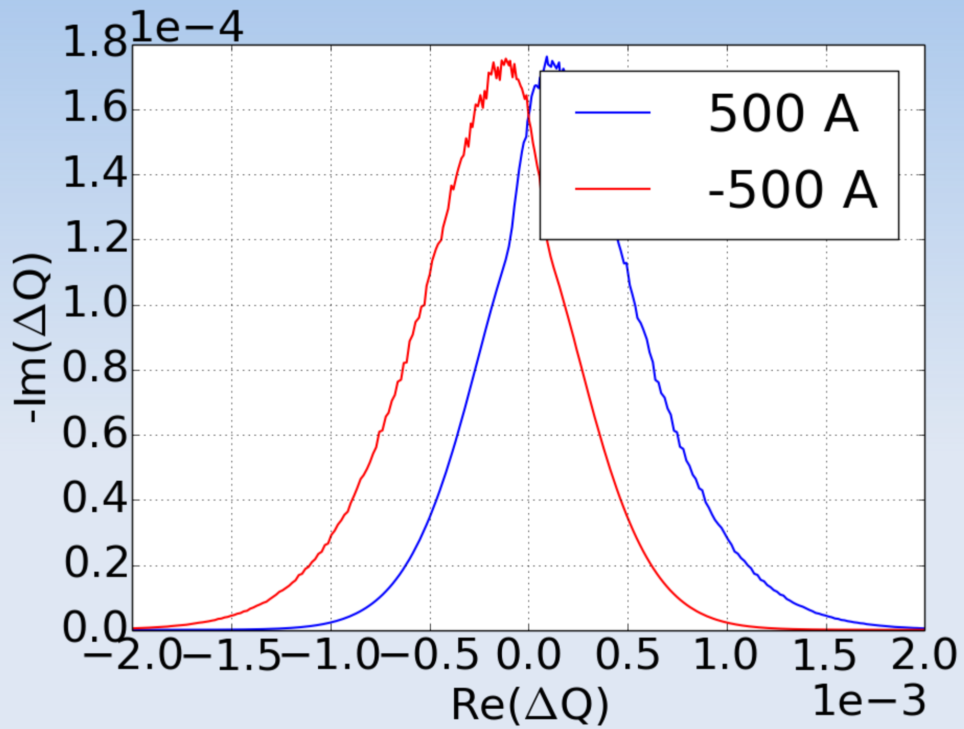
    → Detailed parametric studies (including IP8 levelling) are needed to fully asses the margins (see T. Pieloni @ Beam-Beam meeting 14.10.2016)

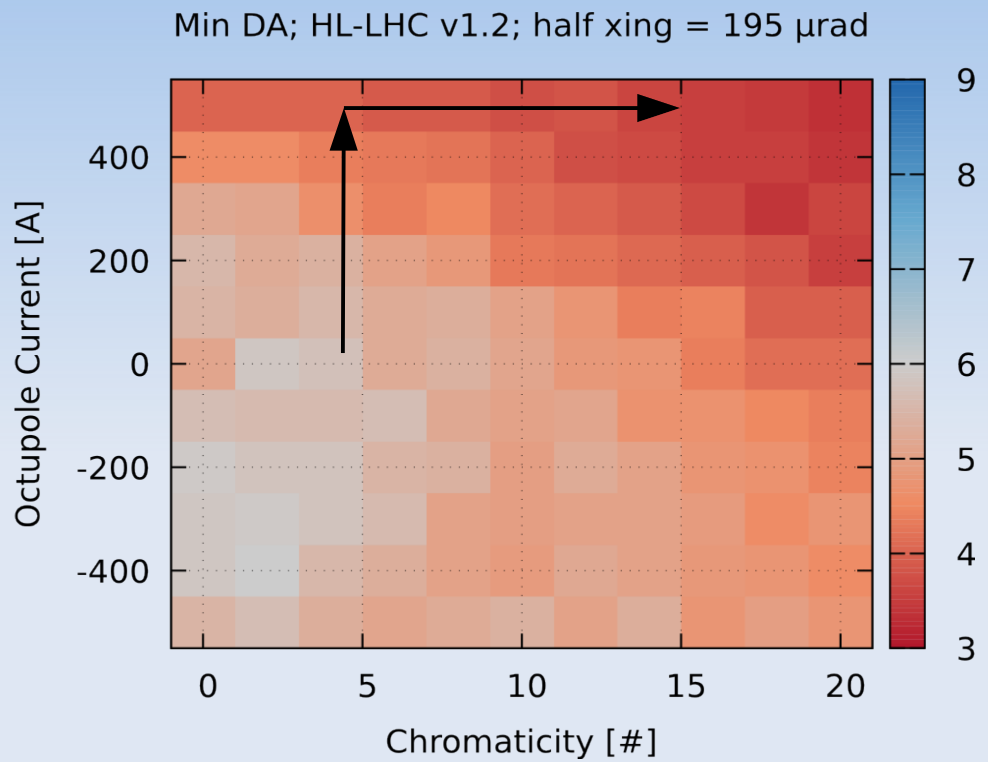
Coherent stability during the squeeze LHC



- Compensations of tune spread from the octupoles and the long-range beam-beam interactions can lead to loss of Landau damping
  - The positive polarity of the octupoles was chosen in 2012 attempting to increase the stability margins

Why negative polarity ?

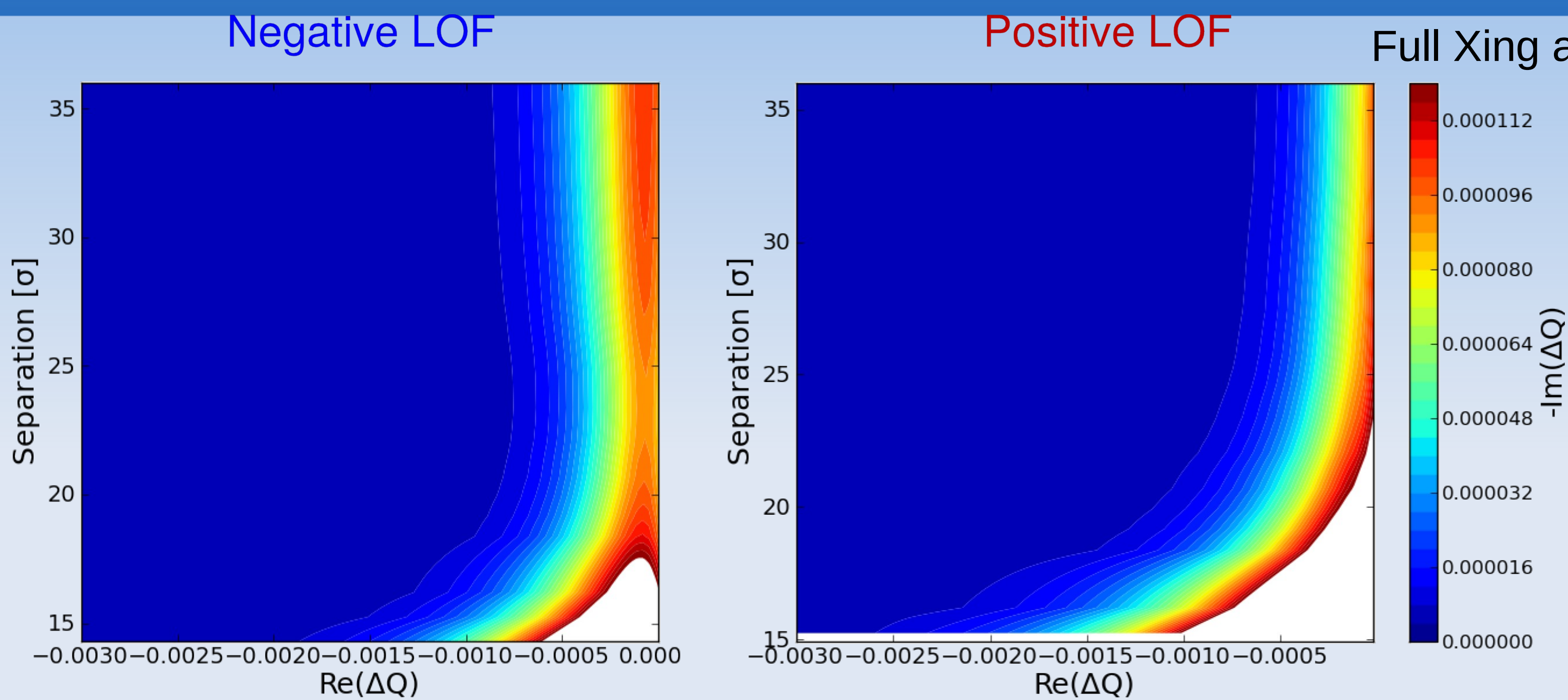




- More margins for single beam coherent stability without long-range interaction (i.e. flat top and part of the squeeze)
  - Tune shifts due to the impedance have negative real parts
- Dynamic aperture is significantly reduced with strong positive octupoles

Coherent stability during the squeeze Baseline HL-LHC

Full Xing angle = 590 μrad



C. Tambasco @ HiLumi-LARP meeting 2015

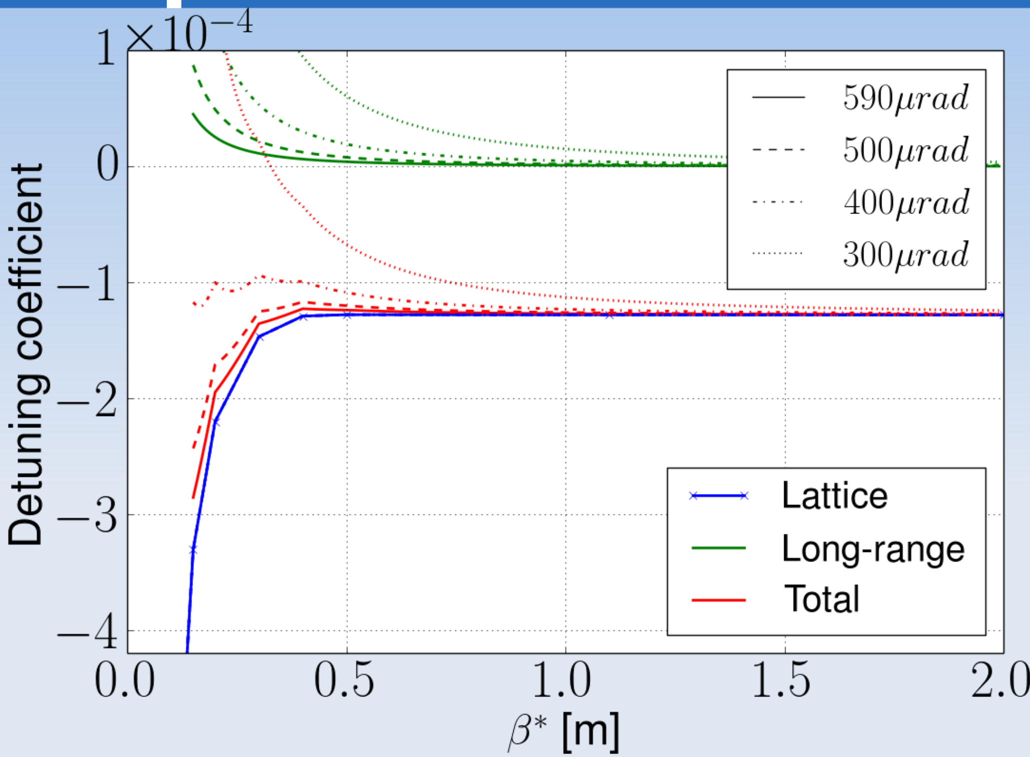
- The effect of long range beam-beam interactions is mitigated by the increase of the β function at the octupole location when performing the ATS
- Thanks to the large normalised beam-beam separation at the beginning of β* leveling, the effect of long-range interaction is negligible during the pre-squeeze in the baseline HL-LHC scenario
  - Both mitigations are no longer valid if one starts with a reduced separation during the pre-squeeze

Coherent stability during the squeeze

- Simple model : The stability diagram is roughly proportional to the linear detuning coefficient:

$$Q_x = Q_{0,x} + a \cdot J_x + b \cdot J_y$$

$$a_{LR} \approx \frac{3}{2} \frac{N_{LR} \cdot \xi}{d^4} \quad \left(\xi = \frac{r_0 N}{4 \pi \epsilon}, d = \sqrt{\frac{\beta^* \gamma}{\epsilon}} \right)$$



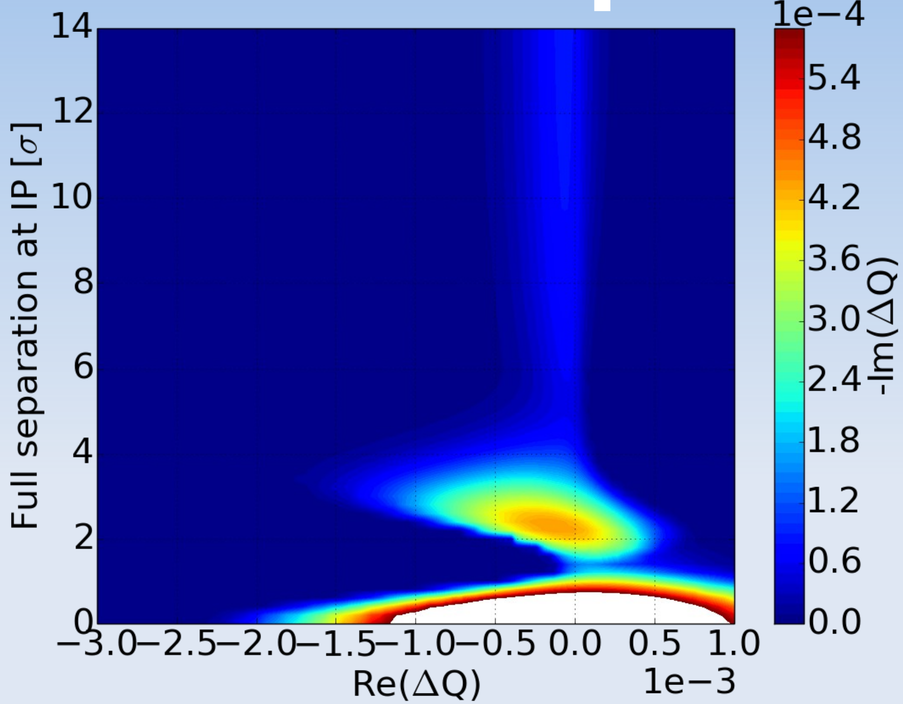
- Lattice detuning coefficient (i.e. due to sextupoles, octupoles)
- The total detuning coefficient due to the effect of the octupoles and of the long-range beam-beam interactions only increases during the squeeze with the baseline parameters
  - Reducing the crossing angle at the beginning of the levelling can lead to a reduction of the stability diagram during the squeeze → reduction wrt margins at flattop

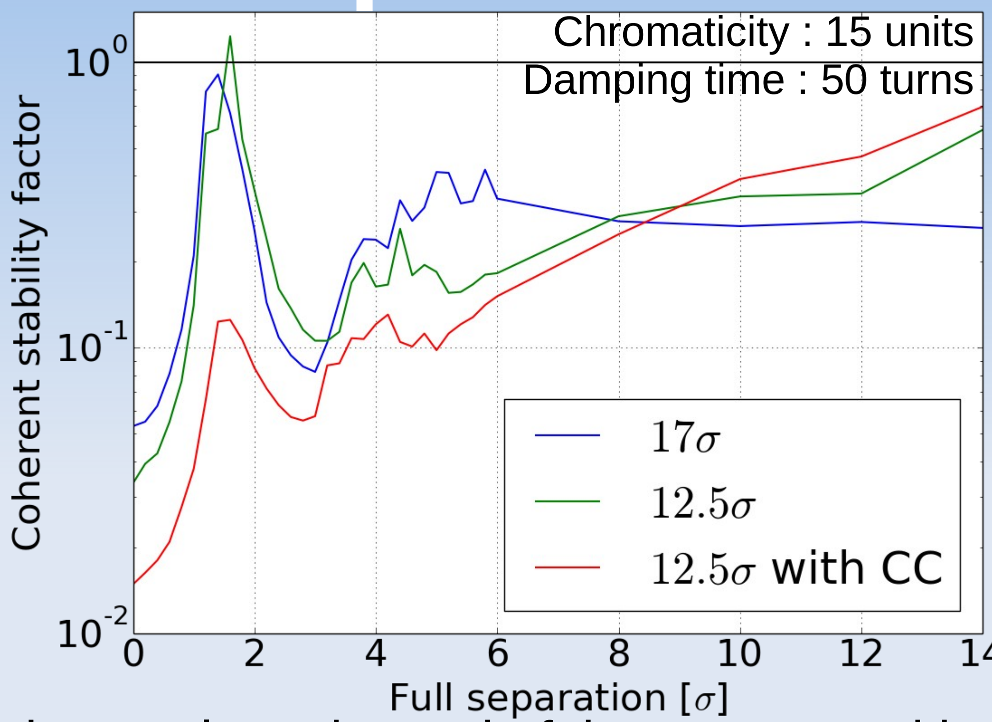
→ Start the increase of the arc β earlier in the pre-squeeze (~1-1.5m)

→ Reduce the crossing angle once in collision

→ Change the polarity of the octupole once in collision (transient losses due to low DA)

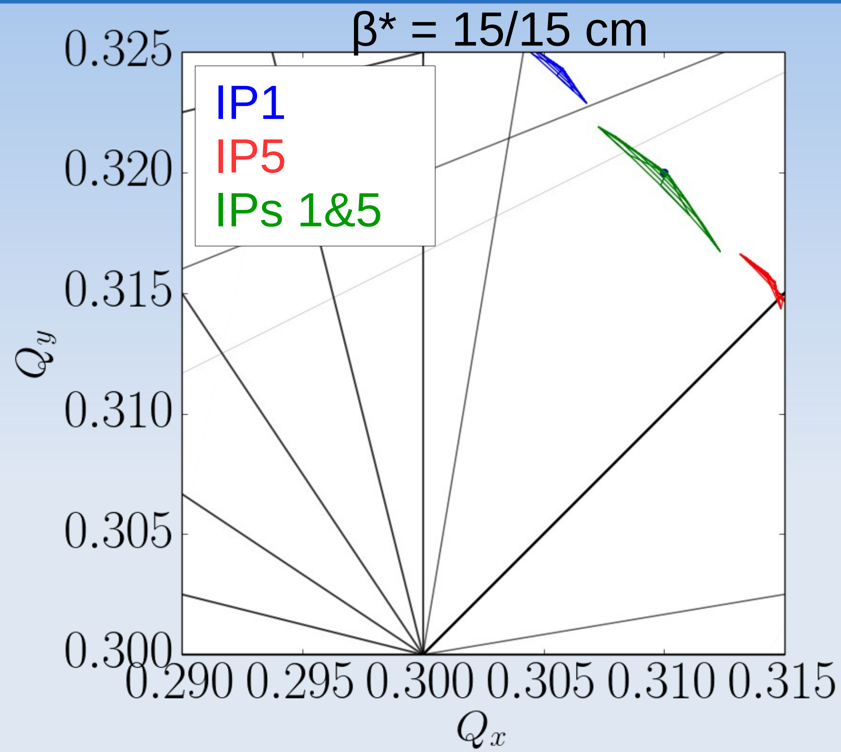
Collapsing the separation bumps

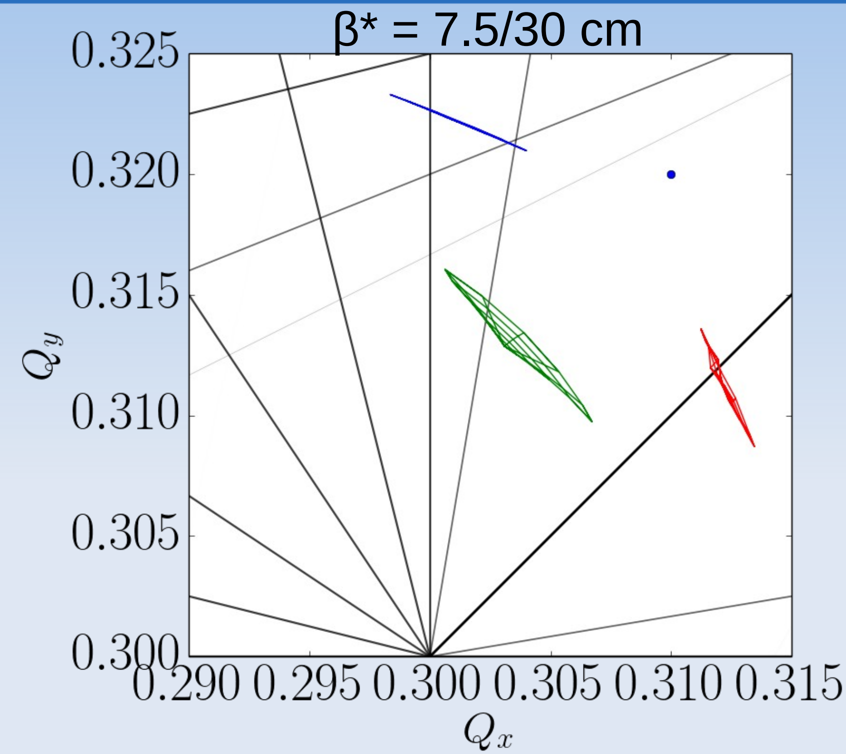




- The CSF is twice larger with smaller crossing angle at the end of the squeeze with a reduced angle (12.5 σ)
  - Absolute value of the CSF depends on the impedance model (N. Biancacci @ HL-LHC TC Meeting 5.11.2015)
- The beneficial impact of the head-on tune spread is more important when fully crabbed → CC should be turned on before collapsing the bumps (C. Tambaso @ WP2 meeting 19.04.2016)
- The transverse feedback is required during this phase for both the coupled bunch instability but also for beam-beam coupling instabilities

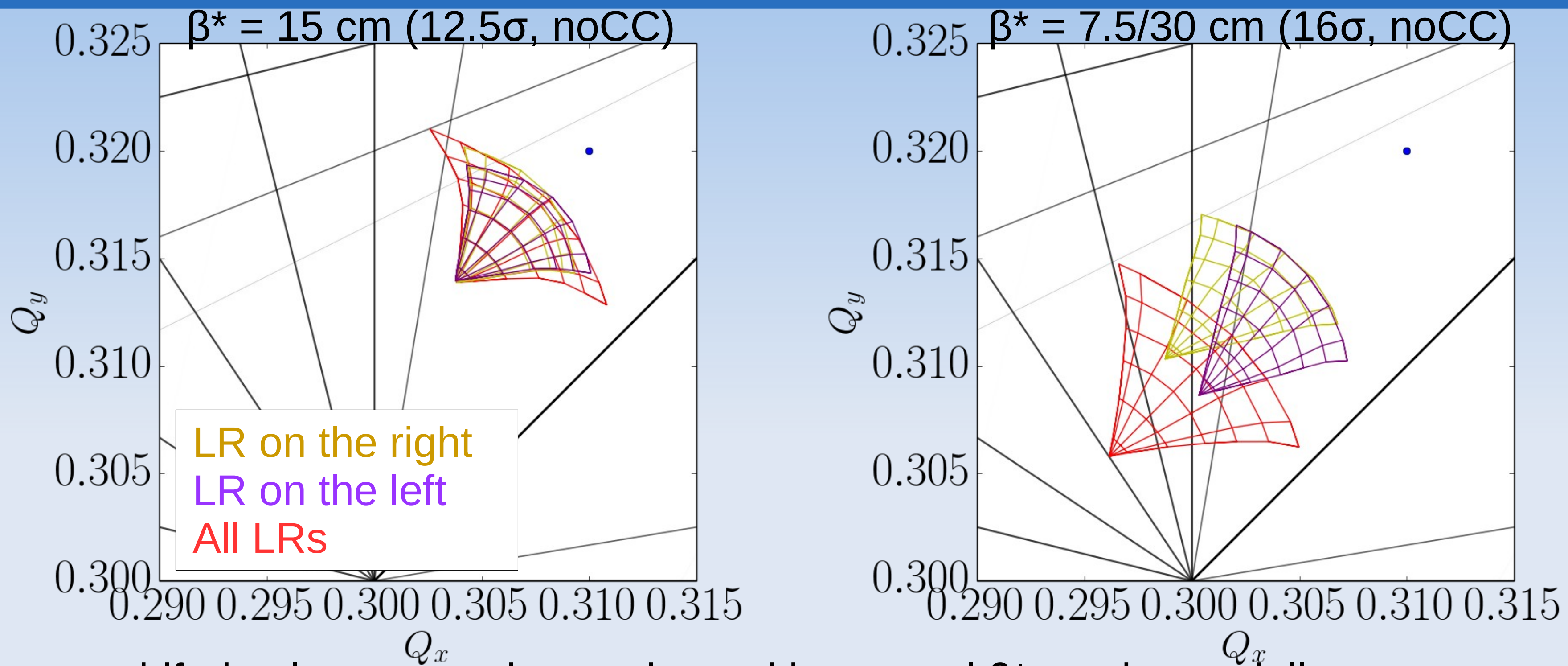
Flat beams
Passive compensation





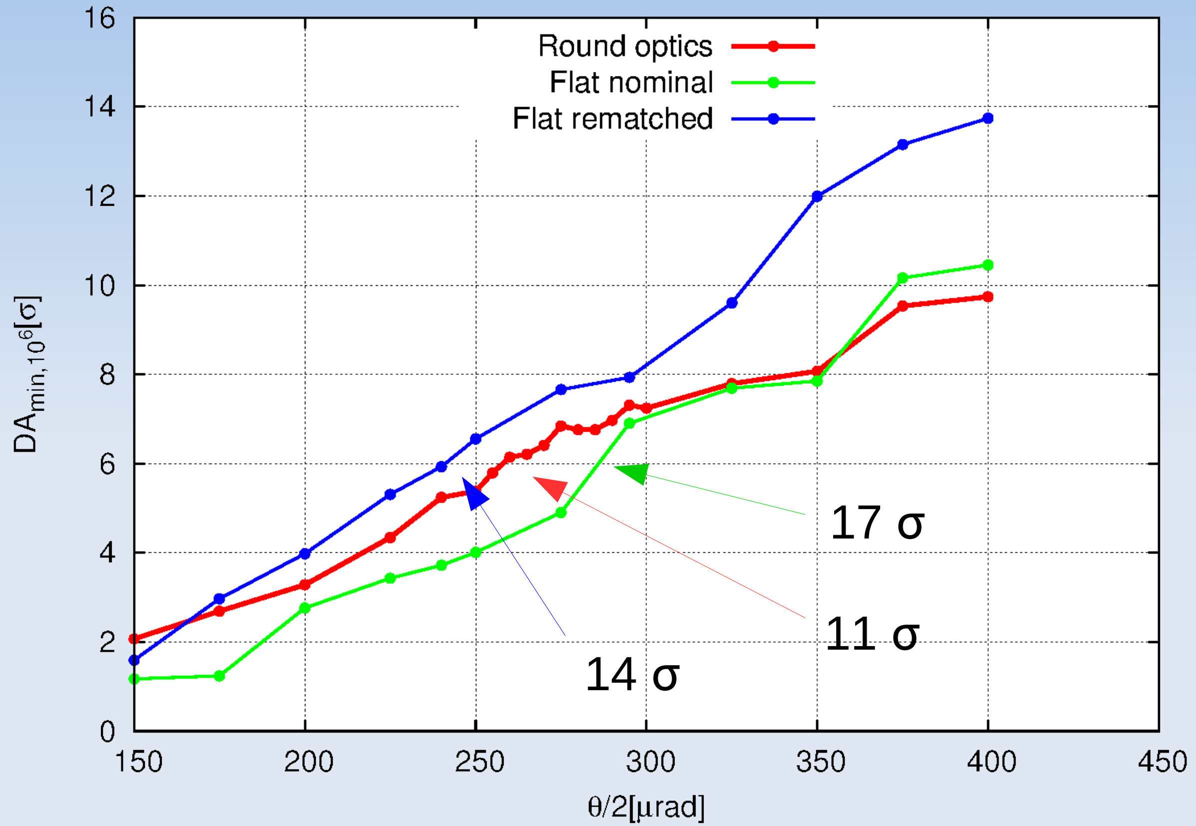
- With round beams the tune shift of a single IR due to long-range interaction follows $\Delta Q_x \sim -\Delta Q_y$
  - → Alternating H-V in the two main IRs result in $\Delta Q \approx 0$
  - → The compensation of the tune shift is mostly relevant for PACMAN bunches
- With flat beams $\Delta Q_{xing} >> \Delta Q_{sep}$
  - → Alternating the H-V brings the tunes back with a shift along the diagonal

Flat beams
Passive compensation



- The tune shift due long-range interactions with unequal β* can be partially compensated with a global tune change
  - PACMAN bunches remain with different tunes
  - The tune shift has to be adjusted to the varying intensity (and emittance)
- The non-compensation of the PACMAN effect along the diagonal can only be mitigated by a pulsed wire / e-lense
  - The non-compensation normal to the diagonal could be mitigated by restoring the H-V symmetry between the two main IPs (i.e. not only alternating crossing, but also alternating optics)

Round vs Flat beams Dynamic aperture



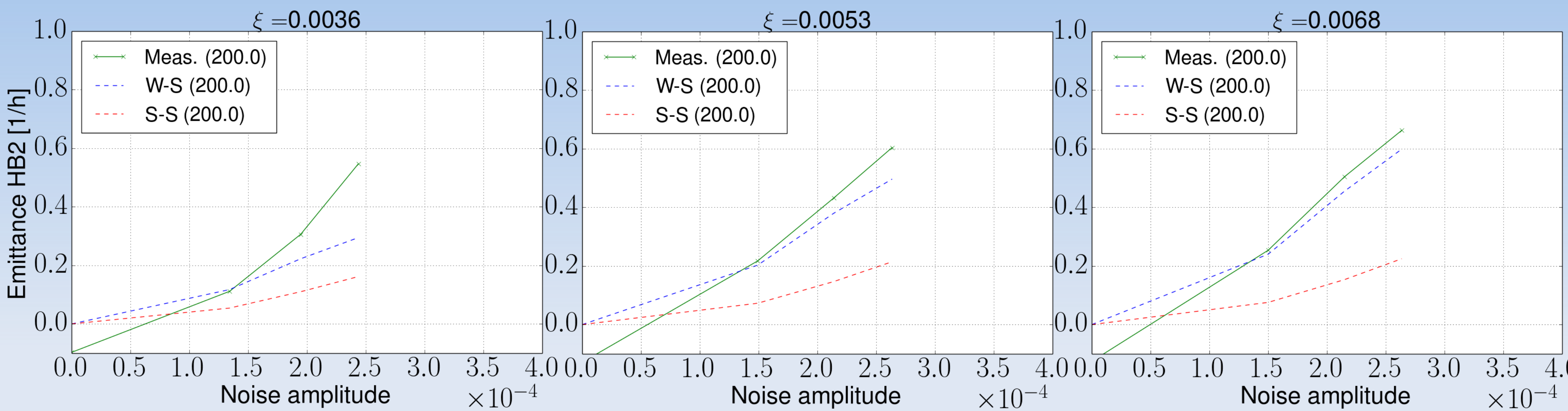
β^*_{flat} = 30 / 7.5 cm

β^*_{round} = 15 cm

- The increased normalised separation required with flat beams wrt round beams* can be mitigated by compensating the tune shift along the diagonal

*D. Banfi @ HiLumi-LARP meeting 2014

Update on the effect of noise on colliding beams



- Crab cavity noise tolerances are based on a weak-strong beam-beam model*
- The strong-strong model predicts a potential reduction of the emittance growth thanks to the efficiency of the feedback against coherent beam-beam modes
  - The beneficial impact is very sensitive and seemed difficult to obtain in complex configurations of beam-beam interactions such as at the LHC

    → Conservative approach seems supported by first measurements at 6.5 TeV in the LHC

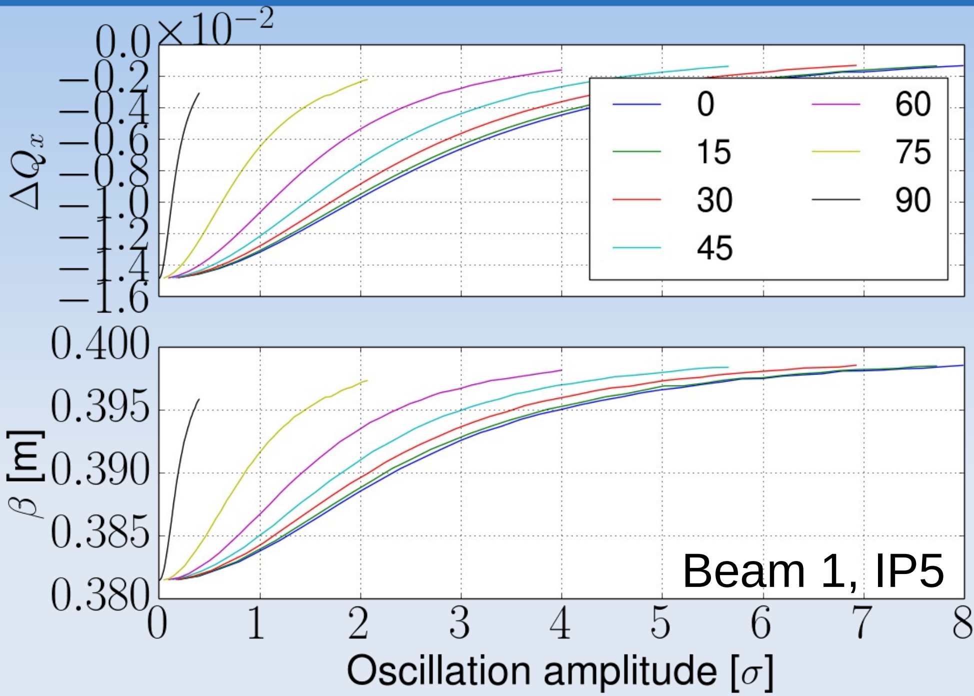
*P. Baudrenghien and T. Mastoridis, Phys. Rev. ST Accel. Beams 18, 101001 (2015)

Conclusion

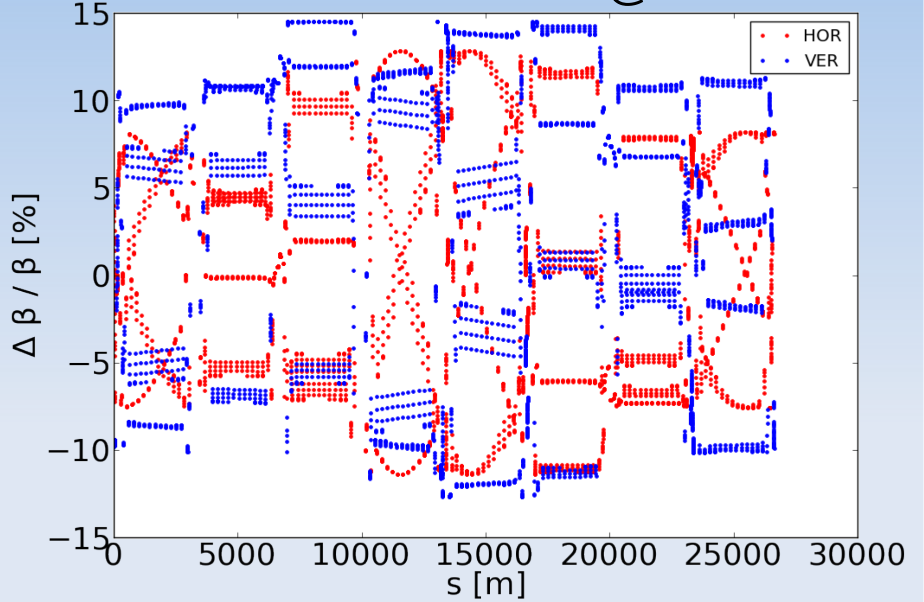
- A reduction of the crossing angle to 400 μrad (→ more than 12.5σ at the beginning of the leveling, 10σ at the end) seems within reach
  - To be confirmed with detailed simulations including magnetic errors, IP8 levelling, as well as quasi-full crabbing
  - Adapting the crossing angle to the evolution of the beam parameter allows to remain fully crabbed almost all along the fill (β^*=20 cm), having a positive impact on luminous region length
  - The reduced crossing angle during the pre-squeeze reduces the coherent stability margins, which could be mitigated by anticipating the telescopic part of the ATS in the pre-squeeze, or by reducing the crossing angle only once in collision
- The additional normalised separation (16σ) required for flat beam configurations can be partly recovered by compensating the tune shift
  - Detailed study required to fully assess the potential, including PACMAN bunches
- First experiments with noise on colliding beams seem to support the conservative approach chosen to define crab cavity noise tolerance

BACKUP

β-beating due to beam-beam interactions



See T. Pieloni@HB2016



- Head-on interactions with a large beam-beam parameters (~0.03) may result in β-beating larger than achieved with regular optics corrections and beyond tolerances :
  - → Dynamic change of β* (Luminosity imbalance)
  - → Impact on collimation (cleaning and protection)
  - → Impact on beam instrumentation (e.g. beam profile monitors)
- Amplitude dependent detuning and β-beating
  - → Is an optimised correction needed ?
  - → Is an adjustment of the phase advances needed to minimise the impact on critical parameters (i.e. β*, β at the collimators, etc.) ?