Fifth Joint Hi-Lumi LHC LARP Meeting (WP2)

Beam-beam effects and stability of the beams during operational cycle

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Acknowledgements: E. Metral, G. Arduini, W. Herr, R. De Maria, N. Biancacci, L. Carver
Y. Alexahin, Y. Papaphilippou, A. Valishev

Contents

- Introduction to Landau damping and stability diagrams
- Stability diagram during the HL-LHC operational cycle before collisions
- Compensation of stability diagram reduction at small β*
- Stability diagram during the collapse:
  - Crab-crossing OFF
  - Crab-crossing ON
- Stability diagram in stable beams during β* leveling
- Conclusions

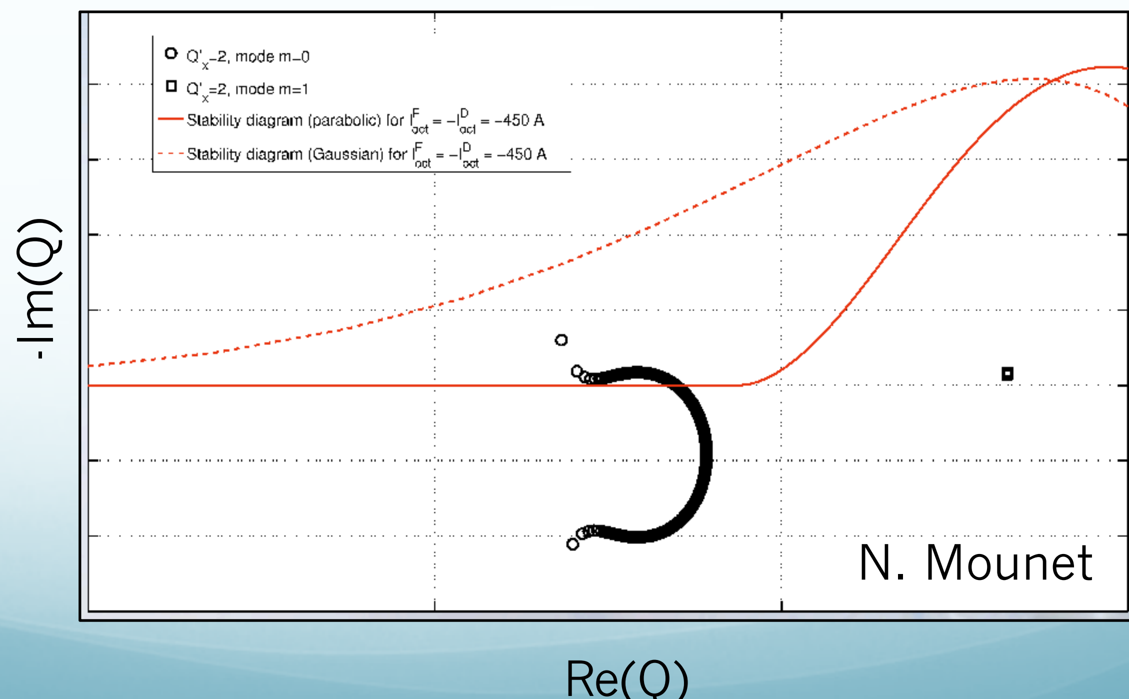
Stability Diagrams

Landau octupoles used to provide necessary tune spread to stabilize coherent modes from Impedence

Any non linearity (i.e. bb) creates other sources of tune spread

To be stable coherent modes must lie inside the stability diagrams area

"Landau Damping by non-linear space charge forces and Octupoles" (D.Mohl & H. Schonauer)

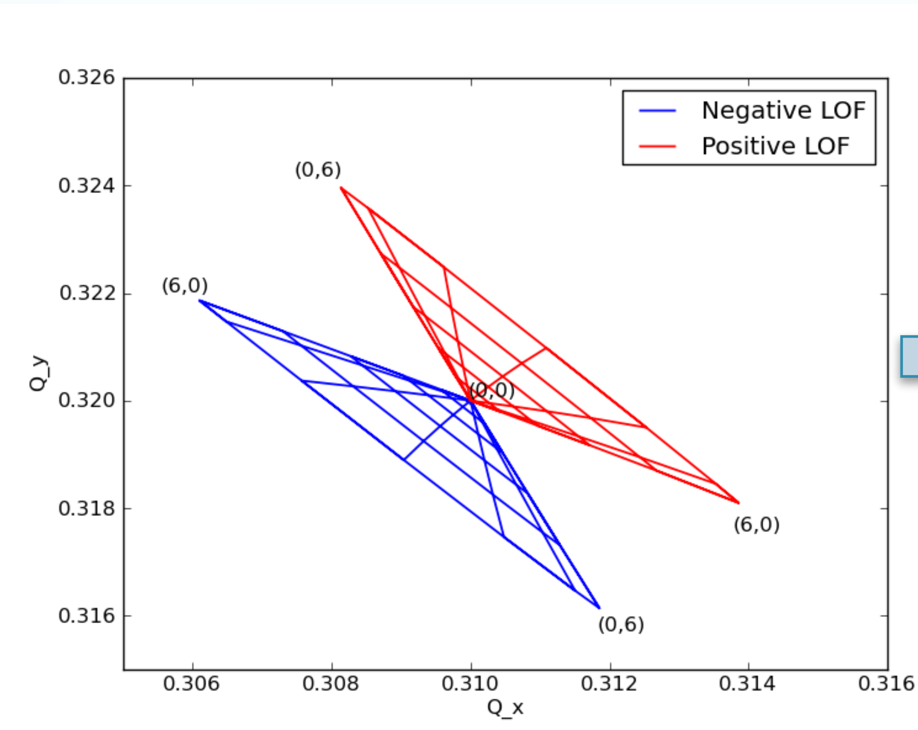


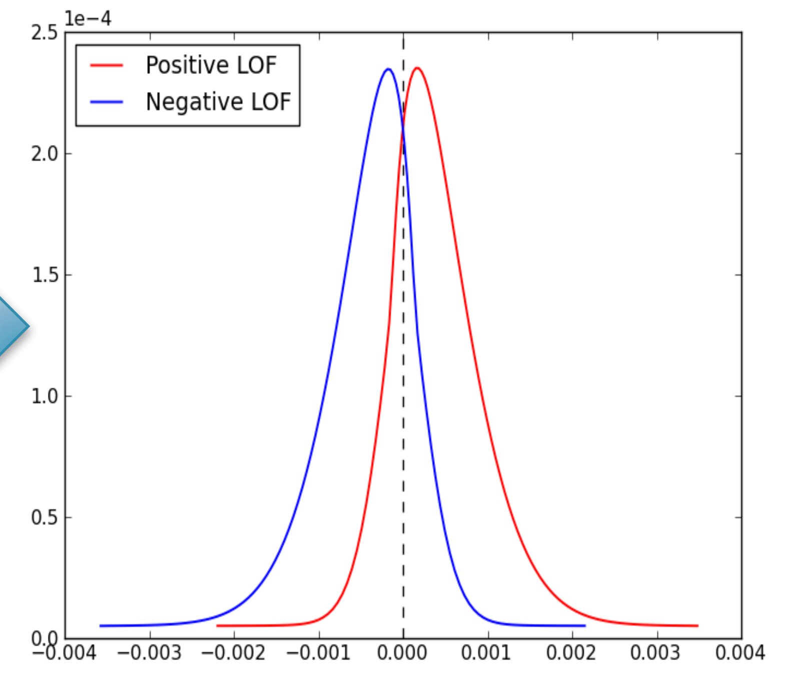
Landau Stability from spread

Dispersion Integral:

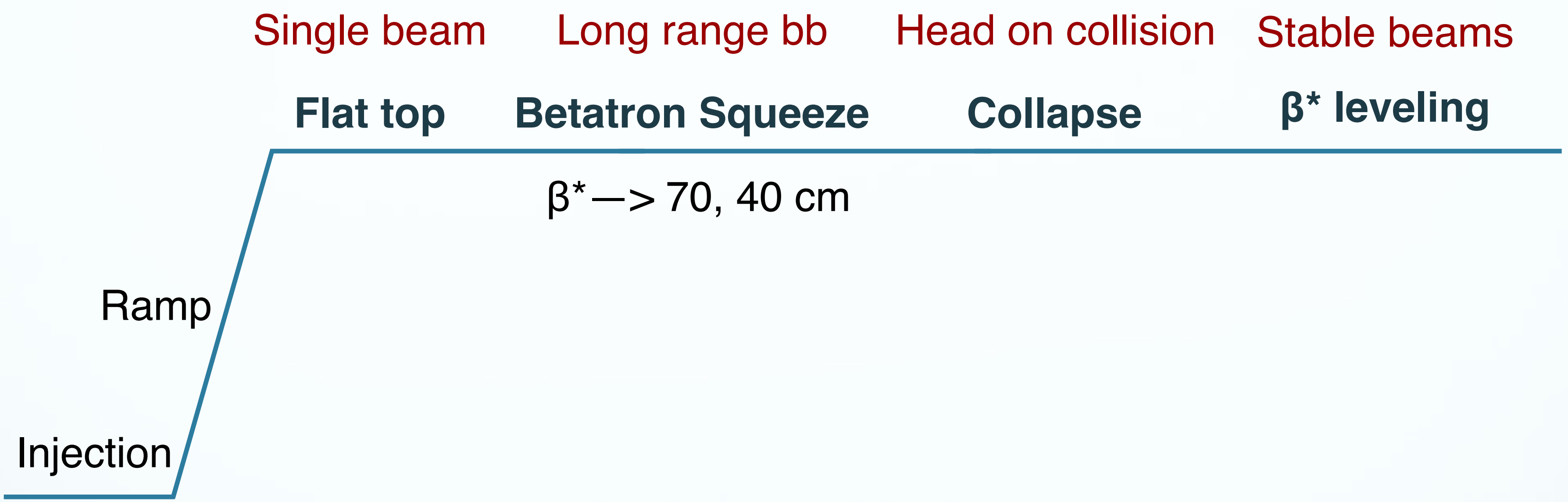
$$SD^{-1} = \frac{-1}{\Delta Q_{x,y}} = \int_0^\infty \int_0^\infty \frac{J_{x,y} \frac{d\Psi_{x,y}(J_x,J_y)}{dJ_{x,y}}}{Q_0 - q_{x,y}(J_x, J_y) - i\epsilon} dJ_x dJ_y$$

from Tracking (MAD-X)



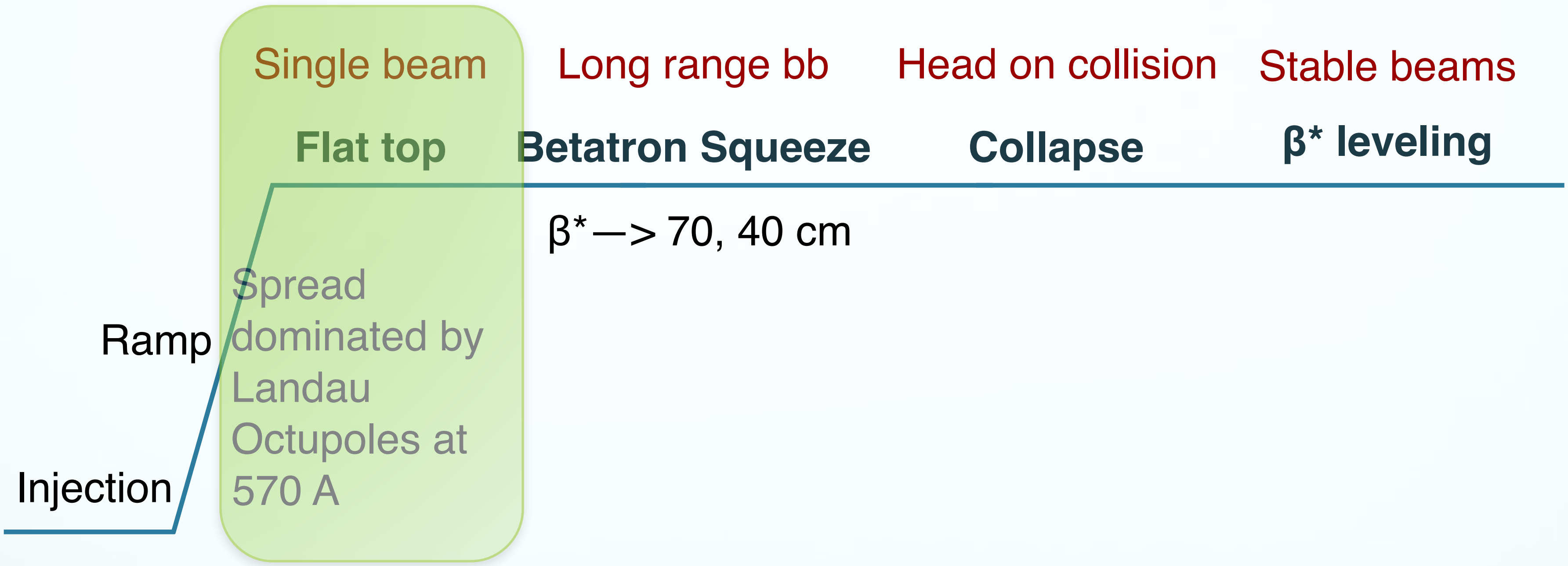


HL-LHC operational cycle

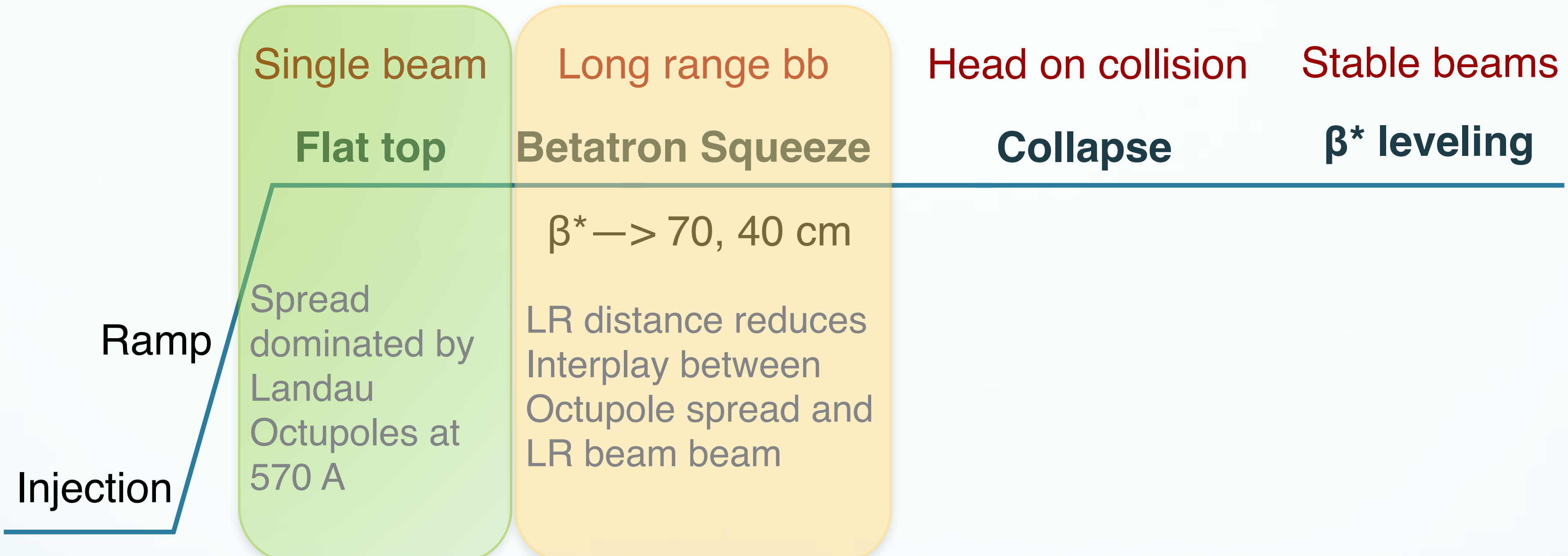


“HL-LHC Operational Scenarios” E. Metral *et al.*

HL-LHC operational cycle



HL-LHC operational cycle

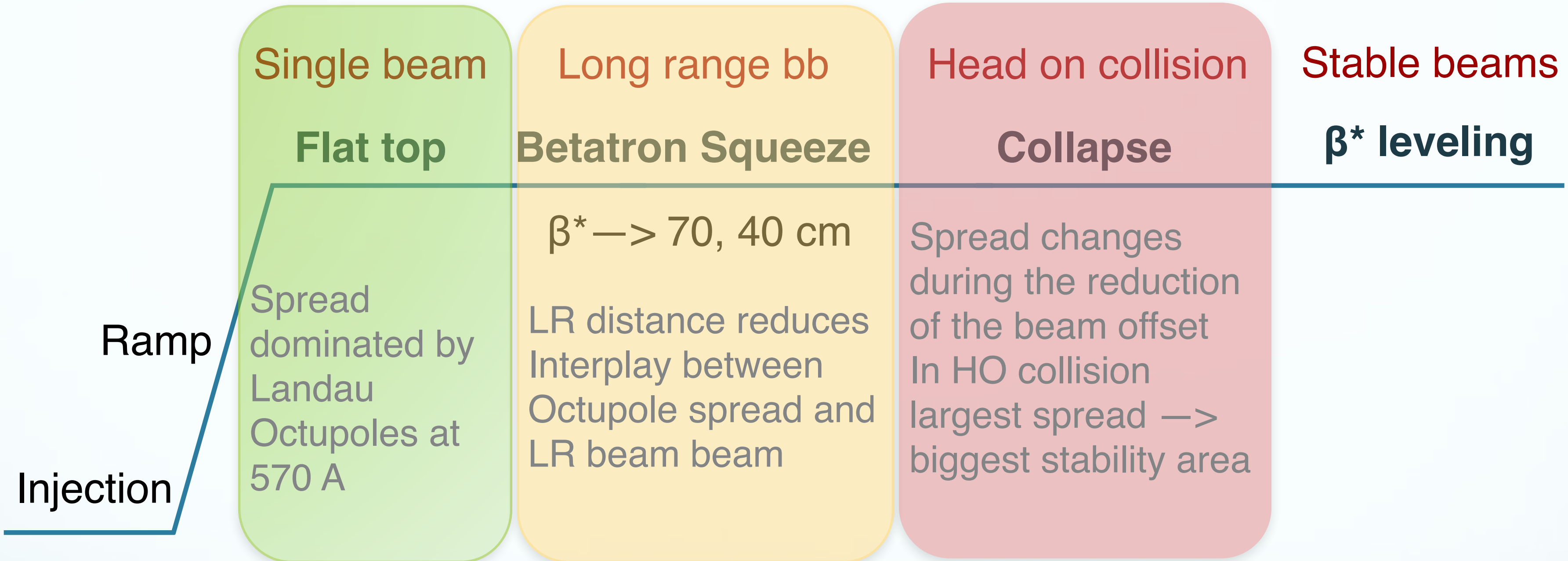


Scenario	Luminosity $cm^{-2}\ s^{-1}$	β^* at collision	LR separation σ
Baseline	*5 10^{34}*	*~70 cm*	*26*
Ultimate	*7.5 10^{34}*	*~40 cm*	*20*

I=2.2e11 pb ε=2.5 μm

β^* leveling

HL-LHC operational cycle



Scenario	Luminosity $cm^{-2}\ s^{-1}$	β* at collision	LR separation σ
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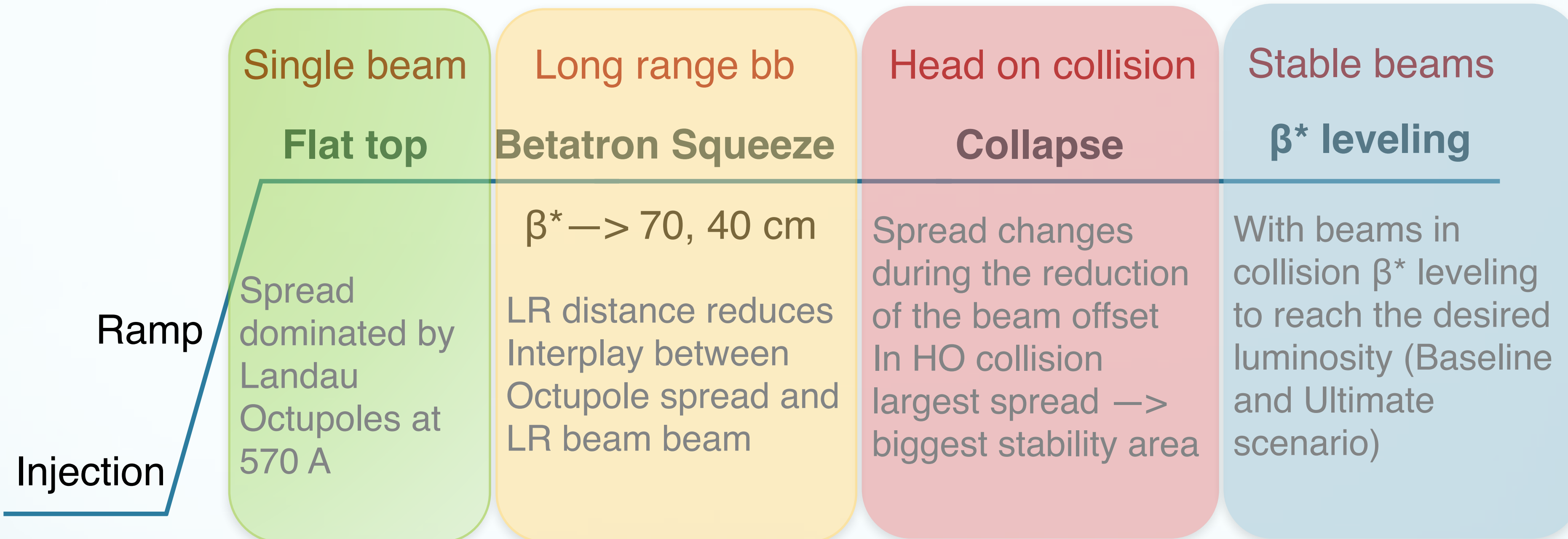
I=2.2e11 pb ε=2.5 μm

β* leveling

HL-LHC operational cycle



Scenario	Luminosity $cm^{-2}\ s^{-1}$	β^* at collision	LR separation σ
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I=2.2e11 pb ε=2.5 μm

β* leveling

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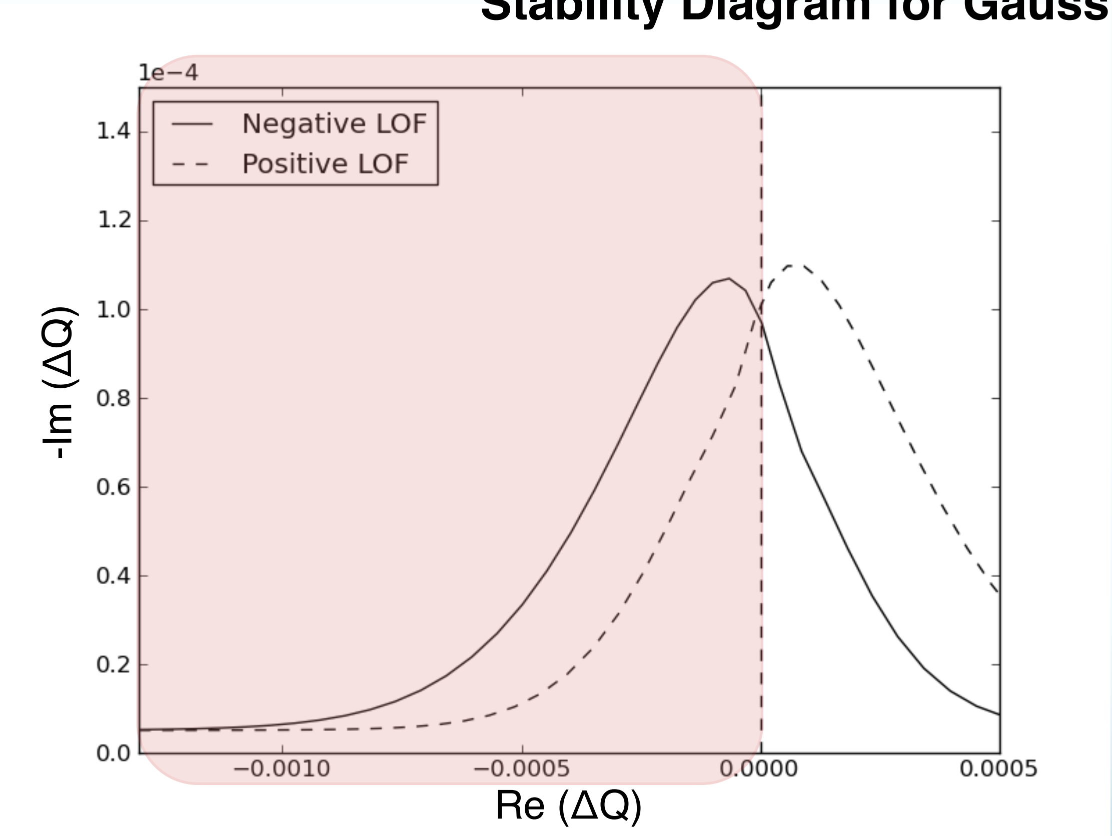
HL-LHC flat top

Octupoles only, single beam

I=2.2e11 ppb ε=2.5 μm ± 570A Oct current

Stability Diagram for Gaussian distribution



Negative polarity preferred for single beam

HL-LHC SD during the squeeze

Beam-beam separation at the 1st LR:

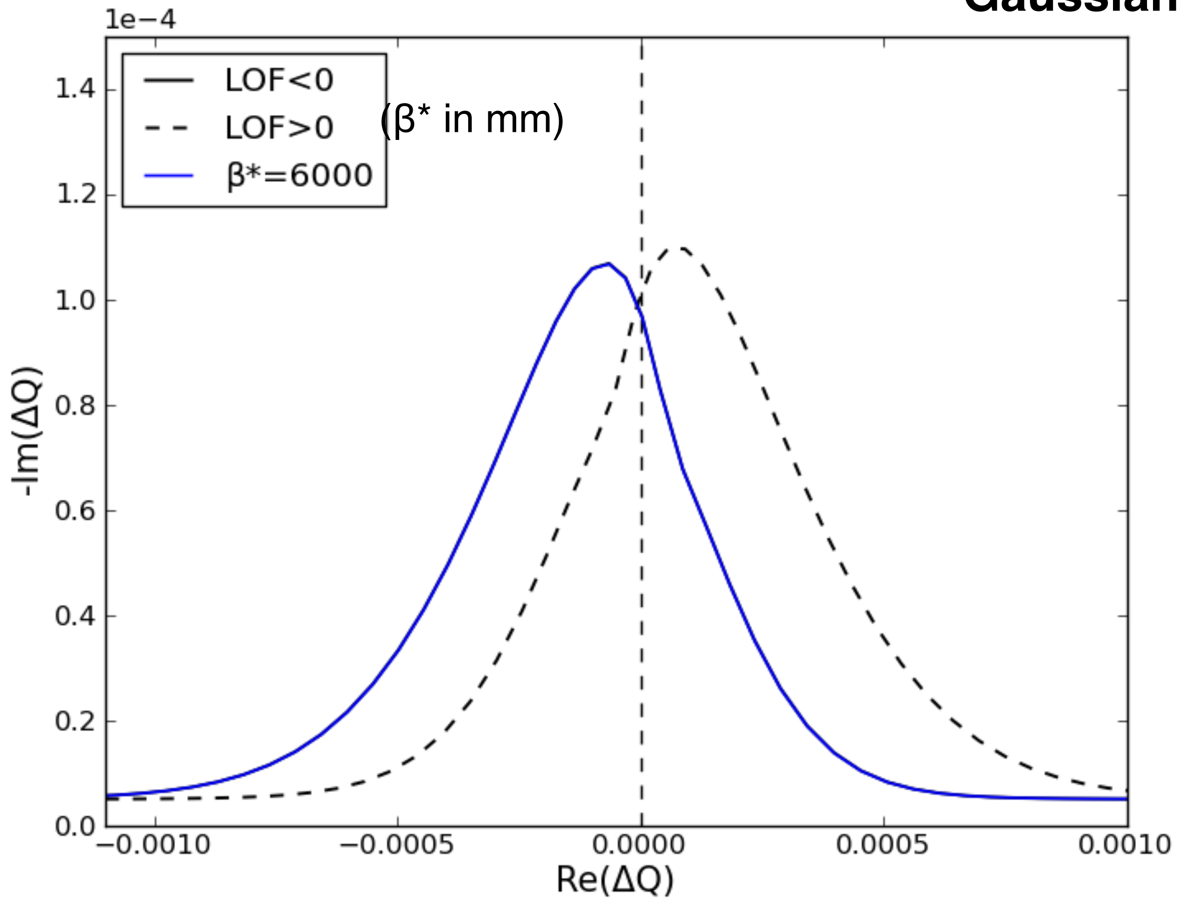
$$d_{sep} = \frac{\sqrt{\beta*} \cdot \sqrt{\gamma}}{\sqrt{\epsilon_n}} \cdot \alpha$$

I=2.2e11 ppb ε=2.5 μm -570A Oct current

Gaussian distribution

d=50.6 σ

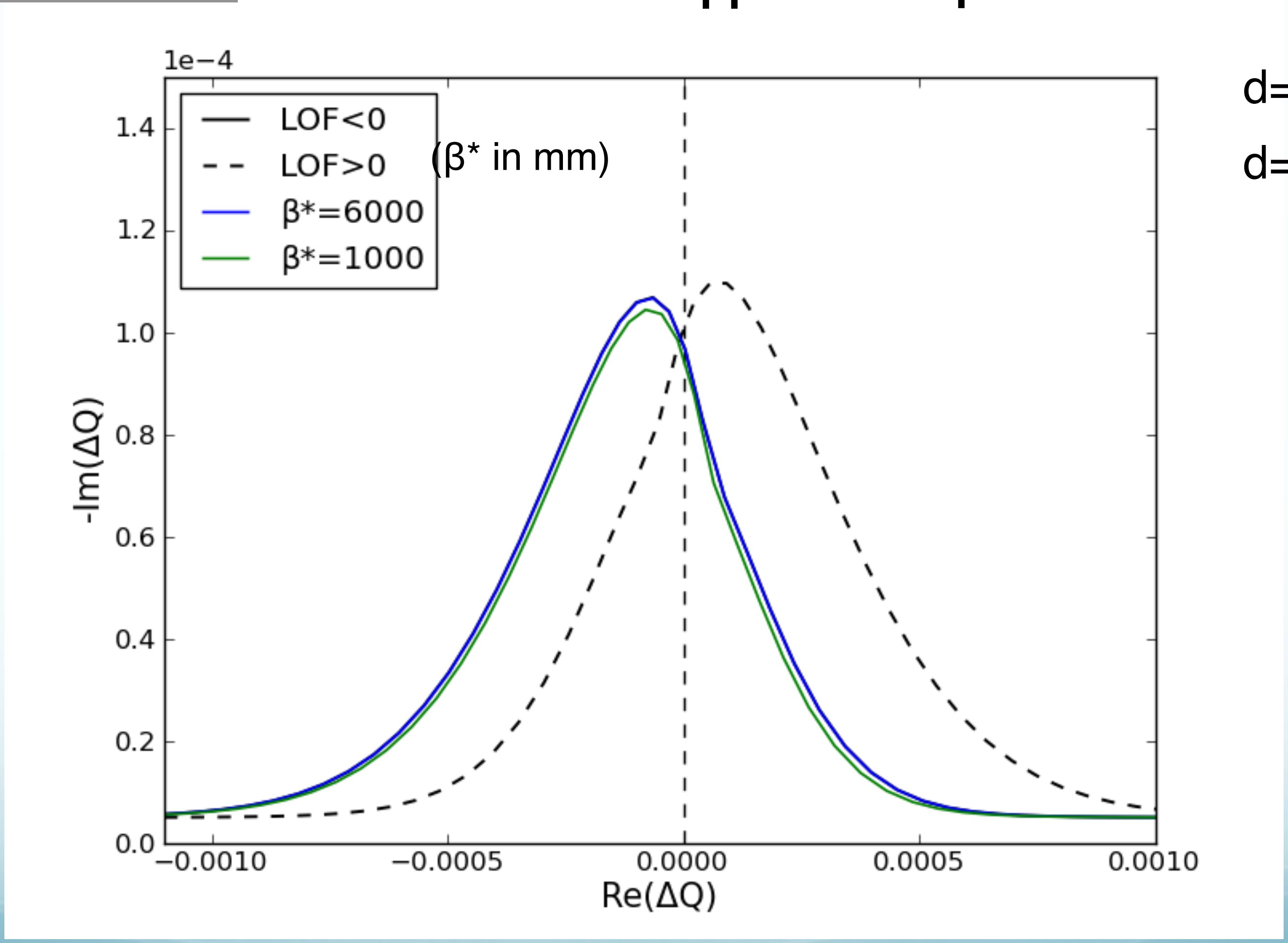
(β* in mm)



HL-LHC SD during the squeeze

$$d_{sep} = \frac{\sqrt{\beta *} \cdot \sqrt{\gamma}}{\sqrt{\epsilon_n}} \cdot \alpha$$

I=2.2e11 ppb ε=2.5 μm -570A Oct current



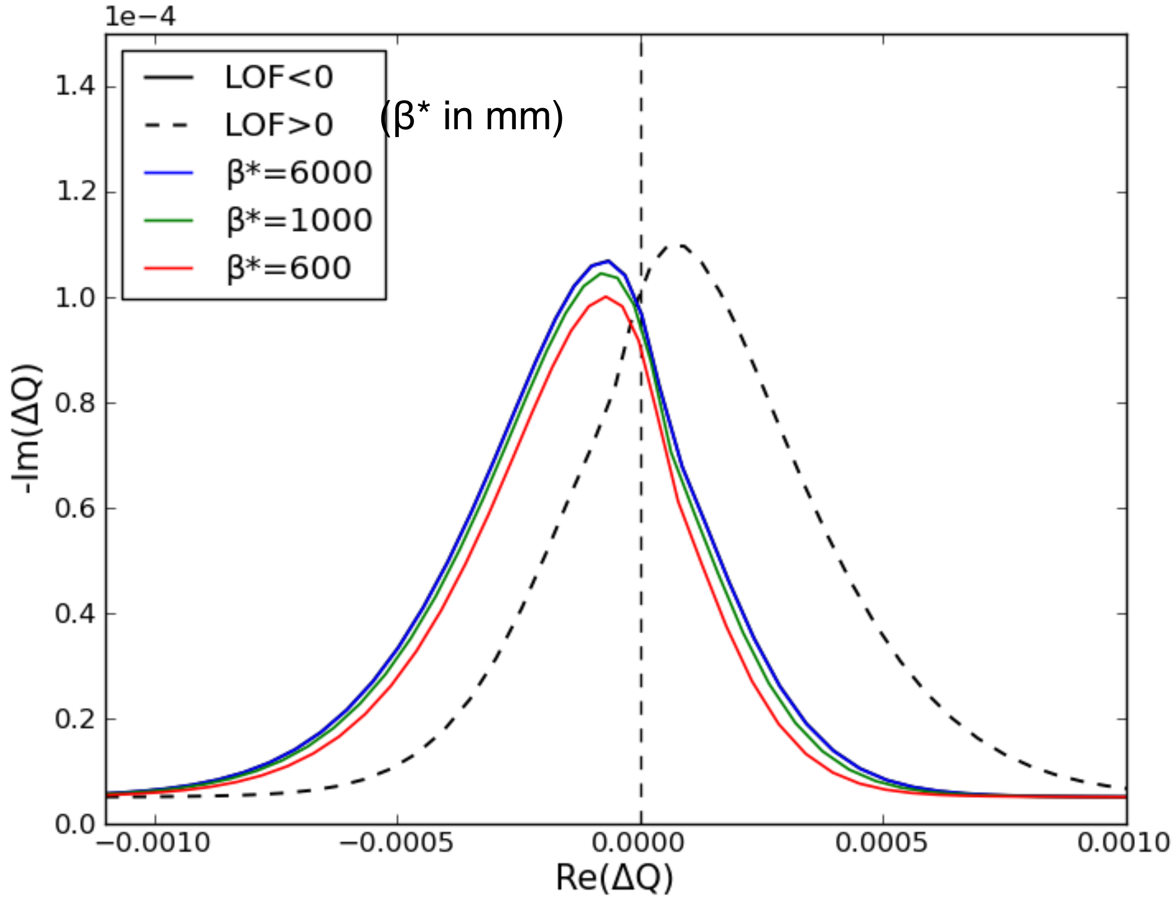
d=50.6 σ

d=37.7 σ

HL-LHC SD during the squeeze

$$d_{sep} = \frac{\sqrt{\beta*} \cdot \sqrt{\gamma}}{\sqrt{\epsilon_n}} \cdot \alpha$$

I=2.2e11 ppb   ε=2.5 µm   -570A Oct current



d=50.6 σ

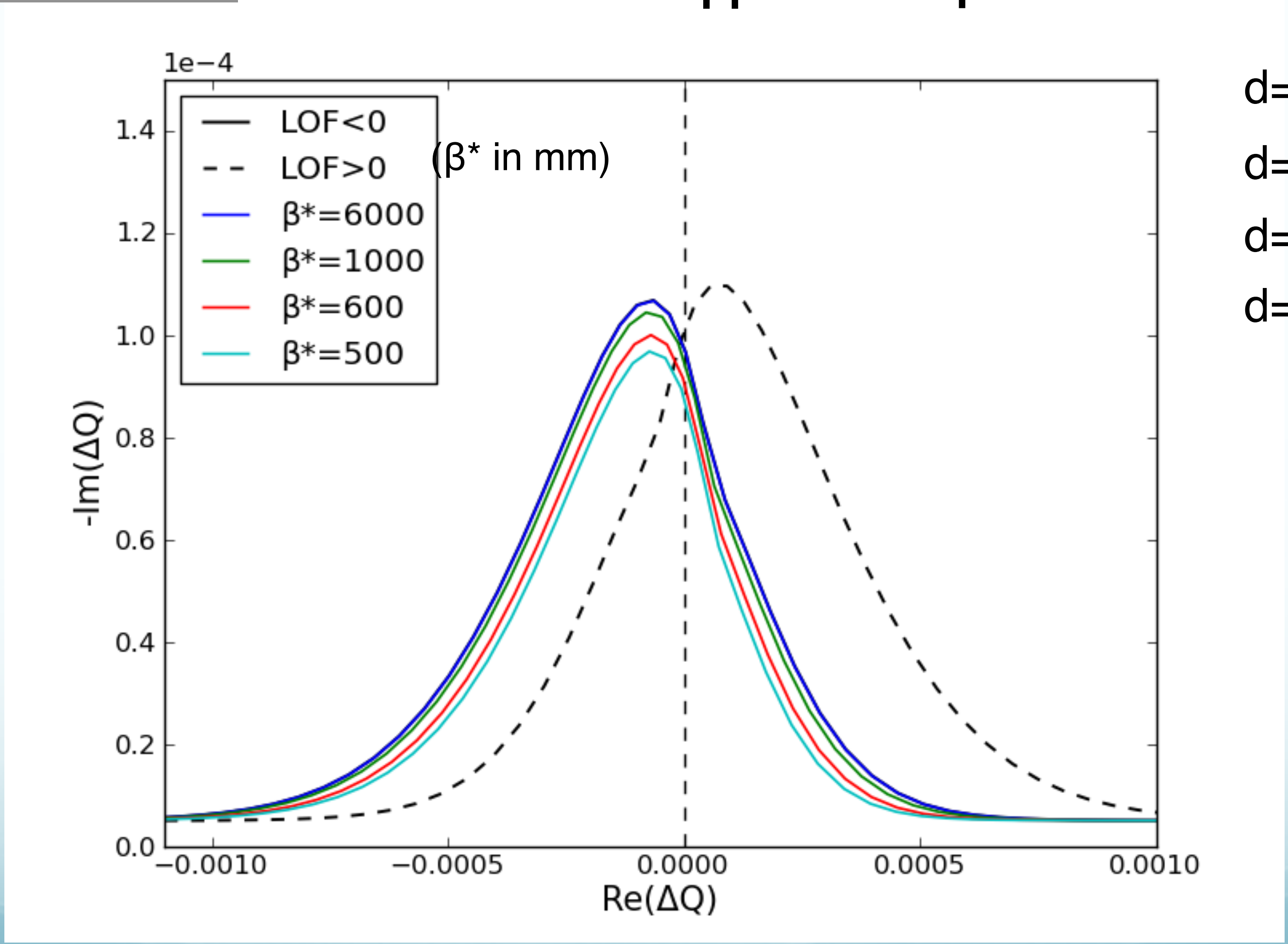
d=37.7 σ

d=29.9 σ

HL-LHC SD during the squeeze

$$d_{sep} = \frac{\sqrt{\beta^*} \cdot \sqrt{\gamma}}{\sqrt{\epsilon_n}} \cdot \alpha$$

I=2.2e11 ppb ε=2.5 μm -570A Oct current



d=50.6 σ

d=37.7 σ

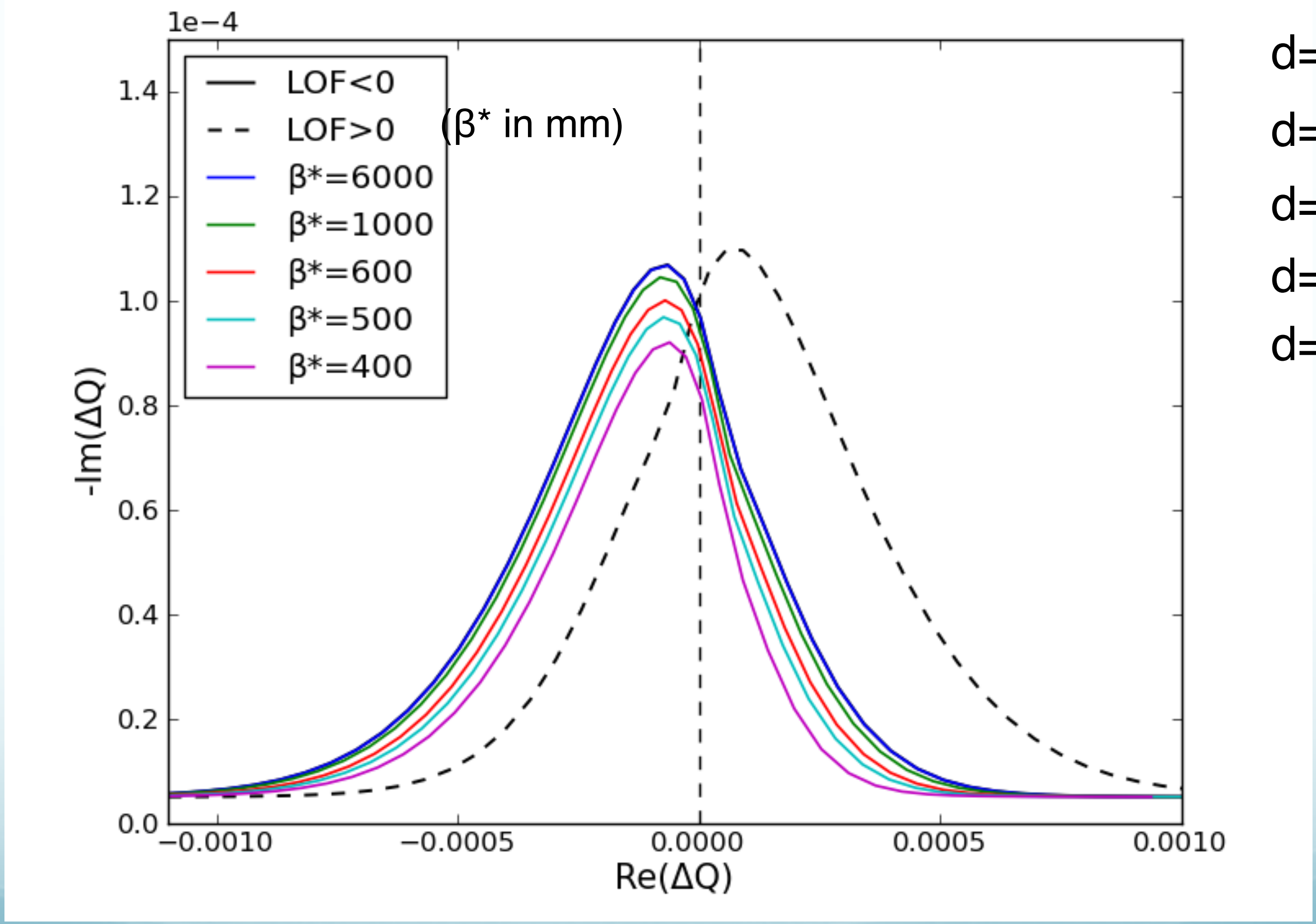
d=29.9 σ

d=27.4 σ

HL-LHC SD during the squeeze

$$d_{sep} = \frac{\sqrt{\beta^*} \cdot \sqrt{\gamma}}{\sqrt{\epsilon_n}} \cdot \alpha$$

I=2.2e11 ppb   ε=2.5 μm   -570A Oct current



d=50.6 σ

d=37.7 σ

d=29.9 σ

d=27.4 σ

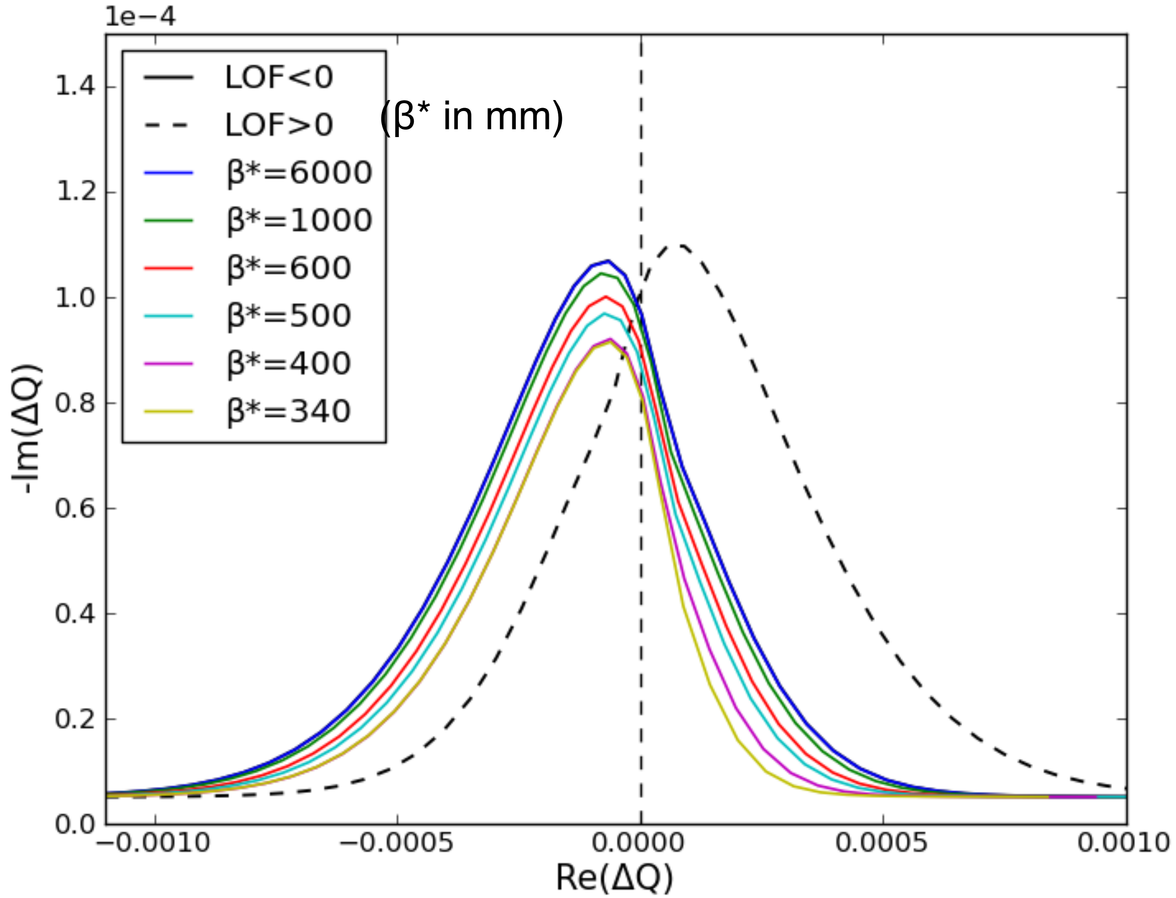
d=24.6 σ

Reduction at β*=40 cm

HL-LHC SD during the squeeze

$$d_{sep} = \frac{\sqrt{\beta*} \cdot \sqrt{\gamma}}{\sqrt{\epsilon_n}} \cdot \alpha$$

I=2.2e11 ppb   ε=2.5 μm   -570A Oct current



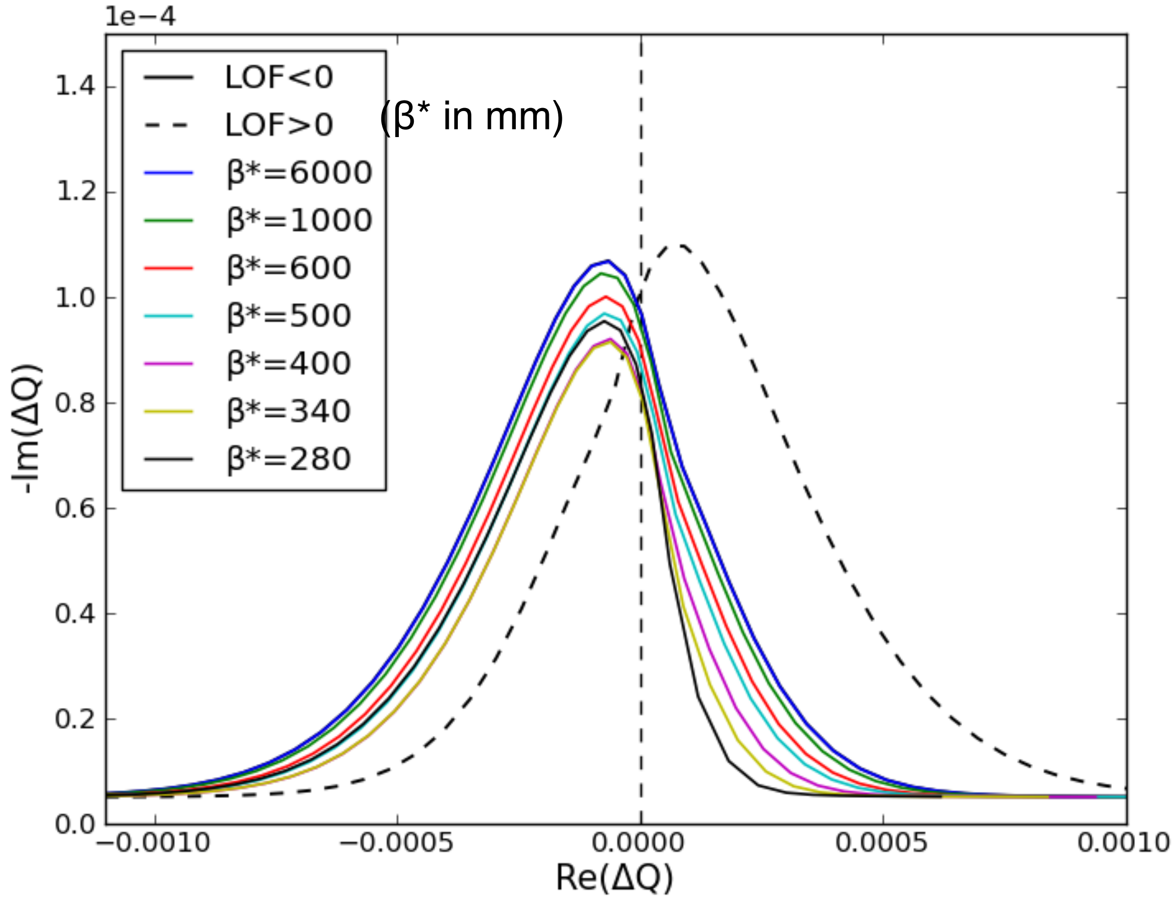
d=50.6 σ
d=37.7 σ
d=29.9 σ
d=27.4 σ
d=24.6 σ
d=22.7 σ

After β*=40 cm, ATS optics more effective leading to an SD increase (larger beta at the octupoles in the arcs)

HL-LHC SD during the squeeze

$$d_{sep} = \frac{\sqrt{\beta^*} \cdot \sqrt{\gamma}}{\sqrt{\epsilon_n}} \cdot \alpha$$

I=2.2e11 ppb   ε=2.5 μm   -570A Oct current

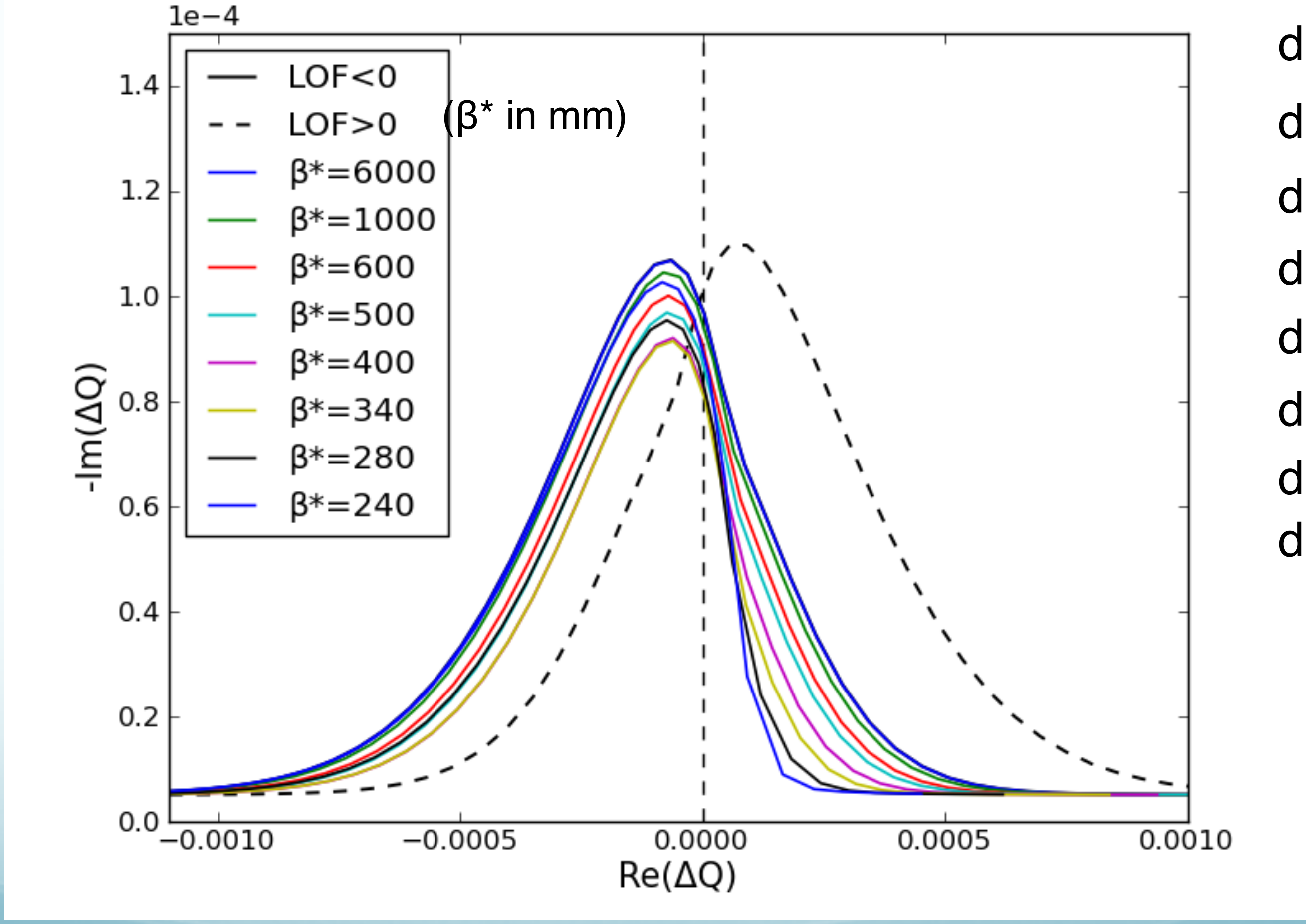


d=50.6 σ
d=37.7 σ
d=29.9 σ
d=27.4 σ
d=24.6 σ
d=22.7 σ
d=20.7 σ

HL-LHC SD during the squeeze

$$d_{sep} = \frac{\sqrt{\beta^*} \cdot \sqrt{\gamma}}{\sqrt{\epsilon_n}} \cdot \alpha$$

I=2.2e11 ppb   ε=2.5 μm   -570A Oct current

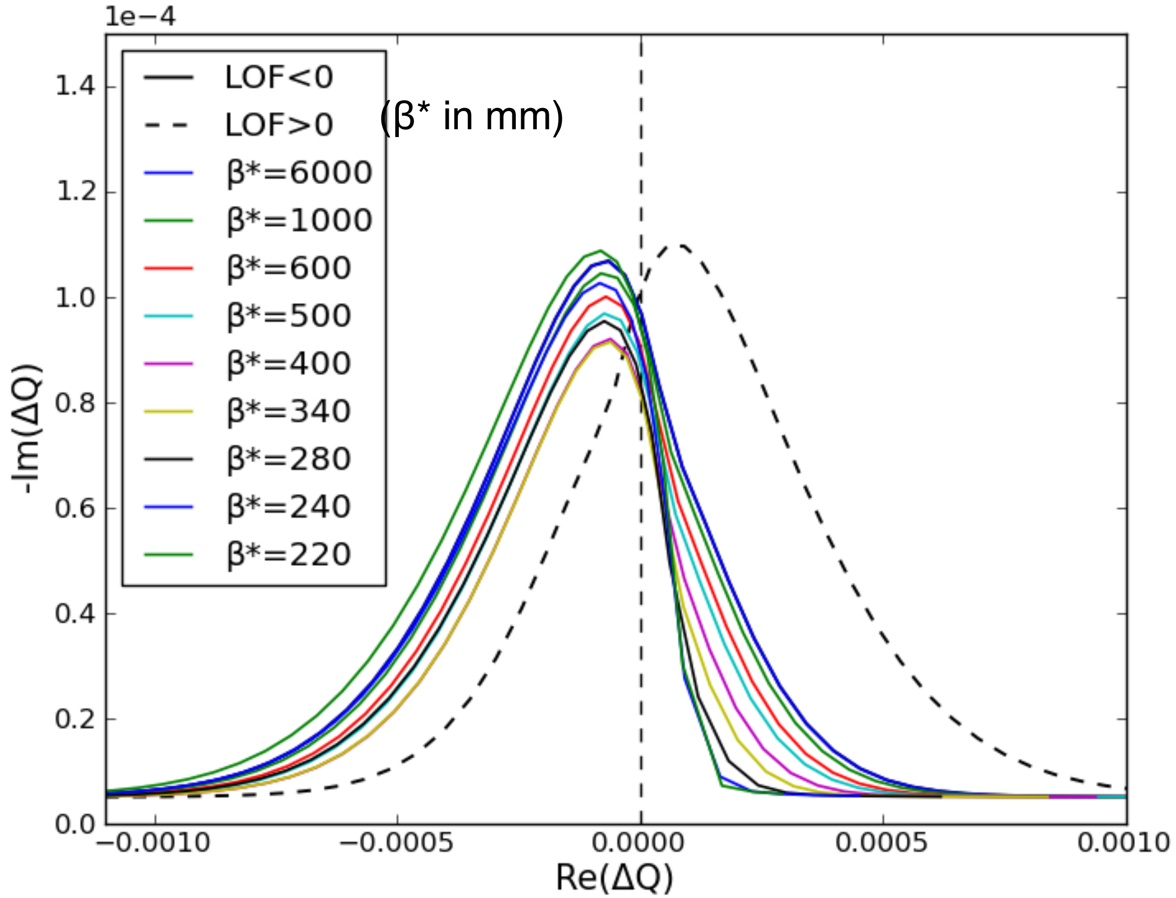


d=50.6 σ
d=37.7 σ
d=29.9 σ
d=27.4 σ
d=24.6 σ
d=22.7 σ
d=20.7 σ
d=19.2 σ

HL-LHC SD during the squeeze

$$d_{sep} = \frac{\sqrt{\beta^*} \cdot \sqrt{\gamma}}{\sqrt{\epsilon_n}} \cdot \alpha$$

I=2.2e11 ppb   ε=2.5 μm   -570A Oct current

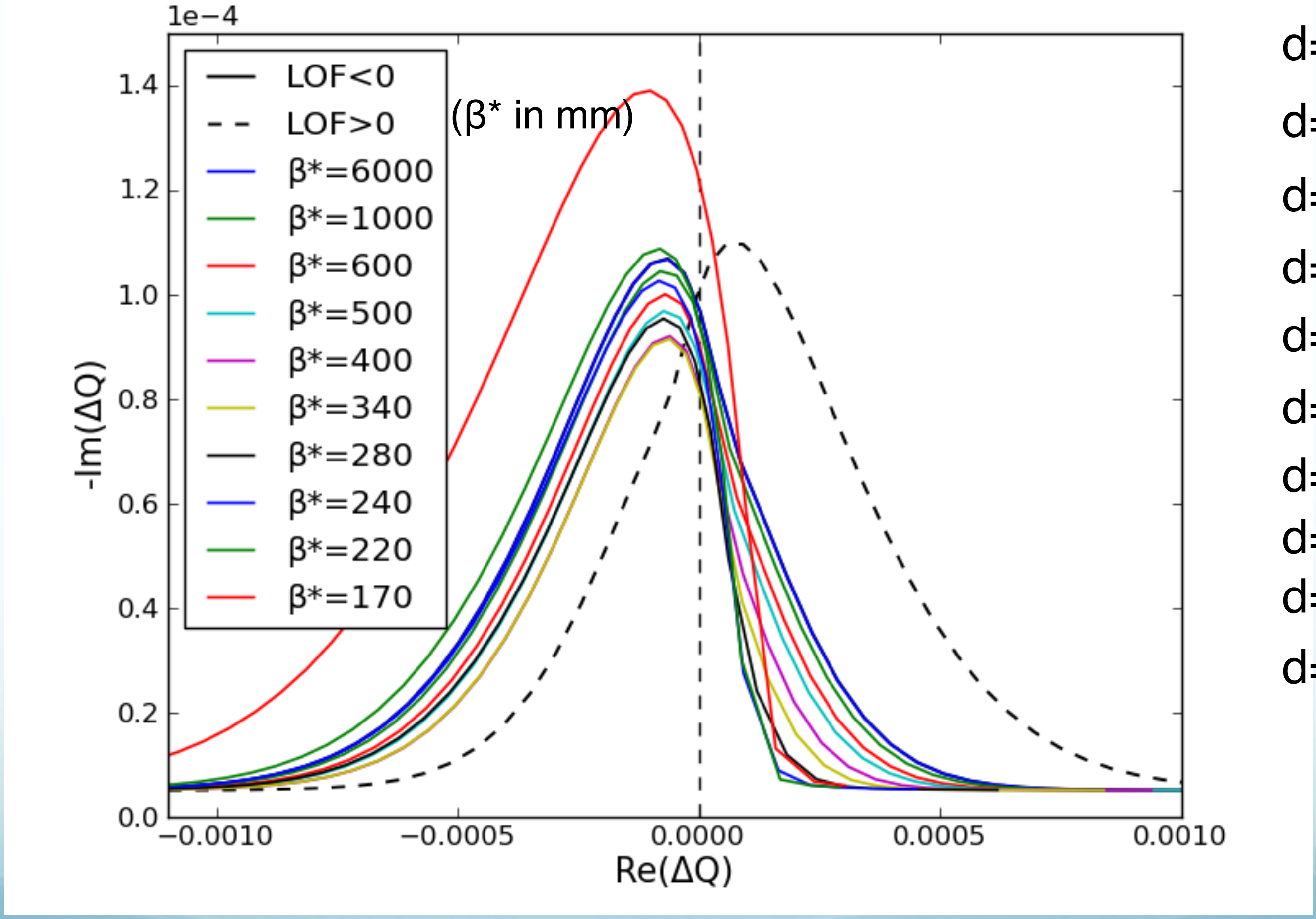


d=50.6 σ
d=37.7 σ
d=29.9 σ
d=27.4 σ
d=24.6 σ
d=22.7 σ
d=20.7 σ
d=19.2 σ
d=18.4 σ

HL-LHC SD during the squeeze

$$d_{sep} = \frac{\sqrt{\beta*} \cdot \sqrt{\gamma}}{\sqrt{\epsilon_n}} \cdot \alpha$$

I=2.2e11 ppb ε=2.5 μm -570A Oct current



d=50.6 σ

d=37.7 σ

d=29.9 σ

d=27.4 σ

d=24.6 σ

d=22.7 σ

d=20.7 σ

d=19.2 σ

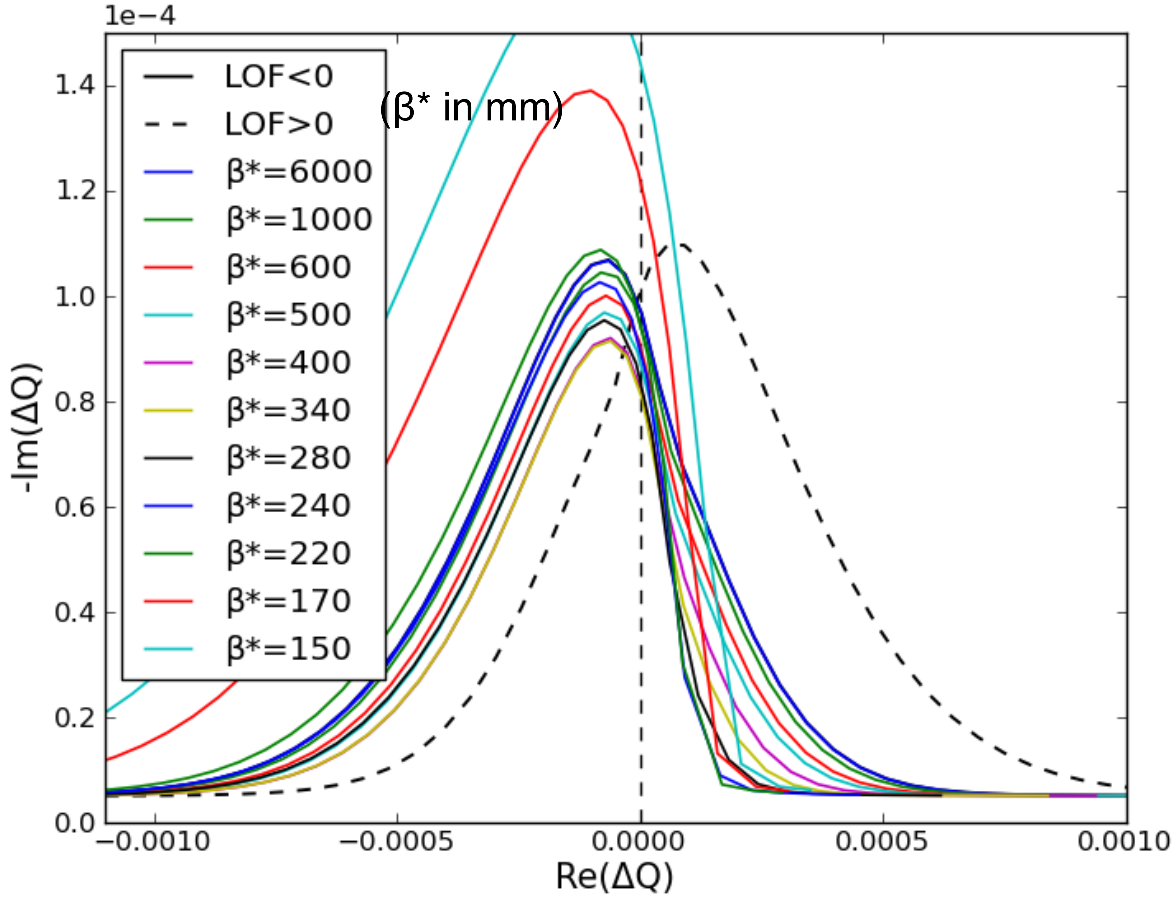
d=18.4 σ

d=16.2 σ

HL-LHC SD during the squeeze

$$d_{sep} = \frac{\sqrt{\beta^*} \cdot \sqrt{\gamma}}{\sqrt{\epsilon_n}} \cdot \alpha$$

I=2.2e11 ppb ε=2.5 μm -570A Oct current

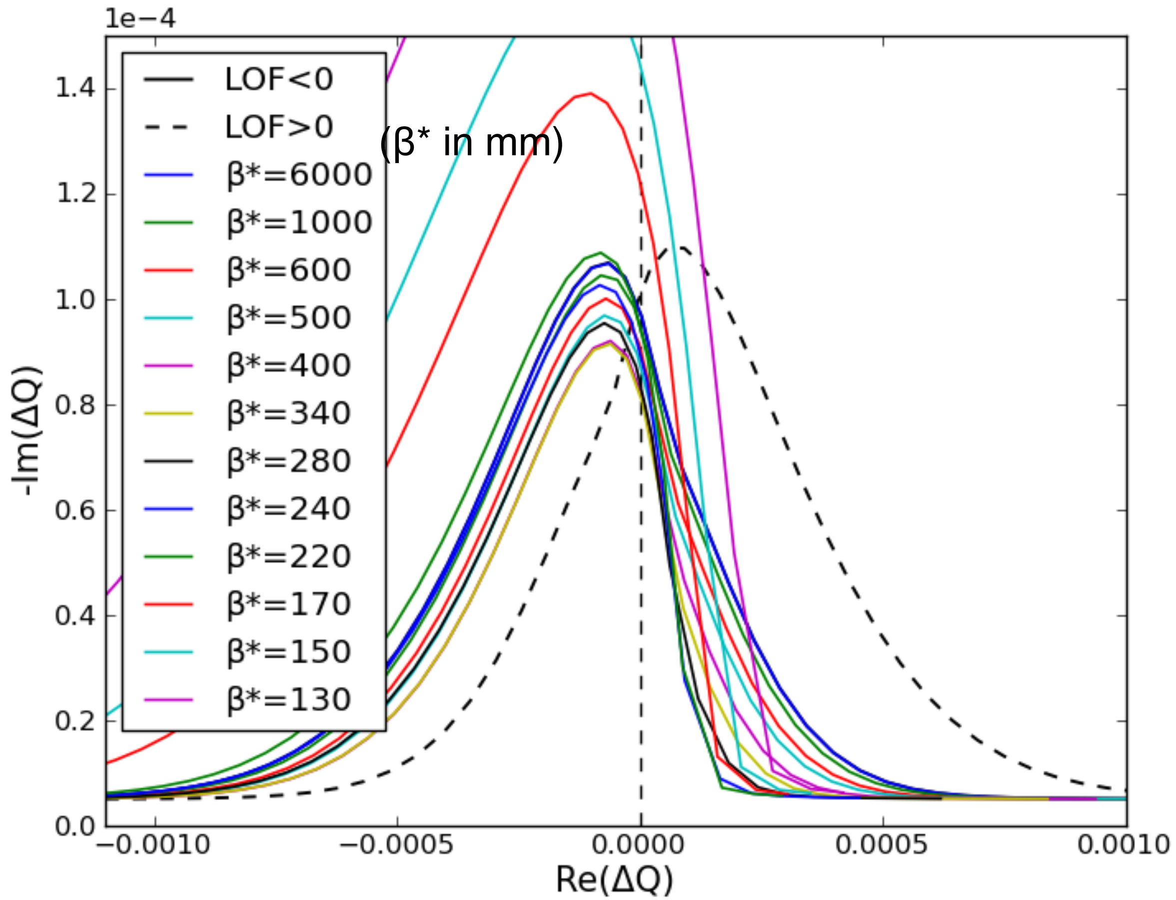


d=50.6 σ
d=37.7 σ
d=29.9 σ
d=27.4 σ
d=24.6 σ
d=22.7 σ
d=20.7 σ
d=19.2 σ
d=18.4 σ
d=16.2 σ
d=15.2 σ

HL-LHC SD during the squeeze

$$d_{sep} = \frac{\sqrt{\beta^*} \cdot \sqrt{\gamma}}{\sqrt{\epsilon_n}} \cdot \alpha$$

I=2.2e11 ppb ε=2.5 μm -570A Oct current



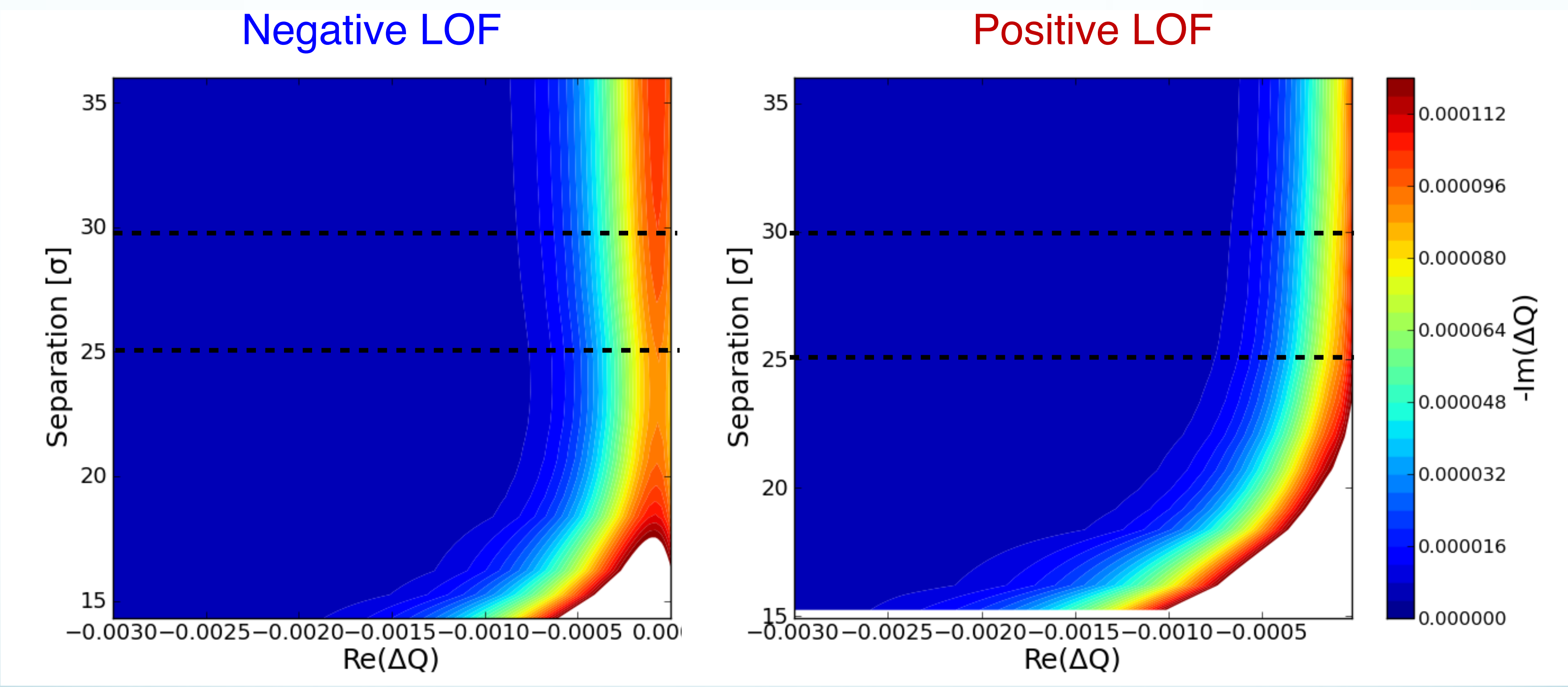
d=50.6 σ
d=37.7 σ
d=29.9 σ
d=27.4 σ
d=24.6 σ
d=22.7 σ
d=20.7 σ
d=19.2 σ
d=18.4 σ
d=16.2 σ
d=15.2 σ
d=14.2 σ

SD BB+Oct Negative LOF always larger than positive LOF case alone

HL-LHC betatron squeeze

Evolution of the **betatron squeeze**: **LR beam-beam in IP1 and IP5**

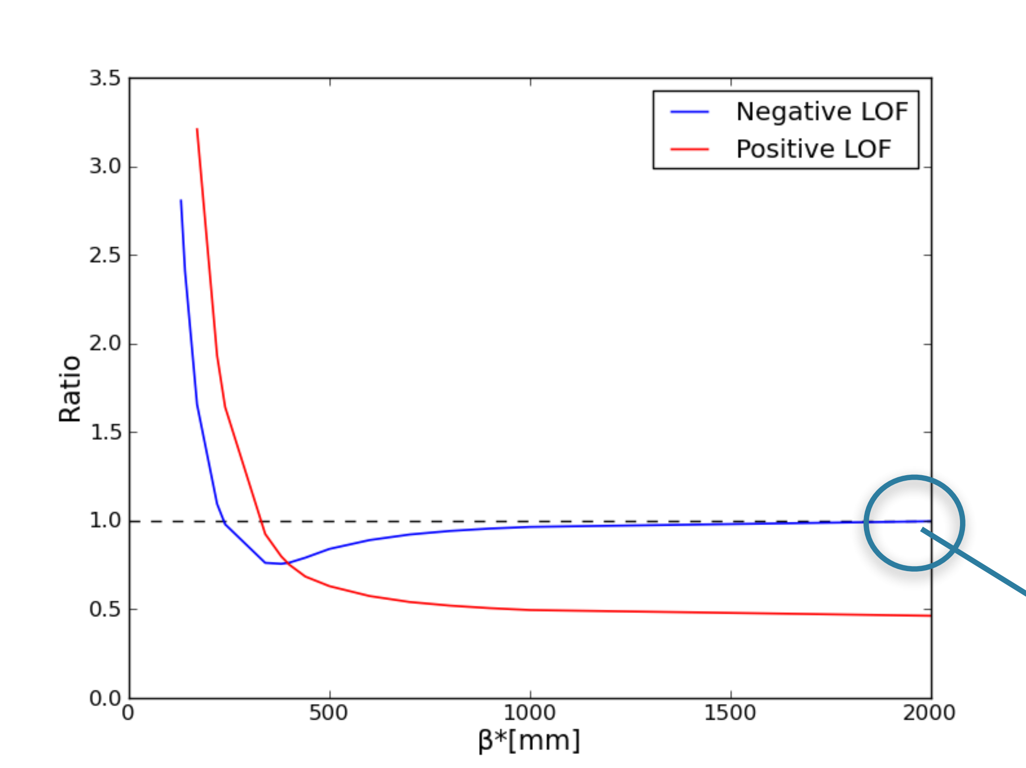
I=2.2e11 ppb ε=2.5 μm ± 570A Oct current



Operational scenario proposed with negative octupole polarity

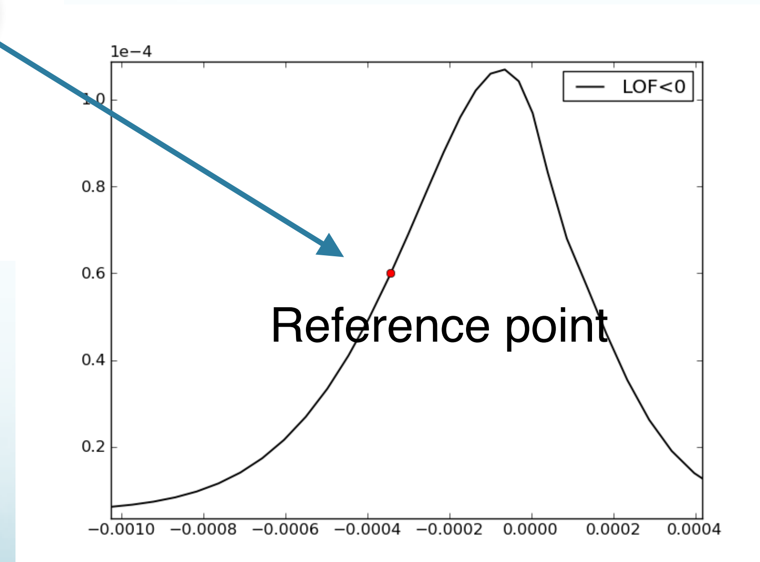
Also for Dynamic Aperture considerations: "Dynamic Aperture studies with Beam-beam Octupoles and Chromaticity effects" D. Banfi T. Pieloni

HL-LHC beta squeeze summary

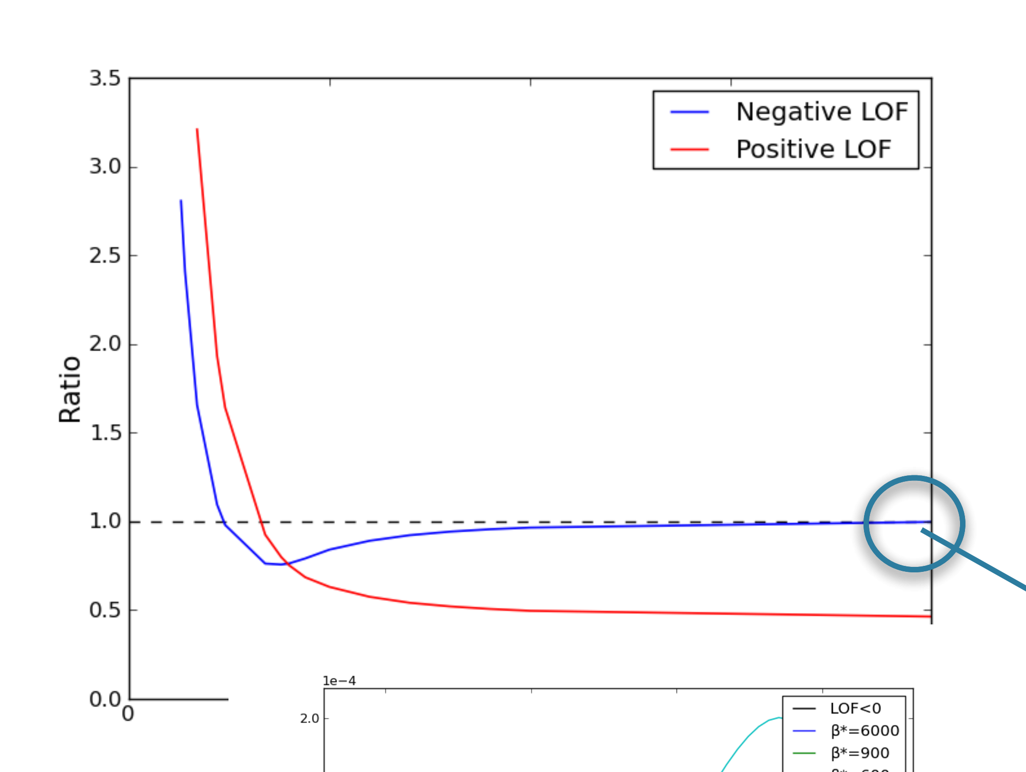


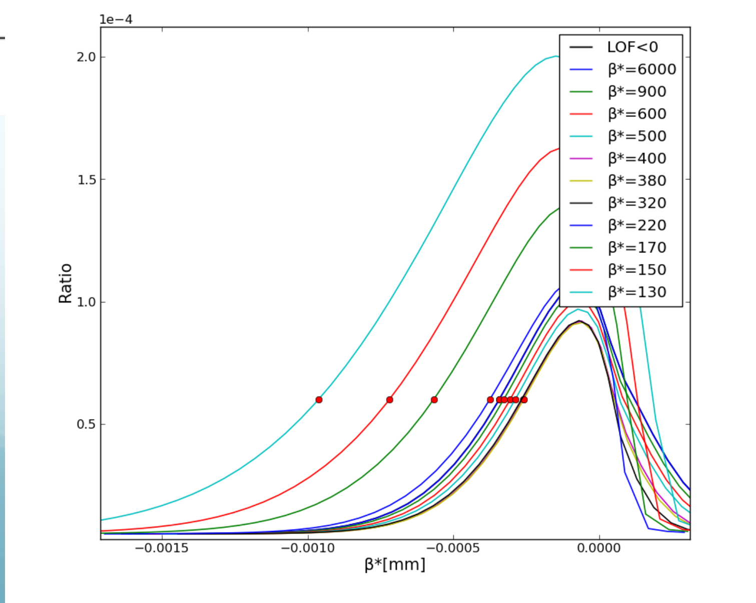
Negative polarity always preferred

Positive polarity gives larger SD from β* ~0.39m



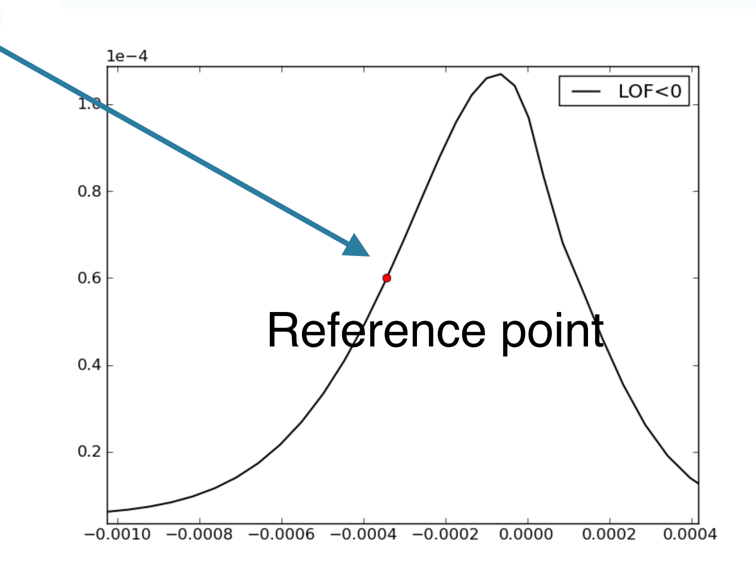
HL-LHC beta squeeze summary



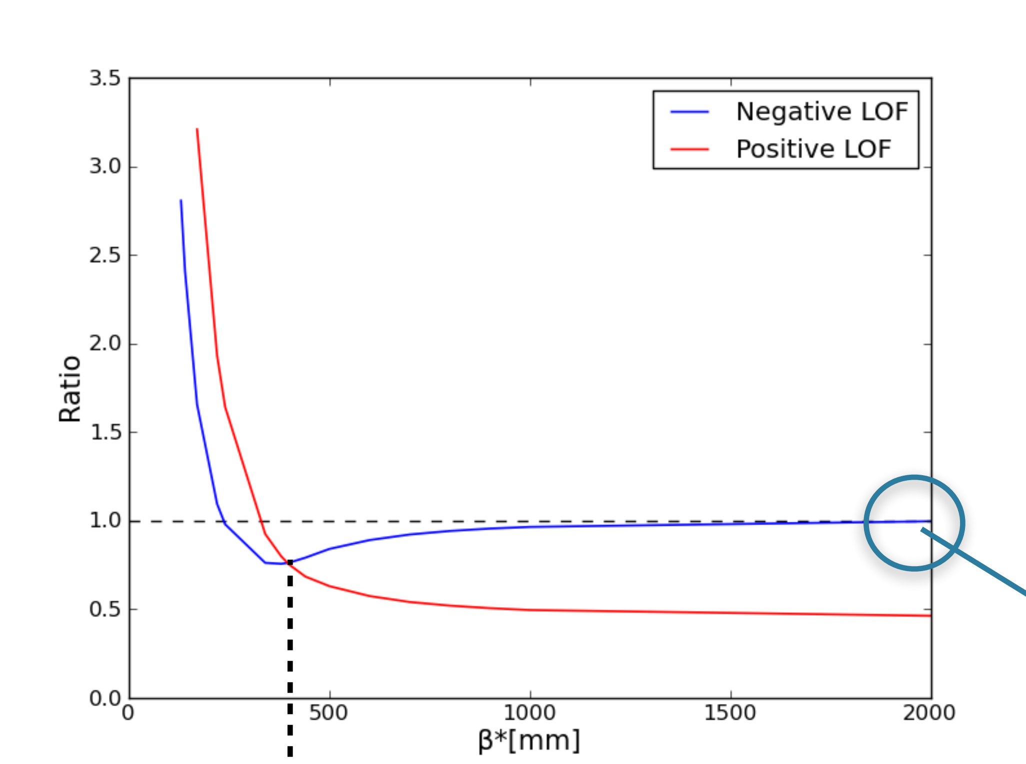


Negative polarity always preferred

Positive polarity gives larger SD from β* ~0.39m



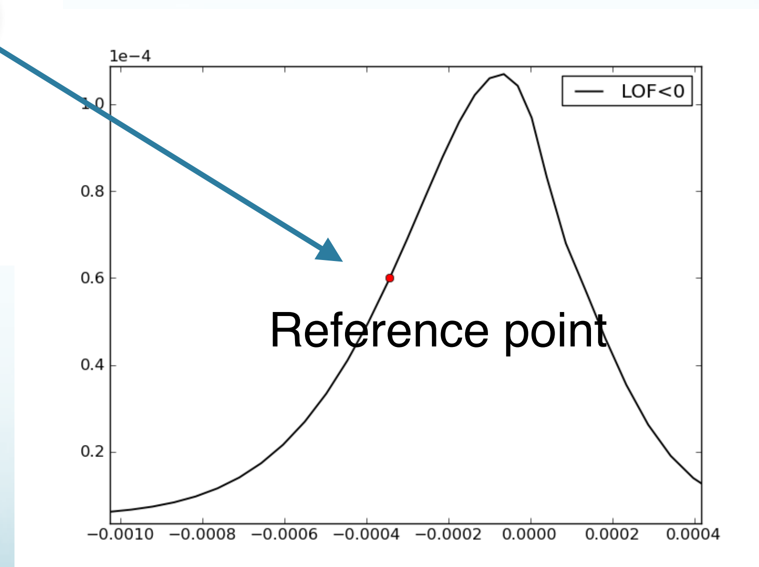
HL-LHC beta squeeze summary



β*≃0.39cm

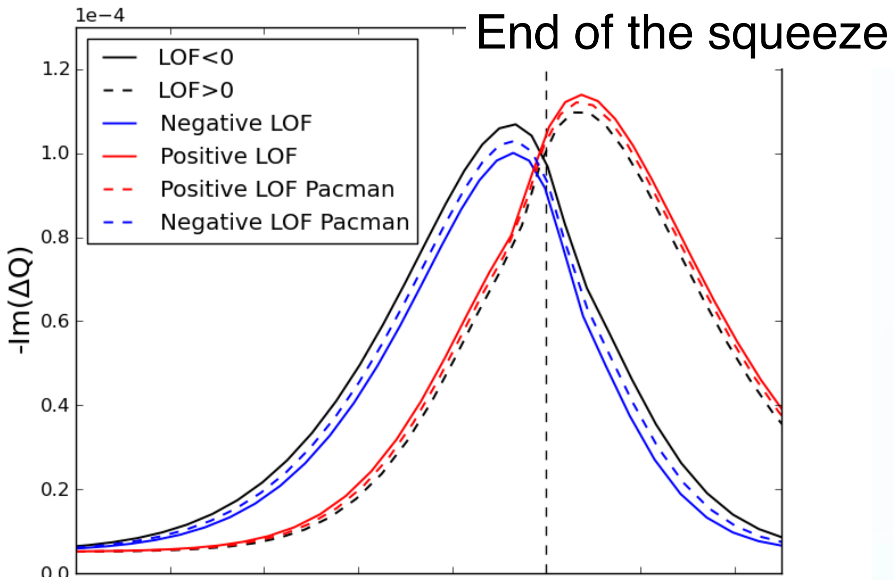
Negative polarity always preferred

Positive polarity gives larger SD from β* ~0.39m



Reference point

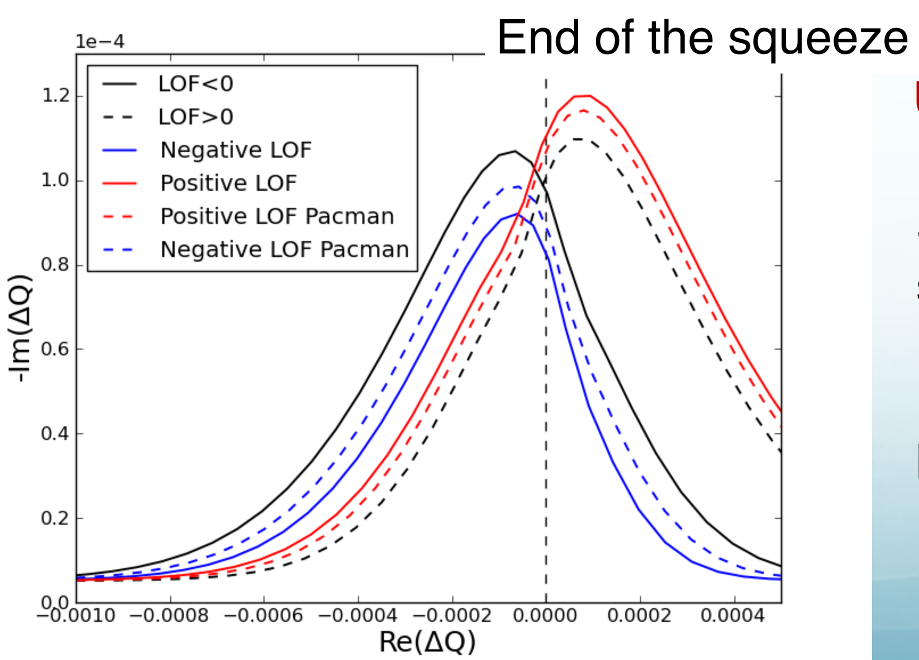
HL-LHC beta squeeze summary



Baseline scenario

Negative polarity is preferred for single beam

Negative polarity still preferred with beam-beam



Ultimate scenario

Same considerations as baseline scenario

PACMAN bunches similar behavior than nominal

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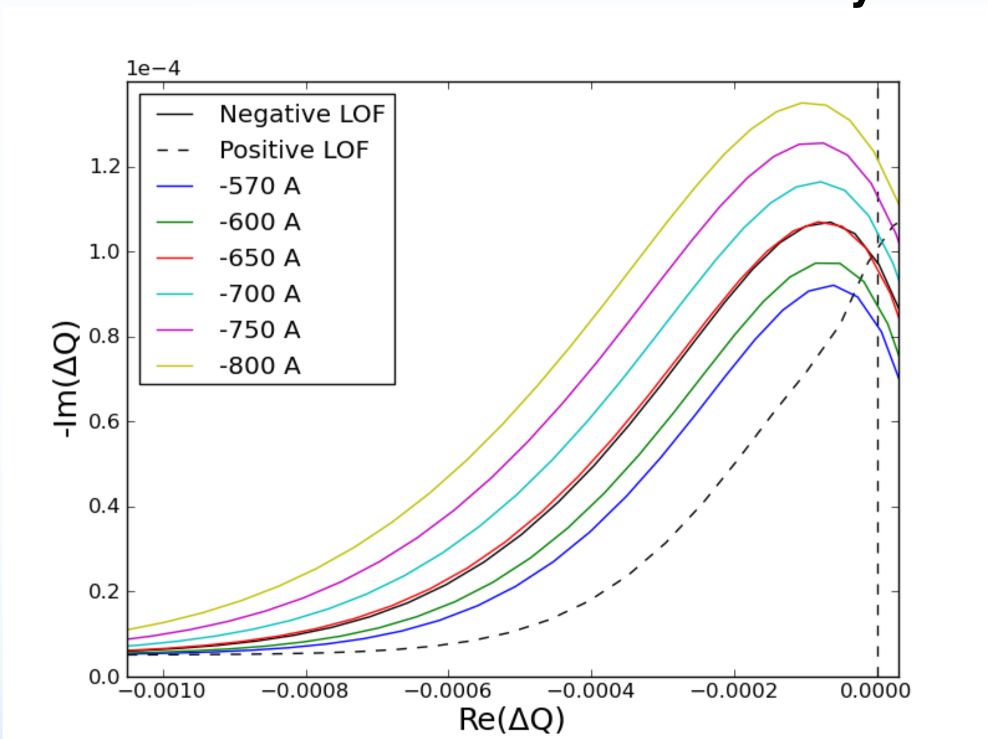
Compensation of the reduction at 40cm β*

Maximum reduction at β*=40 cm → apply telescopic ATS to compensate reduction by increasing the beta function in the arcs
We estimate the beta increment needed by an octupole current scan



Octupole current scan at β*=40 cm (with LR beam-beam)

For -650 A octupole current, the reduction at beta 40 cm is fully compensated

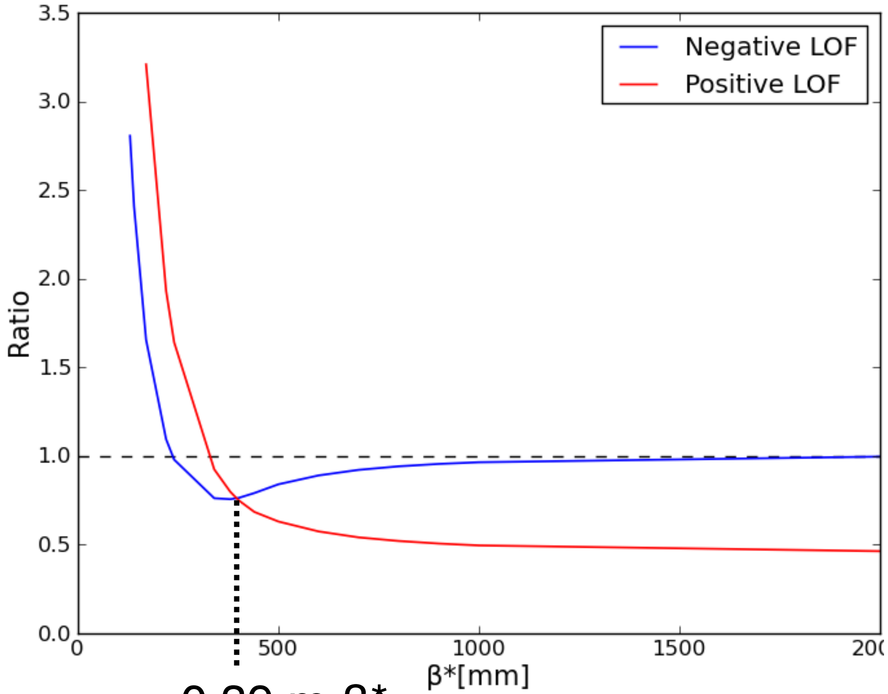
Landau Damping, Dynamic Aperture and Octupoles in LHC

J. Gareyte, J.P. Koutchouk and F. Ruggiero

$$\Delta Q_x = \left[\frac{3}{8\pi}\int \beta_x^2 \frac{O_3}{B\rho}\,ds\right] J_x - \left[\frac{3}{8\pi}\int 2\beta_x\beta_y \frac{O_3}{B\rho}\,ds\right] J_y,$$

$\Delta Q_{oct} \propto \beta(s)^2$ Compensation at -650 A Oct: 14% more octupole strength
→**equivalent to 8% larger betas in arcs**

HL-LHC beta squeeze summary

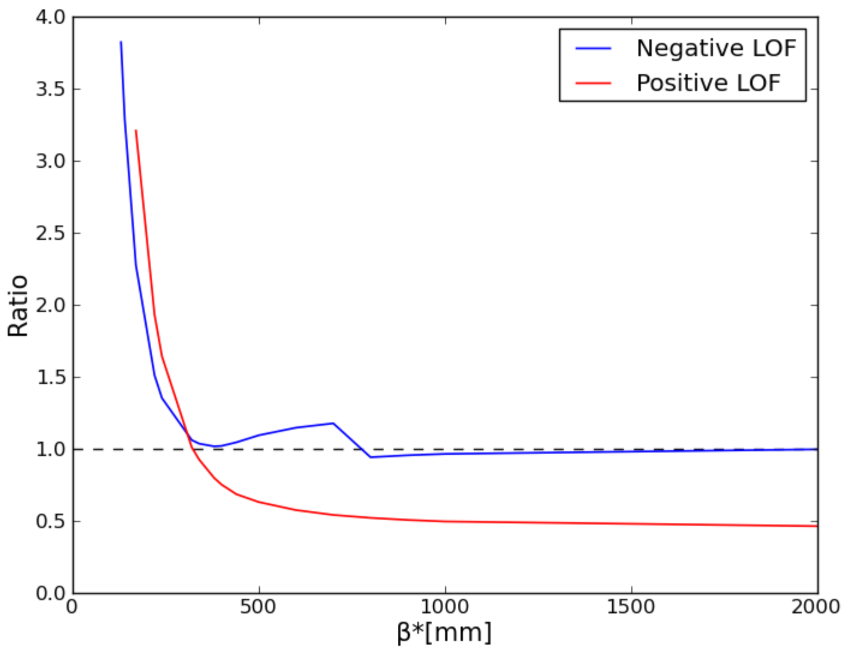


~0.39 m β*

Negative polarity always preferred

Positive polarity gives larger SD from β* ~0.39m

Correction applied at β*=70cm



Reduction can be compensated by increasing the beta in the arcs by a factor of 8% at β*=70cm

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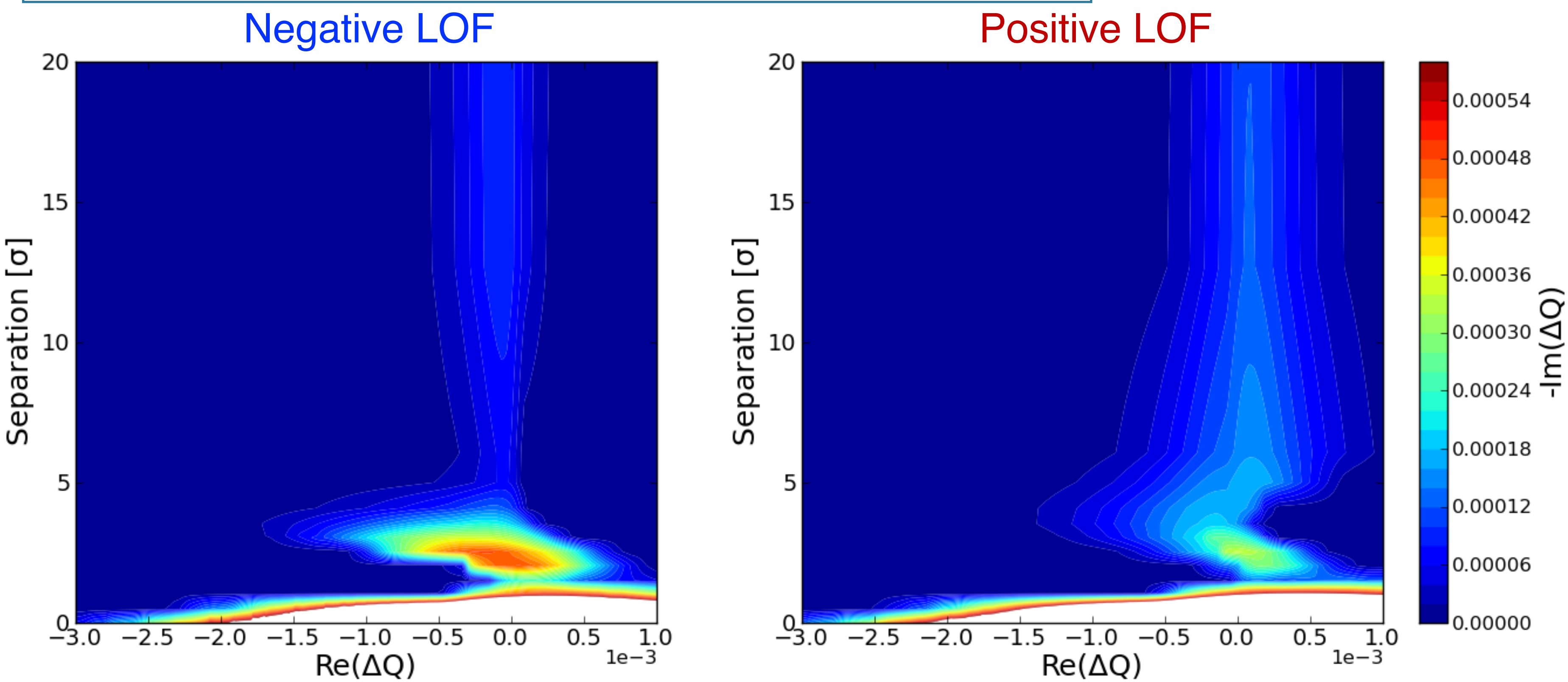
HL-LHC collapse for Baseline scenario

Evolution of the **SD during collapse of separation** (**crab-crossing off**):
LR+HO beam-beam in IP1 and IP5

Beseline scenario

± 570A Oct current



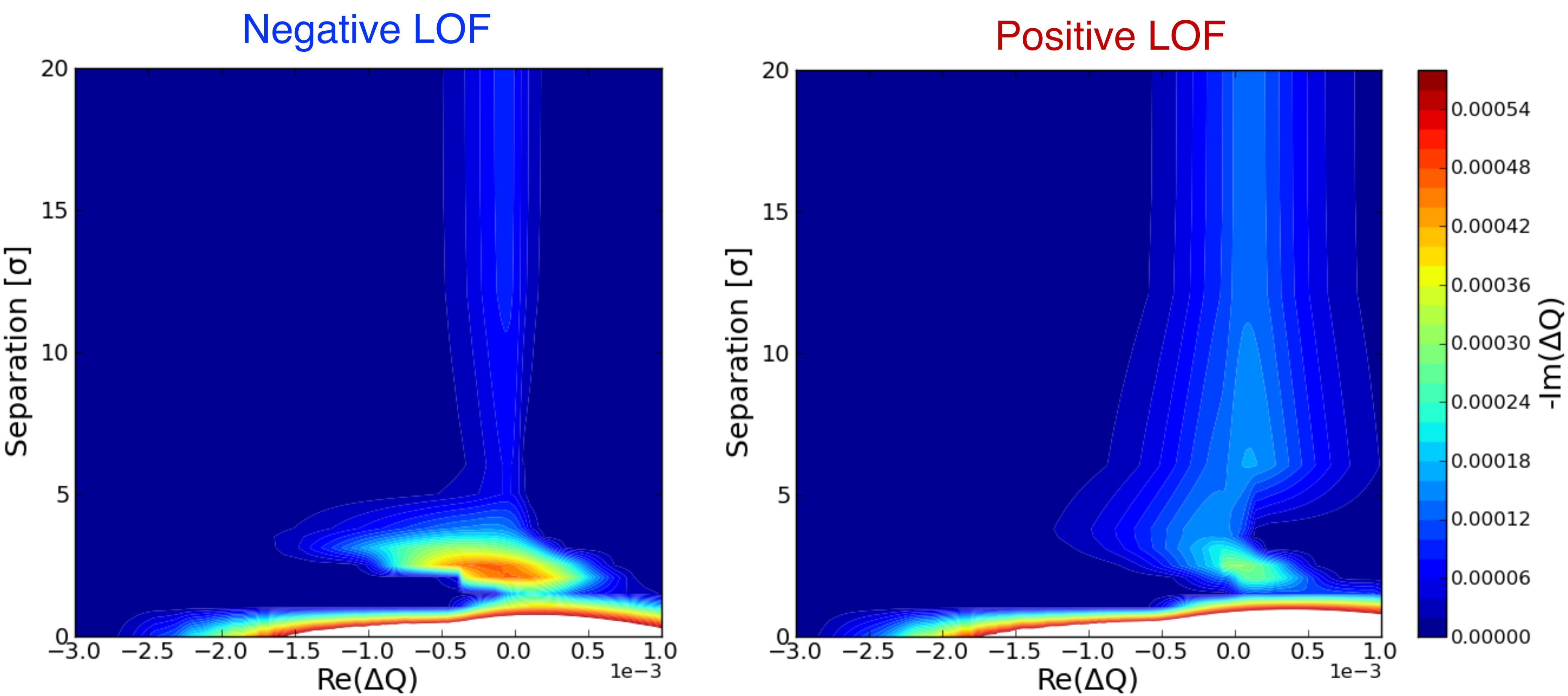
Negative LOF: two reductions at ~6σ and ~1.5σ

Positive LOF: reduction at ~1.5σ

HL-LHC collapse for Ultimate scenario

Evolution of the **SD during collapse of separation** (**crab-crossing off**):
LR+HO beam-beam in IP1 and IP5

Ultimate scenario
± 570A Oct current



Negative LOF: two reductions at ~6σ and ~1.5σ

Positive LOF: reduction at ~1.5σ

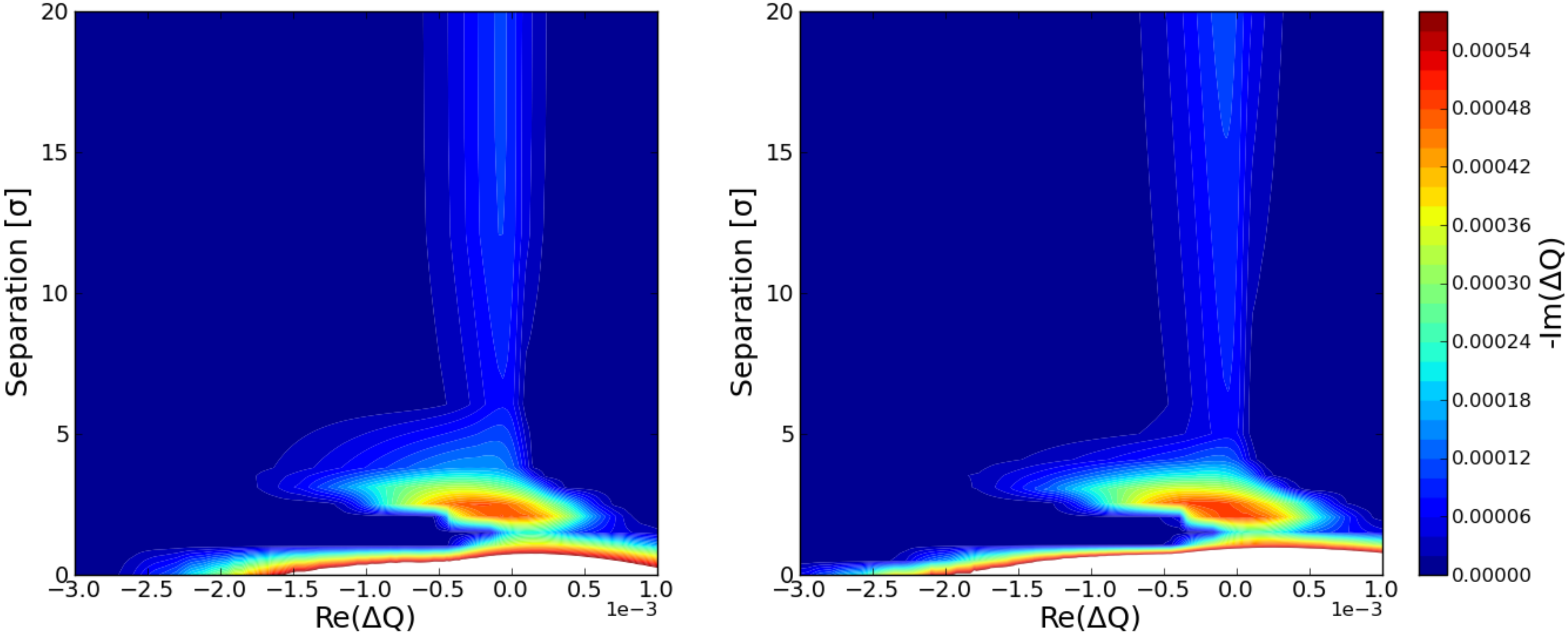
HL-LHC collapse -650A Oct current

Evolution of the **SD during collapse of separation** (**crab-crossing off**):
LR+HO beam-beam in IP1 and IP5

-650A Oct current

Negative LOF Ultimate

Negative LOF Baseline



Negative LOF: larger SD with -650 A but still two reductions at ~6σ and ~1.5σ

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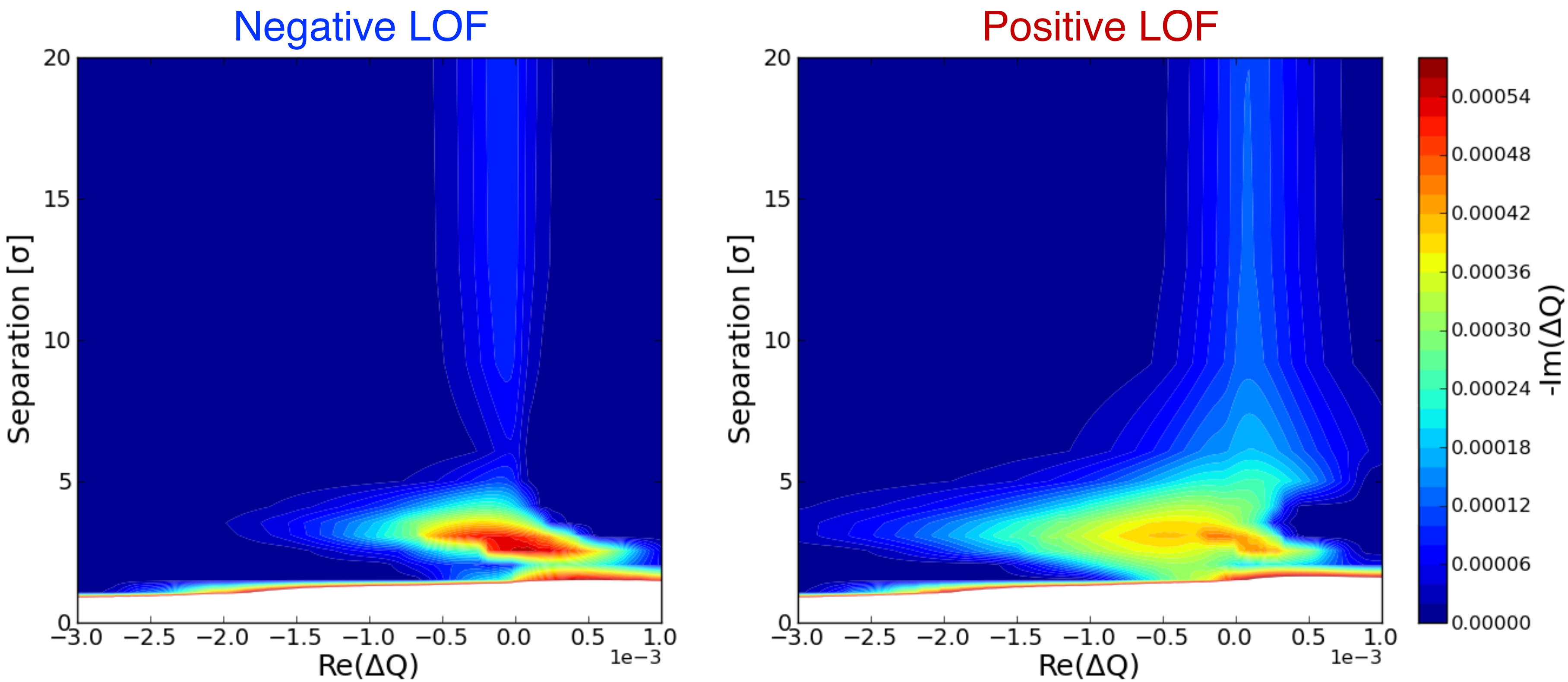
HL-LHC collapse for Baseline scenario

Evolution of the **SD during collapse of separation** (**crab-crossing on**):
LR+HO beam-beam in IP1 and IP5

Baseline scenario

± 570A Oct current



Negative LOF: two reductions at ~6σ and ~1.5σ

Positive LOF: always a larger SD during the collapse (except while full separated beams)

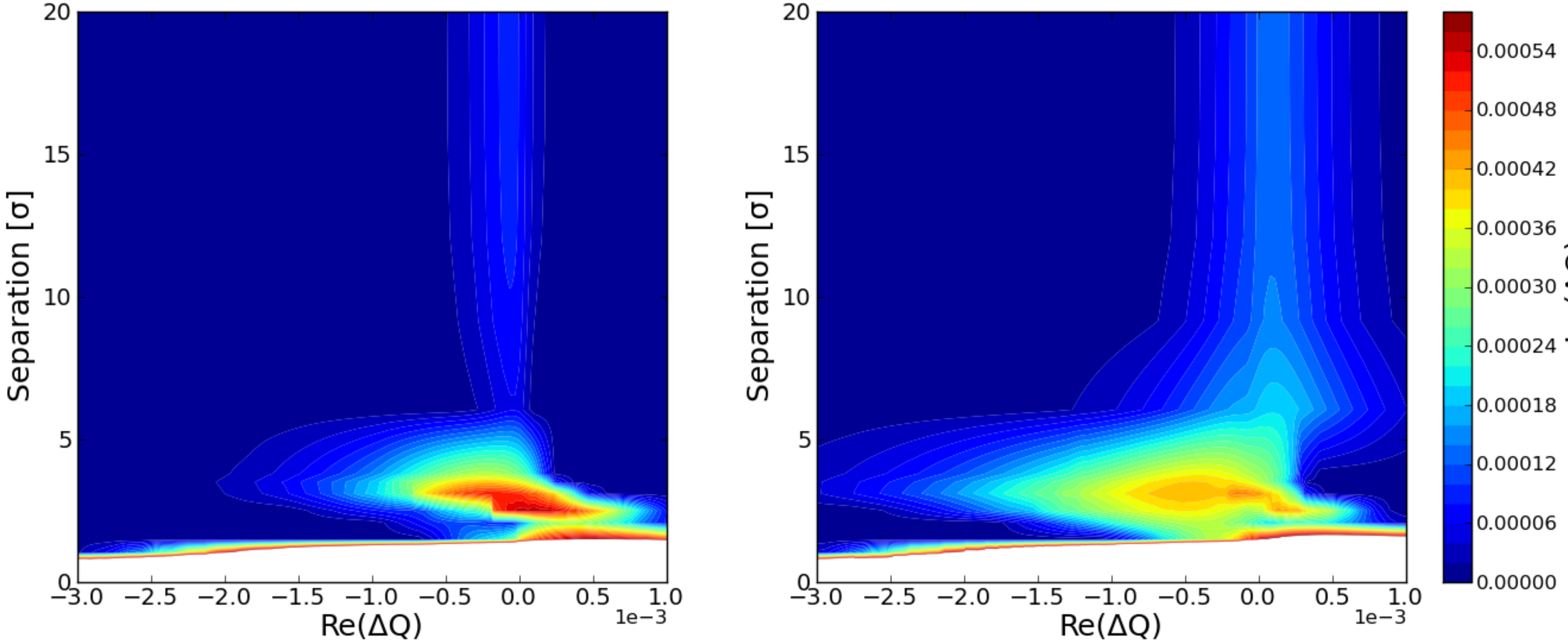
HL-LHC collapse for Ultimate scenario

Evolution of the **SD during collapse of separation** (**crab-crossing on**):
LR+HO beam-beam in IP1 and IP5

Ultimate scenario

± 570A Oct current

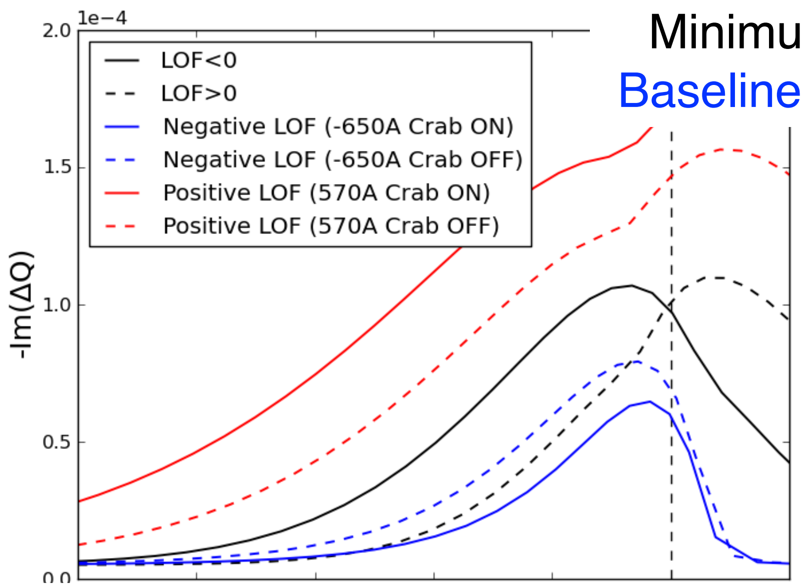
Negative LOF | Positive LOF



Negative LOF: two reductions at ~6σ and ~1.5σ
Positive LOF: always a larger SD during the collapse

Reduction at 6σ during collapse

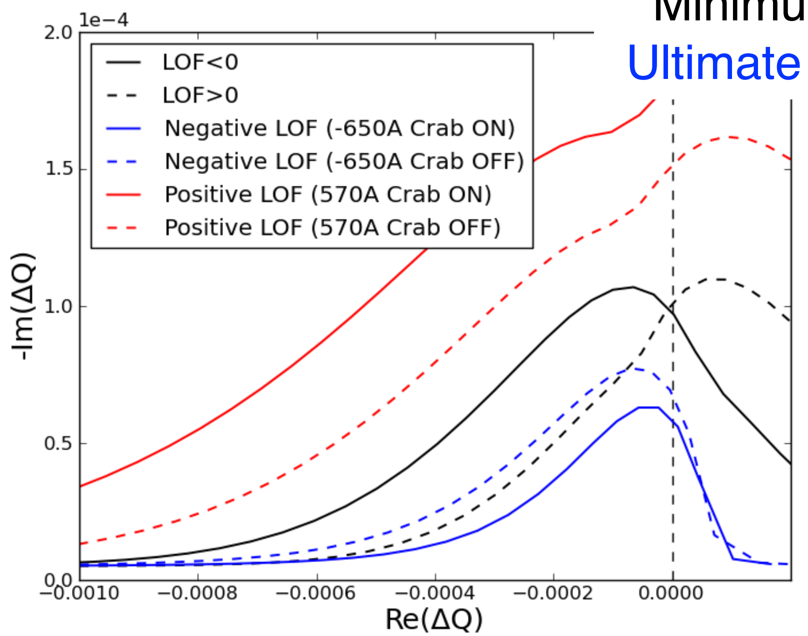
Minimum at 6σ
Baseline scenario



SD with crab-crossing off similar to positive LOF for single beam

Larger reduction for negative LOF with crab-crossing ON

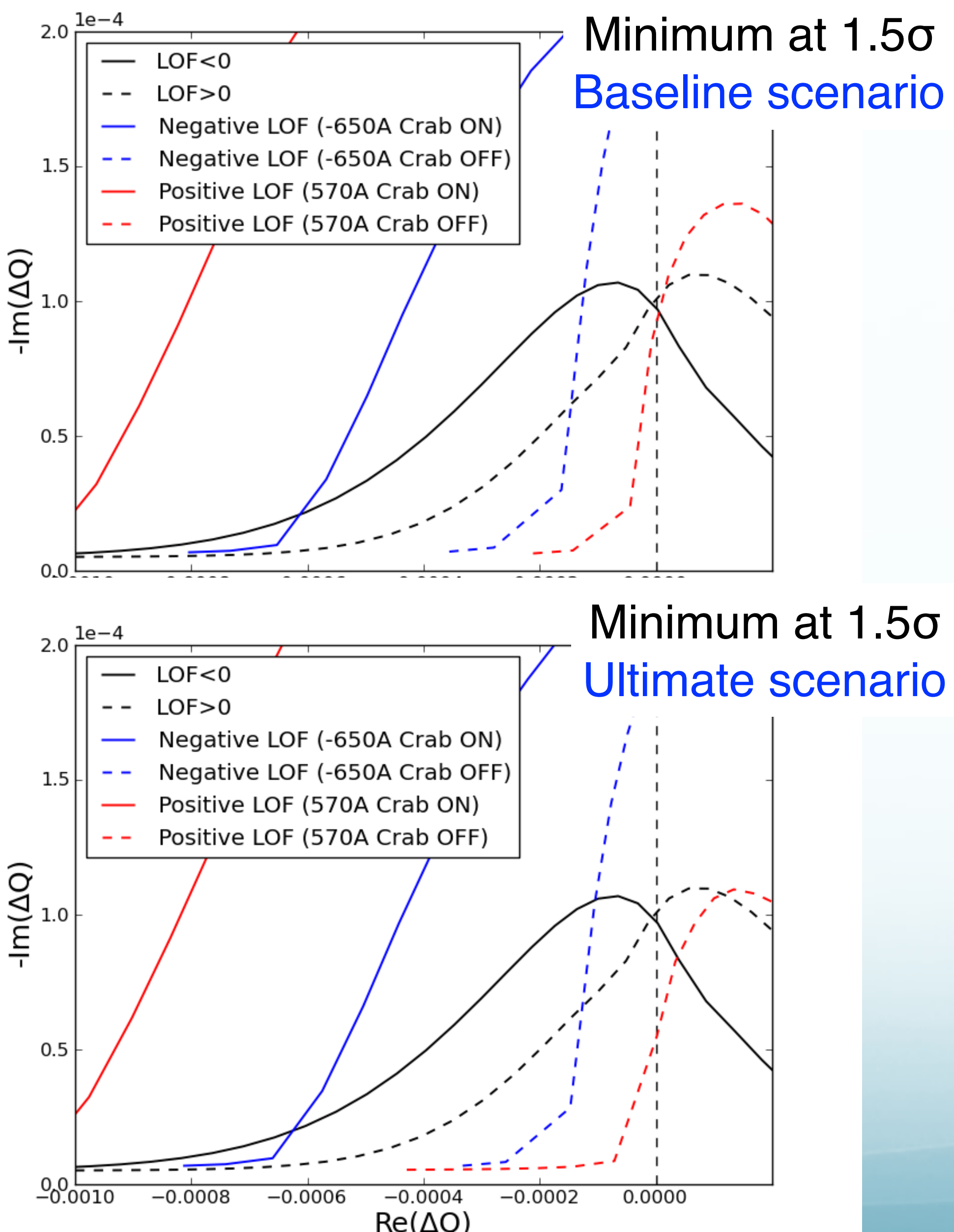
Minimum at 6σ
Ultimate scenario



Same considerations as baseline scenario

Never observed instability during collapse of separation bumps in LHC

Reduction at 1.5σ during collapse



Crab crossing on:
larger SD for positive LOF
for negative LOF much larger SD w.r.t. the crab off, almost as negative LOF at flat top

Crab crossing off:
Negative polarity larger SD than positive case
Minimum reached at 1.5σ

Same consideration as baseline scenario

Never observed instability during collapse of separation bumps in LHC

Contents

- Introduction to Landau damping and stability diagrams
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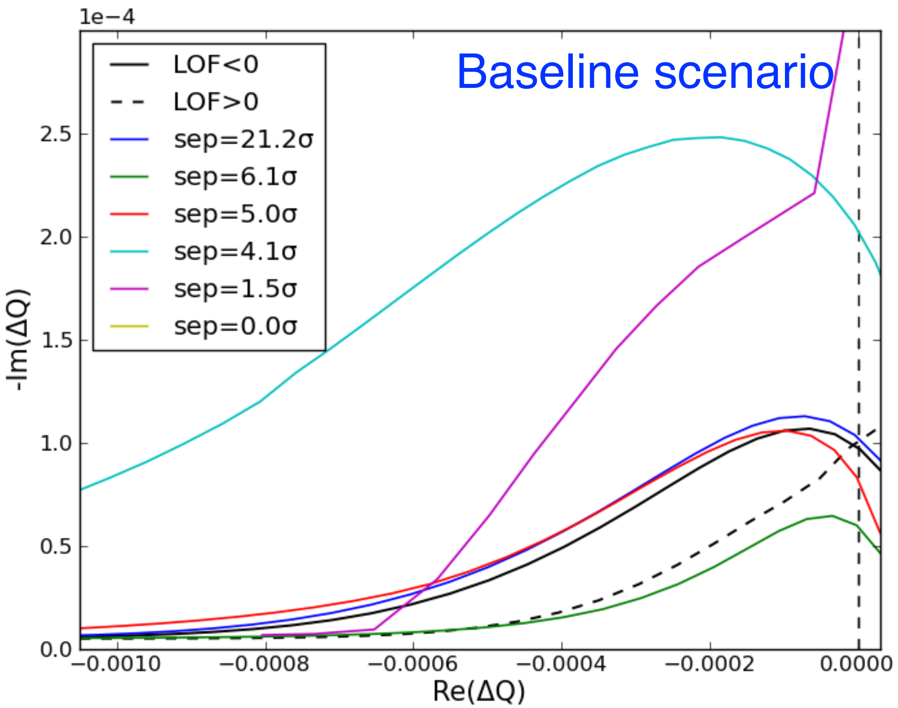
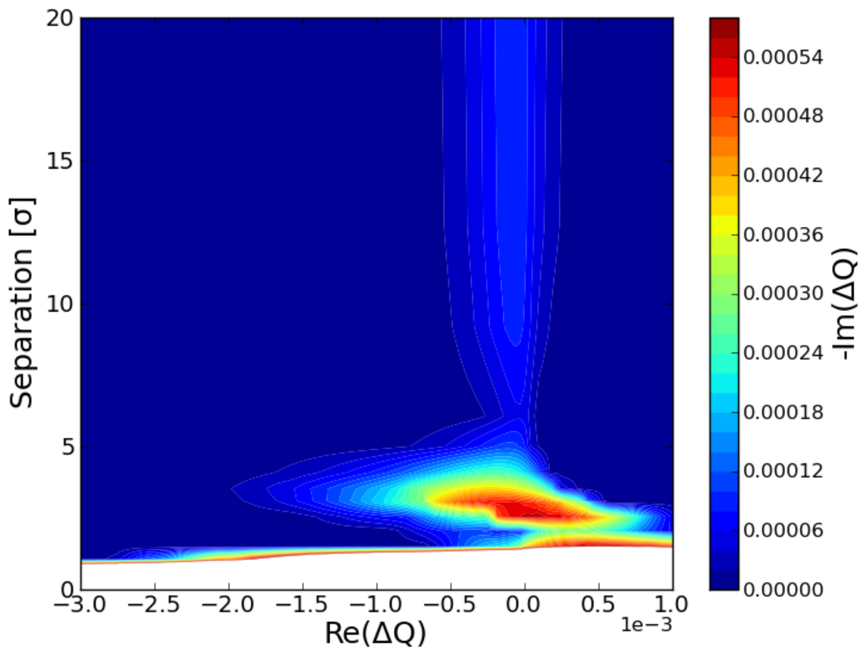
    - Crab-crossing ON
- Stability diagram in stable beams during β* leveling
- Conclusions

Stability diagram during β* leveling in collision

Head on collision is independent of β*

Crab-crossing ON: minimum stability at 6σ and 1.5σ

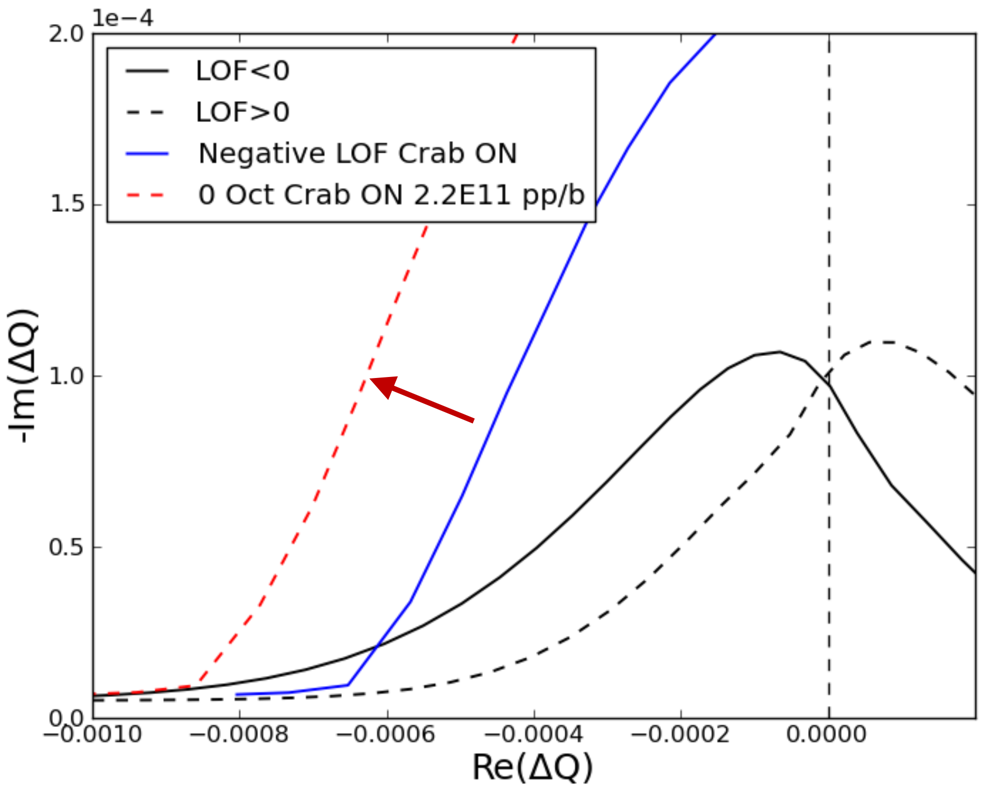




Constraint on bb separation during β* leveling could be relaxed above 1σ

Stability diagram during β* leveling in collision

Baseline scenario



With 0A Oct current we remove the LR contribution on the tune spread with negative LOF

Now the SD is even larger than the LOF negative

So we do not need to care about the reduction at 1.5σ anymore

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Conclusions

At flat top (single beam): negative LOF preferred

- Scenario with negative octupole polarity has been proposed to have larger stability and dynamic aperture

ATS optics: larger β function in the arcs for β* < 40 cm

Squeeze: stability diagram preserved in presence of bb LR (Baseline and Ultimate)

- with negative LOF reduced stability diagram till β*= 40 cm
- compensation of reduction proposed by increasing β function in the arcs of 8%

Conclusions

Collapse: two minima identified at 6σ and 1.5σ for negative polarity

Crab-crossing ON:

- at 6σ SD below the positive LOF for single beam
- at 1.5σ SD comparable with negative LOF single beam
- with 0 octupole current even larger than negative LOF single beam

Crab-crossing OFF:

- at 6σ SD comparable with positive LOF for single beam
- at 1.5σ SD largest reduction of the SD

- Both cases have 1 "bad" separation offset
- For LHC never observed instability during collapse of separation —> fast collapse of separation bumps helps

β* leveling in collision: HO bb with Crab-crossing is very strong also for separation >1σ

→ allows to relax constraints on orbit control during β* leveling (0 - 4σ)

Conclusions

Collapse: two minima identified at 6σ and 1.5σ for negative polarity

Crab-crossing ON:

- at 6σ SD below the positive LOF for single beam
- at 1.5σ SD comparable with negative LOF sin... ...eam

Crab-crossing OFF:

- at 6σ SD comparabl... ...m
- at 1.5σ SD ...

Thanks for the attention!

- Both cases hav...
- For LHC never c... ...ollapse of separation
  —> fast collapse ... ...ps helps

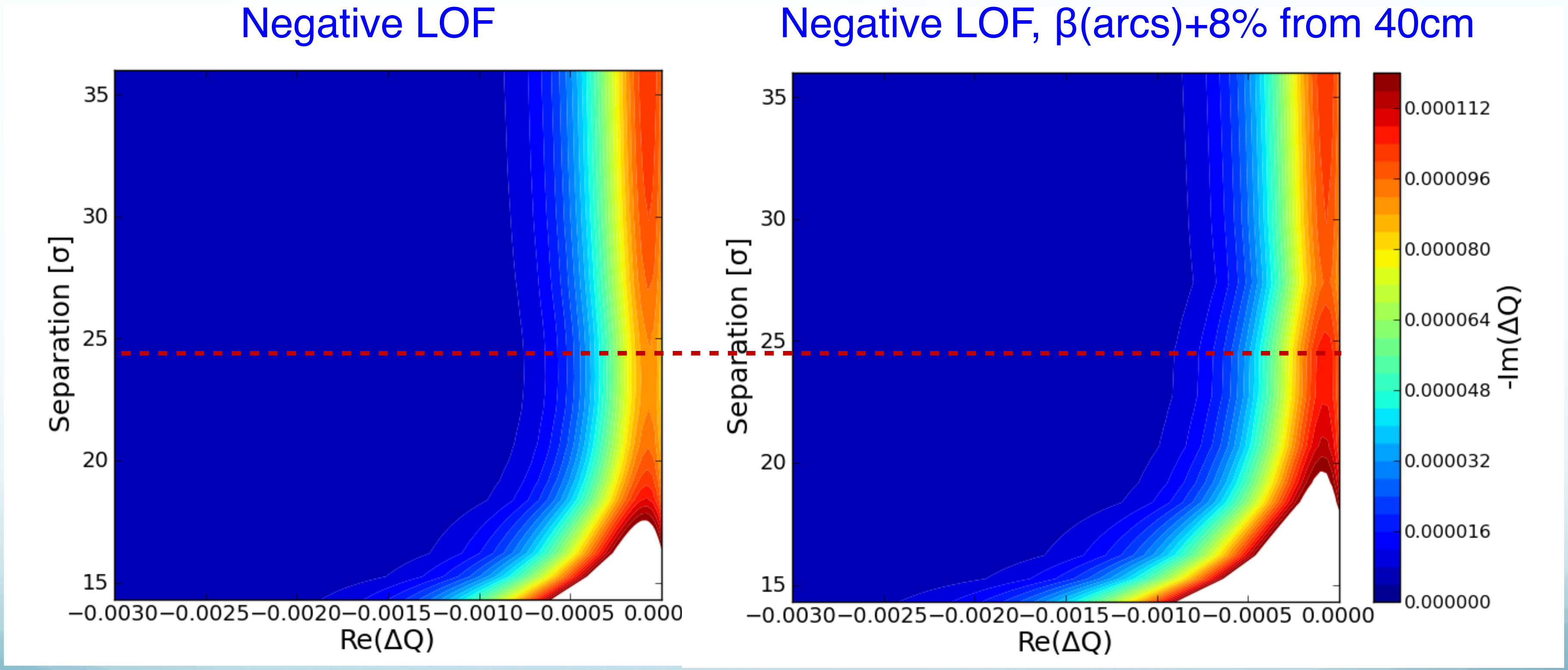
β* leveling in collis... ...HO bb with Crab-crossing is very strong also for separation >1σ

→ allows to relax constraints on orbit control during β* leveling (0 - 4σ)

Back-up slides

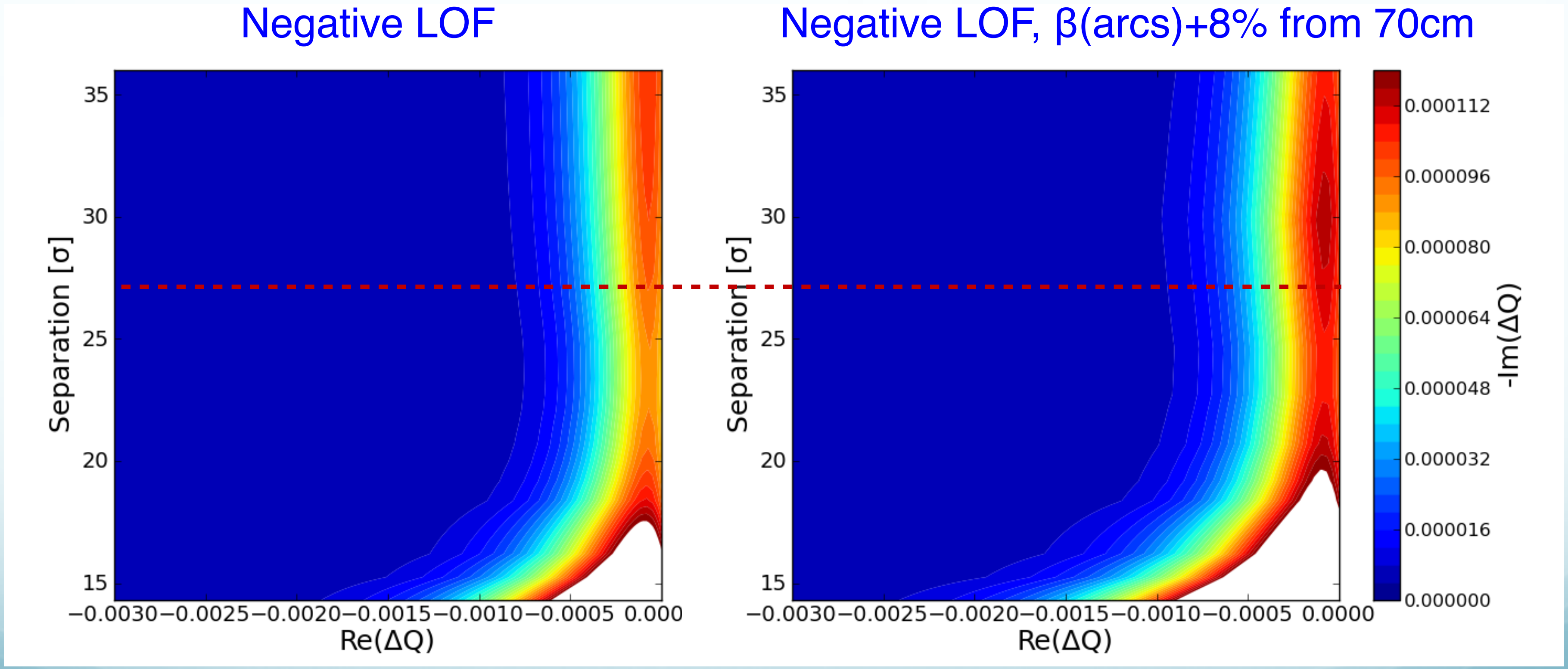
Compensation by increment of beta in the arcs

Evolution of the **betatron squeeze**: **LR beam-beam in IP1 and IP5**

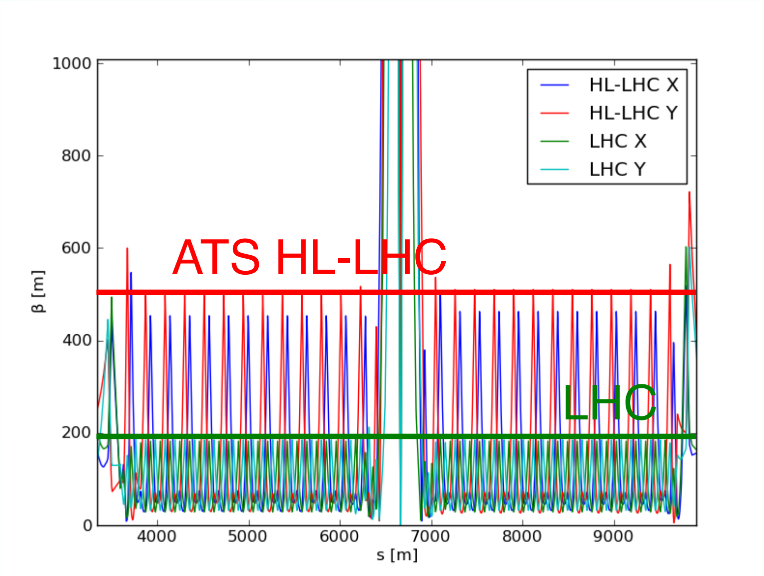


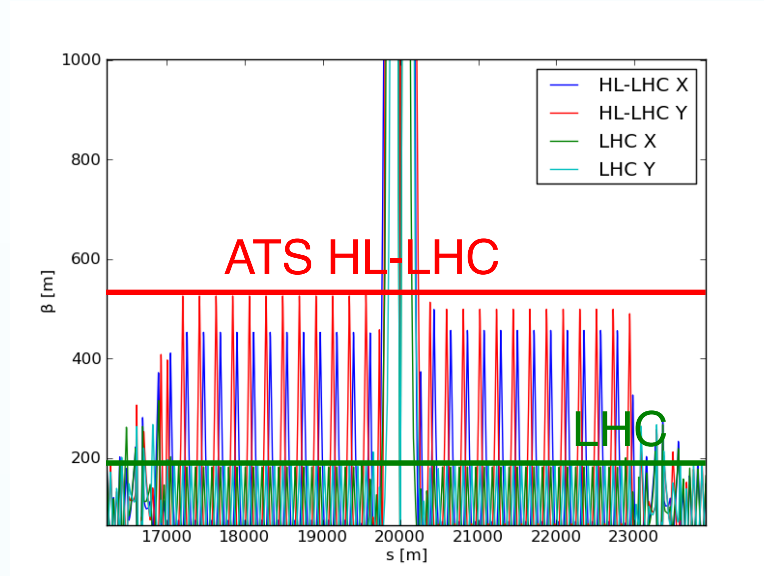
Compensation by increment of beta in the arcs

Evolution of the **betatron squeeze**: **LR beam-beam in IP1 and IP5**



ATS optics





Optics β*=15cm

Reference paper on ATS optics:

Achromatic telescopic squeezing scheme and application to the LHC and its luminosity upgrade

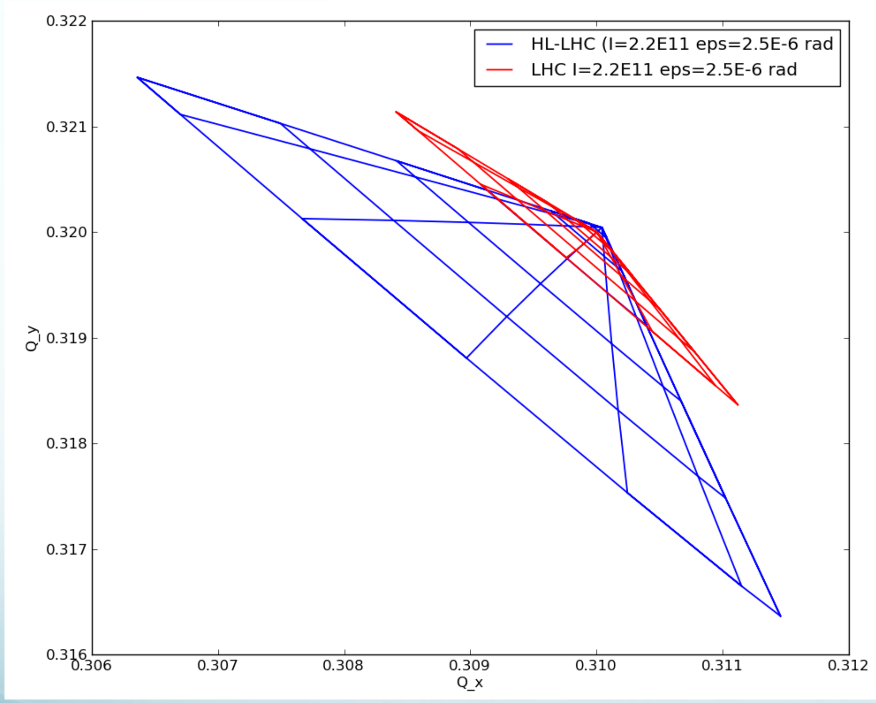
Stéphane Fartoukh*
CERN, CH 1211 Geneva 23, Switzerland
(Received 26 July 2013; published 19 November 2013)

Strong impact from ATS optics with respect to LHC: larger betas in arcs

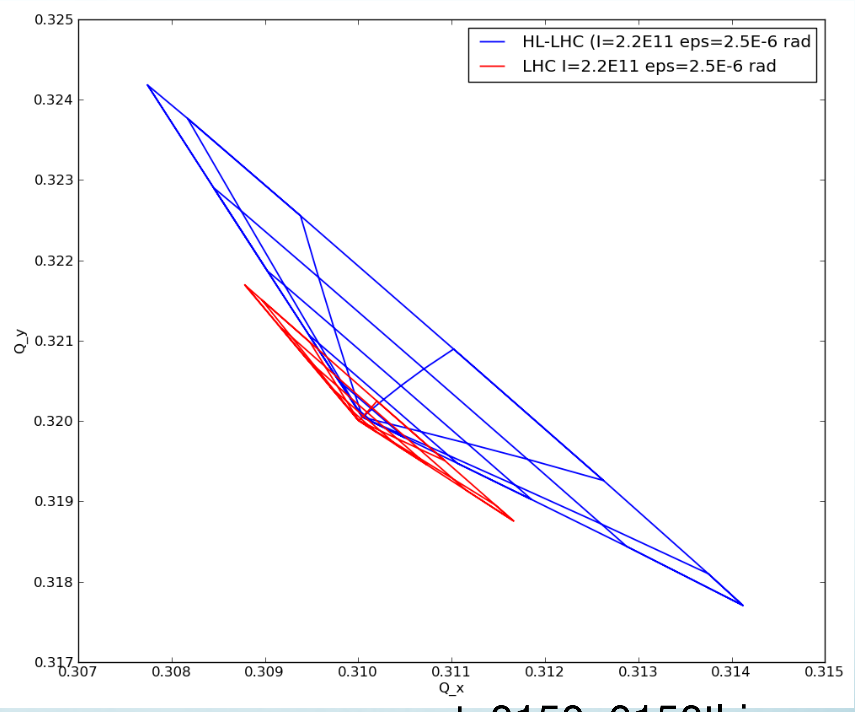
ATS: optics impact on footprint

Footprint comparisons: LHC and HL-LHC case

Negative LOF



Positive LOF



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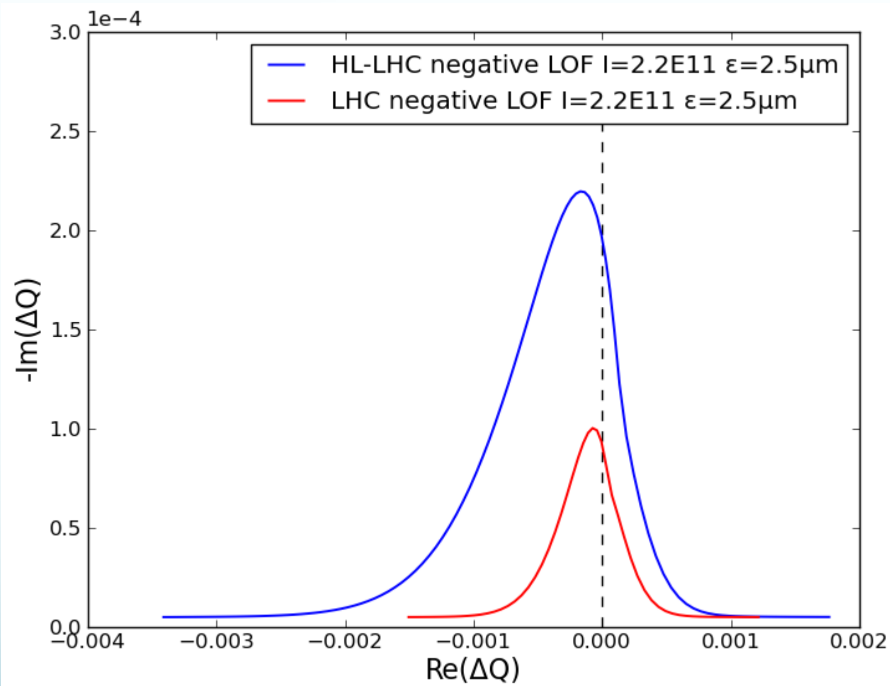
Strong impact for ATS optics with respect to LHC

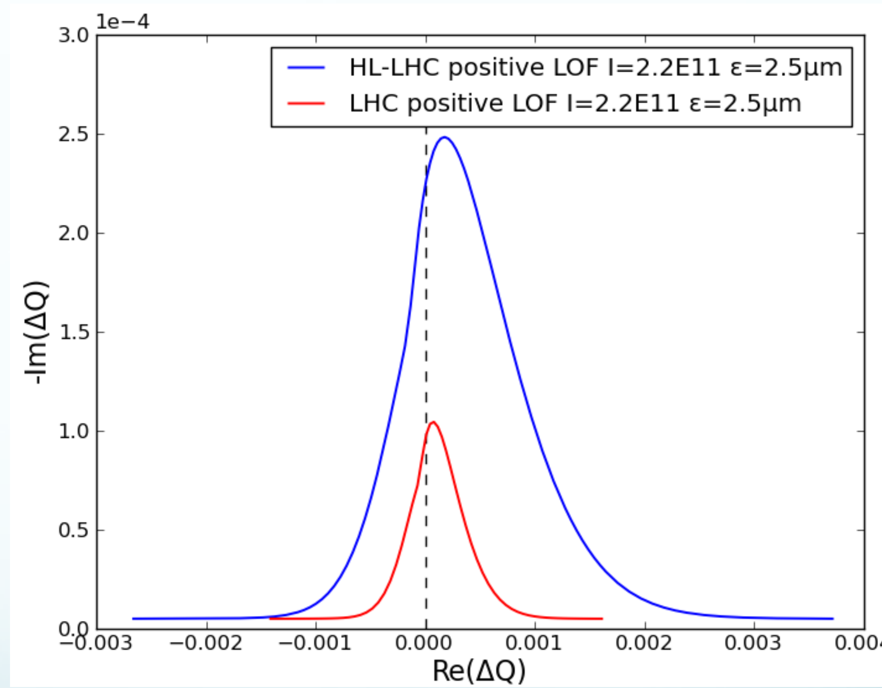
ATS: optics impact on stability diagrams

HL-LHC vs LHC (I=2.2E11, ε=2.5μm)

Negative LOF



Positive LOF



Landau Damping, Dynamic Aperture and Octupoles in LHC

J. Gareyte, J.P. Koutchouk and F. Ruggiero

$$\Delta Q_x = \left[\frac{3}{8\pi}\int \beta_x^2 \frac{O_3}{B\rho}\,ds\right] J_x - \left[\frac{3}{8\pi}\int 2\beta_x\beta_y \frac{O_3}{B\rho}\,ds\right] J_y,$$

$\Delta Q_{oct} \propto \beta(s)^2$ $\beta(s)^2_{HL\text{-}LHC}/\beta(s)^2_{LHC}$ ≈2.5 larger than the LHC case