ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Work supported by the Swiss State Secretariat for Education, Research and Innovation SERI

Landau damping of head-tail modes in the presence of beam-beam interactions

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Acknowledgements: E. Metral, D. Schulte, S, Antipov, W. Herr, S. Arsenyev, L. Carver

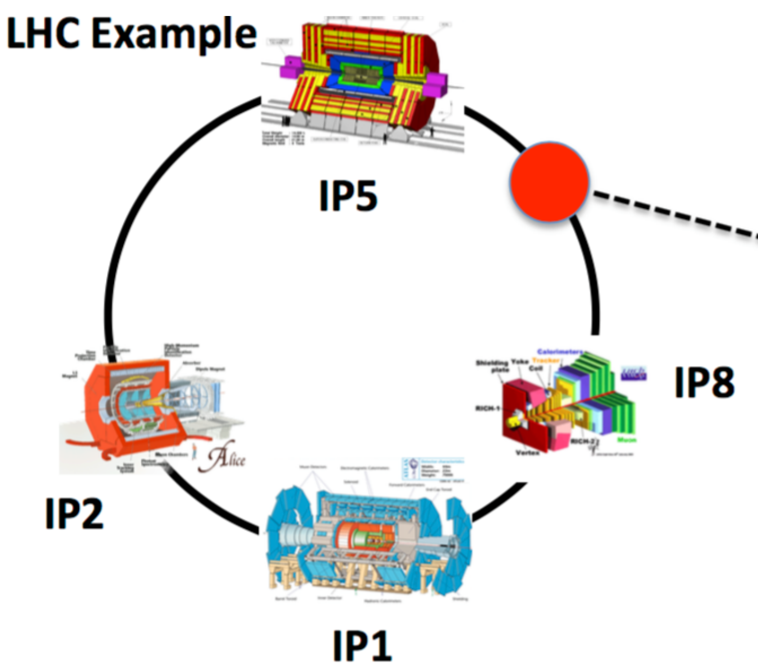
Workshop on Beam-beam effects in Circular Accelerator

5-7 February 2018, Lawrence Berkeley National Laboratory, Berkeley

Contents

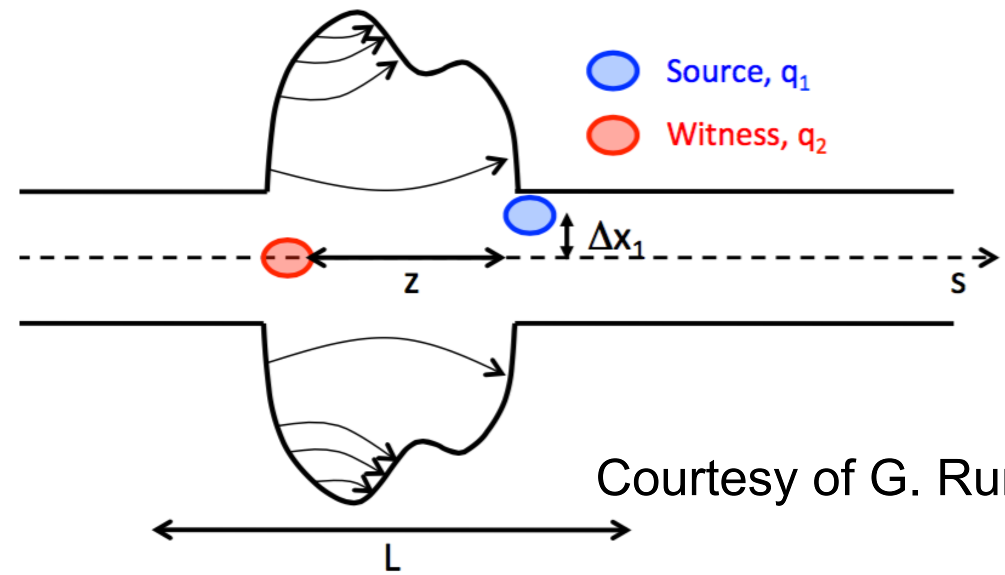
- Landau damping of head-tail modes
- Dispersion integral and stability diagram
- Impact of particle distribution on Stability Diagram
- Beam-beam effects on Landau damping:
    - beam stability in presence of BB long range interactions (betatron squeeze)
    - beam stability during the collapse of the separation bumps
    - beam stability in collision
- Summary

Beam Coupling Impedance



Accelerator surroundings:

- Beam pipe
- Collimators (5.5 RMS beam size)



Courtesy of G. Rumolo

The source particle induces electromagnetic wake fields (**impedance**) that act back on the following particles

Stronger for high luminosity:

- High brightness beams (N/σ)

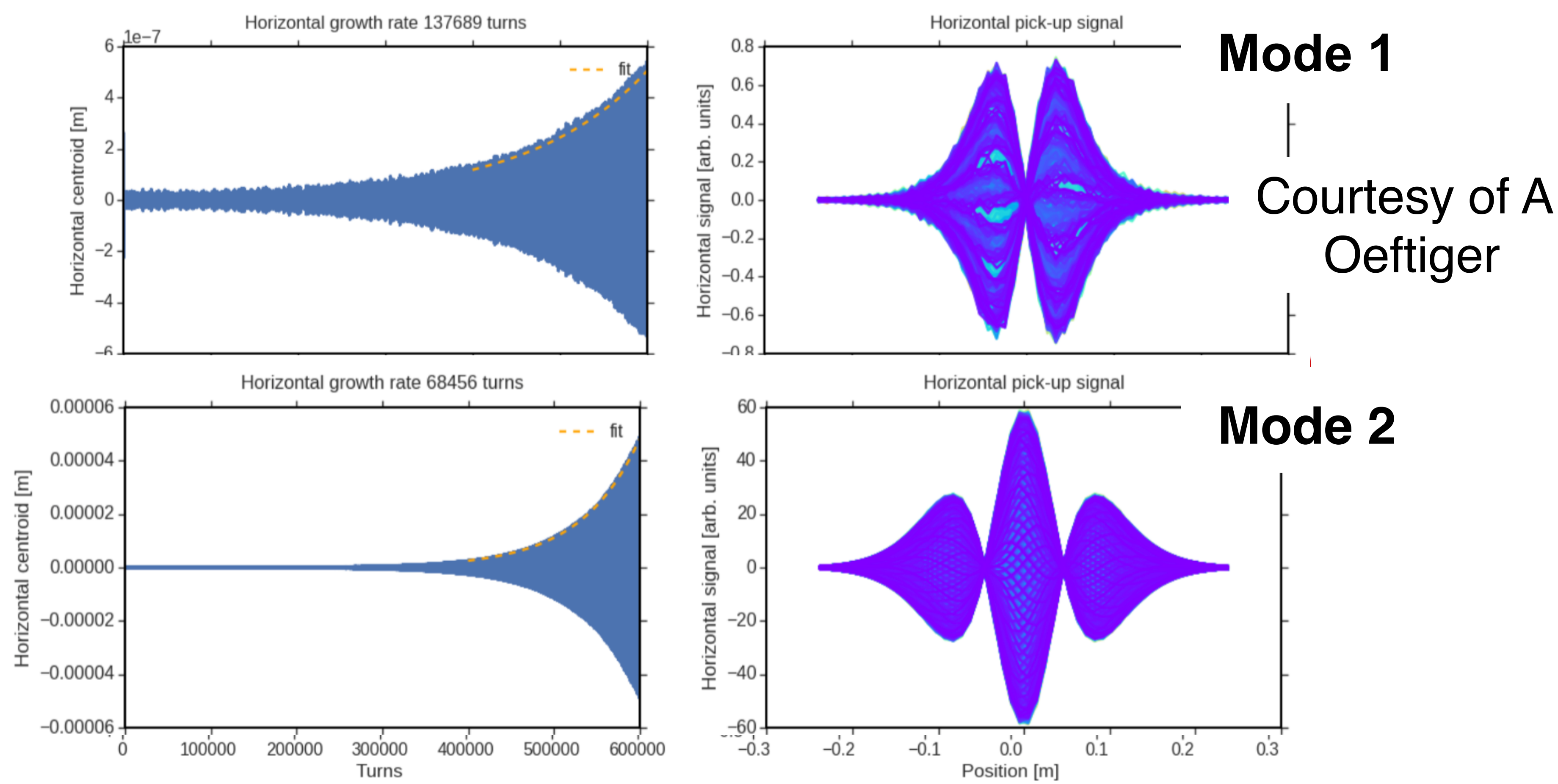
- Small aperture elements (collimator 5.5σ)

Head-tail instability

Impedance drives the so-called head-tail coherent instability

Complex Tune shifts:

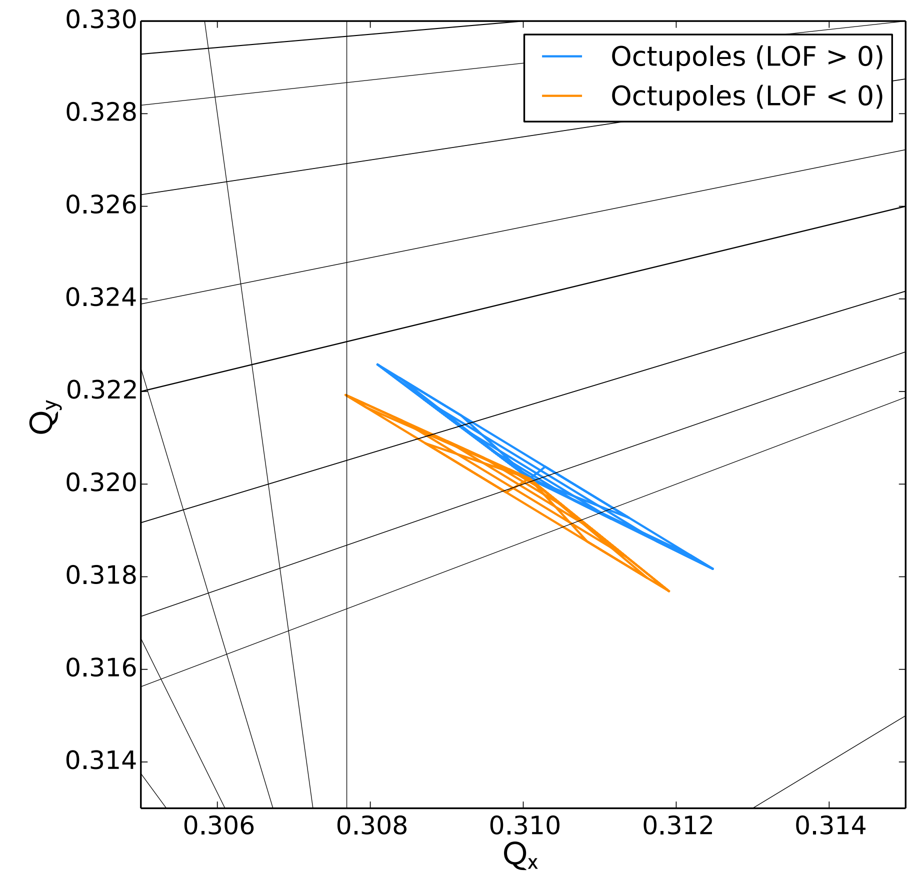
- Im(ΔQ): growth rate
- Re(ΔQ): coherent real tune shift



Mitigation techniques

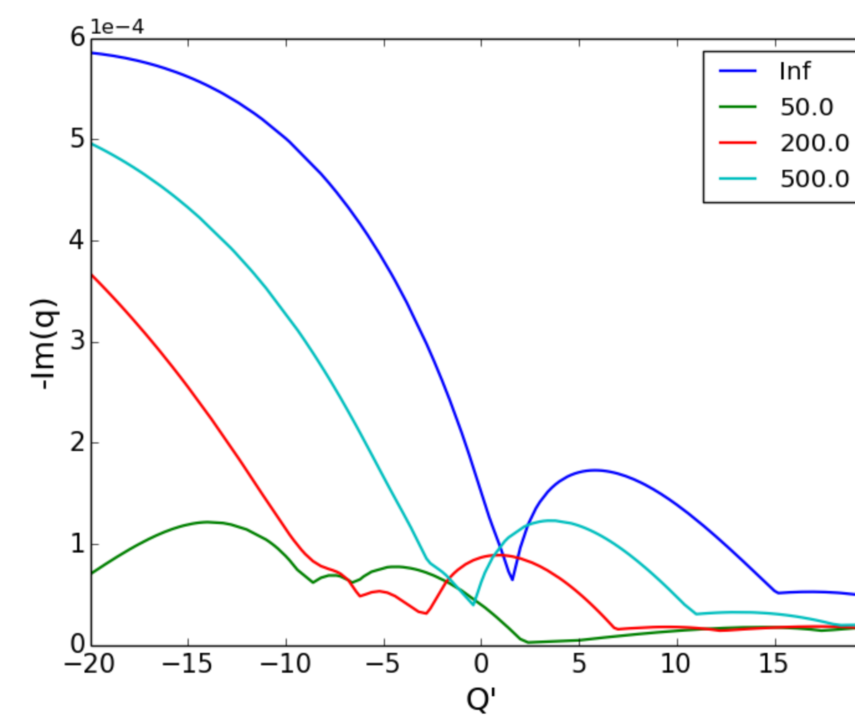
- **High chromaticity ➔** in the 2012 LHC run from Q'=+2 units to Q'=15-20 units
- **Transverse Feedback ➔** easily damp m=0, intra-bunch modes are more complicated
- **Landau damping ➔** passive mitigation
  wave↔particles interaction (energy of the wake is not absorbed)

$$\partial f / \partial J_x \big|_{\omega=\Omega_{coh}}$$



Landau damping mechanisms are provided by any non-linear elements (tune spread):

- machine non-linearities (octupoles magnets)
- beam-beam interactions
- e-lens [6]



[6] V. Shiltev *et al.*, *Landau Damping of Beam Instabilities by Electron Lenses*, Phys. Rev. Lett. 119, 134802

Dispersion integral and Stability diagrams

Landau damping of the impedance modes can be quantified by the **dispersion integral [1]**:

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

[1] J. Berg and F. Ruggero, *Landau damping with two dimensional betatron tune spread*, CERN SL-AP-96-71 (1996)

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Detuning with amplitude
(Octupoles magnets, machine non-linearities)

Beam-beam (highly non-linear) modifies
Landau damping from octupoles
→ Tracking is needed

[1] J. Berg and F. Ruggero, *Landau damping with two dimensional betatron tune spread*, CERN SL-AP-96-71 (1996)
[2] X. Buffat, EPFL Thesis 6321 (2015)
[3] X. Buffat et *al.*, *Stability diagrams of colliding beams in the Large Hadron Collider*, PRSTAB 111002 (2014)

Dispersion integral and Stability diagrams

In presence of **diffusive mechanisms the particle distribution changes**

Particle distribution [4,5]

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

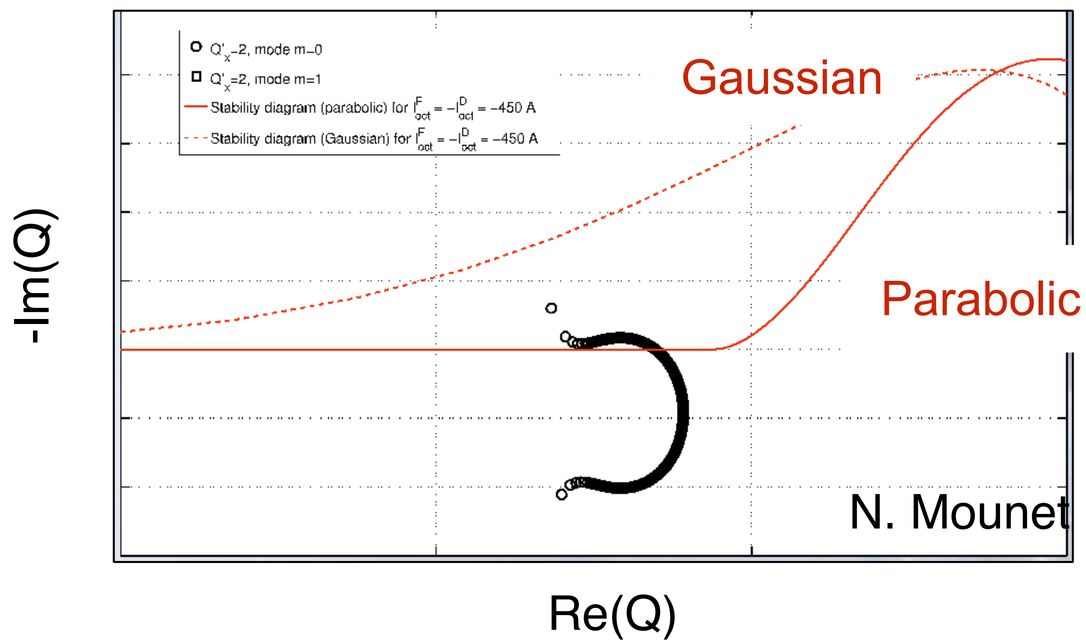
Detuning with amplitude (Octupoles magnets, machine non-linearities)

Beam-beam (highly non-linear) modifies Landau damping from octupoles
→ Tracking is needed

[4] C. Tambasco, EPFL Thesis 7867 (2017)
[5] C. Tambasco *et al.*, *Impact of incoherent effects on stability diagram at the LHC*, IPAC TUPVA031 2017

Effects of particle distribution on Landau damping

Coherent modes (m=0) are not stabilized as for Gaussian distribution case



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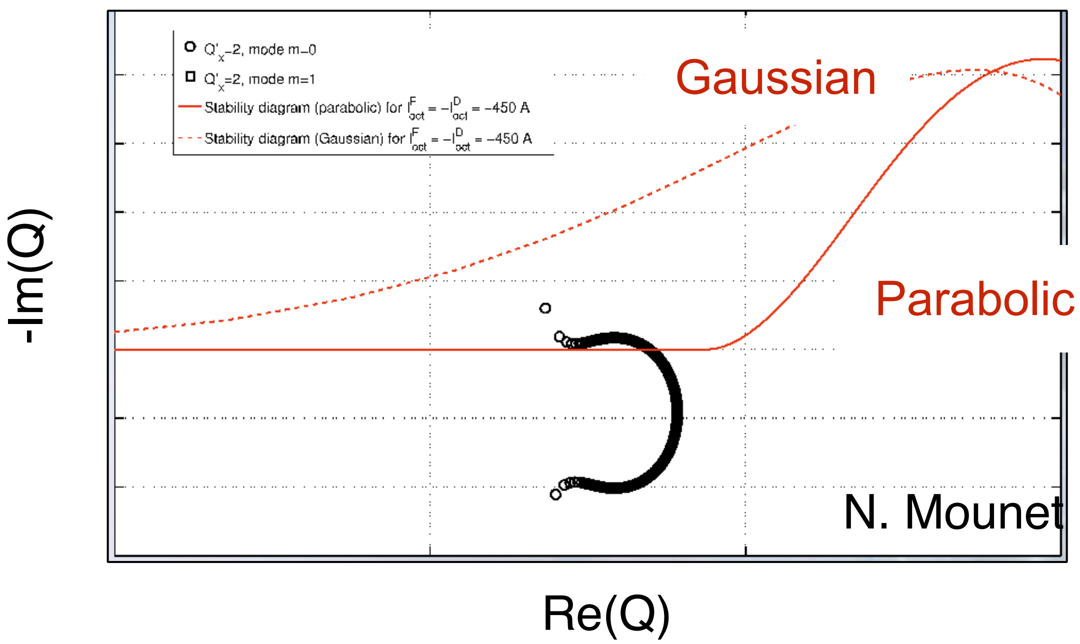

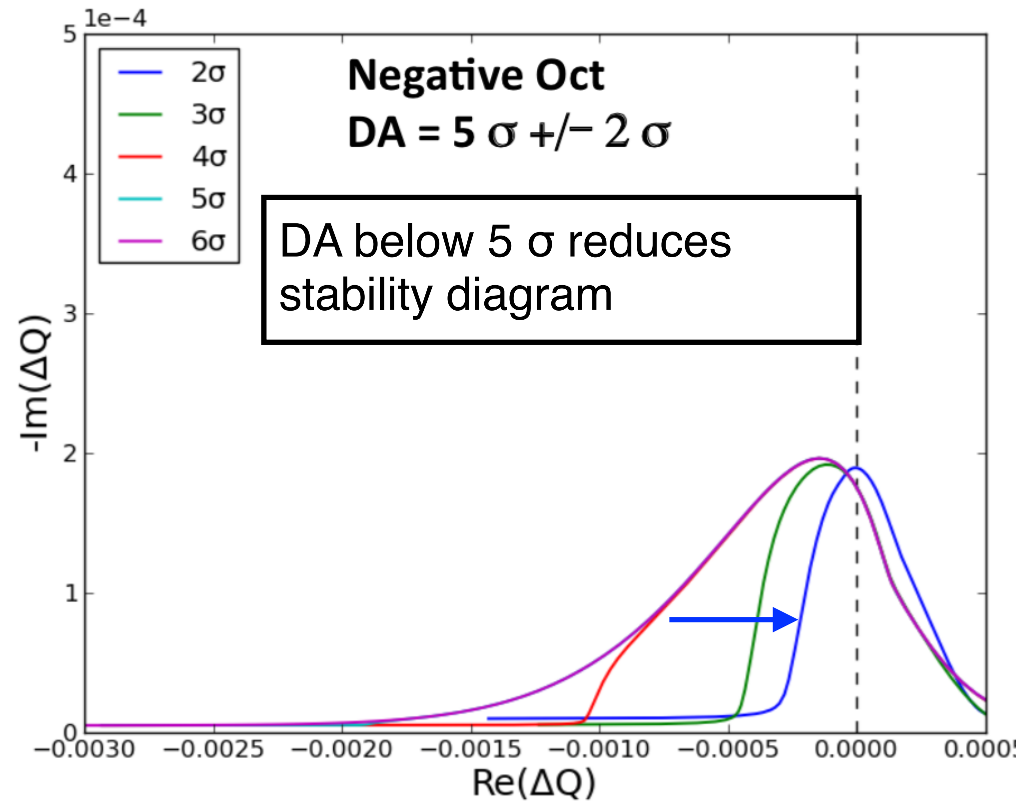

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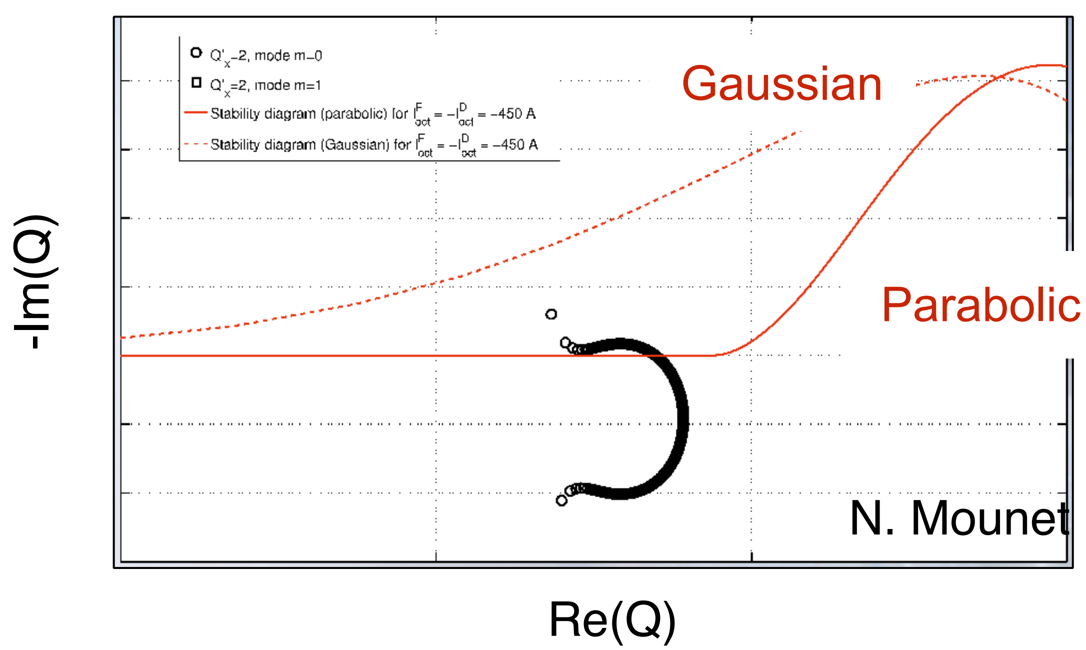

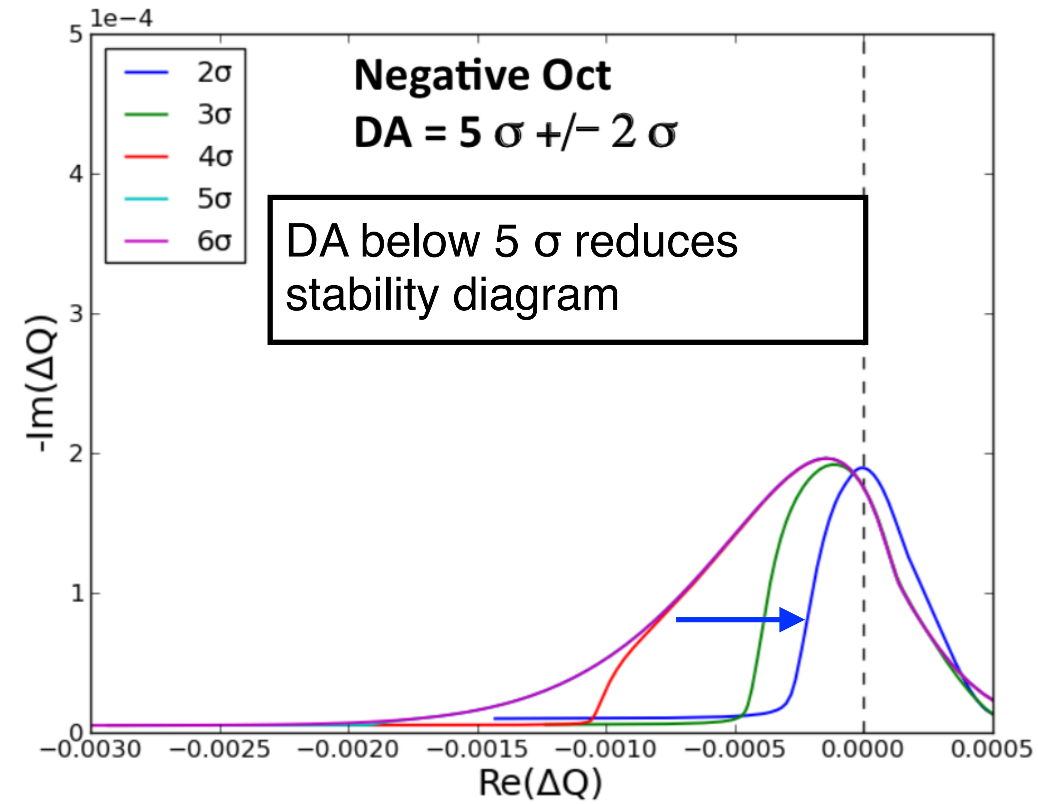

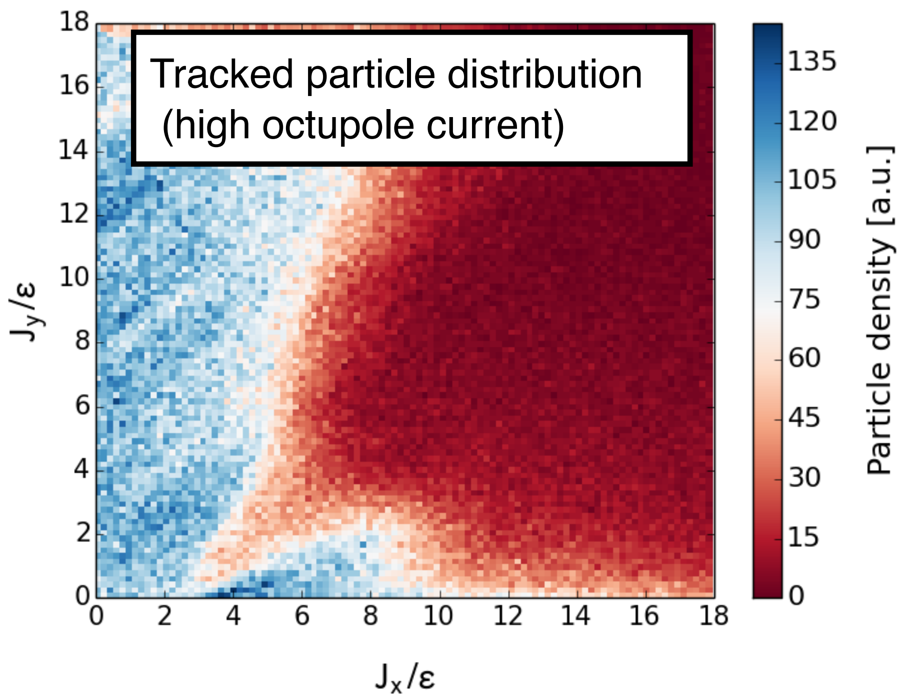

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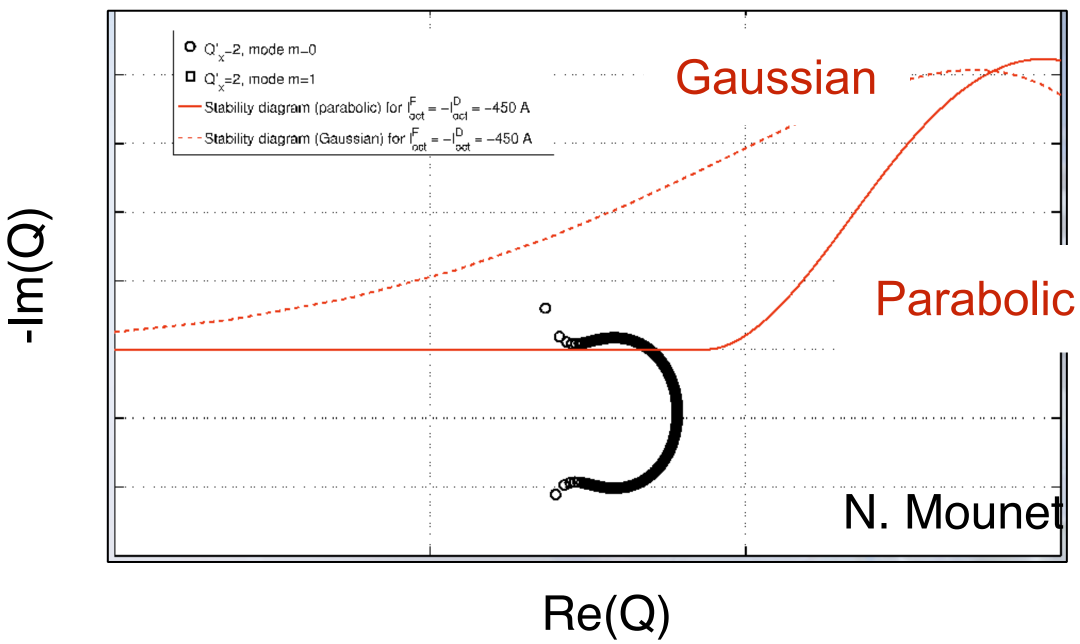

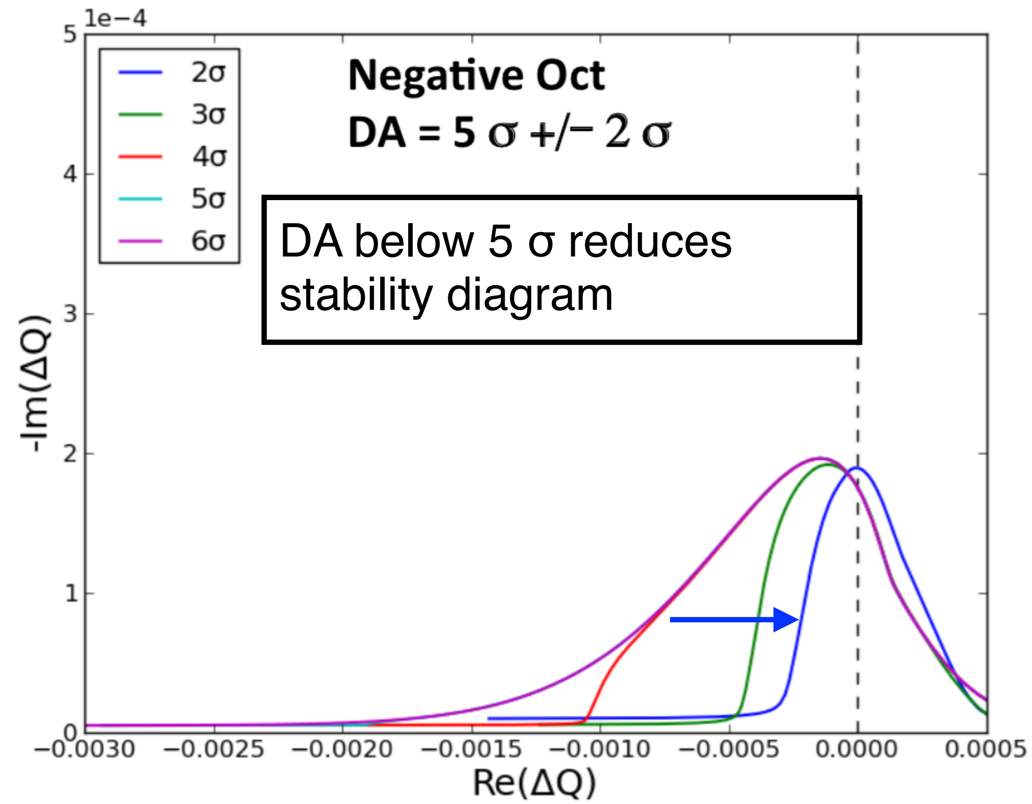

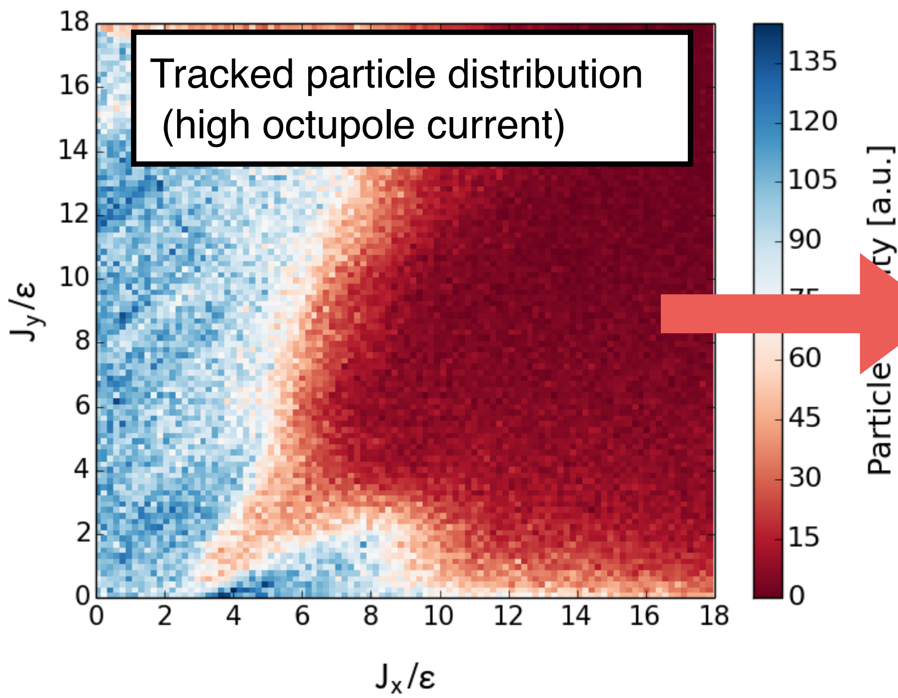

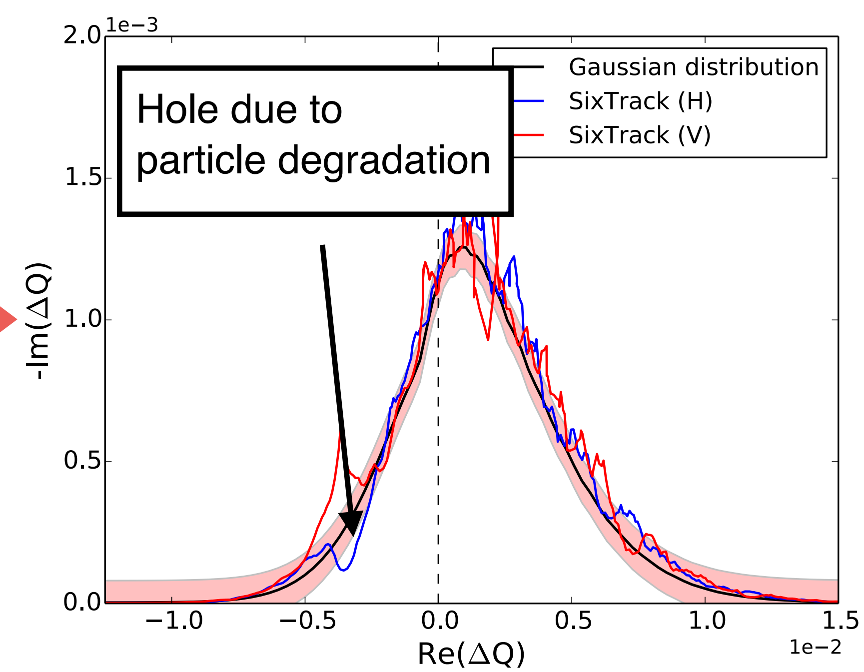

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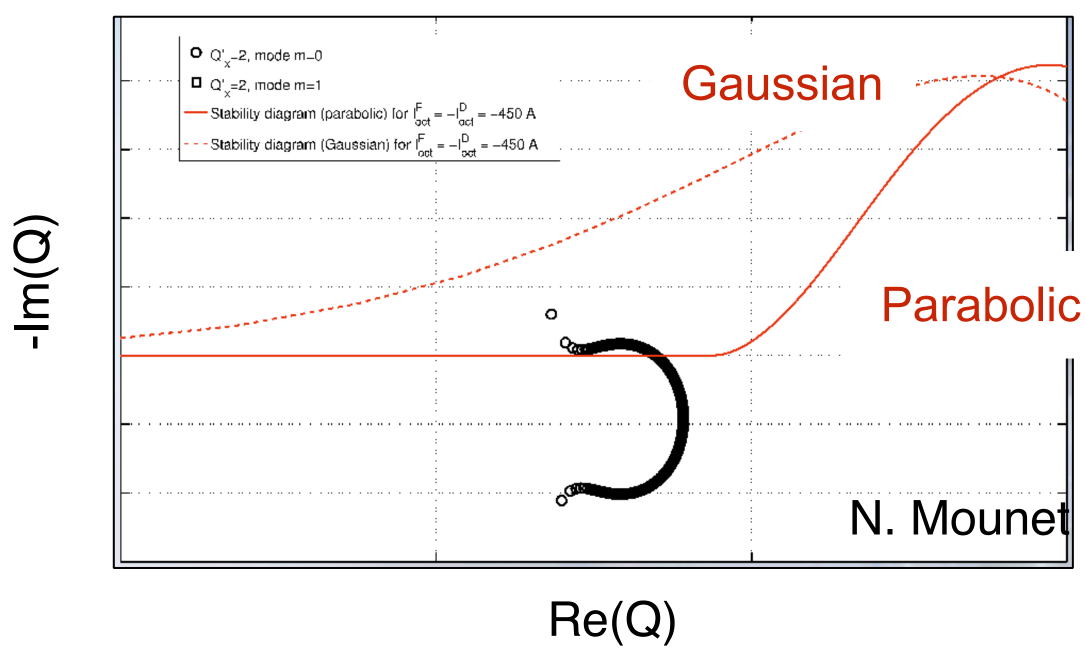
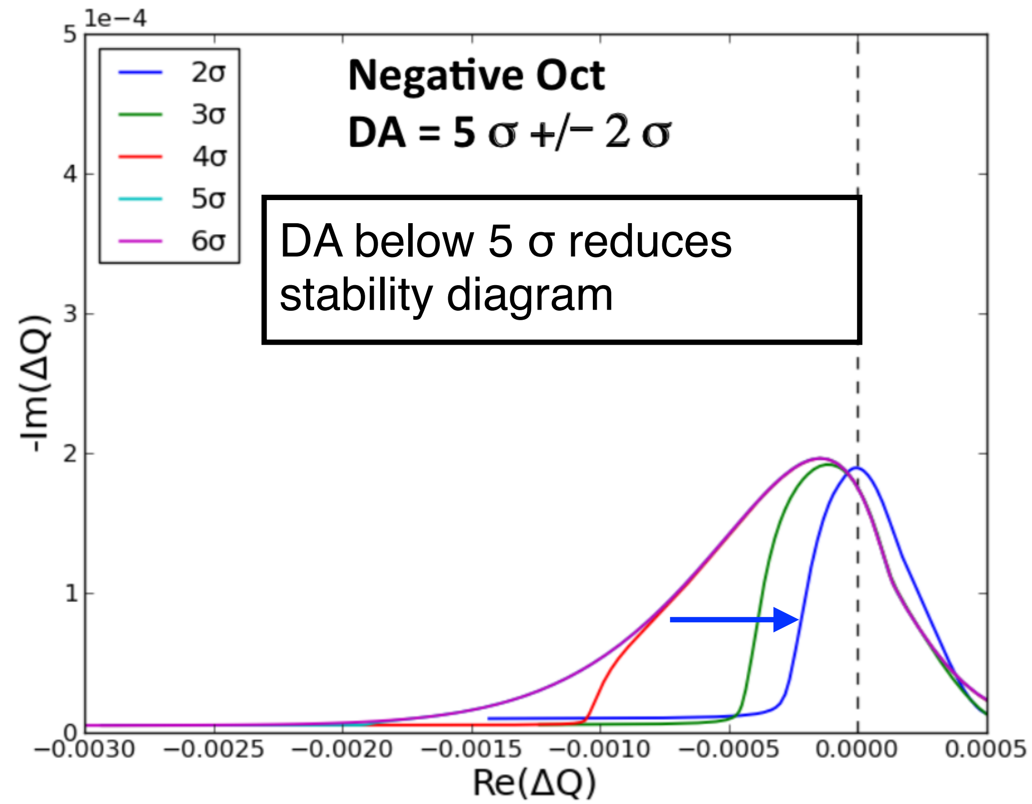
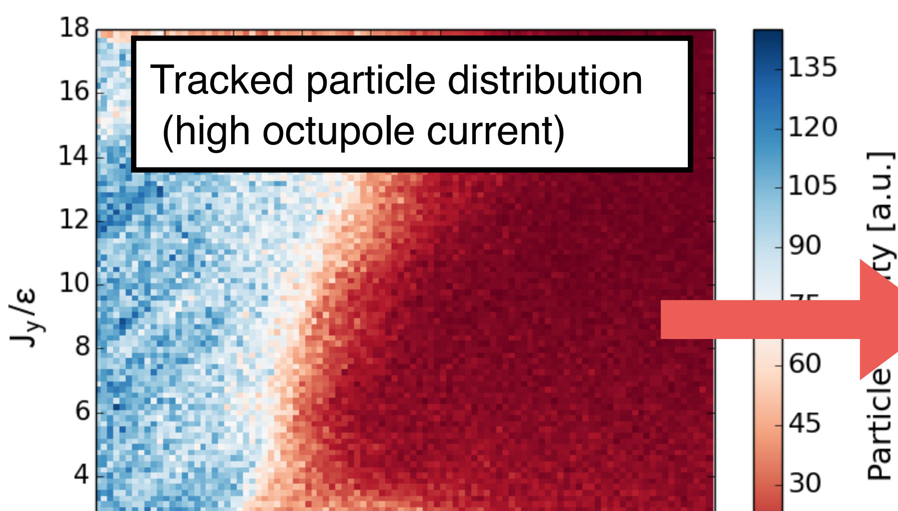
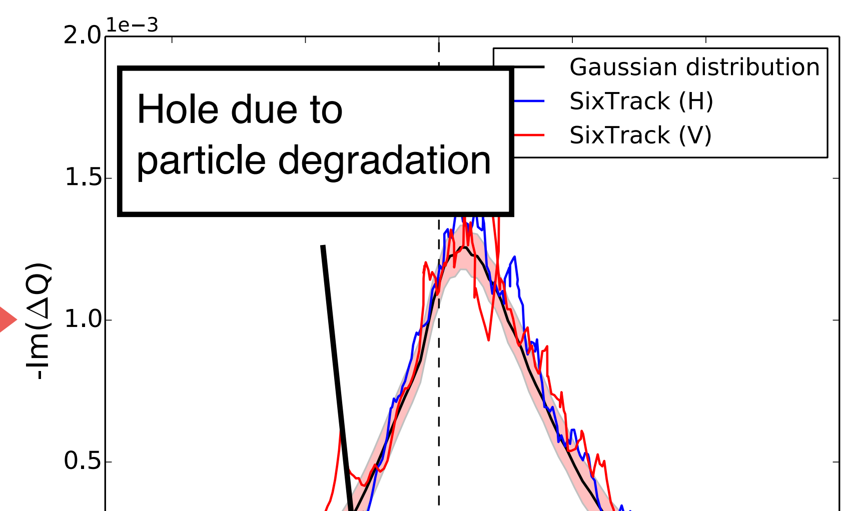








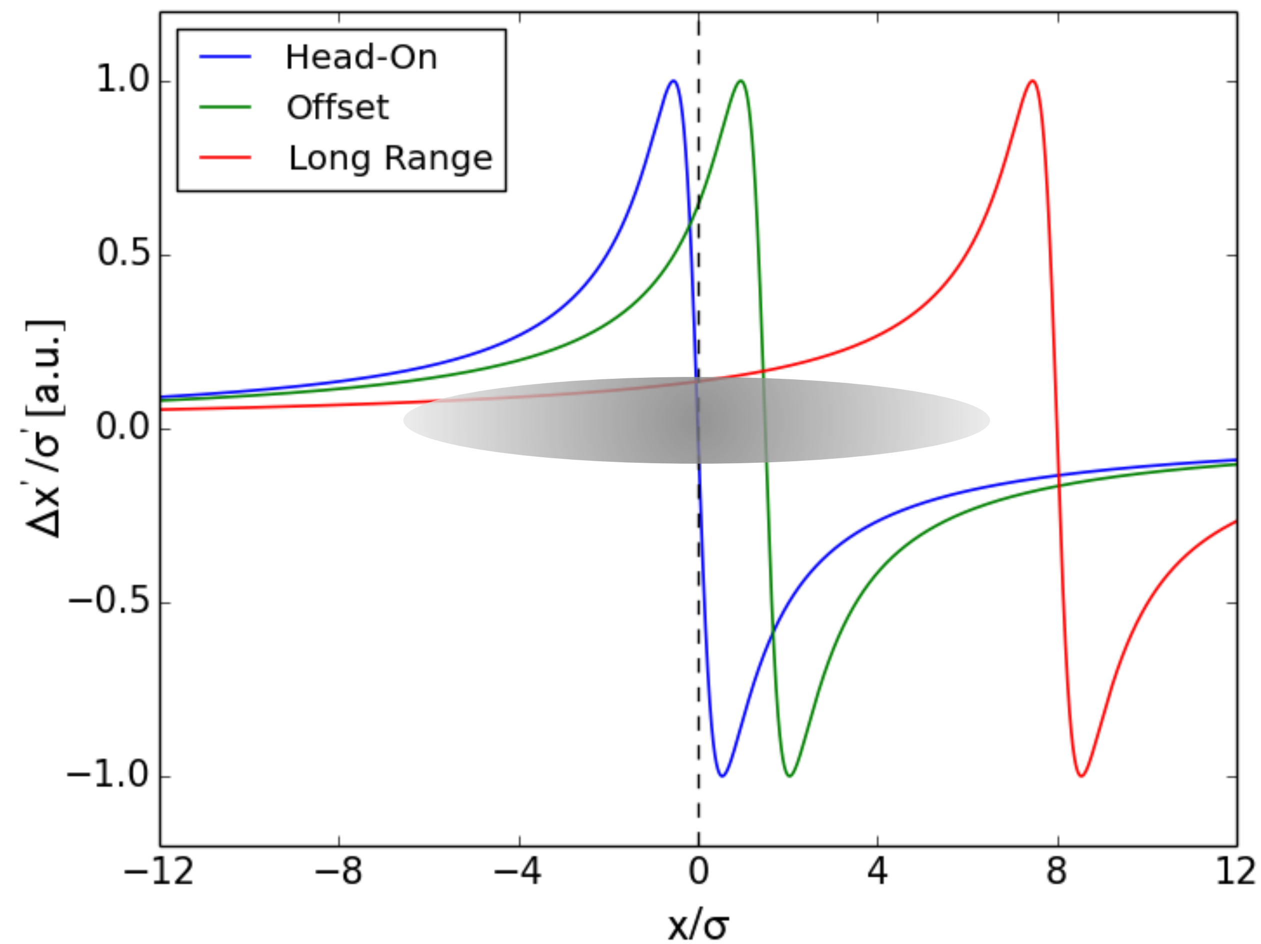
In case of diffusive mechanisms and/or reduced dynamic aperture with particle losses or redistribution → Effects on coherent stability

The Beam-Beam force

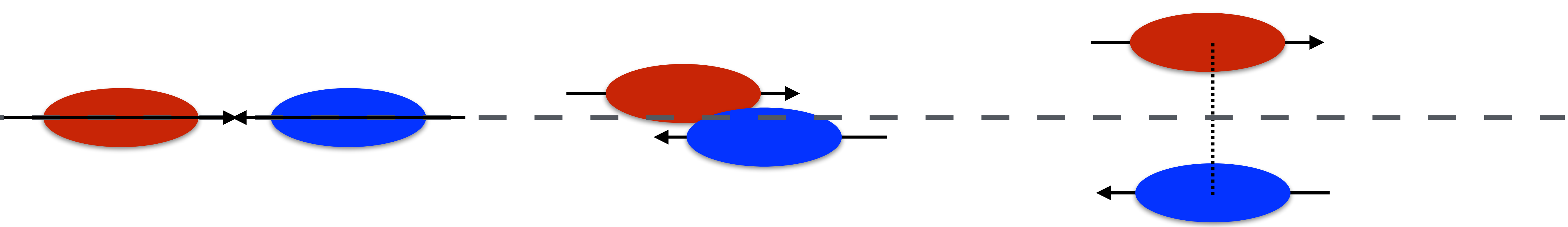
Stronger for high brightness beams

Deflection of a test particle due to the Beam-Beam force (incoherent):

$$\Delta x' = -\frac{2 r_0 N}{\gamma}\frac{x}{r^2}\left(1 - \mathrm{e}^{-\frac{r^2}{2\sigma^2}}\right)$$

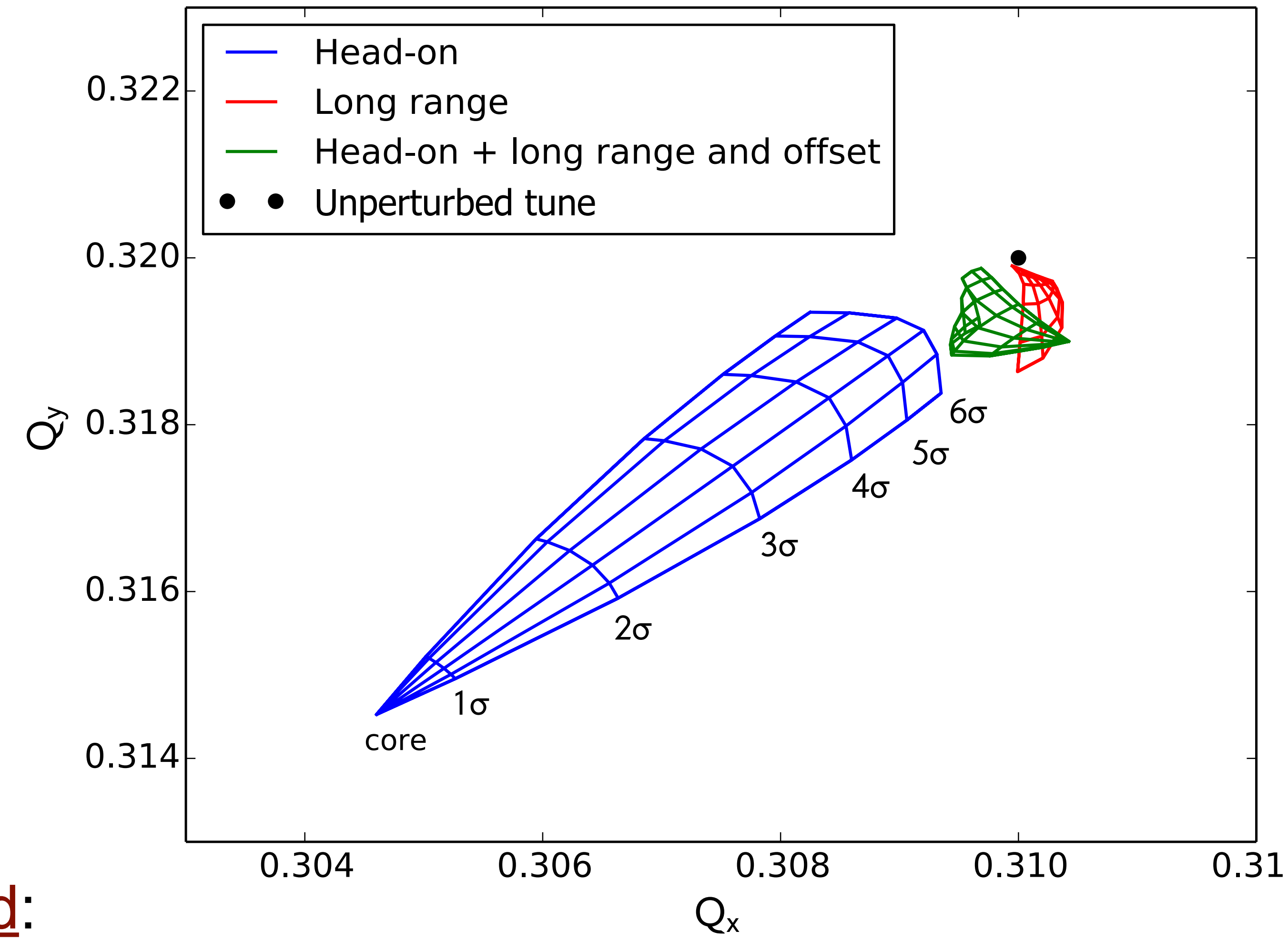


Head-on | **Offset** (sep ~ σ) | **Long range (LR)** (sep >> σ)



Beam-Beam incoherent effects

Tune Footprint with beam-beam



- Particles with different amplitudes oscillate at different betatron frequencies → **detuning with amplitude (tune spread)**

- Each type of beam-beam interaction (LR, HO) produces different incoherent effects

<u>Some sources of (transverse) tune spread</u>:

- Beam-beam interaction (**strongest**)
- Octupole magnets ➔ Used to provide Landau damping in the LHC

Beam-Beam incoherent effects

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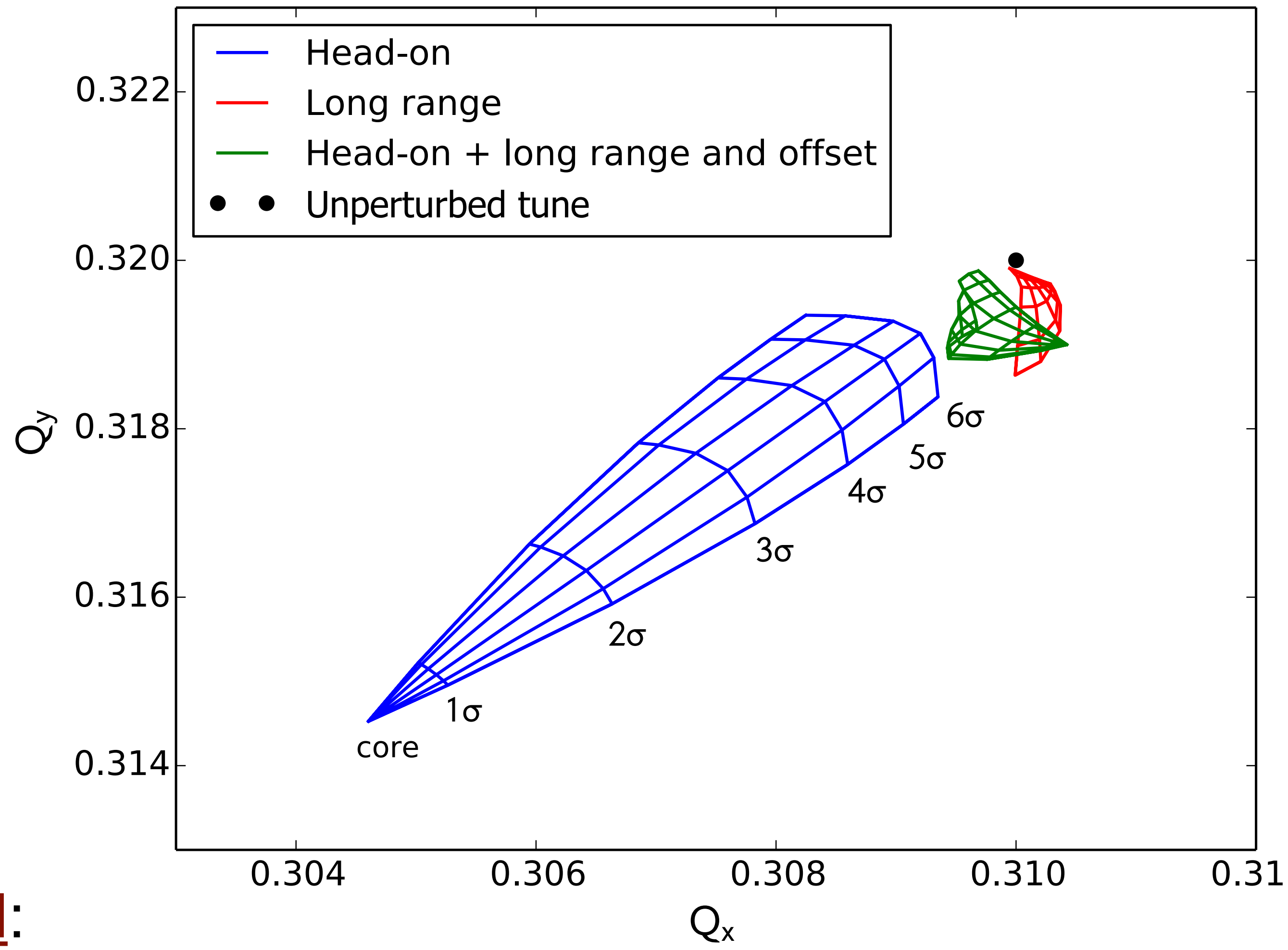
Tune Footprint with beam-beam

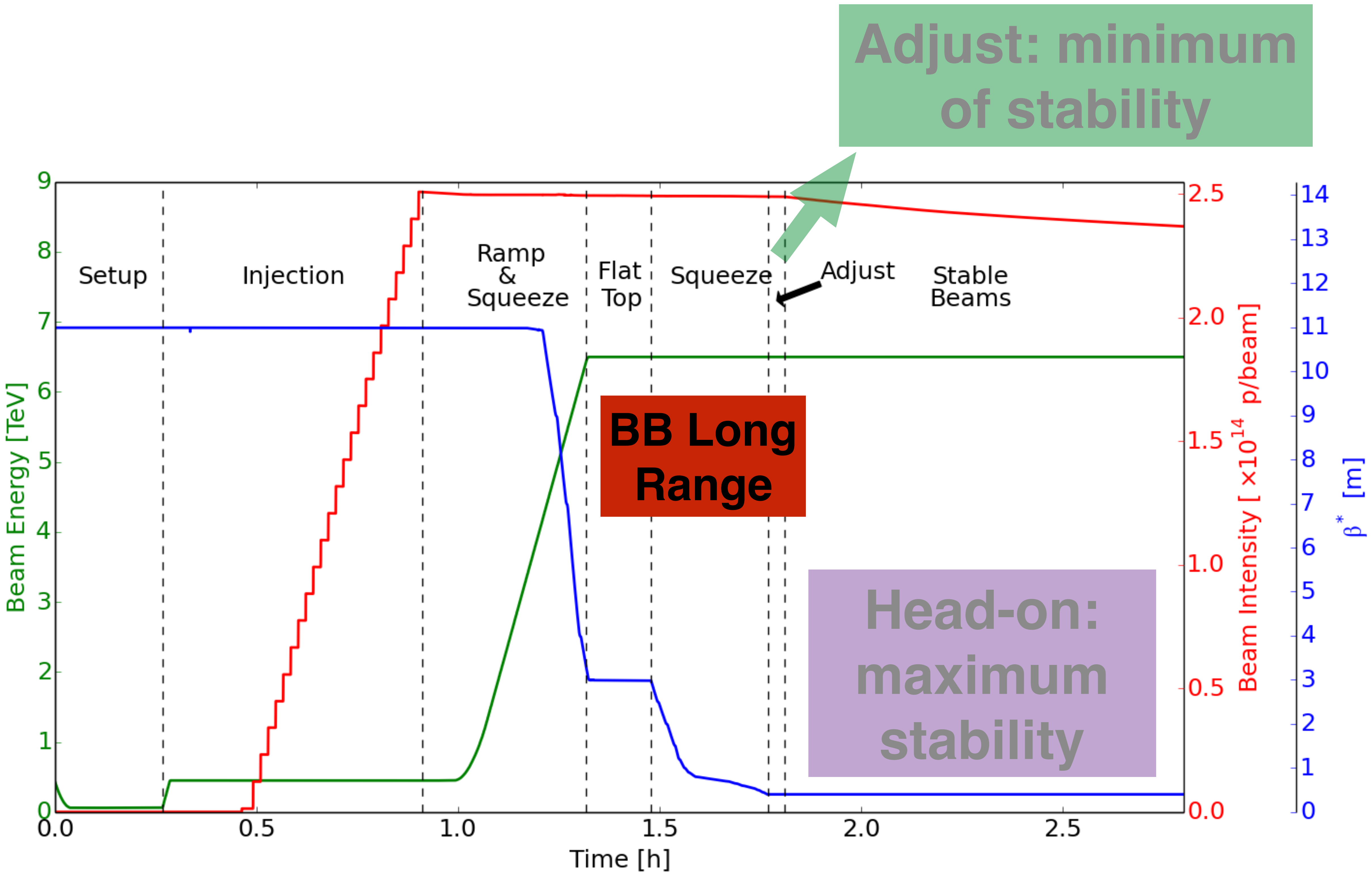


Some sources of (transverse) tune spread:

- Beam-beam interaction (**strongest**)
- Octupole magnets ➔ Used to provide Landau damping in the LHC

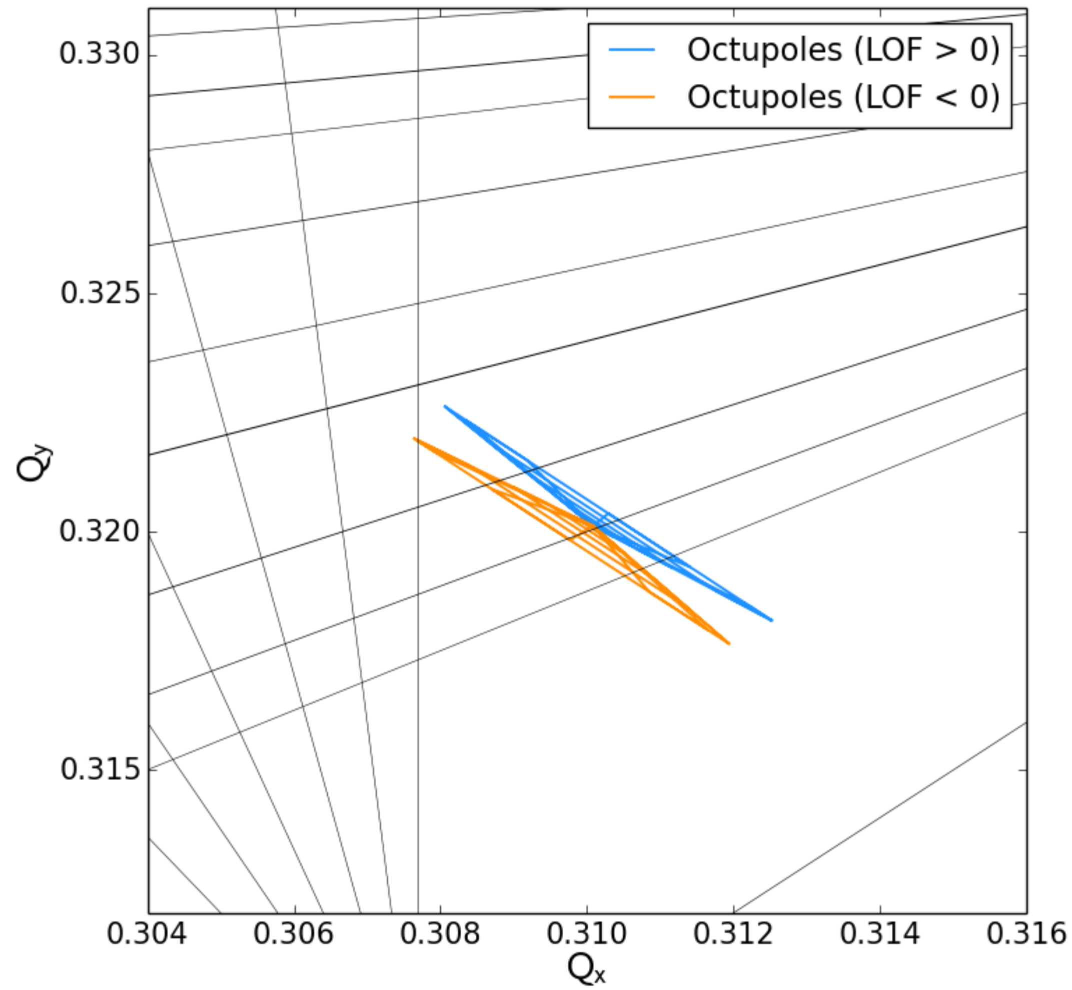
Beam-beam interactions modify the stability provided by the Landau octupoles → tracking needed to evaluate effects (stability diagram [3] and DA [4])

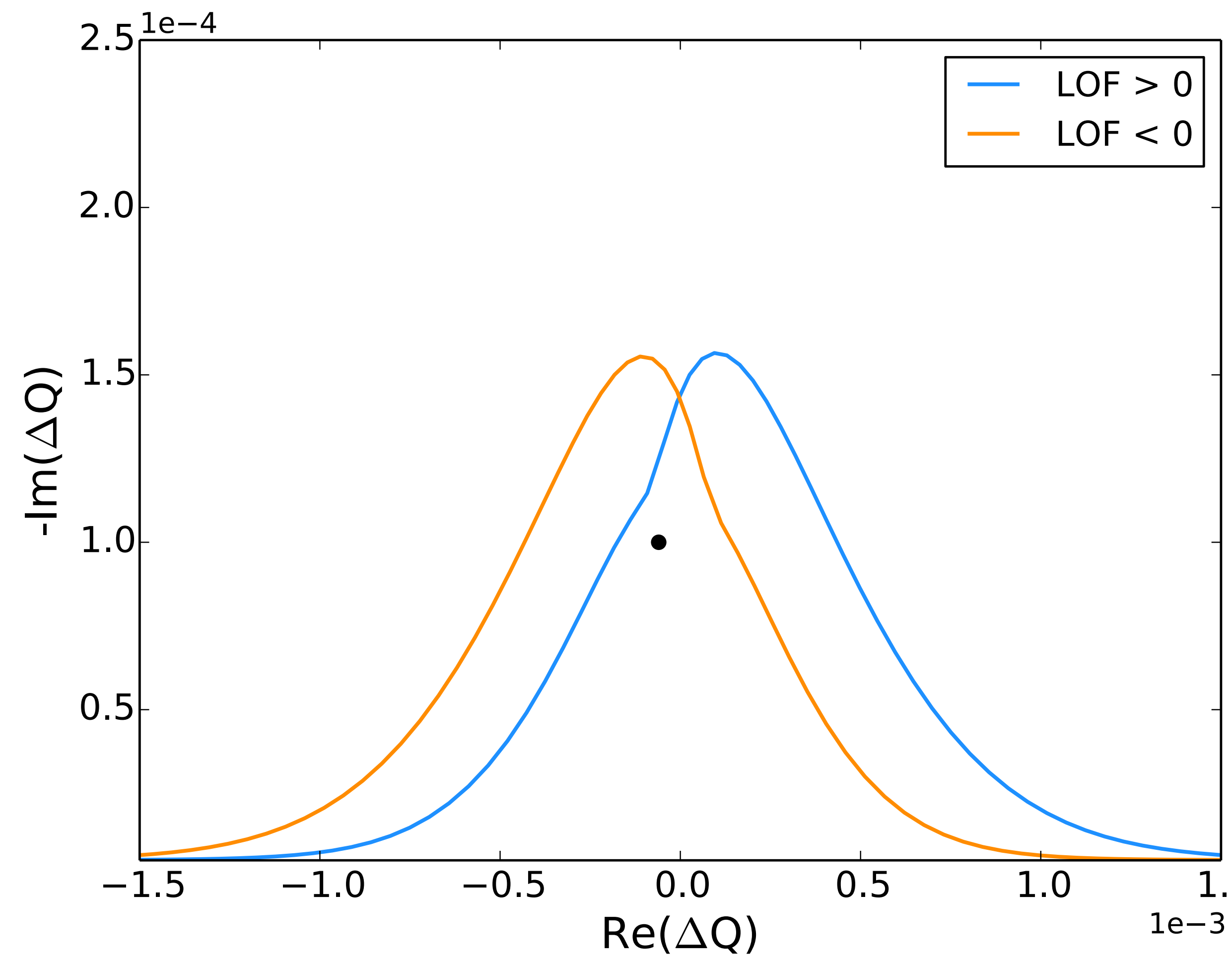
Beam stability during the operational cycle



Stability from octupoles at flat top

FCC case (50 TeV)





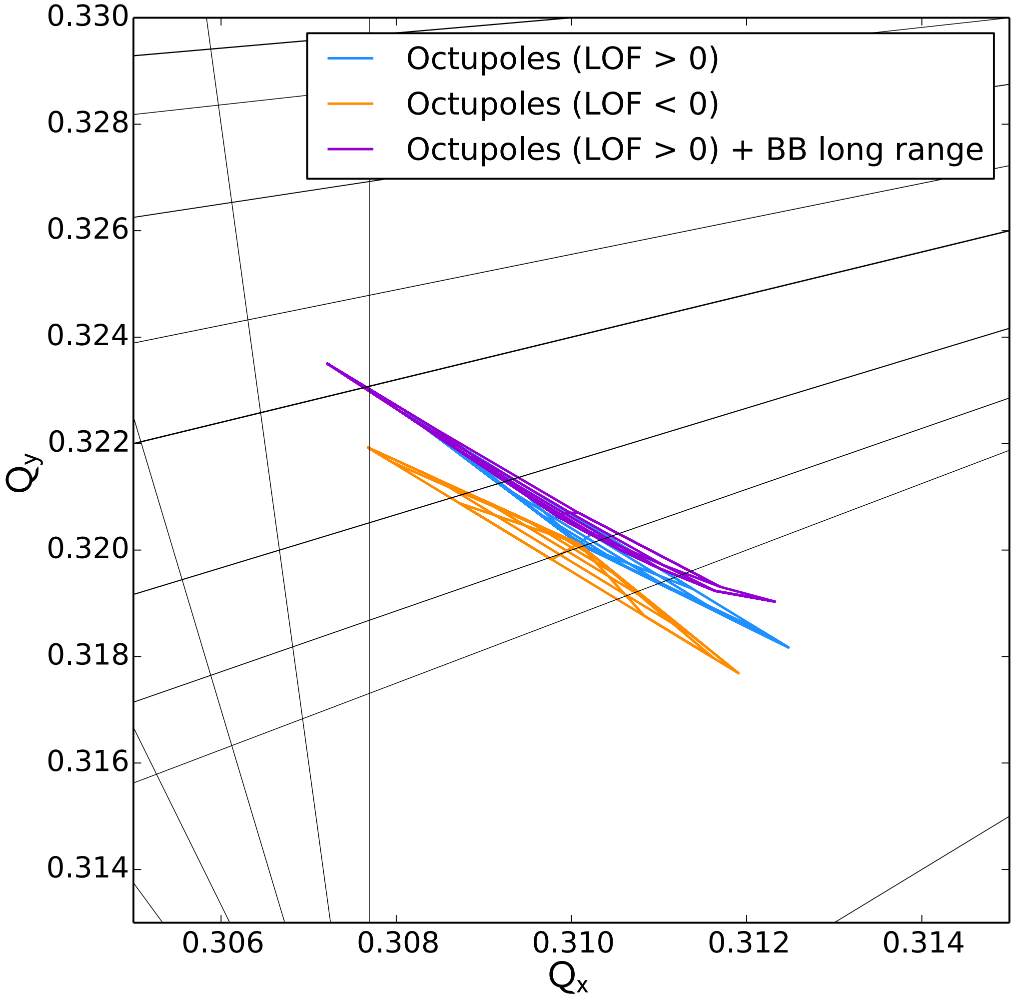
- Beam stability from octupoles magnets with negative and positive polarity

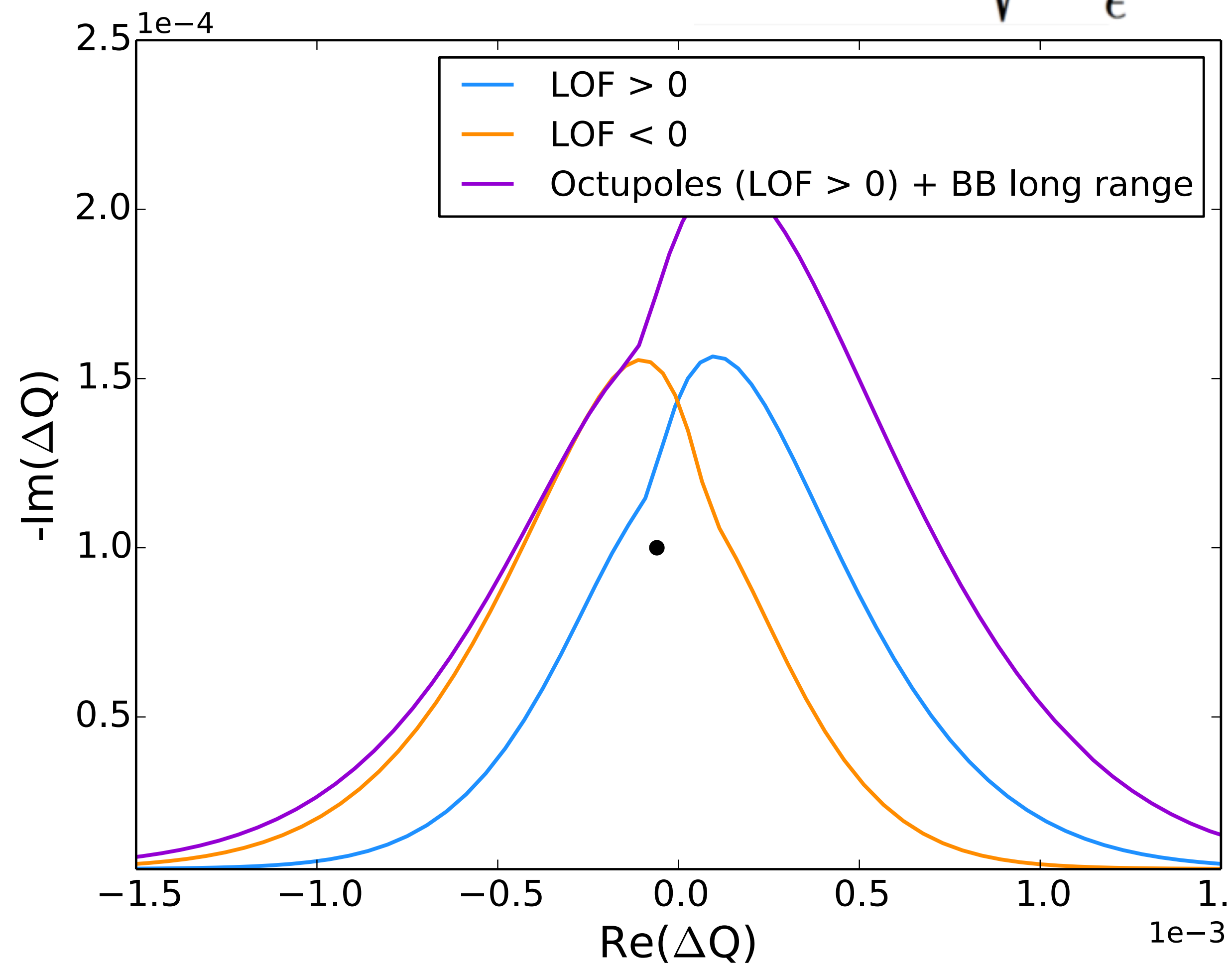
Stability in presence of beam-beam long range (end of squeeze)

BB LR separation:

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

FCC case (50 TeV)

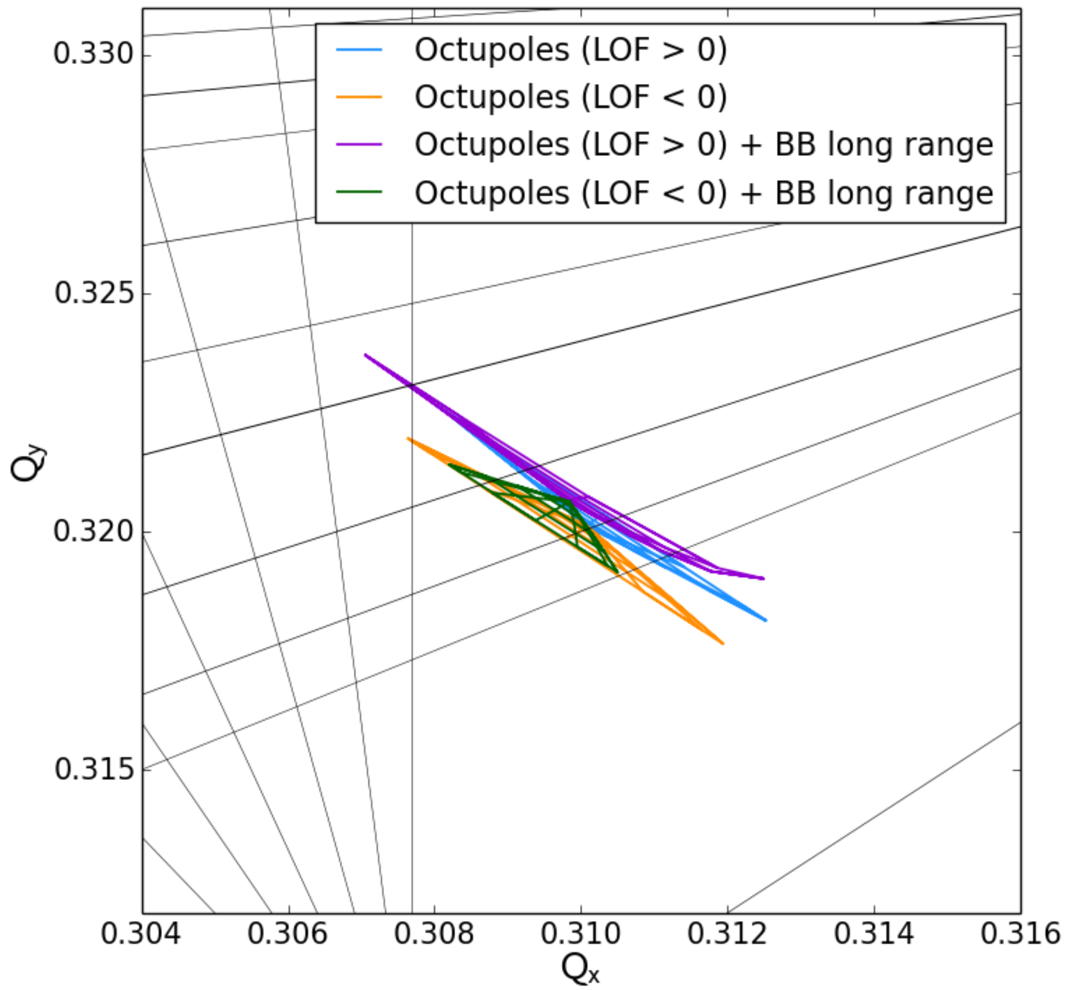


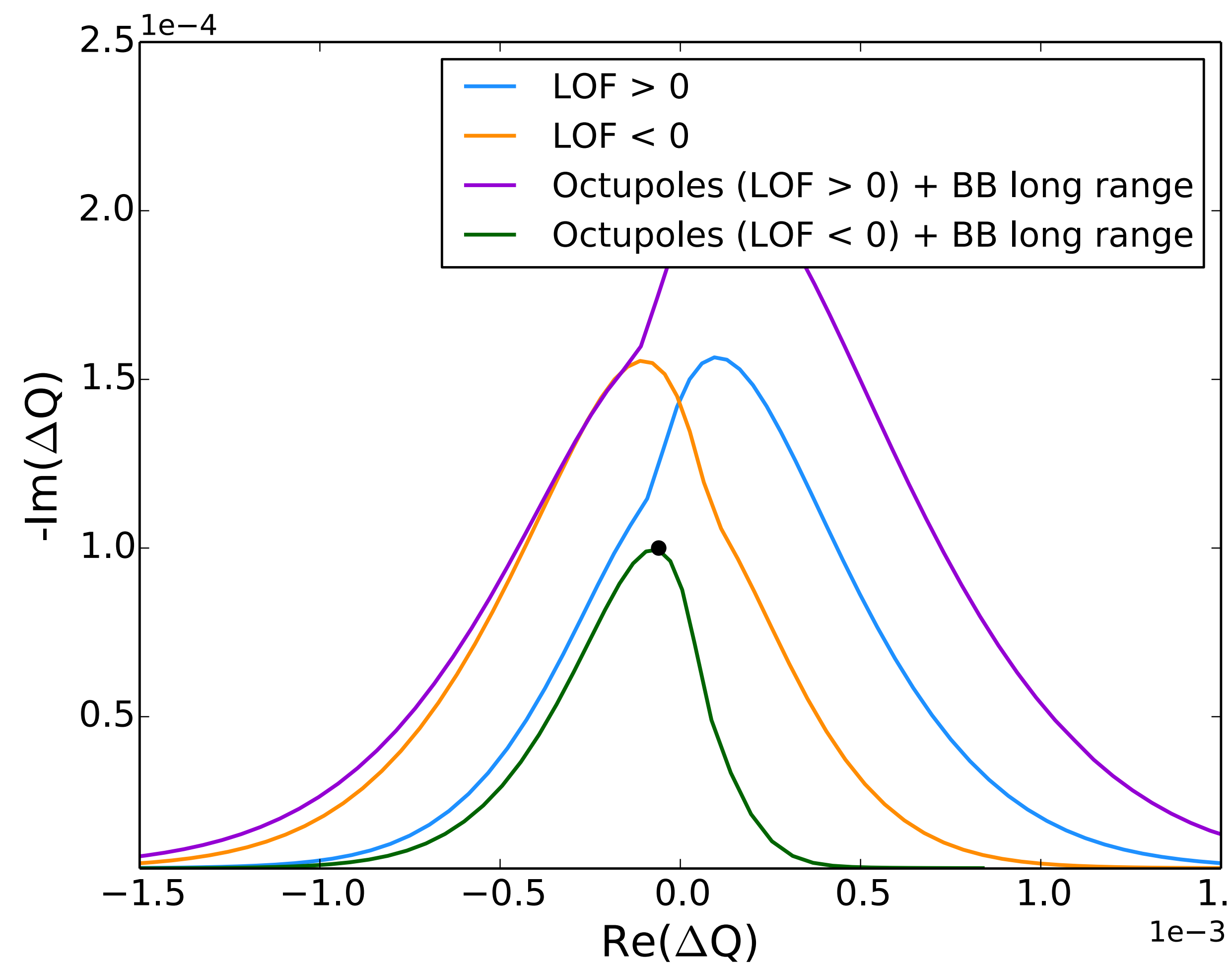


- Beam beam long range interaction (end of squeeze configuration) modifies the stability provided by the Landau octupoles
- With positive octupole polarity and BB long range interactions, the stability with negative polarity is recovered ➔ **impact on DA must to be taken into account**

Stability in presence of beam-beam long range (end of squeeze)

FCC case (50 TeV)

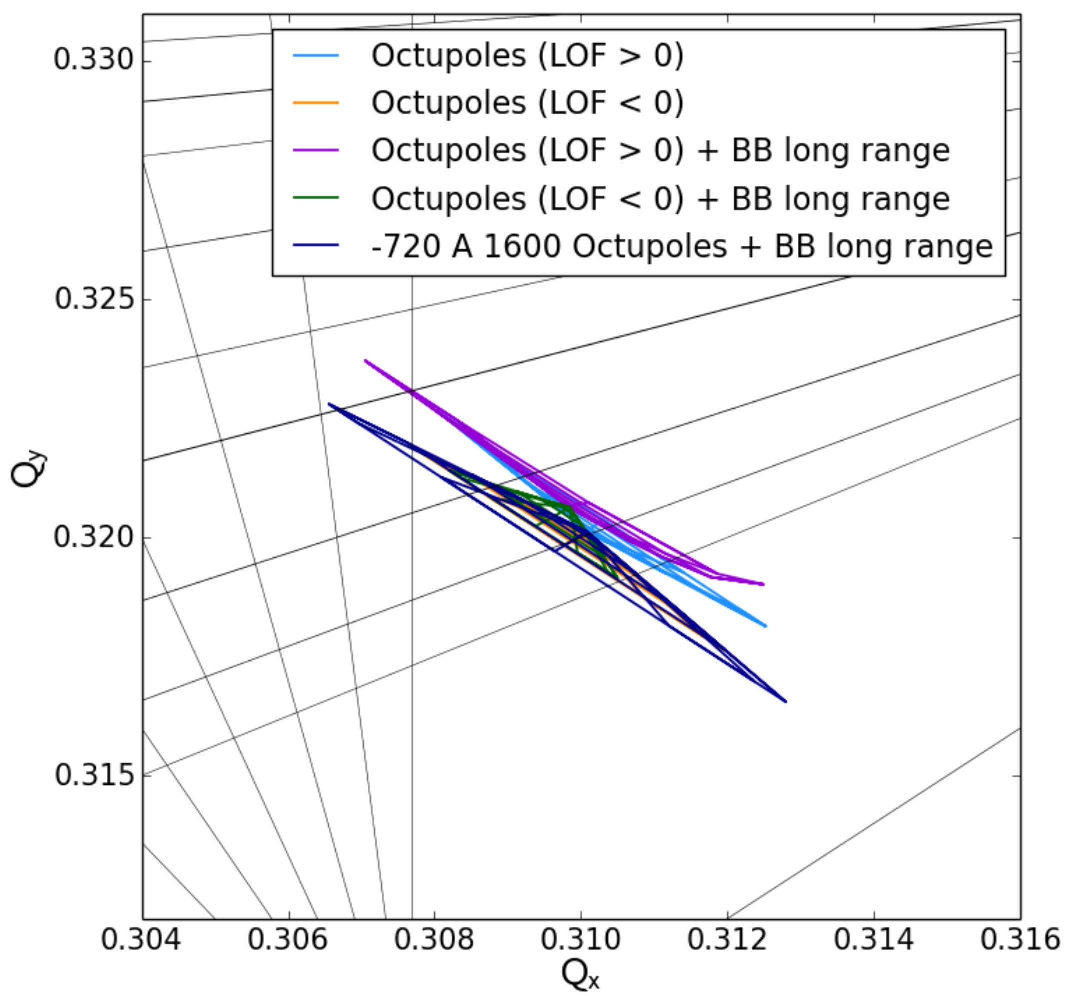


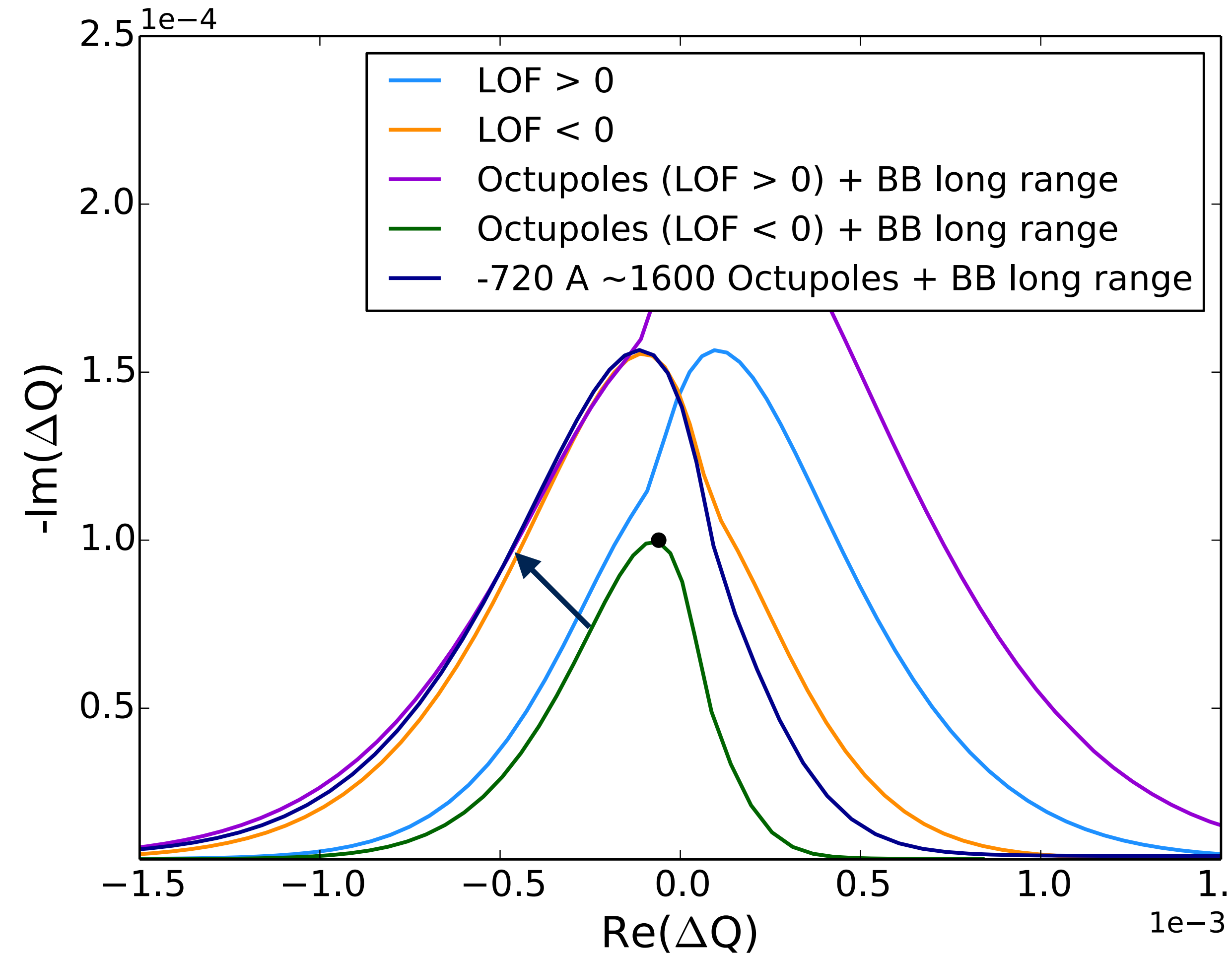


- With negative octupole polarity and BB long range interactions, the stability is strongly reduced ➔ **the coherent impedance mode is not Landau damped**

Stability in presence of beam-beam long range (end of squeeze)

FCC case (50 TeV)

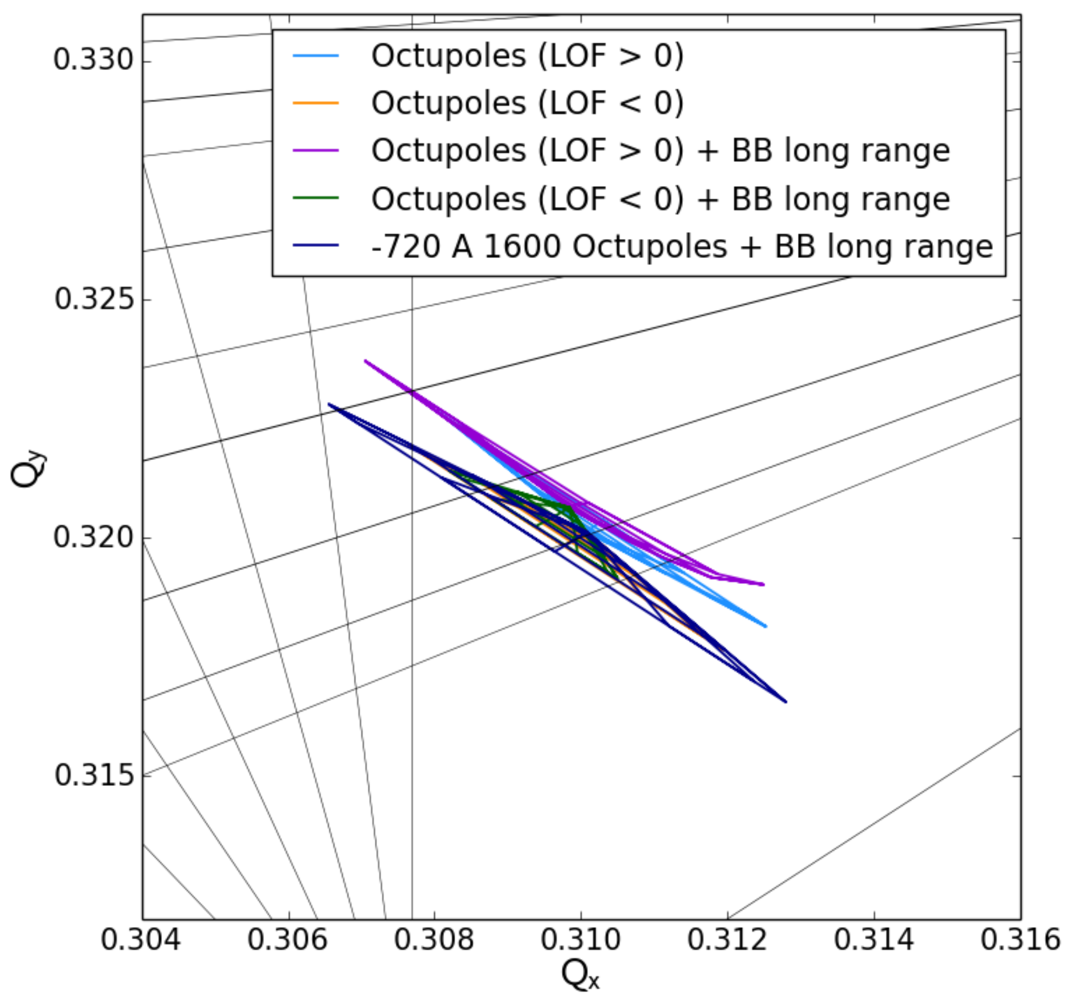


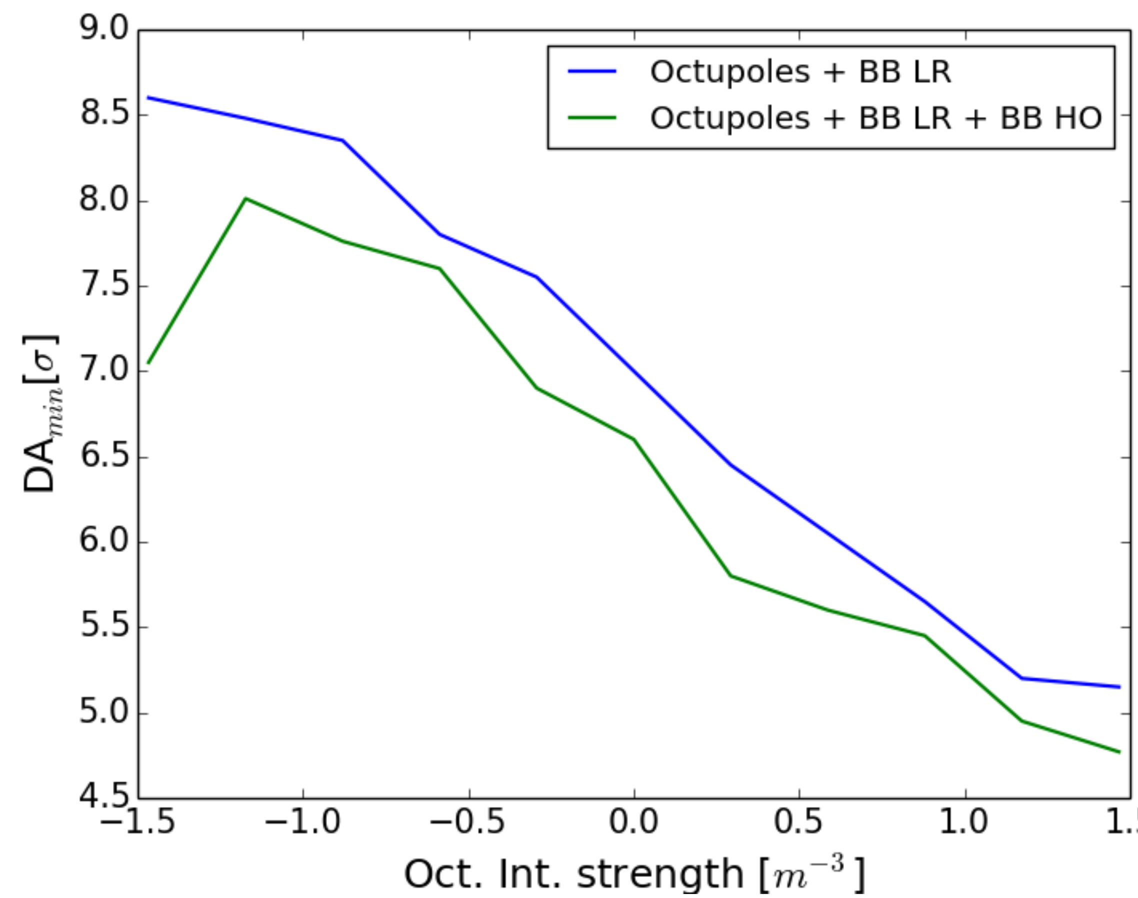


- To compensate stability reduction with negative octupole polarity an increase of the octupole strength is needed

Stability in presence of beam-beam long range (end of squeeze)

FCC case (50 TeV)

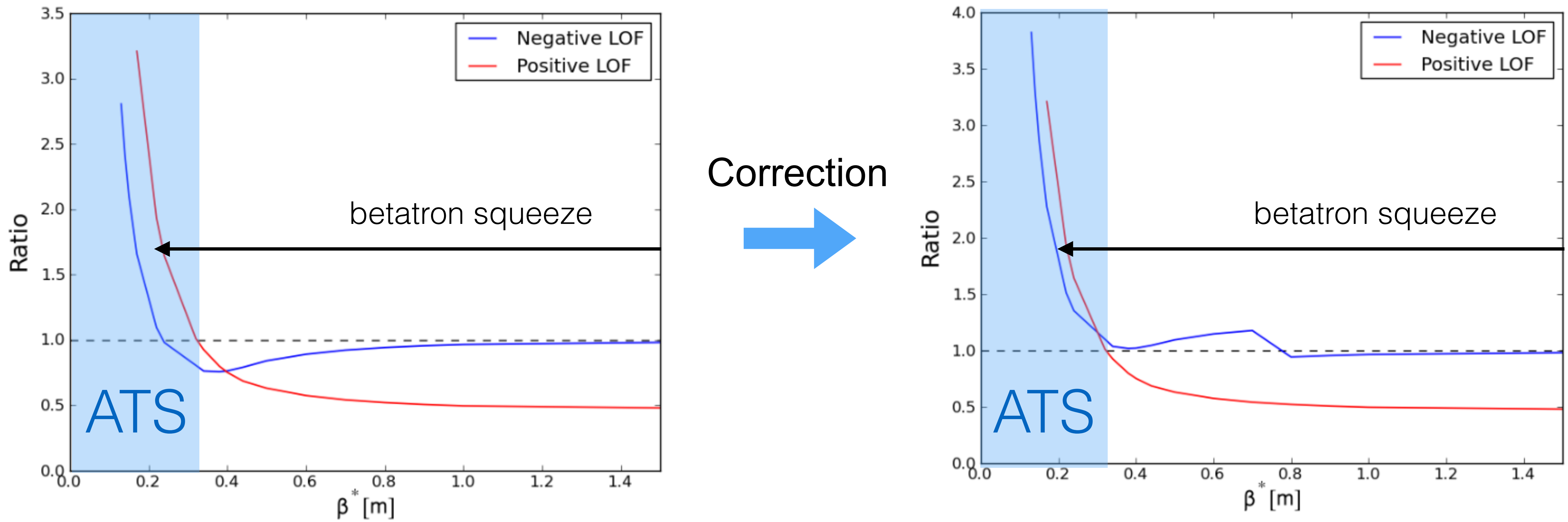




- Beam-beam long range interactions excite resonances, according to the octupole polarity the tune spread (Landau damping) increases or decreases with impact on DA
- **Compensation of LR BB observed for negative octupoles**
- **DA is reduced in case of positive octupole polarity and beam-beam long range**

Compensation of the stability reduction during the betatron squeeze

HL-LHC CASE (BASELINE SCENARIO β*=70)

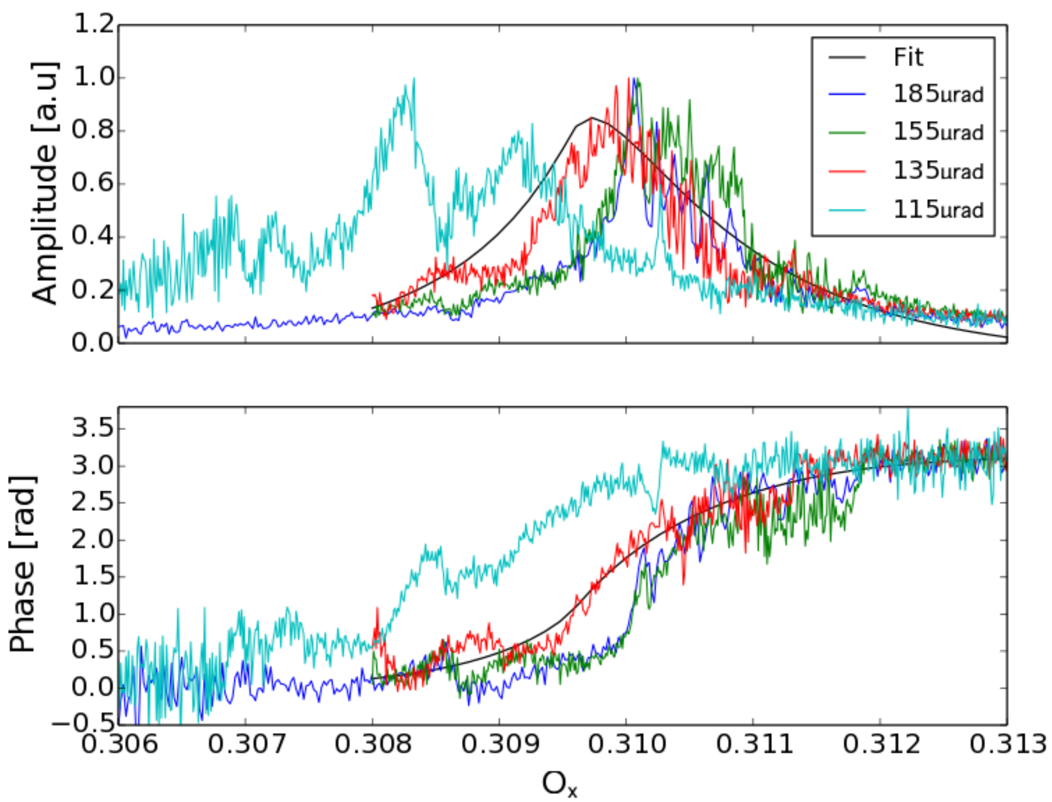


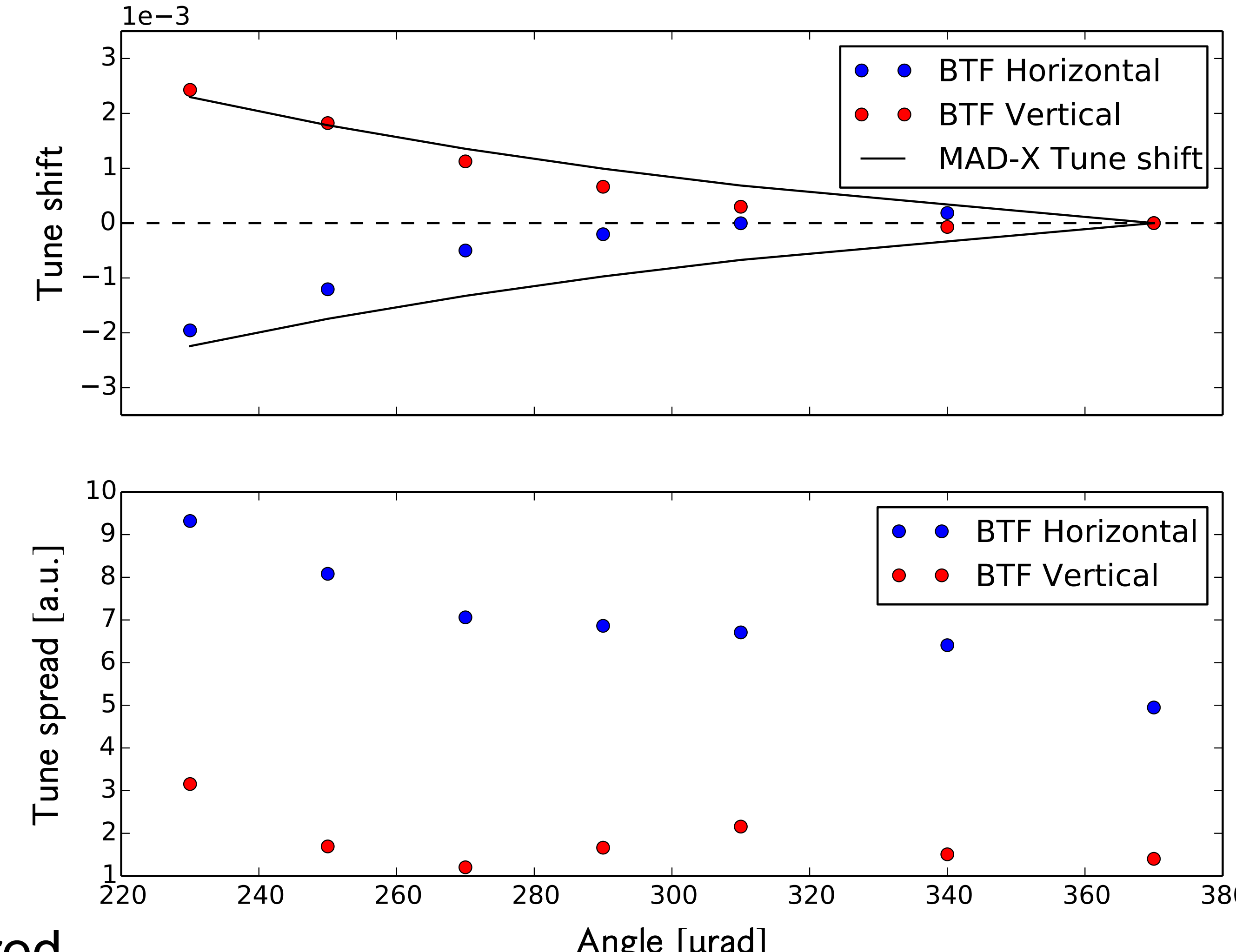
By applying a correction of the β-function of the 8% (ATS [7] contribution) in the arcs from β^*=70 cm the stability reduction is compensated

[7] S. Fartoukh, Achromatic telescopic squeezing scheme and application to the LHC and its luminosity upgrade Phys. Rev. ST Accel. Beams 16

Tune spreads and tune shifts due to beam-beam long range interactions

Crossing angle scan at the IPs → **Beam-beam long range separation scan to measure beam-beam long range contribution to stability**

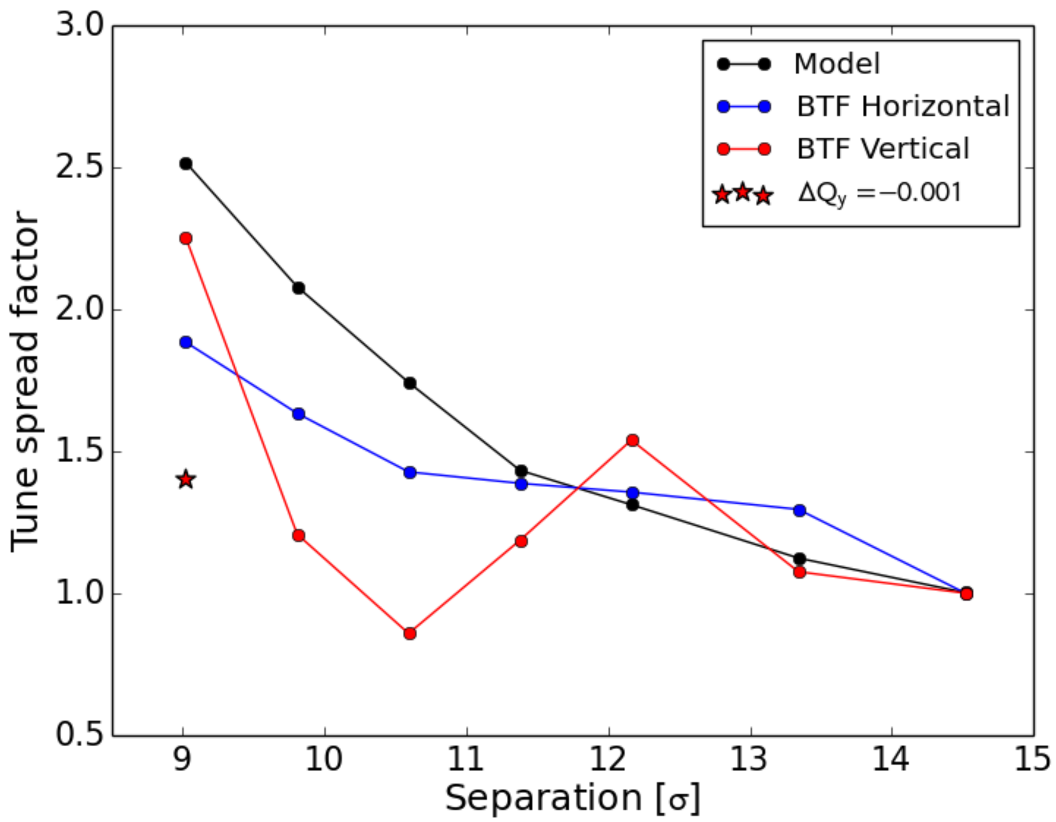


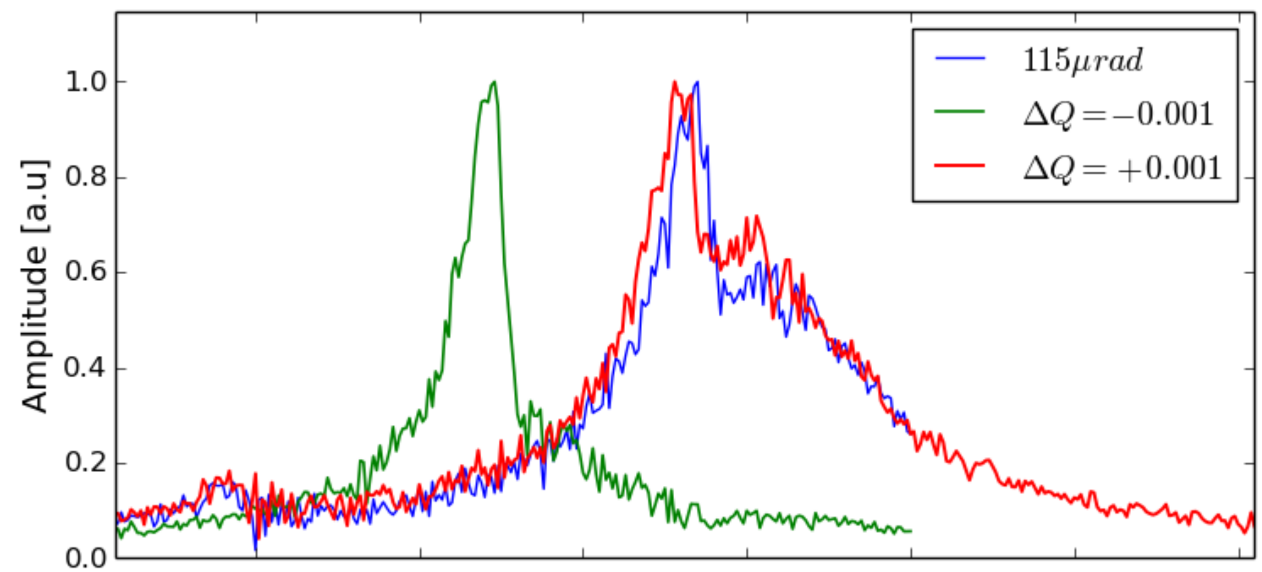


- Asymmetric tune spread and shifts in horizontal/vertical planes
- Tune shifts are comparable with measured tune shifts from beam-beam LR

BTF measurements with BB long range interactions

Measured LR contribution on the stability diagram as a function of crossing angle step (bb LR separation) respect to EOS (positive octupole polarity)





- Unexpected behavior respect to models
- Dependence on working point
- Not expected from models, it may have strong impact on SD

→ Other mechanisms should play a role

2012 Physics Run configuration at the end of betatron squeeze

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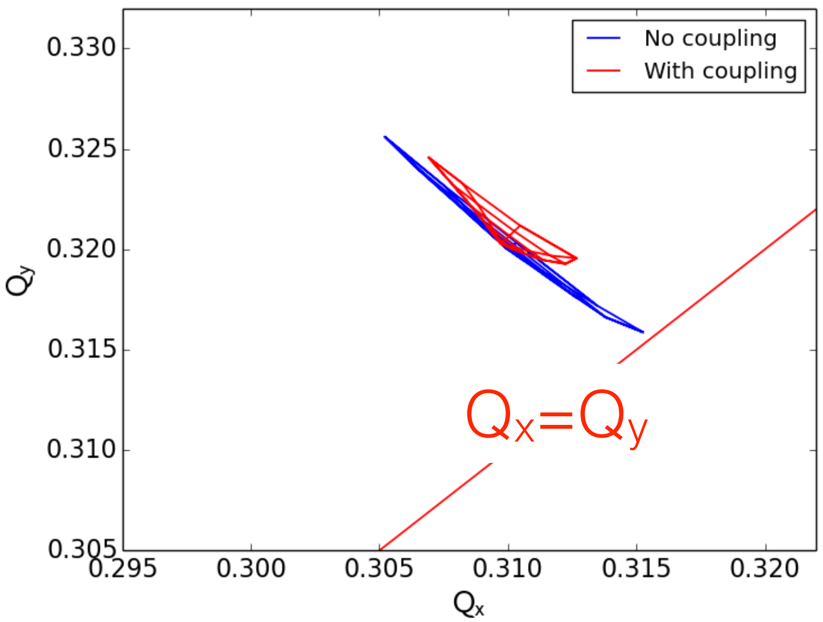
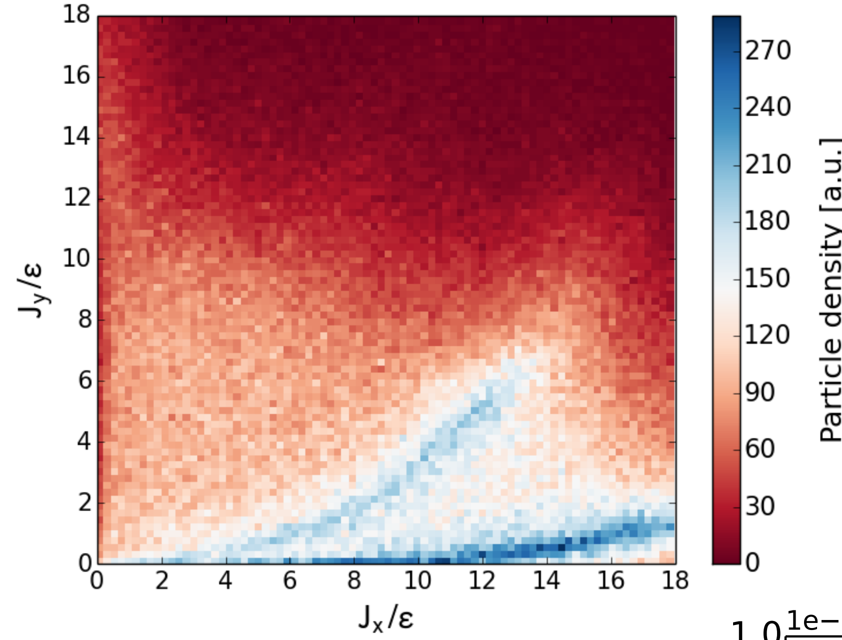
Amplitude Detuning

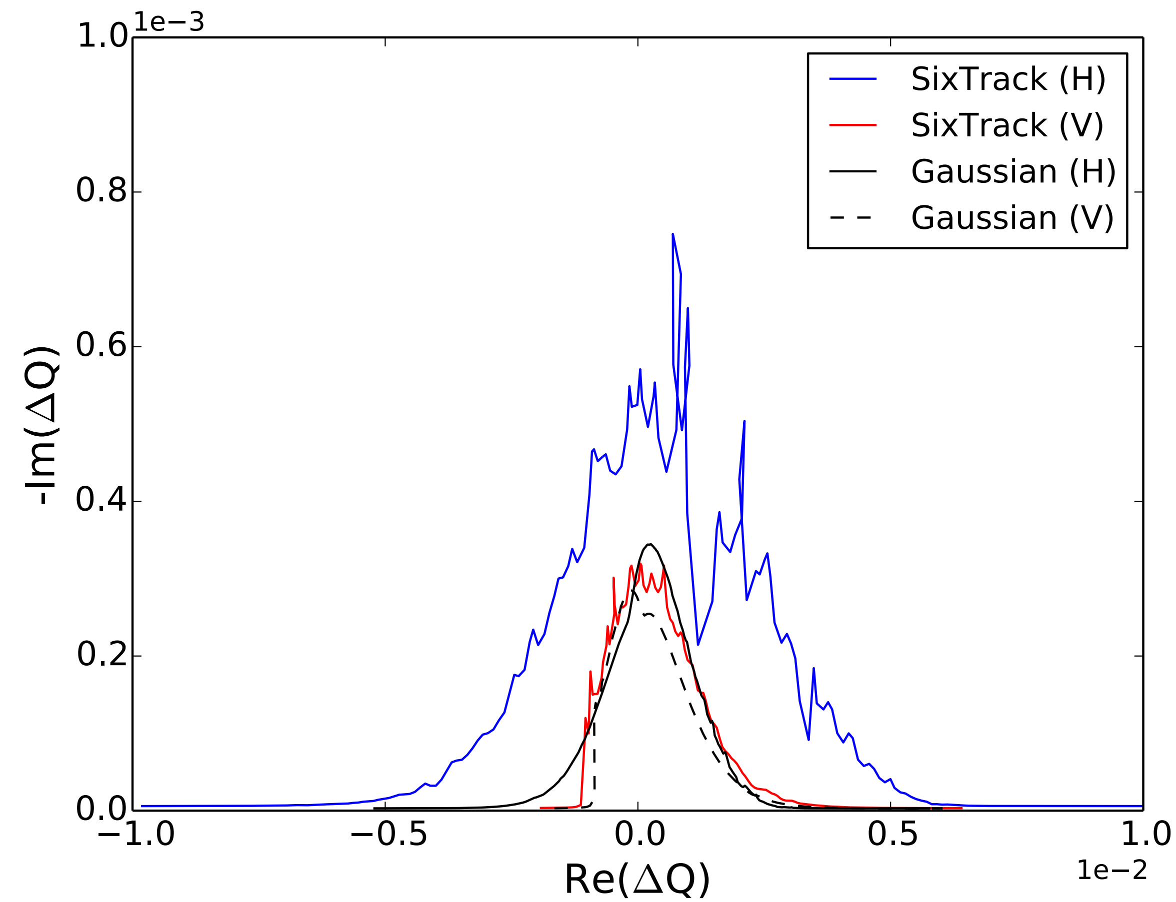


Tracked distribution



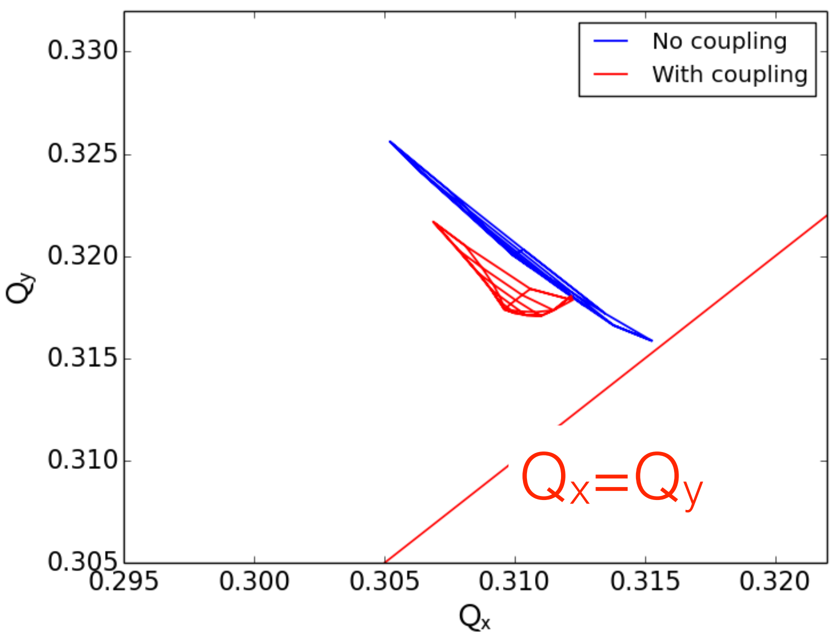
Important effect visible for larger footprint (as in 2012 end of betatron squeeze)

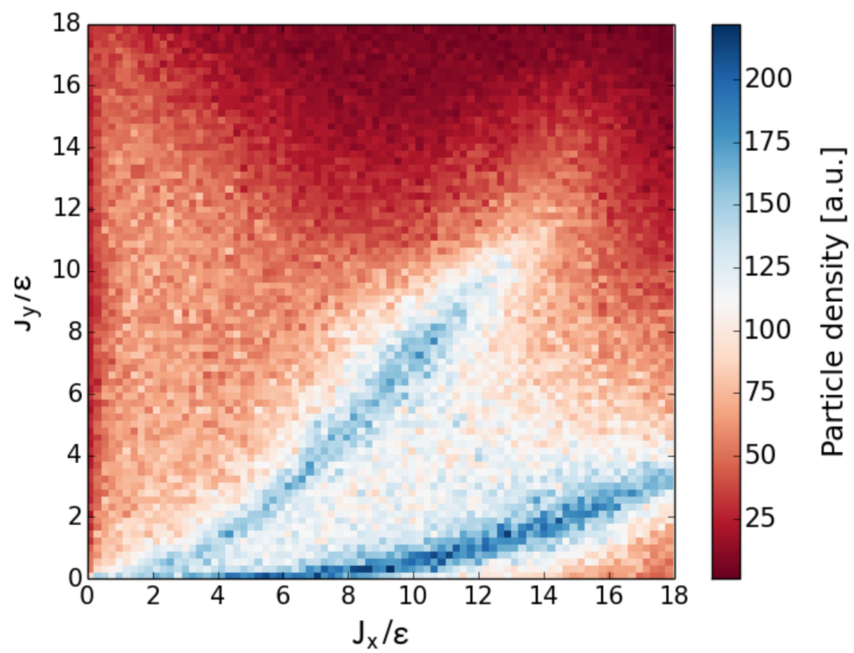
- Visible cut in the computed stability diagram
- Strong effect on the particle distribution



2012 Physics Run configuration at the end of betatron squeeze

Vertical tune shift: ΔQ_y= -0.003

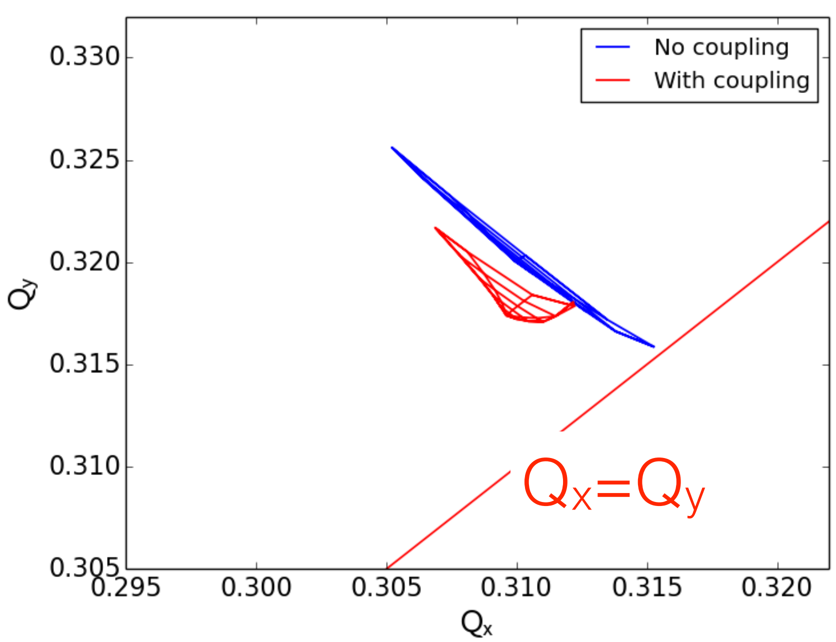


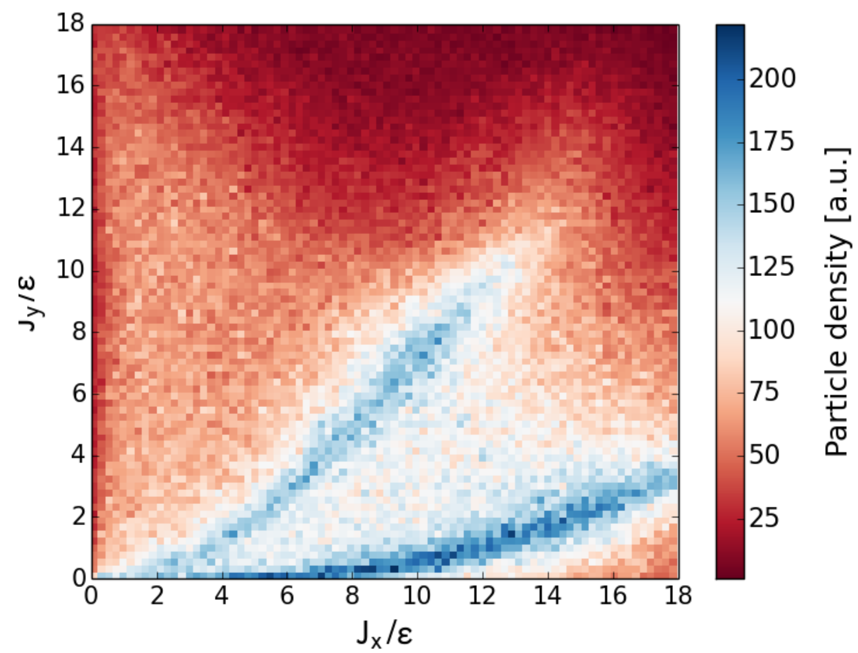


Particles approach more the diagonal and the effects are stronger

2012 Physics Run configuration at the end of betatron squeeze

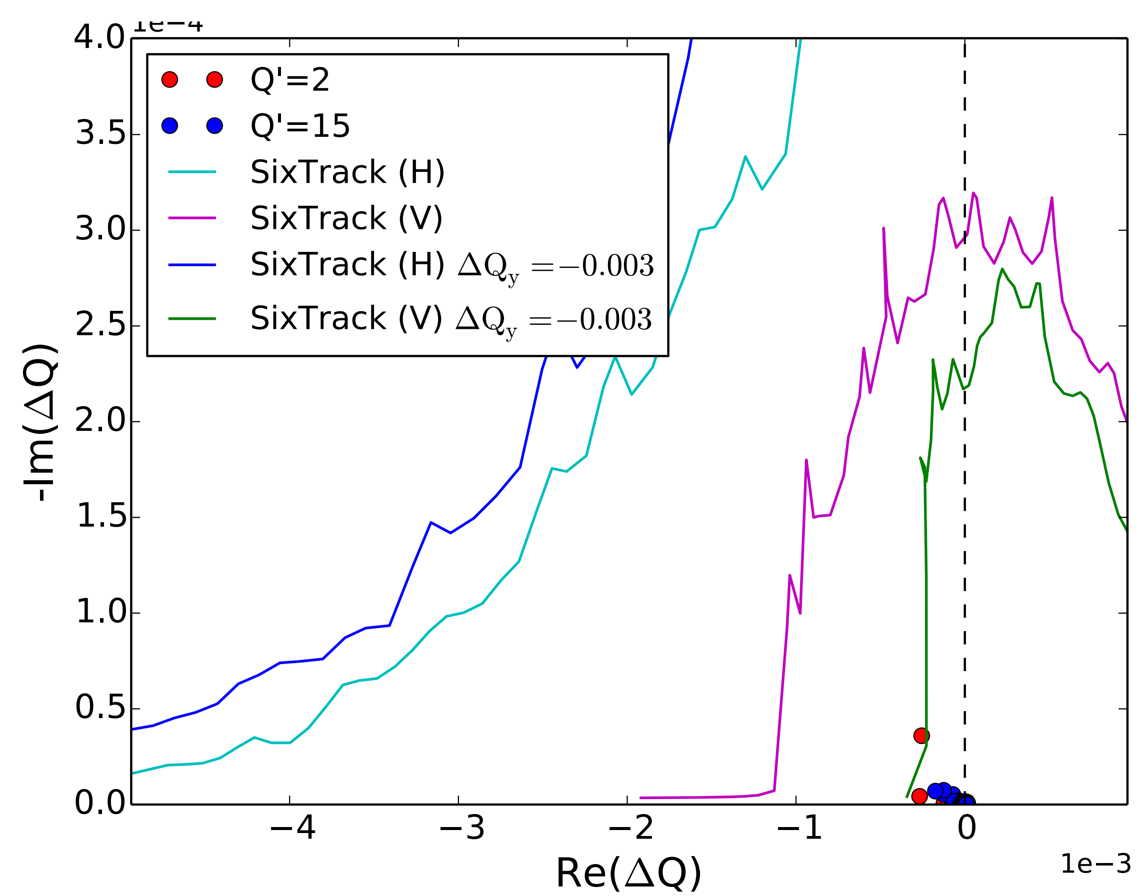
Vertical tune shift: ΔQ_y= -0.003



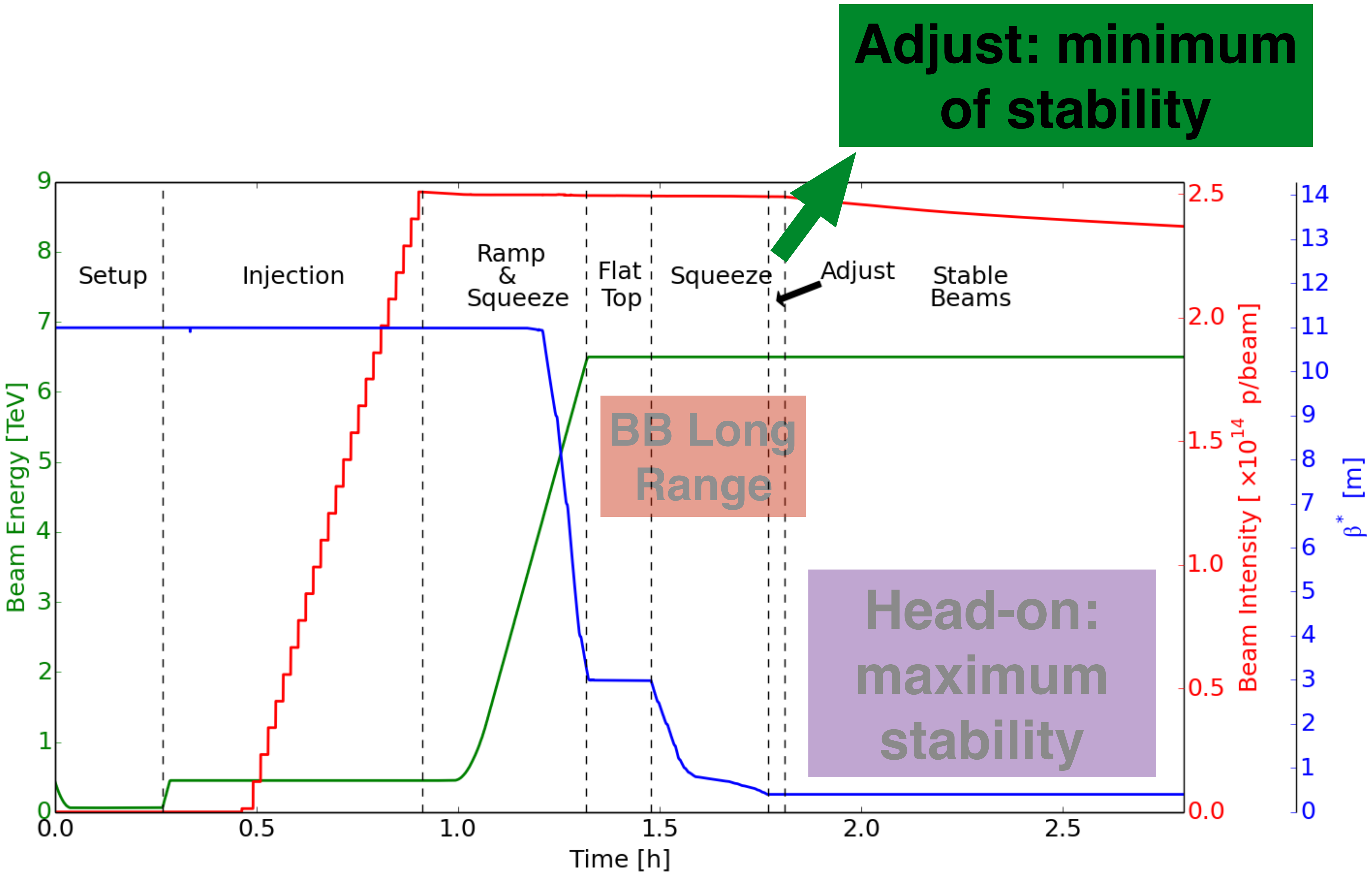


Particles approach more the diagonal and the effects are stronger

- Large effects of working point
- Sharp cut visible in the vertical SD (0 - 3 σ particles approach the diagonal)
- Modes can become unstable

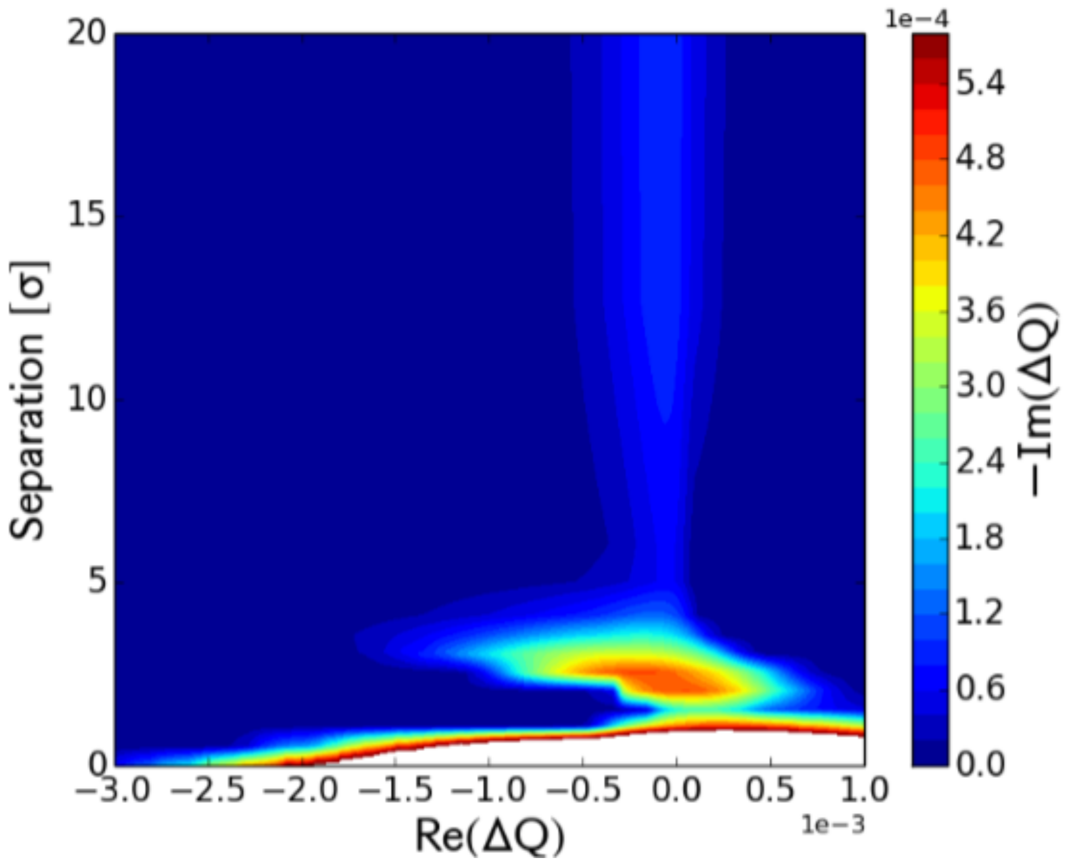


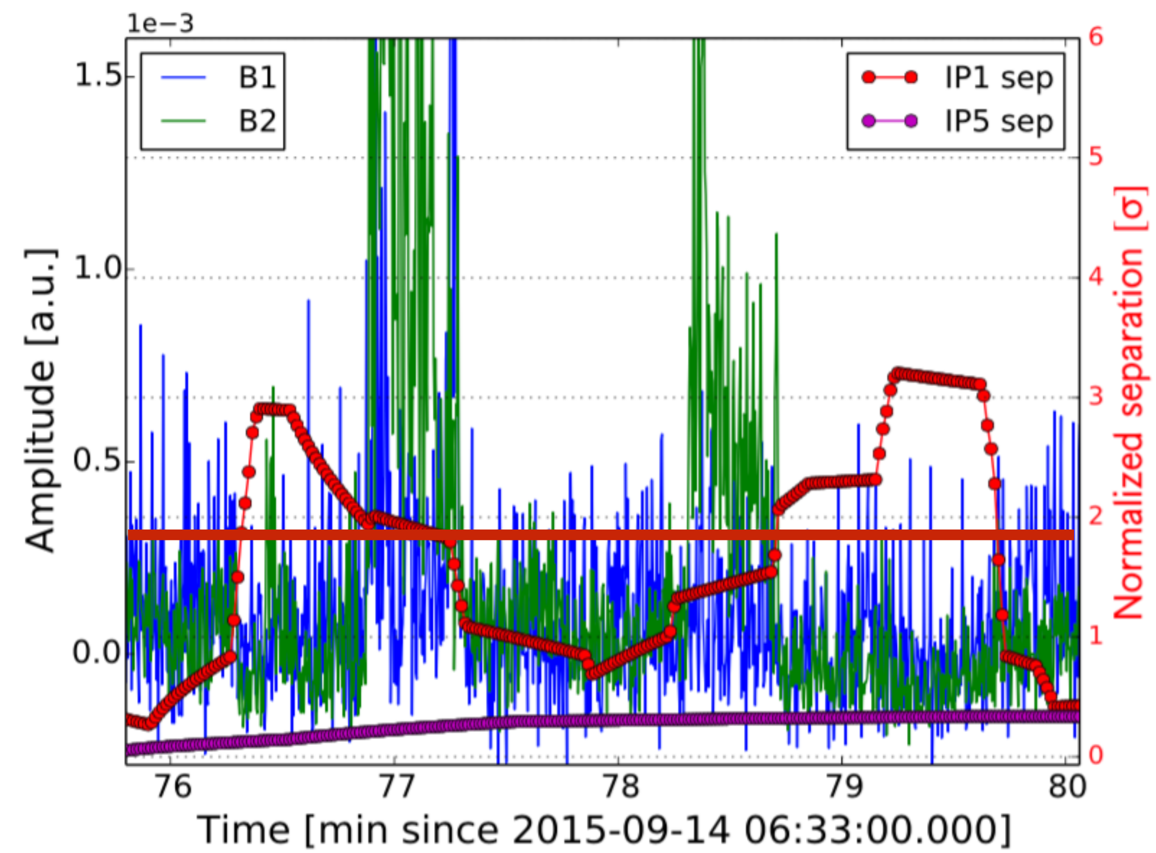
Beam stability during the operational cycle



Stability during the adjust beam process (collision process)

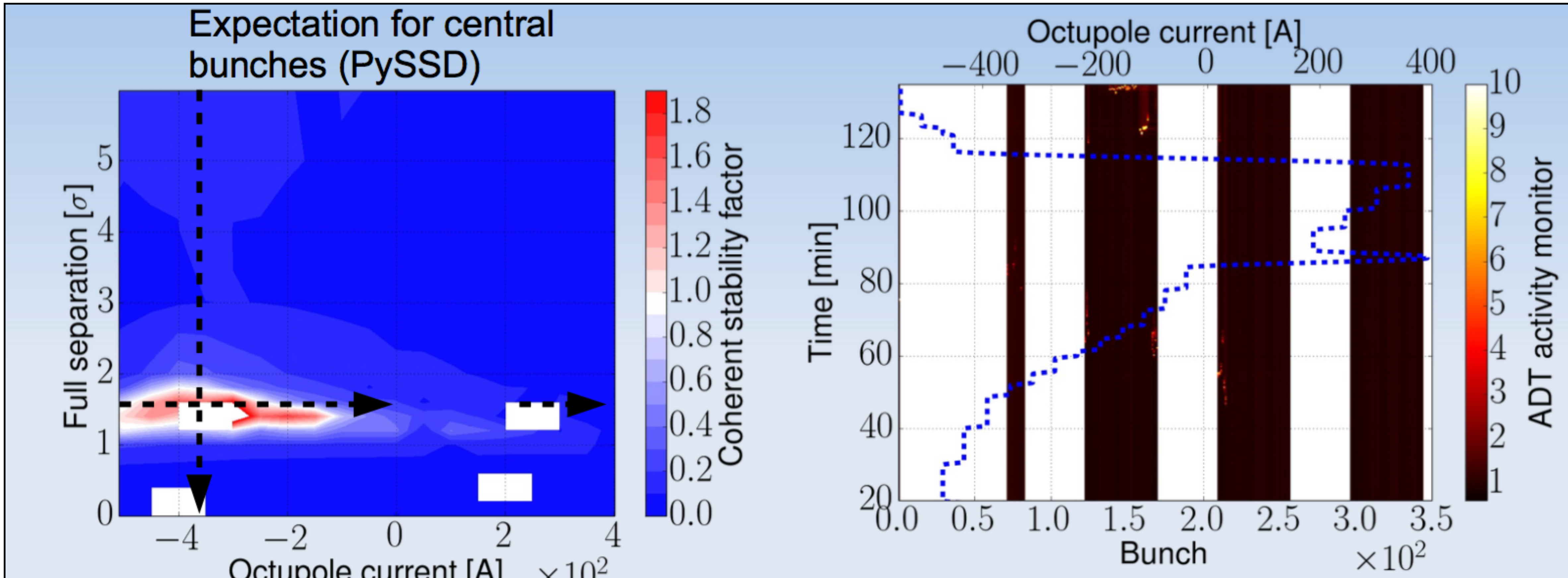
HL-LHC Baseline scenario





- Two minima expected with negative polarity, one with positive octupole polarity [2, 3]
- The minimum is about 1.5-2 σ separation
- Several instabilities observed at this moment: we need to pass through this minimum very fast (LHC: ~40s)

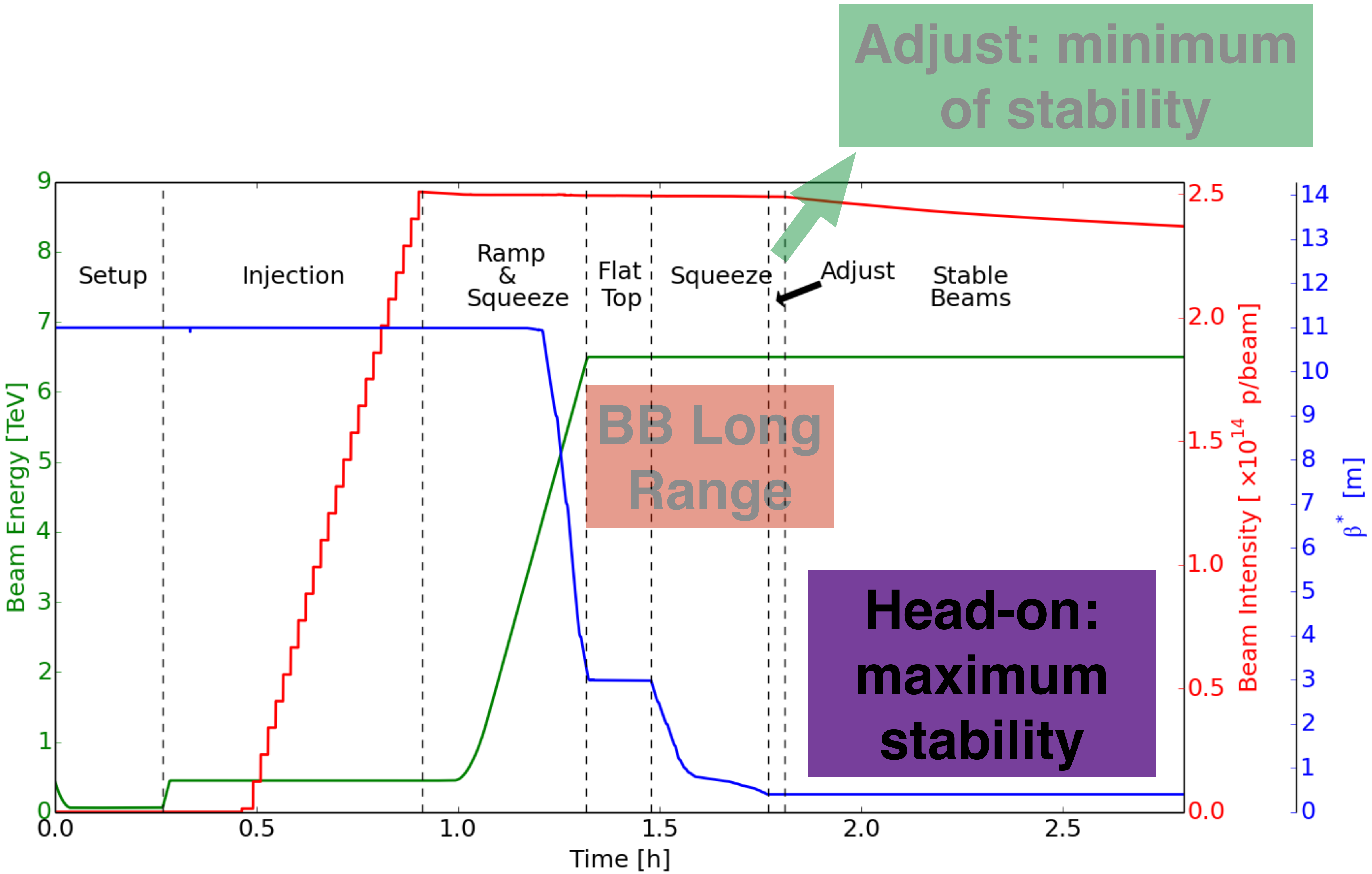
Measurements in the LHC in 2017



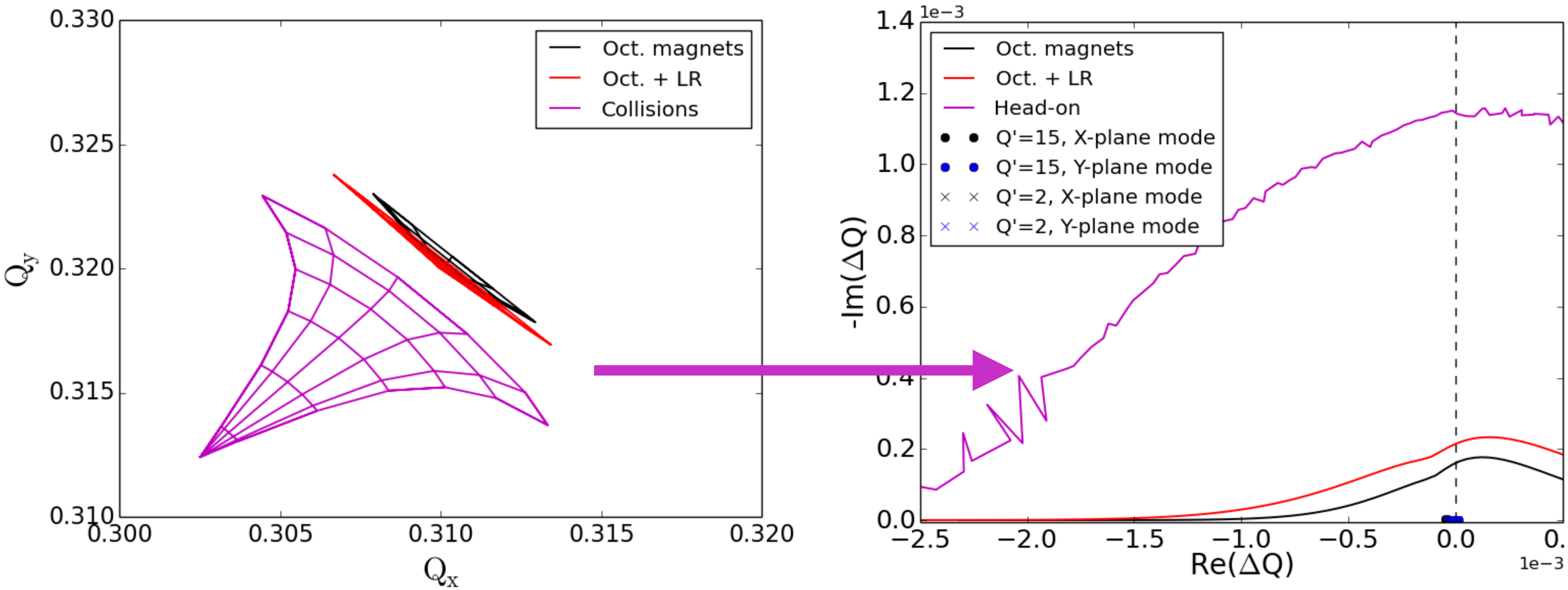
X. Buffat, S. Antipov, E. Métral, S. Fartoukh

- The octupole scan is performed at the separation of minimum stability ~1.5 σ
- The instability is expected at ~ -400 A ➞ central bunches became unstable at -550 A (end of the scan) which may be due to additional non-linearities
- Additional proof of the instability mechanism proposed and confirmed already in 2012 [2, 3] and observed e.g. last year during VdM scans for LHCb and ALICE (positive oct. polarity)

Beam stability during the operational cycle



Stability provided by head-on collisions

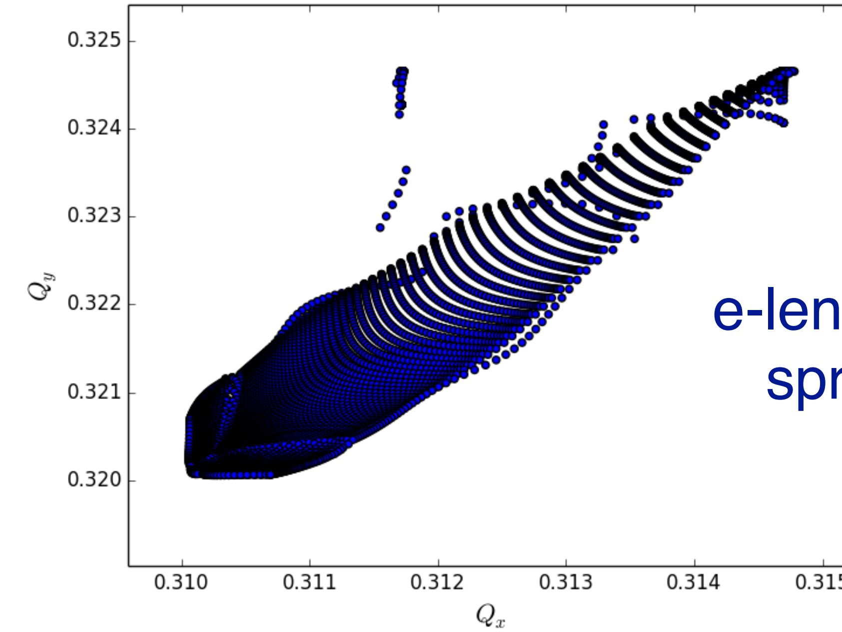


Beam-beam head-on: strongest non linearity → Largest stability of the beams

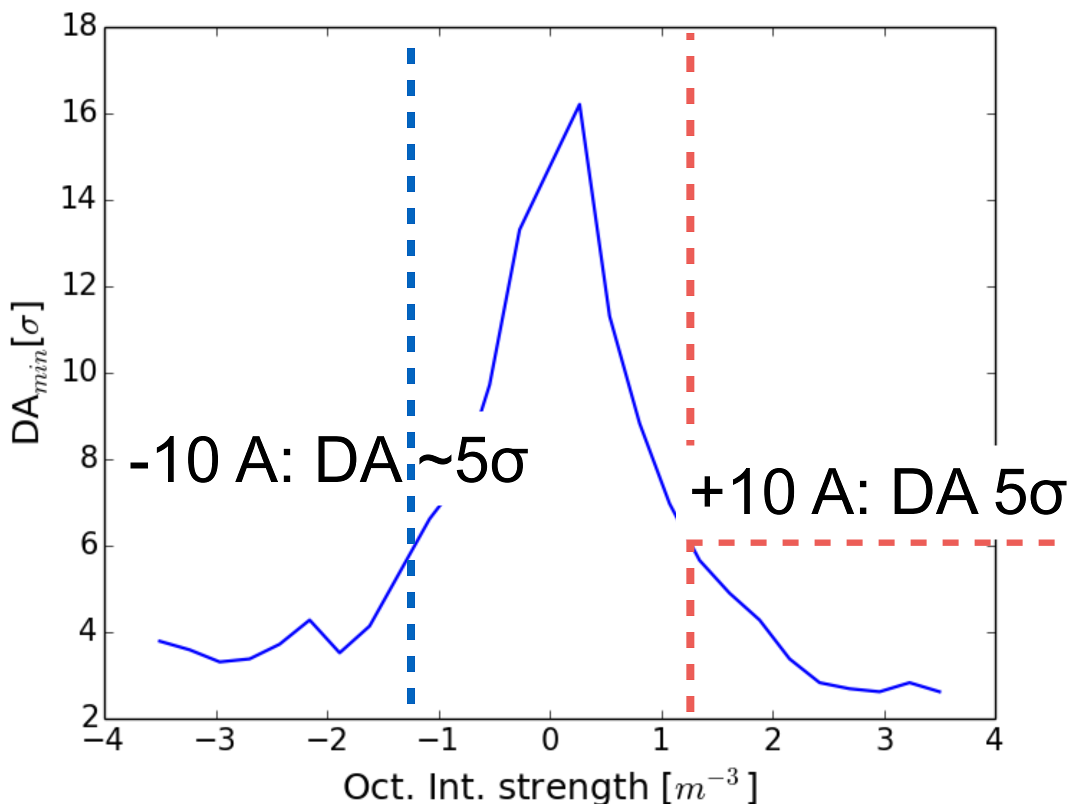
Stability from electron lens

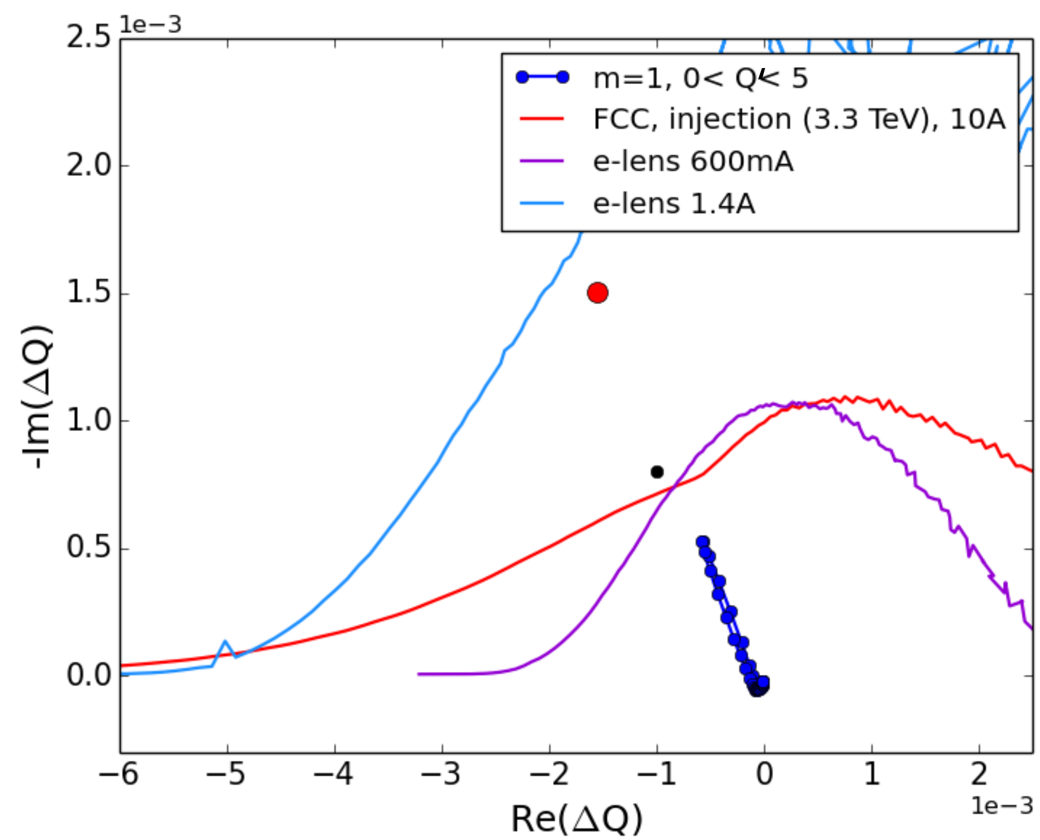
Electron lens comparable to bb head-on: **very effective to provide Landau damping [6] when octupoles fail** (as FCC at injection energy)

[6] V. Shiltev *et al.*, *Landau Damping of Beam Instabilities by Electron Lenses*, Phys. Rev. Lett. 119, 134802



3.3 TeV (single beam)





Summary

Landau damping of head-tail modes is modified in presence of beam-beam interactions, **it is important to study the stability during the full operational cycle:**

At the end of squeeze, BB long range interactions reduce or increase stability according to octupole polarity → impact on **DA must be taken into** account

Compensation of BB LR observed with negative octupole polarity (larger DA): tune spread can be recovered by increasing the effectiveness of the octupoles (current, β-function)

BTF measurements in presence of long range interactions showed different behavior w.r.t. models: **linear coupling + high octupole current and beam-beam provoke frequency cut and diffusive mechanisms** that reduce Landau damping and produce important H-V asymmetry ➔ **measured for the first time**

During the **collapse of the separation bumps** a minimum of stability is expected (1.5 ~ 2 σ): instability mechanism already observed (op scans, snowflake instability) but an additional proof was provided by a recent 2017 MD with a scan of octupoles current

In collisions the stability is maximum, the head-on tune spread affect mostly the core of the beam providing maximum Landau damping (as principle of the electron lens)

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Thanks for your attention!

Back-up slides

Fitting method to reconstruct Stability Diagram from measurements

BTF (complex) → **Amplitude (Q)**, **Phase (Q)**

SD ∝ 1/BTF = $A^{-1} e^{-i\varphi}$

Fitting method allows to compare measurements respect to models (reference case, i.e. octupoles)

$$Q_{fit} = p_0 + p_1 \cdot (Q_{analyt} - Q_0)$$
$$A_{fit} = p_2 / p_1 \cdot A_{analyt}$$

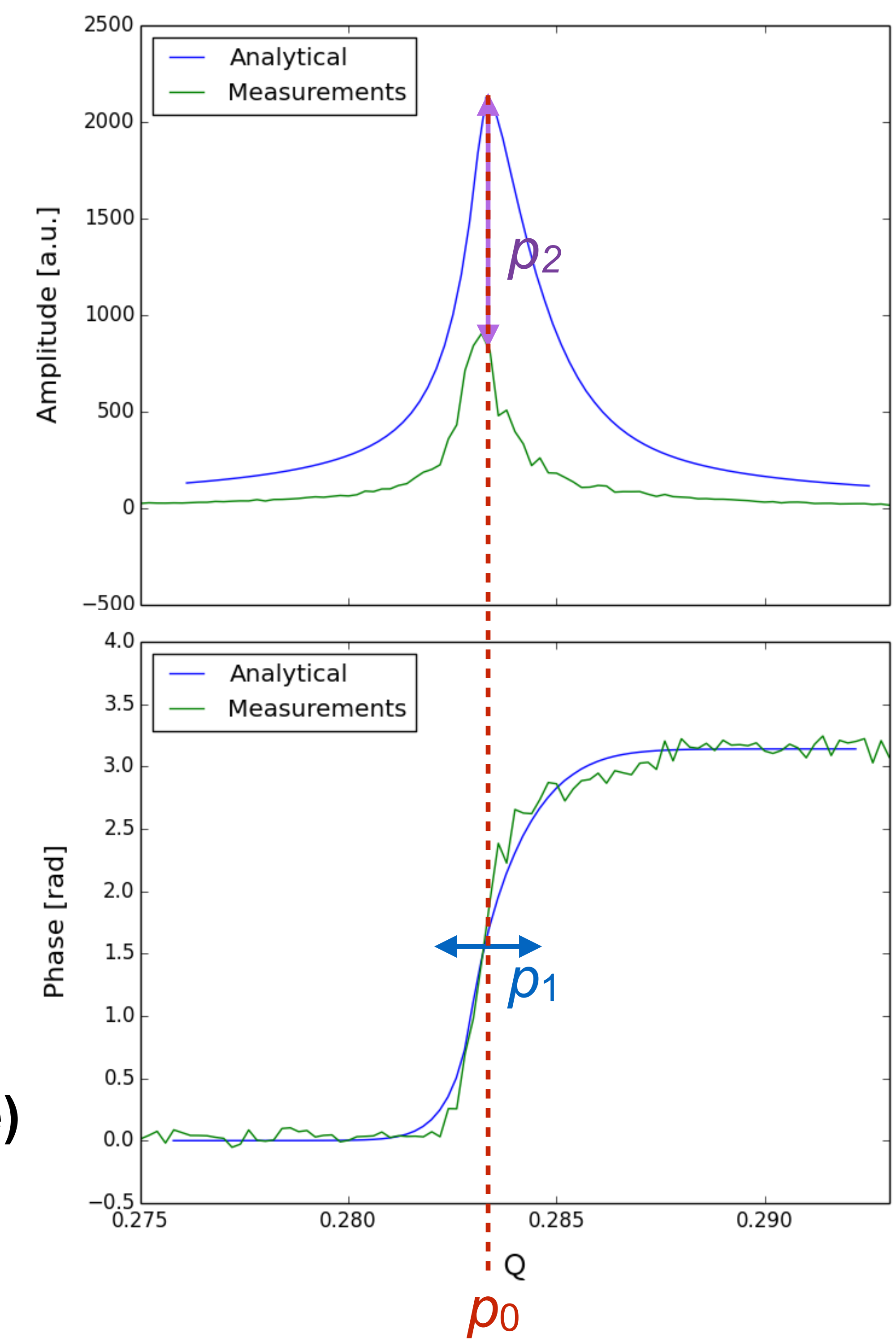
p_0 = Tune

p_1 = Tune spread factor respect to a reference case

independent from calibration factor, (phase slope)

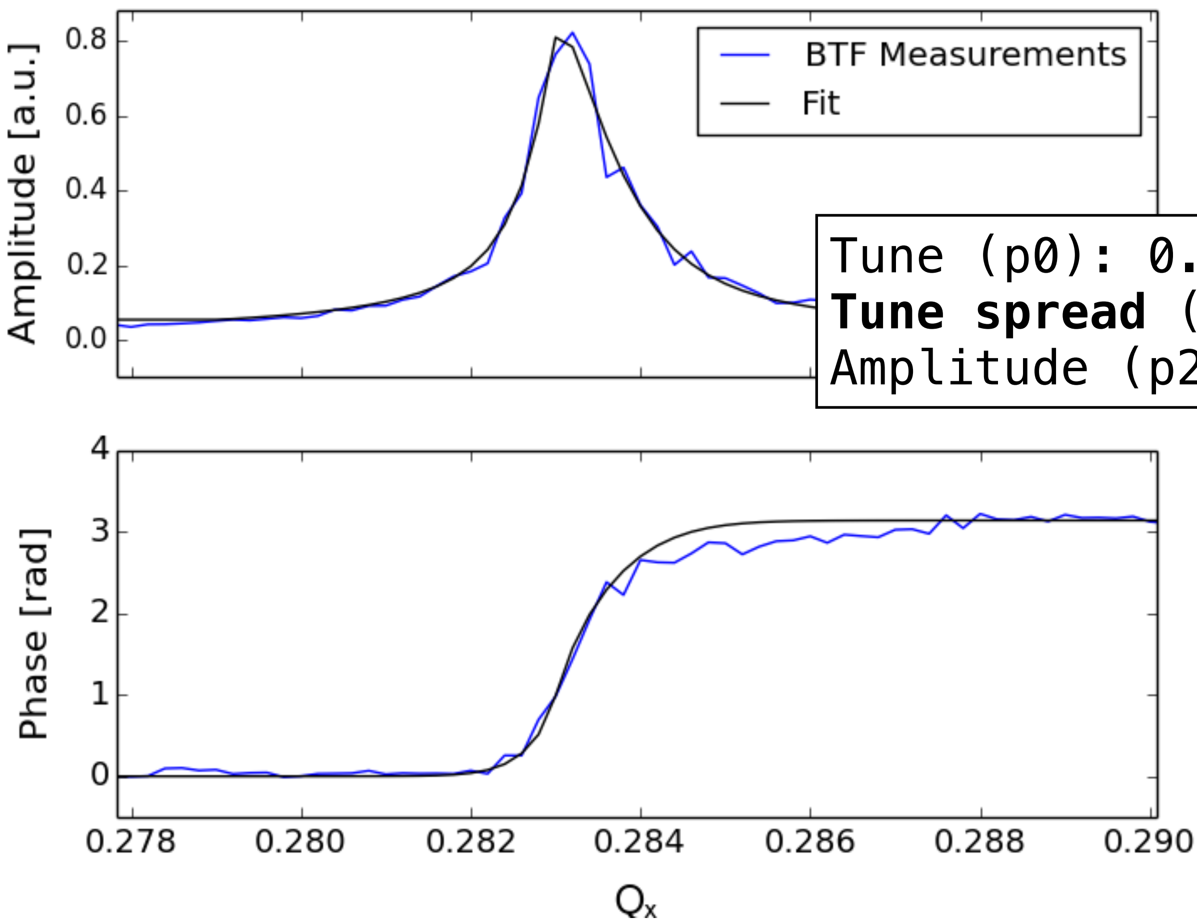
p_2 = Amplitude factor:

calibration, proportionality constant



Stability diagram reconstructed from BTFs in the LHC

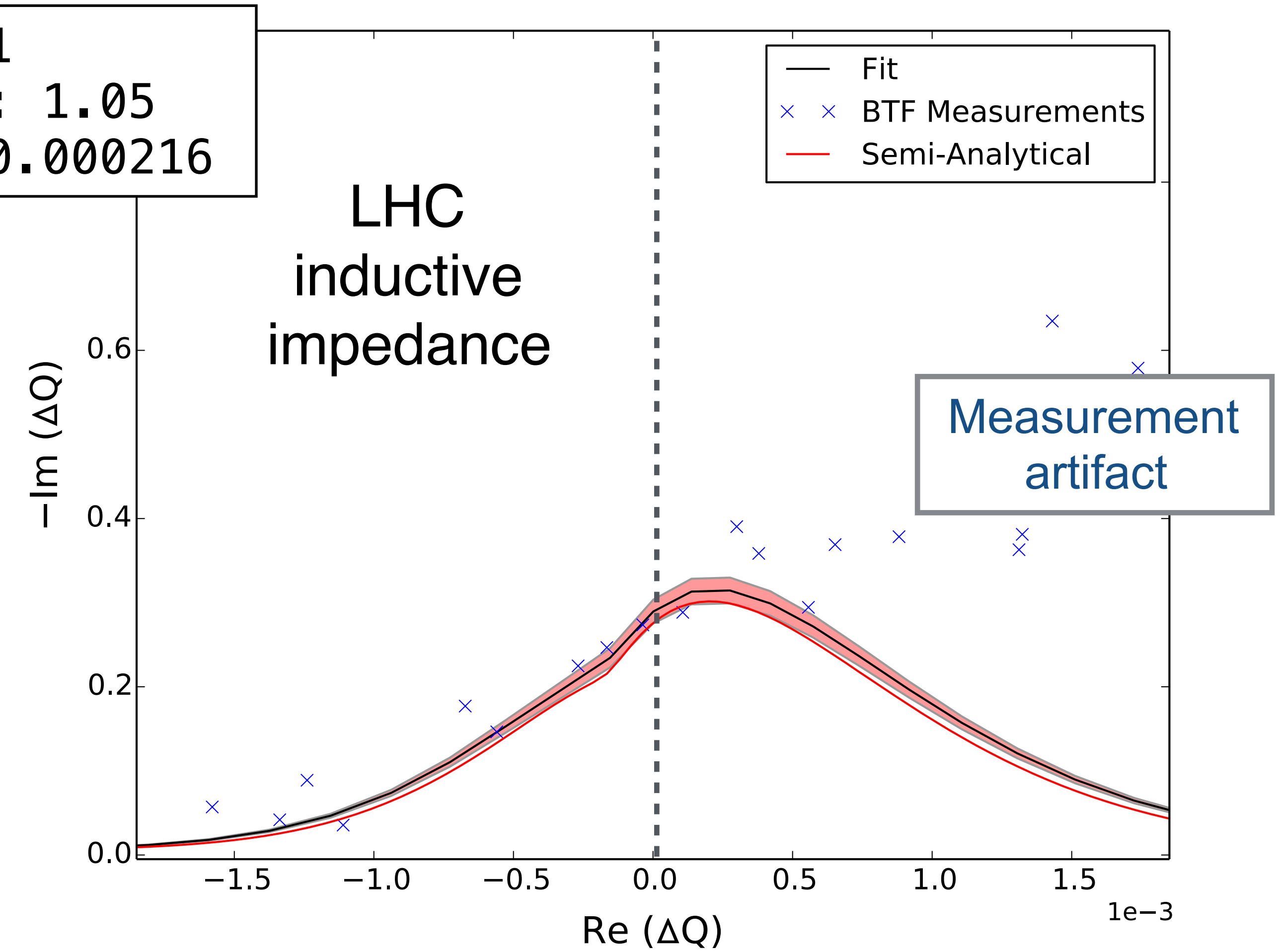
Single bunch, Injection, 6.5 A (2016)



Tune (p0): 0.2831
Tune spread (p1): 1.05
Amplitude (p2): 0.000216

$$Q_{fit} = p_0 + p_1 \cdot (Q_{analyt} - Q_0)$$

$$A_{fit} = p_2 / p_1 \cdot A_{analyt}$$

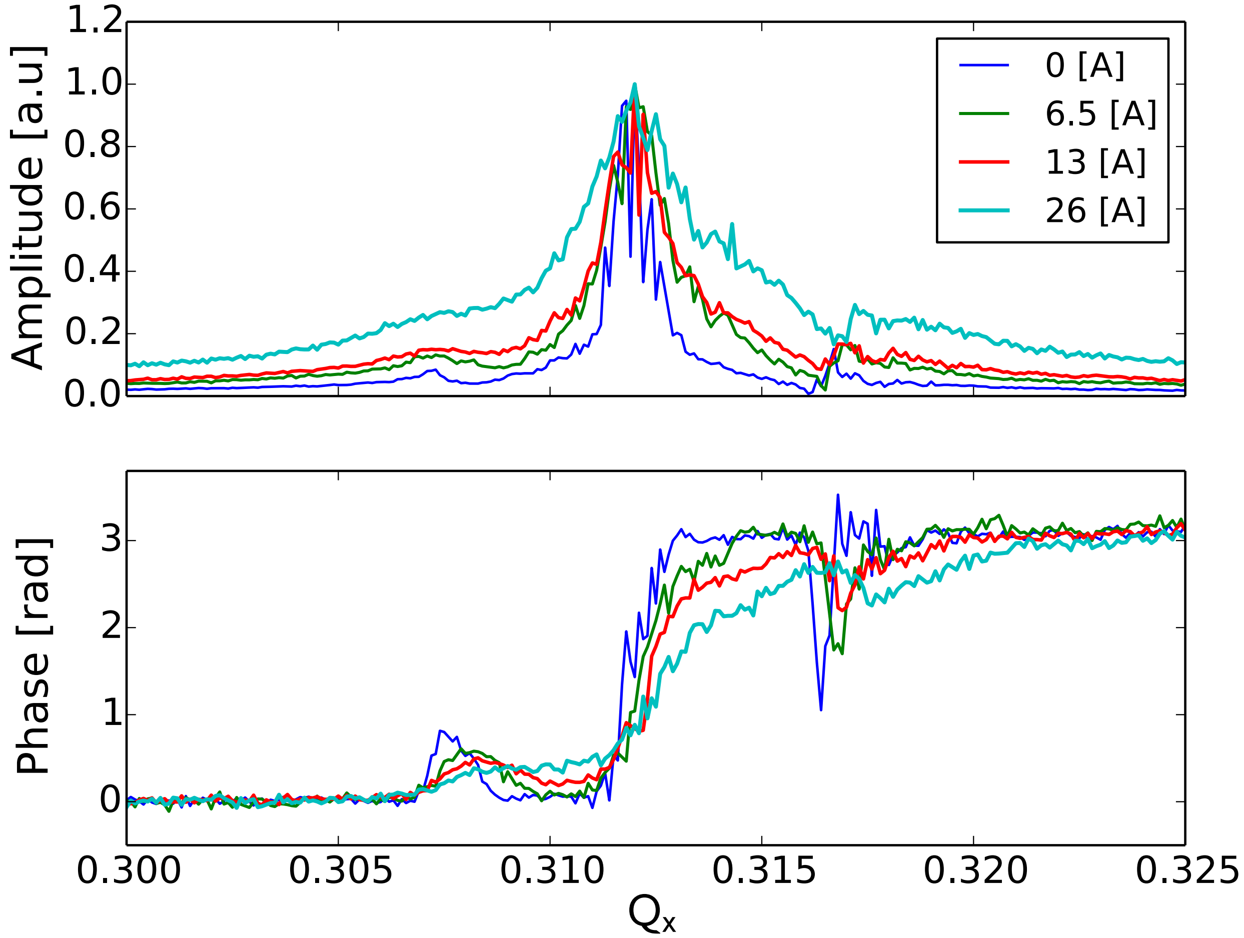


Good agreement between measurements and expectations for the 2016 measurements

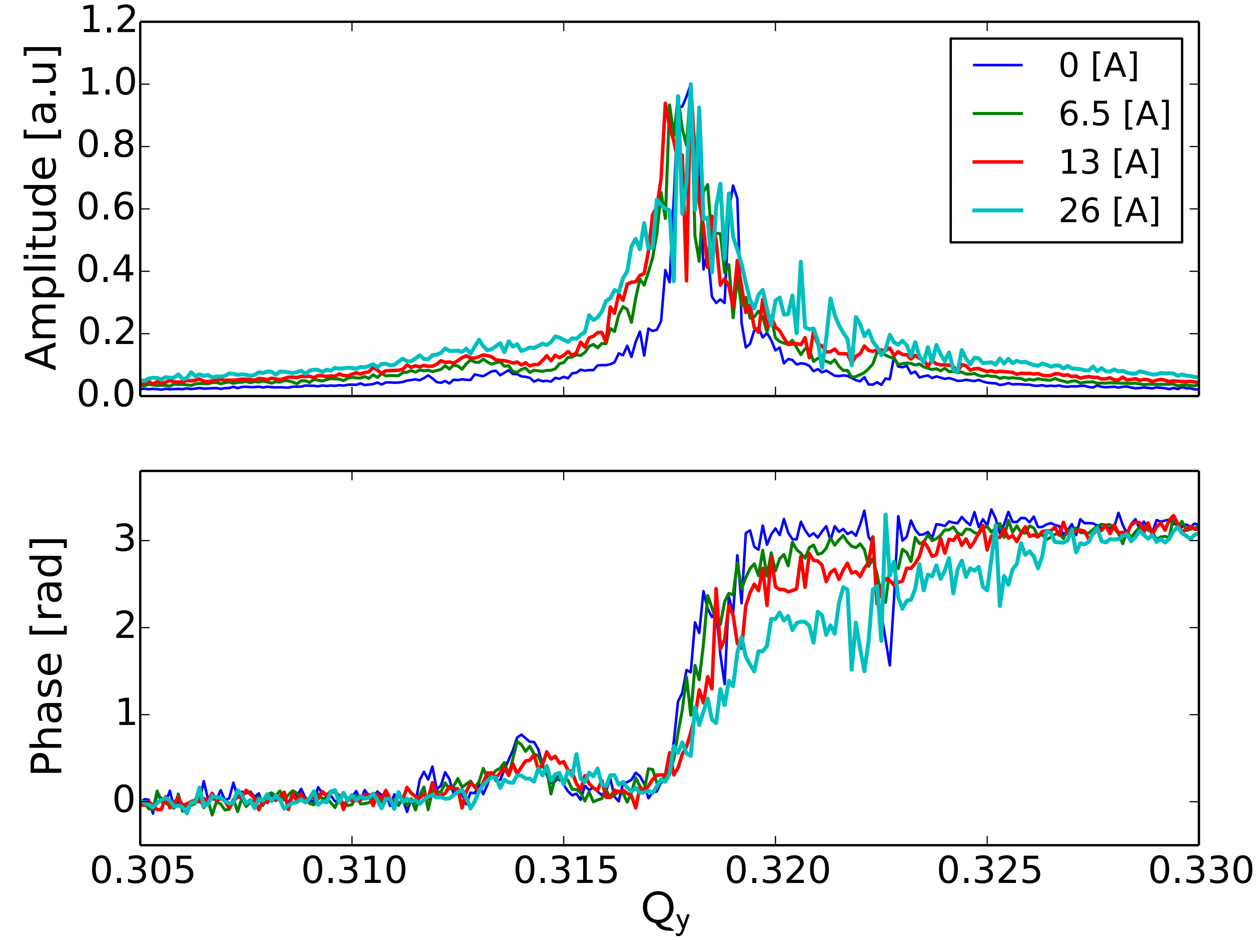
Single beam: stability at injection

Tune spread given by Landau octupoles and lattice non linearities

Horizontal plane



Vertical plane

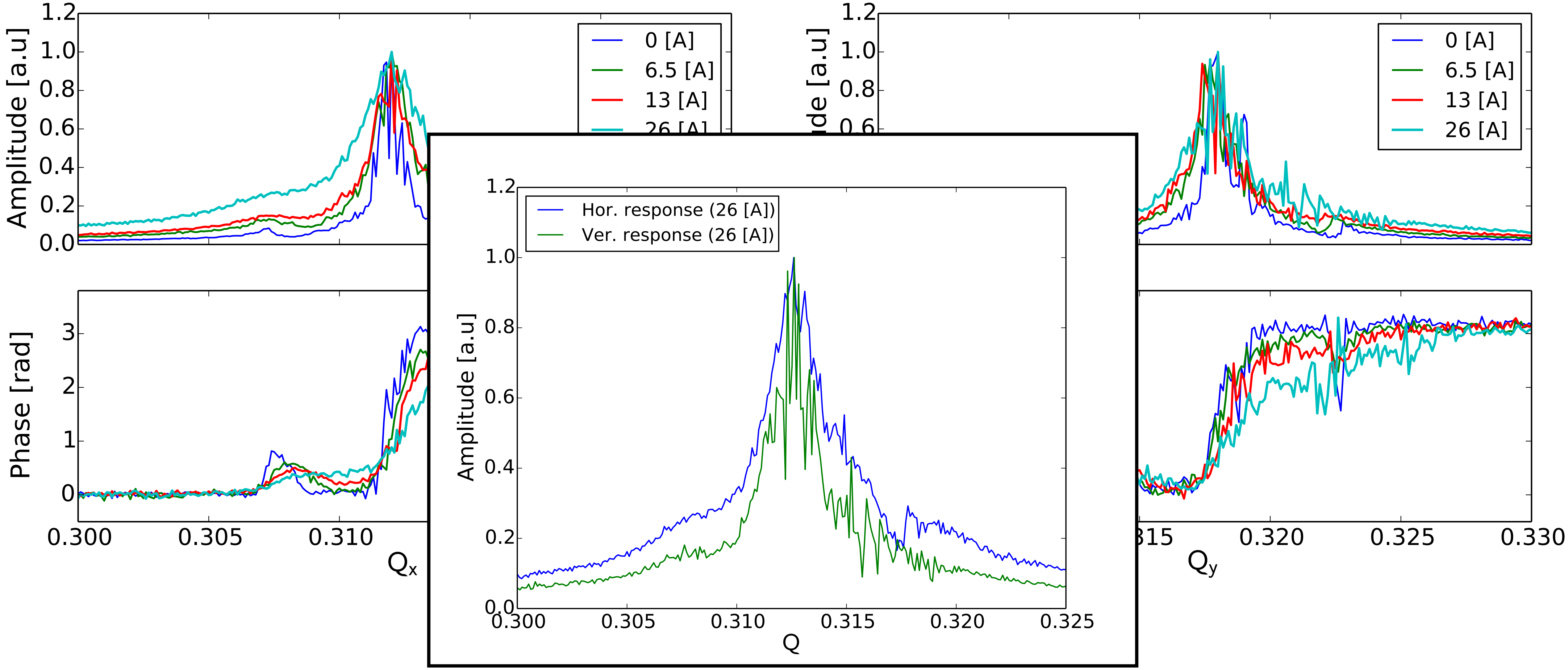


For the largest octupole strength (26 A) larger spread in the horizontal plane, smaller in the vertical plane

Single beam: stability at injection

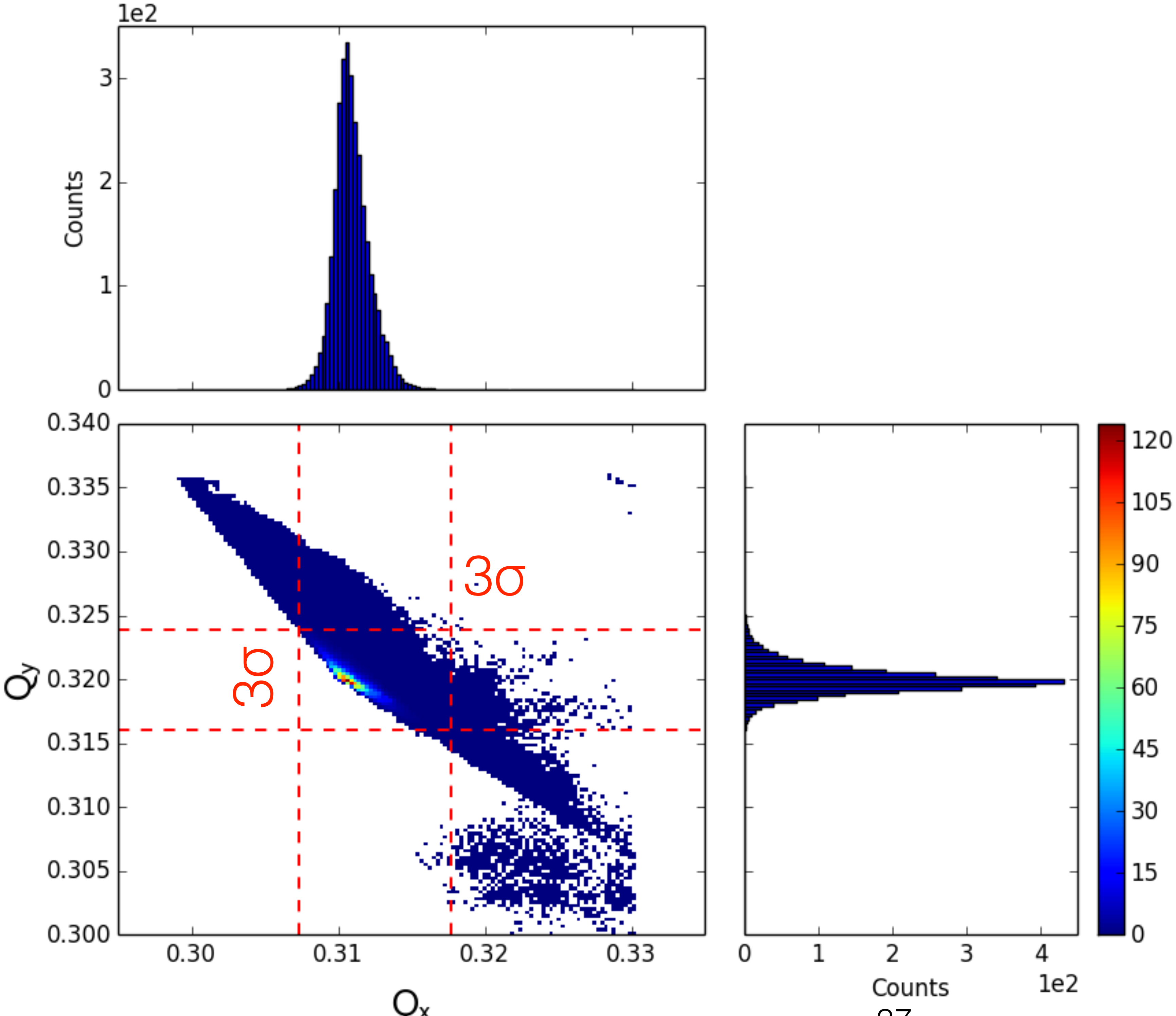
Tune spread given by Landau octupoles and lattice non linearities

Horizontal plane | **Vertical plane**



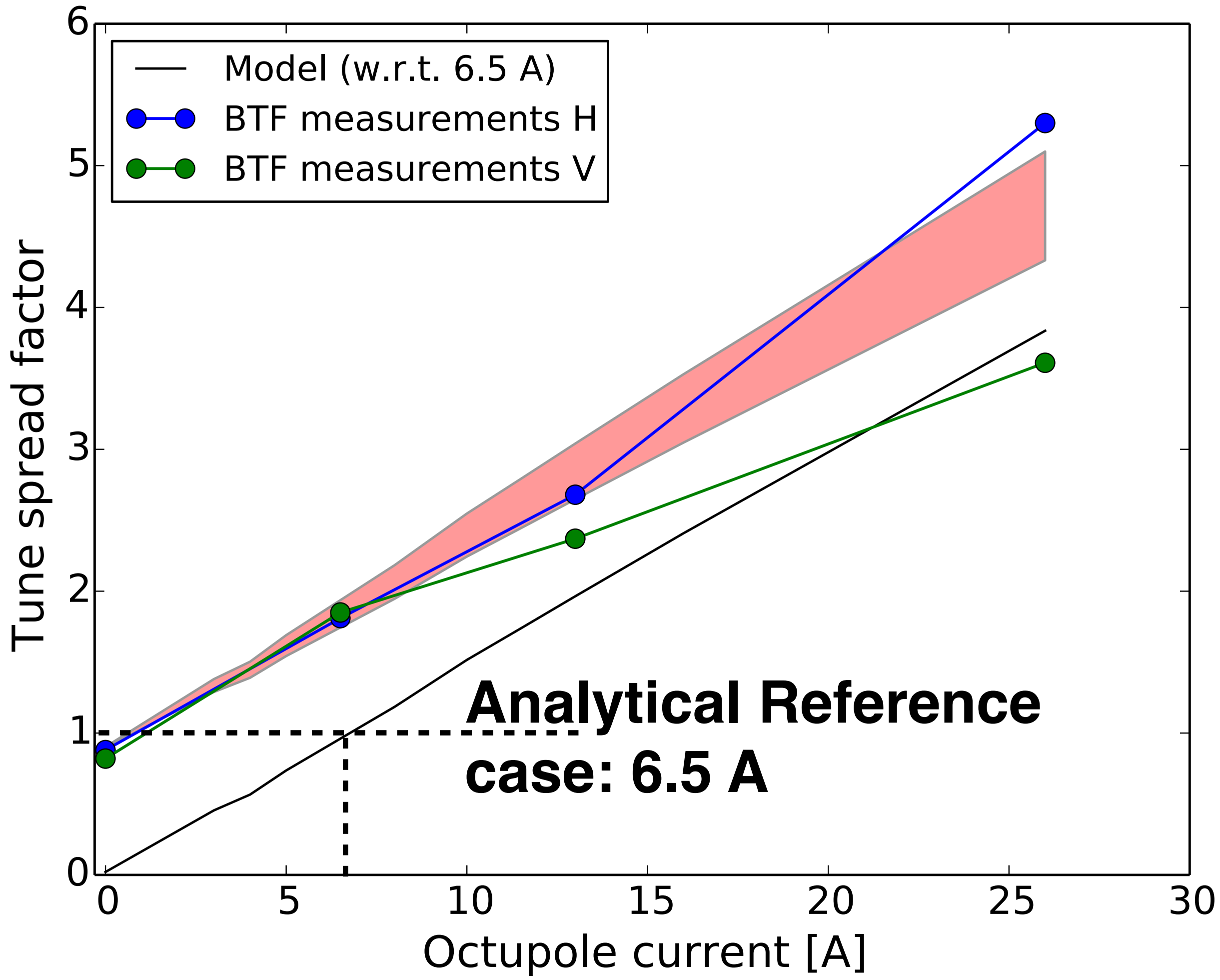
For the largest octupole strength (26 A) larger spread in the horizontal plane, smaller in the vertical plane

Frequency distribution at injection for 26 A octupole current



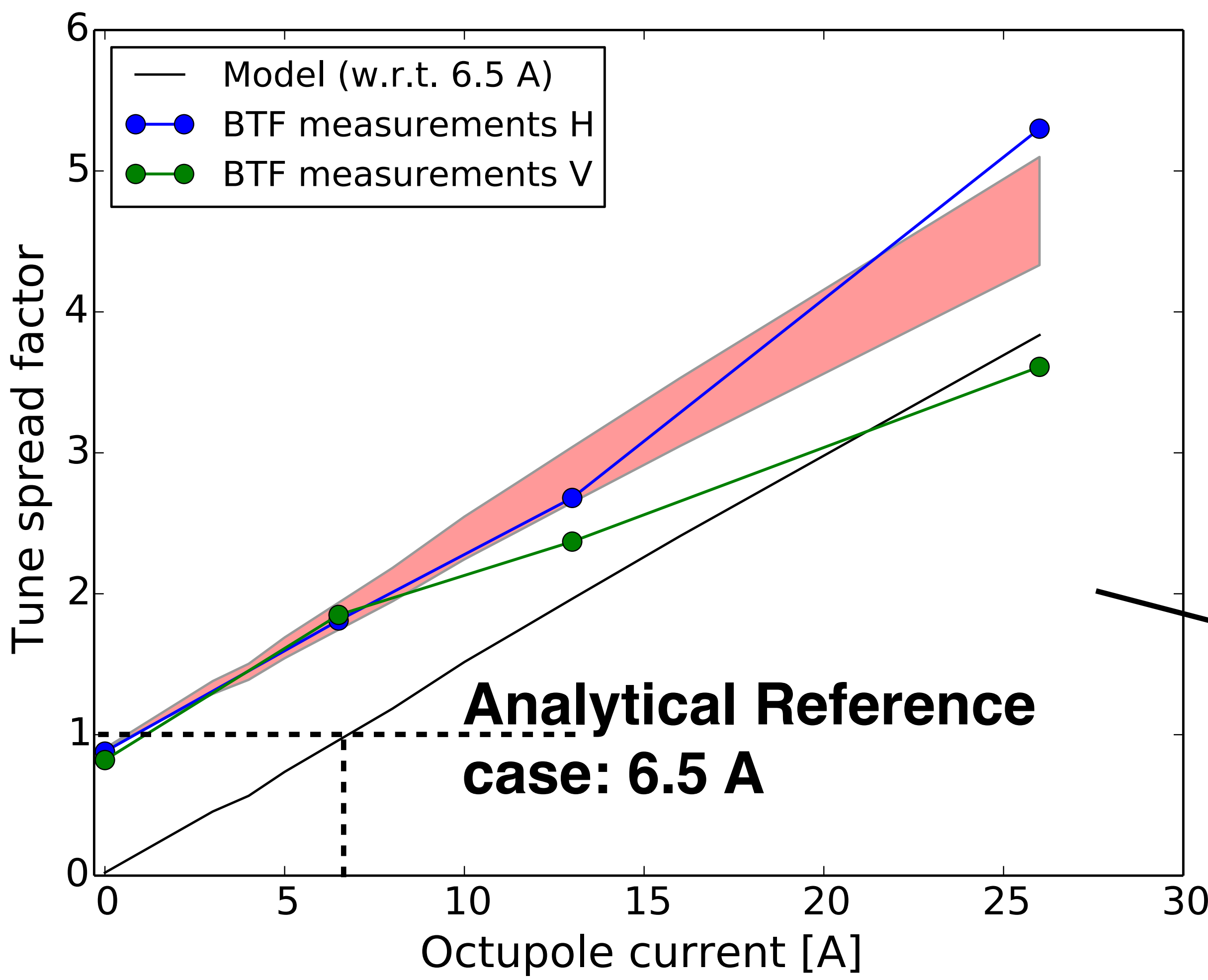
No drastic change in the frequency distribution and it can not explain H-V BTF asymmetry

Octupole scan at injection: evaluation of beam tune spread



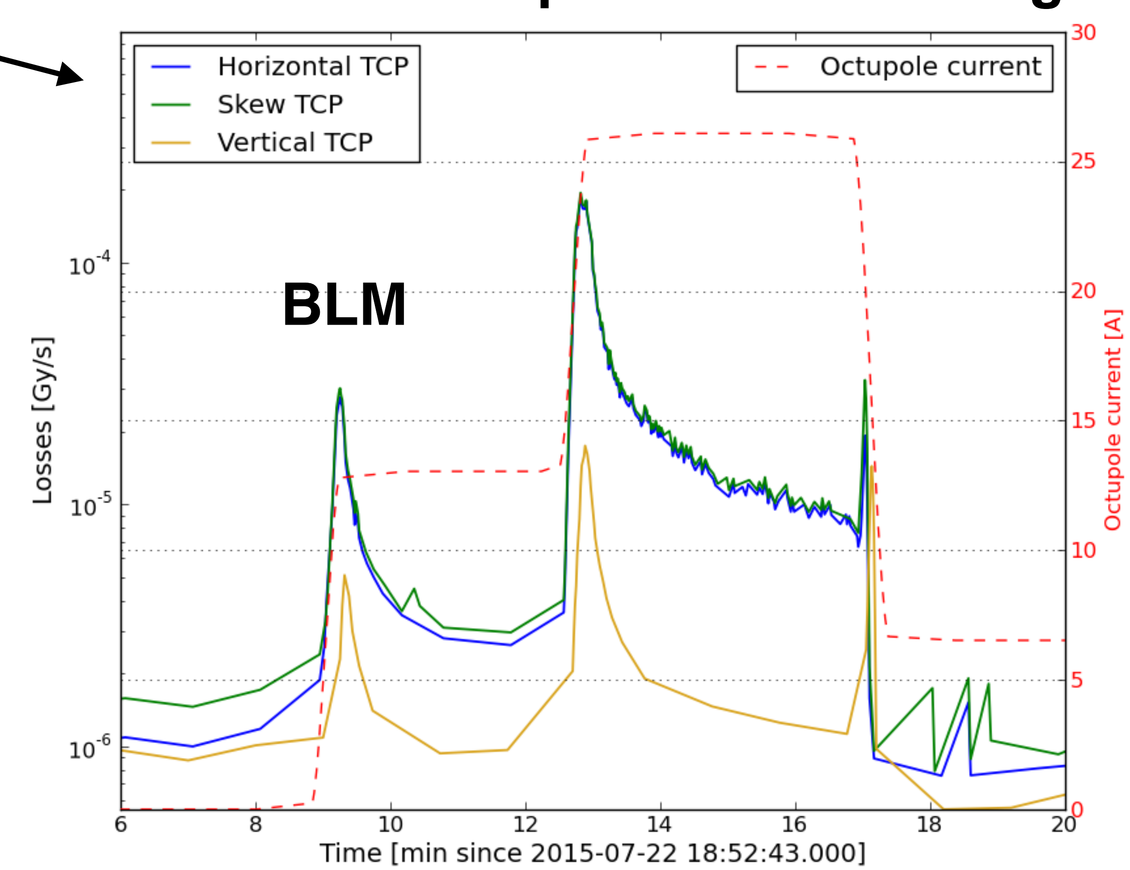
- Fitting method to compare measurements and expectations from model (tune spread factor)
- Case with no octupoles: consistent with optics measurements in the 2015
- Linear trend reproduced

Octupole scan at injection: evaluation of beam tune spread



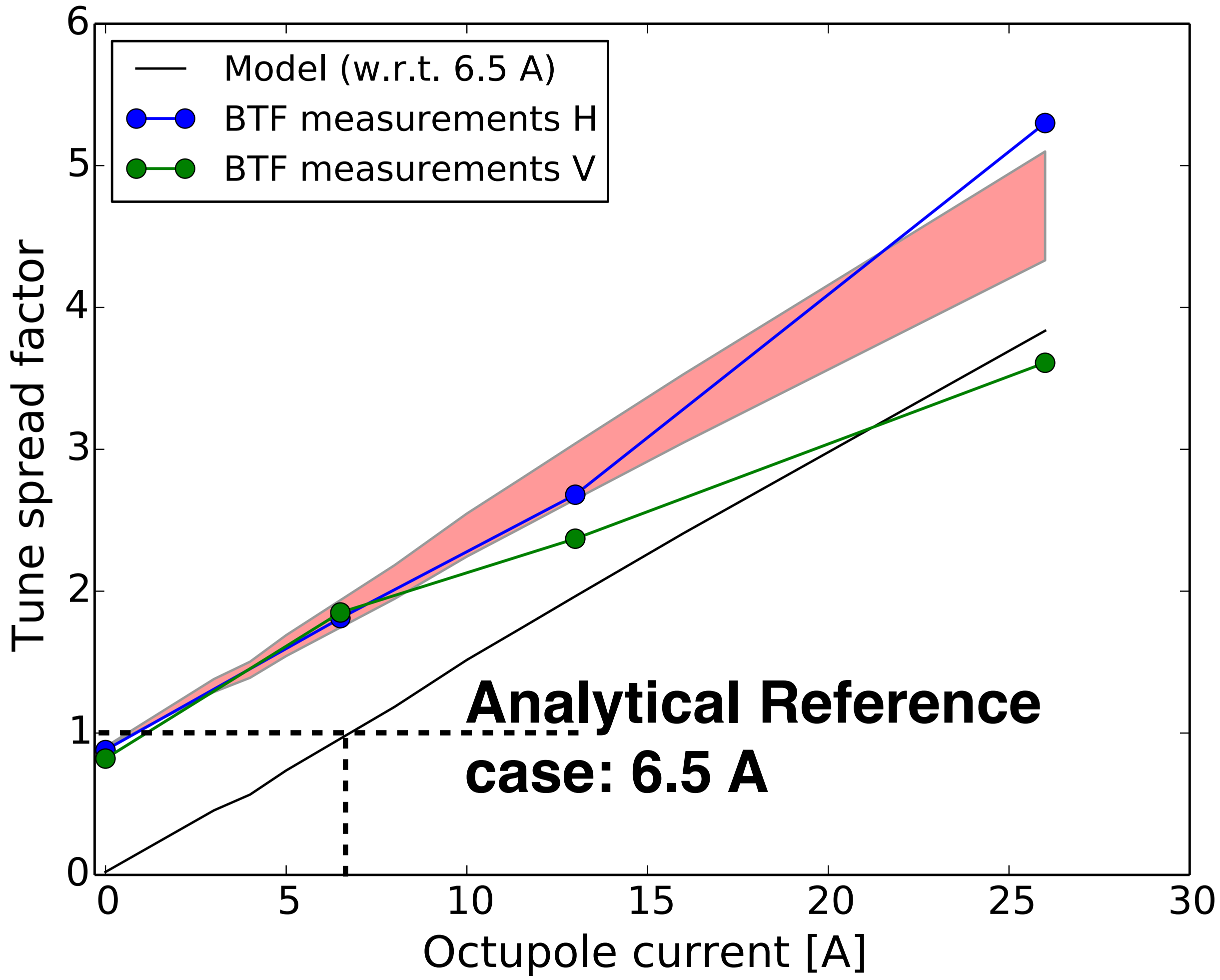
- Fitting method to compare measurements and expectations from model (tune spread factor)
- Case with no octupoles: consistent with optics measurements in the 2015
- Linear trend reproduced

Losses observed in the vertical plane correlated with octupole current changes



Losses very low➔ **negligible impact on beam lifetimes and collimation system**

Octupole scan at injection: evaluation of beam tune spread



- Fitting method to compare measurements and expectations from model (tune spread factor)
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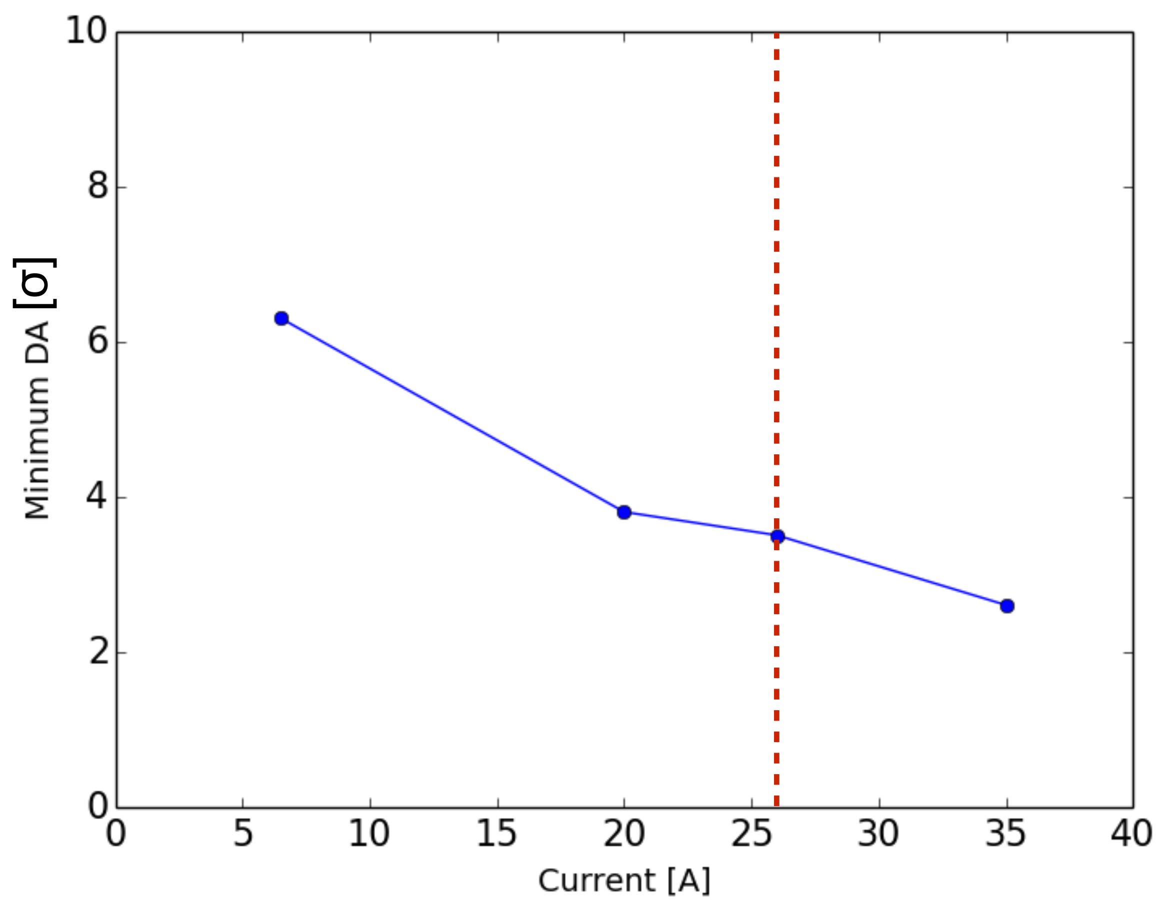
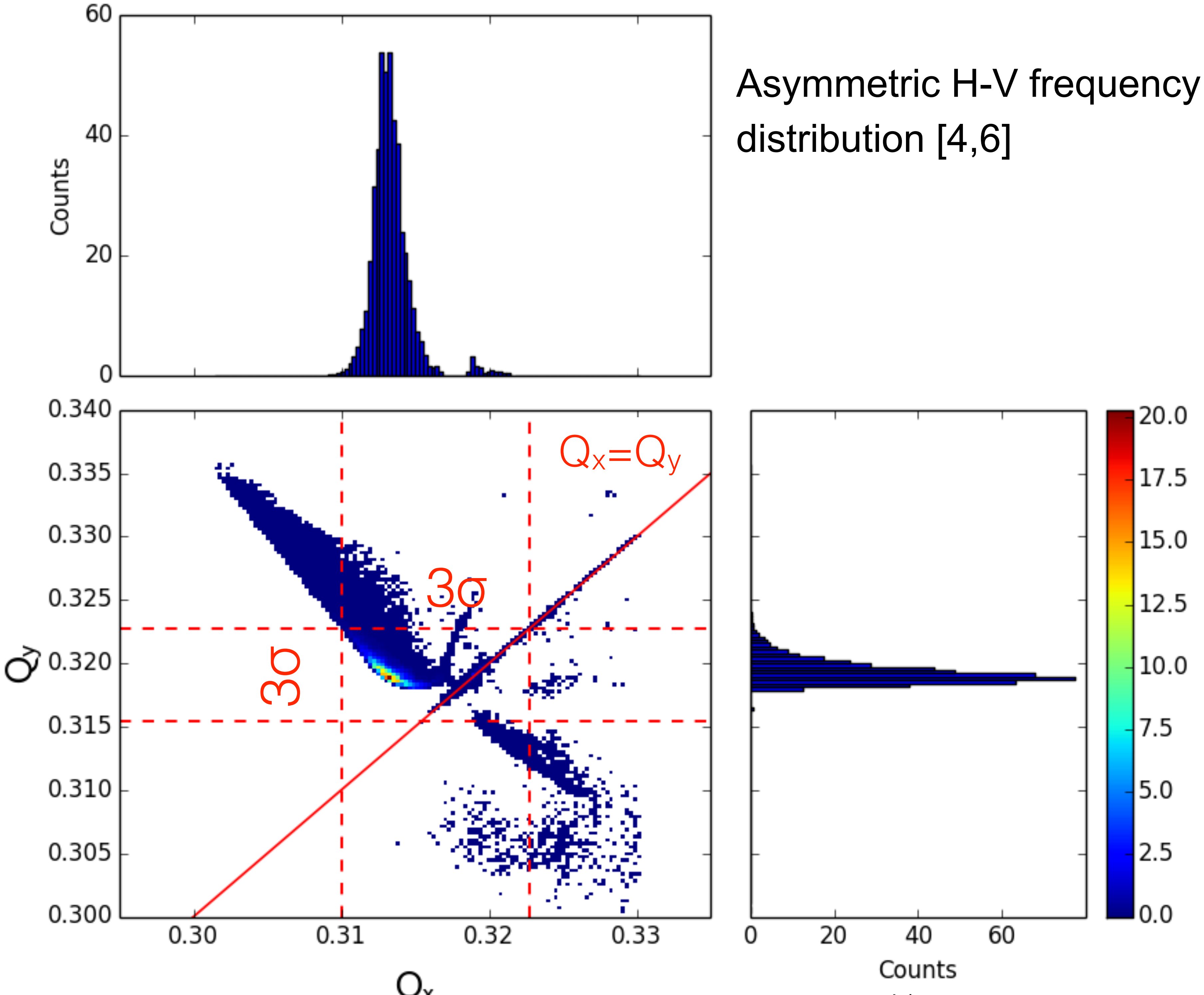


Losses observed as a function of octupole strength due to a reduction of DA
→ Increasing the tune spread is beneficial for Landau damping as long as any diffusion mechanism is not present

Frequency distribution at injection with linear coupling

Effect of **linear coupling**: coupled motion between H-V plane

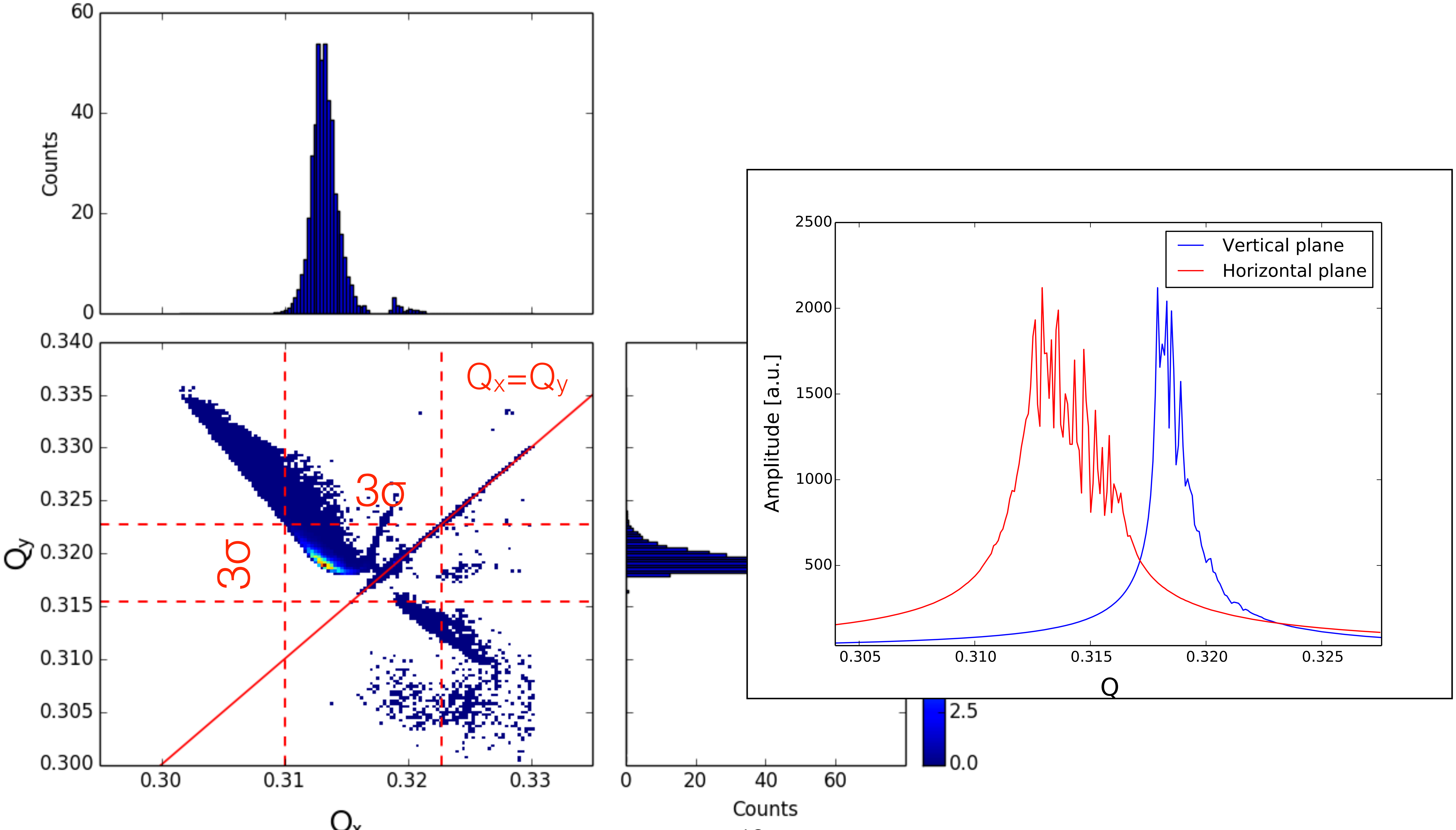


Asymmetric H-V frequency distribution [4,6]

[6] L. Carver et al., *Destabilising effect of linear coupling in the LHC*, Proceedings of IPAC 2017, Copenhagen, Denmark (2017)

Frequency distribution at injection with linear coupling

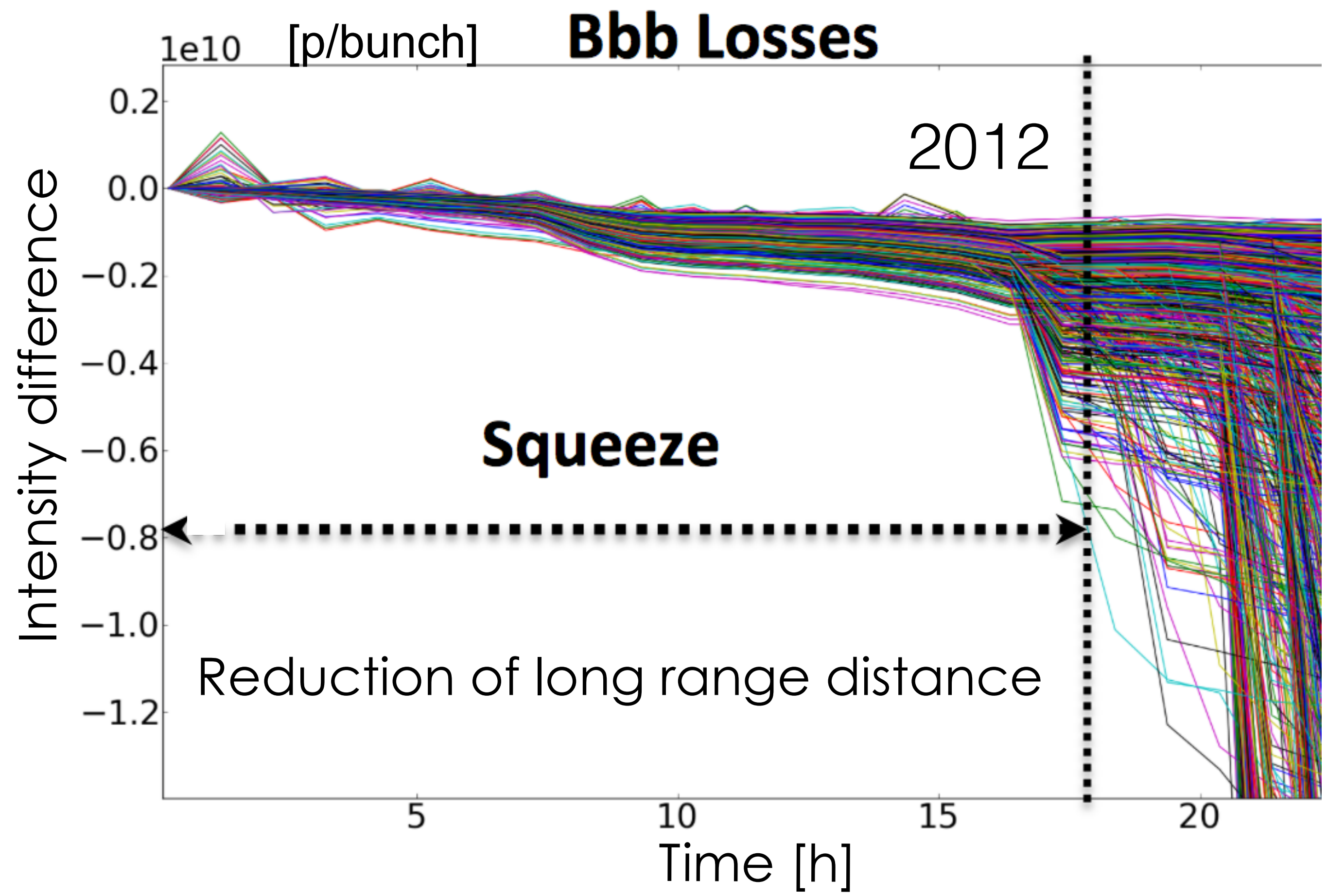
Effect of **linear coupling**: coupled motion between H-V plane



Coherent instability

Several coherent instabilities since the first run:

- Coherent oscillations of single bunches
- Emittance blow up
- Loss of intensity



Chaotic motion due to beam-beam +Q'+Oct drives diffusive mechanism (particle losses and emittance blow-up)