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Beam distribution and Dynamic Aperture impact on Landau damping properties of proton beams

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Acknowledgements: E. Metral, B. Dalena, D. Shulte, L. Carver

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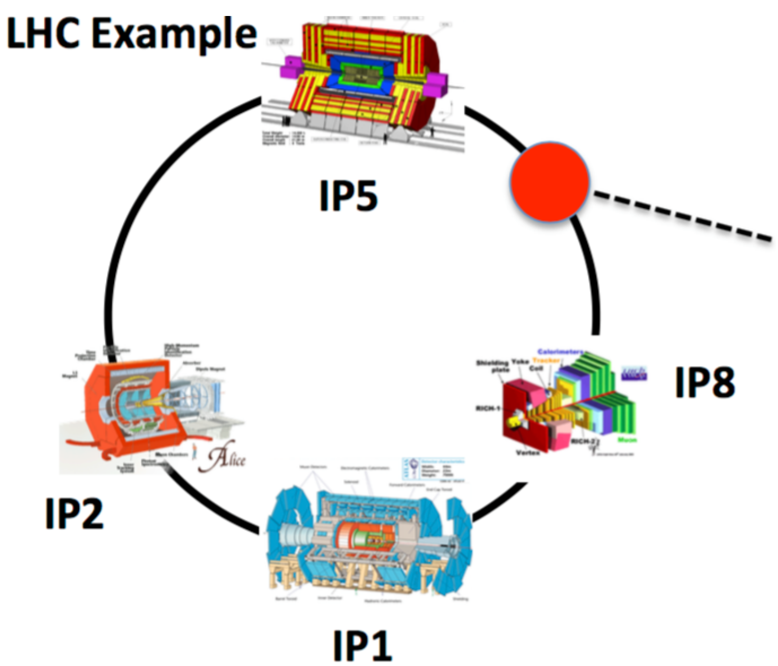
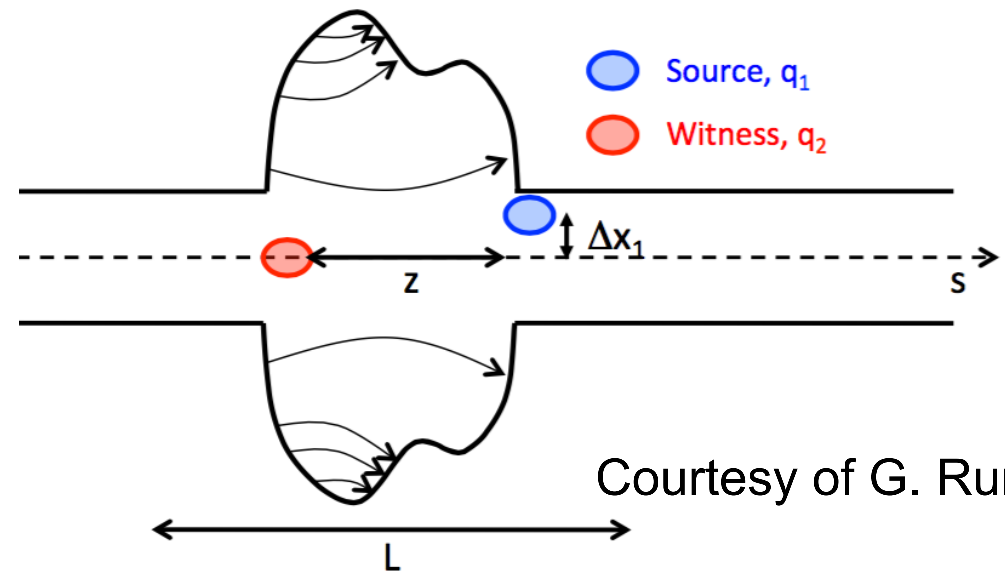
- Beam coupling impedance and instabilities
- Landau damping of head-tail modes
- Dispersion integral and stability diagram
- Impact of particle distribution on Stability Diagram
- Effect of linear coupling on Stability Diagram
- Effects of beam-beam interactions on DA
- Summary

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)

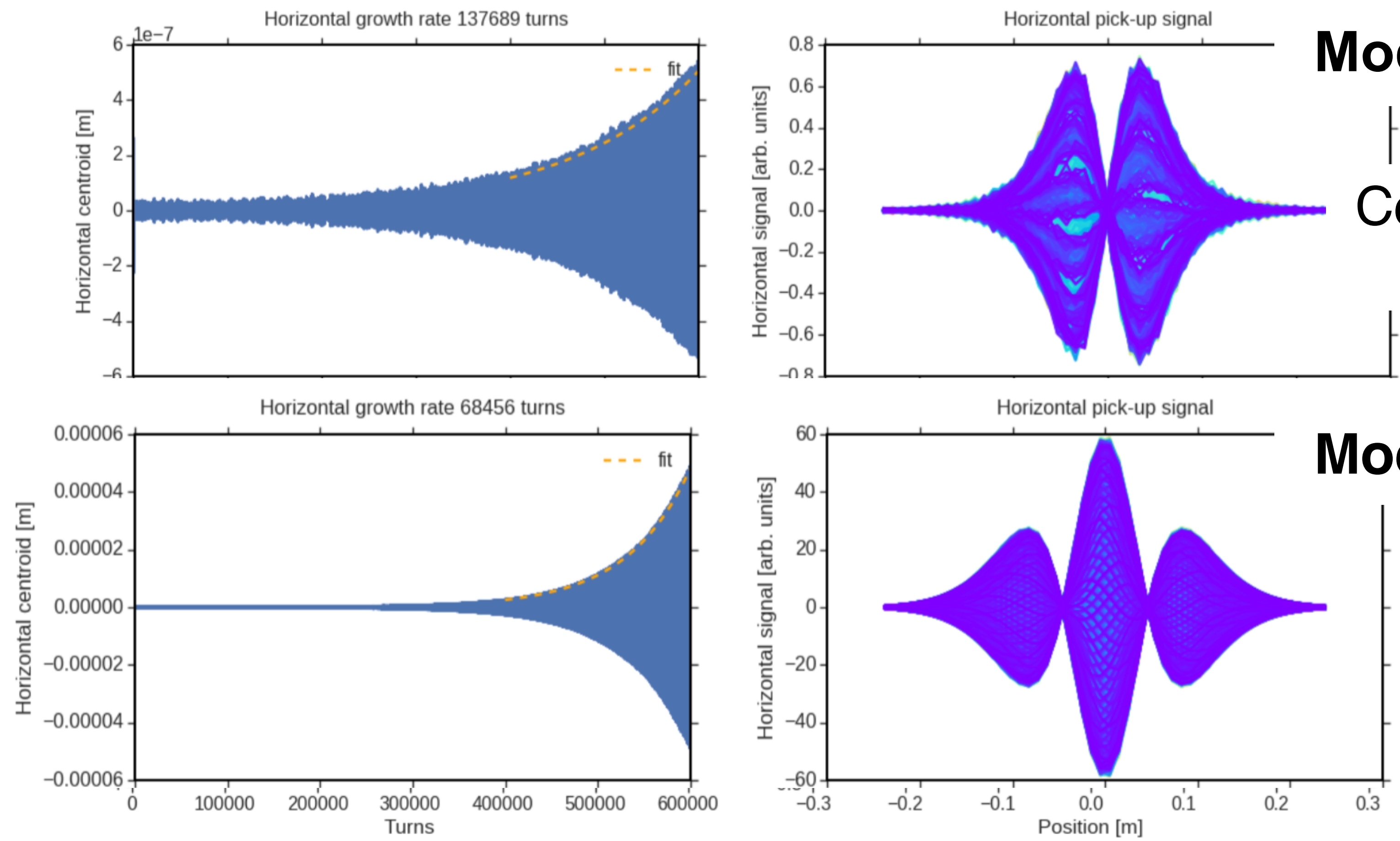
- Small aperture elements (collimator 5.5σ)

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



Mode 1

Mode 2

Courtesy of A. Oeftiger

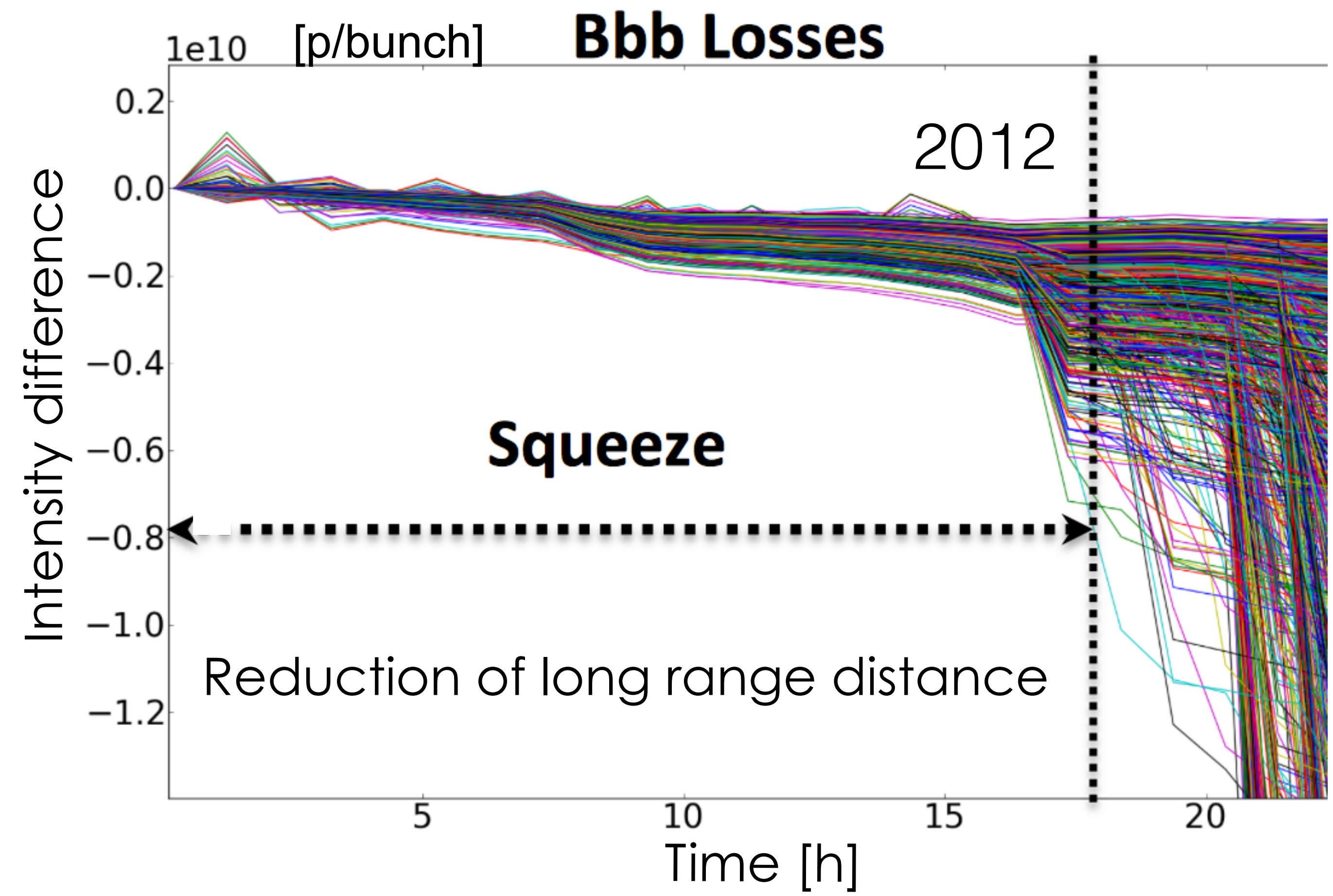
Coherent instabilities

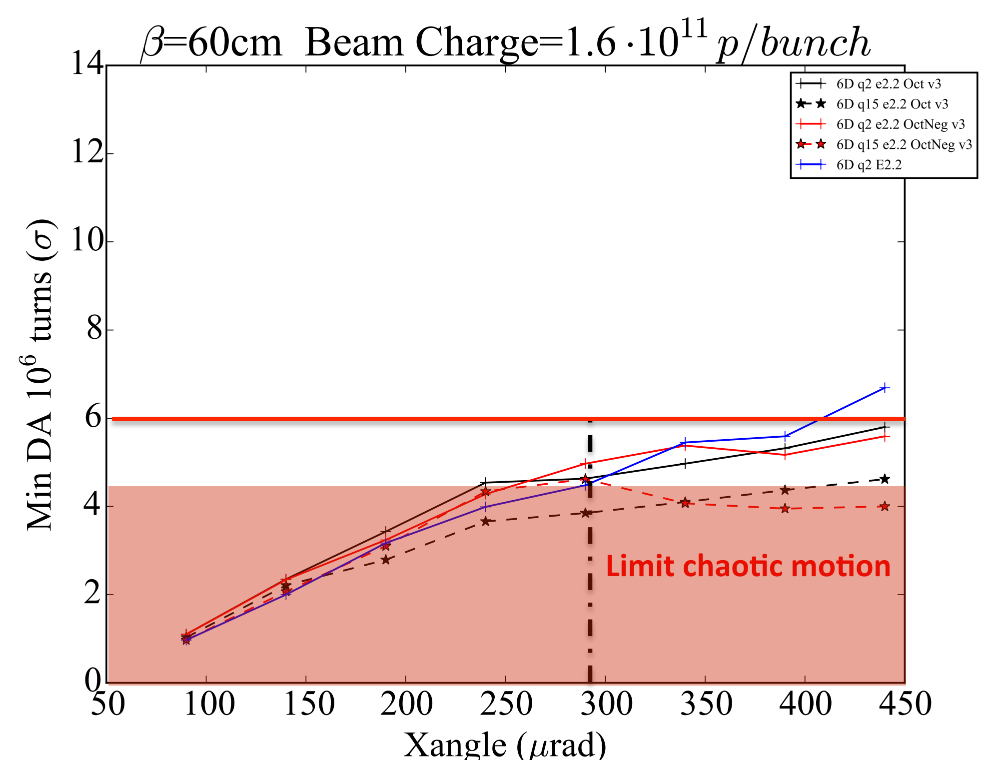
Several coherent instabilities since the first run:

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

Limitation of machine performances (luminosity reach)

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





LHC instabilities

Transverse loss of Landau damping (rise times of 1 to 10 s)
- End of squeeze instability (2012)
- Snowflakes (2012, beam-beam with offset)
- Linear coupling with collision tunes (2015)
- CB^2 (coupled bunch coupled beam instability, 2016)
- Weird B1V instability (2016), weird B1H instability (2017)
- Hunchback instability (2015, 2017)
- Popcorn instability

Mode coupling instability with colliding beams (2012 ~1 s)

Electron cloud instabilities (~1 s)

16L2 instability (~20 turns)

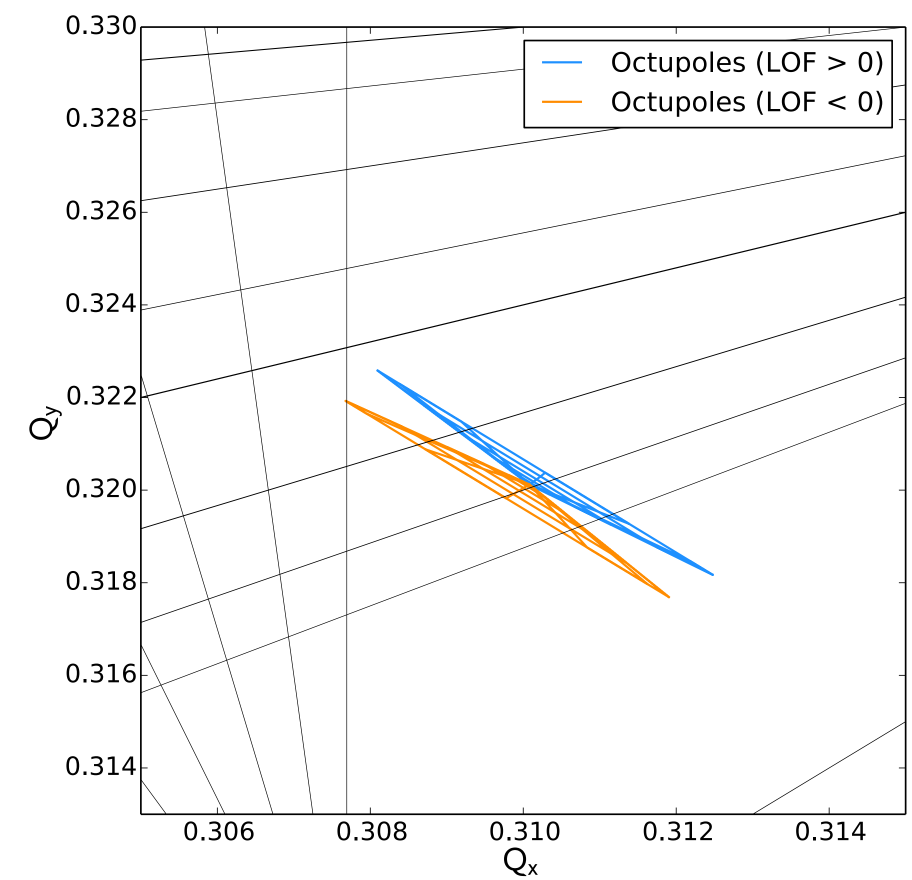
Courtesy of B. Salvant

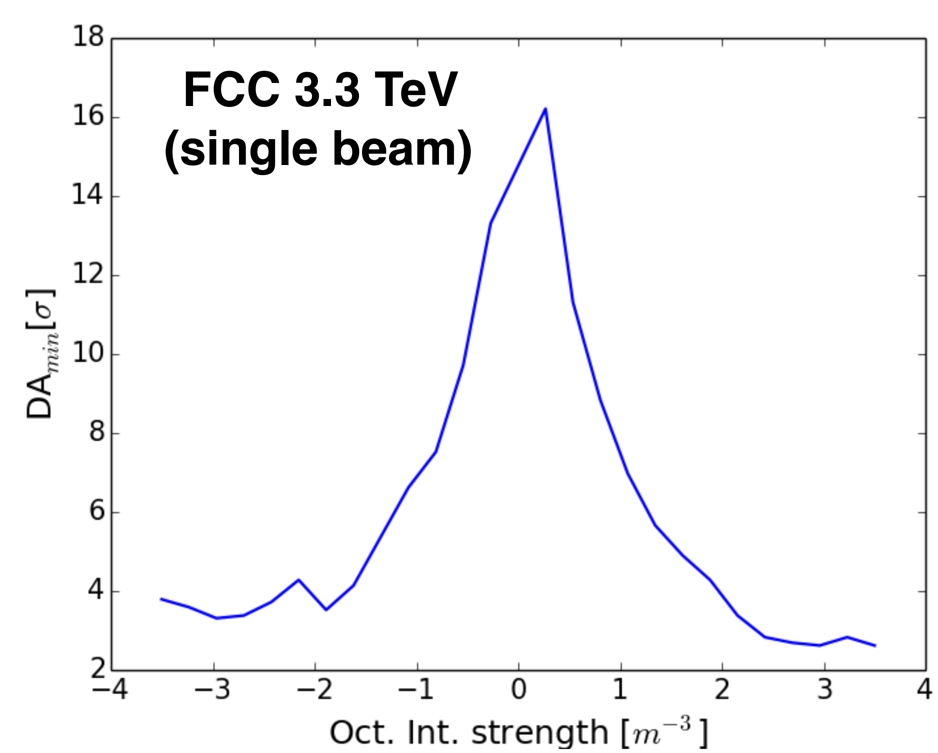
In view of future colliders (HL-LHC, HE-LHC, FCC…) with double beam intensity and/or high beam energy → understand limitation of our models

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 mainly provided by non linear elements i.e. octupole magnets ➔ **impact on DA and Landau damping**

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. Ruggiero, *Landau damping with two dimensional betatron tune spread*, CERN SL-AP-96-71 (1996)

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Detuning with amplitude [2,3]
(J_x - J_y phase space amplitude)

For accelerators, the Landau damping is generated by the **tune spread** (LHC equipped with 168 Landau octupoles to stabilize the beam)

[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]
(reduced DA)

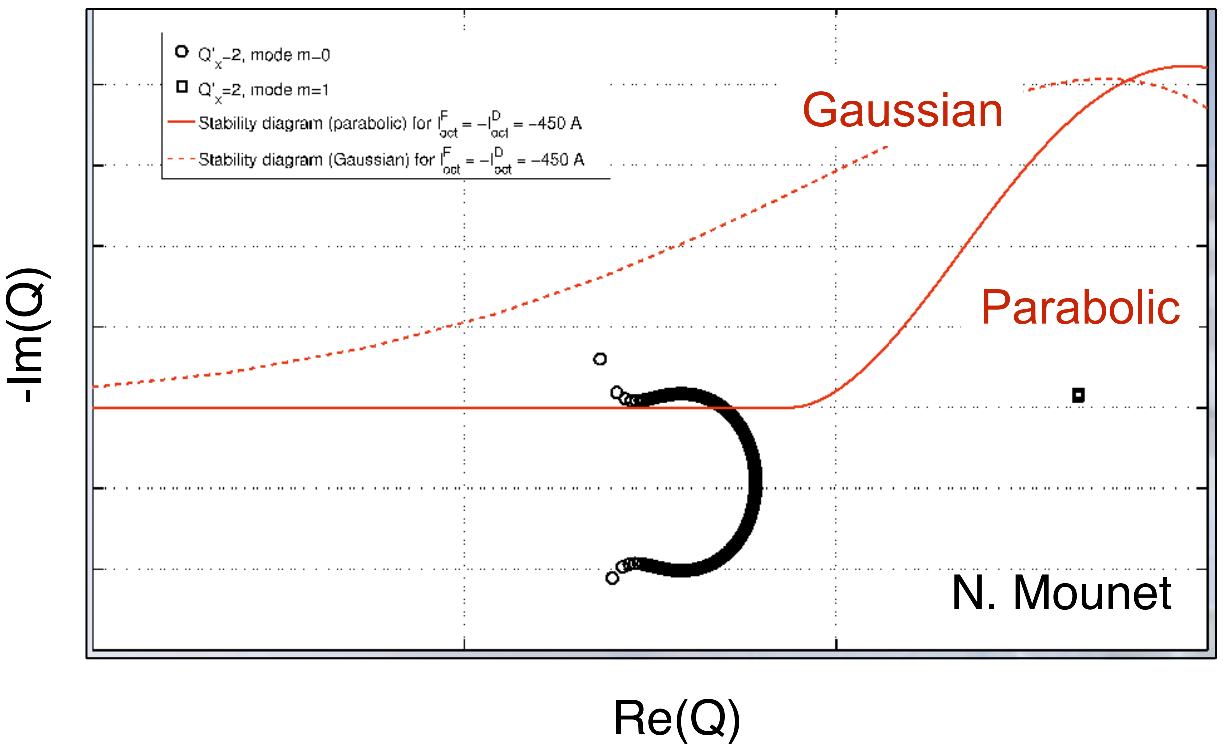
$$SD^{-1} = \frac{-1}{\Delta Q_{x,y}} = \int_0^\infty \int_0^\infty \frac{J_{x,y} \frac{d\Psi_{x,y}(J_x,J_y)}{dJ_{x,y}}}{Q_0 - q_{x,y}(J_x, J_y) - i\epsilon} dJ_x dJ_y$$

Detuning with amplitude [1,2]
(J_x - J_y phase space amplitude)

For accelerators, the Landau damping is generated by the **tune spread** (LHC equipped with 168 Landau octupoles to stabilize the beam)

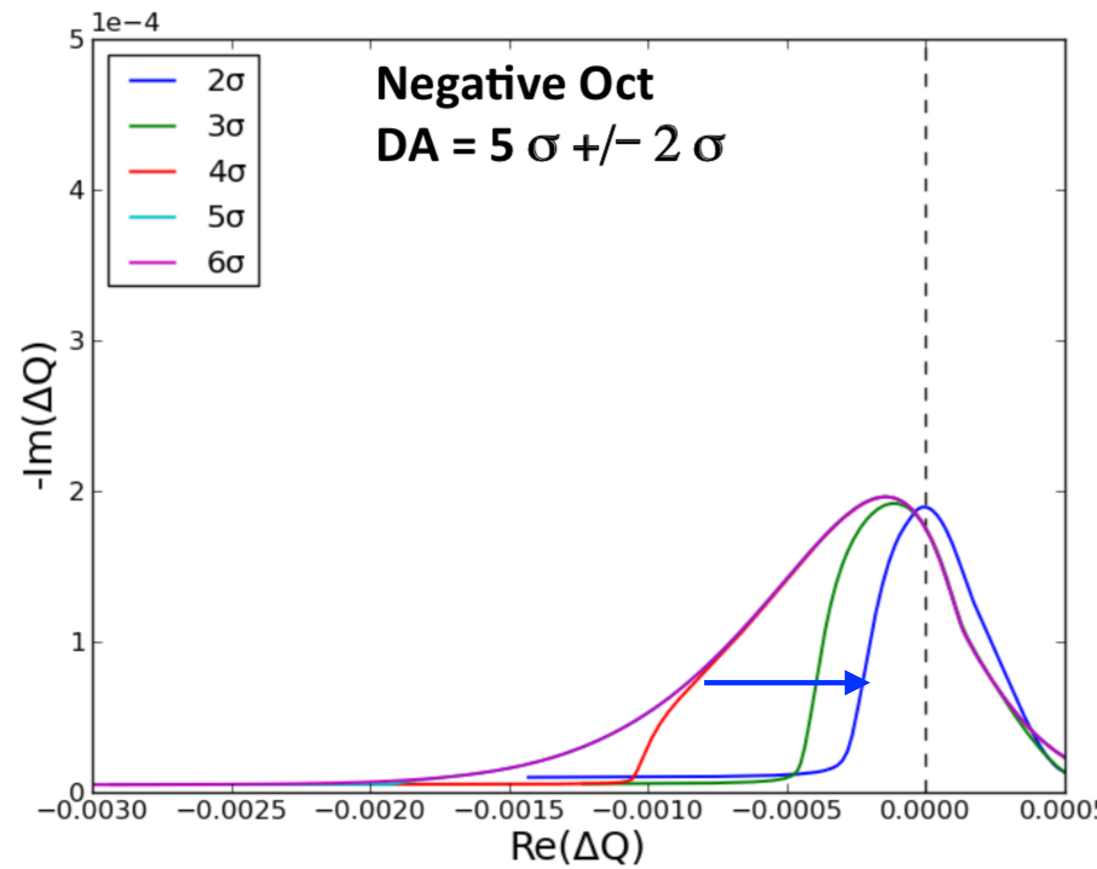
[4] C. Tambasco, EPFL Thesis 7867 (2017)
[5] C. Tambasco *et al.*, *Impact of incoherent effects on stability diagram at the LHC*, IPAC TUPVA031 2017

Effects of particle distribution on Landau damping

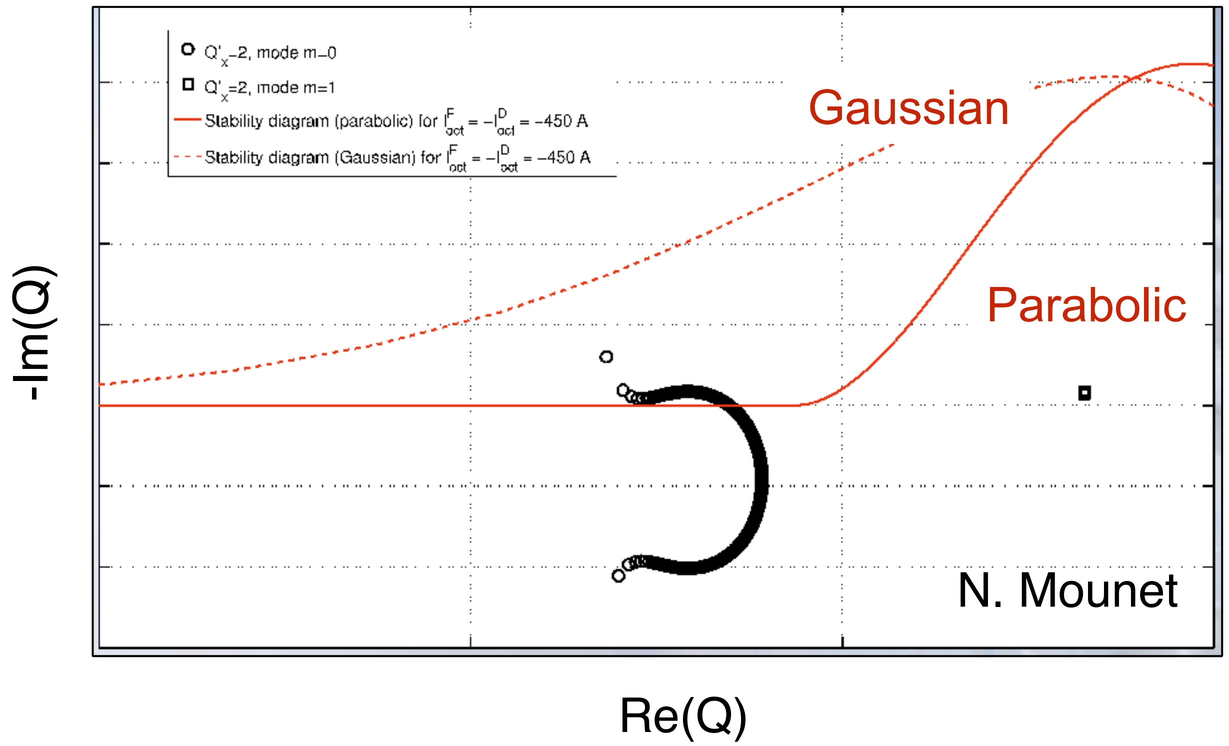


Coherent modes (m=0) are not stabilized as for Gaussian distribution case

Particle distribution degradation below 5 σ reduces stability diagram



Effects of particle distribution on Landau damping



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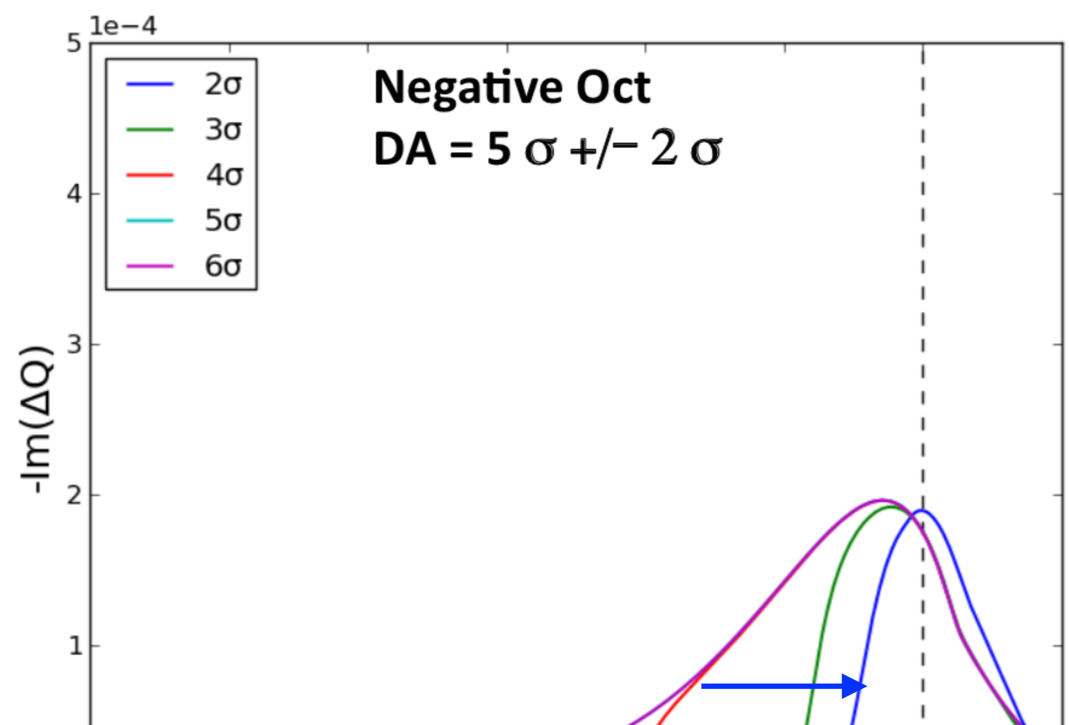
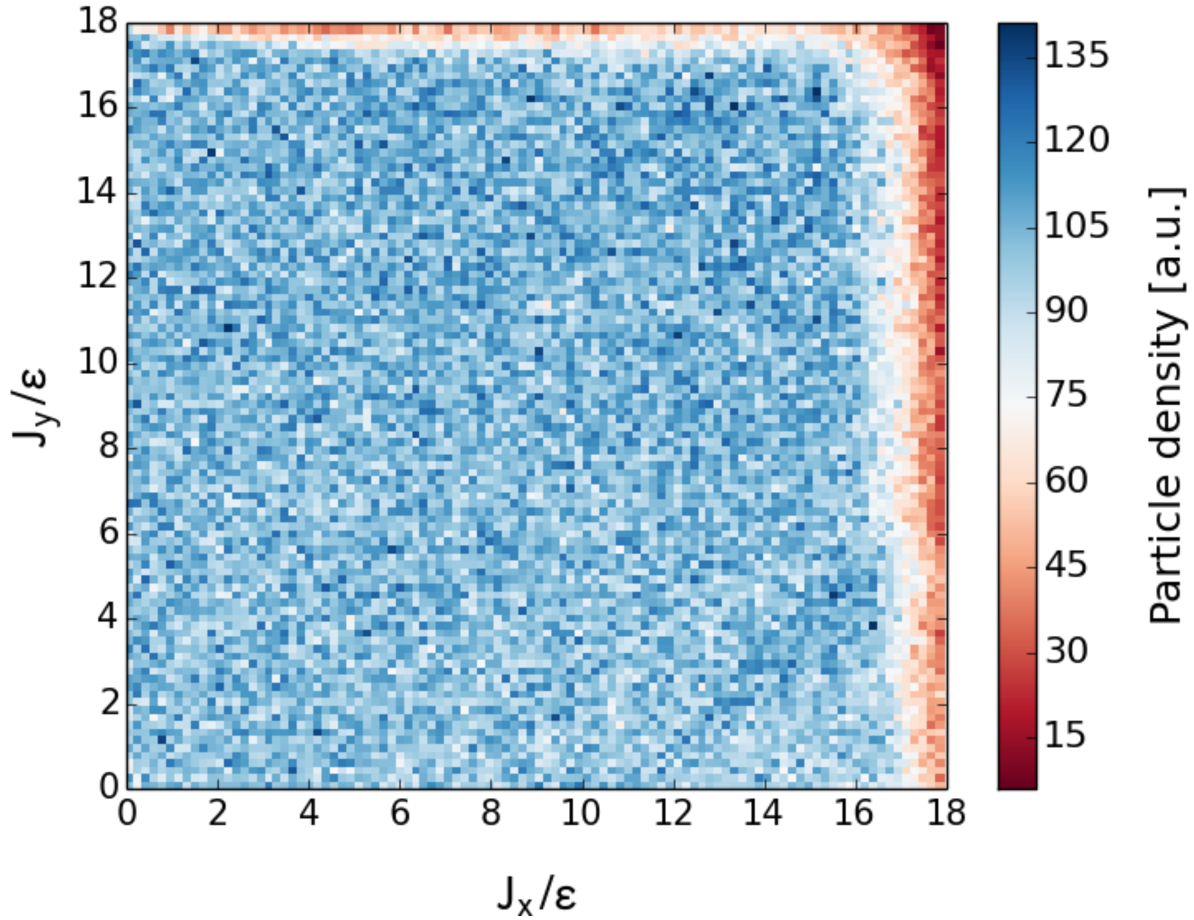


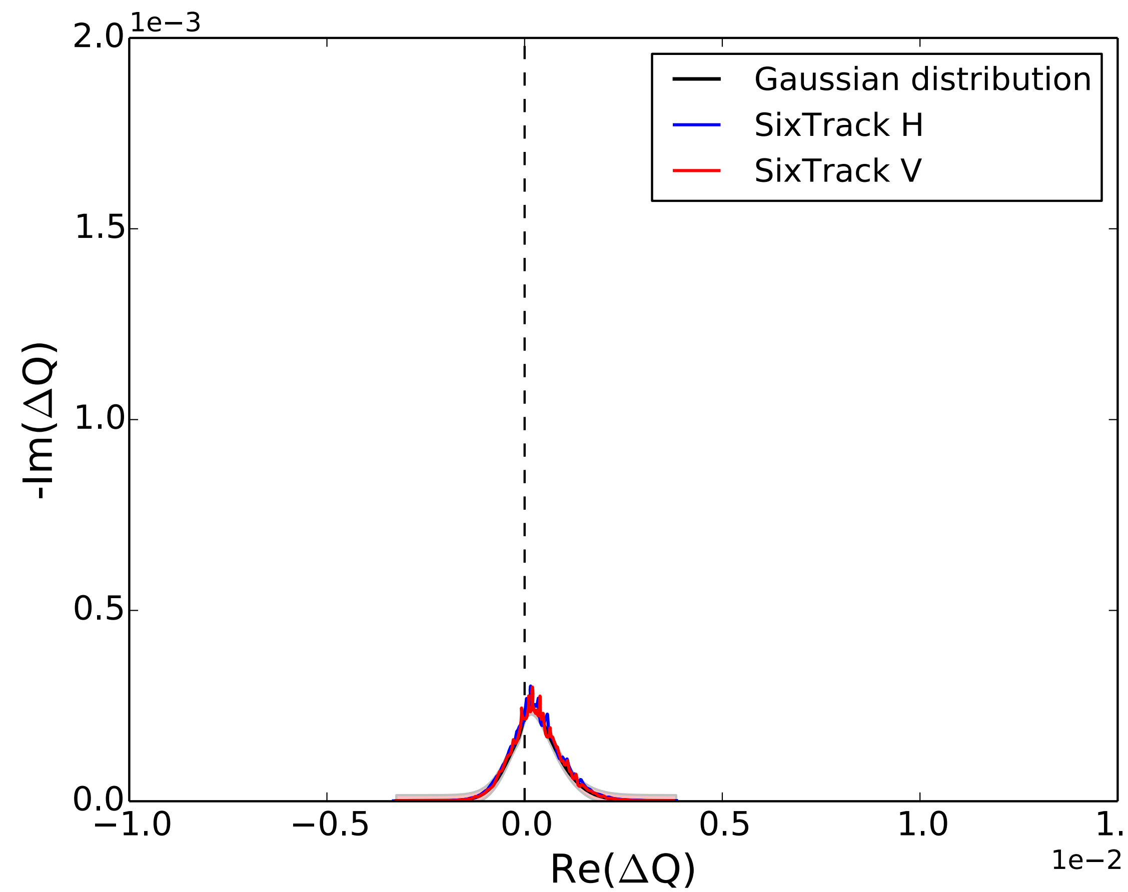
In case of diffusive mechanisms and/or reduced dynamic aperture with particle losses or redistribution → Characterize the impact of realistic lattice on particle distribution

Impact of incoherent effects on the Stability Diagram

Tracking of 10^6 particles under realistic lattice configuration for 10^6 turns (SixTrack by F. Schmidt et al.) ➔ Impact of DA, lattice and beam-beam excited resonances

Tracked distribution (tune spread provided by octupoles current 6.5 A)

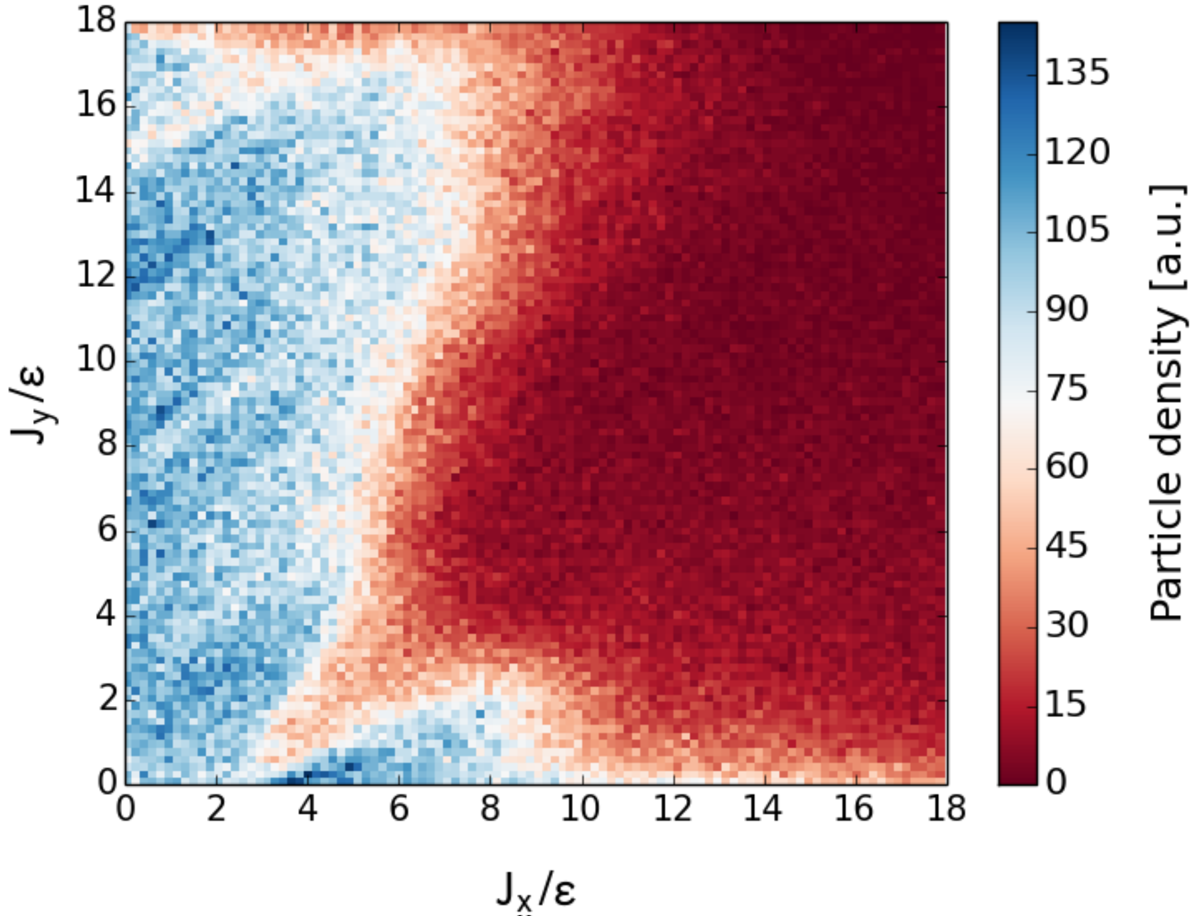


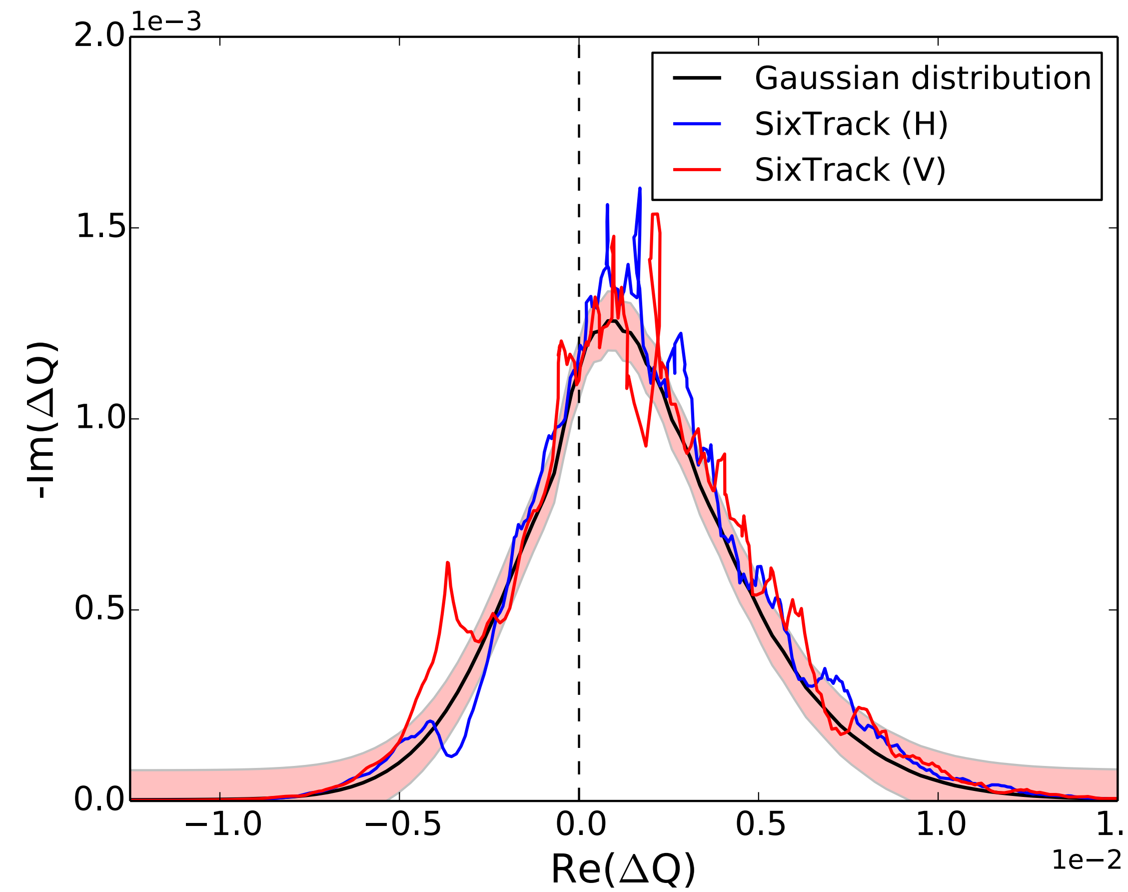


- No evident distortion compared to Gaussian distribution case
- **Red** points represent the particles that are lost (out of the dynamic aperture)

Impact of incoherent effects on the Stability Diagram

Tracked distribution (tune spread provided by octupoles current 35 A)





- Small amplitude particles are lost (amplitude < 3.5 σ)
- Distortion visible on the Stability Diagram due to modification of particle distribution (reduced dynamic aperture)

Incoherent effects on the particle distribution modify coherent stability

BTF to measure transverse beam stability

Beam **T**ransfer **F**unction measurements are direct measurements of the dispersion integral

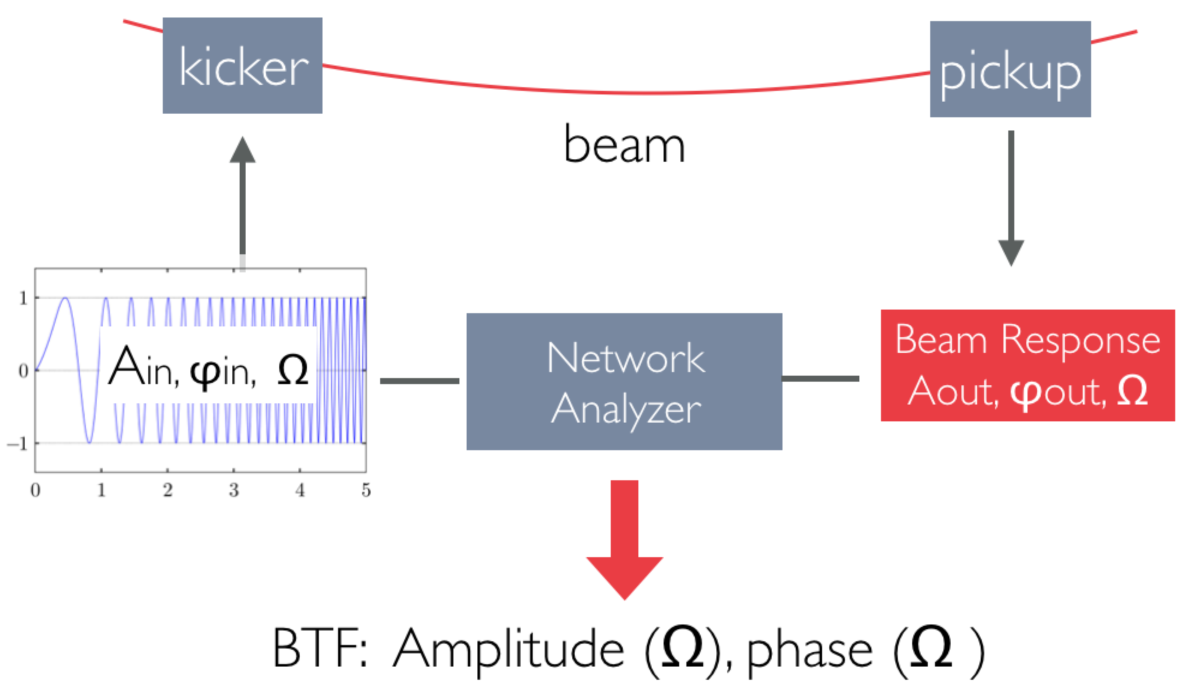
$$\mathrm{BTF} \;\propto\; \int_0^\infty \int_0^\infty \frac{J_{x,y}\frac{d\Psi_{x,y}(J_x,J_y)}{dJ_{x,y}}}{Q_0 - q_{x,y}(J_x, J_y) - i\epsilon} dJ_x dJ_y$$

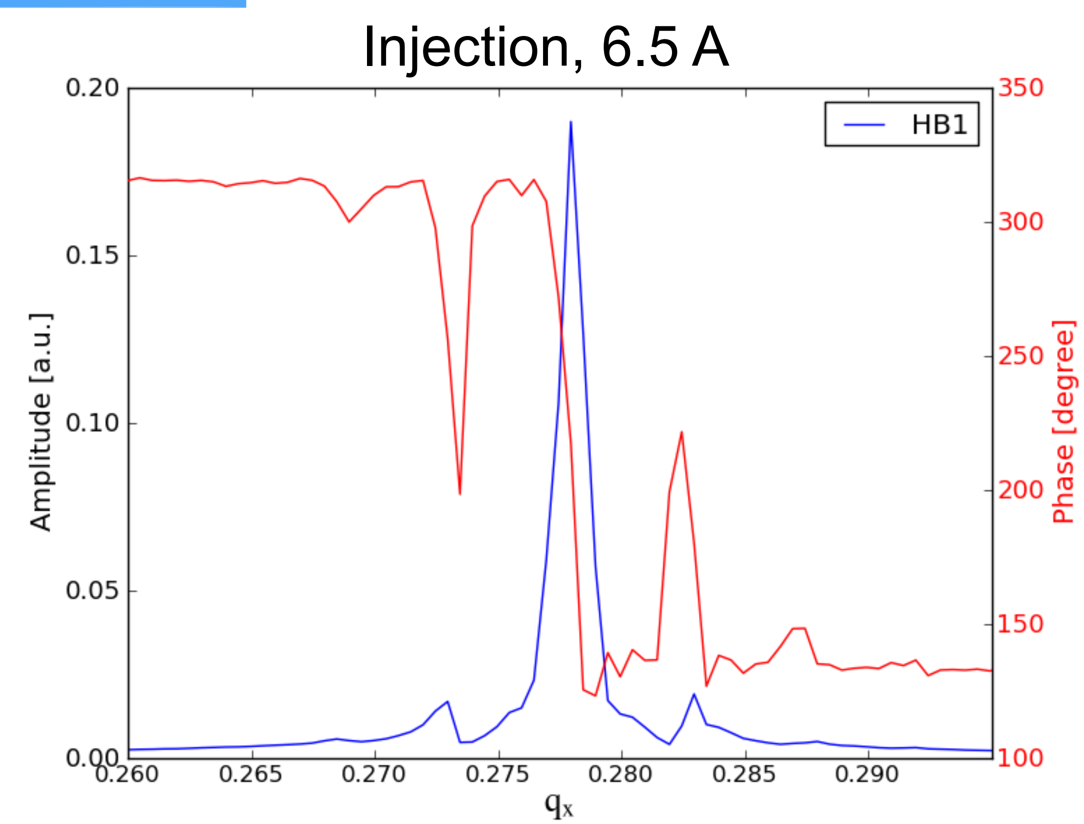
BTF can experimentally verify the stability → direct measurements of SD!

- Tune (high resolution, operationally used at RHIC), chromaticity measurements
- Coherent mode observations
- **Sensitive to particle distribution changes**
- **Tune spread of the beams**

The transverse BTF system at the LHC

Beam Transfer Function:
beam amplitude response per driving excitation frequency

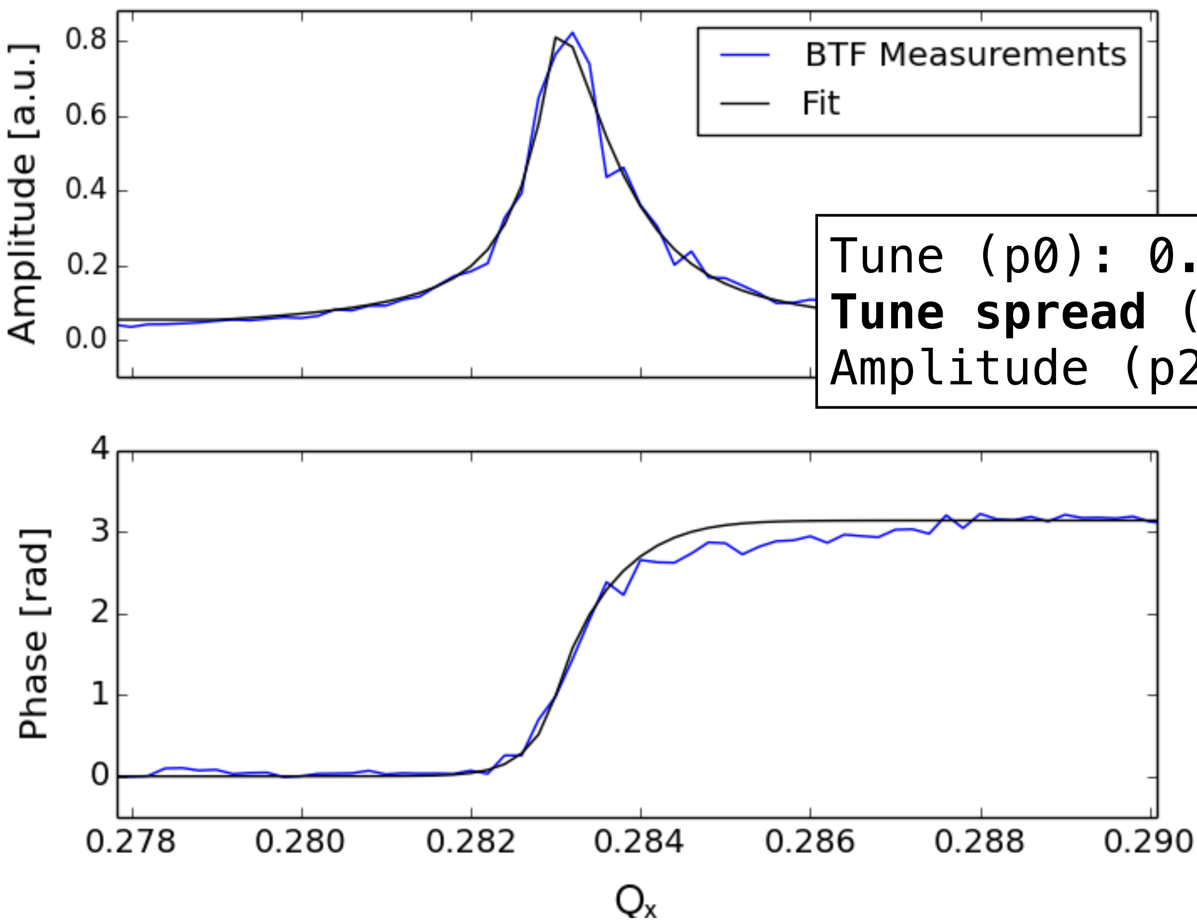




- Installed in **LHC** in the 2015 for the **first time**
- Small excitation, **small impact on the beam quality**
- **Uncalibrated system (dependency on measurement conditions)**

Stability diagram reconstructed from BTFs in the LHC

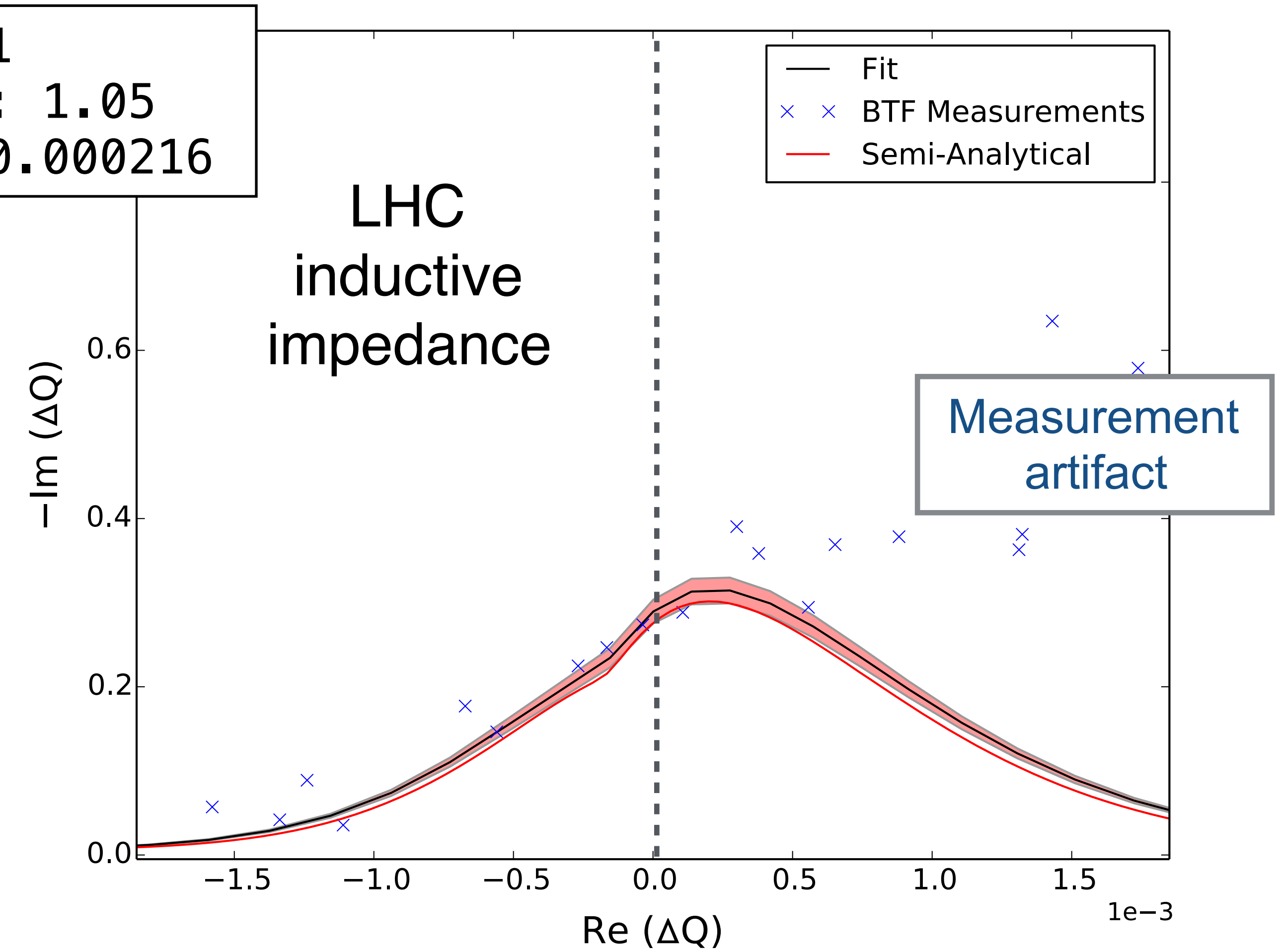
Single bunch, Injection, 6.5 A (2016)



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

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

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

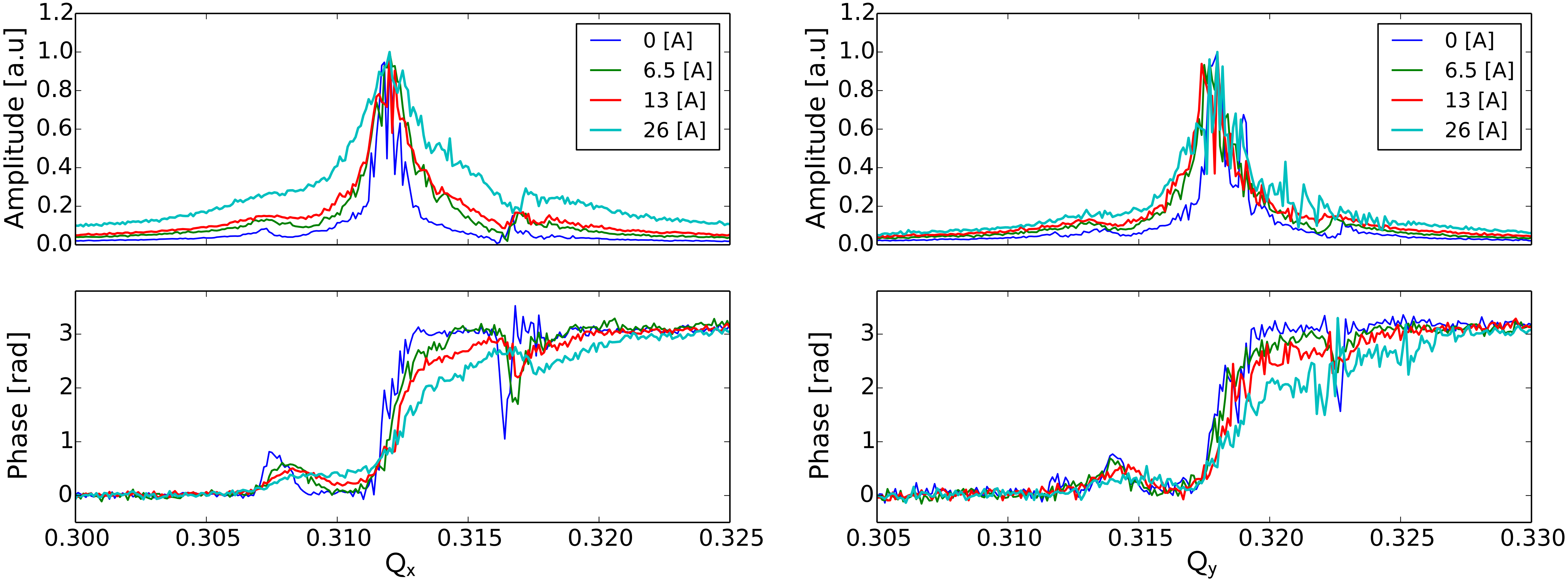


Good agreement between measurements and expectations for the 2016 measurements

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

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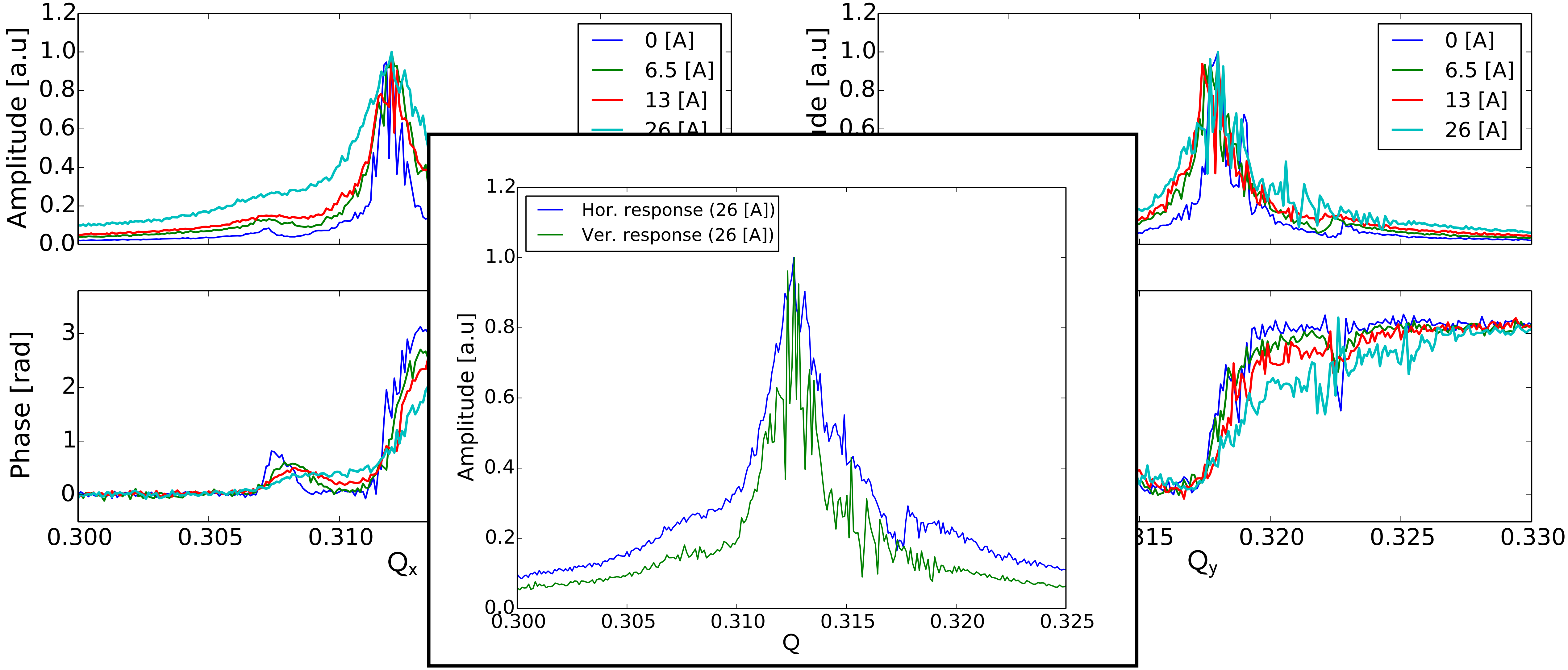
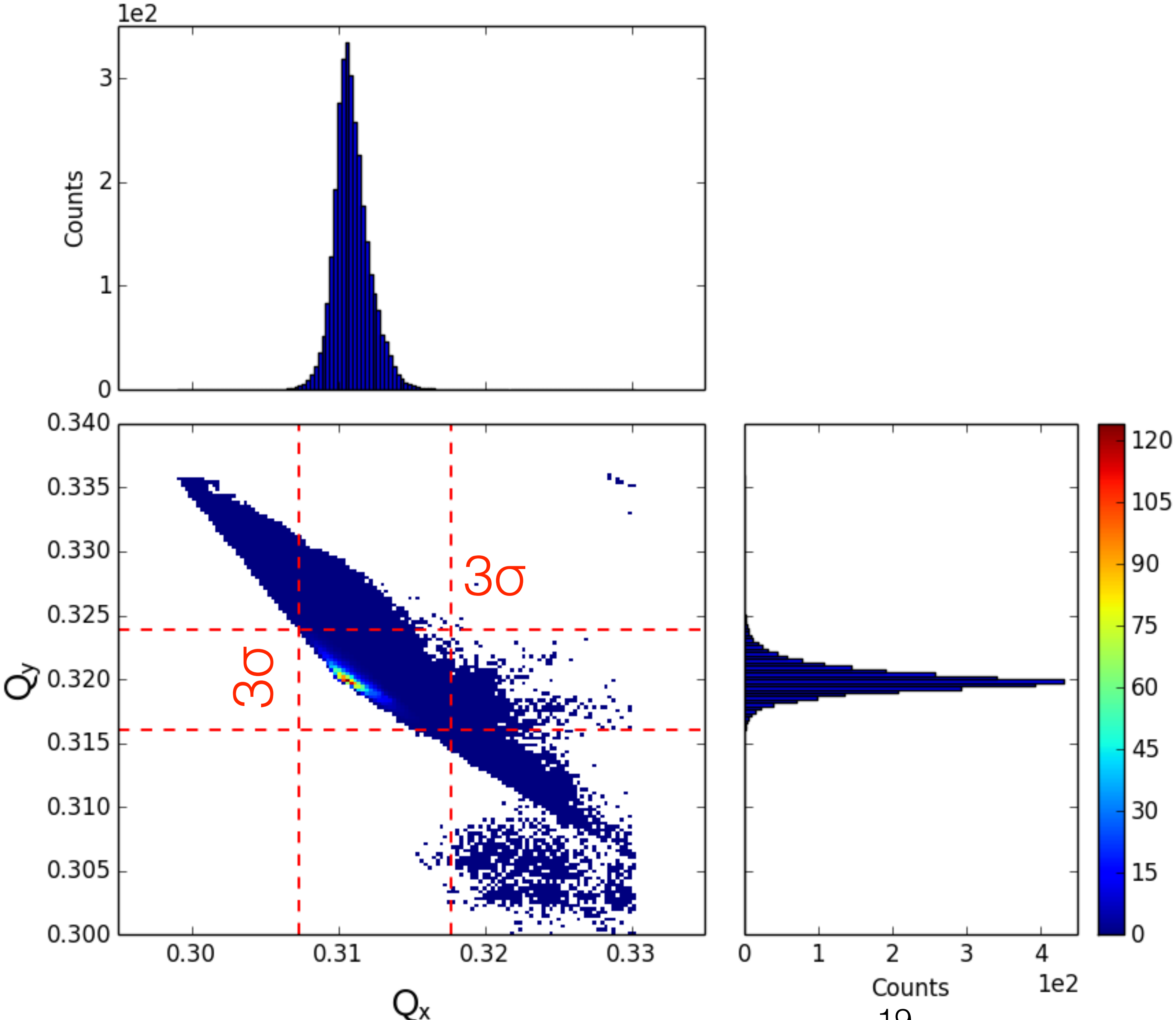


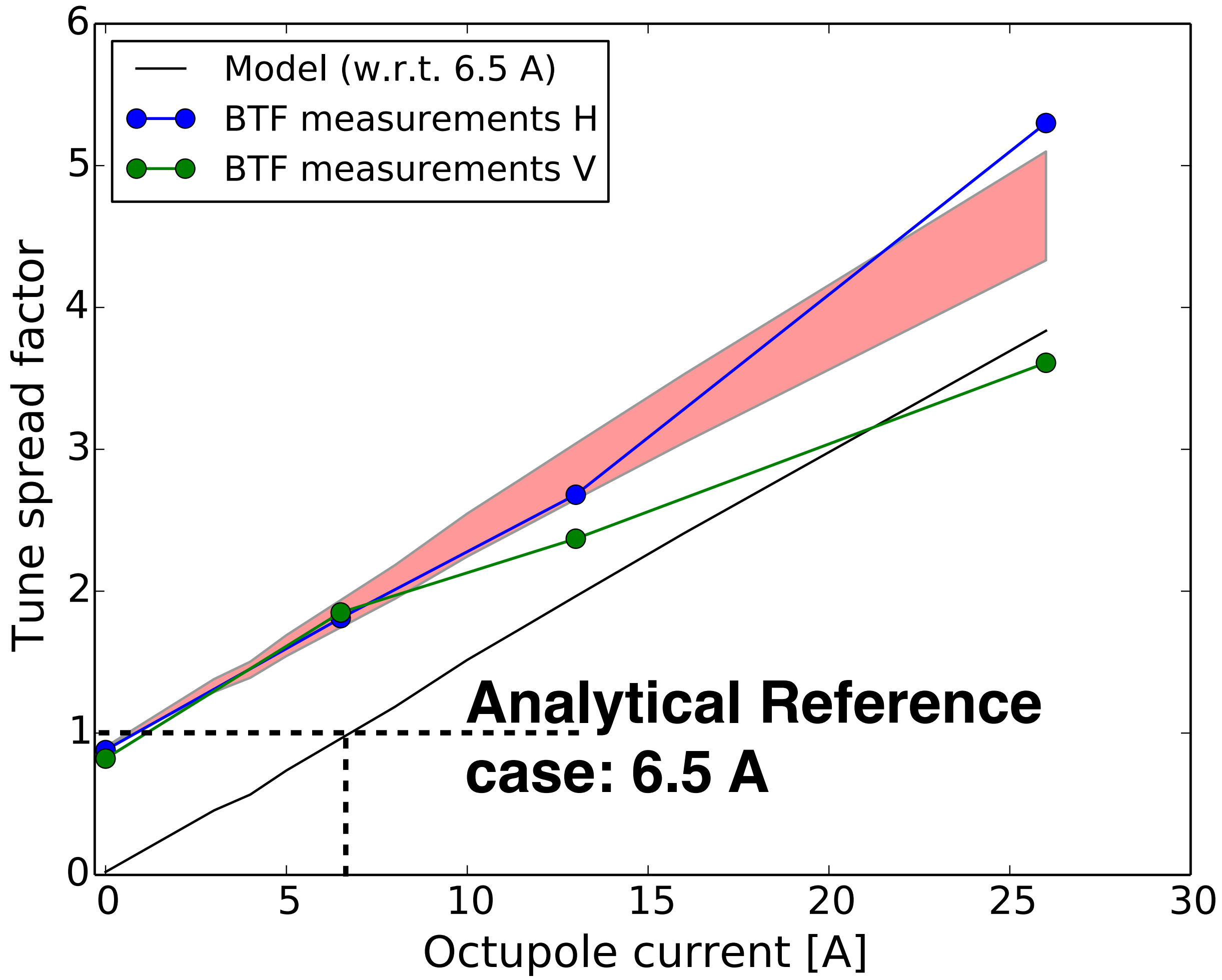
For the largest octupole strength (26 A) larger spread in the horizontal plane, smaller in the vertical plane

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

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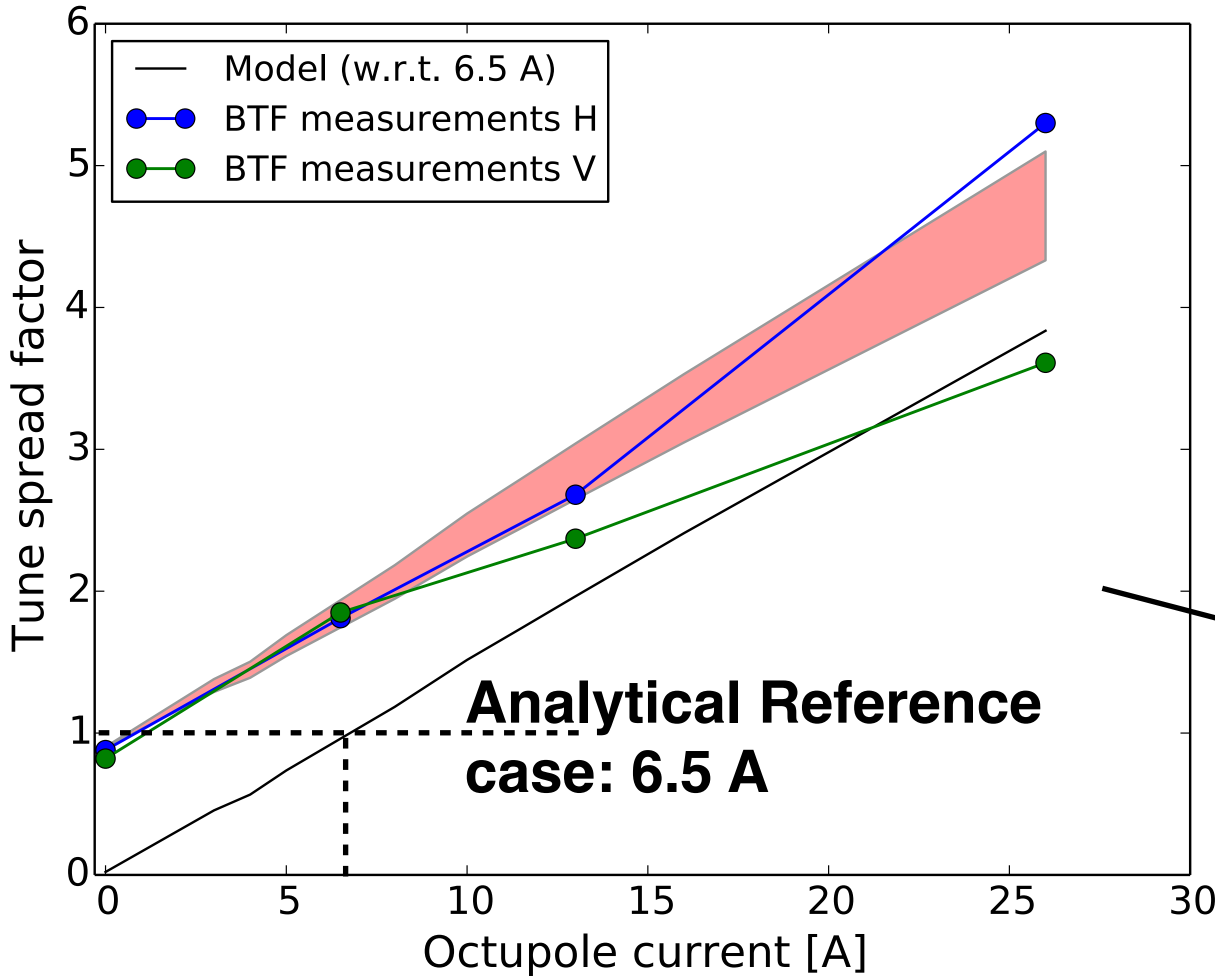

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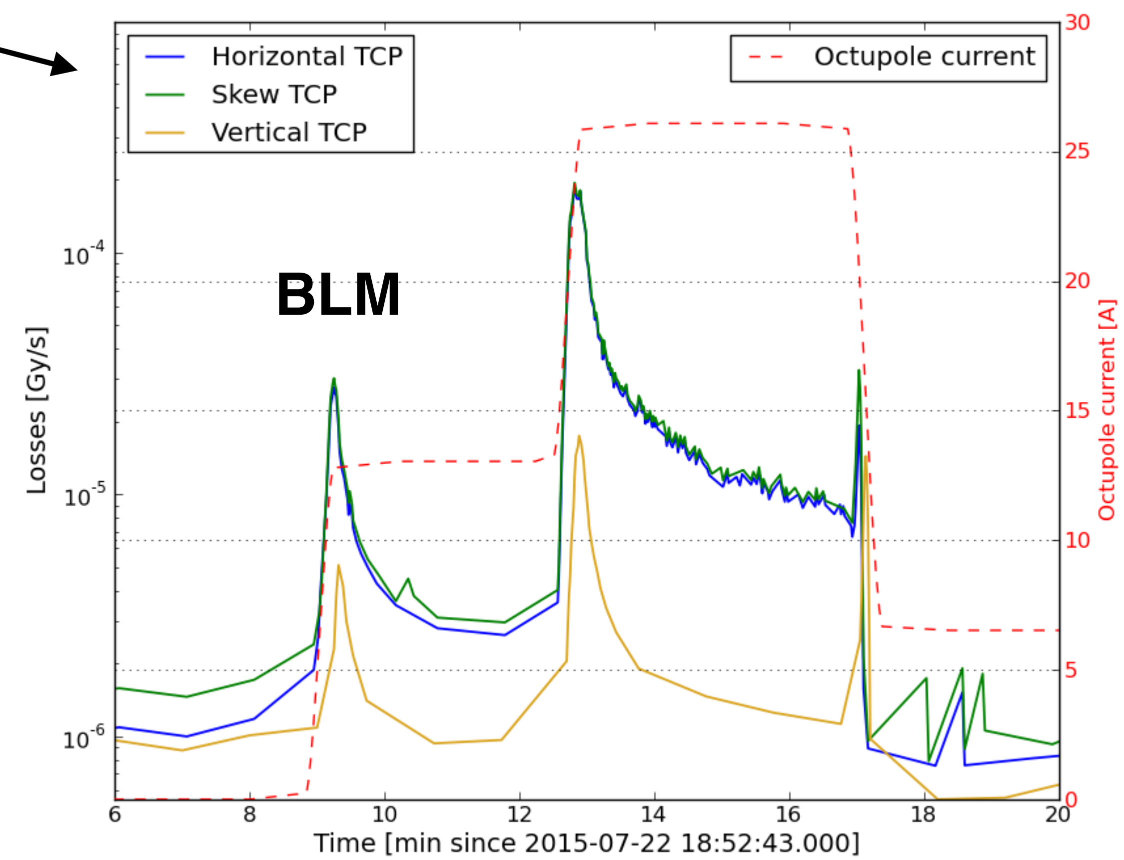
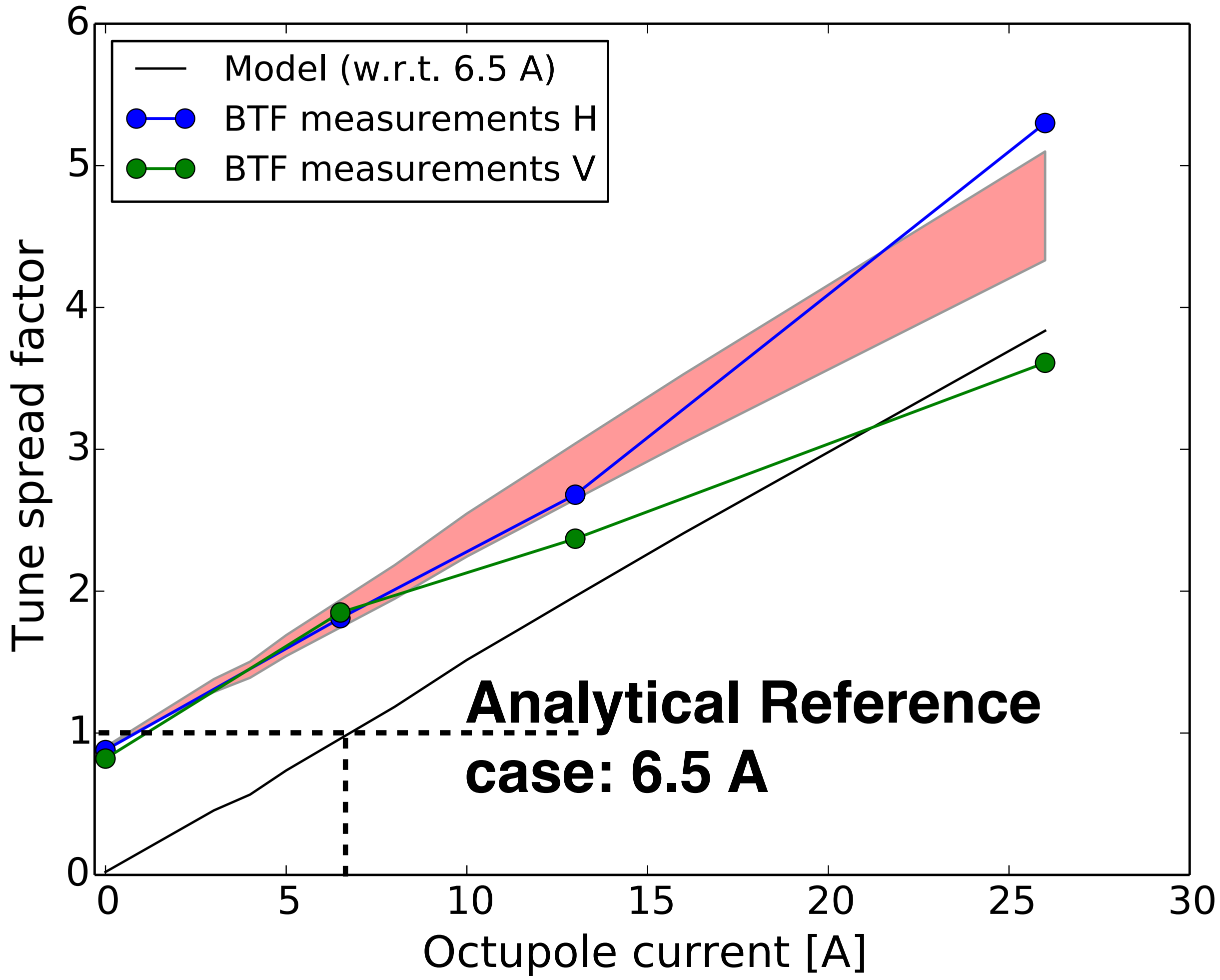
Losses observed in the vertical plane correlated with octupole current changes



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

Octupole scan at injection: evaluation of beam tune spread



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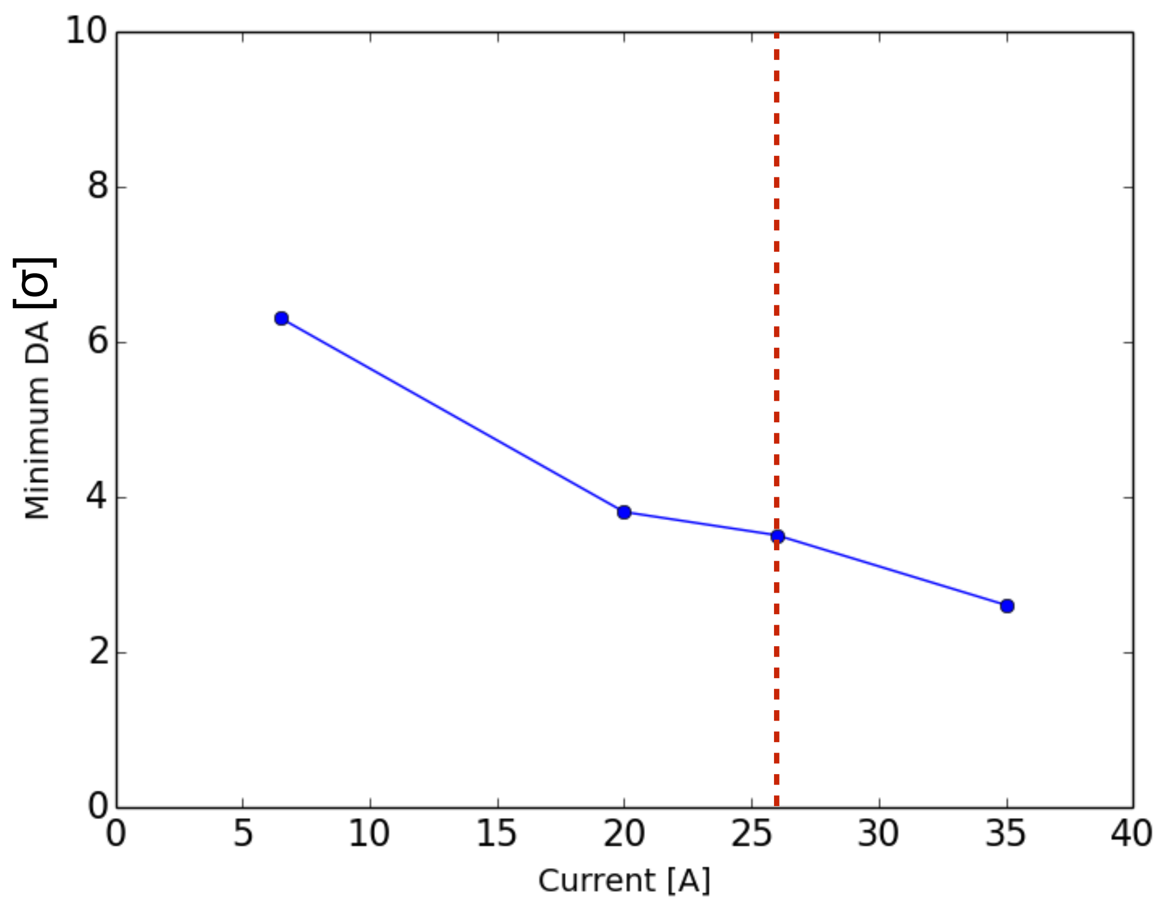
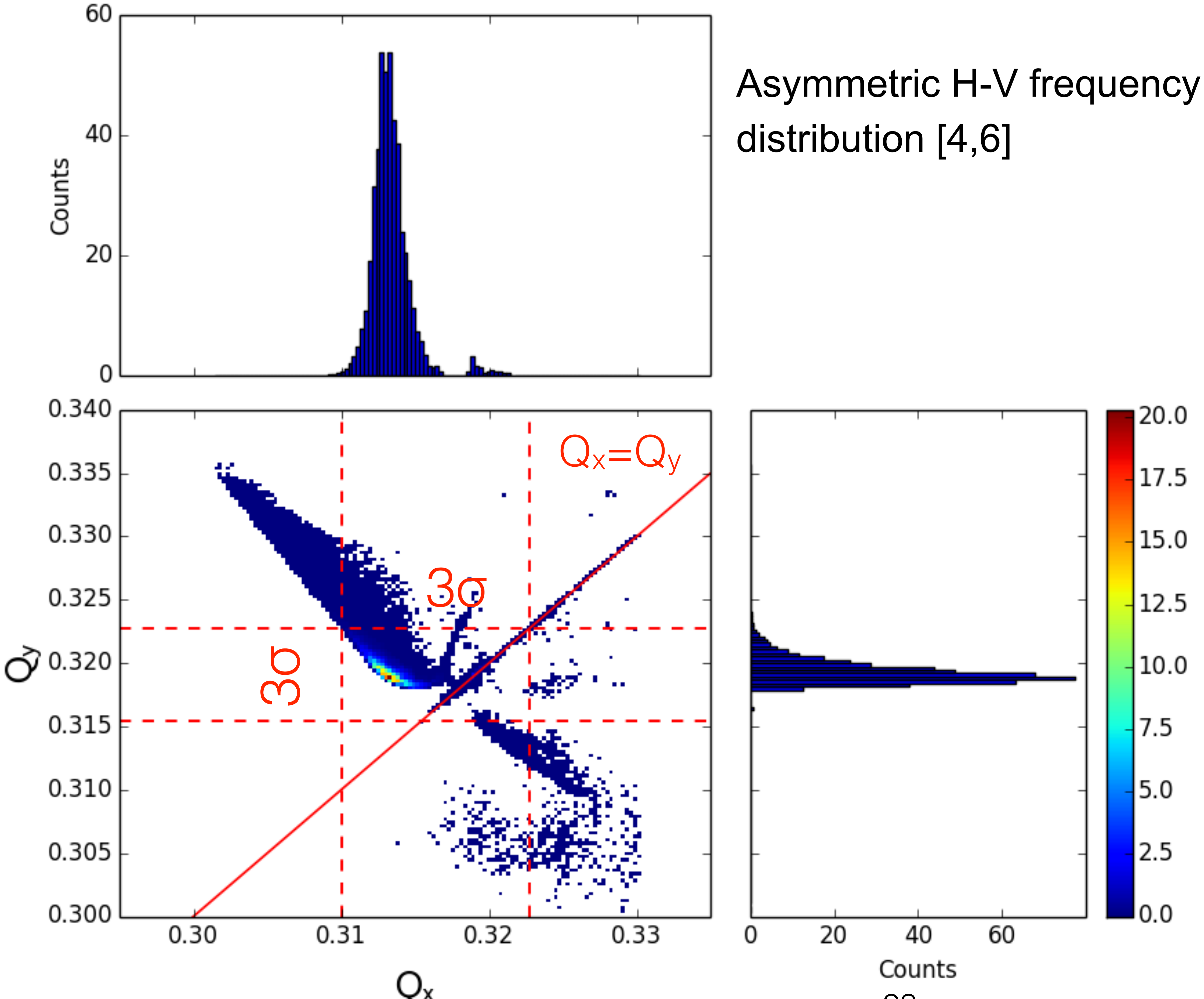


Losses observed as a function of octupole strength due to a reduction of DA

→ 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

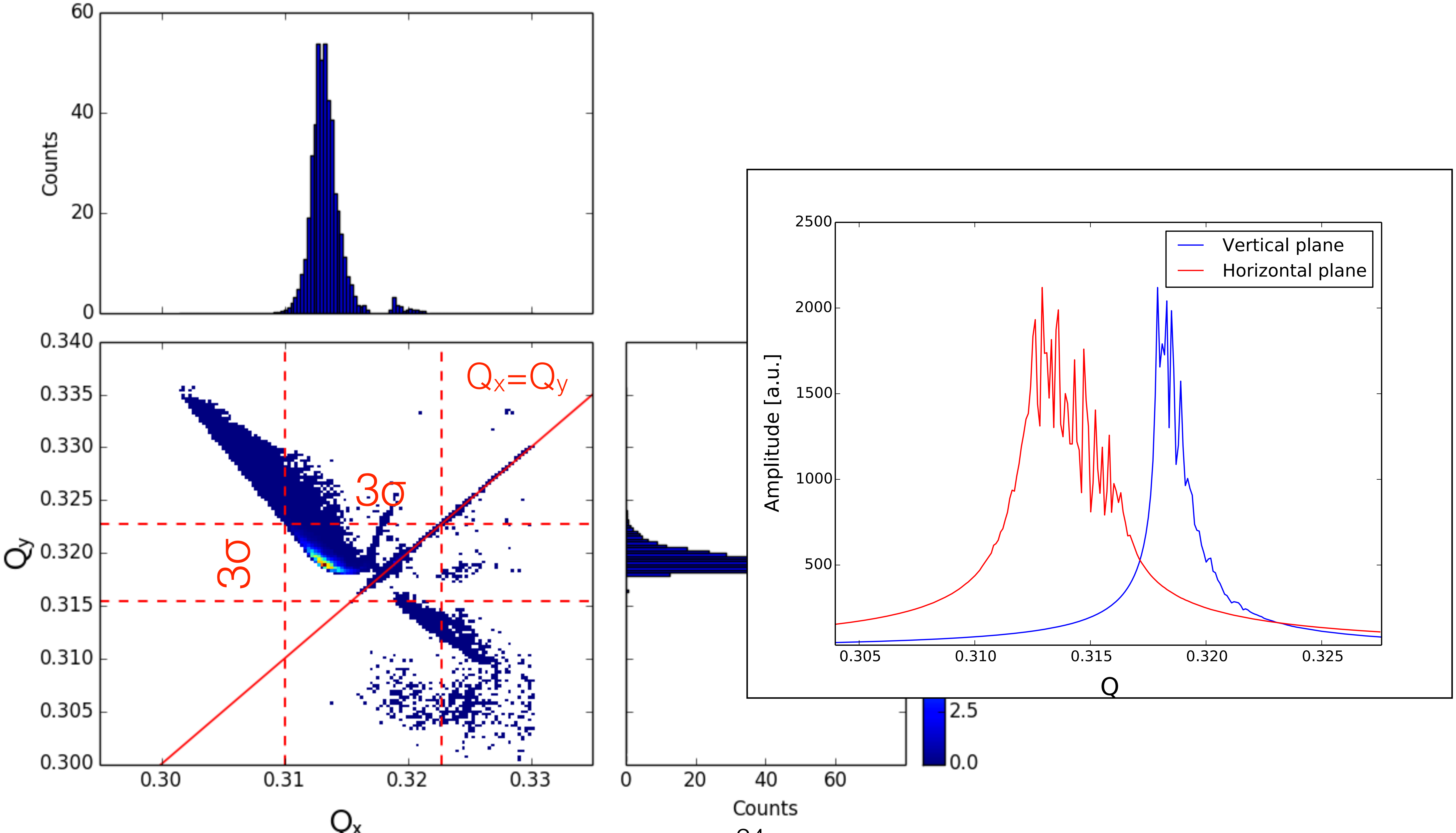


Asymmetric H-V frequency distribution [4,6]

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

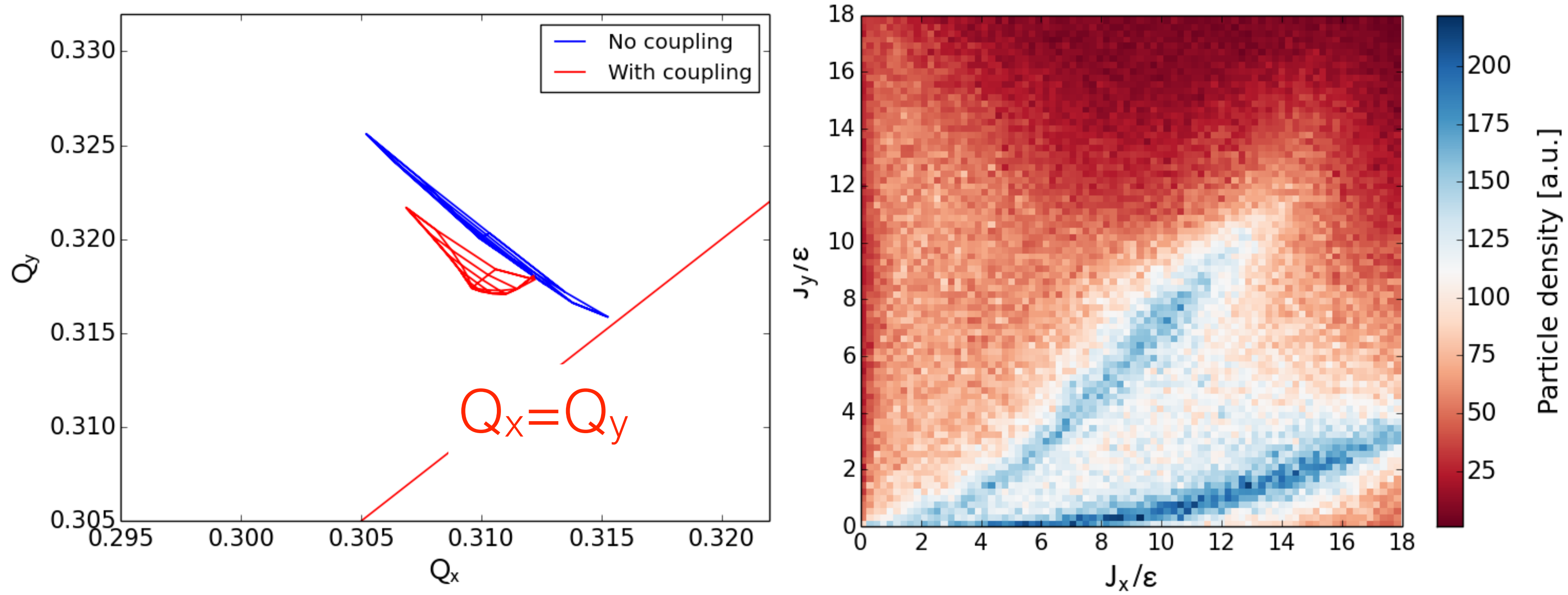
Frequency distribution at injection with linear coupling

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



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

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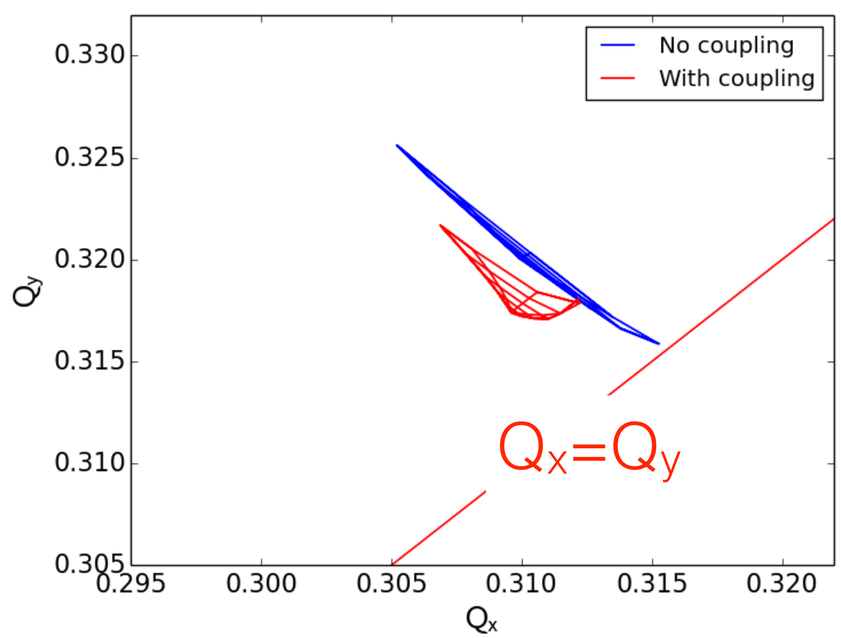
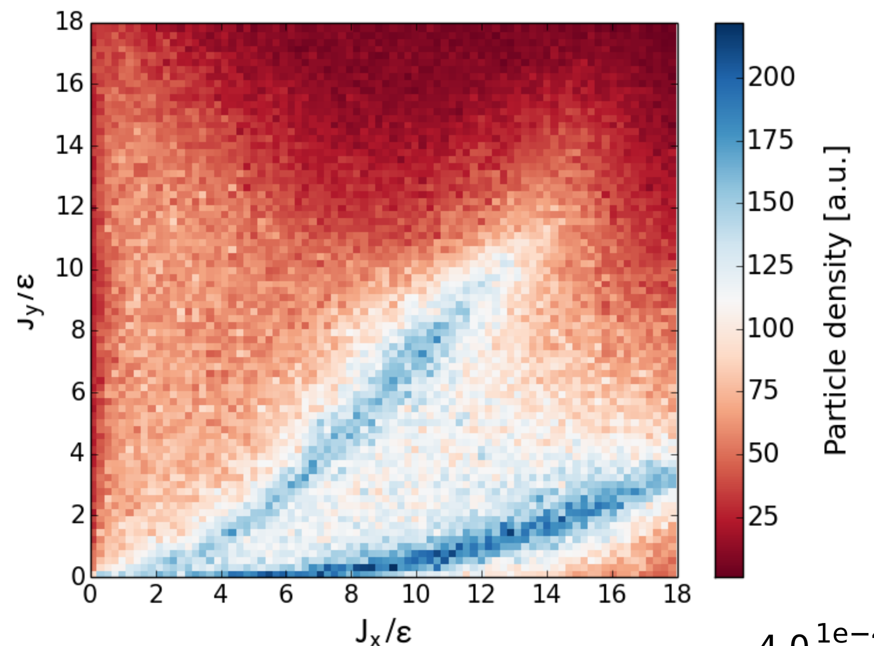
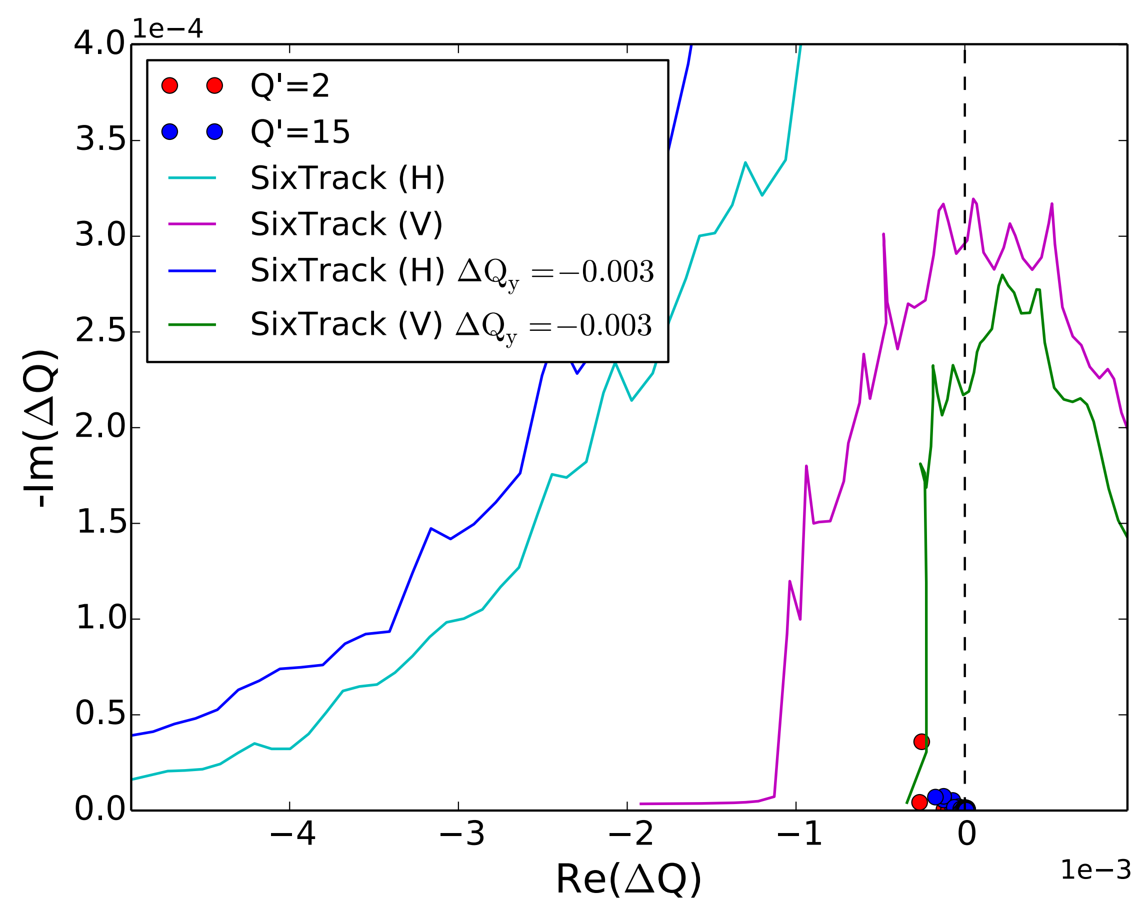


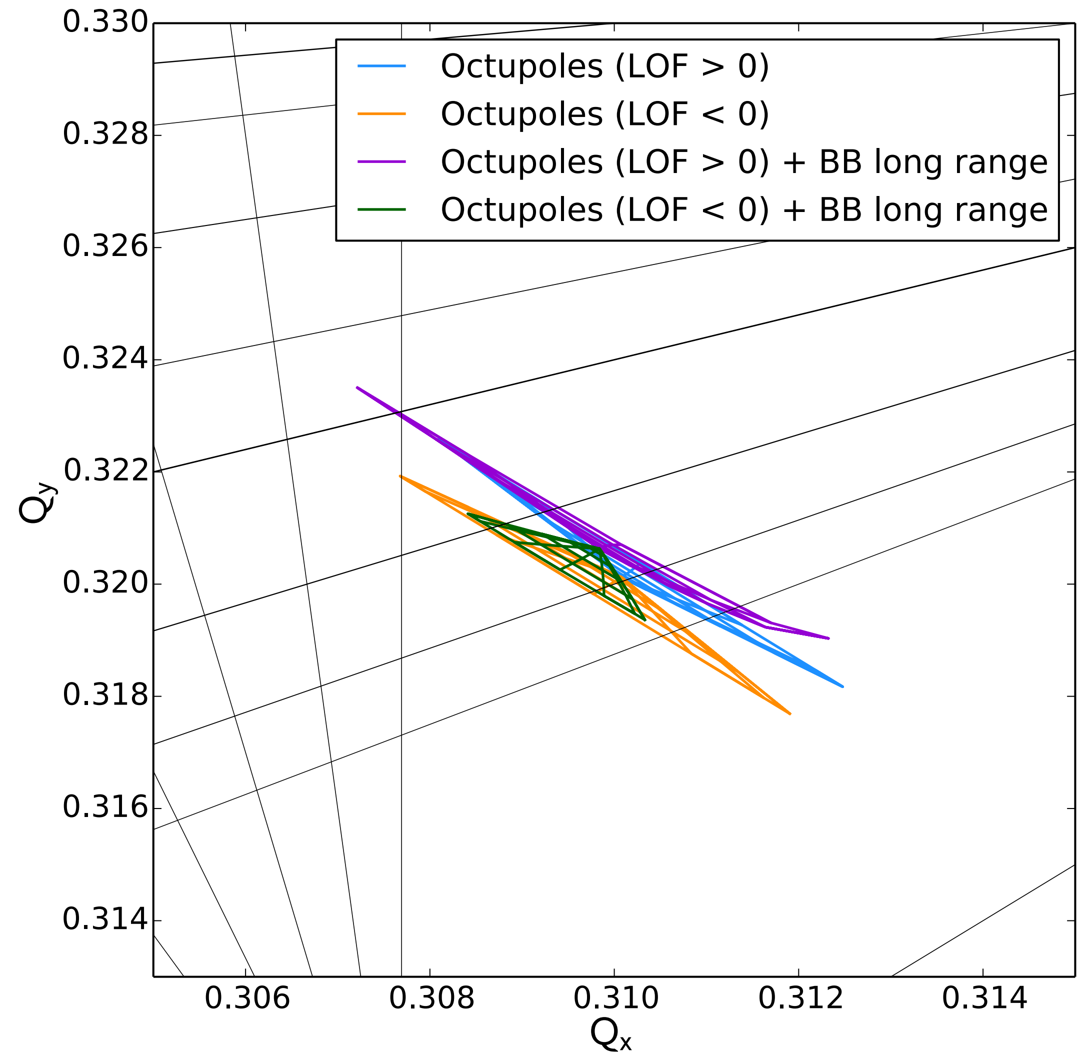


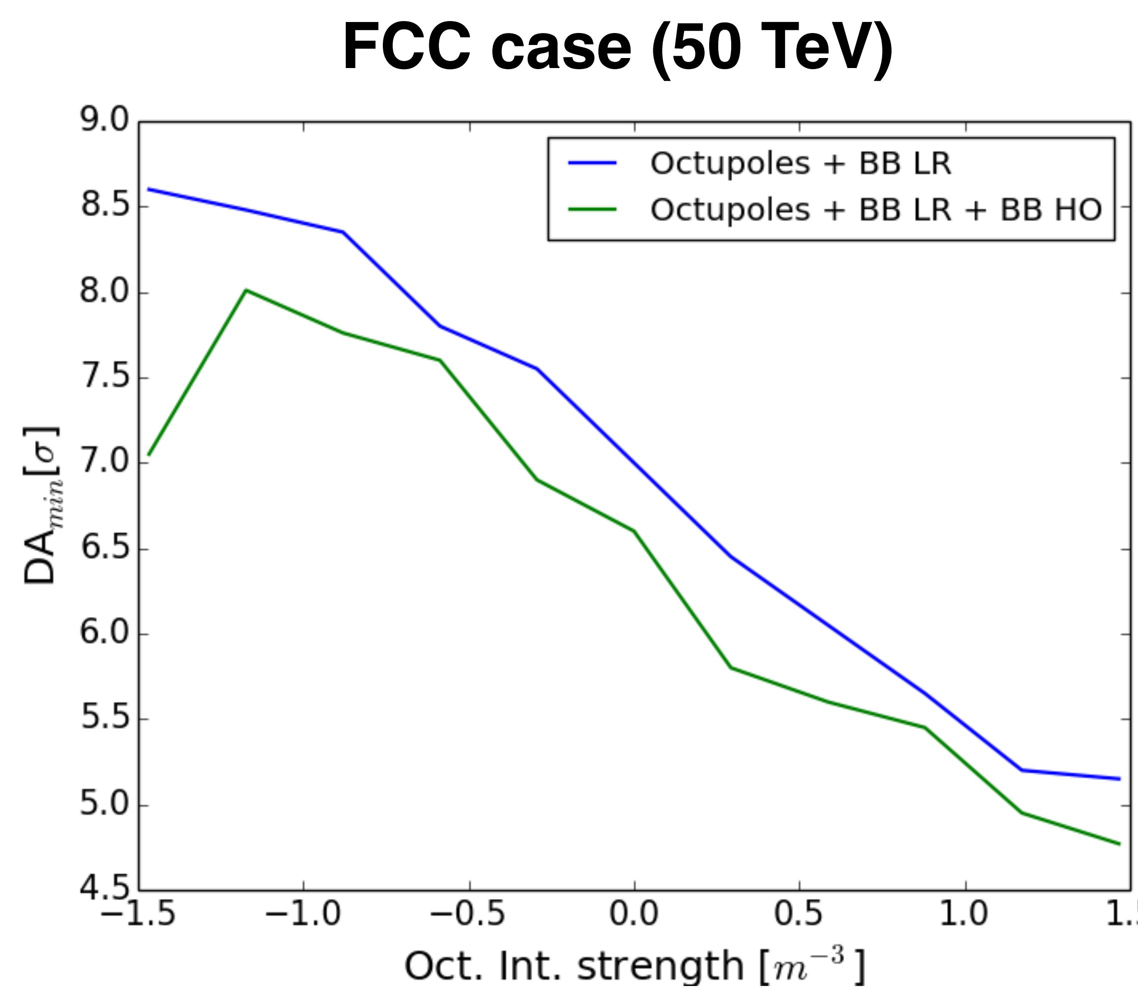
Particles approach more the diagonal and the effects are stronger

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



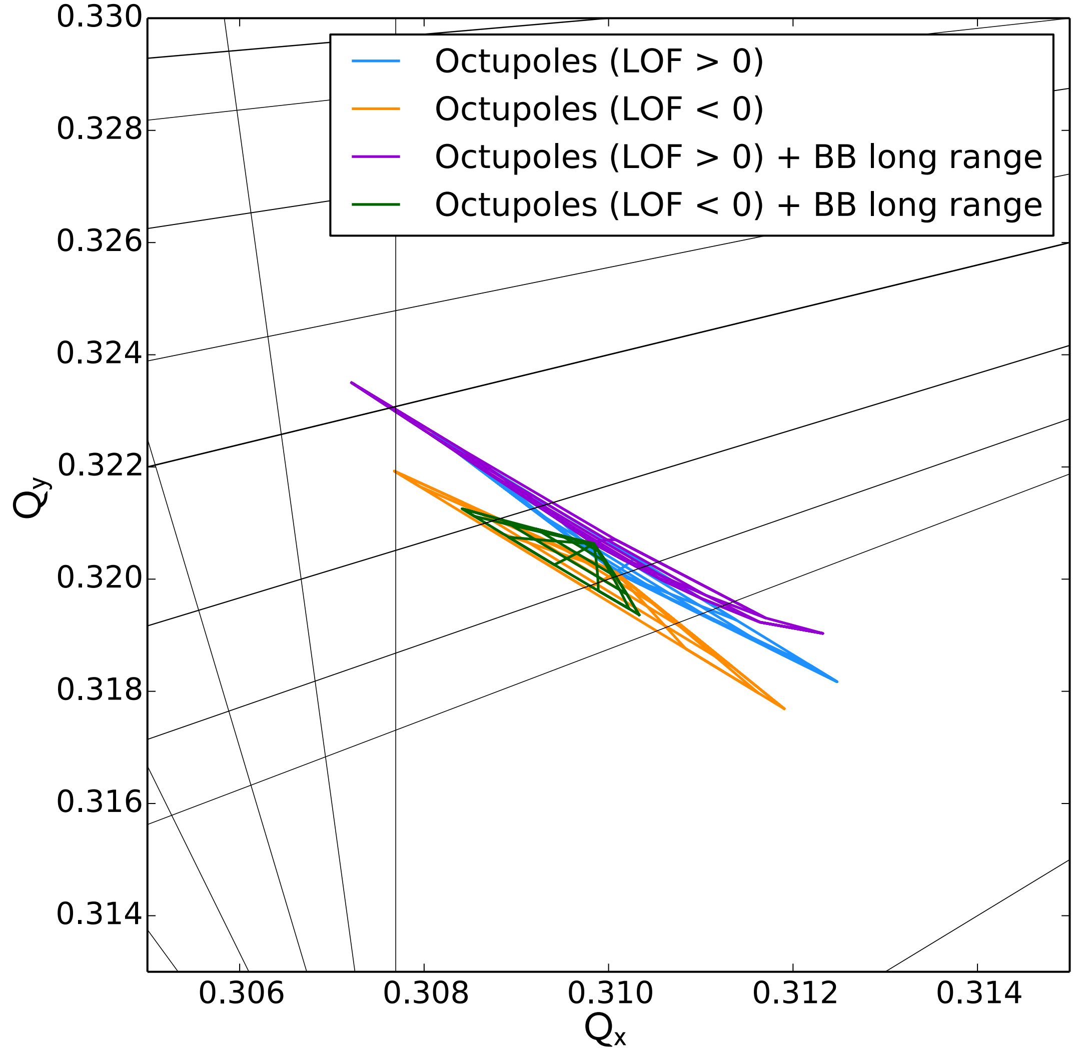
Landau damping and DA in presence of beam-beam interactions

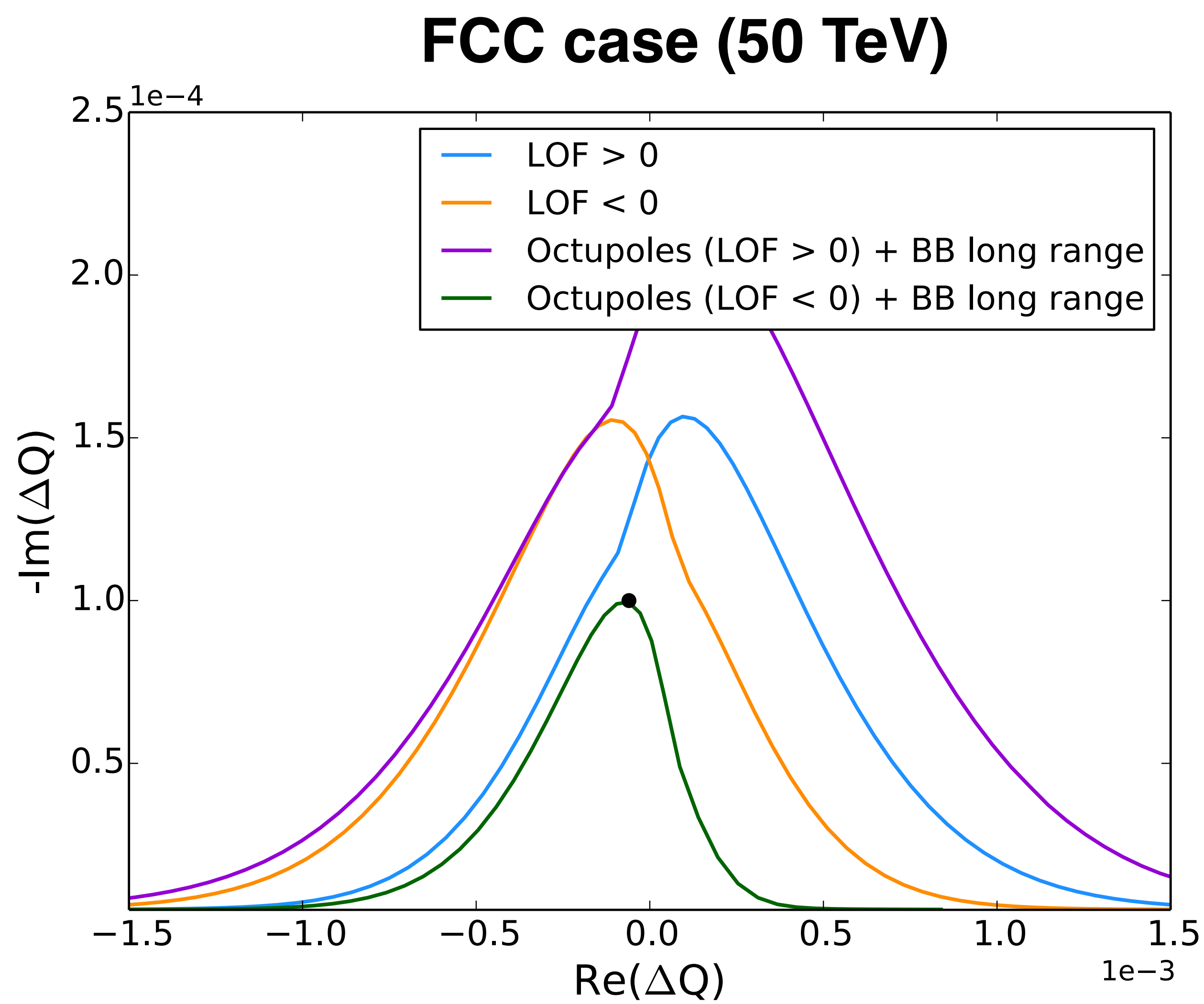




- Beam-beam long range interactions excite resonances, according to the octupole polarity the tune spread (Landau damping) increases or decreases in presence of beam-beam long range with different impact on DA
- **Compensation of LR BB observed for negative octupoles → DA above 6.5 σ**
- **DA is reduced in case of positive octupole polarity and beam-beam long range interactions (5.5 σ)**

Landau damping and DA in presence of beam-beam interactions





DA > 5 σ stability diagram, Gaussian distribution is a good approximation

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Summary

CERN

- Landau damping depends both on tune spread and particle distribution: increasing the tune spread (octupoles, beam-beam) is not always beneficial for Landau damping: **reduction of DA (< 4 σ) ➔ reduction of Landau damping**

- The beam stability has to be maximized during the full cycle (different machine configurations): in presence of BB the tune spread with single beam (octupoles) is modified ➔ impact on **DA must be taken into account (better for negative octupole polarity because of beam-beam compensation)**

- **Linear coupling + high octupole current provoke diffusive mechanisms and frequency cut that reduce Landau damping** compared to expectations producing important H-V asymmetry ➔ **measured for the first time (BTF in LHC)**

- The particle distribution (DA, losses or redistribution) may have strong impact on stability diagram:

    - **Distortion of shape** compared to a Gaussian distribution

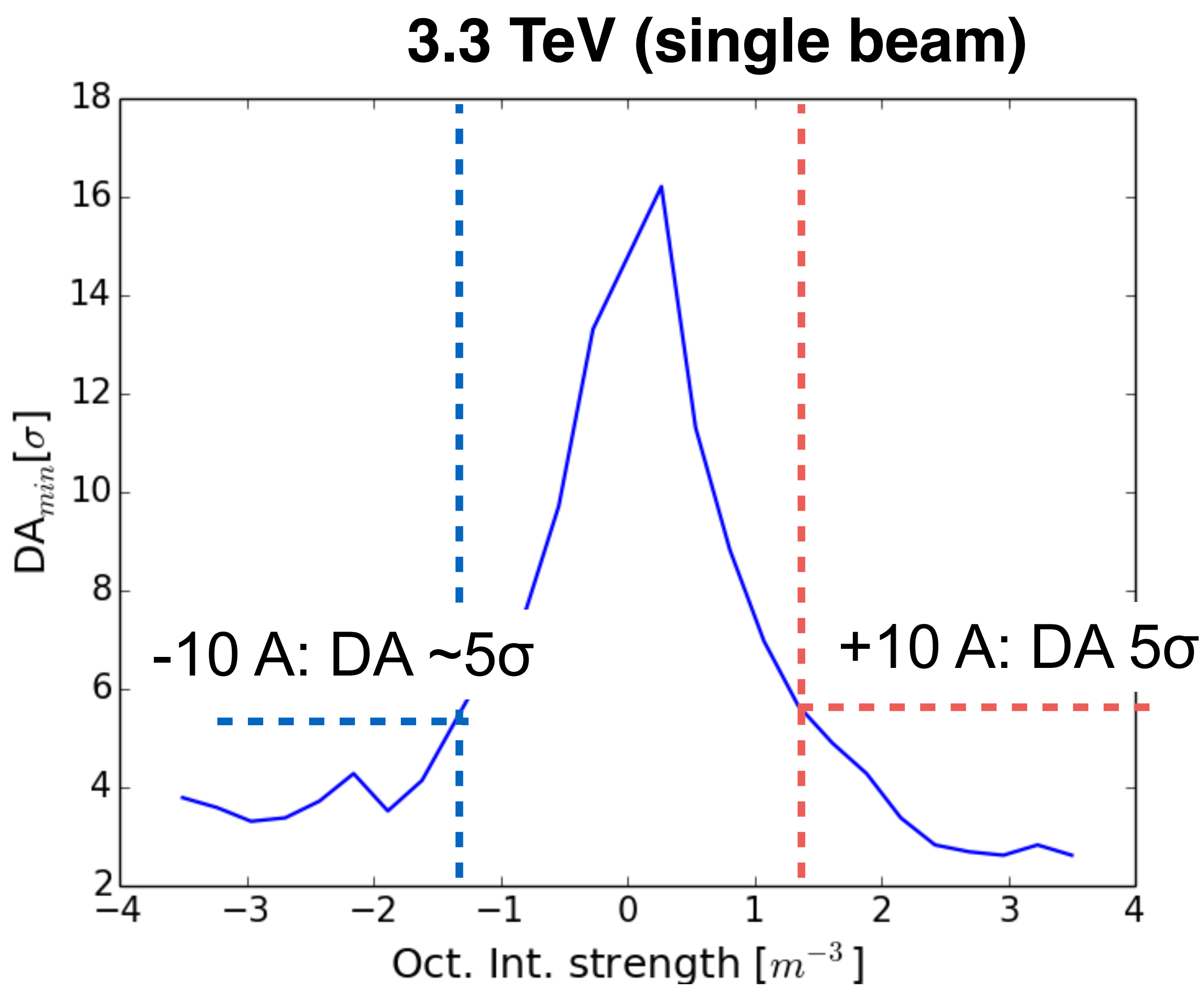
    - **Asymmetric Landau damping in H-V** plane as in presence of linear coupling

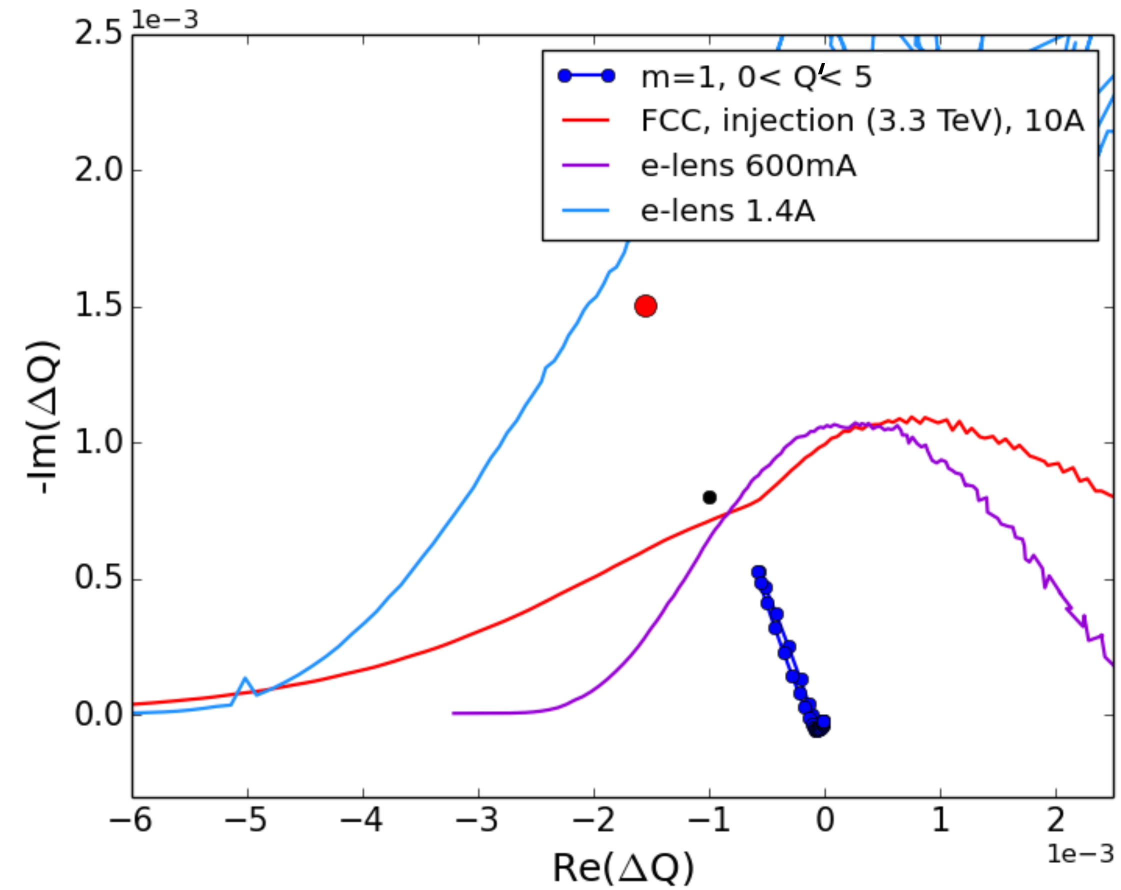
- The dispersion integral is valid when collective forces are treated as a small perturbation, not true anymore in presence of strong excited resonance: ➔ **test limitation of the model together with dedicated experiments (BTF)**

Thanks for your attention

Back-up slides

FCC Stability at injection





- Bad impact of Landau octupoles at injection on DA (168 Octupoles only): **with multipolar errors situation gets worse!**
- 10 A octupole current is required at injection ➔ DA ~ 5σ Not acceptable! Need to explore different scenaria (feedback, octupoles, high chromaticity ➔ BIM-BIM code with impedance wakes)

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)

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

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

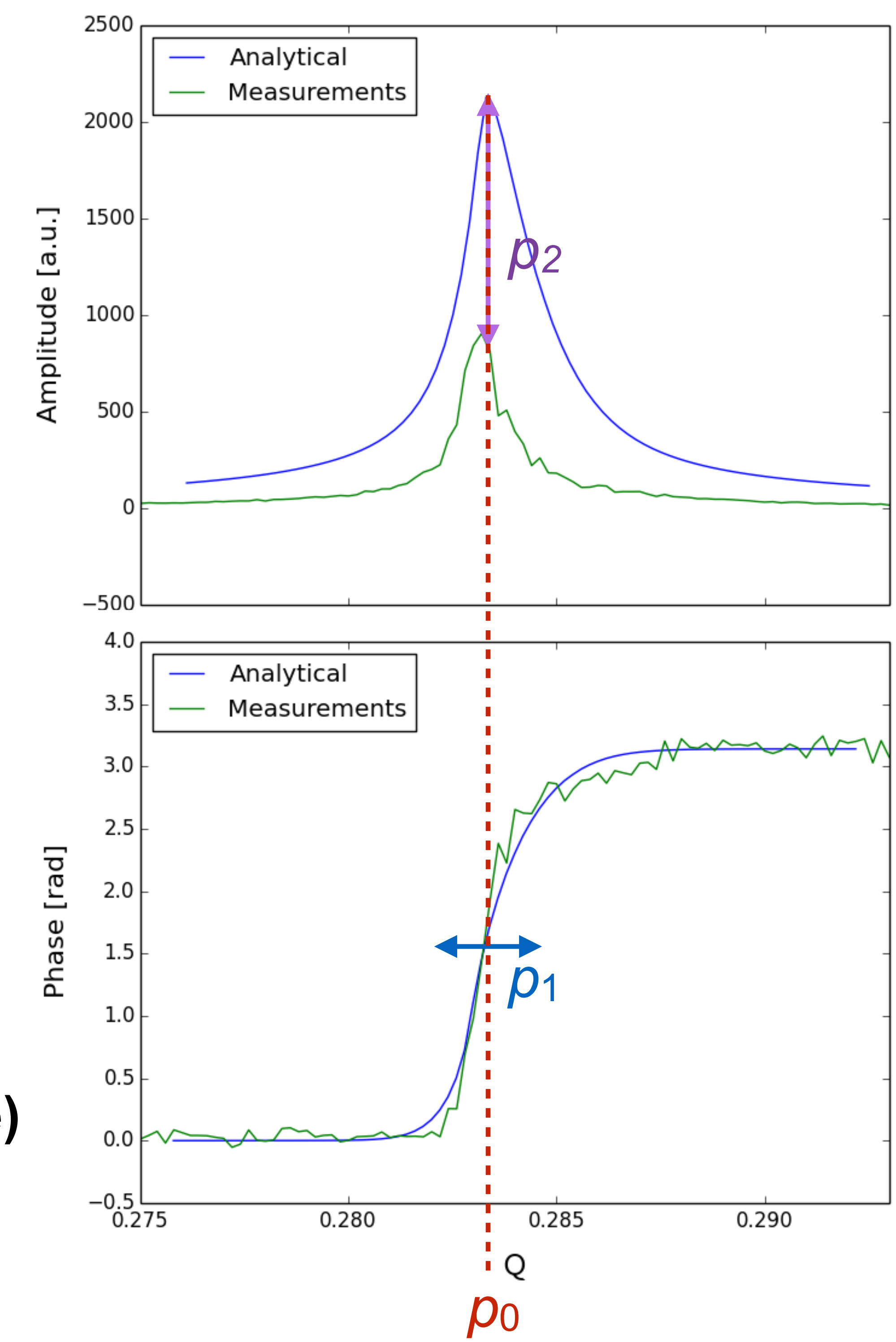
p_0 = Tune

p_1 = Tune spread factor respect to a reference case

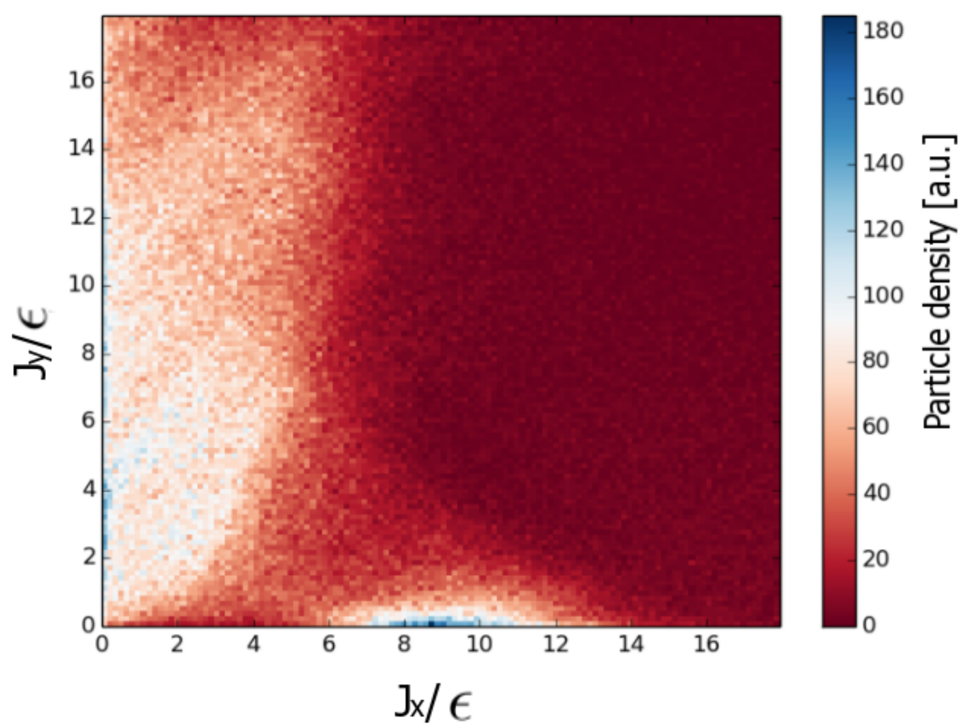
independent from calibration factor, (phase slope)

p_2 = Amplitude factor:

calibration, proportionality constant



Distribution in presence of linear coupling



Injection energy (26 A)