Beam Transfer Function measurements: what do they tell us?

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Acknowledgements: J. Wenninger, D. Valuch, MD coordinators

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CHART Swiss Accelerator Research and Technology

Contents

- What is a Beam Transfer Function measurement?
- Tune measurements
- Chromaticity
- Stability area (Landau Damping)
- Tune spread
- Summary

Beam Transfer Function measurements

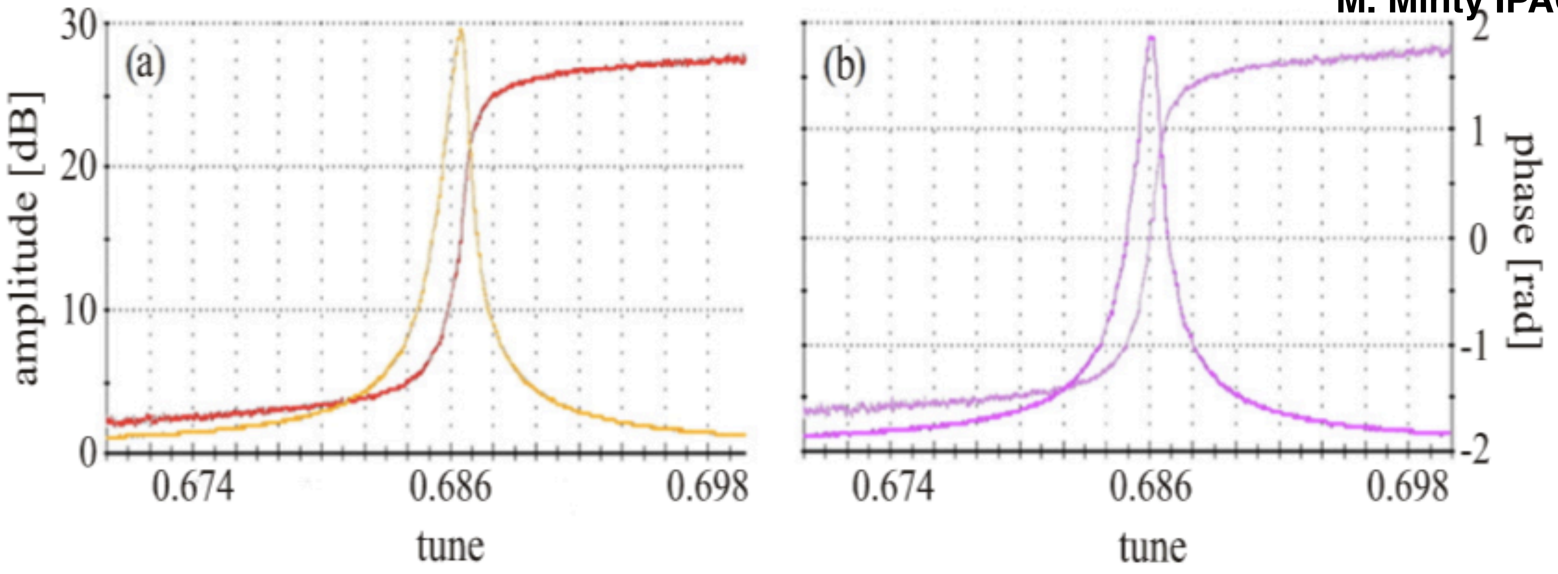
BTF R(Ω):
Fraction of the complex response amplitude A(Ω) of the beam per driving amplitude D(Ω) of a beam excited at the frequency Ω
R(Ω) = A(Ω)/D(Ω)

$$R_i(\Omega) = c \cdot \int_0^\infty \int_0^\infty \frac{1}{\Omega - w_i(J_x, J_y)} \frac{J_i d\psi_{x,y}(J_x, J_y)}{dJ_i} dJ_x dJ_y$$

- white noise and measure amplitude-phase response
- swap frequency of excitation over range of interest and store amplitude and phase

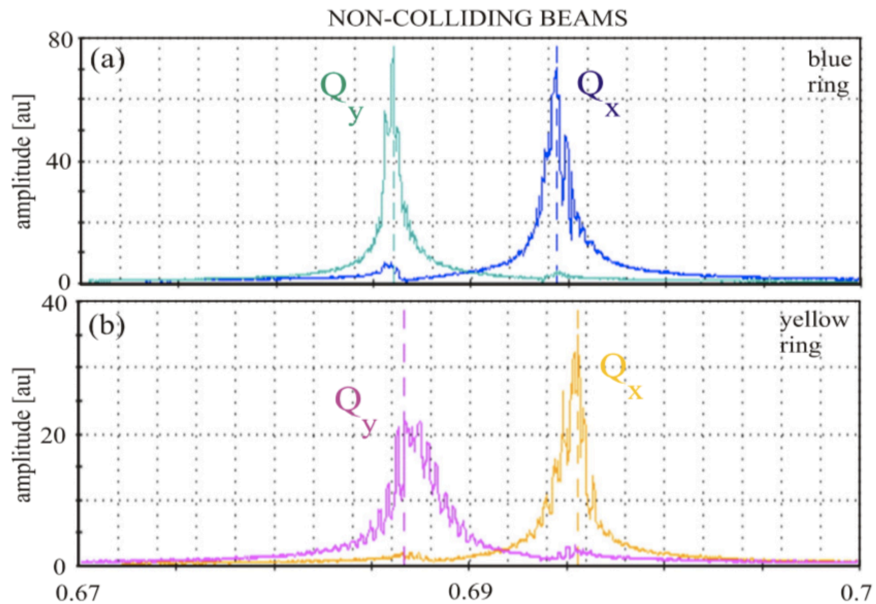
BTF Measurements

M. Minty IPAC2010



Can give information on:

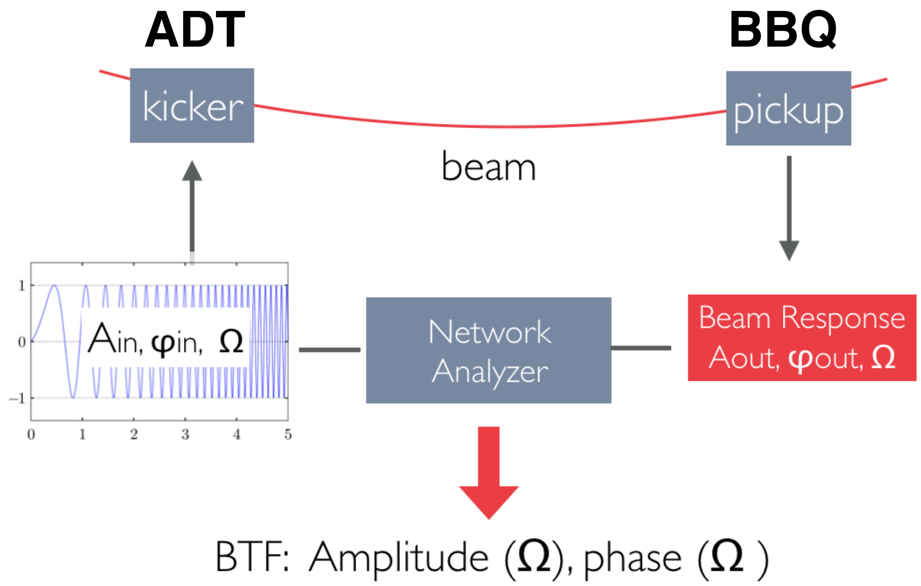
- tune
- chromaticity
- tune spread
- coherent modes (driven by beam-beam or impedance)
- stability area (Landau Damping and particle distributions)

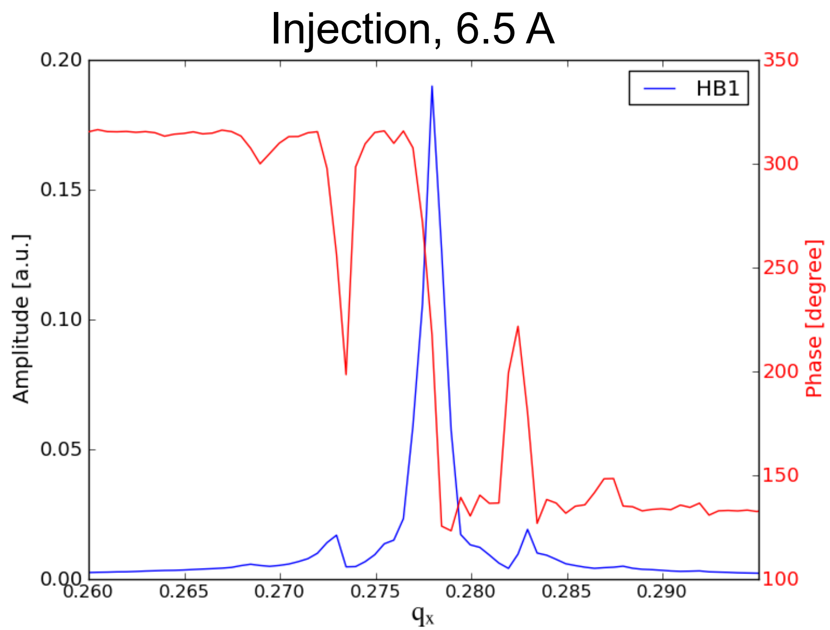


Operationally used in RHIC, used in Fermilab, Diamond… also in the LHC

The transverse BTF system at the LHC

Beam Transfer Function:
using an existing LHC BBQ system we record the beam amplitude response while applying a driving excitation frequency

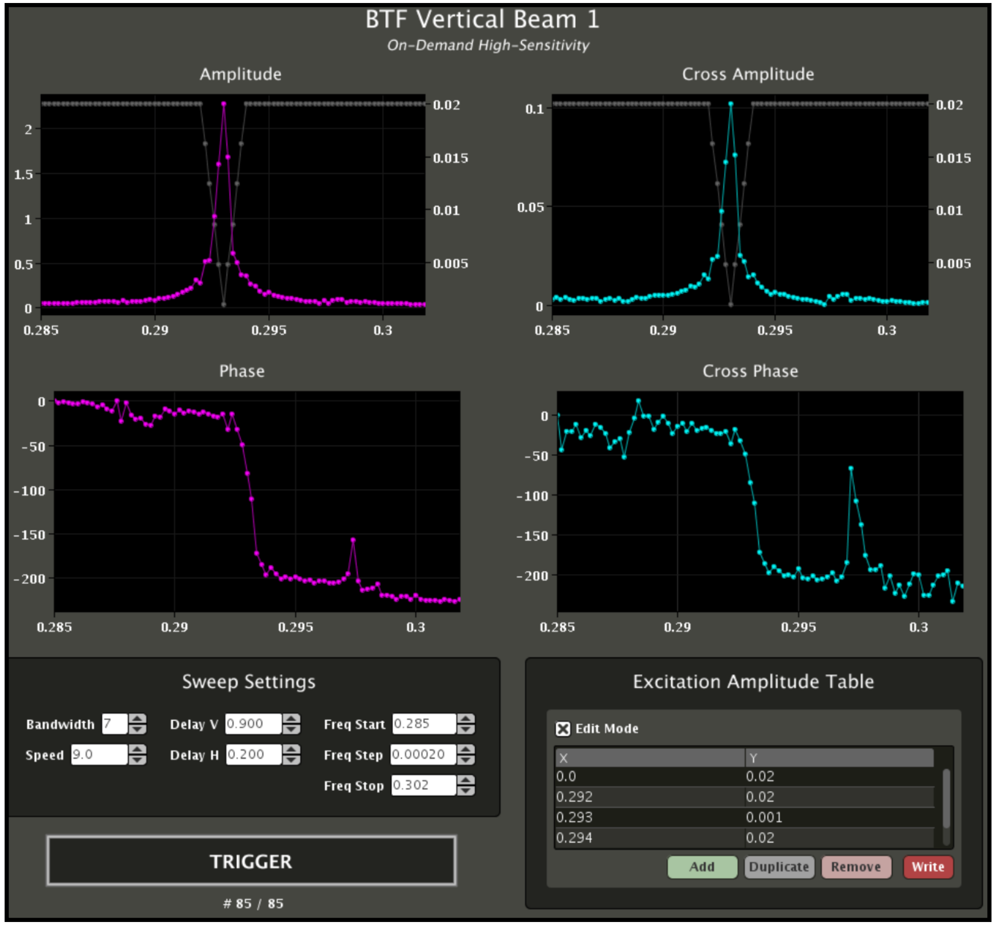




- Small excitation, **small impact on the beam quality → transparent to operation**
- LHC measurements **need special non-operational conditions** due to use of transverse feedback to damp coherent impedance instabilities → cannot be applied to full beam
- **Uncalibrated system → calibration will depend strongly on beam and operational conditions**

BTF at the LHC

- Use of **existing BBQ** system (possibility to have gated or full beam measurements)
- **On-demand device:** need transverse feedback off on measured beam (to be used in operation will need gated system with ADT off on selected bunches)
- **Adaptable BTF excitation amplitude** to improve signal-to-noise ratio (S/N) with less impact on beam quality (high resolution and high S/N required)



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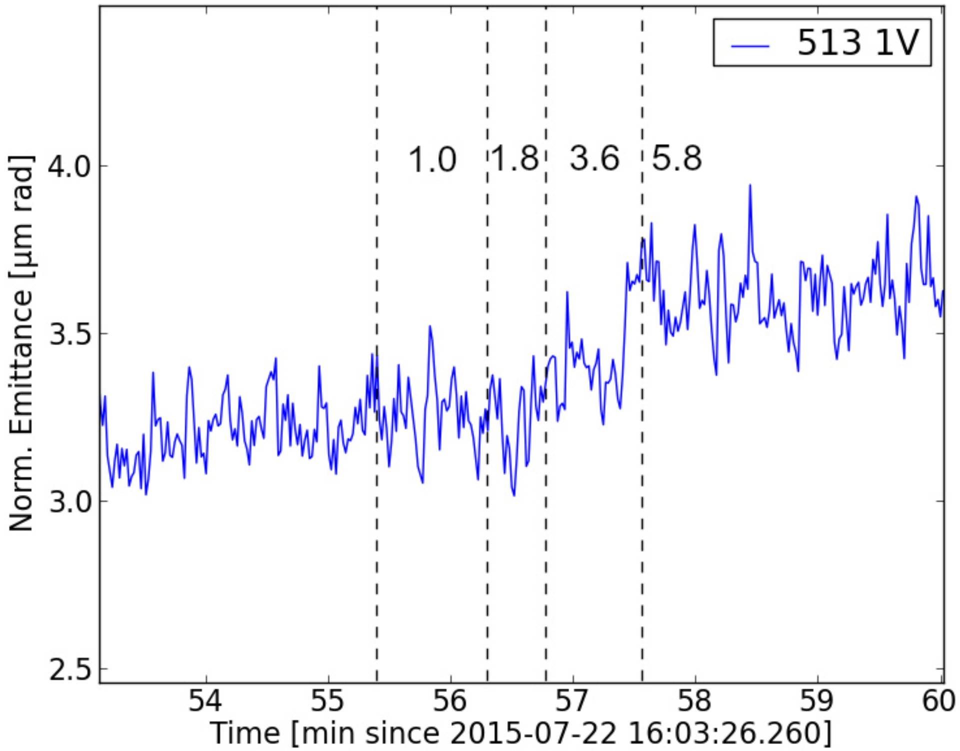
BTF at the LHC

- Use of **existing BBQ** system (possibility to have gated or full beam measurements)
- **On-demand device:** need transverse feedback off on measured beam (to be used in operation will need gated system with ADT off on selected bunches)
- **Adaptable BTF excitation amplitude** to improve signal-to-noise ratio (S/N) with less impact on beam quality (high resolution and high S/N required)
- **Un-calibrated system:** BBQ pick ups and excitation amplitudes not calibrated and strongly dependent on beam properties
- **Amplitude of excitation adjusted** by impact on beam losses and emittance (to be transparent to the beam)



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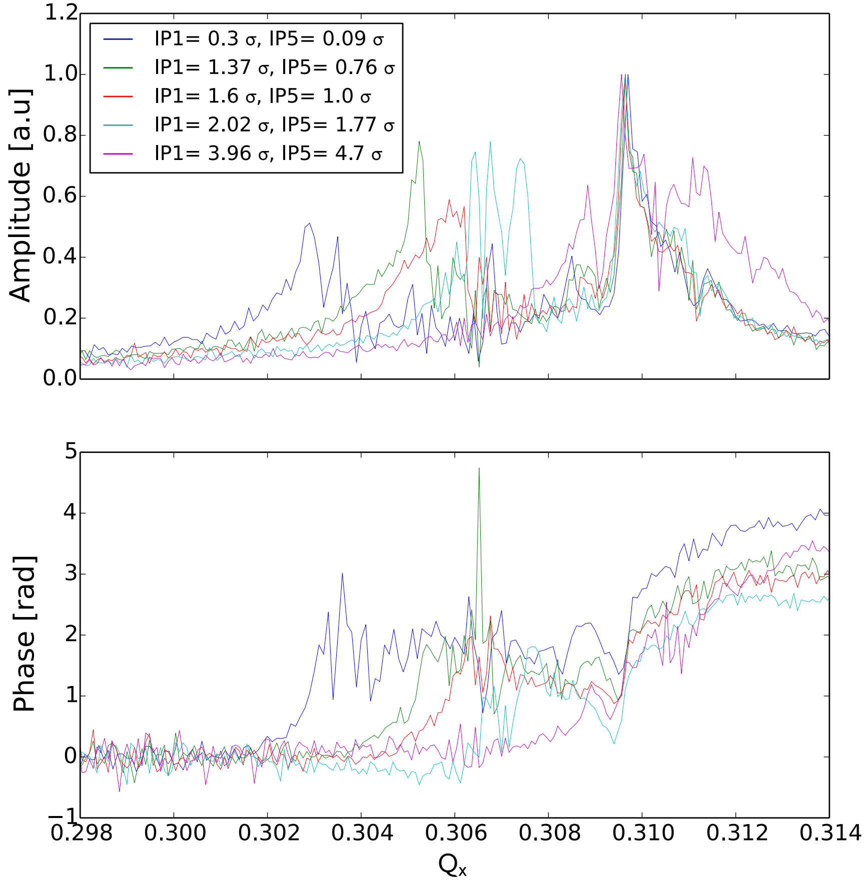
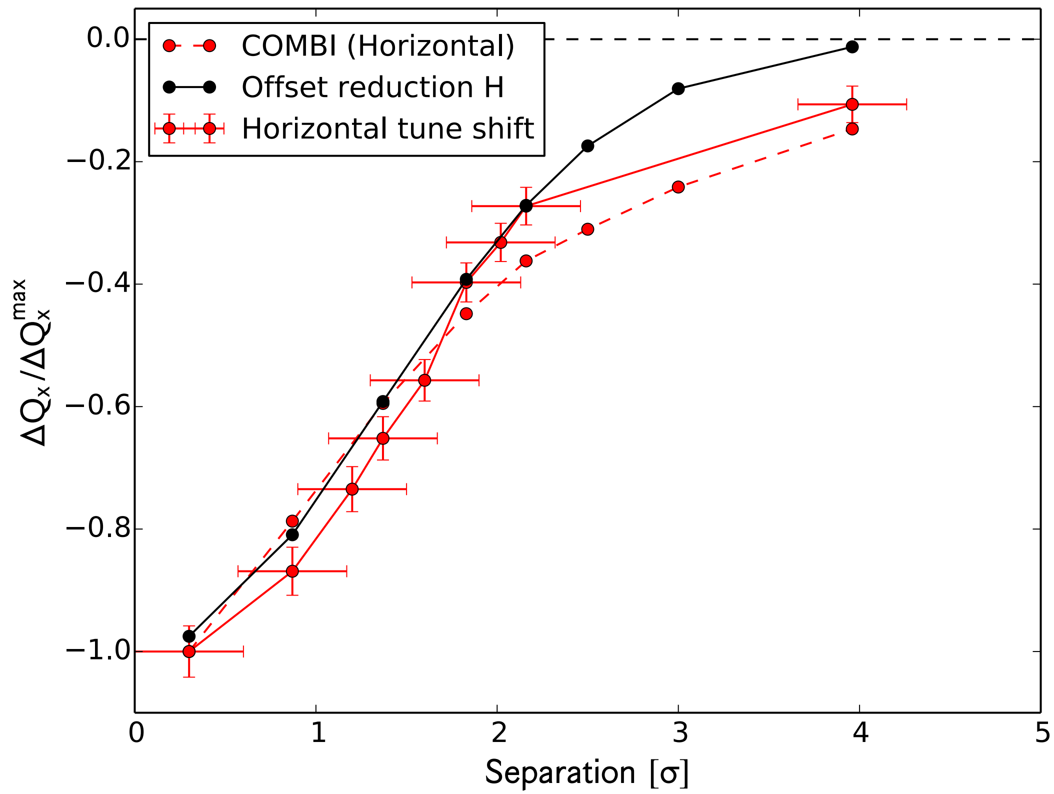
Tune Measurements with BTF

Beam-Beam separation scan between ATLAS(IP1) and CMS(IP5)



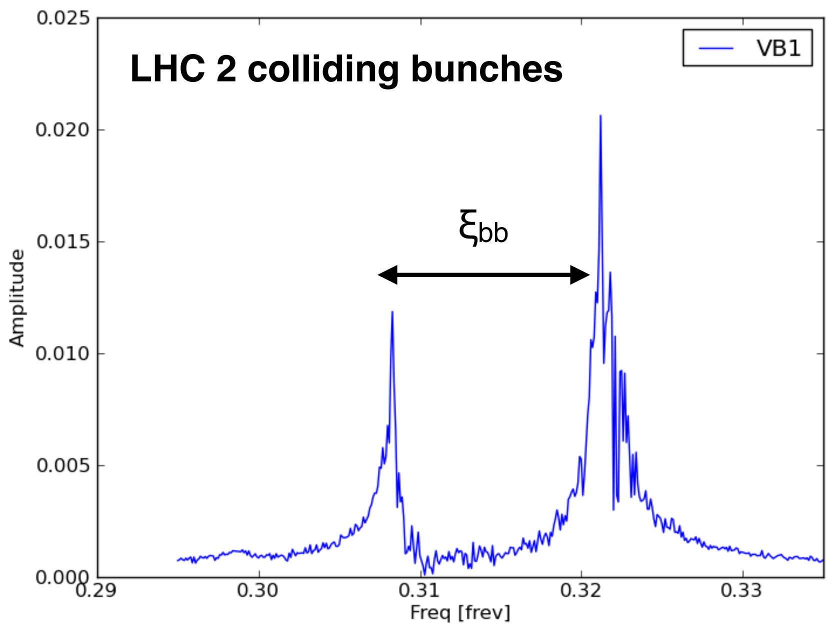


Can provide tune measurements very precisely and in very good agreement with multi particle models

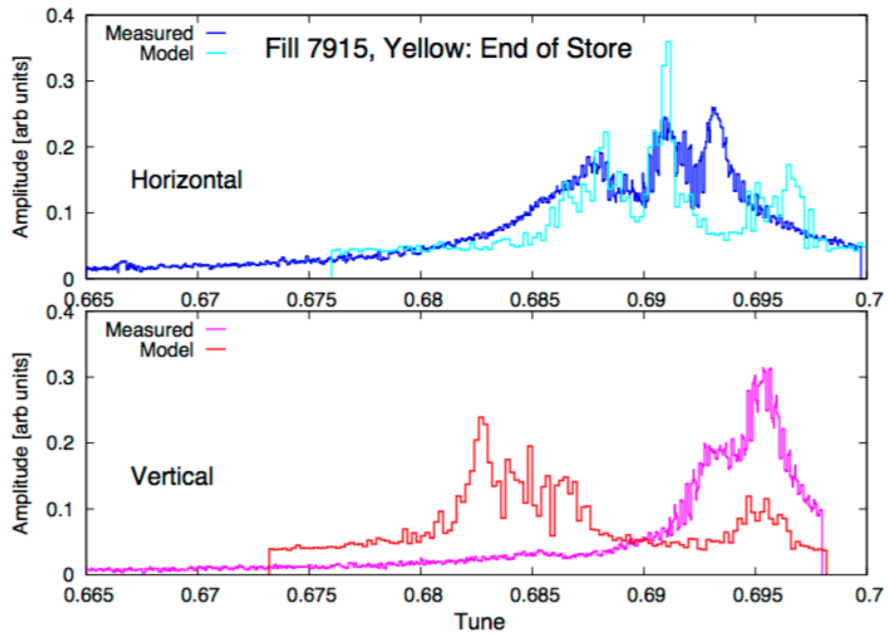
Coherent mode detection

Coherent mode detection and beam cross talk → measure beam-beam parameter (ξ_{bb}) with beams in collisions in order to identify coherent modes structures even if Landau damped

BTF on colliding beams **after collision optimization (IP1&5)**



RHIC (Super Pacman) 2007 and COMBI simulations



$$\Delta Q = 2 \cdot Y \cdot \xi_{bb} \qquad Y = 1.21$$

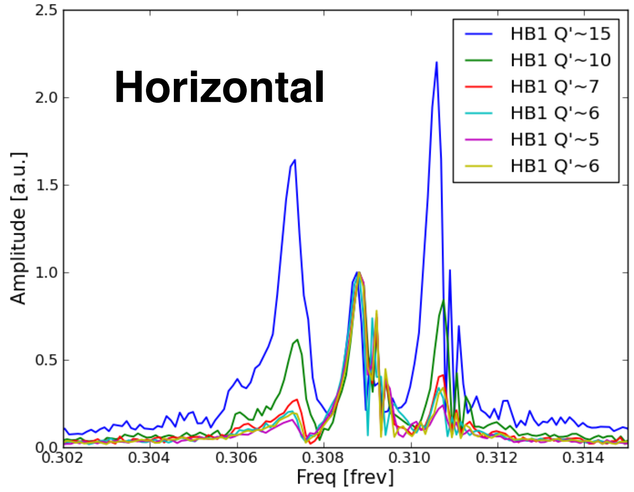
$$\Delta Q \approx -0.0133$$

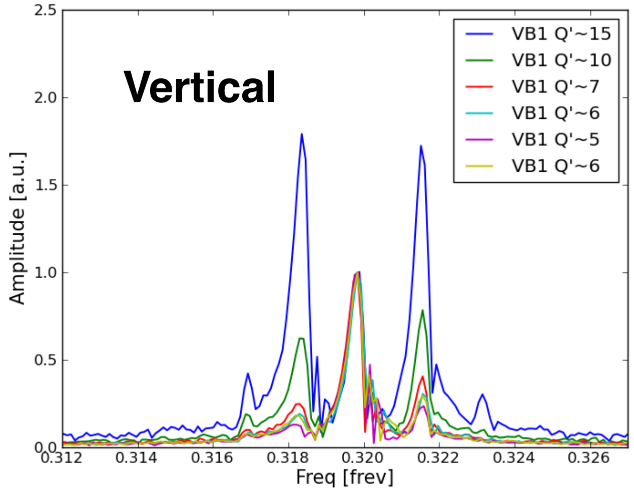
→ consistent with BTF measurements

Provides an insight into coherent modes even if Landau damped
In the presence of coherent BB modes it is challenging to extract incoherent informations

Chromaticity measurements

BTF measurements for different chromaticity values

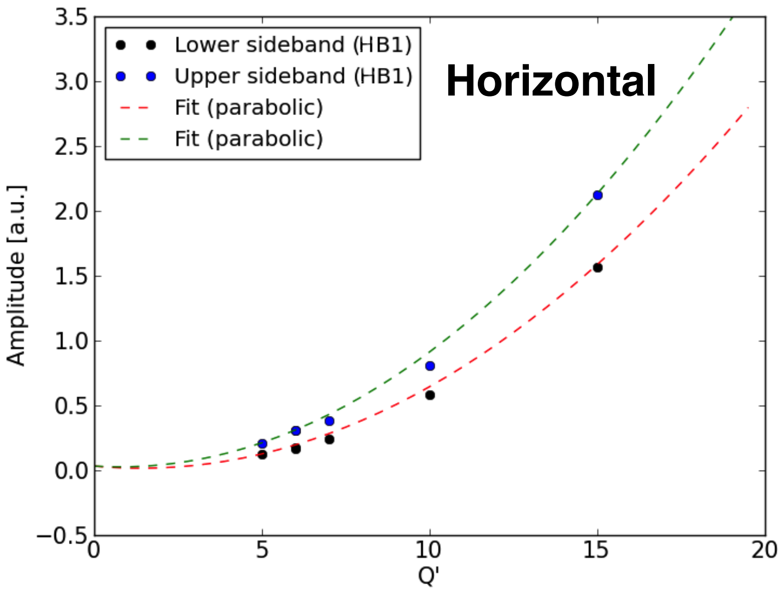


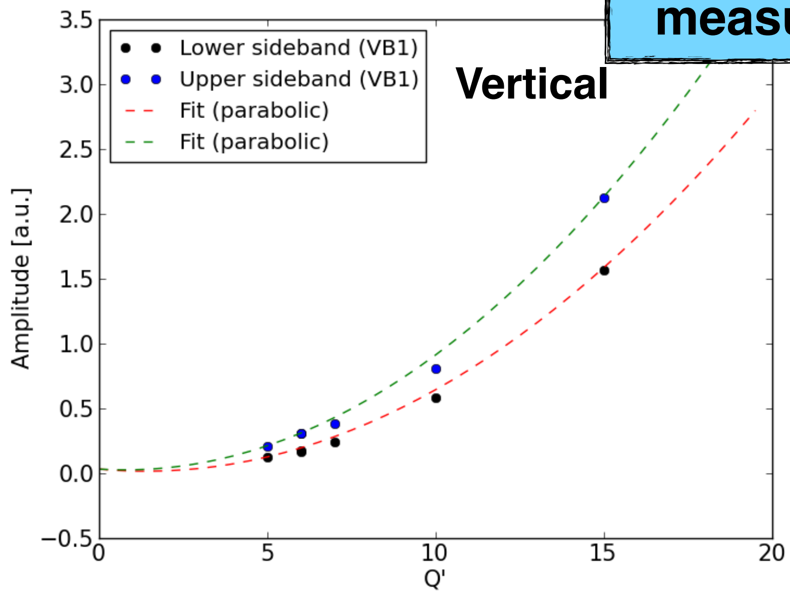


The amplitude of the synchrotron sidebands increases as a function of the chromaticity value (Q')
Similar results observed at Diamond

Parabolic dependency → possible extrapolation for chromaticity measurements online!?

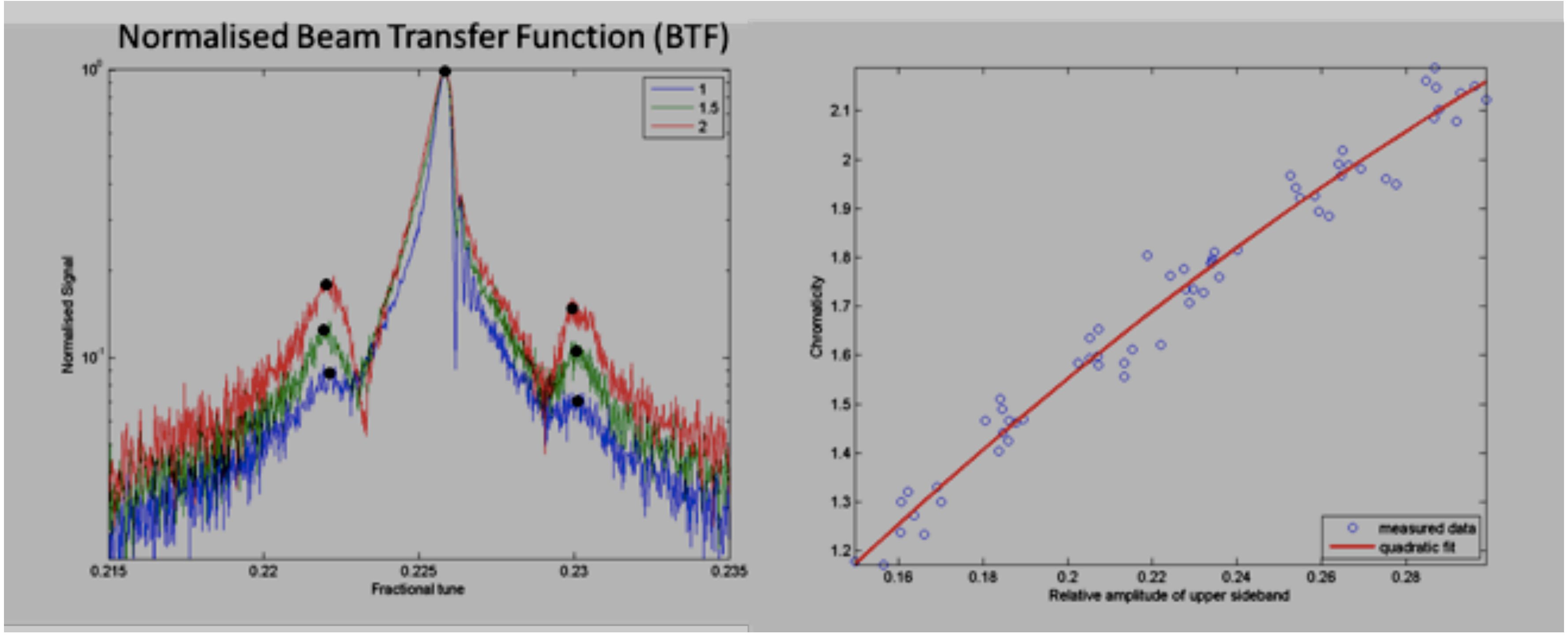
Sidebands amplitude ratio w.r.t. tune amplitude





Chromaticity measurements

from R. Jones 2015 Beam Dynamics Meeting Diagnostics WS



From Empirical Fit to Theoretical Approach @ DIAMOND:

- Use expression for sideband amplitude that is ratio of Bessel functions
- As relationship cannot be inverted analytically, use a piecewise fit with a square root and a 9th order polynomial

Similar to what observed at Diamond…

Why BTF measurements?

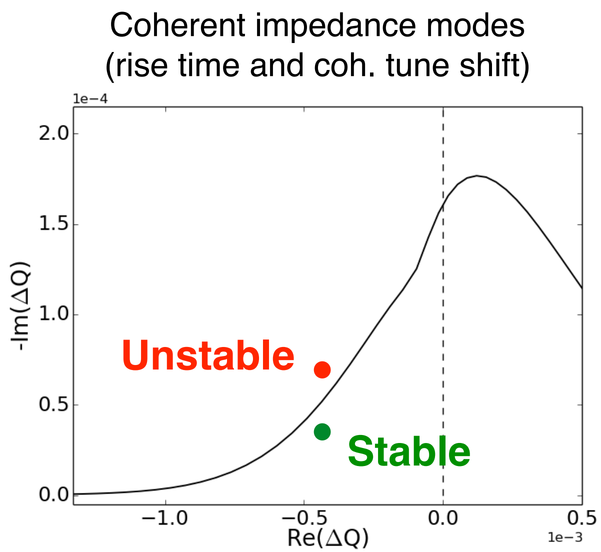
LHC have shown several coherent instabilities and stability threshold far above the expected values

Predictions of instability thresholds are based on computation of the **Landau damping** by calculating the **Stability Diagrams (SD)** with all ingredients (octupoles, beam-beam …) **BTF= SD^{-1}**

Particle distribution

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

Detuning with amplitude (tune spread)
Octupoles + beam-beam



LHC shows still coherent instabilities developing at top energy at different stages of the cycle (emit. growth, losses)

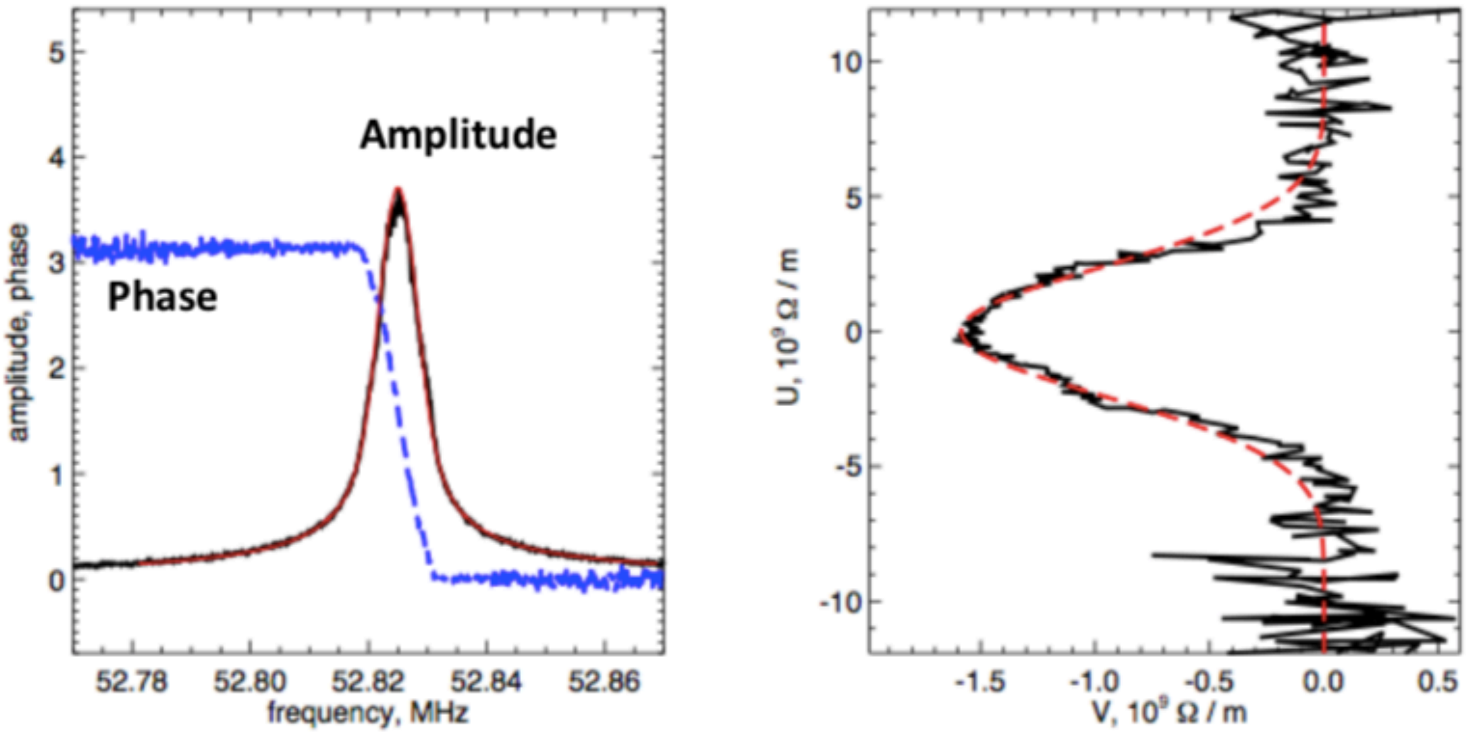
Are we missing some important contributions in our prediction? What is the real stability area?

BTF can experimental verify the stability of beams→ direct measurements of SD!
Tune spread information
Particle distribution information

Chromaticity measurements

BTF = Inverse of Stability diagram

$$BTF = SD^{-1} = R_i(\Omega) = c \cdot \int_0^\infty \int_0^\infty \frac{1}{\Omega - w_i(J_x, J_y)} \frac{J_i d\psi_{x,y}(J_x, J_y)}{dJ_i} dJ_x dJ_y$$



Measurements and Analysis of the Transverse Beam Transfer Function (BTF) at the SIS 18 Synchrotron
V. Kornilov; O. Boine-Frankenheim, W. Kaufmann, P. Moritz

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Chromaticity measurements

CERN

BTF = Inverse of Stability diagram

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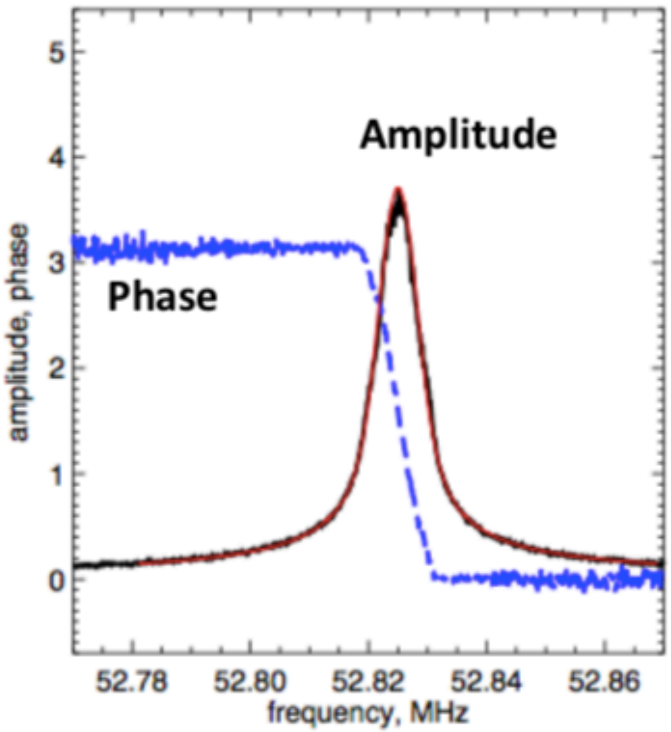

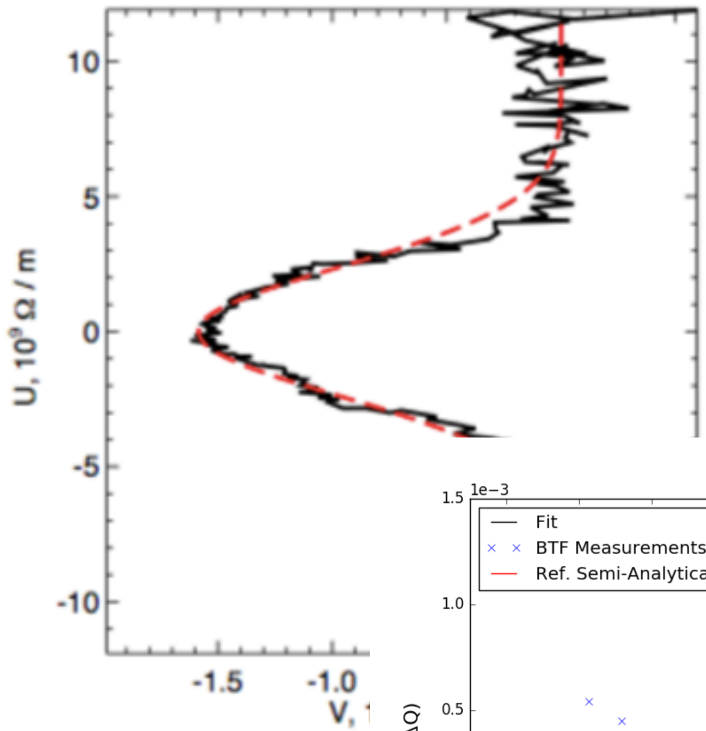

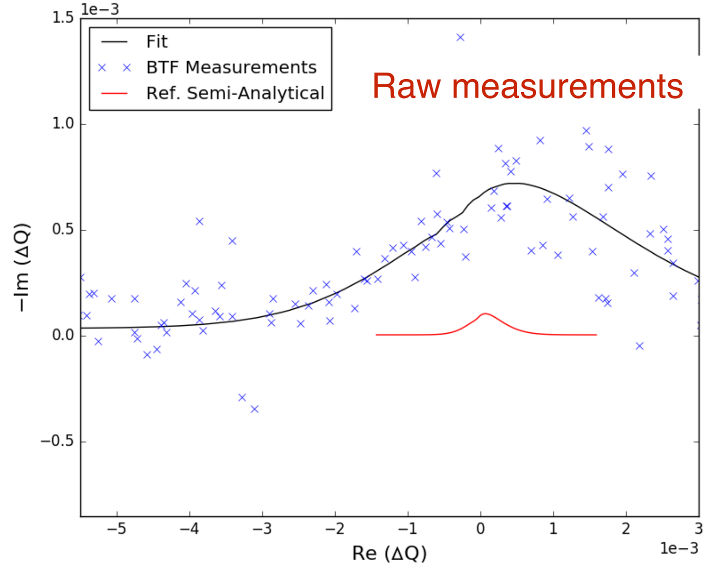

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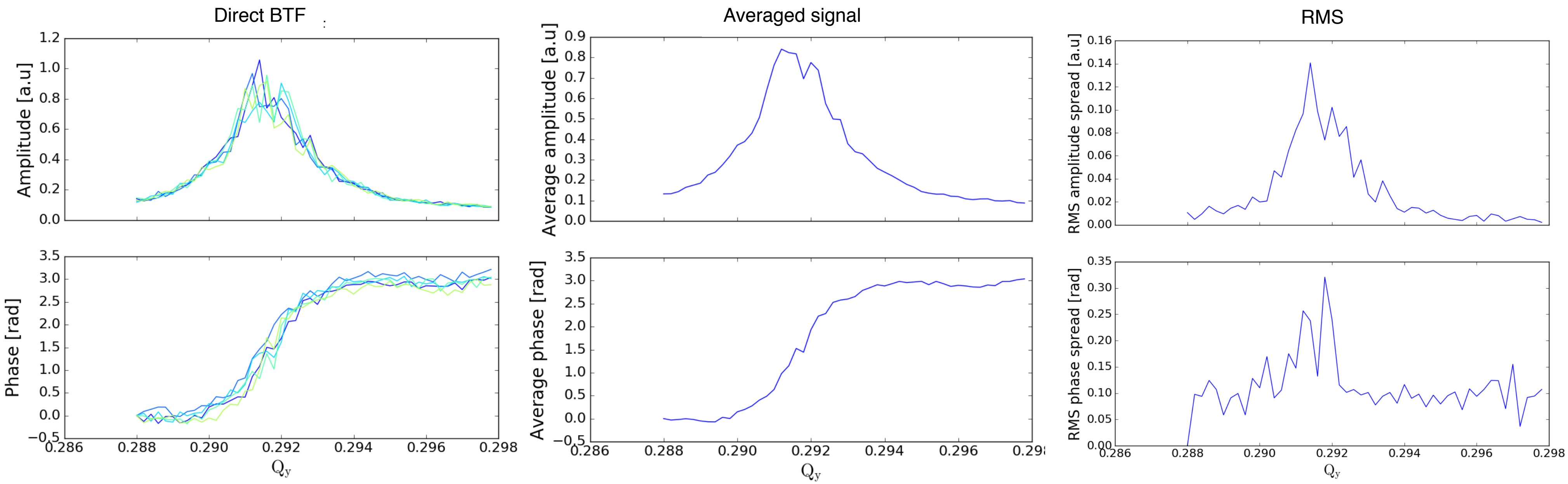
Difficulties 1: Signal averaging

Several BTF settings were tried in order to improve signal to noise ratio however the only way to improve the SD reconstruction was to average the signal over several acquisitions in the same conditions



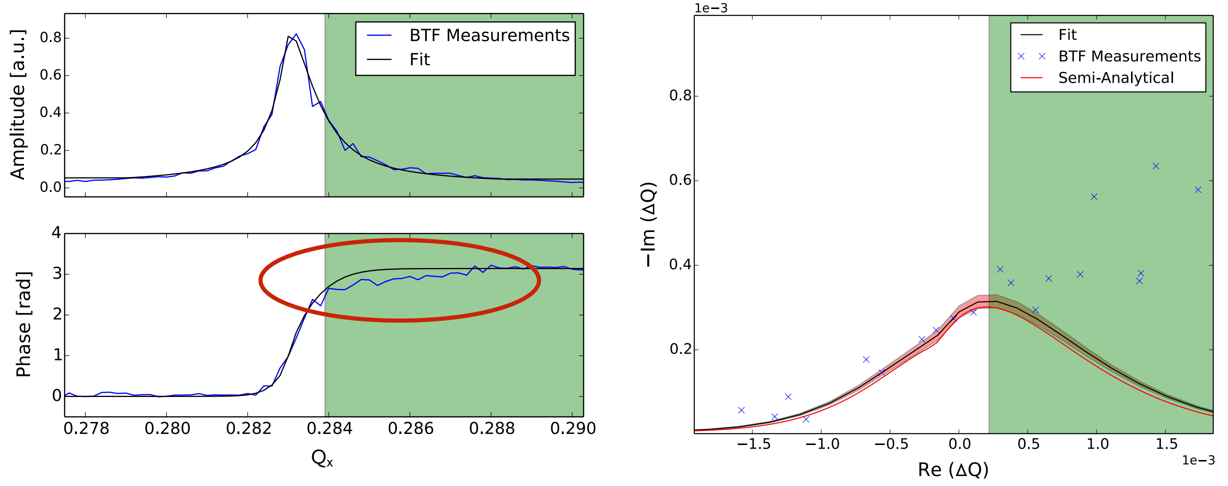
- For each set-up we acquired several measurements in the same configurations
- The average and the RMS of the different BTF acquisitions are computed

Averaging signal improves the signal/noise ratio

Data treatment 2: Sweep direction dependency

- **Delay between excitation steps ➔** removes "fake spread" effect after tune excitation (dependency on excitation direction)
- **Adapting BTF excitation amplitude** to improve signal to noise ratio with less impact on beam quality for reconstruction of SD (high resolution and high S/N required)

2016 Measurements



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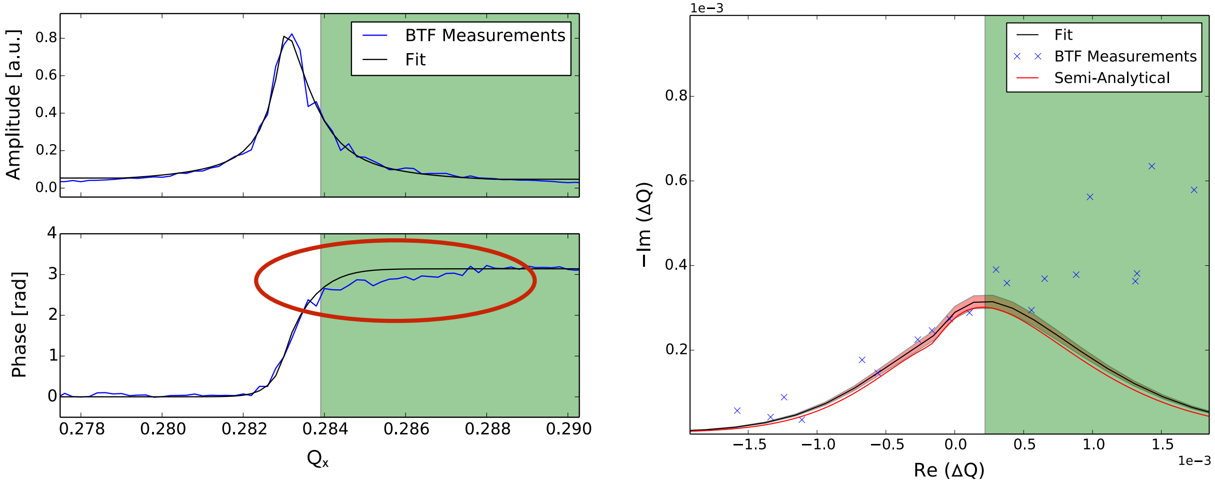
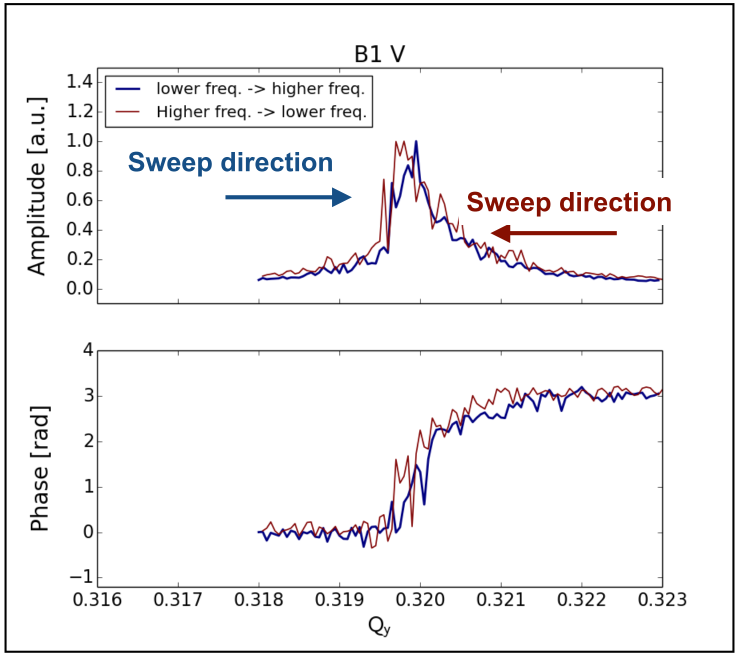


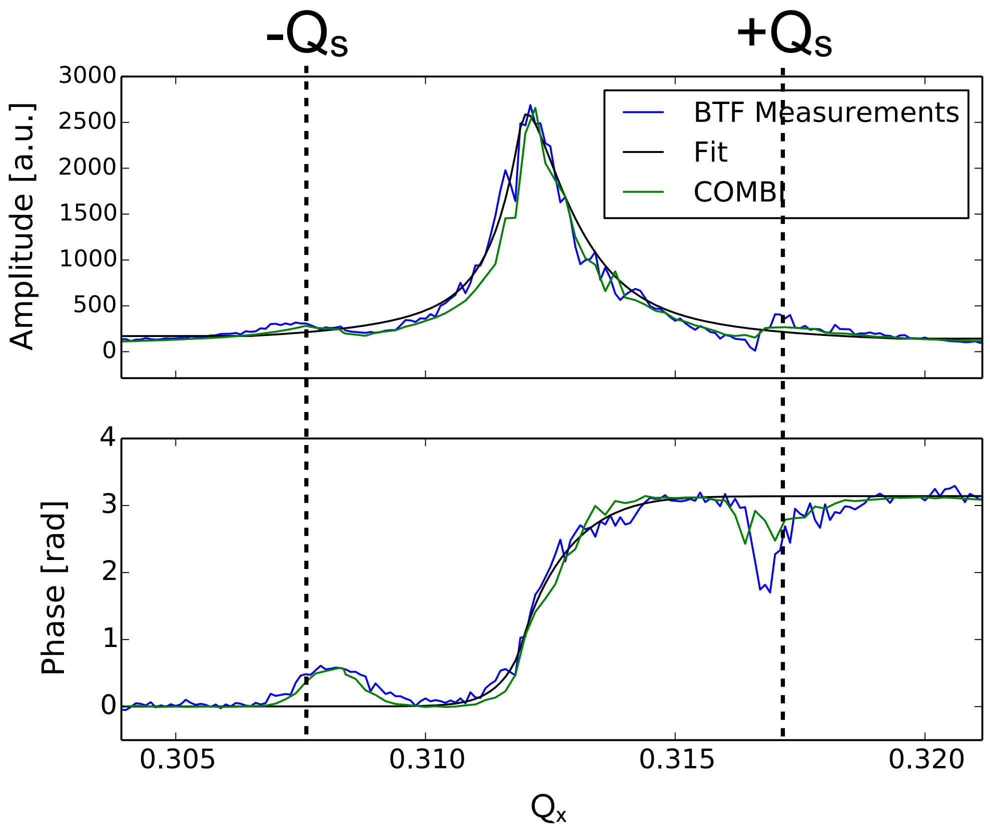
2017 Measurements

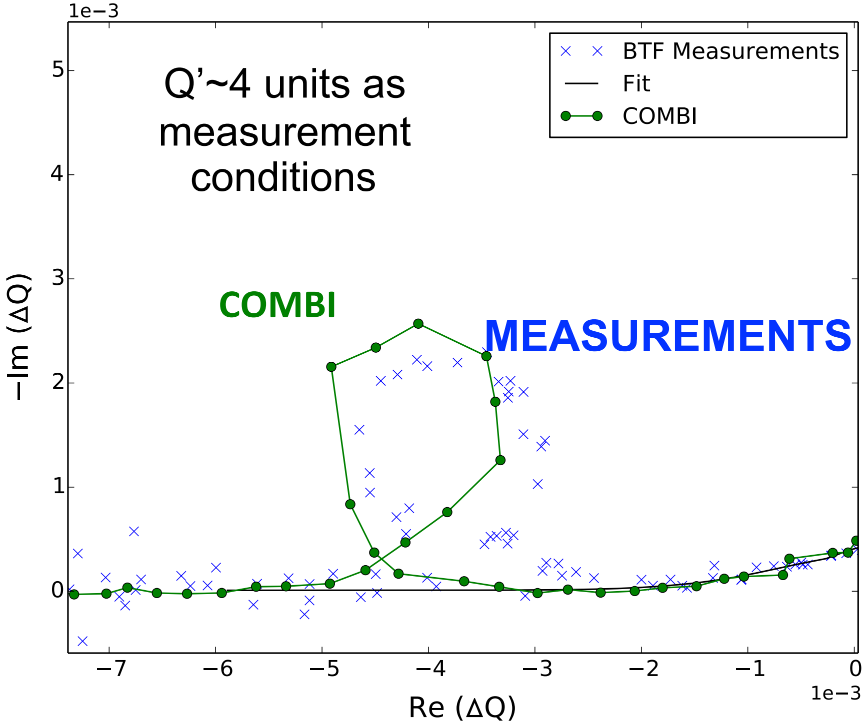


The delay time removes dependency on excitation direction
Adapting the amplitude of excitation reduces the impact on beam emittance

Data treatment 3: Chromaticity effects

Synchrotron sidebands appear in the BTF amplitude and phase jumps (at ±n · Qs from tune)

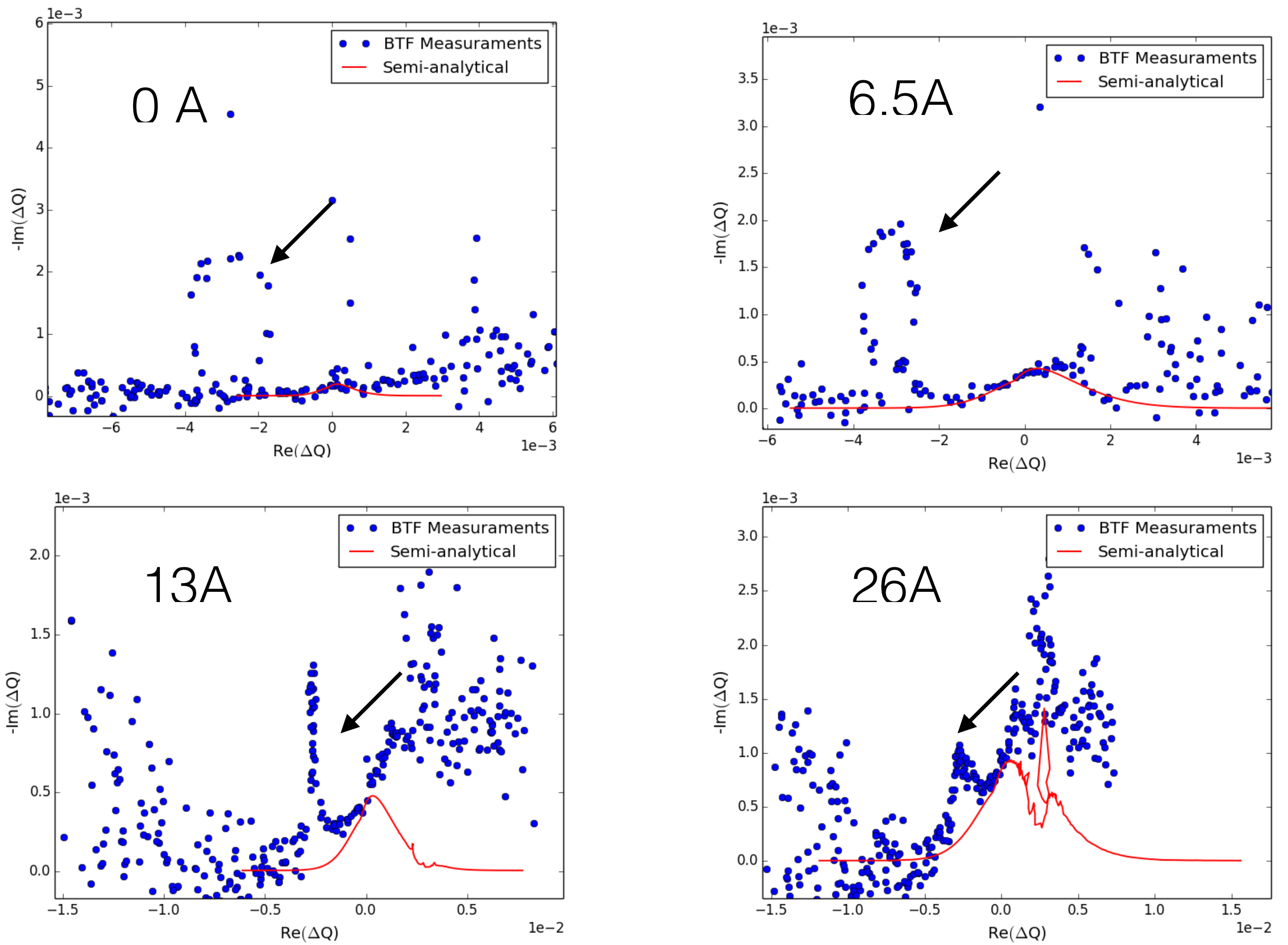




3D model simulations (COMBI) needed to reproduce the longitudinal contribution in the BTF

Data treatment 3: Chromaticity effects

- The loops (and deformations of it) are always present in measurements due to Q’
- High octupole current: deformation of the SD and loops —> sidebands included in the transverse spread



Q’ very small during measurements

Need to disentangle from Q’ effects to have quantitative results

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)

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

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

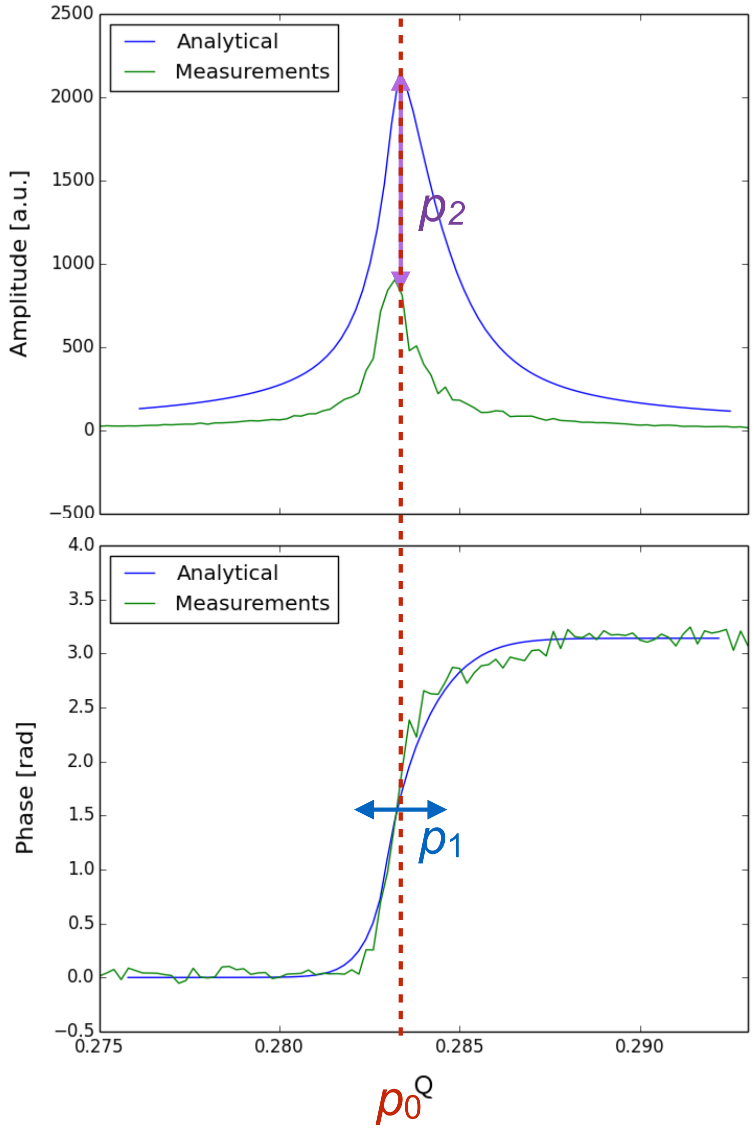
p_0 = Tune

p_1 = Tune spread factor respect to a reference case

independent from calibration factor, (phase slope)

p_2 = Amplitude factor:

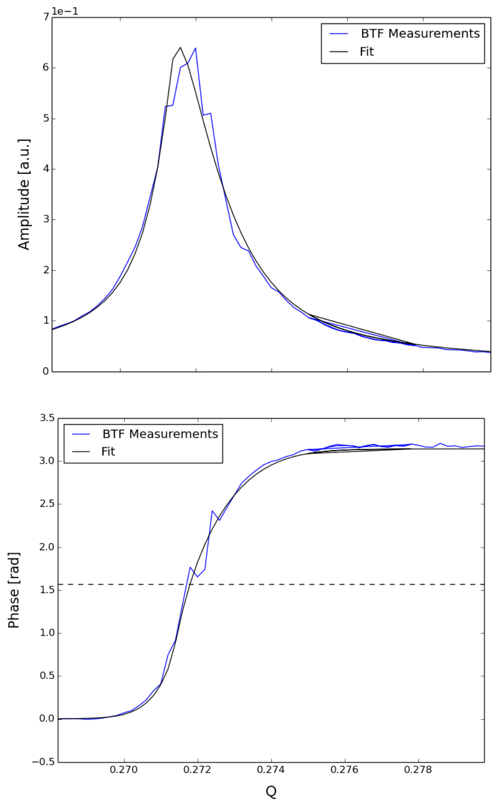
calibration, proportionality constant



C. Tambasco PHD Thesis EPFL 7867

Stability diagram reconstruction

Applying the Fitting method to the averaged signal allows a clear reconstruction of the stability area



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

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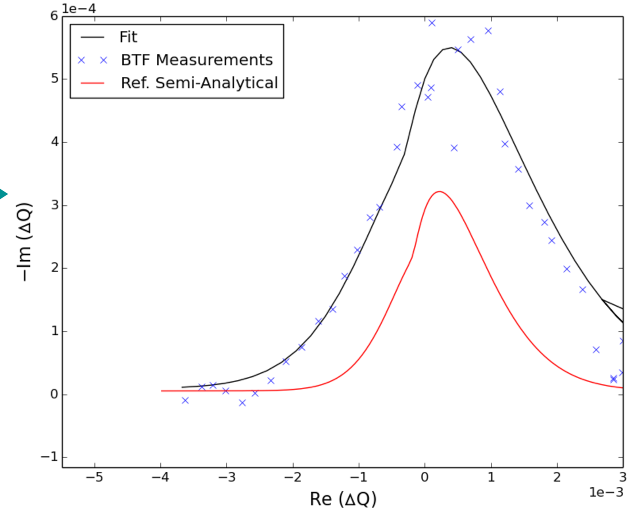
Reconstructed Stability Diagram with averaging and fitting method



Tune spread p_1=1.71

(10 A octupole current@injection energy)

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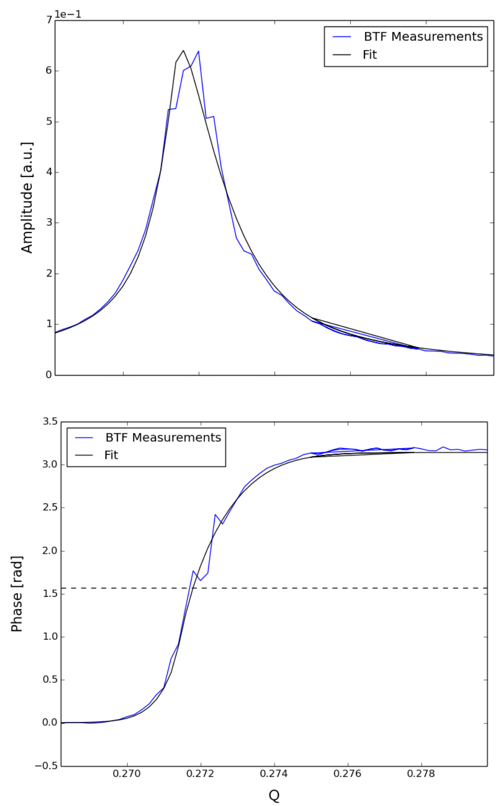

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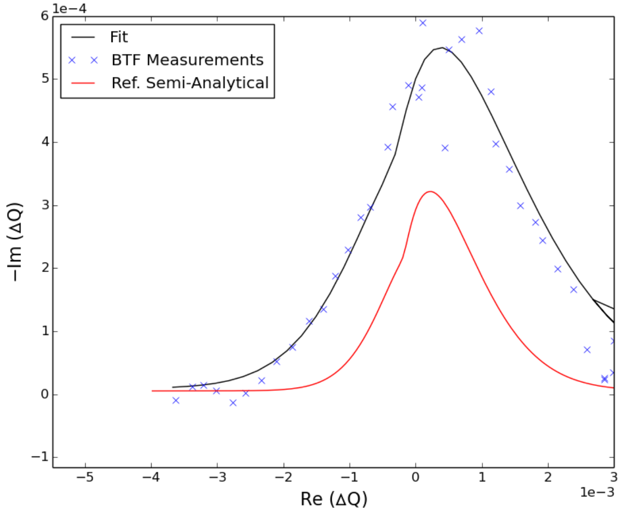

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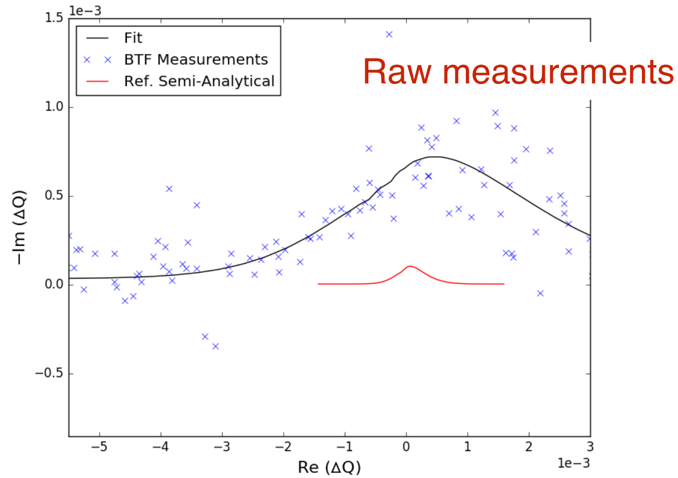


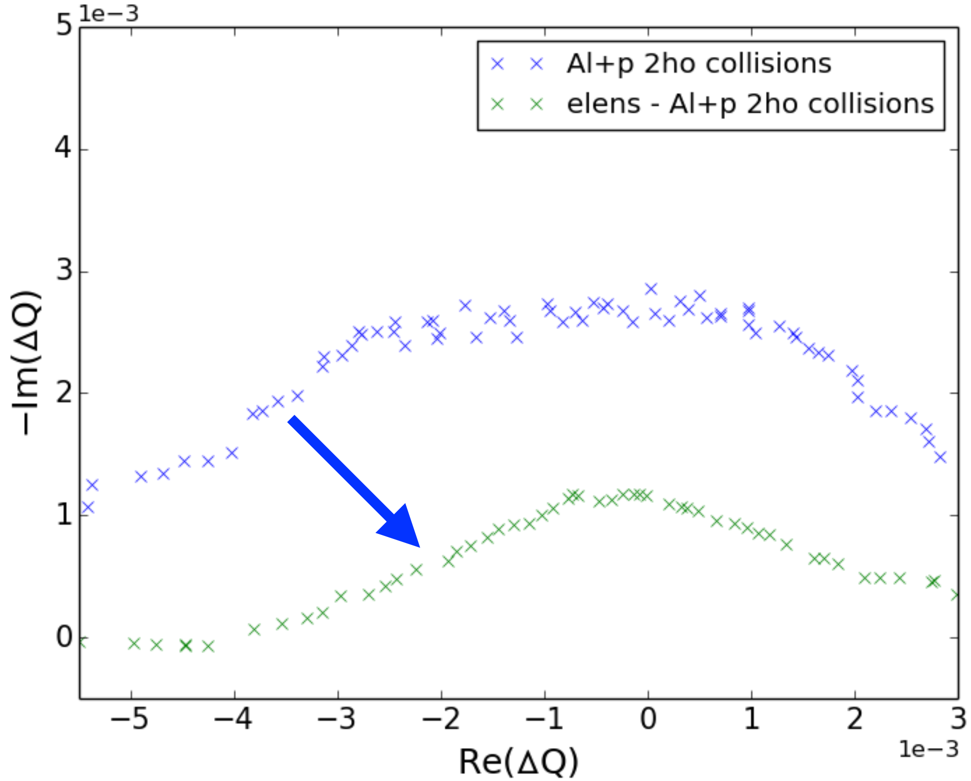
Stability Diagrams can be reconstructed and tune spread extracted

Stability diagram with an e-lens

An e-lens is used at RHIC to compensate beam-beam tune spread
Fitting method applied to RHIC data in different beam-beam configurations
BTF data have been used to reconstruct stability diagram:

- clean reconstruction of SD from raw data
- tune spread has been evaluated with fitting function using an arbitrary initial tune spread ➞ improved model needed

Preliminary



Apply to other data/machines:

e-lens compensation of tune spread with reduction of the Stability Diagram

RHIC data courtesy of W. Fischer

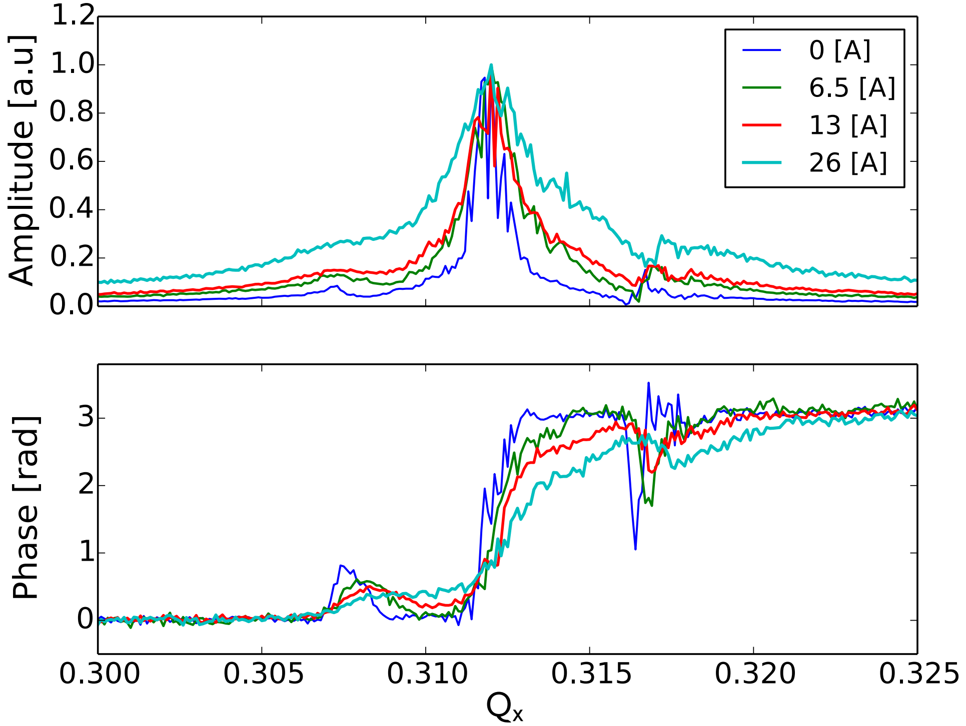
Single beam: LHC stability at injection

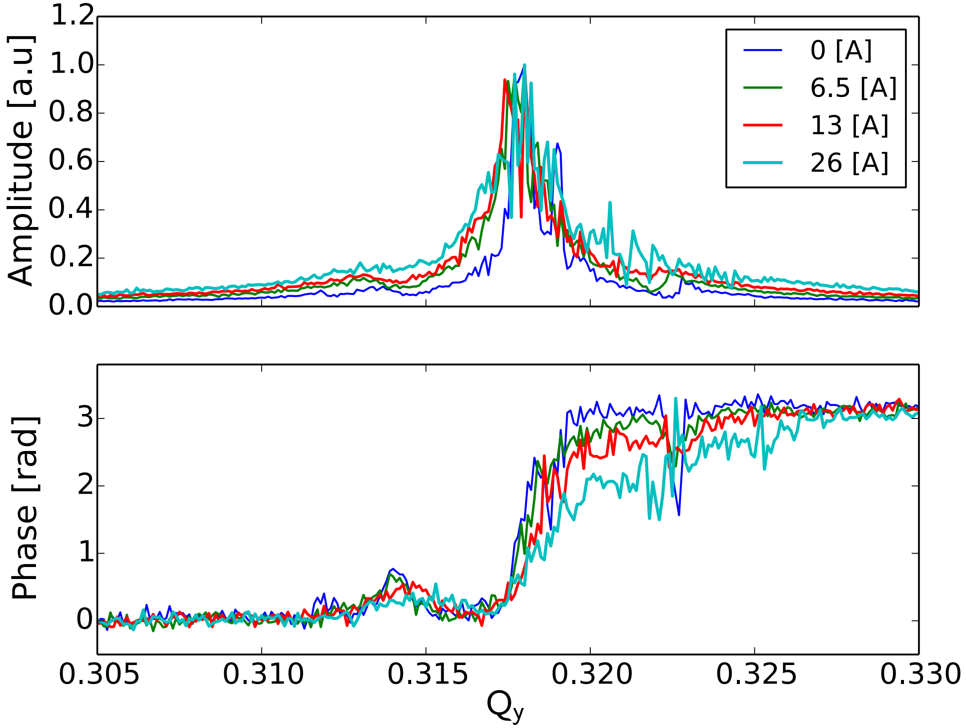
Tune spread given by Landau octupoles and lattice non linearities

Horizontal plane

Vertical plane

2015 MD



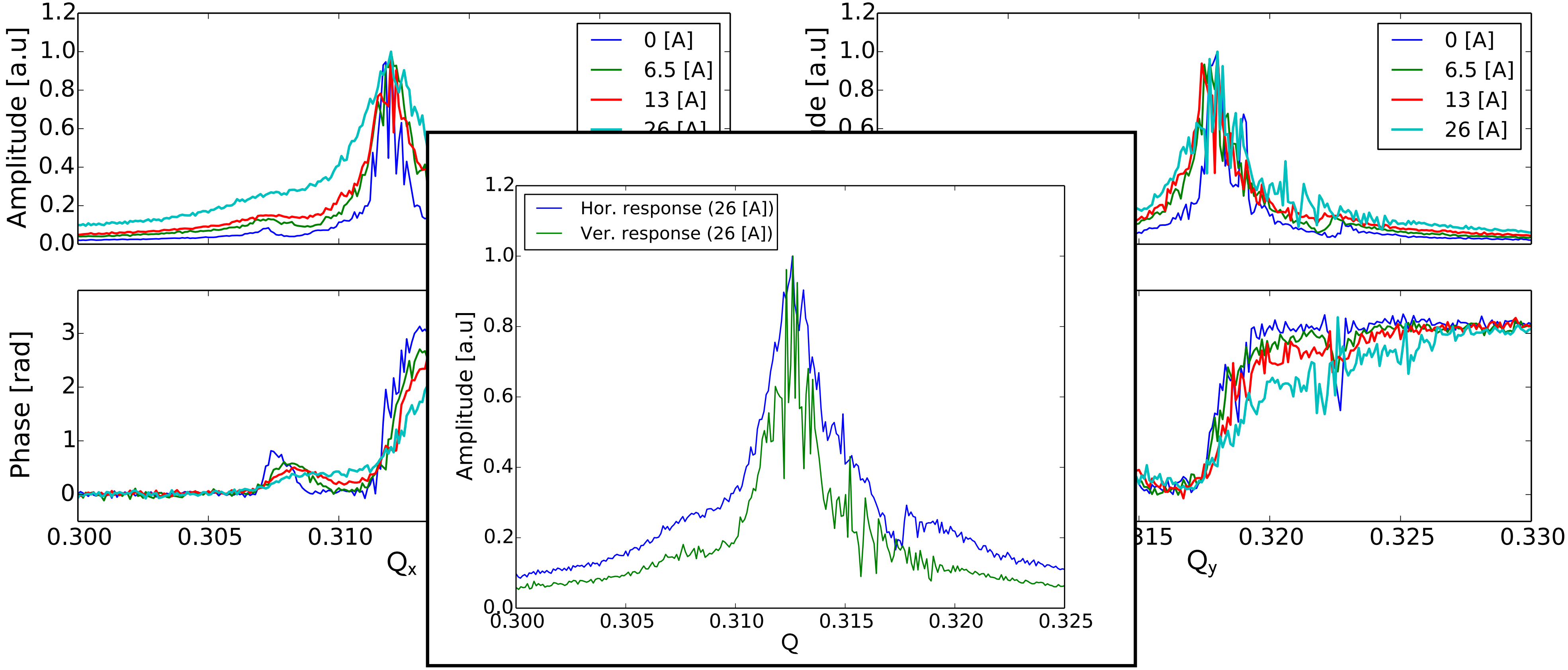


For the largest octupole strength (26 A) larger spread in the horizontal plane, smaller in the vertical plane

Single beam: LHC stability at injection

Tune spread given by Landau octupoles and lattice non linearities

Horizontal plane **Vertical plane** 2015 MD



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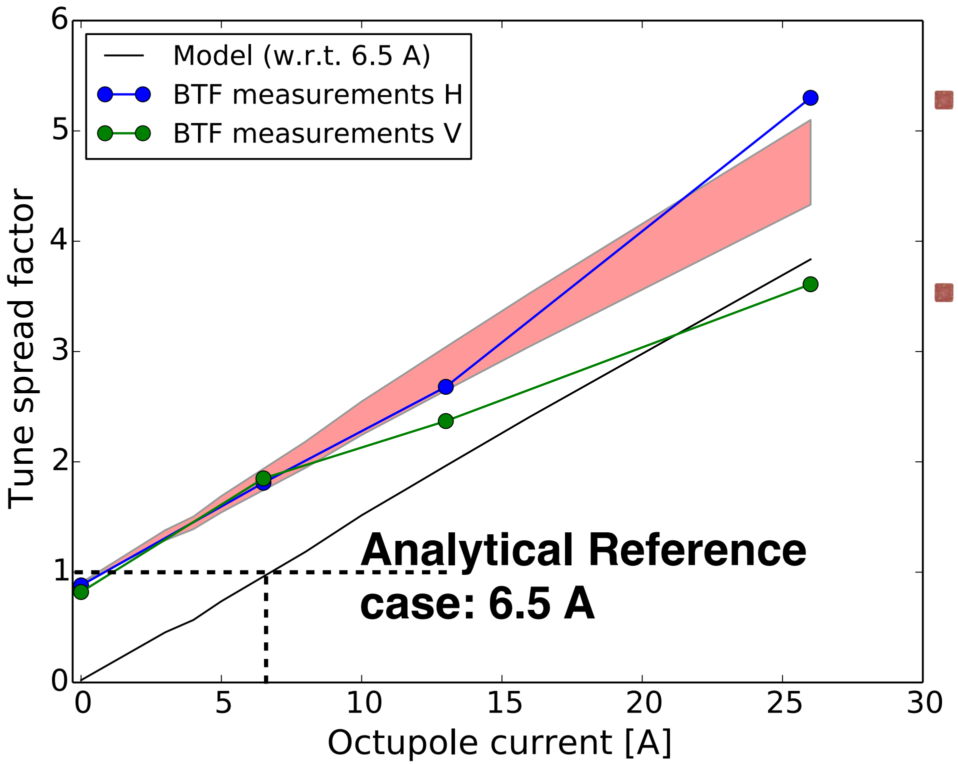
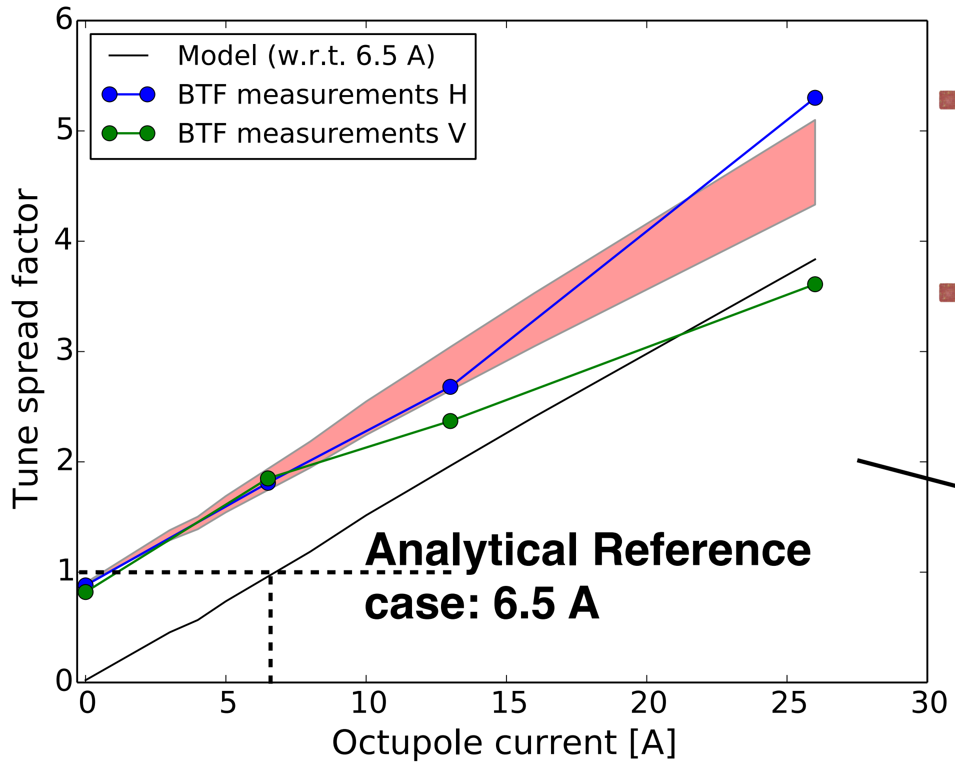
Octupole scan at injection: evaluation of the tune spread



- **Fitting method to compare measurements and expectations from model (tune spread factor)**
- Case with no octupoles: consistent with optics measurements in the 2015 of spread from magnets non-linearities (equivalent to 5 A octupole spread)
- Linear trend reproduced

Octupole scan at injection: evaluation of the tune spread



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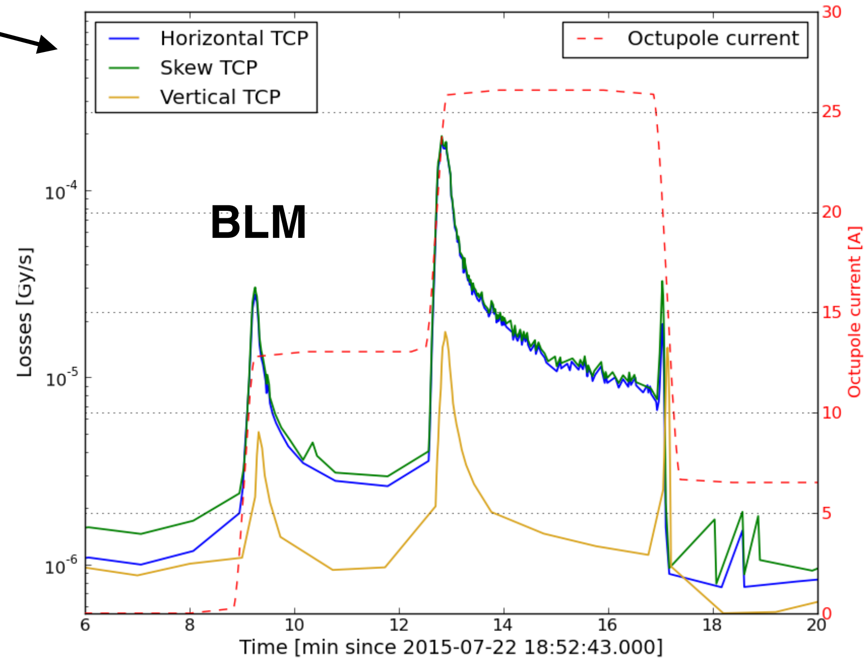
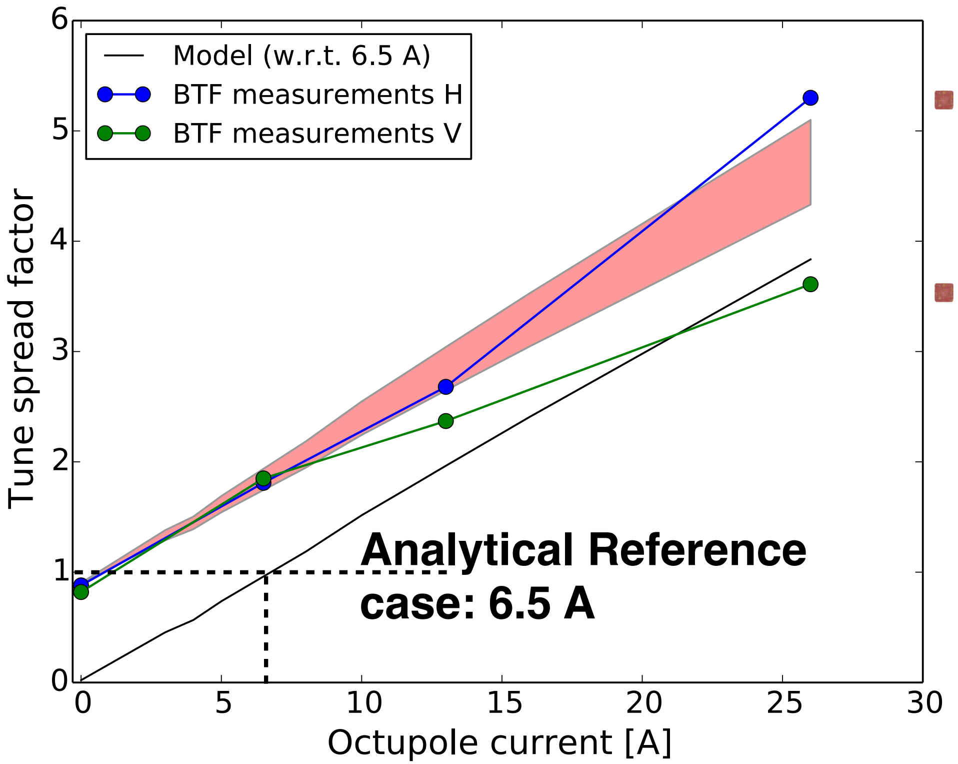
Losses observed in the vertical plane correlated with octupole current changes



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

Octupole scan at injection: evaluation of the tune spread



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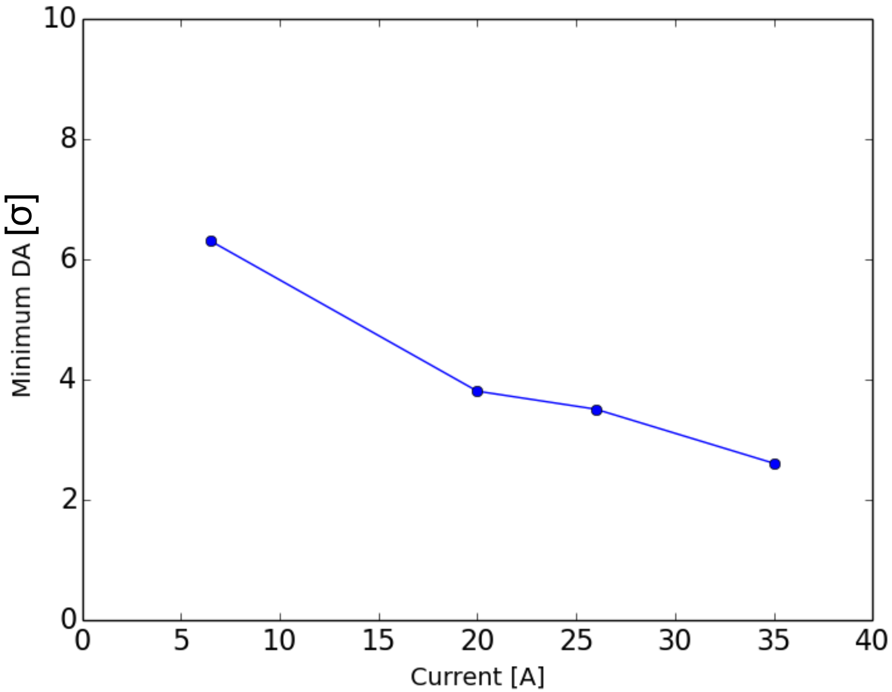
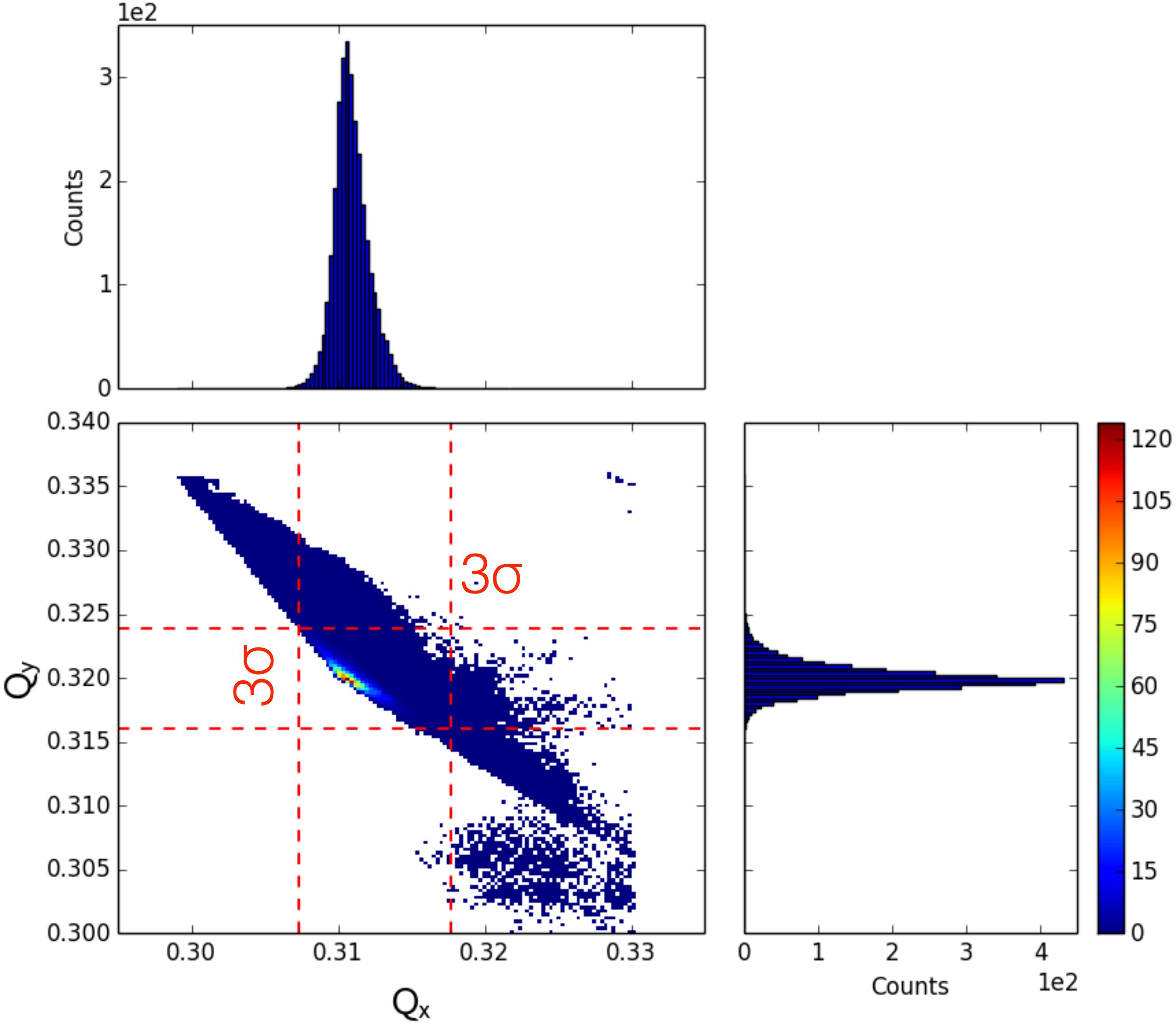


→ Result:
losses observed as a function of octupole strength due to a reduction of DA → **Increasing the tune spread is beneficial for Landau damping as long as any diffusion mechanism is not present**

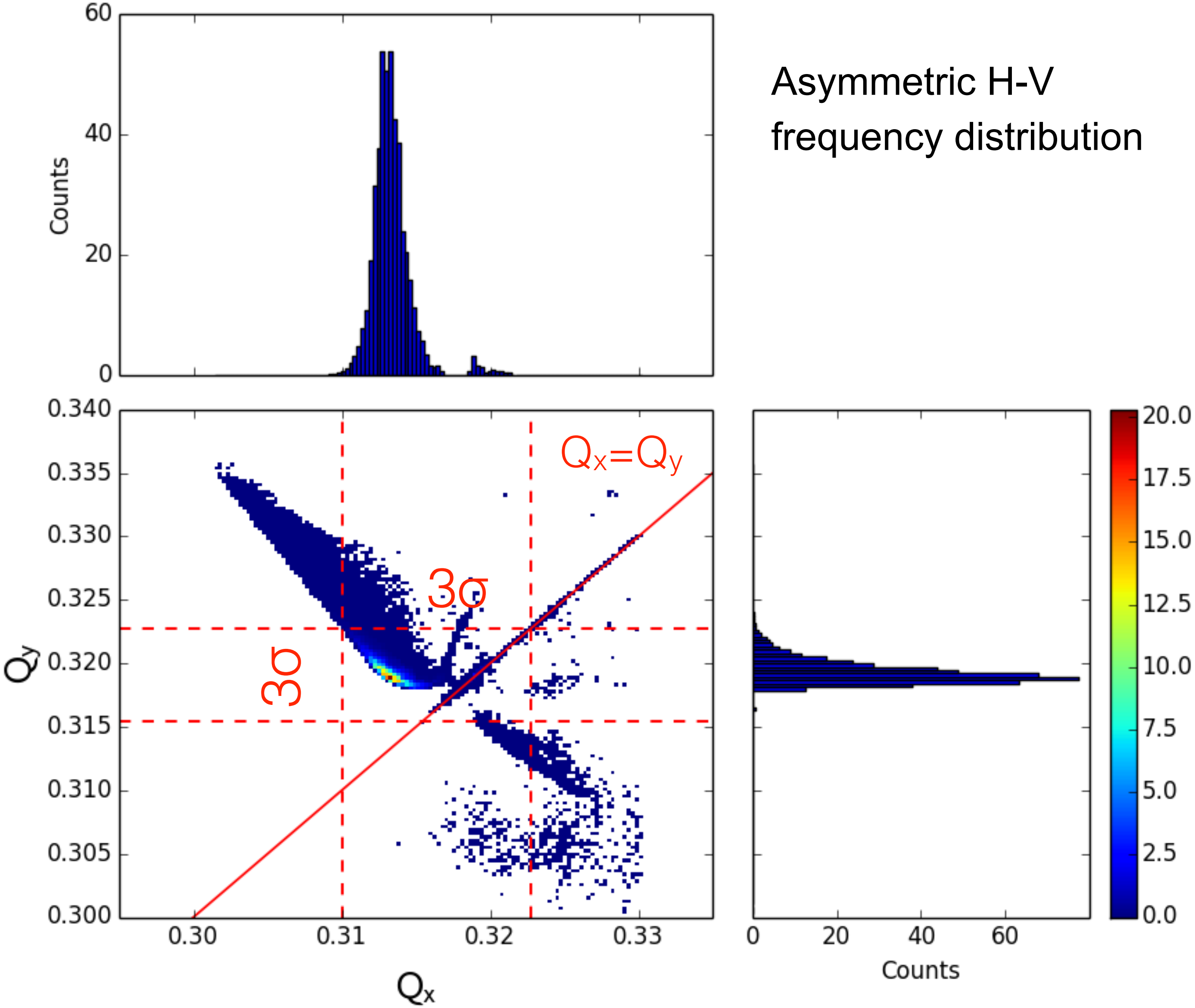
Frequency distribution at injection for 26 A octupole current



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

Frequency distribution at injection with linear coupling

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



Asymmetric H-V frequency distribution

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Frequency distribution at injection with linear coupling

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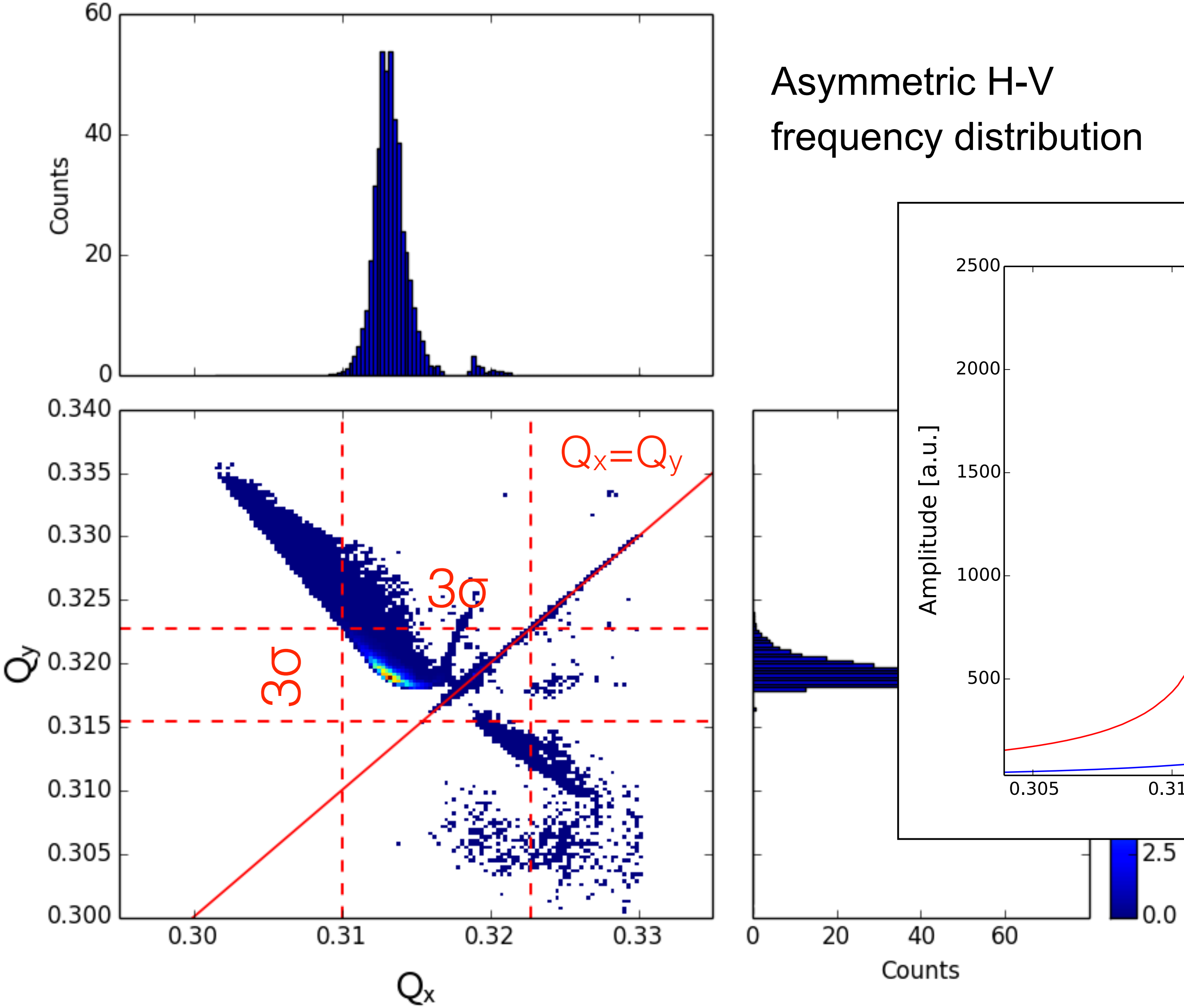
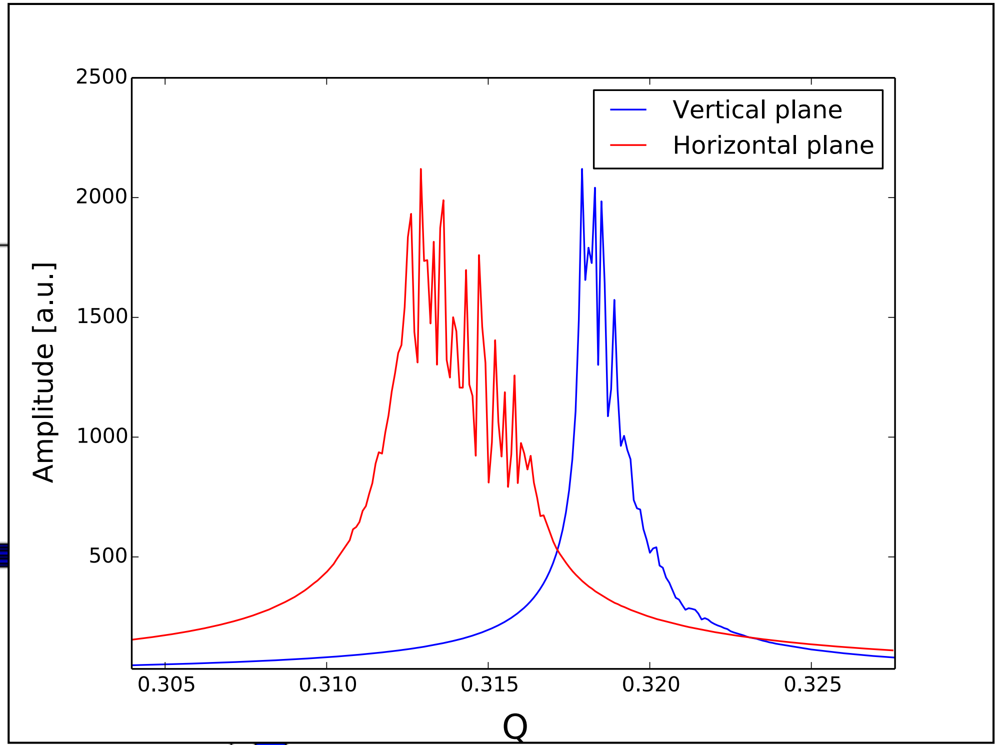
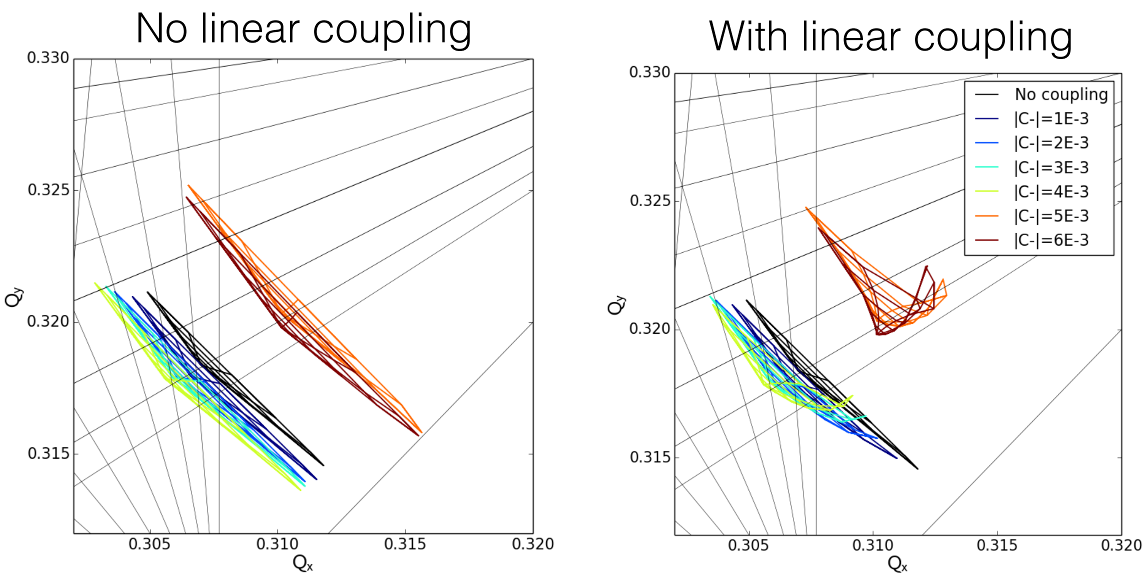
Asymmetric H-V frequency distribution





Impact of linear coupling on Landau damping and BTF

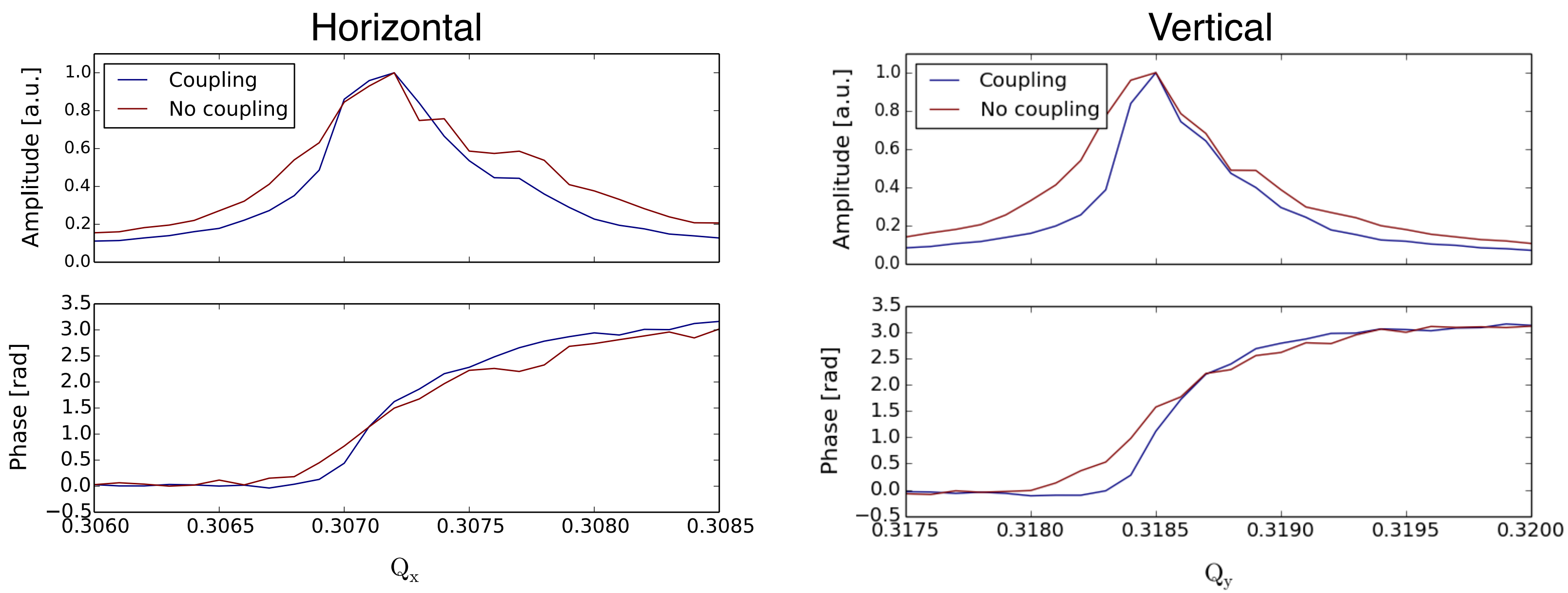


Effects of coupling*:

- Reduction of the overall tune spread
- Distortion of the footprint
- Asymmetry between H and V plane

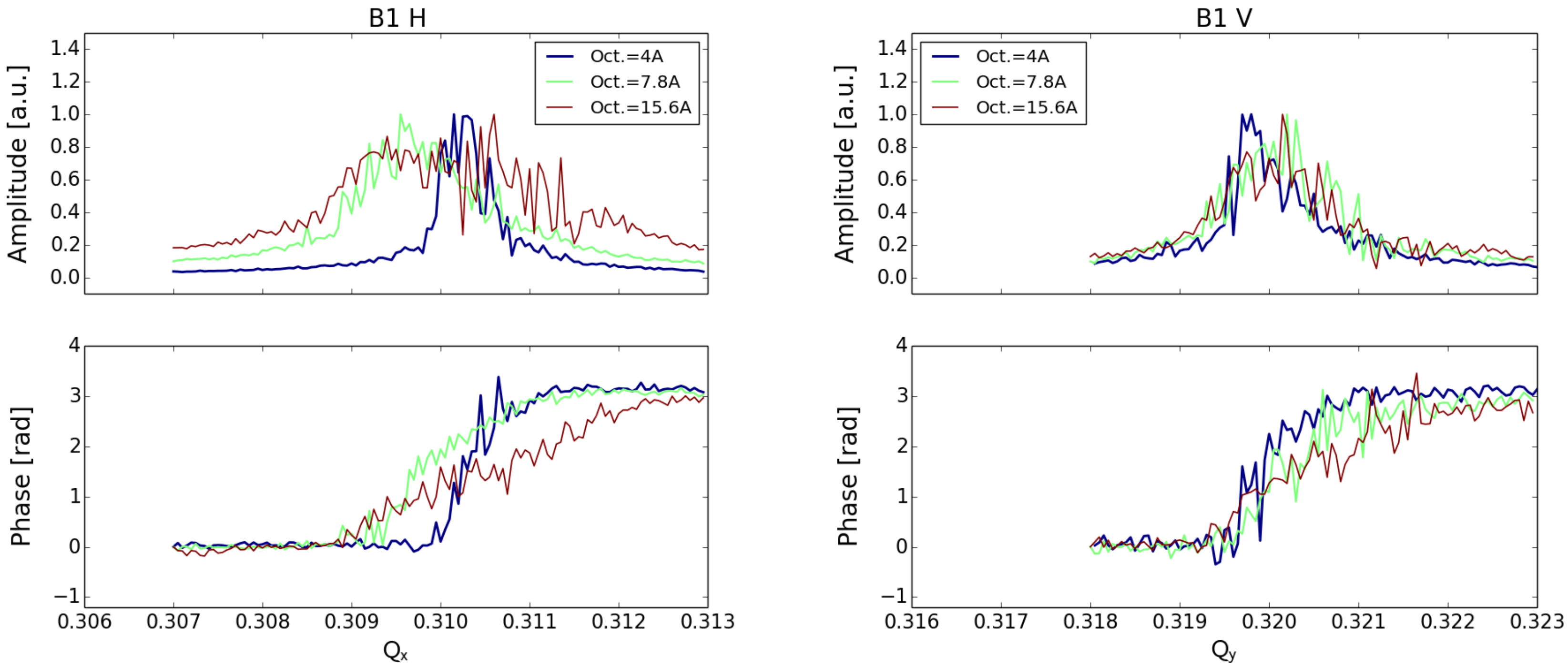
* E. Metral, L. Carver, X. Buffat et al., Destabilizing effects of transverse linear coupling on Landau damping, IPAC 2017

COMBI simulated BTF



Octupole scan at injection energy

Octuple scan with fixed linear coupling value (C^{-}~0.006)

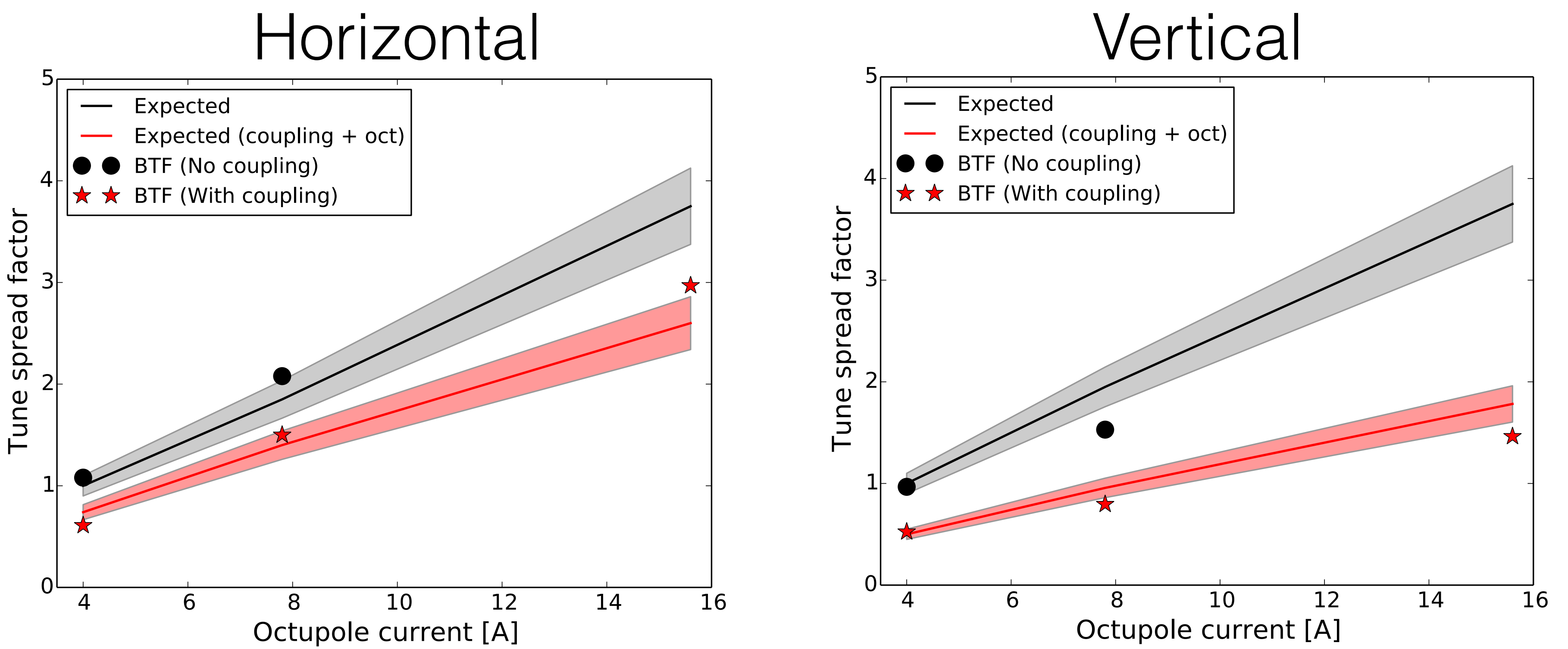


Asymmetric H - V behavior: larger spread in the horizontal than in the vertical plane

Horizontal plane much more affected by tune spread increase w.r.t. vertical plane

Measured tune spread: octupoles and linear coupling

Fitting function method applied to measure tune spread from BTFs (w.r.t to an analytical reference case of SD with 4 A octupole current)

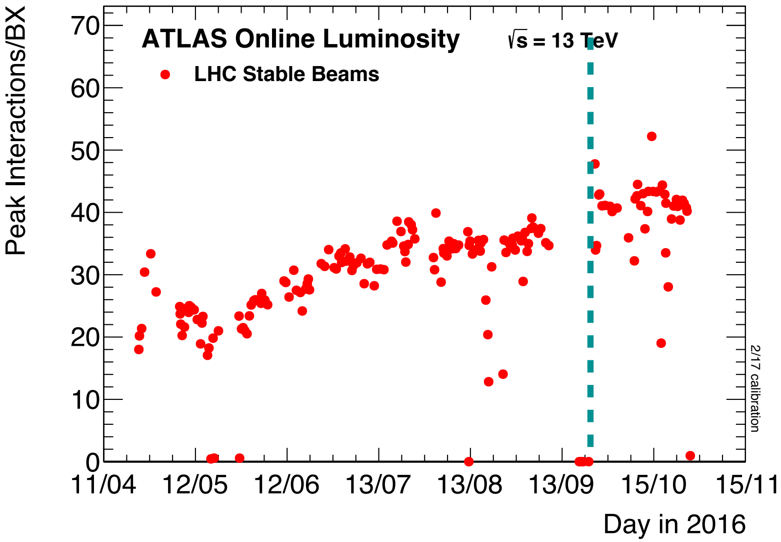


Quantitative comparison w.r.t to expectations (MAD-X + PySSD with and without linear coupling)

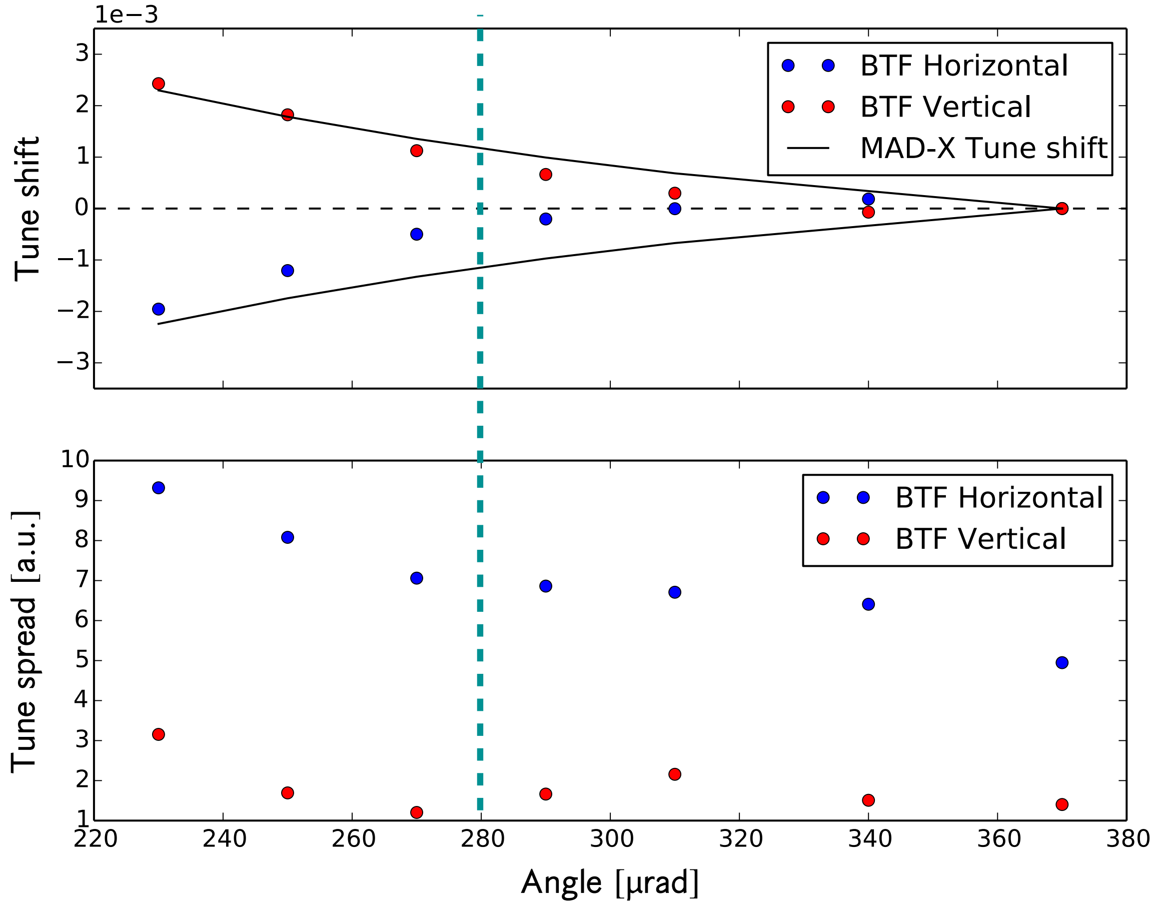
➔ BTF measurements well agree with expectations!

Tune shift and spread due to beam-beam long range interactions

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



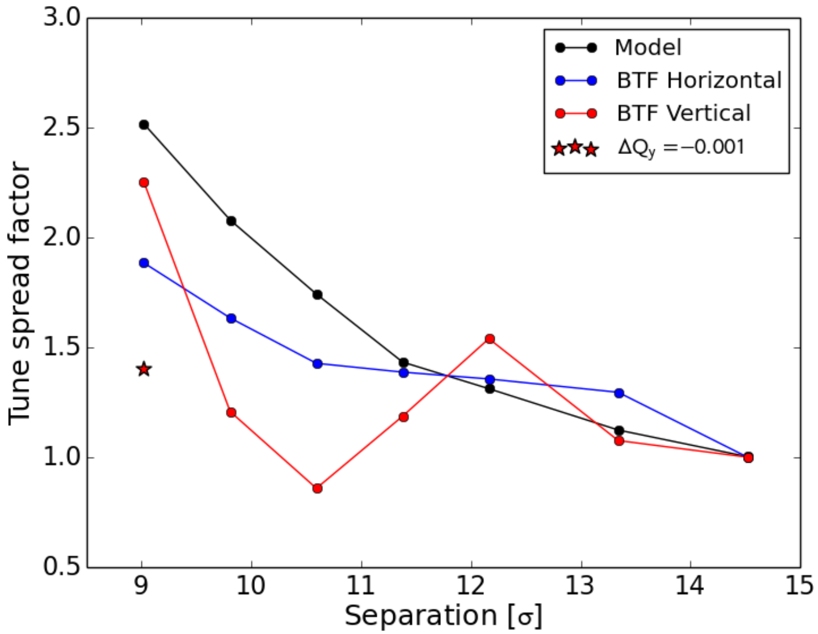
"Observations of Beam Losses at the LHC During Reduction of Crossing Angle" IPAC 2017 (TUPVA025)



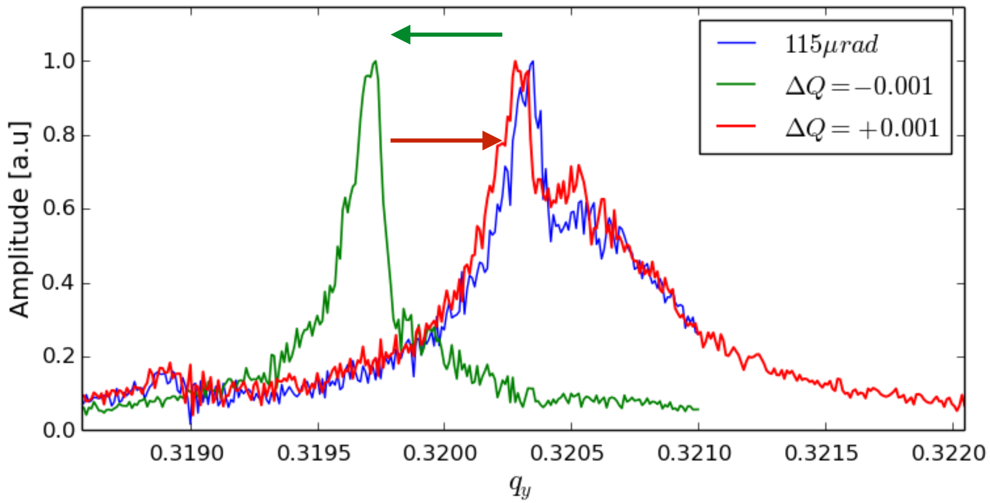
Correction of Long-Range Beam-Beam induced tune shift with direct increase of beam lifetimes

Tune spread due to beam-beam long range interactions and coupling

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



Tune scan in V plane

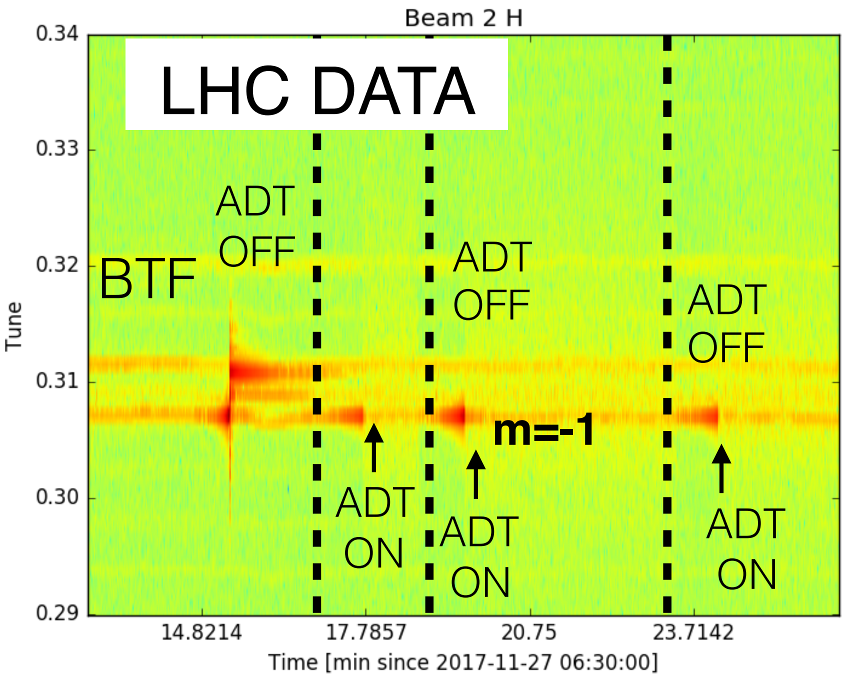


- Unexpected behavior respect to models
- Dependence on working point
- Not expected from models, it have strong impact on stability and measured SD

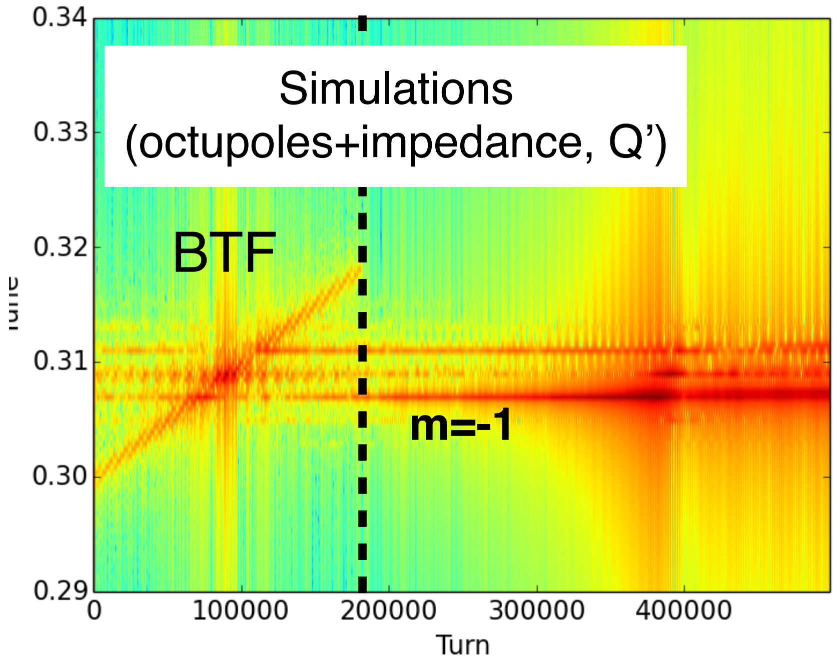
→ **Other mechanisms should play a role: linear coupling**

Effect of excitation on beam stability

Q' ~ 10 units, Oct. current 510 A



BTF Exc. Amplitude = $2 \cdot 10^{-4}\,\sigma$



- Instability B2 H after (small) BTF excitation (in order of 10^{-4} beam RMS size) in the same plane (with a rise time of ~ 2 s)
- Never observed instability triggered by BTF excitation (without excited coherent modes)
- Increase of 30% impedance in the 2017 ➔ (closer to stability limit?)

Simulations show loss of Landau damping of impedance head-tail mode m=-1 at -Qs

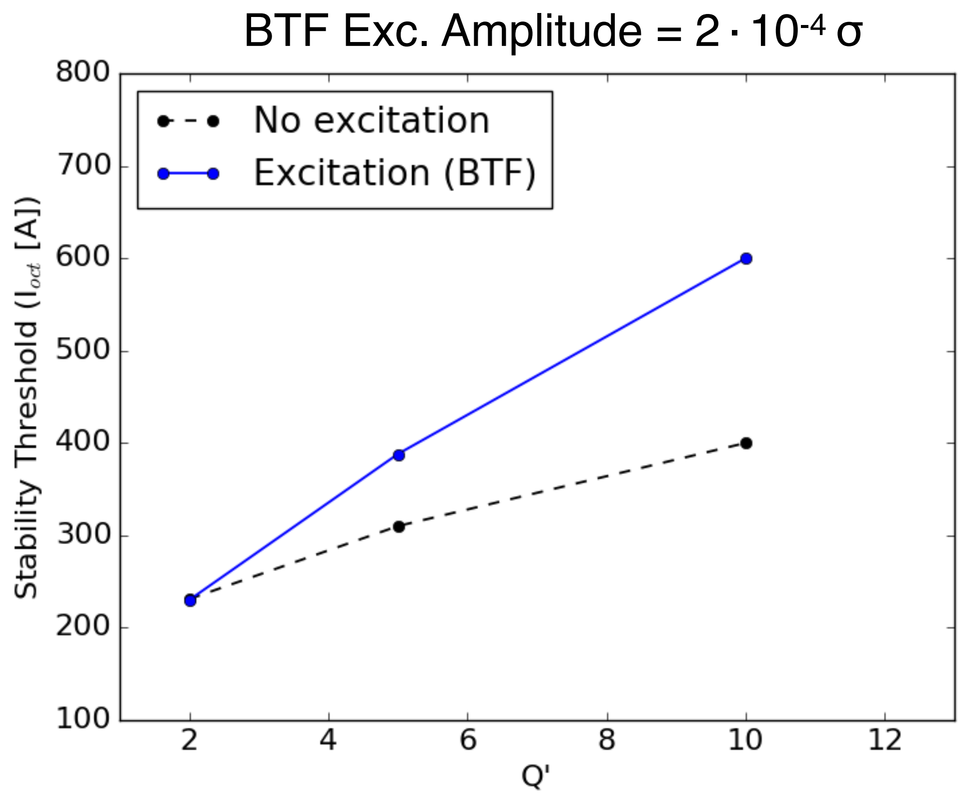
BTF induced instabilities when at stability limit with impedance

Higher octupole current is required to stabilize the beams in the presence of external excitation: noise ➔

Small amplitude external excitation increases stability thresholds in terms of octupoles

This could be a possible mechanism to explain the observed higher octupole threshold needed during LHC operation

Shows a clear limitation for the BTF measurements as exiting device



- Machine Development studies are planned to continue the understanding of instability and BTFs in the LHC
- BTF GATED system required for a possible use in operation and have clear signals

Summary

- **BTF is a powerful tool:** high precision **tune** and **chromaticity** measurements, **coherent modes detection** (beam-beam interactions) and **measurements of beam stability** (main purpose in the LHC)
- **Fitting method allows to compute tunes, tune spread and finally the stability diagrams** from measured data using the phase signal which is not dependent on the BBQ calibration
- System in LHC showed **good agreement between models and measurements** in the LHC for **tunes, chromaticity and tune spread**
- **Many improvements of the system in 3 years** fundamental to collect the experimental data**:**
    - signal averaging, delayed excitation, amplitude modulation, gated system for operational use
    - Chromaticity correlation could be used for online Q' measurements (need further investigation)
    - Fitting method works well and gives the needed informations quantitatively
- For the first time **stability expectations have been compared to LHC data giving enormous insights in the observed instabilities**
- **In the presence of strong impedance BTF excitation can trigger beam instabilities: very important insight in LHC stability studies but not obvious how to use such device operationally**