Swiss Accelerator Research and Technology

Injecting ripples on beam: shall we?

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Mitigations approaches for Synchrotrons and Storage Rings Virtual Workshop
22 June 2020 - 1 July 2020

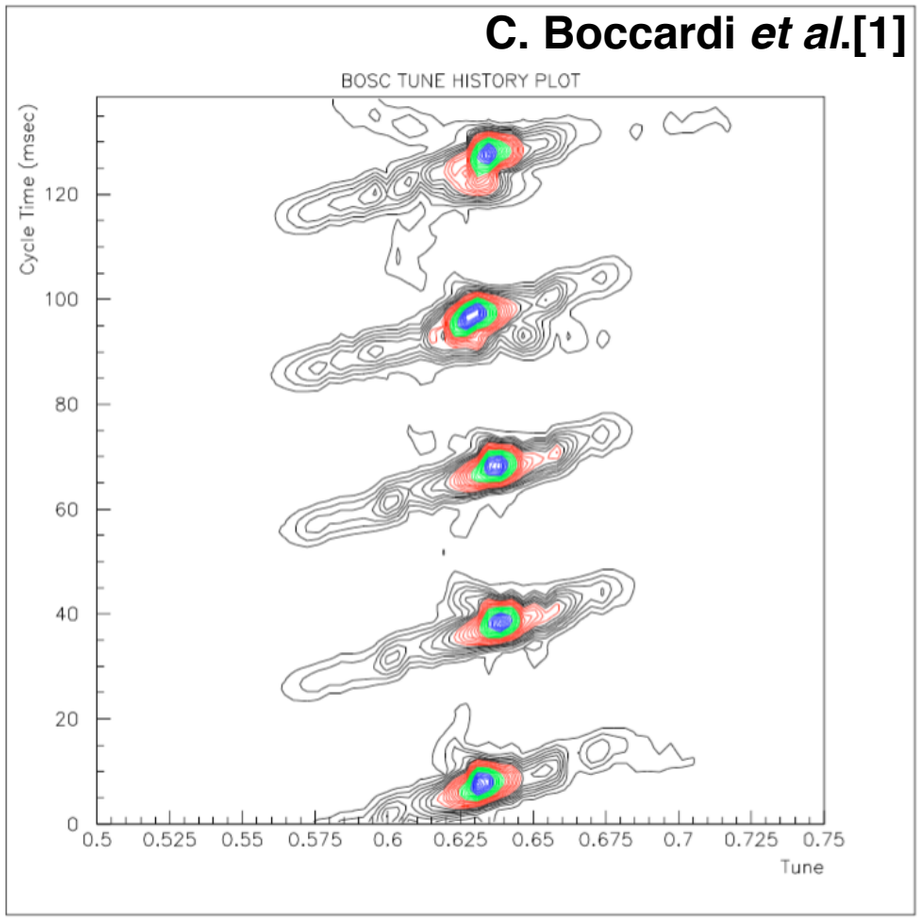
Why injecting ripples?

Ripple = harmonic excitation

Frequency sweep excitations for beam diagnostic:

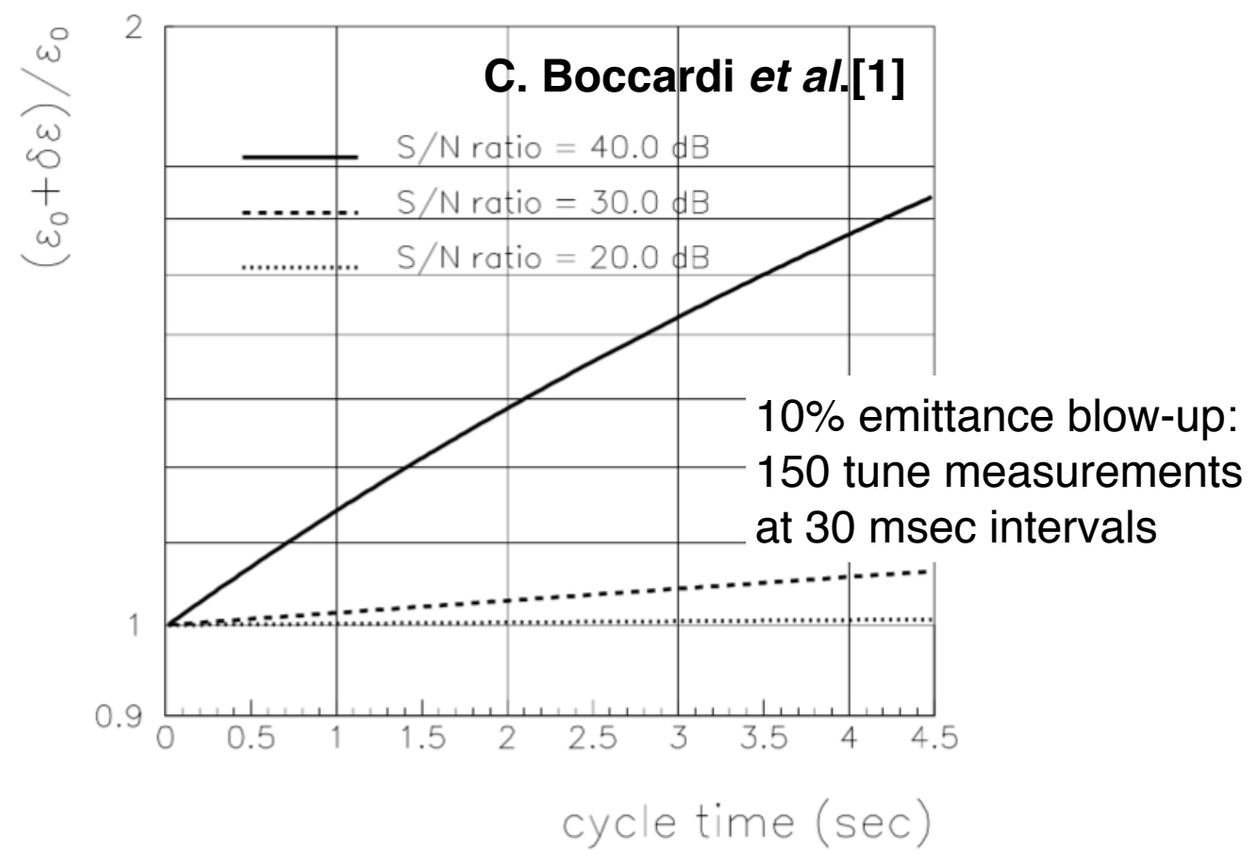
CHIRP excitation (fast sine wave of time variable frequency)
→Tune measurements

CHIRP excitation: fast tune measurements



Beam response to a chirp excitation [1]

- The beams were excited with a sine wave
- The frequency of the sine wave was increased linearly
- Tune measurements were achieved during the proton acceleration cycle
- **Side effect:** emittance blow up and related losses
- **One of the challenges was to find optimal signal to noise ratio to keep emittance blow up small**



[1] "***Tune Measurements in the SPS as Multicycling Machine***", C. Boccardi *et al.*, SL- 96-038, CERN, Switzerland

Why injecting ripples?

Ripple = harmonic excitation

Frequency sweep excitations for beam diagnostic:

CHIRP excitation (fast sine wave of time variable frequency)
→Tune measurements

Beam Transfer Function (steady sinusoidal wave, frequency increased in steps, high accuracy but slower method)

- Tune and chromaticity measurements
- Tune spread estimation
- Detection of coherent modes
- Transverse and longitudinal impedance information
- Investigation of Landau damping (tune spread, stability area)

What is a BTF?

A **B**eam **T**ransfer **F**unction **(BTF)** is the **complex response** of the beam **to a harmonic excitation as a function of frequency** [2]

$$BTF = A(q)\, e^{i\varphi(q)}$$

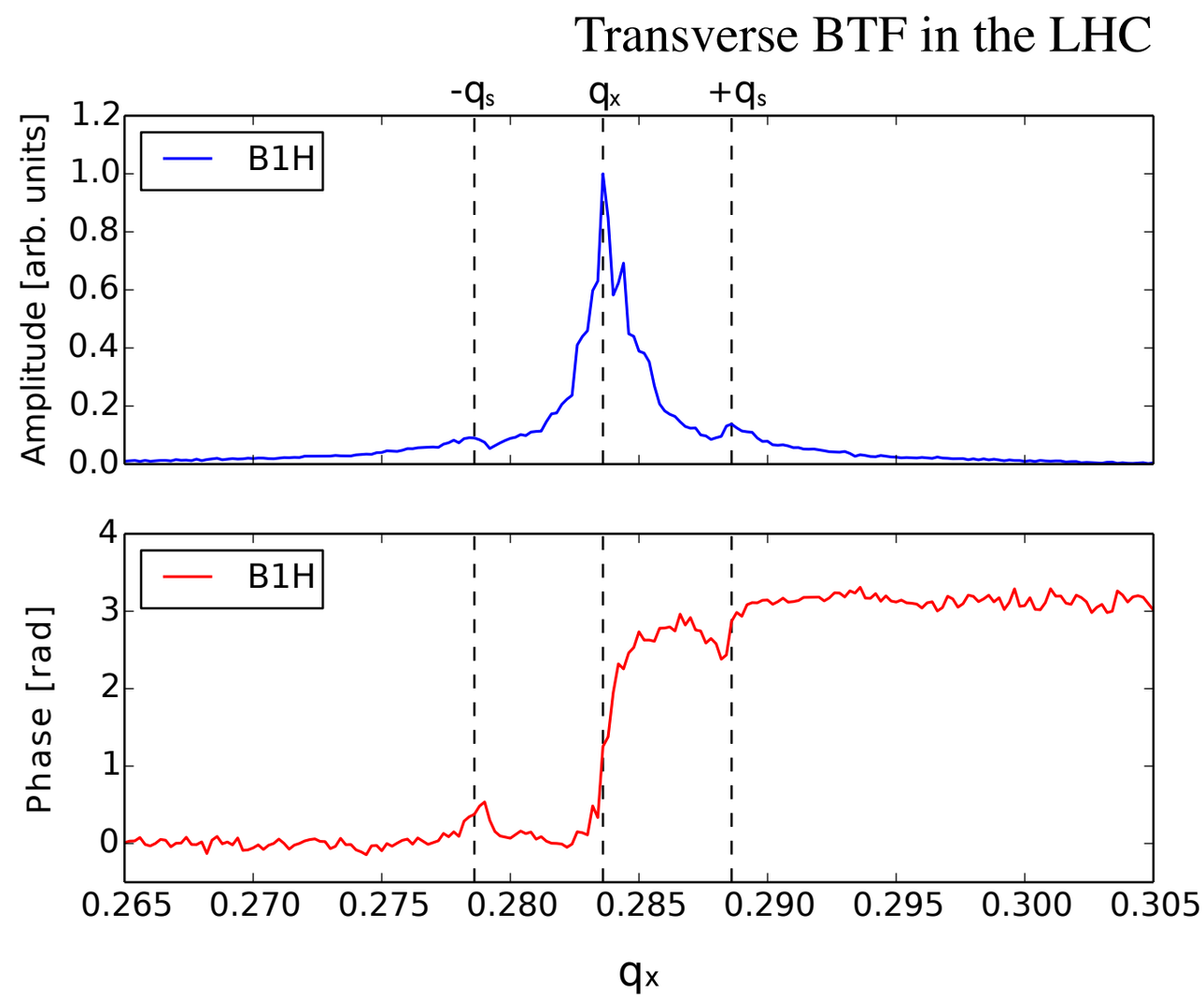
Amplitude (q)

Phase (q)

At the betatron tune:

- the amplitude slope is zero (maximum)
- the phase exhibits maximum slope (π/2)

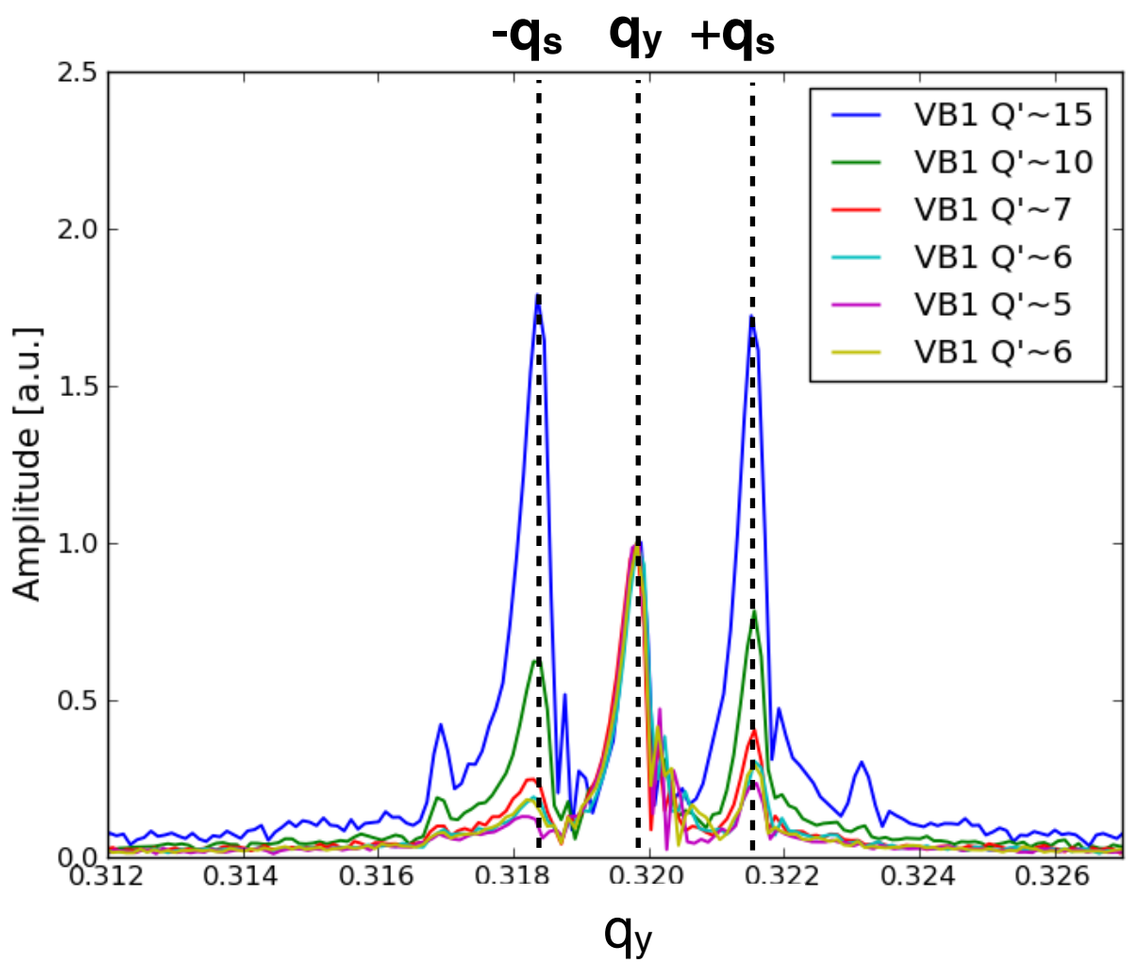
- **Sensitive to particle distribution**
- **Insights into the tune spread of the beams**

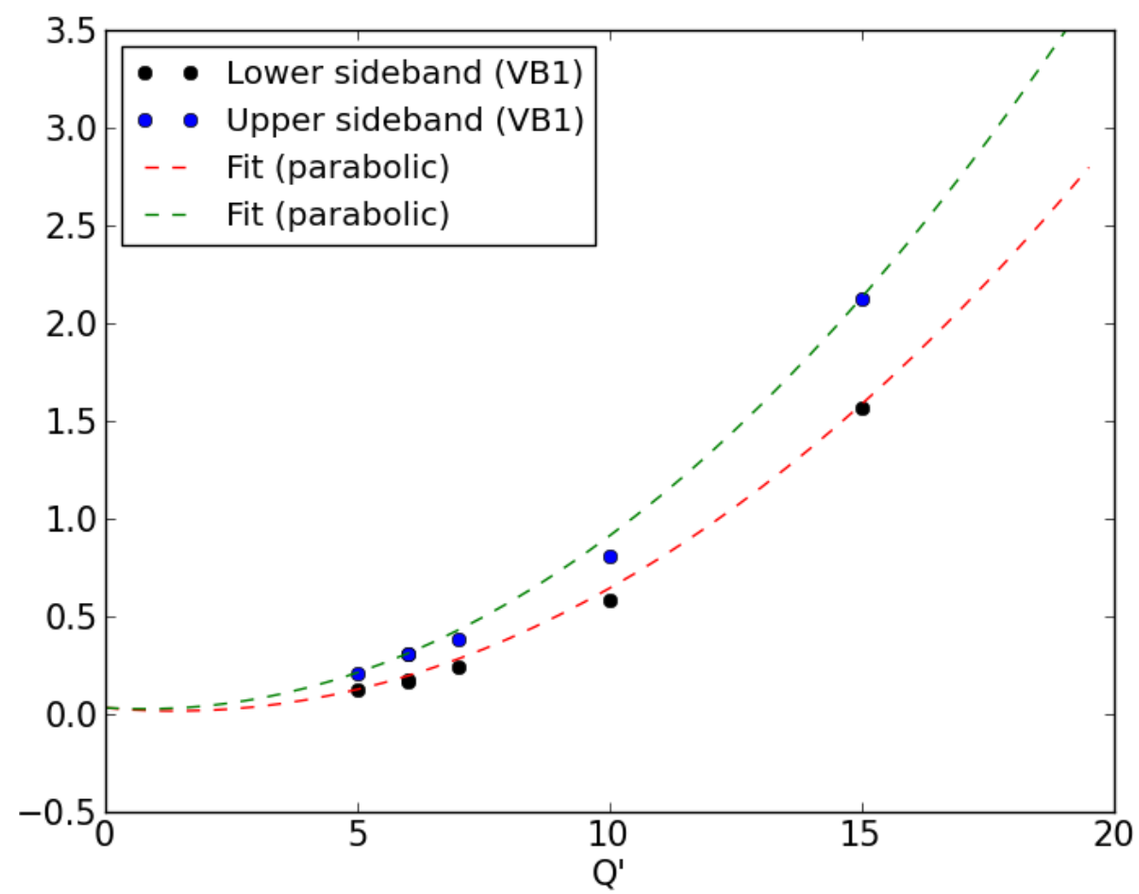


[2]"***Measurement and Control of Charged Particle Beams***", M. G. Minty and F. Zimmermann, (Springer, 2003)

BTF: Tune and chromaticity measurements

- In the presence of chromaticity **synchrotron sidebands appear at $\pm n \cdot q_s$ from the betatron tune peak**
- In the absence of space charge and collective effects, **the amplitude ratio of the sidebands to the main tune peak is a direct measure of the chromaticity** [3,4]

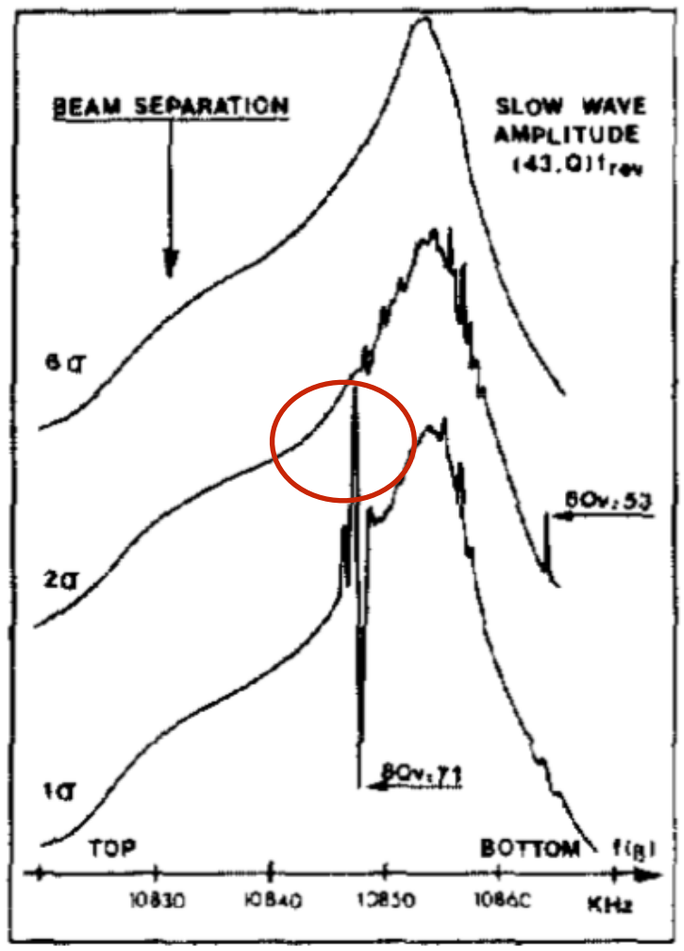


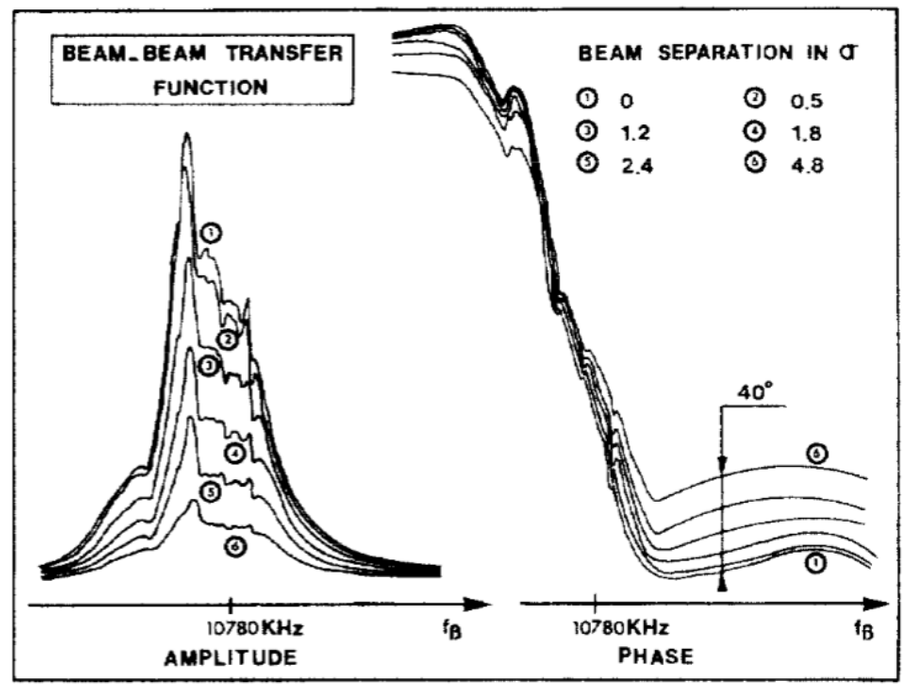


[3] G. Jackson, "***Tune Spectra in the Tevatron Collider***", in Proc. 13th Particle Accelerator Conf. (PAC'89), Chicago, USA, 1989
[4] G. Rehm et al., "***Measurement of lattice parameters without visible disturbance to user beam at Diamond light source***", in Proc. 14th Beam Instrumentation Workshop (BIW'10), Santa Fe, NM, USA, May 2010, MOCNB01

Investigation of beam-beam coupling and coherent modes

Measurements of the Beam-Beam Transfer Function at the ISR [5,6]





BTF measurements used to optimize HO collisions

- BB coherent modes were detected reducing the separation
- The amplitude is proportional to luminosity and may be used to define the position of the head-on collision
- Measurements of resonance excitations increasing BB parameter [7]

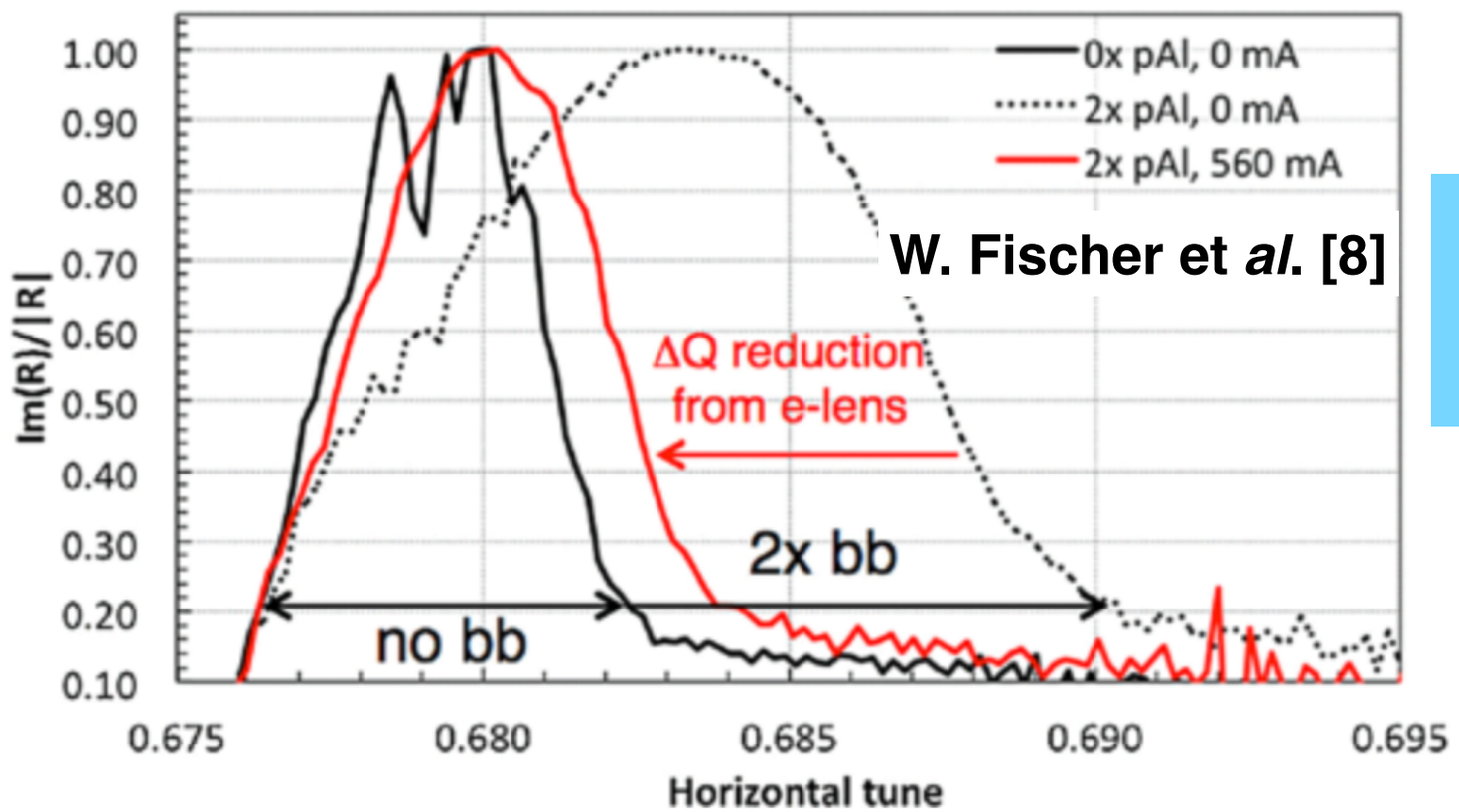
[5] J.-Y. Hemery et al., "***Investigation of the coherent beam-beam effects at the ISR***", NS-28, 2497 (1981)

[6] A. Hofmann, "***The beam-beam transfer function"***, ISR Performance Report (CERN, 1981)

[7]J. Borer et *al.*, "***Information from Beam Response to Longitudinal and Transverse Excitation***", IEEE Transactions on Nuclear Science, Vol. NS-26 No 3 (1979)

BTF: measurements of beam-beam compensation through e-lens @ RHIC

Transverse BTF measurements with head-on electron-proton beam [8]



Measurements of BB tune spread compensation by using an e-lens (W. Fischer [8])

[8] W. Fischer et *al.*, "***Operational Head-on Beam-Beam Compensation with Electron Lenses in the Relativistic Heavy Ion Collider***", Phys. Rev. Lett. **115**, 264801, 2015

BTF measurements for transverse stability studies at the LHC (1)

The beam response to a driven excitation is related to the transverse coherent stability and gives insights into the Landau damping of the beams [9-11]:

Dispersion integral (inverse of Stability Diagram SD):

$$SD^{-1}_{(x,y)} = \int_0^\infty \frac{J_{x,y}}{Q_{x,y} - q_{x,y}(J_x, J_y)} \frac{d\psi}{dJ_{x,y}} dJ_x dJ_y = \frac{BTF_{(x,y)}}{A_{x,y}}$$

[9] A. W. Chao, "***Physics of Collective Beams Instabilities in High Energy Accelerators***", edited by I. J. W. Sons

[10] D. Mohl and A. M. Sessler, "***The use of RF-knockout for determination of the characteristics of the transverse coherent instability of an intense beam***", eConf C710920, 334 (1971)

[11] J. Gareyte et al., "***Landau Damping, Dynamic Aperture and Octupoles in LHC***", LHC Project Report 91 (CERN)

BTF measurements for transverse stability studies at the LHC (2)

Predictions of stability thresholds in the LHC are based on computation of **Landau damping** by calculating the **SD** with all ingredients (Landau octupole magnets, beam-beam [12])

Dispersion integral:

Particle distribution changes

$$SD^{-1}_{(x,y)} = \int_0^\infty \frac{J_{x,y}}{Q_{x,y} - q_{x,y}(J_x, J_y)} \frac{d\psi}{dJ_{x,y}} dJ_x dJ_y = \frac{BTF_{(x,y)}}{A_{x,y}}$$

Detuning with amplitude (**tune spread**)
Octupoles + beam-beam (**any non-linearities**)

- **Modification of the tune spread** (linear coupling) and/or **particle distribution changes** (beam losses due to resonance excitation, reduced DA…) modify Landau damping
- A **factor 2 (w.r.t models)** in Landau octupoles (tune spread) **is required to stabilize** the beams during **operations**

Probe Landau damping through BTF measurements @ LHC

[12] Buffat et al., "***Stability diagrams of colliding beams***" Phys. Rev. ST Accel. Beams 17, 111002

The Fitting Method

Uncalibrated system and dependency on measurements conditions: direct reconstruction of stability diagrams not possible → fitting method for quantitative comparisons with expectations

Fitting method allows to compare measurements with respect to the models (**reference case, i.e. octupoles**) [13]

$$\varphi(Q_{meas}) = \varphi_{model}\left[\phi_{shift} + \phi_{scale} \cdot (Q_{model} - Q_0)\right]$$
$$A(Q_{meas}) = A_{model}(Q_{model}) \cdot A_{scale}/\phi_{scale}$$

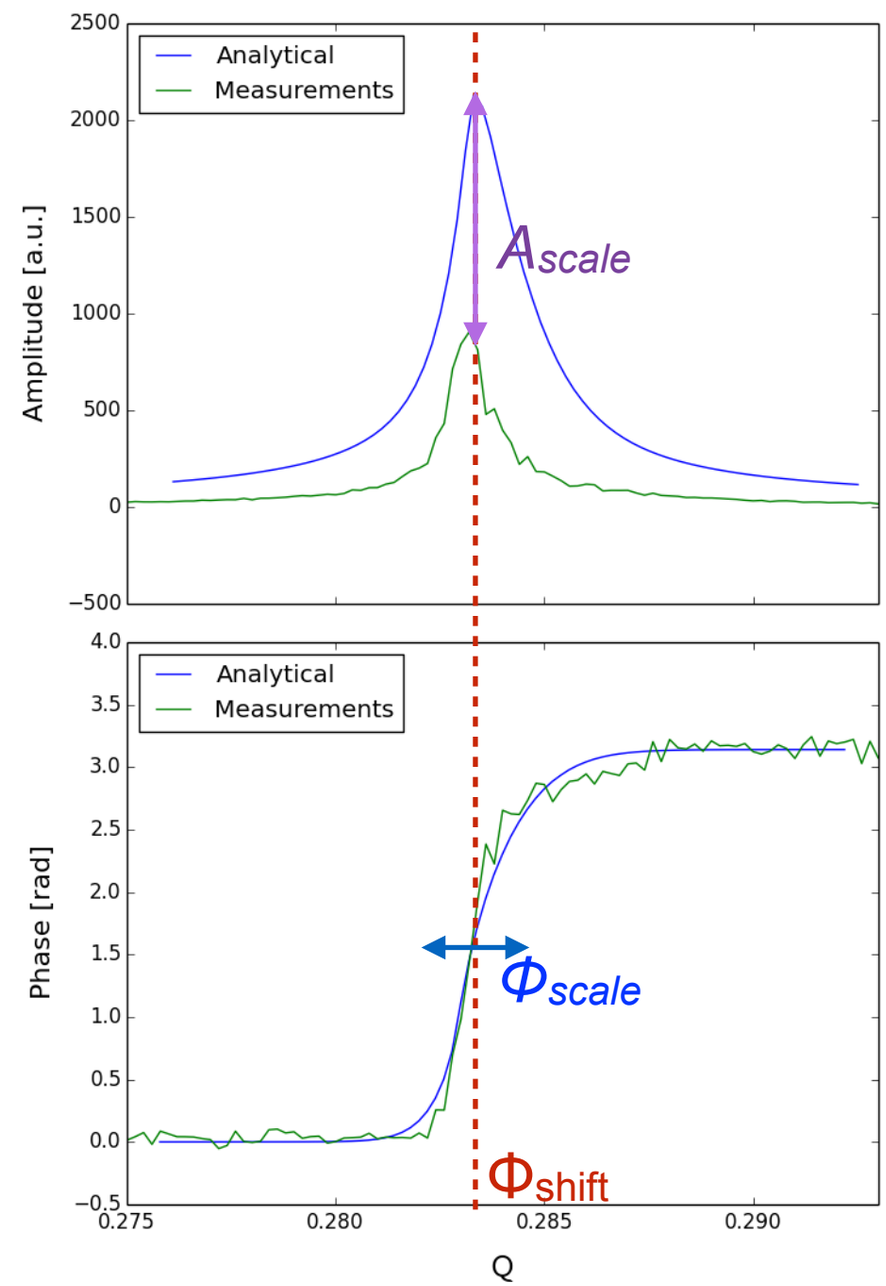
$$Q_{meas} \approx \phi_{shift} + \phi_{scale} \cdot (Q_{model} - Q_0)$$

Φ_{shift} = Phase shift (tune shift w.r.t the models)

Φ_{scale}= Phase scale (tune spread w.r.t the models)

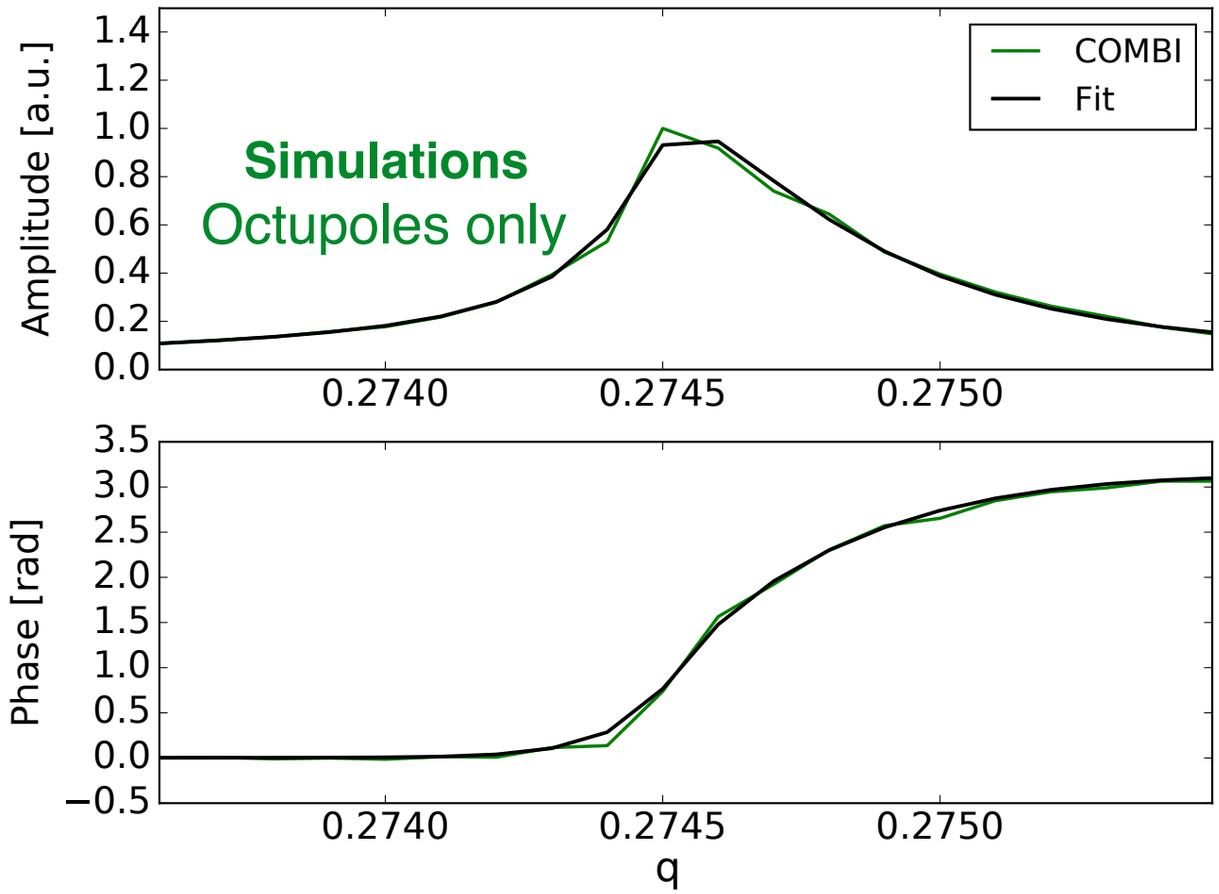
independent from calibration factor (phase slope)

A_{scale} = Amplitude scale **depends on calibration, proportionality constant**



[13] C. Tambasco et *al*, "**Beam transfer function measurements used to probe the transverse Landau damping in the LHC**", PRAB, 2020 In Press

Reconstruction of SD using fitting method



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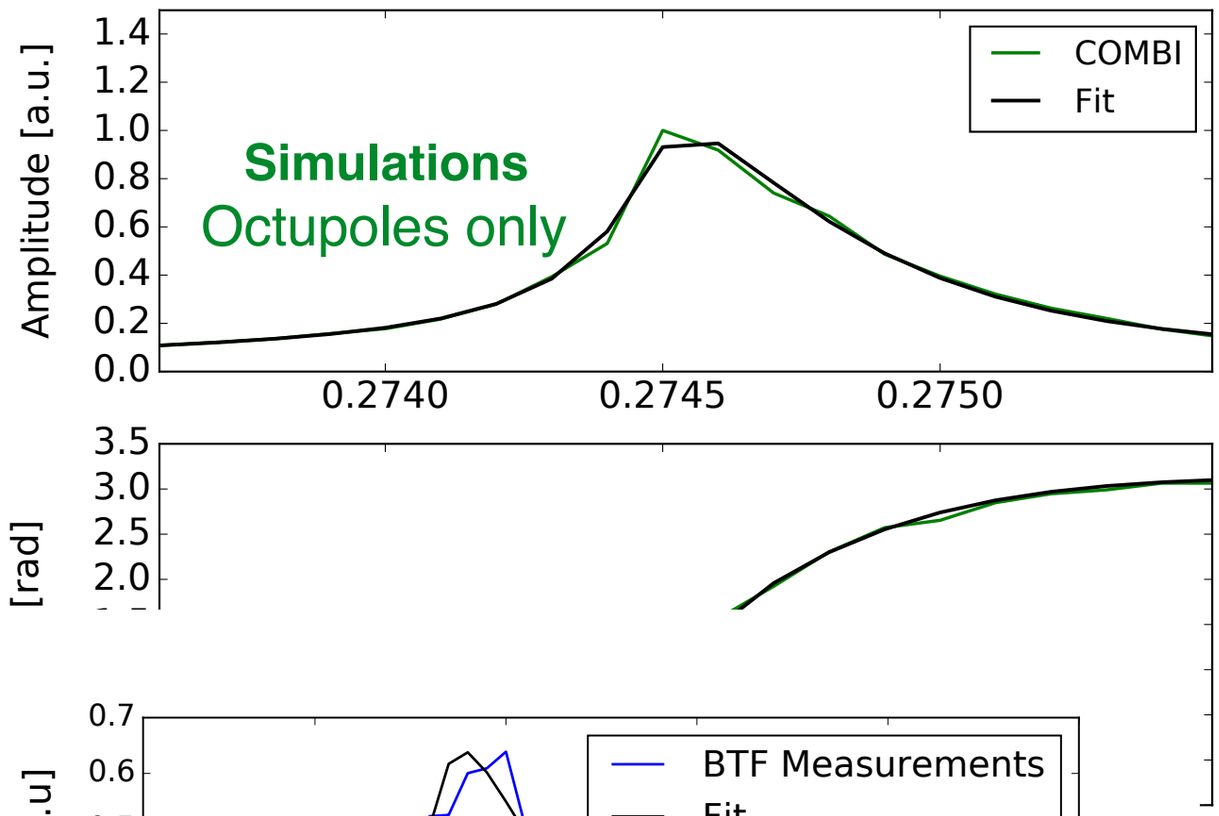
Example applied to simulations:
Well known case of linear detuning with amplitude: tune spread parameter $\Phi_{scale} \sim 1$

Reconstruction of SD using fitting method



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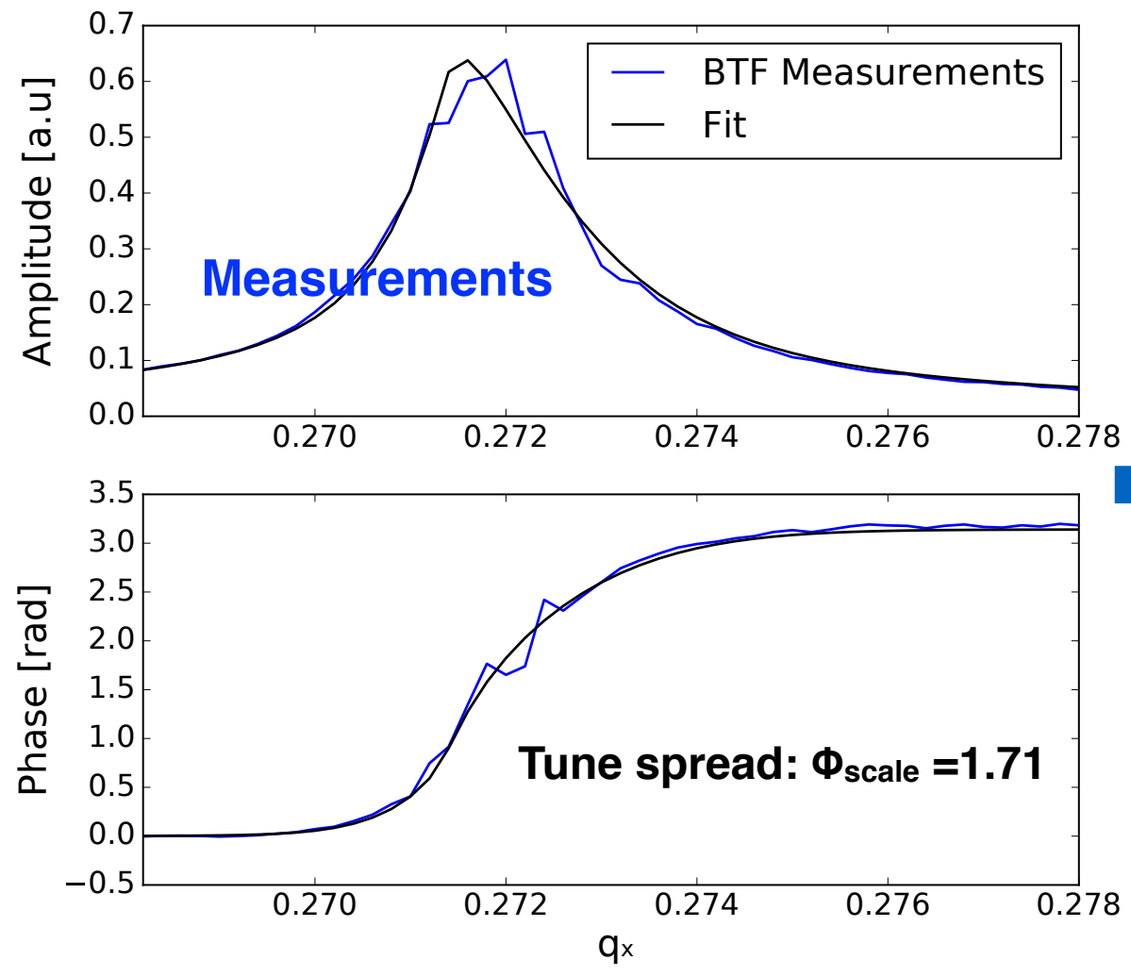
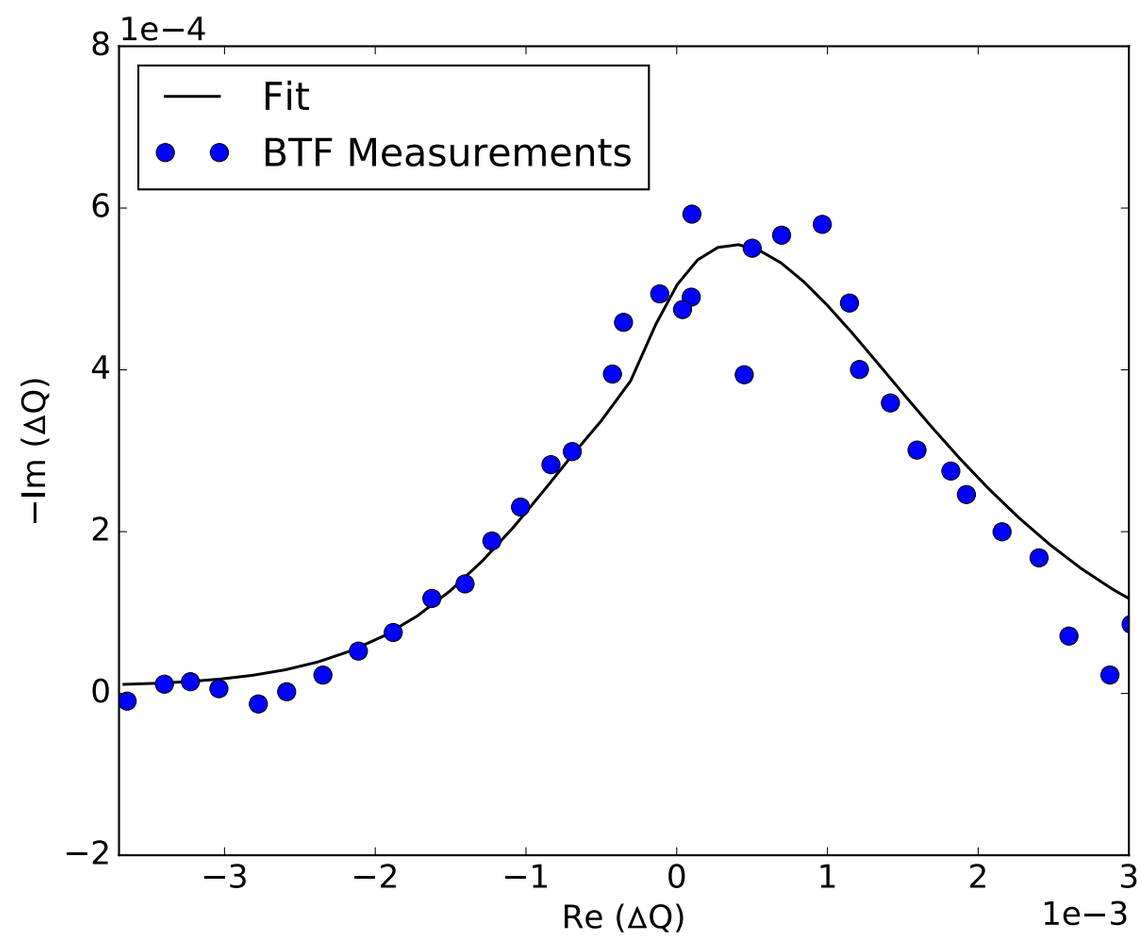
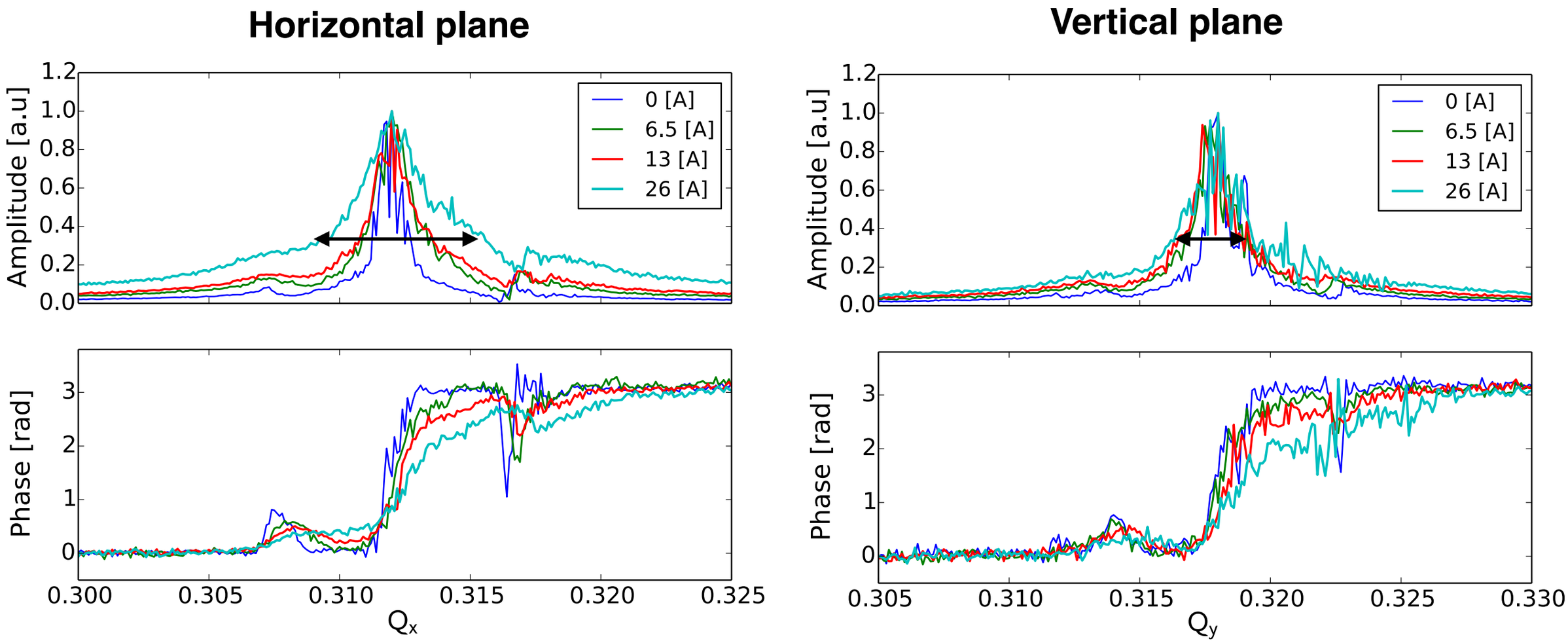
Example applied to simulations:
Well known case of linear detuning with amplitude: tune spread parameter Φ_{scale} ~1





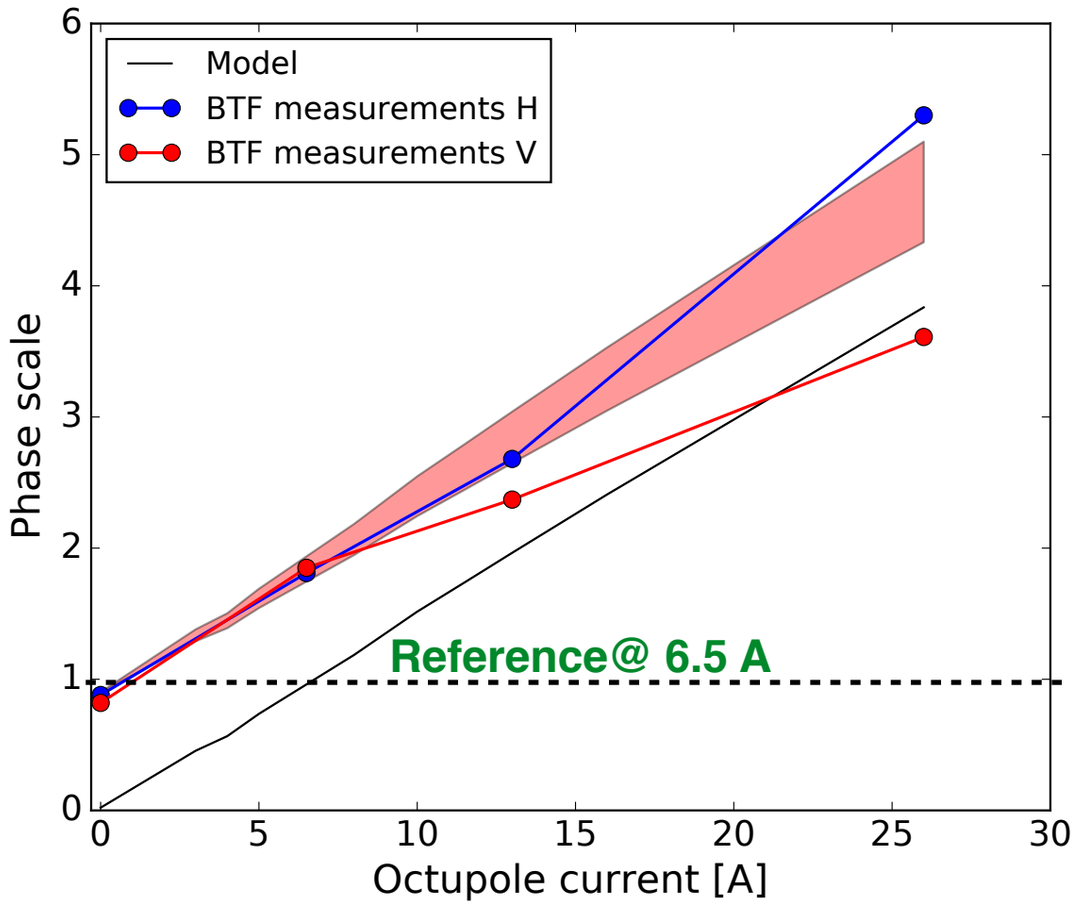
Landau Octupole scan

Tune spread given by Landau octupoles and lattice non linearities @ injection energy



For the largest octupole strength (26 A) larger spread measured in the horizontal plane than in the vertical plane

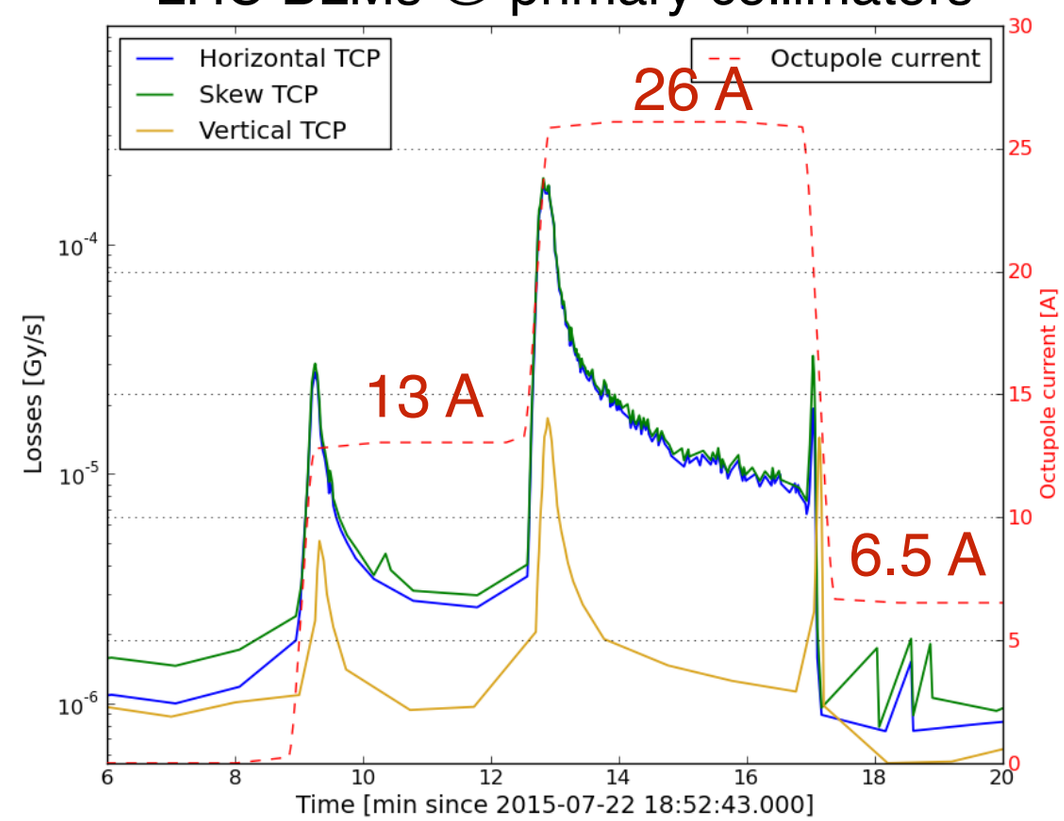
Measured tune spread and beam losses



- Fitting method used to compare measurements and expectations from model (tune spread factor)
- Equivalent to 5 A octupole spread measured at 0 A octupole current
- Linear trend reproduced
- **Deviation observed in the vertical plane for higher octupole currents**

Beam losses observed during data acquisition correlated with octupole current changes

LHC BLMs @ primary collimators



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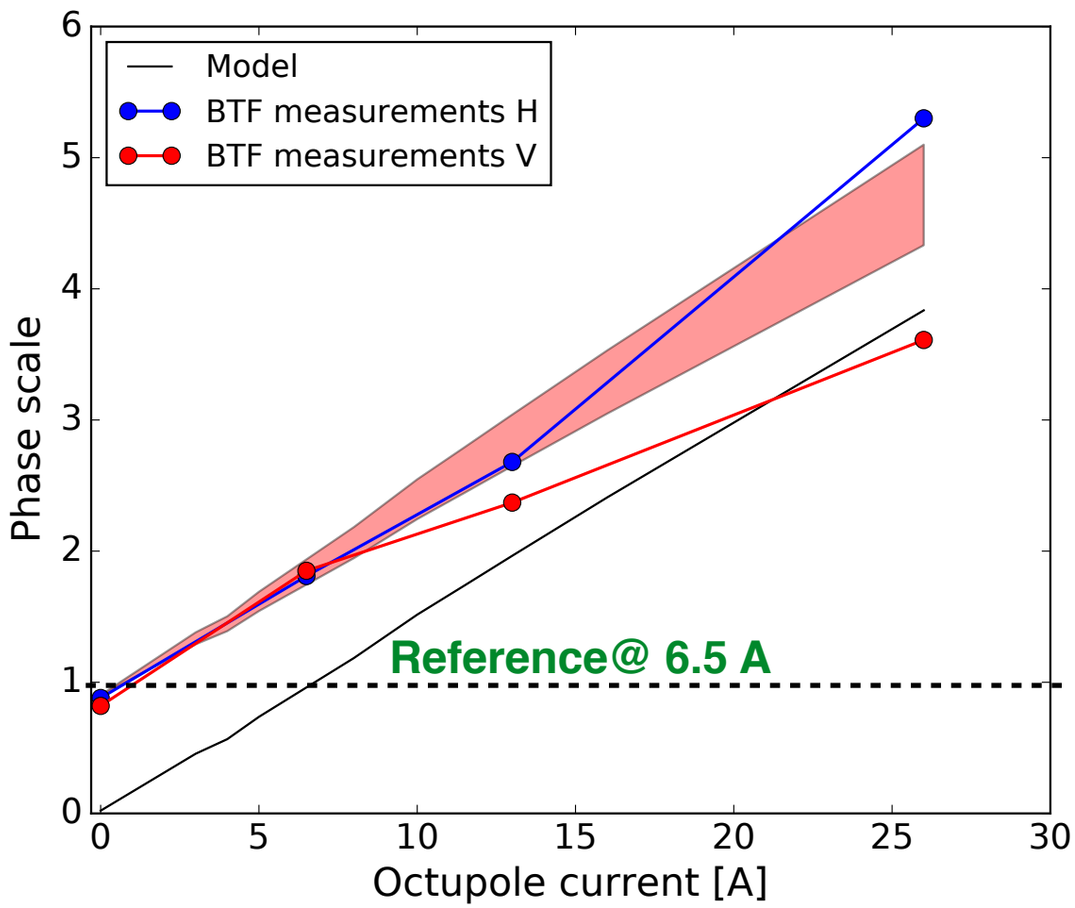

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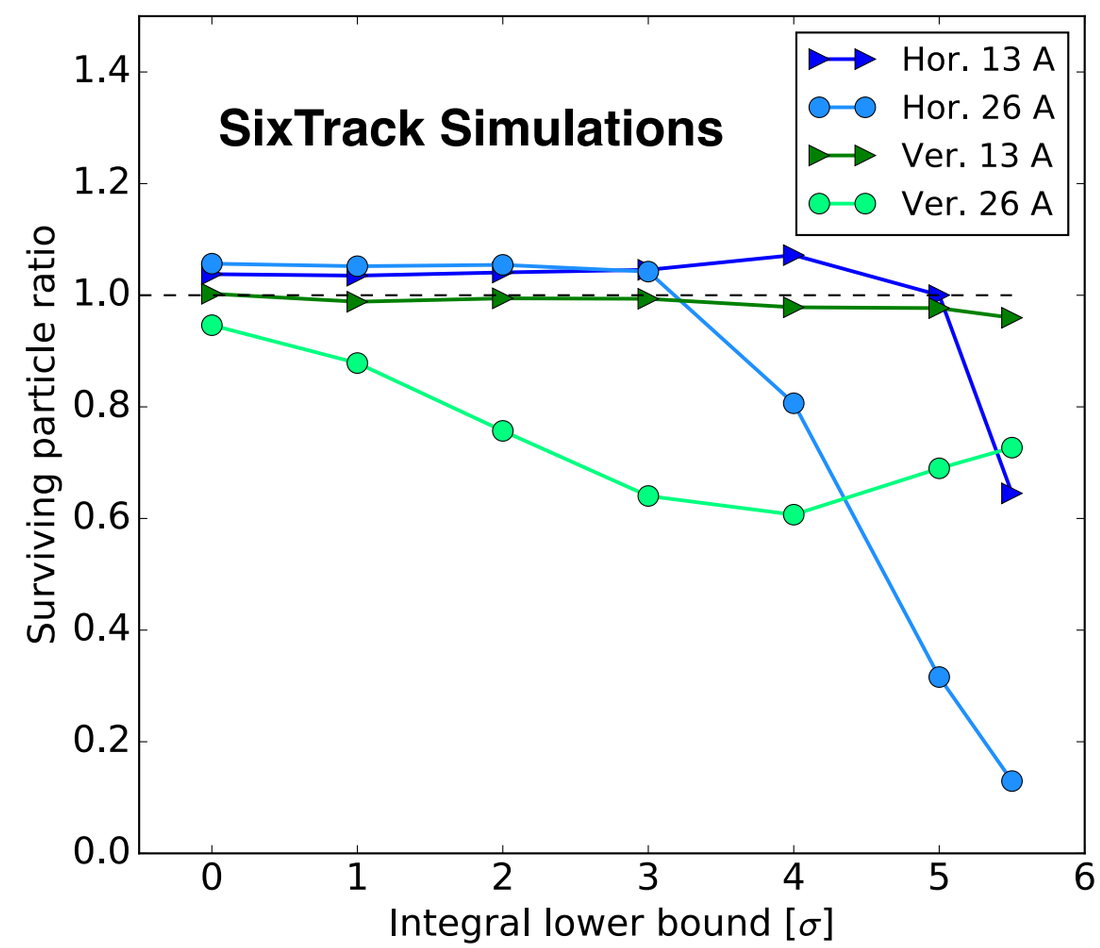


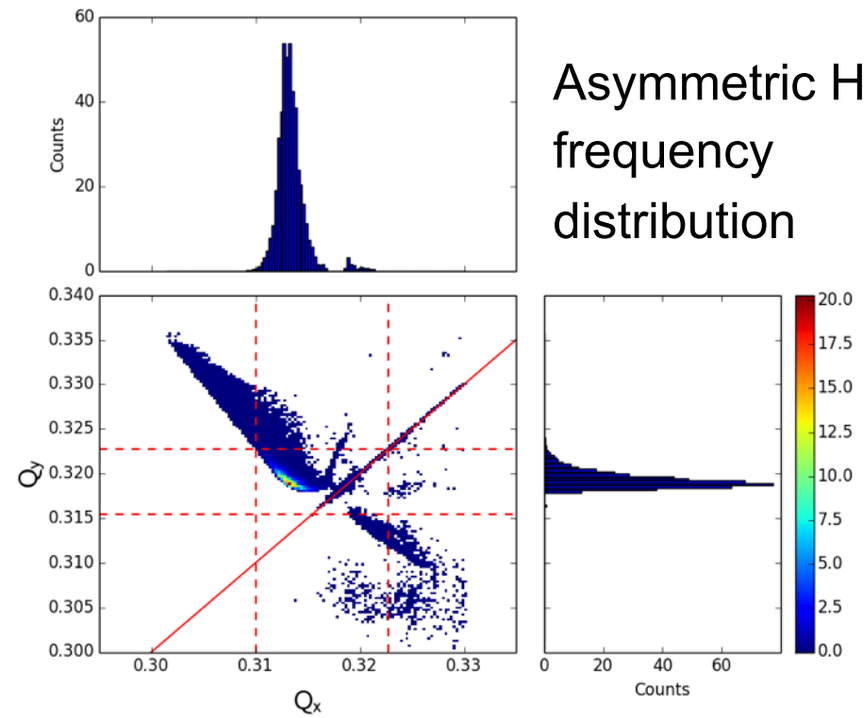
Simulated particle losses show that in the **vertical plane a reduction up to 40%** is observed for amplitudes < 4 σ

→ Increasing the tune spread is not beneficial for Landau damping if particle losses are present

Impact of linear coupling on BTF response

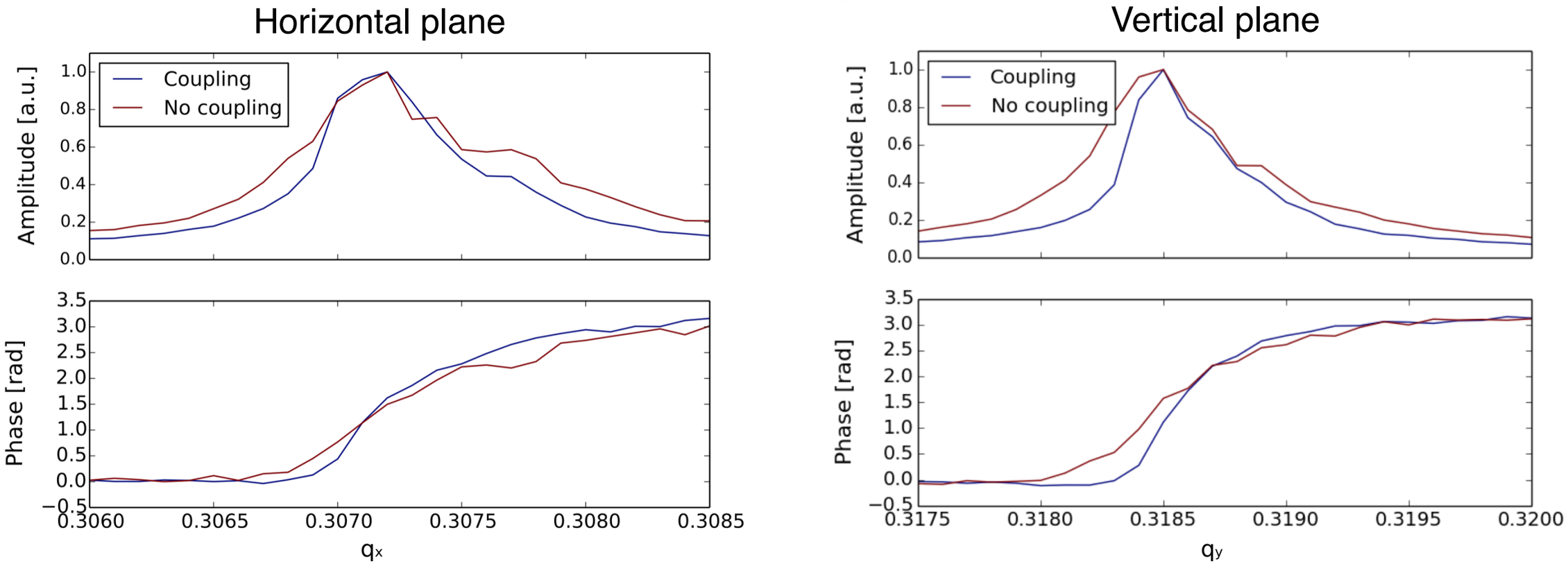
The transverse linear coupling might cause destabilizing effects [14] due to a reduction of the Landau damping of the beams:

- **reduced Landau damping in both planes**
- **asymmetric H-V frequency** distribution (tune spread)
- **stronger effect in the V-plane** (smaller tune spread w.r.t. H-plane)



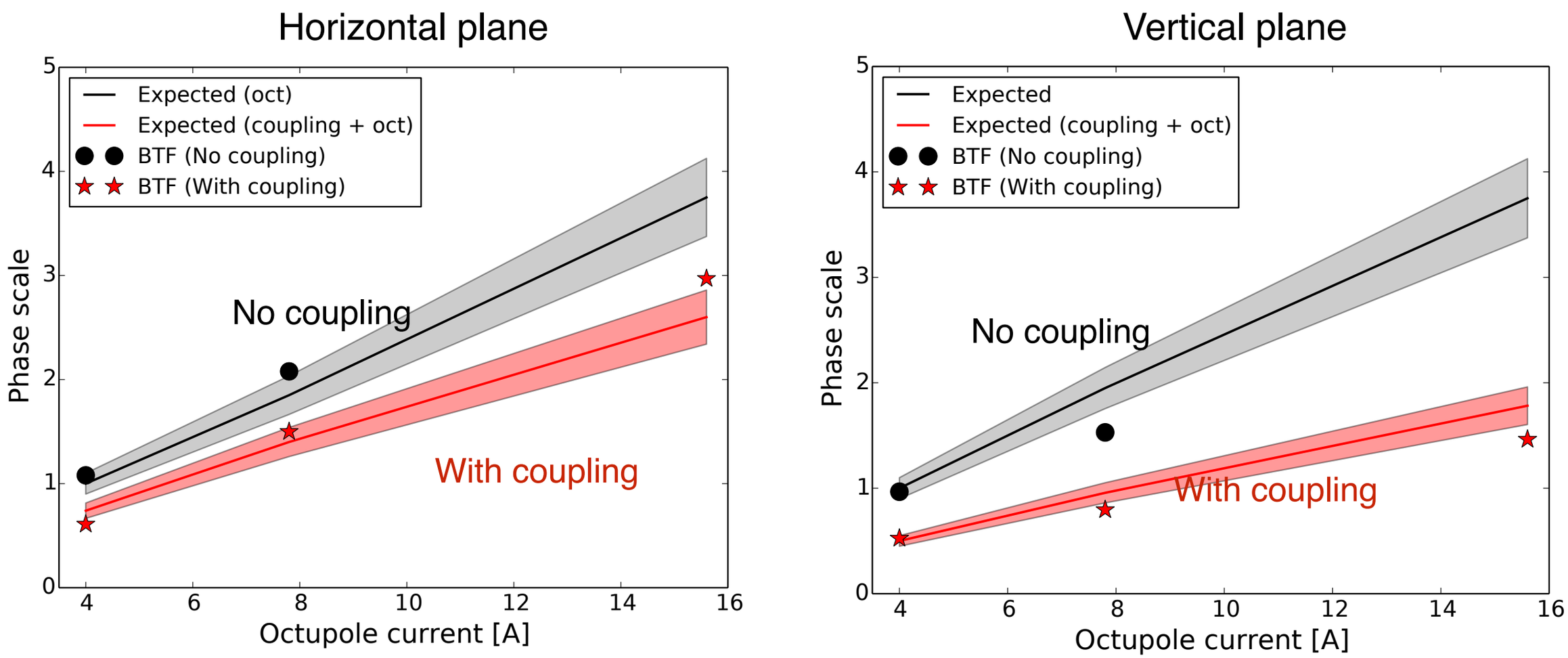
Asymmetric H-V frequency distribution

Simulated BTF response



[14] L. R. Carver, X. Buffat, K. Li, E. Métral, and M. Schenk, Phys. Rev. Accel. Beams 21, 044401 (2018)

Experimental prove of reduction of tune spread due to linear coupling by BTFs

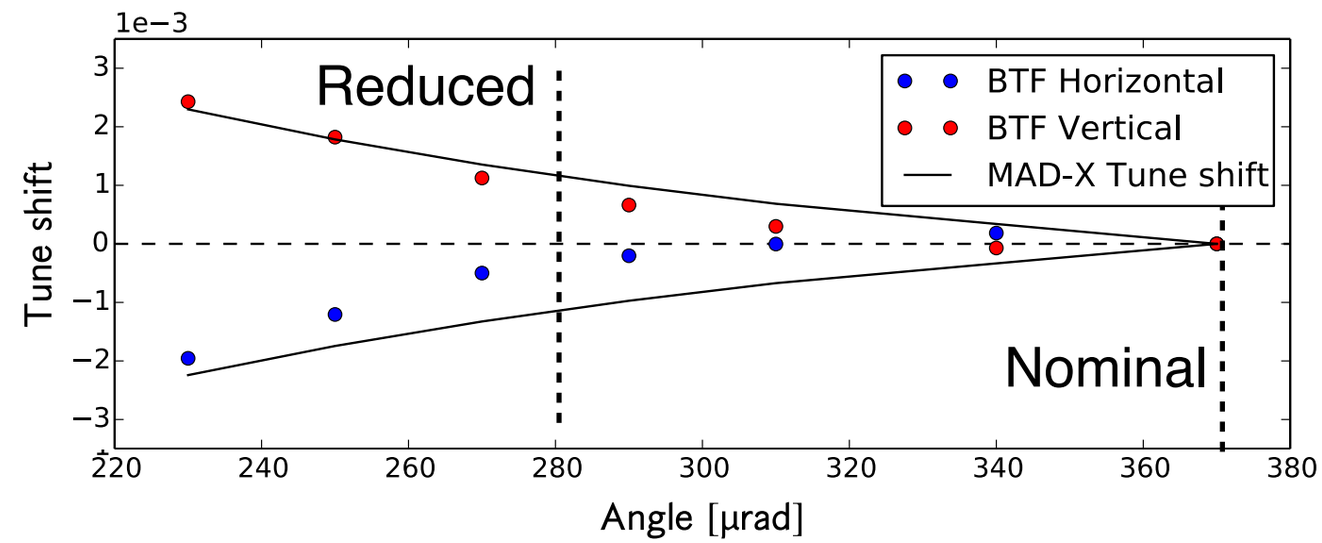


Fitting function method applied to measure tune spread from BTFs (w.r.t to an analytical reference case of SD with 4 A octupole current)

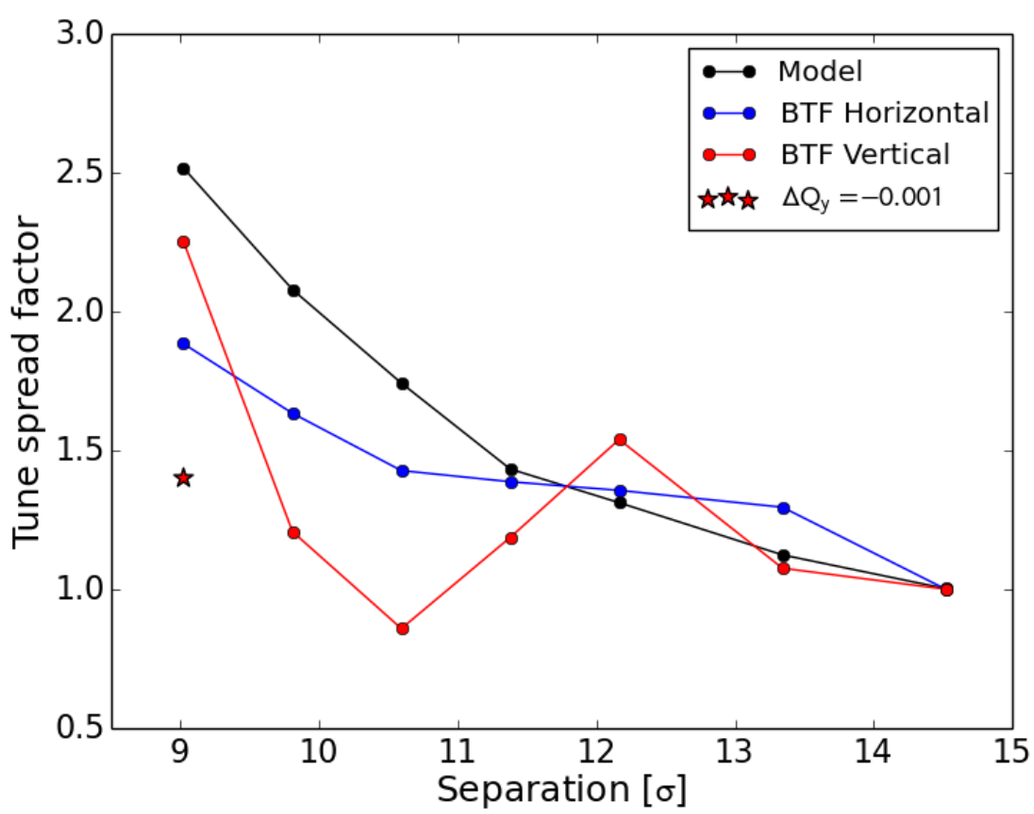
Quantitative comparison w.r.t expectations (MAD-X + PySSD with and without linear coupling)
→ BTF measurements agree well with expectations!

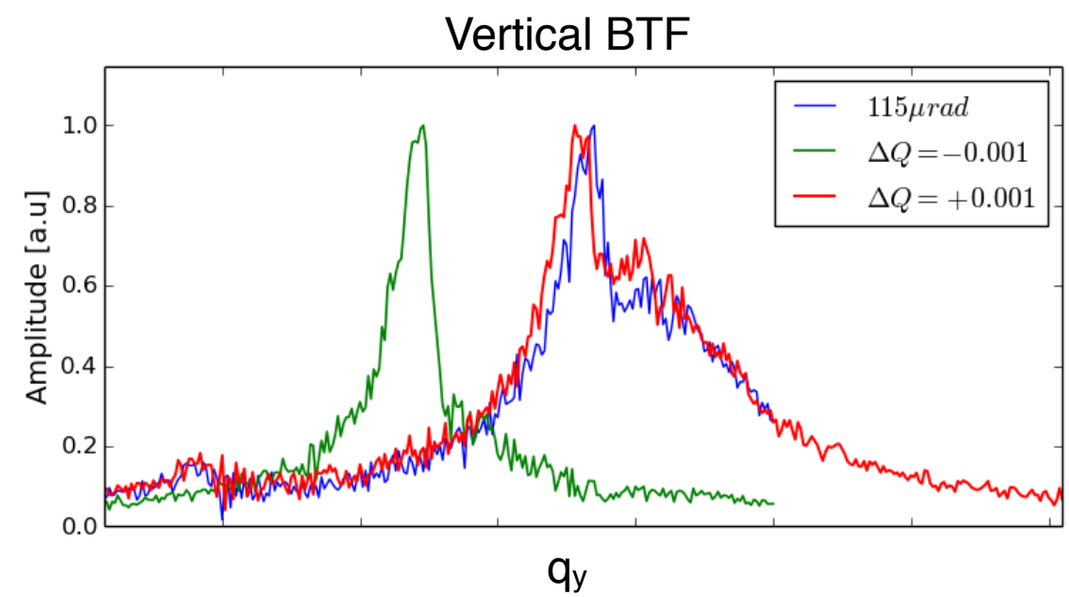
BTFs in the presence of BB LR interactions

- Asymmetric tune shifts in H/V planes
- Correction of BB LR induced tune shift
  → **lifetimes increased above 20 h**
- Reduction of crossing angle in 2016 very successful [15]



Measured LR contribution on stability at the EOS



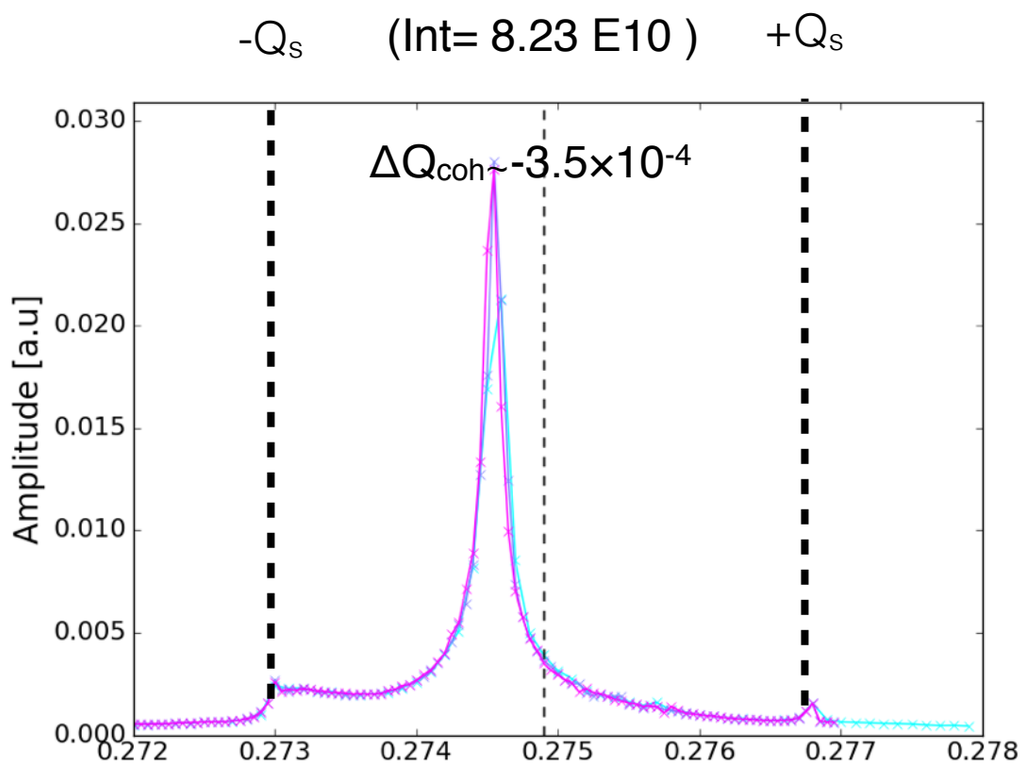


- Asymmetric tune spread
- Dependence on working point

→ **Other mechanisms should play a role**

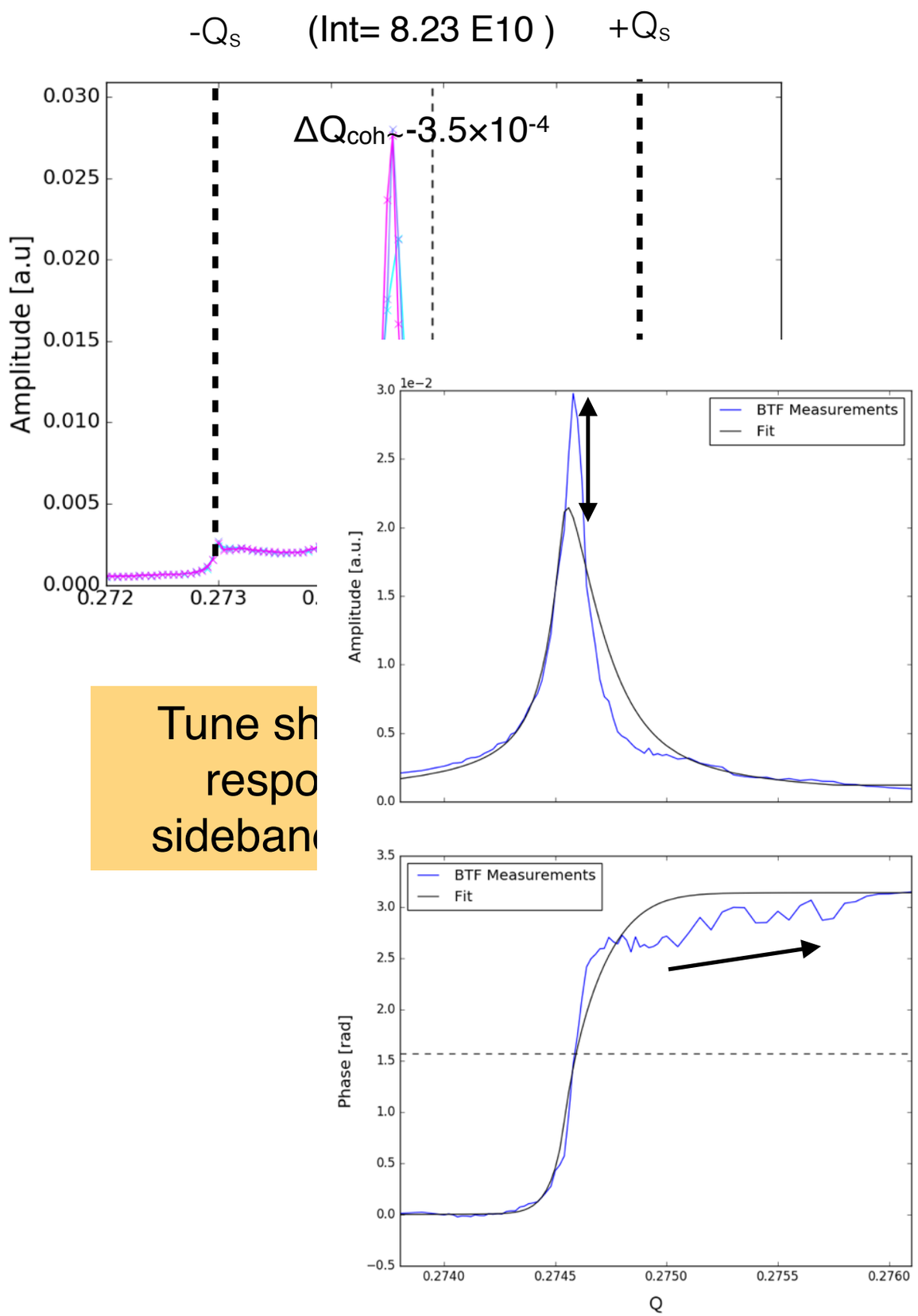
[15] B. Salvachua et *al*, TUPVA025, IP AC 2017

BTF measurements in presence of impedance



Tune shift observed in BTF response (asymmetric sidebands w.r.t. tune peak)

BTF measurements in presence of impedance



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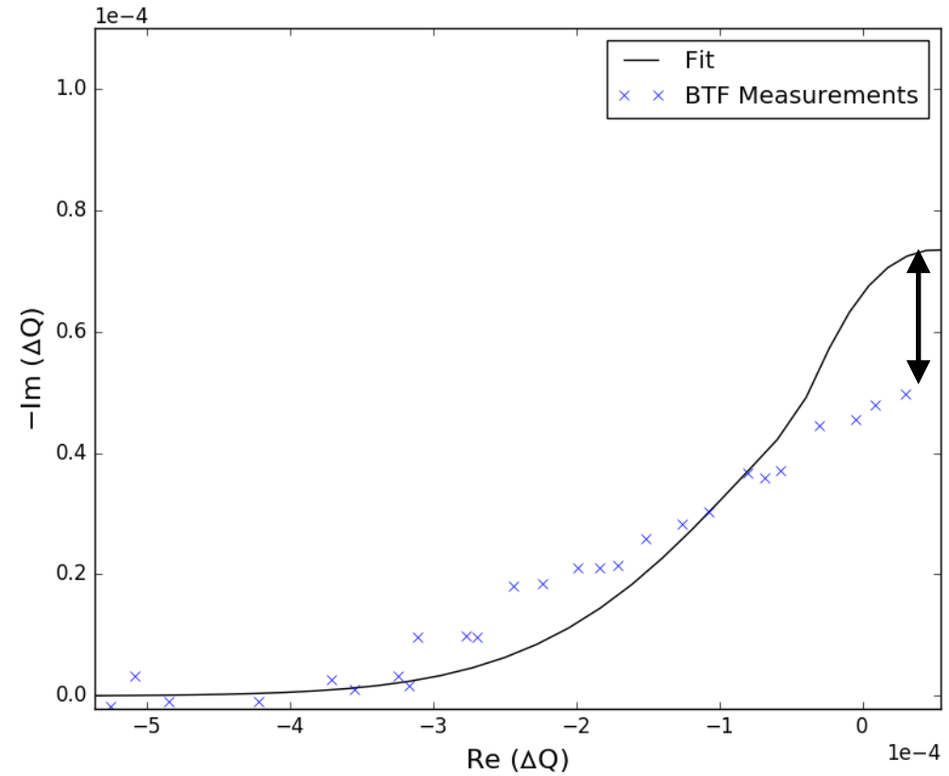
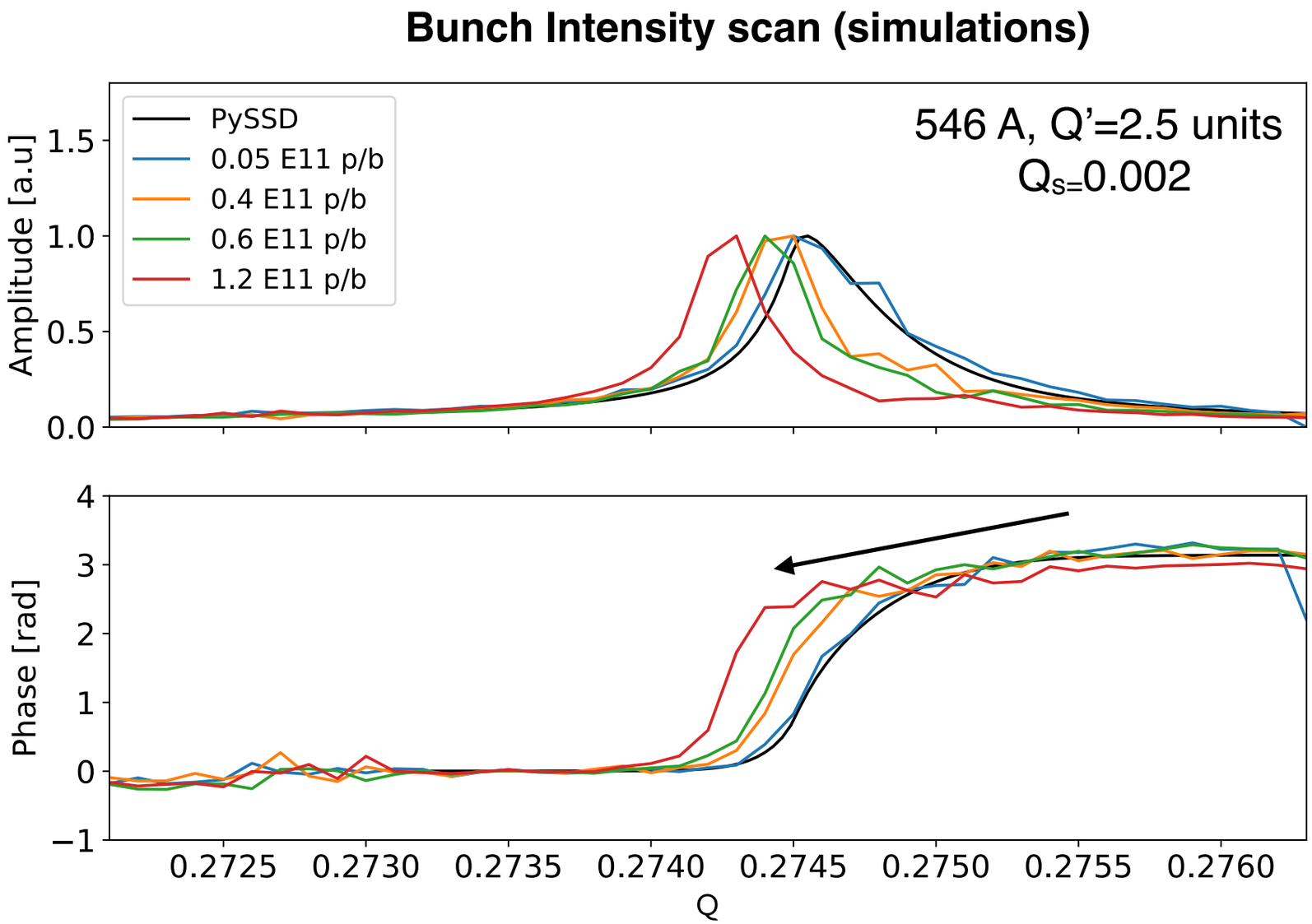
Fitting function is not giving satisfactory results:
the BTF shape is not equal to the analytical one (octupoles)
→ **IMPEDANCE contribution is not negligible!**



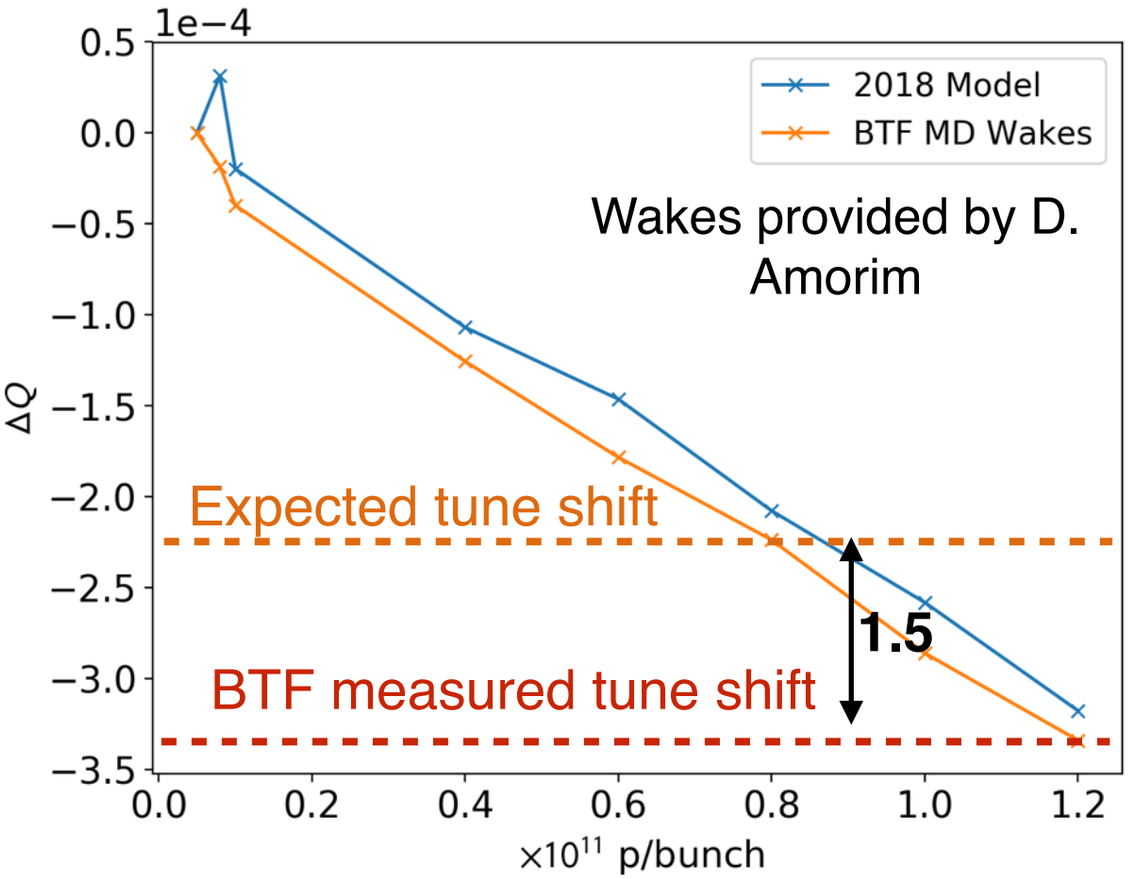
Impedance contribution in the BTF response



Wakefields included

- The coherent tune shift increases with the bunch intensity
- BTF response is distorted with increasing beam intensity (impedance)

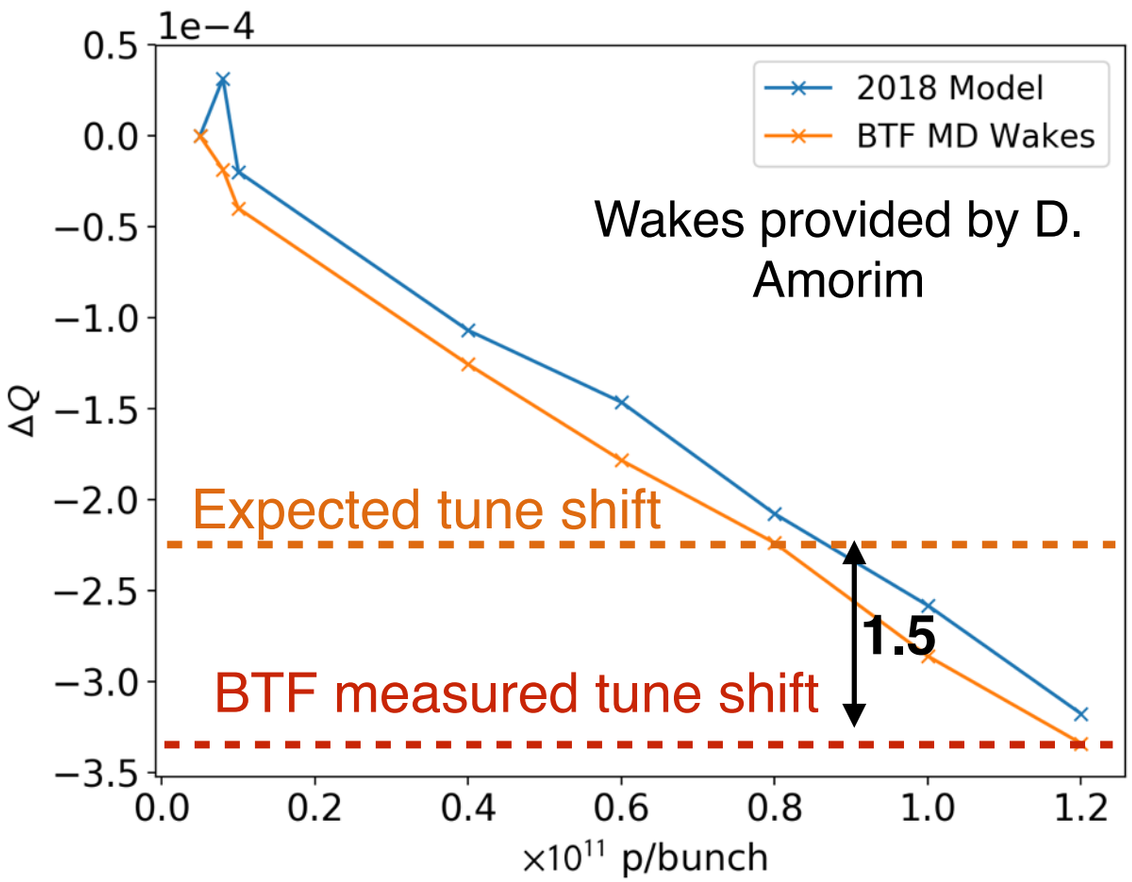
Tune shifts measurements due to impedance



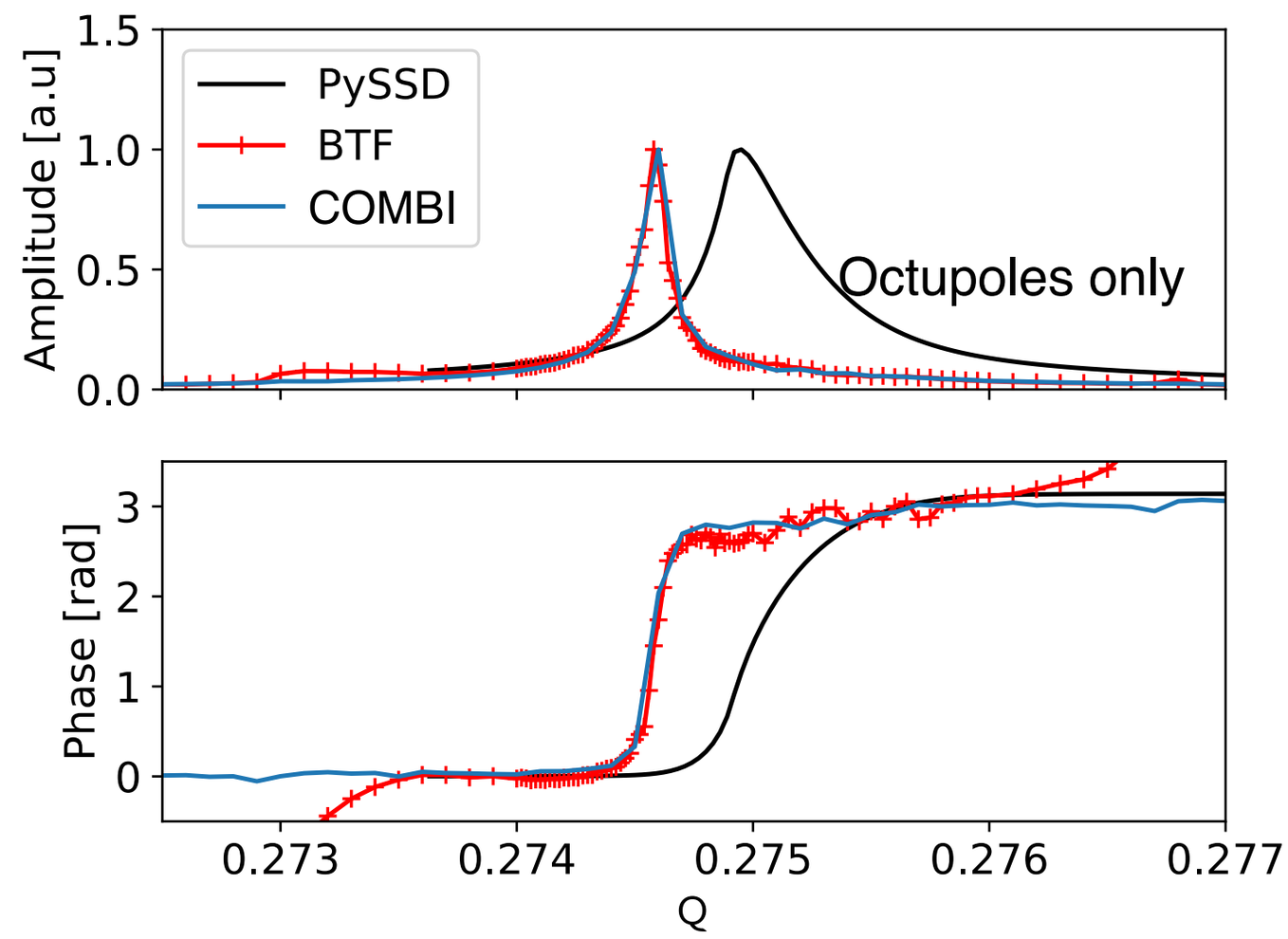
In order to reproduce the observed tune shift N_{bunch}~1.2 x 10^{11} **factor 1.5 more impedance needed** consistent with other independent measurements [16]

[16] D. Amorim *et al*. https://indico.cern.ch/event/743627/

Tune shifts measurements due to impedance



Simulations include chromaticity and impedance model (N_b=1.2 x 10^{11})



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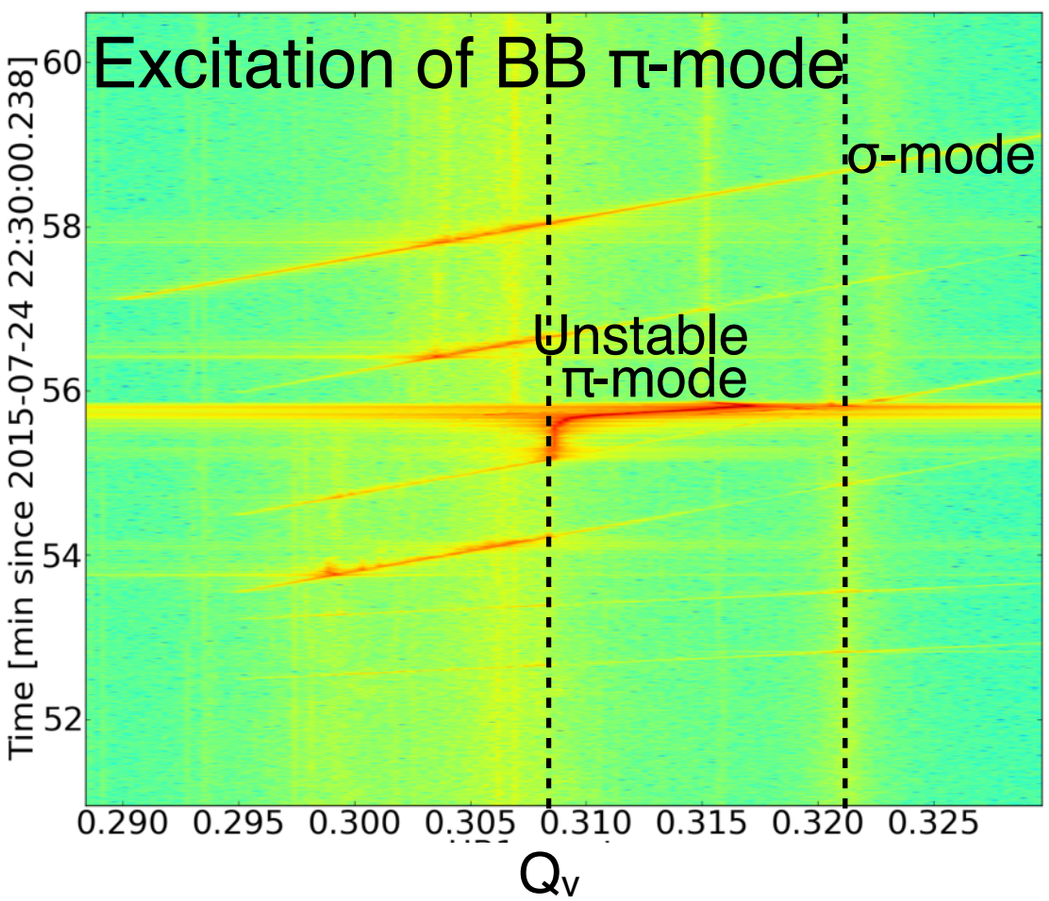
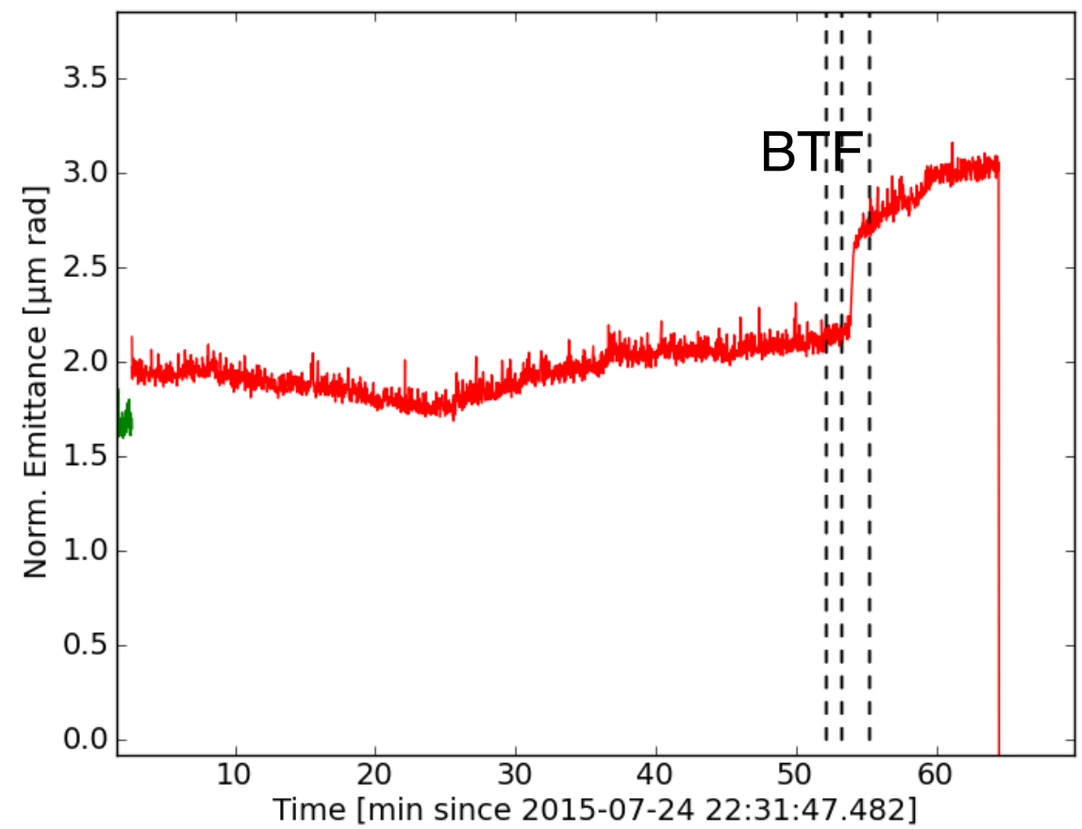
Good agreement with measurements

[16] D. Amorim *et al*. https://indico.cern.ch/event/743627/

Side effects of injecting ripples

- **Beam losses**
- **Emittance blow-up**
- **Coherent instabilities (ADT off)**





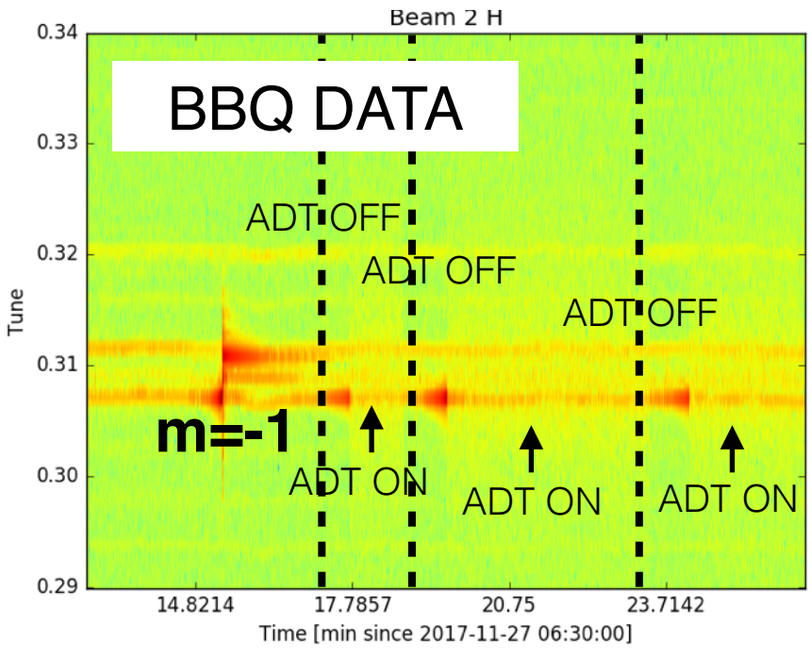
Trade off: signal to noise ratio vs losses and emittance blow-up → Limiting when high accuracy/ resolution required (SD measurements)

- **Varying excitation amplitude (smaller @ tune)**
- **Delay time between consecutive excitations**
- **Averaging of the signal of multiple measurements**
- **Gated BTF system, multi-bunch measurements**

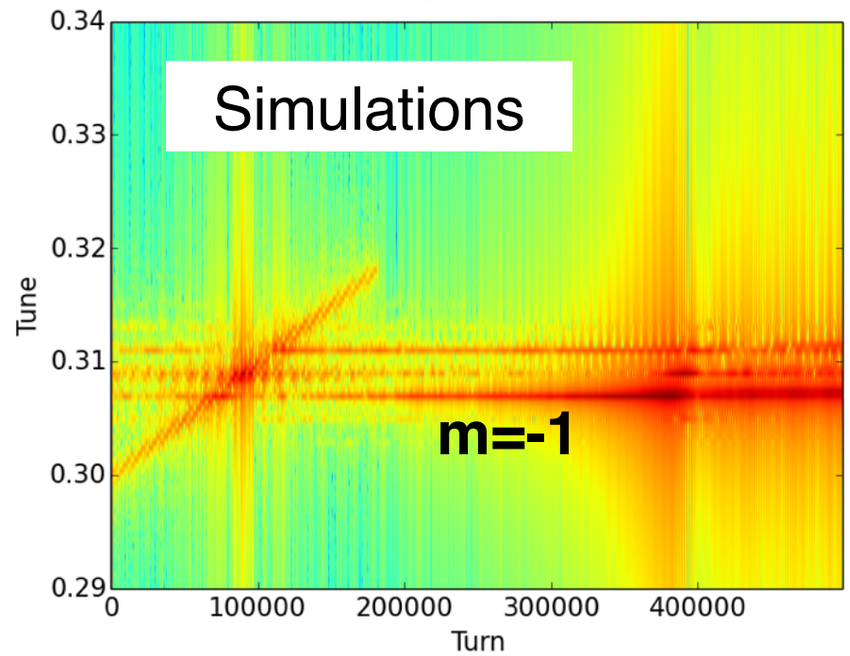
Triggering of instabilities with BTF

Single bunch (I~0.95 × 10^{11} p/bunch)

Q' ~ 10 units, Oct. current 510 A



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



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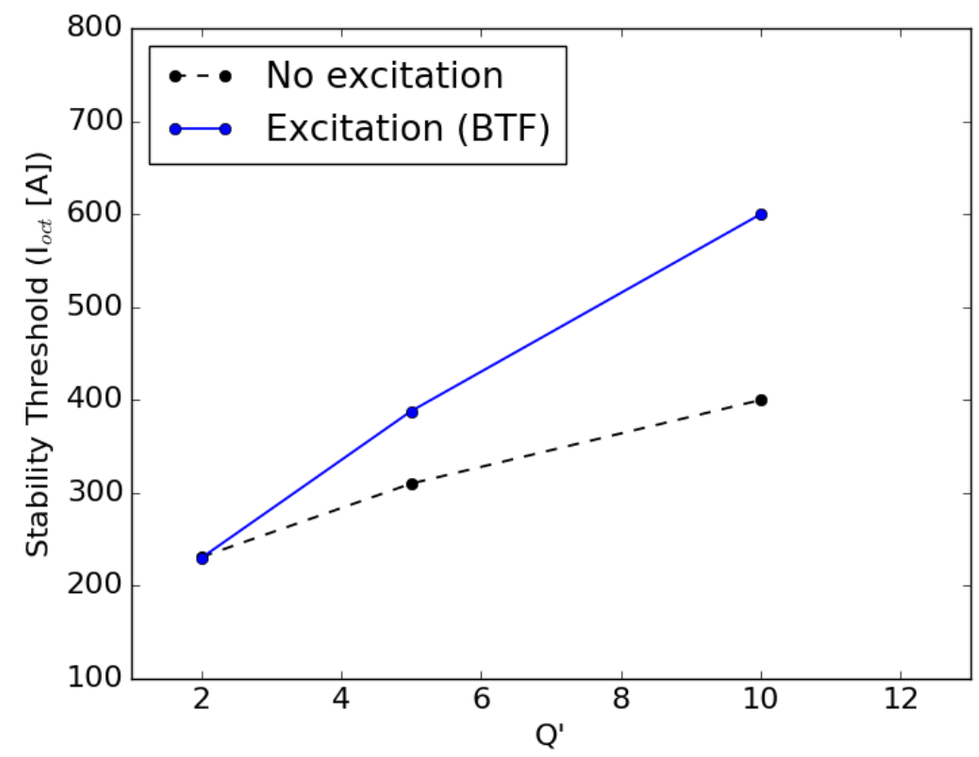


Measurements at top energy in 2017: Instability triggered by BTF due to the impedance increase in 2017

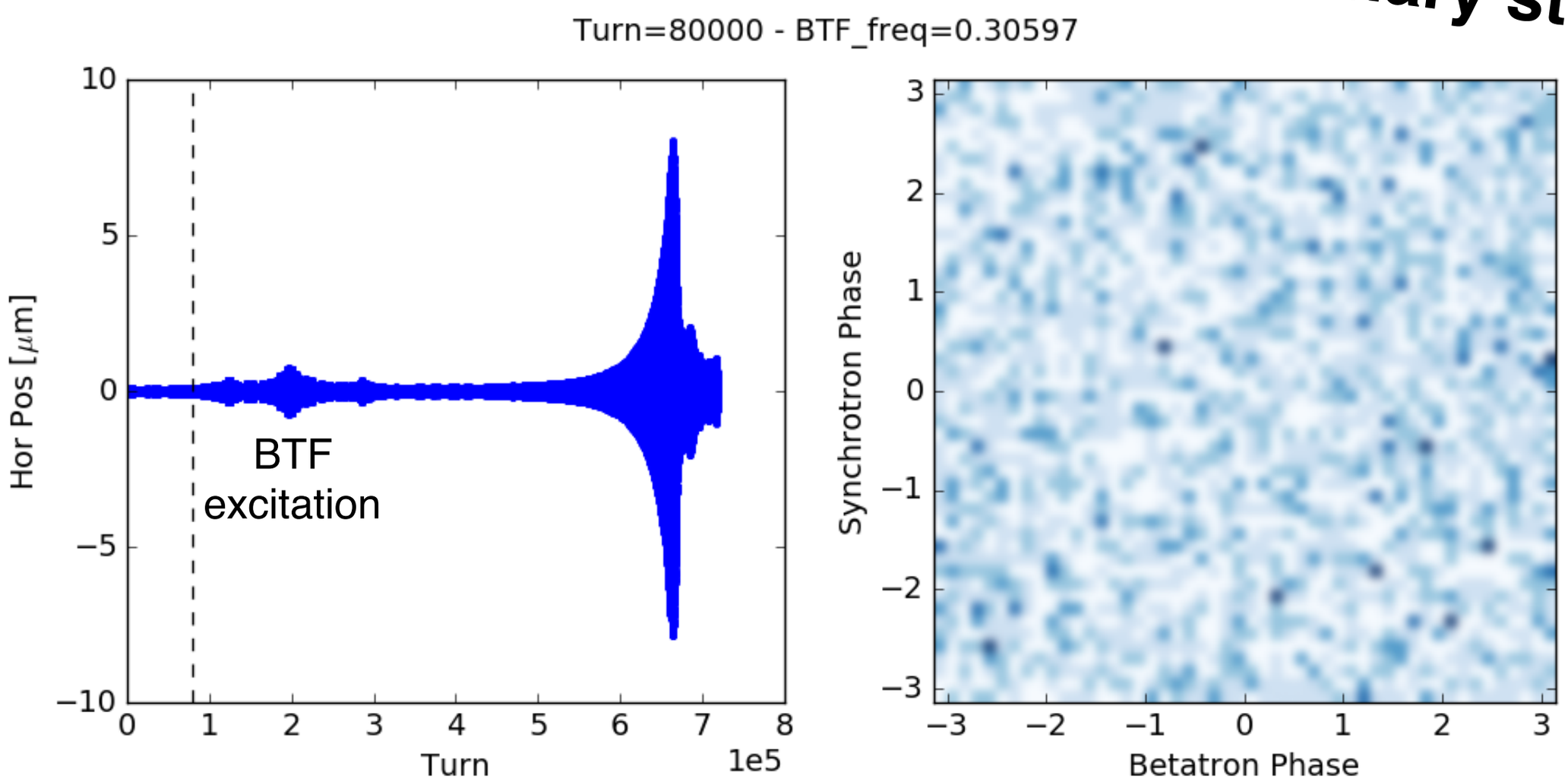
Higher stability thresholds (octupoles) are required in the presence of small external excitation ($2 \cdot 10^{-4}$ σ)

- A gated system has been installed to measure multiple bunches
- **Setup of the BTF excitation amplitude needed according to machine conditions**

Synchro-betatron motion coupled by BTF excitation

Unstable case!

Preliminary studies

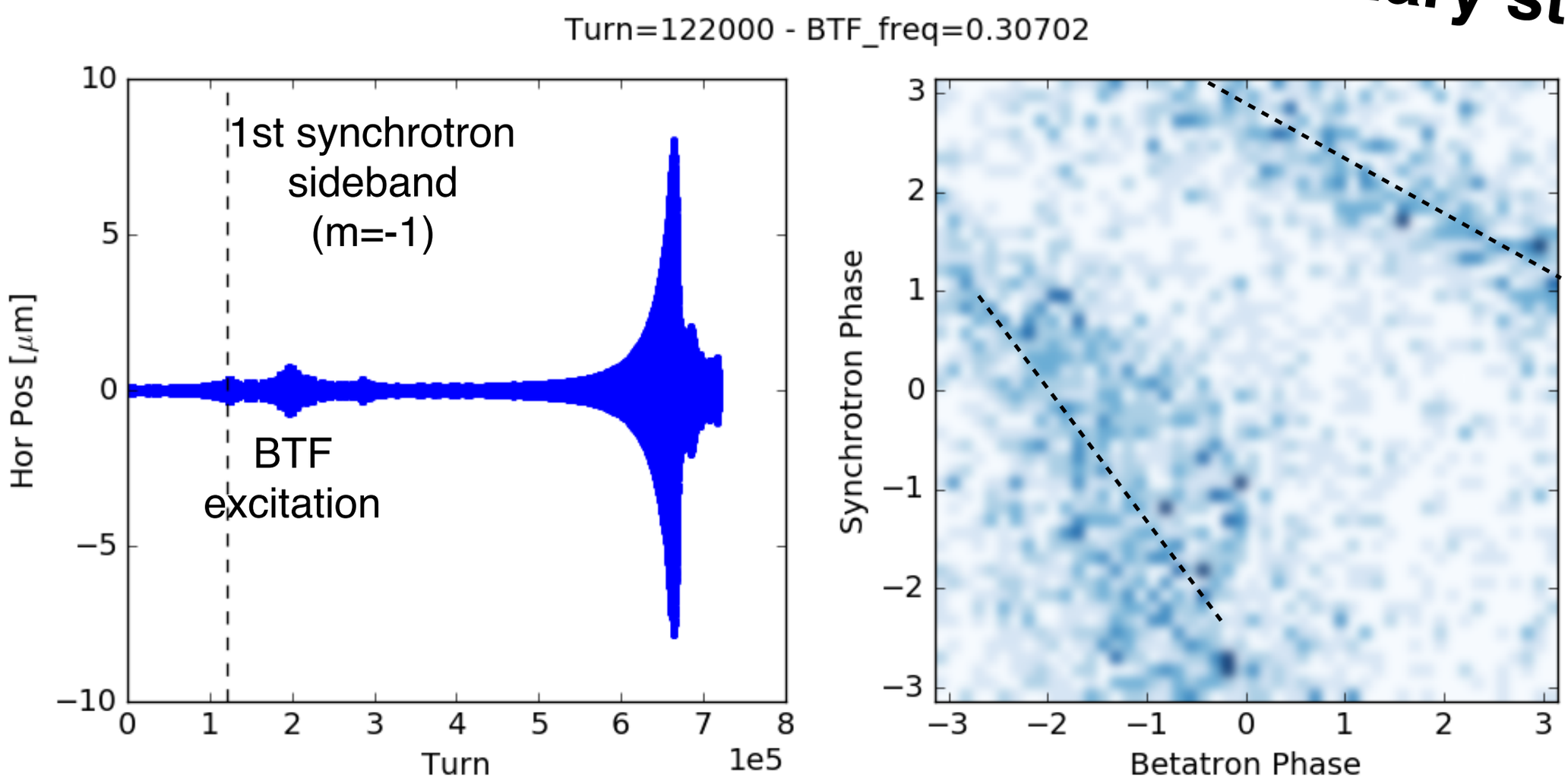


Far away from the synchrotron sidebands there is no visible correlation in the synchro-betatron phase

Synchro-betatron motion coupled by BTF excitation

Unstable case!

Preliminary studies

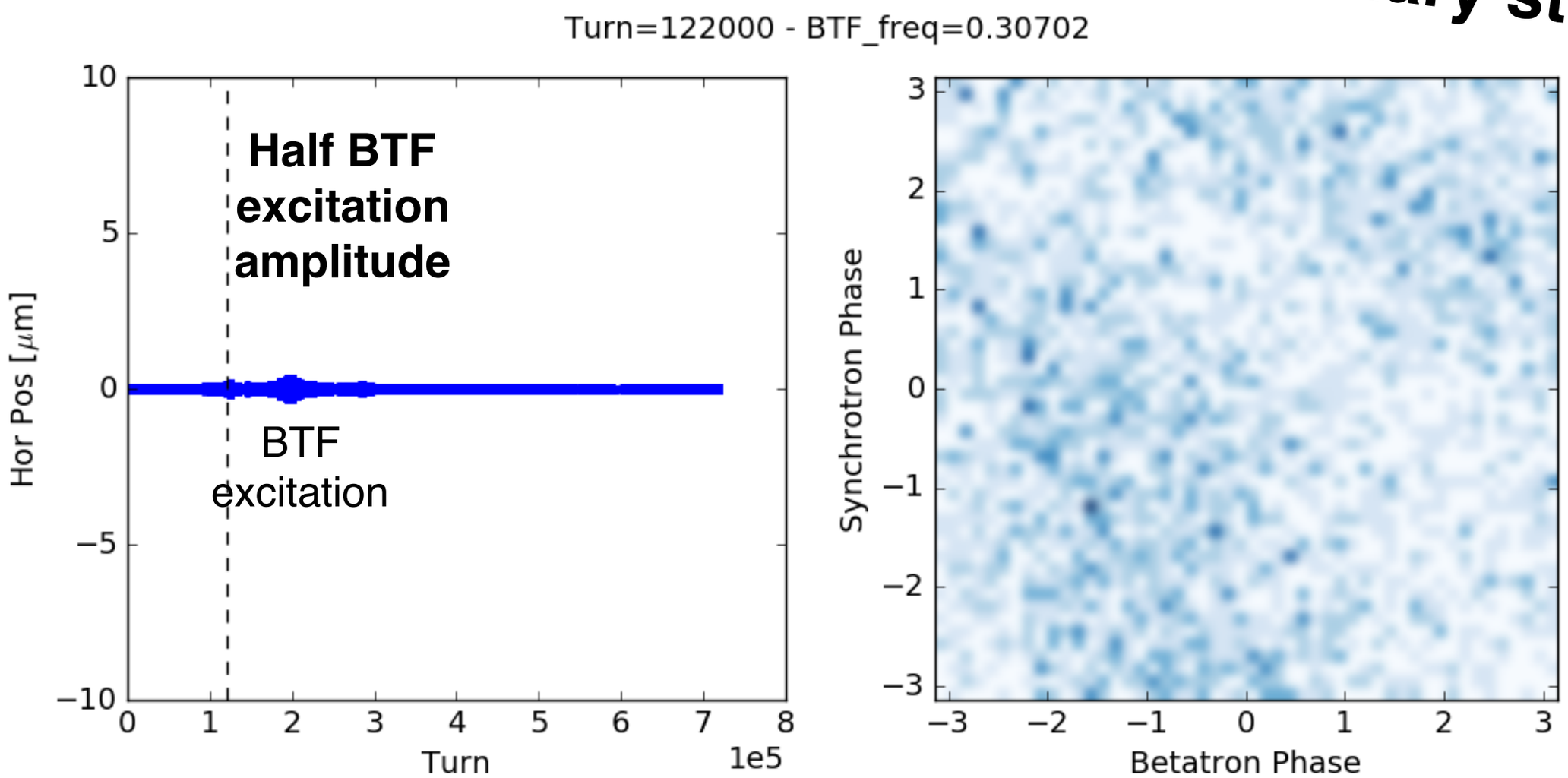


Visible correlation in the synchro-betatron phase space: **higher octupole current required** to stabilize the beams (~2 times higher)

Synchro-betatron motion coupled by BTF excitation

Stable case!

Preliminary studies



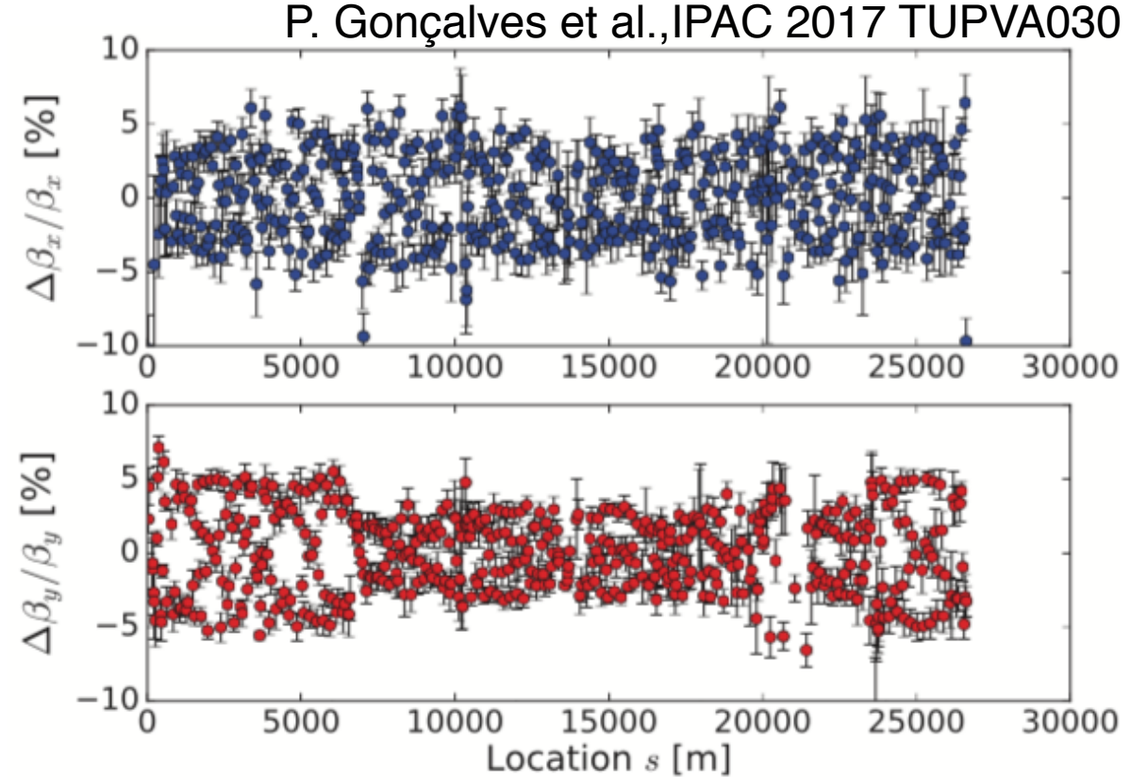
In the presence of external excitation (BTF) higher octupole might be needed if the excitation is sufficiently strong to correlate synchro-betatron motion (phase)

AC dipole excitations

AC dipoles forced oscillations: safe coherent transverse beam oscillations [17, 18]

- Measurements of optics functions (β-beating from BB)
- Linear and nonlinear optics corrections
- Physical aperture measurements and collimator alignment
- Amplitude detuning from HO beam-beam
- Measurements of machine impedance
- Recent measurements of dynamic aperture [F.S. Carlier *et al.*, Phys.Rev.Accel.Beams 22 (2019) 3, 031002]

P. Gonçalves et al.,IPAC 2017 TUPVA030



The slow adiabatic ramp up and down allows to keep losses under control and recover the initial beam emittance

[17] R. Minamoto et al., "***Signal quality of the LHC AC Dipoles and its impact on beam dynamics***", CERN Technical Report No. CERN-ATS-2010-063, 2010.

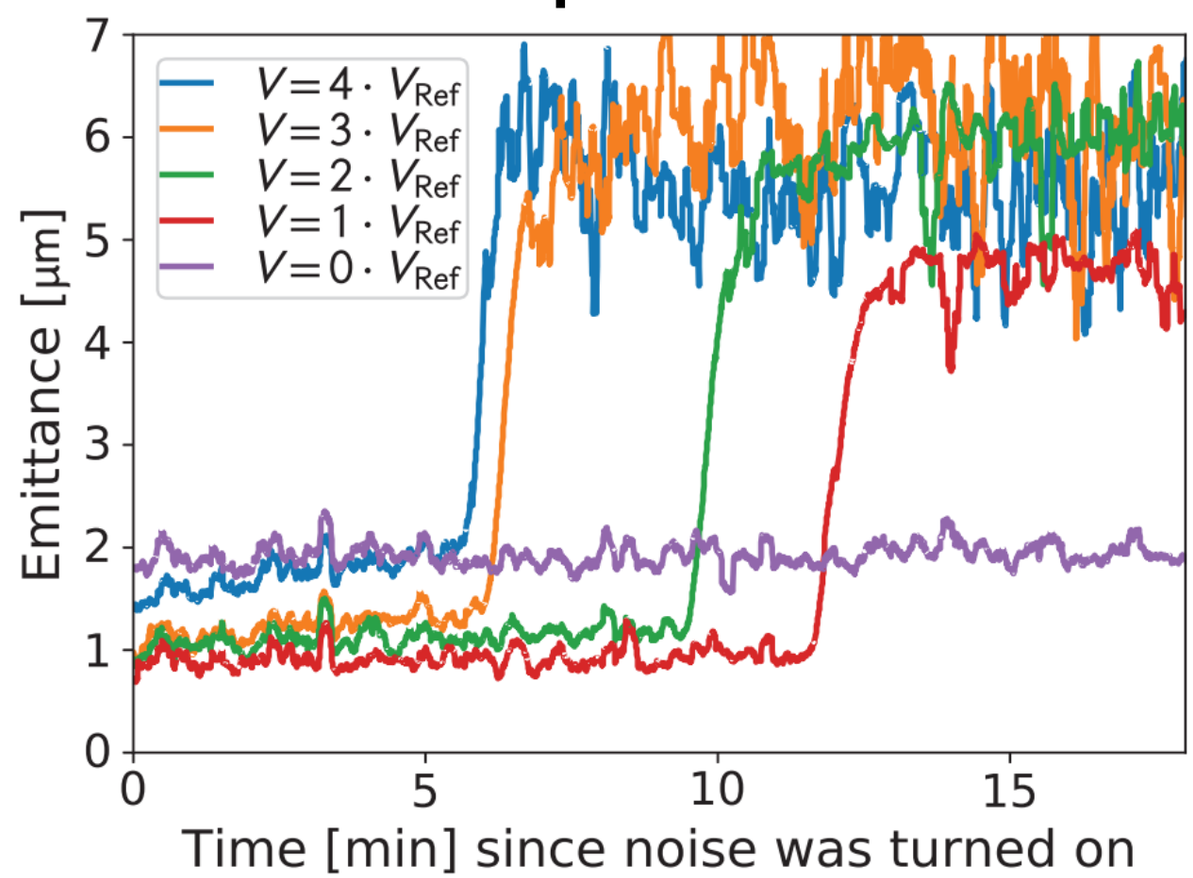
[18] T. Persson, "***LHC optics commissioning: A journey towards 1% optics control***", Phys. Rev.Accel. Beams 20, 061002 (2017)

Impact of noise on beam stability

Unlike ripples, the noise is not intentional

- Diffusion caused by noise modifies beam stability (initially proposed by X. Buffat [19, 20])
- High latency instabilities observed in the LHC linked to the noise level [21]
- Noise excites wakefield causing diffusion → **beam instability** (if close to the instability threshold)

Dedicated experiment in the LHC



[19] X. Buffat, "***Transverse beams stability studies at the Large Hadron Collider***", EPFL THESIS 6321, 2015
[20] V. A. Lebedev, "***Transverse dampers with ultimate gain for suppression of instabilities in large hadron colliders", ICFA Mini-workshop in Mitigation Collective Beam Instabilities***", 2019 Zermatt
[21] S. V. Furuseth et al., "***Instability latency in the LHC***", WEPTS044, IPAC (2019)

Summary

- Injecting ripples → useful method for beam diagnostic
- **CHIRP , BTFs, AC dipoles have several applications** (tune/chromaticity measurements, detection of beam-beam coherent modes and collision optimization, measure BB tune spread compensation with e-lens etc…)
- **Transverse BTF measurements have been performed in the LHC to probe Landau damping** in various configurations:
    - Measured effect of beam losses on Landau damping
    - Experimental proof of reduction of Landau damping due to linear coupling
    - Measurements in the presence of BB interactions
    - Impedance information
- However, **ripples can induce beam losses and emittance blow-up** → **trade off between signal to noise ratio and beam losses needed**
- **High precision measurements require precautions**: varying excitation amplitude, delay time between consecutive excitations might help
- **Ripples can cause coherent instabilities:** excitation of coherent modes and reduction of stability thresholds (synchro-betatron coupling, particle diffusion)

Injecting ripples on beam: shall we?

Intentional ripples (BTFs, CHIRP, AC dipoles)	**Pros**	Tune / chromaticity measurements	Coherent mode detection	Landau damping insights	Impedance information	😀 **Useful for understanding**
	Cons	Beam losses	Emittance blow-up	Coherent instabilities	😕 **Not good but you can control these**
Natural ripples (Noise)	**Pros**	🤔 ?			
	Cons	Emittance blow-up	Beam losses	Latency instabilities	Resonance excitation	😡 **Difficult to control**

Injecting ripples on beam: shall we?

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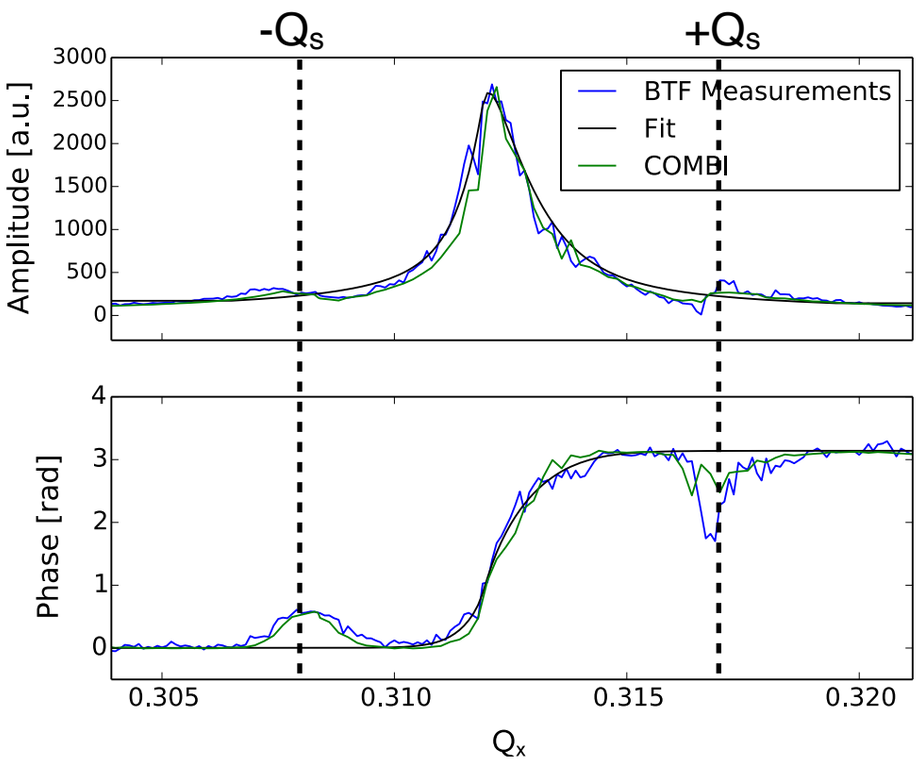
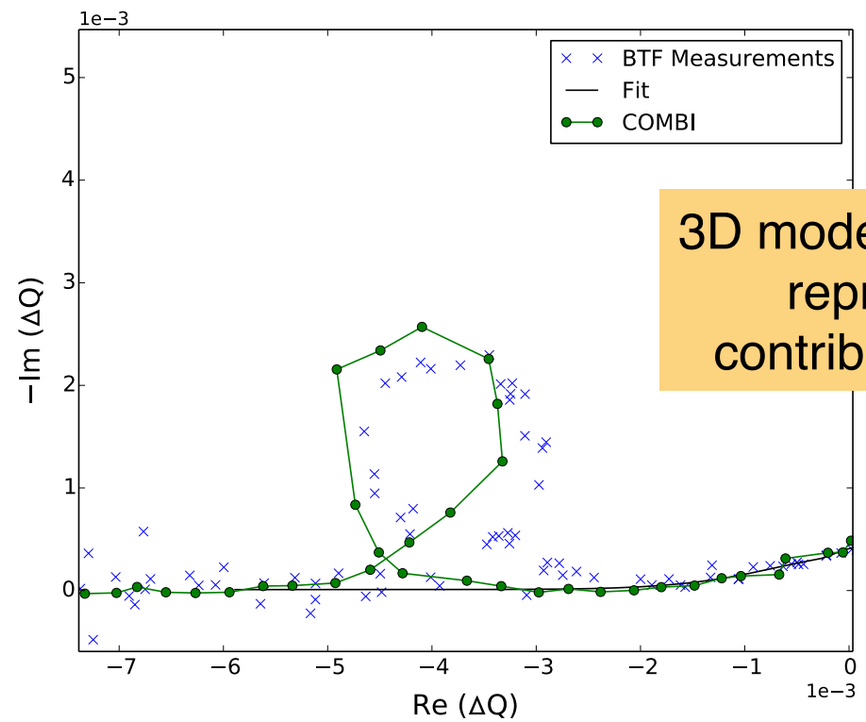
Thanks for your attention!

Back-up slides

Chromaticity impact on BTF and SD

In the presence of chromaticity synchrotron sidebands appear in the BTF amplitude and phase jumps (at ±n · Qs from tune)



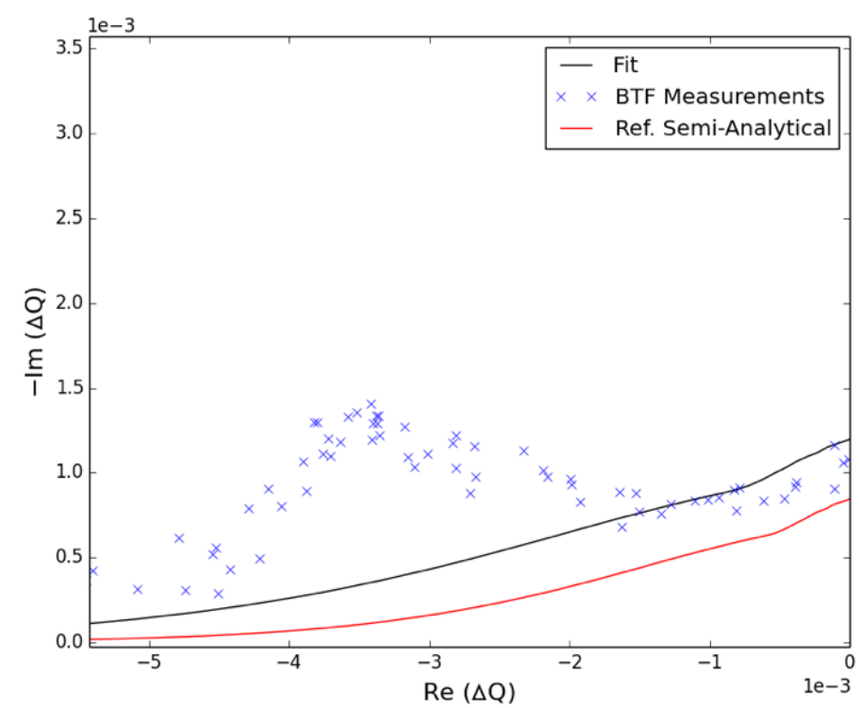


3D model simulations (**COMBI**) well reproduce the longitudinal contribution in the BTF response

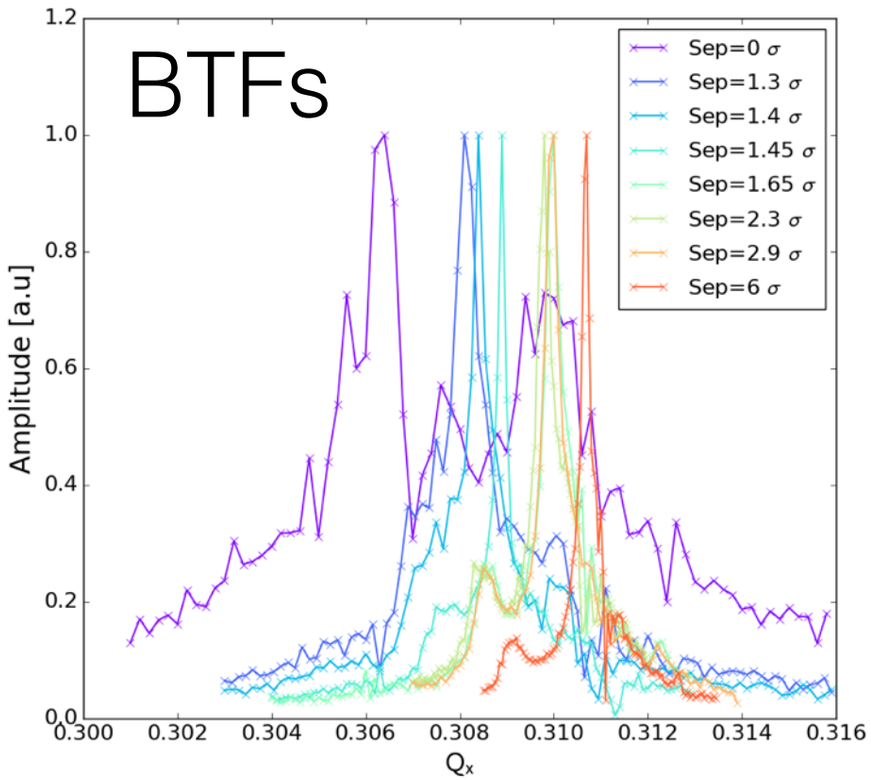
When synchrotron sidebands are close enough to coherent beam response the stability diagram is deformed by the bumps produced by the chromaticity effect in the transverse plane

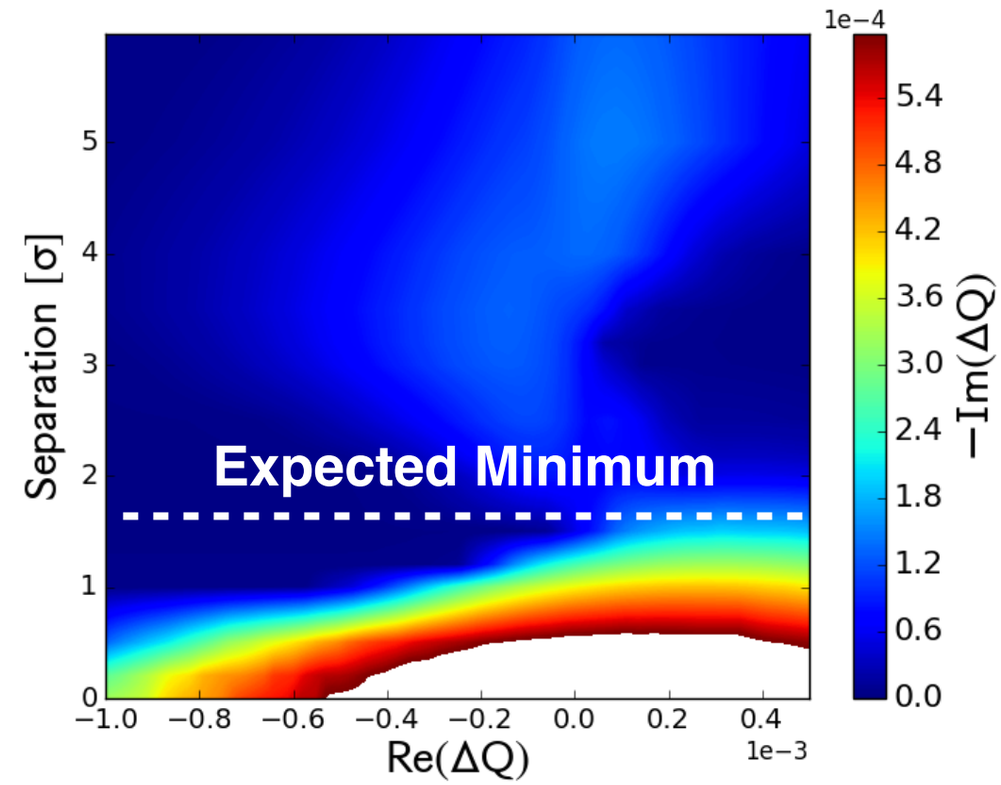
There is no analytical formula to characterize this effect

Does the new area contribute to stabilize the beam or is it just an artifact on BTF response?



Parallel separation scan (head-on interactions)





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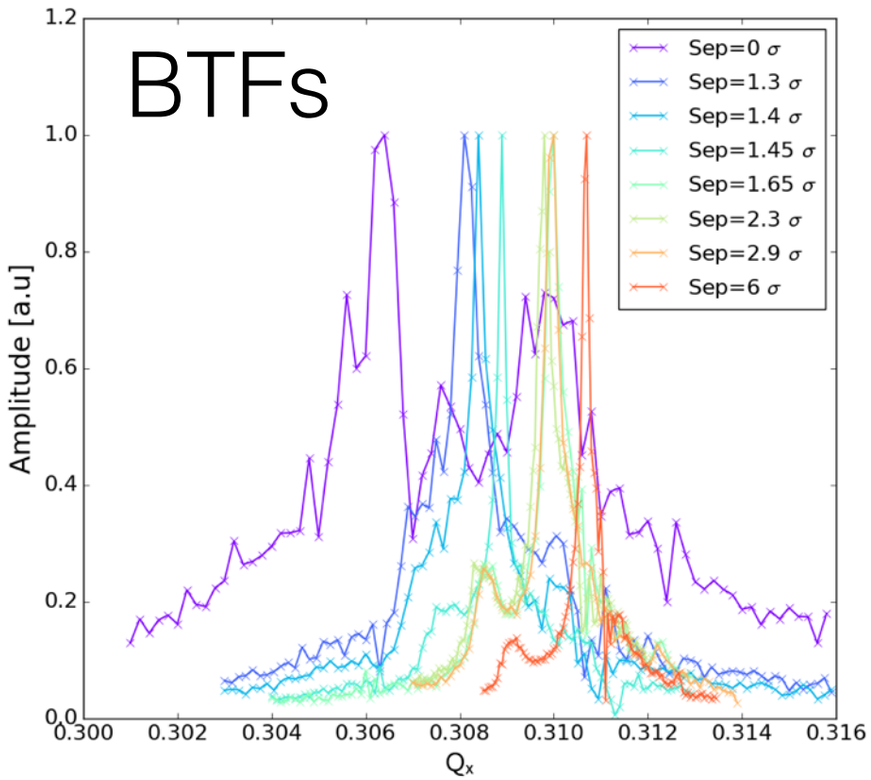
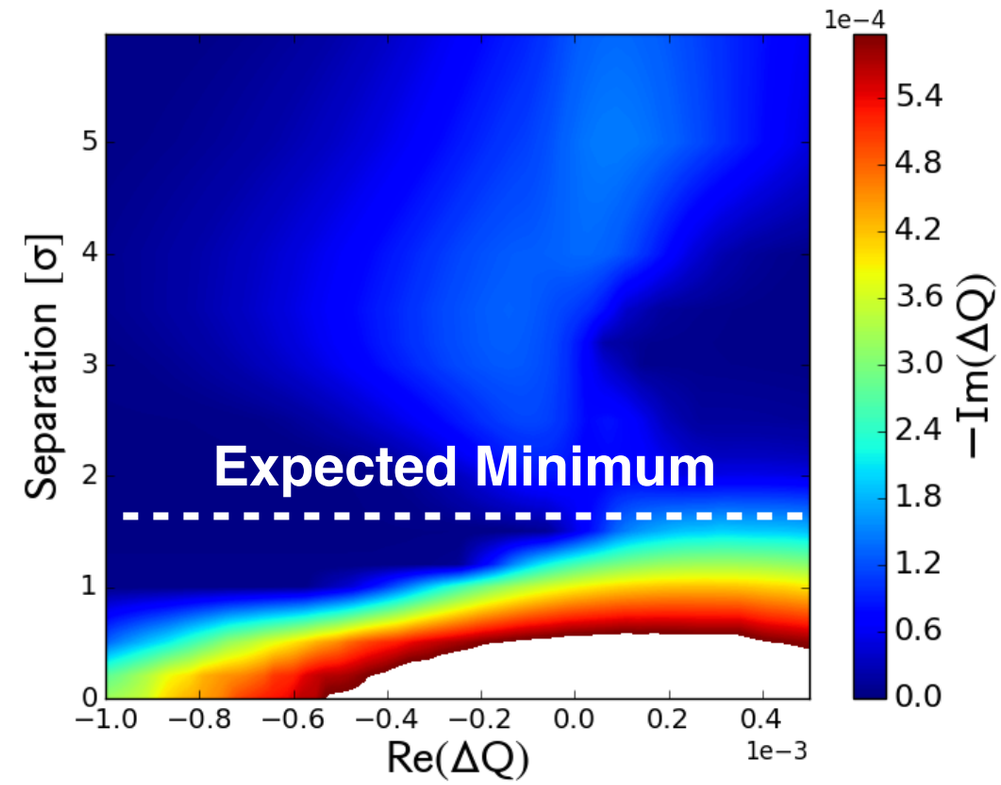
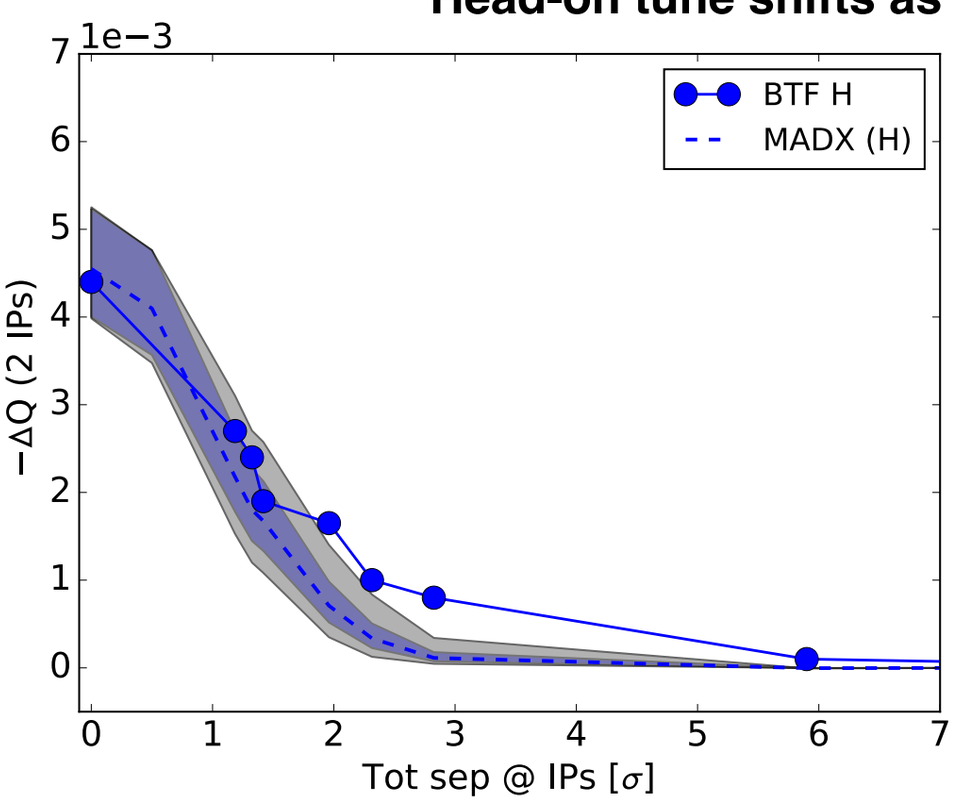
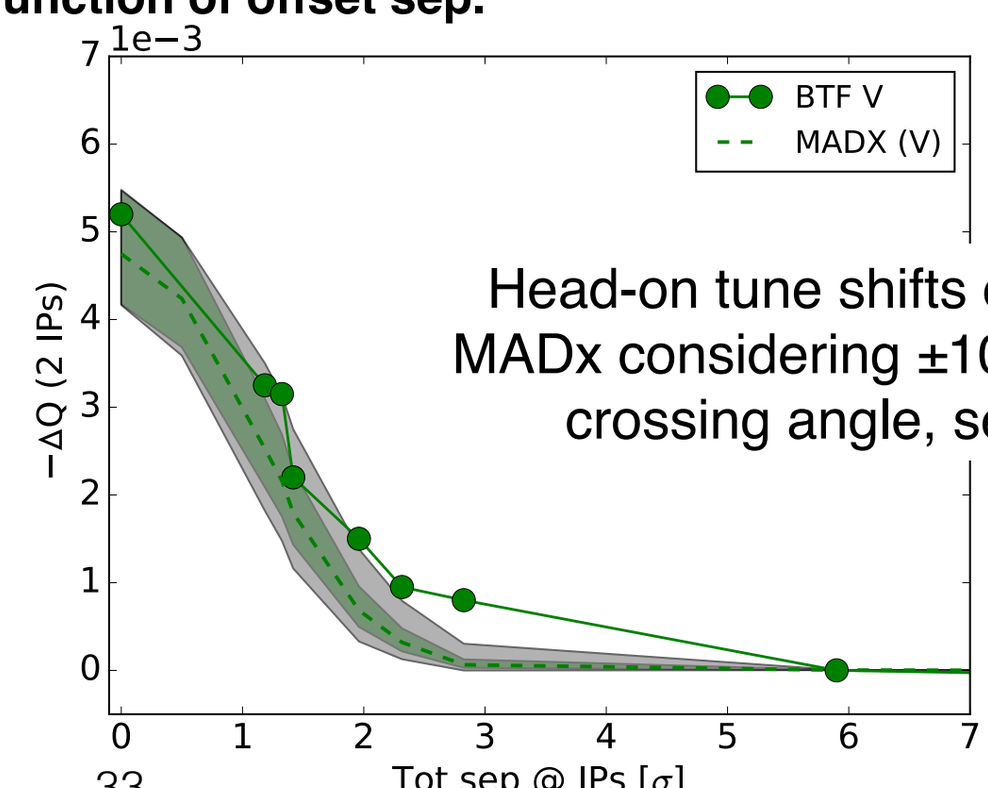




Head-on tune shifts as a function of offset sep.





Head-on tune shifts compared to MADx considering ±10% emittance, crossing angle, separation