What can we learn from BTF measurements for BBLRs?

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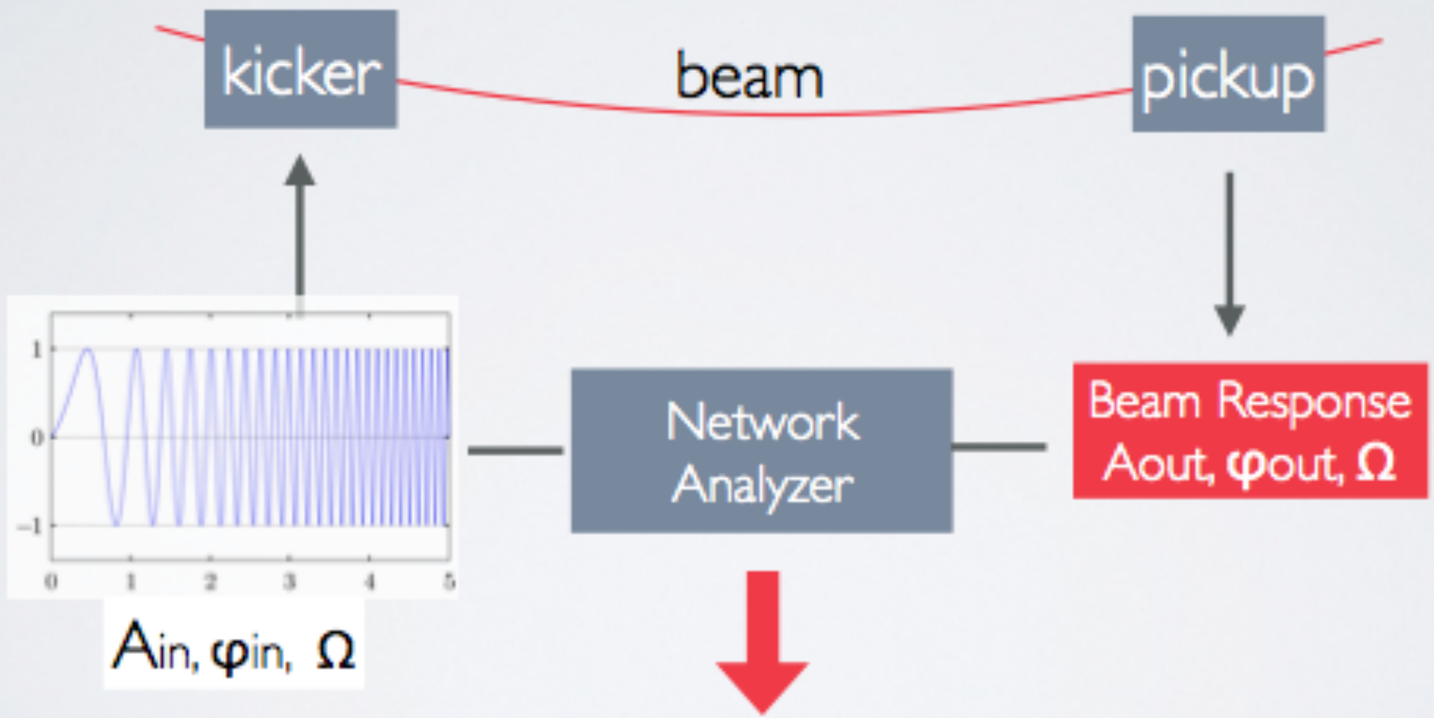
Outline

- What is a BTF measurement
- Motivations for a BTF measurement in the LHC
- Impact on beam parameters and operation
- Preliminary results
- Possible use for BBLR compensation tests

What are BTF measurements?

Beam Transfer Function:
beam amplitude response per driving excitation frequency



BTF: Amplitude (Ω), phase (Ω)

Beam Transverse Function Measurement

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

$$R(\Omega) = \frac{A(\Omega)}{D(\Omega)}$$

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

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

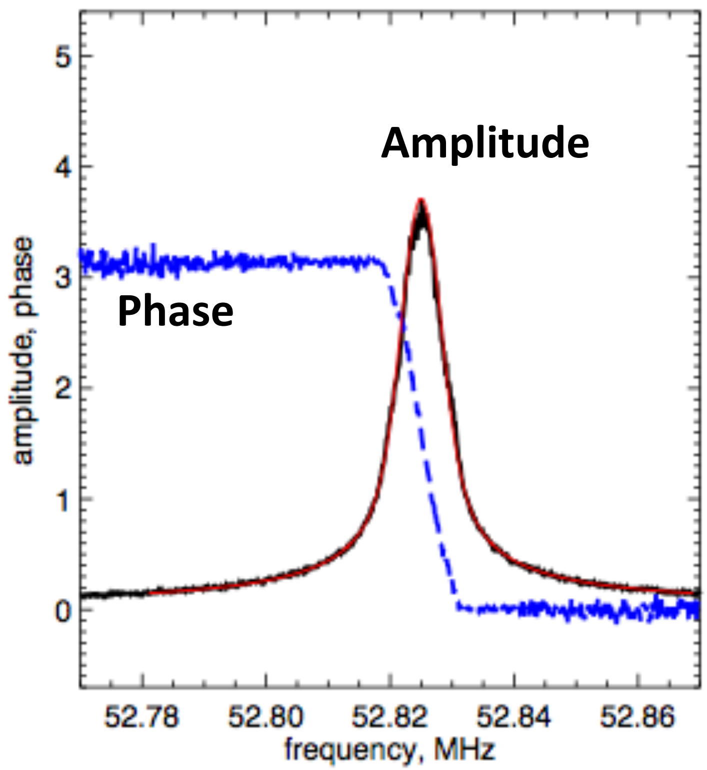
BTF powerful diagnostic tool
"Direct" measurement of Stability diagrams

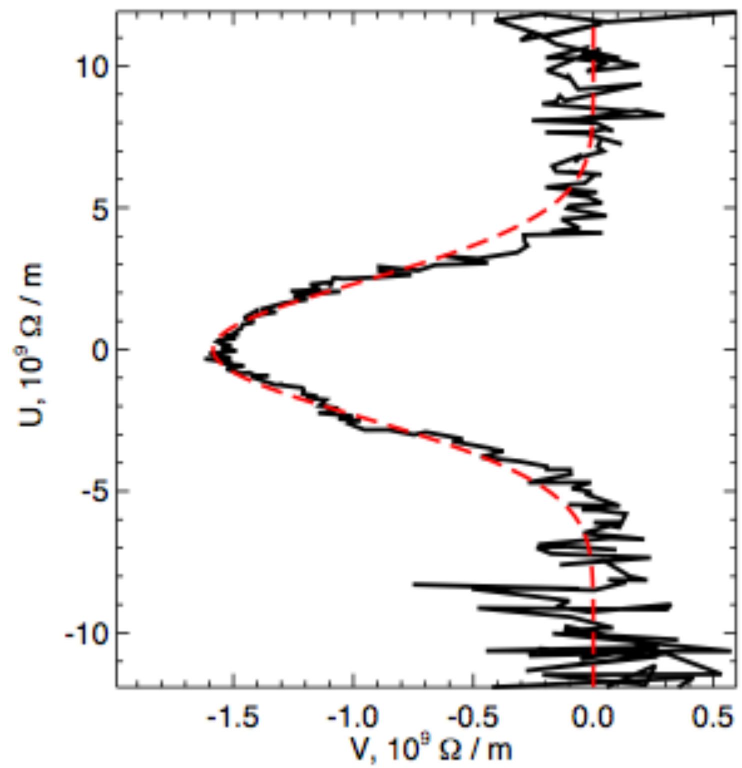
"The Use of RF-Knockout for Determination of the Characteristics of the Transverse Coherent Instability of an Intense Beam"
D. Mohl & A. M. Sessler

- Estimate distribution effect and spread (in relative)
- tune measurement, spread (RHIC) operationally used
- Coherent mode observation in Landau damping region
- Impedance 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

Stability Diagrams

The numerical computation of the stability diagrams can be set up for different machine configuration (MAD-X code)

Inverse of the **dispersion integral**

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

Frequency Distribution

Tracking MAD-X

Particle distribution

Integration Pyssd code

Stability Diagrams

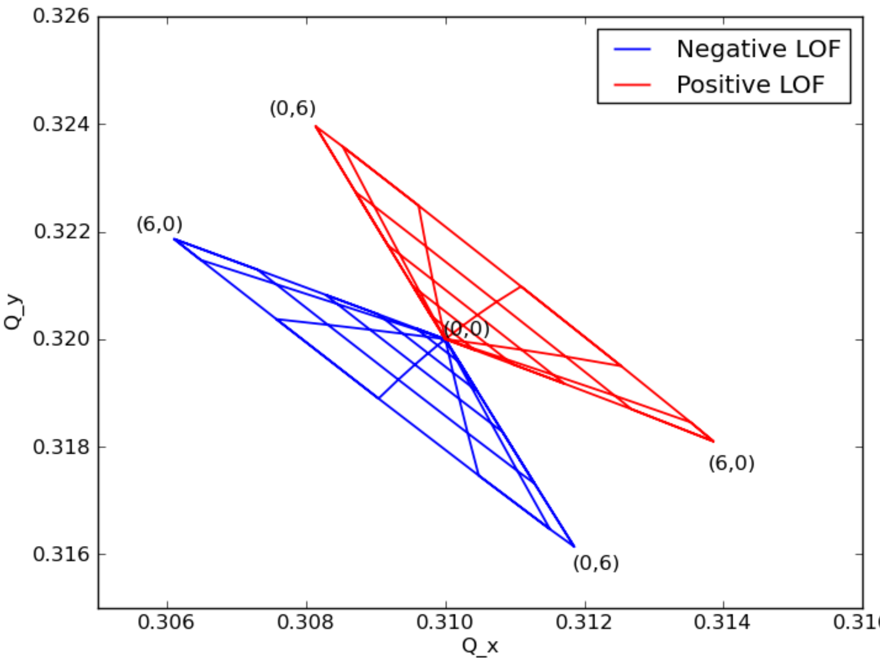
Footprint → Stability Diagram
Detuning with amplitude

Dispersion Integral:

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

from Tracking

- **"Landau Damping by Non-Linear Space-Charge Forces and Octupoles" D. Mohl & H. Schonauer**
- **J. Berg and F. Ruggiero, "Landau Damping with Two-dimensional Betatron Tune Spread," CERN SL-AP-96-71.**

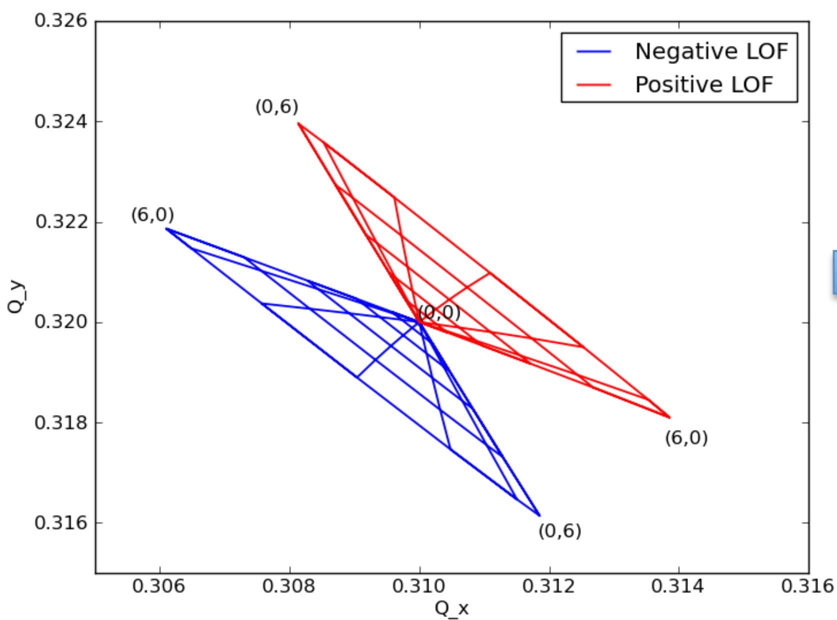


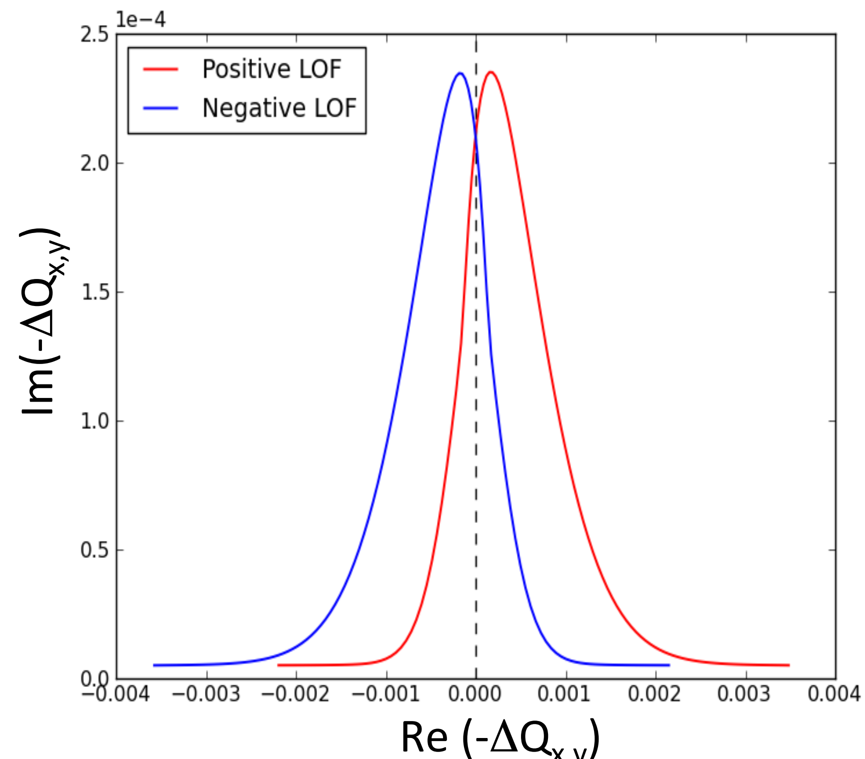
Landau Damping → Stability Diagram
Particle distrubutions

Dispersion Integral

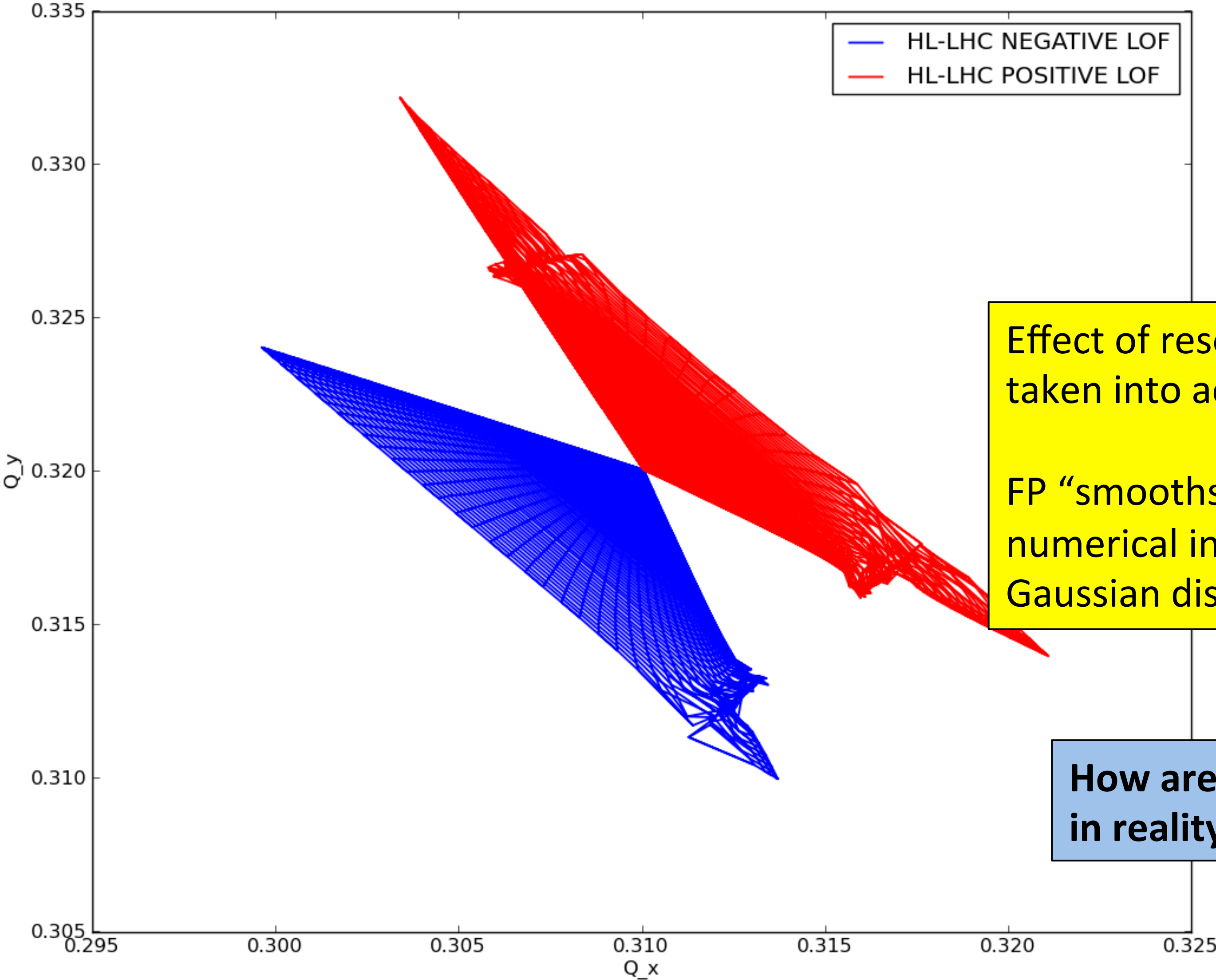
Gaussian Distribution

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





Modified distribution: Non-Linear Resonances



Effect of resonances are not fully taken into account

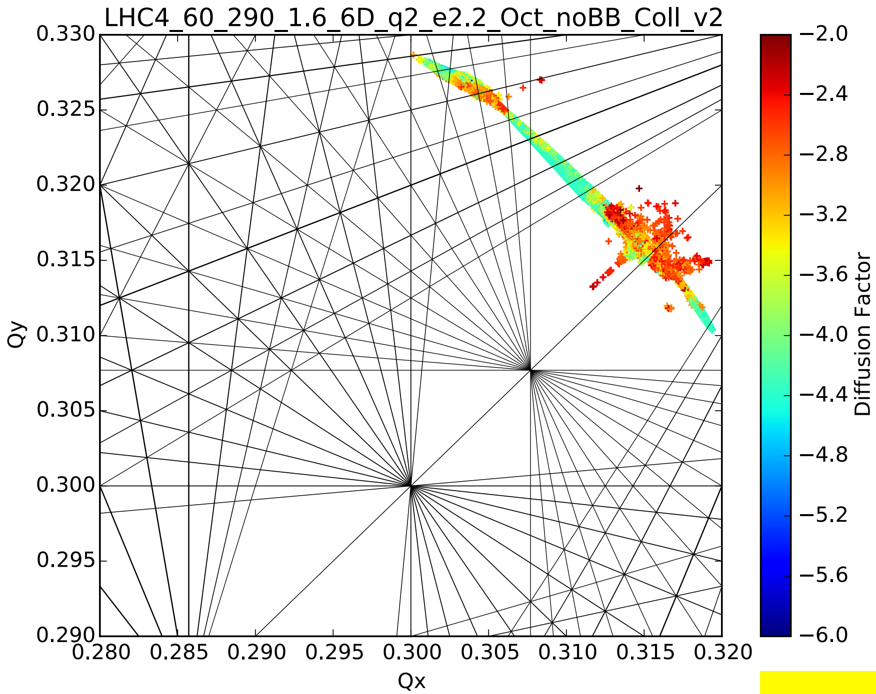
FP "smooths" the resonances and numerical integration assumes Gaussian distributions

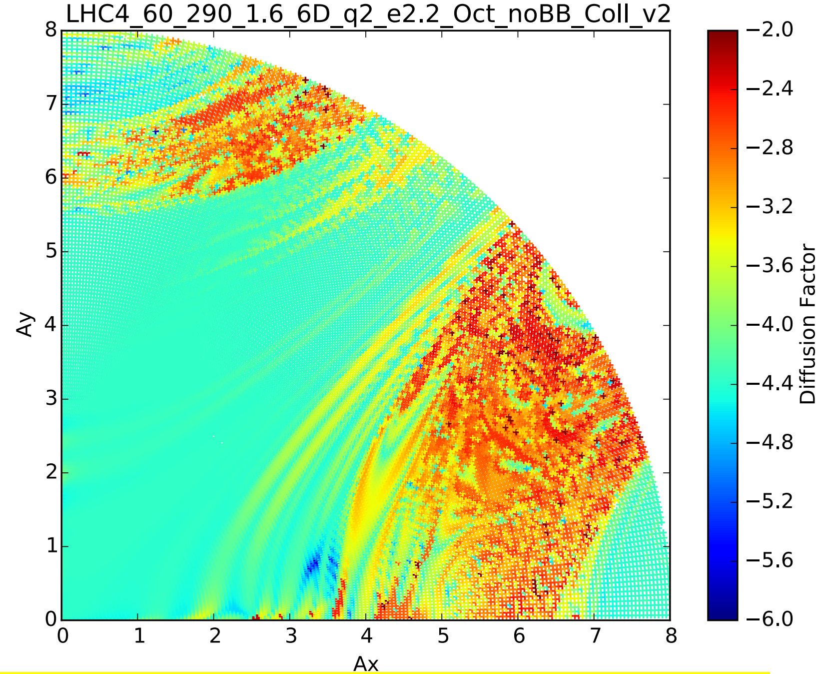
How are particles distributed in reality along resonances?

BBLR effects

Tune spread

- **Resonance excitation**
- **Particle distribution modification**





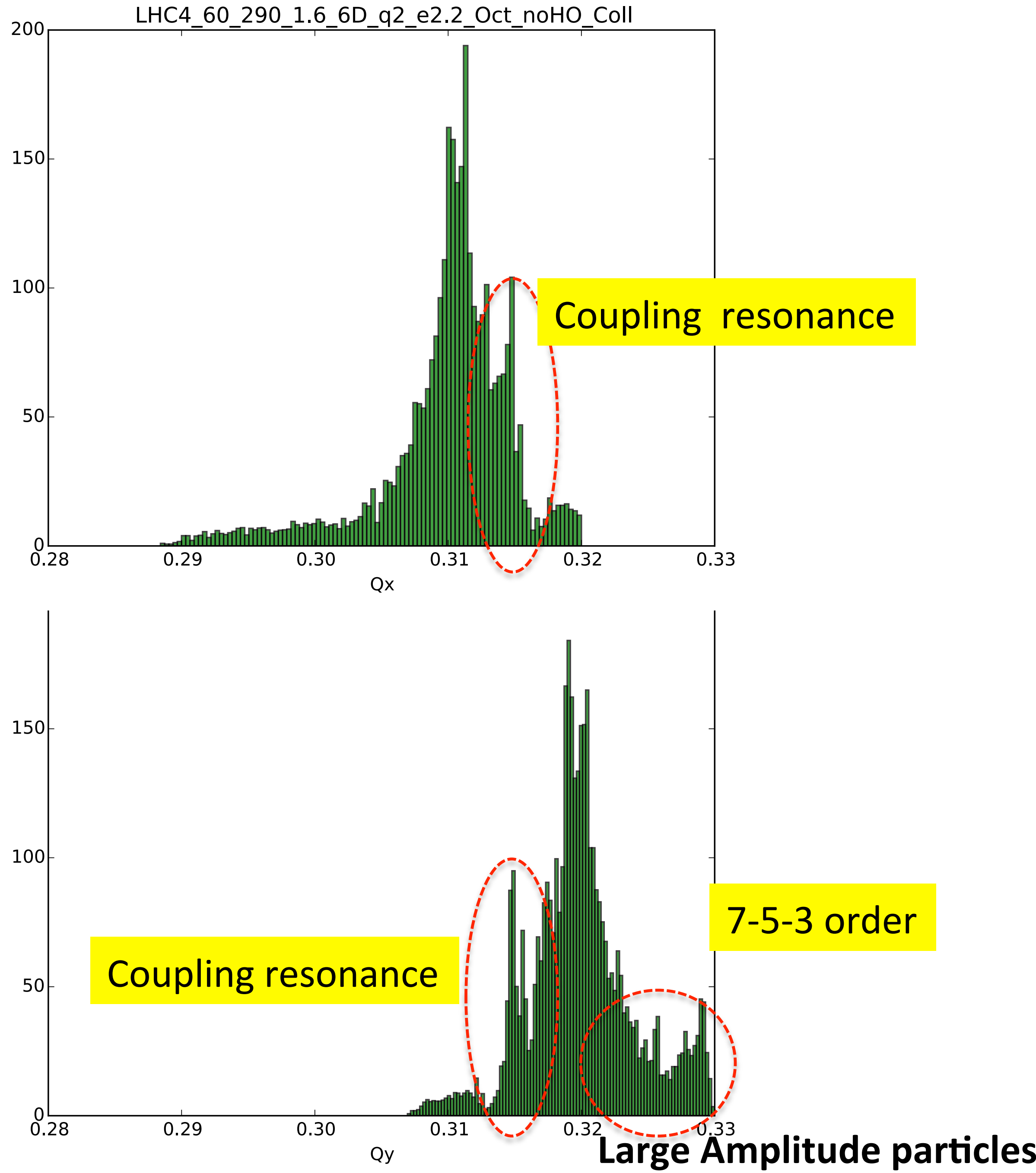
Clear modification of particle distribution on resonances Q' still low

H/V asymmetry

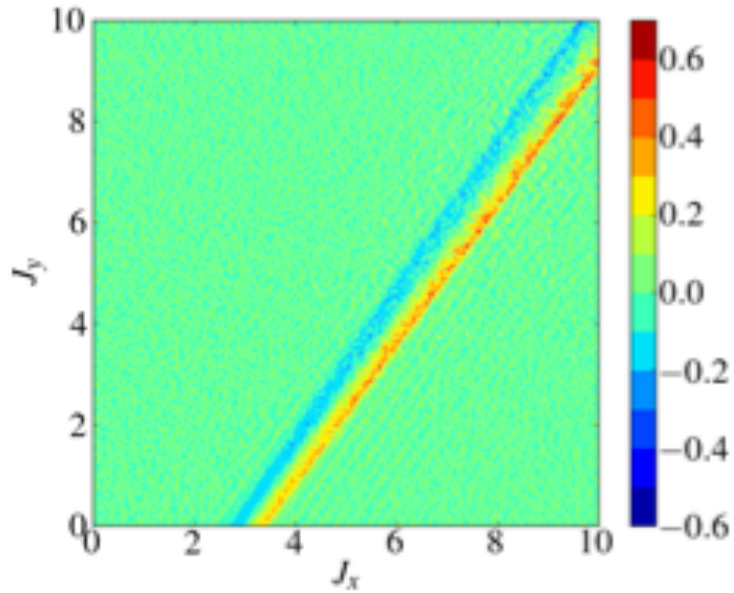
Clear modification of particle distribution on resonances from distribution tracking

We want to see how and if BTF can measure the strong effect of LR BB interaction when LR BB are not only a perturbation!

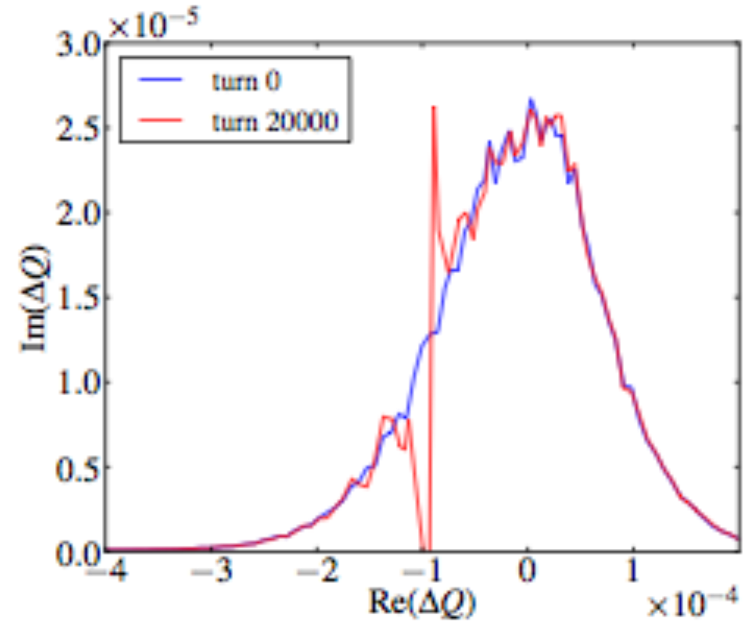
Can this be measured in a BTF?



What happens to SD (BTF) if particle distribution modified?



(a) Relative deviation from the initial distribution in action space

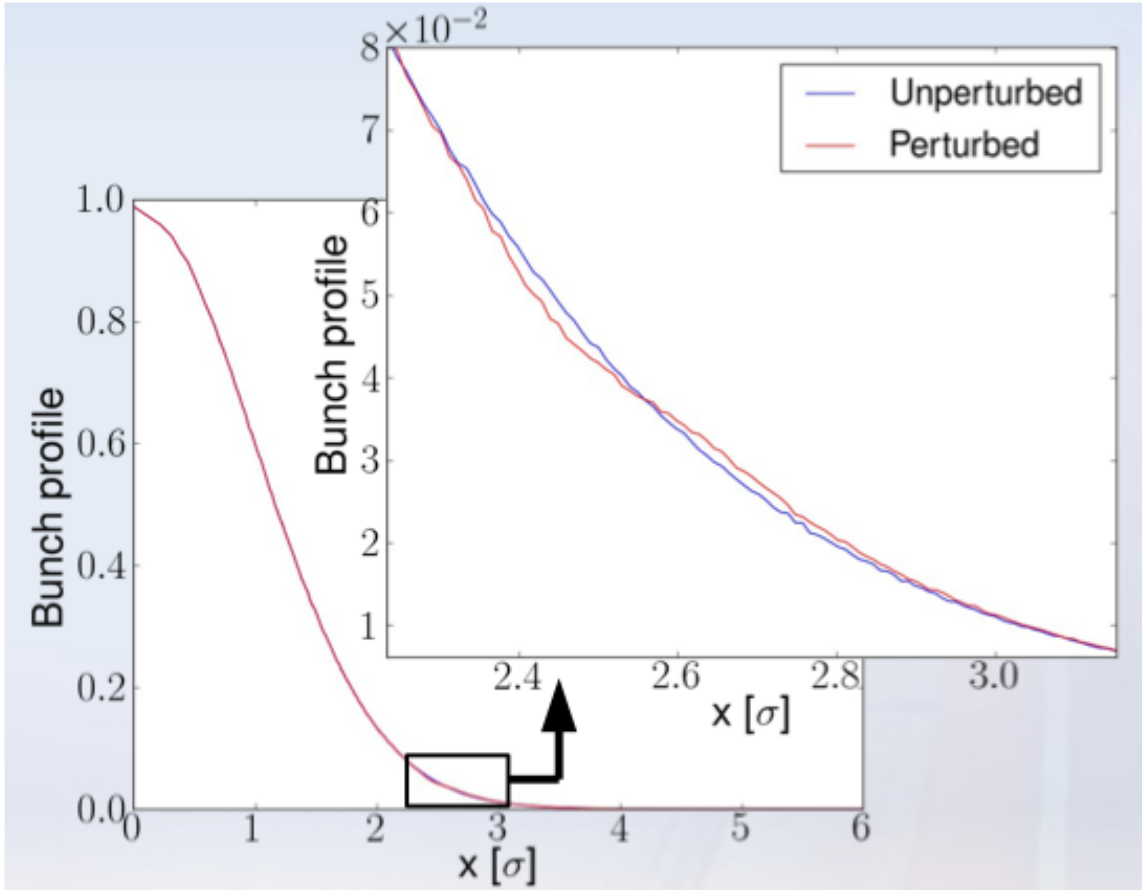


(b) Stability diagram before (blue) and after (red) the distortion of the distribution.

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

- Colored Noise source → Diffusion of resonant particles
- Modification of particle density in action space with time
- **Strong effect on stability diagram at edge of variation (derivative of distribution)**

Modified distribution: Colored Noise

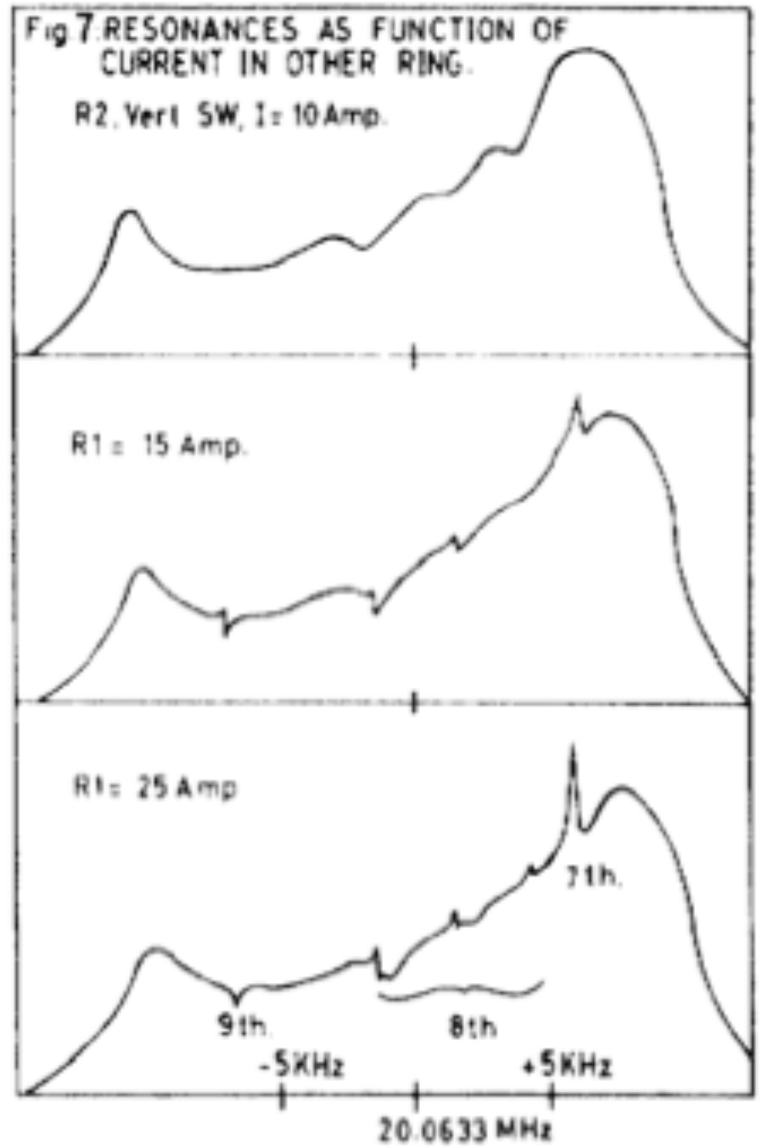


- Effect on particle distribution very small (% level)
- Profile measurement dominated by core of beam

→ **Impossible to measure the effect with profile measurement!**

CERN ISR

Beam-Beam Exciting non linear resonances

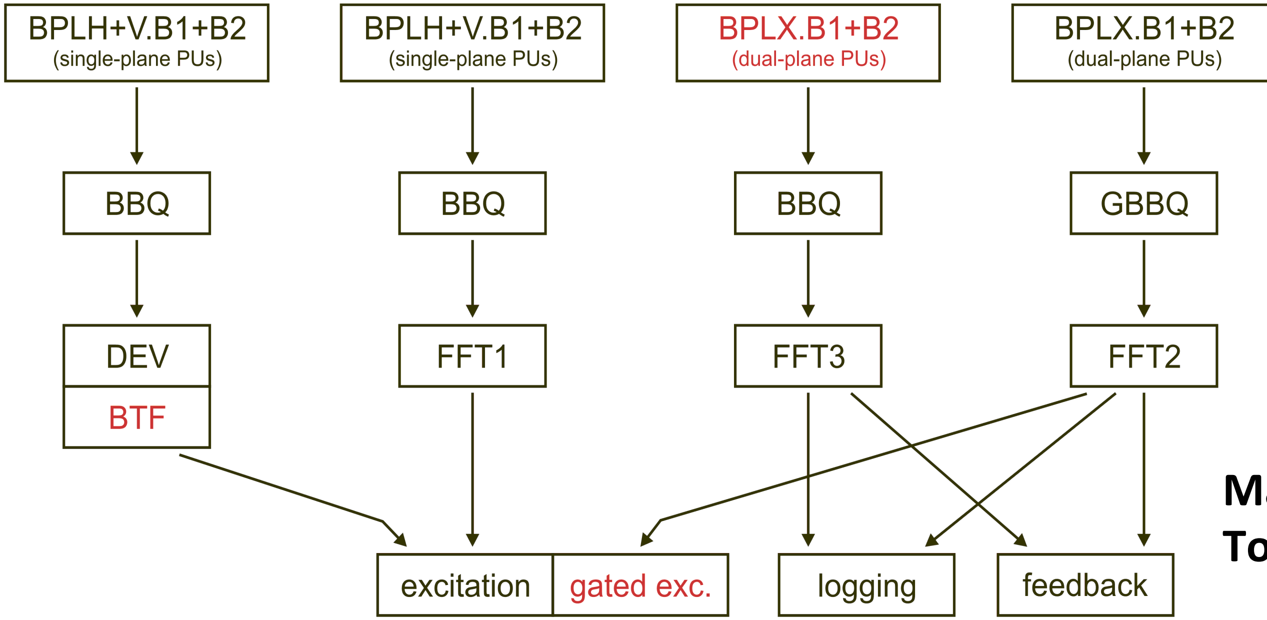


INFORMATION FROM BEAM RESPONSE TO LONGITUDINAL AND TRANSVERSE EXCITATION J. Borer, G. Guignard, A. Hofmann, E. Peschardt, F, Sacherer and B. Zotter

Here we see the impact of resonances excited by head-on collision. Effect small but evident.

But what happens when we have much smaller Landau Damping and effect of resonances are strongest (reduced BBLR separation and possibly improve with wire)?
Effect of BBLR should be visible and compensation as well…

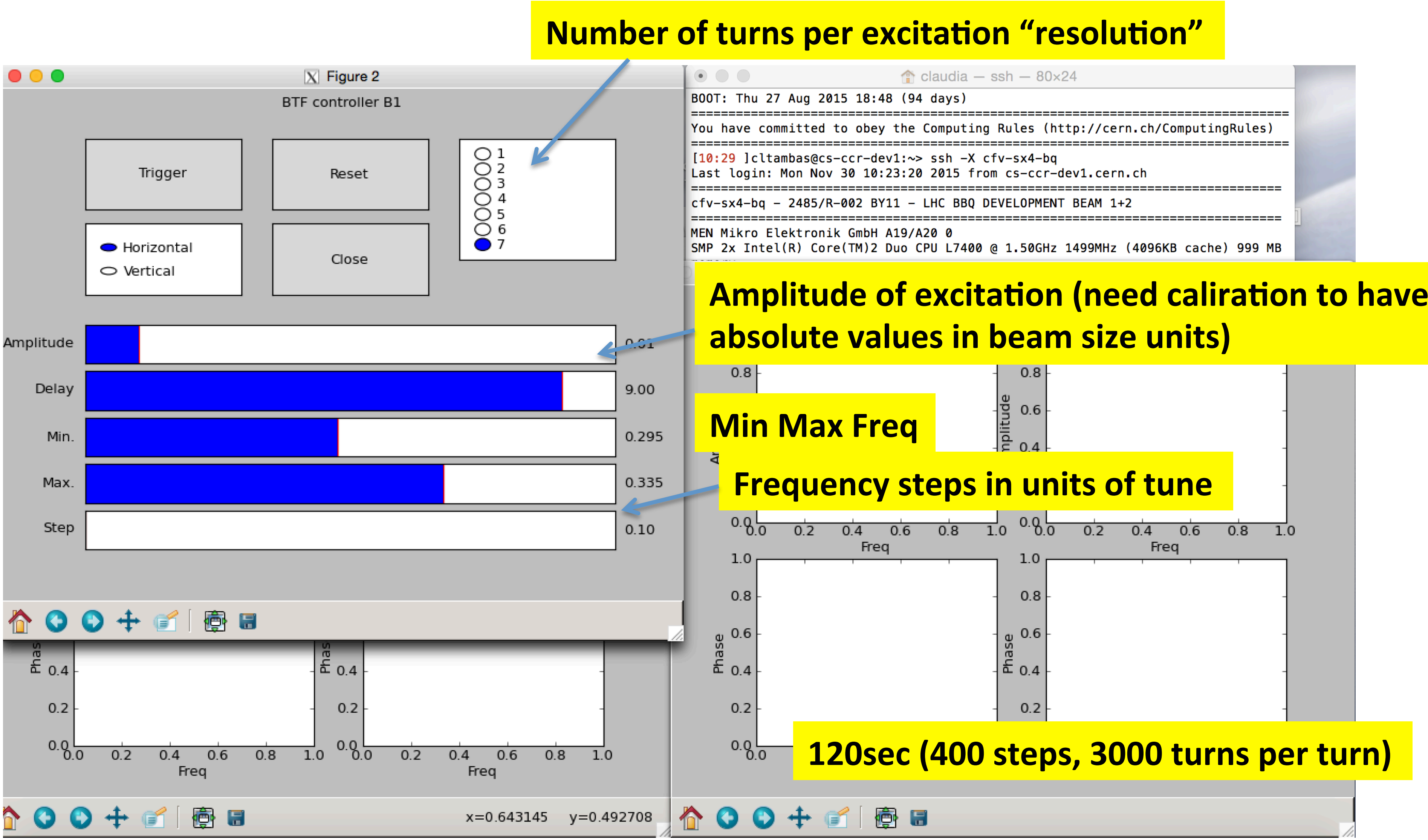
LHC BBQ systems in 2015



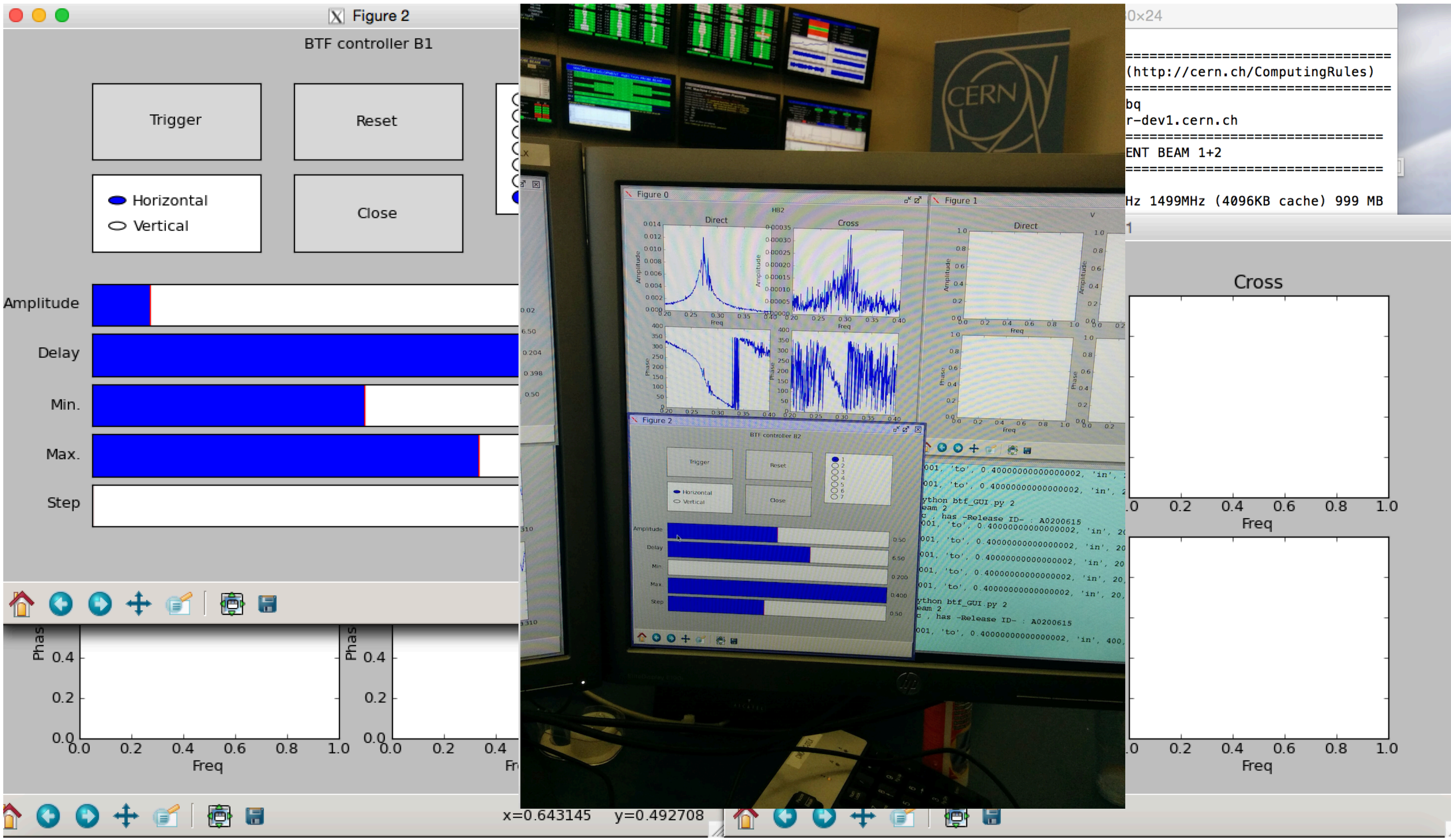
Marek, Andrea, Tom, Thibaut

- The Beam Transfer Function (BTF) functionality option would be the only interesting functionality from the former PLL system. At the beginning the BTF would be an MD tool deployed "on demand" on the development (DEV) system.
- BTF would use the same hardware as the standard DEV FFT system. The only difference would be that the DEV FPGA would run the BTF code instead of the FFT one. The changes FFT/BTF and BTF/FFT could be done within a few minutes (providing that the appropriate software is prepared).
- Why the PLL would not be efficient for regular tune measurement and feed-back:
  - For the PLL the "natural" beam oscillations are just useless "noise", while for the FFT systems most of the time they are sufficient for regular operation.
  - The PLL needs always an excitation, that is the required excitation level would have to be well above the "natural" oscillation amplitudes.
  - The PLL gives only one point on the beam spectra while the FFT gives the whole picture allowing to determine where the tune picks are with even quite complex algorithms.
  - The PLL would have to be accompanied by an FFT system anyway, showing the whole beam spectrum.

BTF GUI in the CCC: simple and expert based…



BTF GUI in the CCC: simple and expert based… not yet operational!



BTF measurements

BTF powerful diagnostic tool:

- Tune measurements, chromaticity, tune spread (at RHIC operationally used)
- Feed-down effects from non linear elements
- Stability diagram measurements our interest
- Sensitive to particle distribution changes
- Coherent mode observation in Landau damping
- Impedance measurements...

BTF measurements is the only way to test the model of the Landau stability diagrams

BTFs measurements have been collected at LHC in several configurations

Summary of the BTF measurements

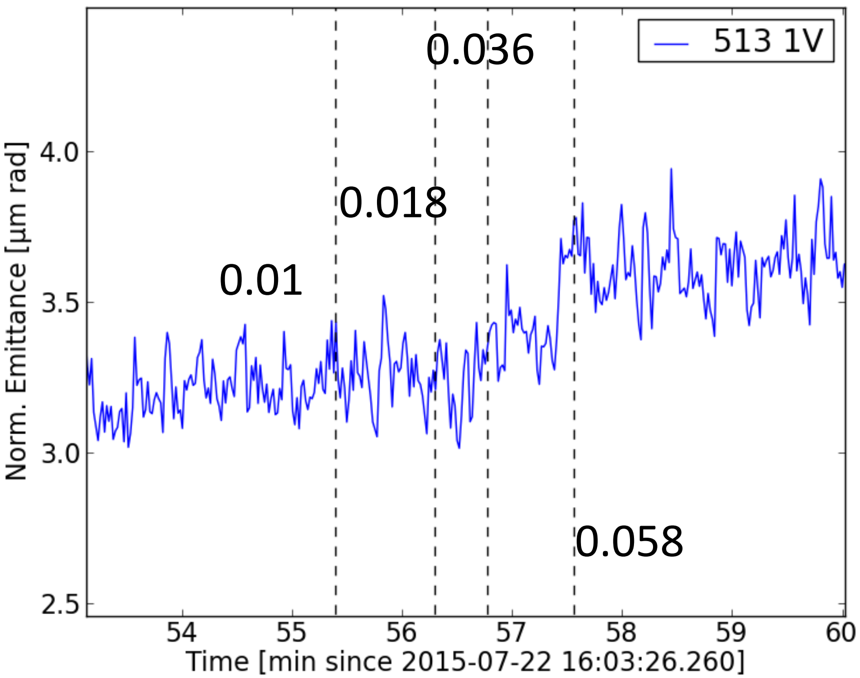
BTF measurements tested on pilot and nominal bunches at injection and at flat top

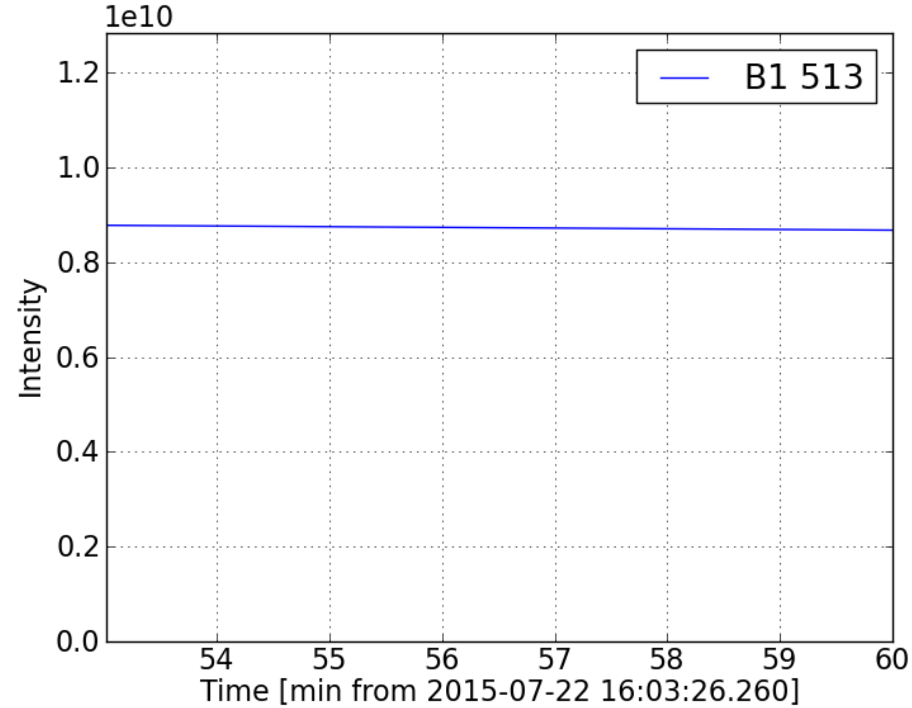
Excitation amplitude scan: good settings have been found to be **transparent**

- BTF with beams in collision: injection and flat top
- ADT gain scan: flat top, to characterize the BTF amplitude response
- Chromaticity scan: flat top, to characterize sidebands
- Octupole scan: injection and flat top (nominal bunches)
- BTF with LR contribution: end of the squeeze, LR separation $\sim 14\sigma$

Safety of the BTF operation

Excitation amplitude scan





Dashed lines correspond to amplitude step

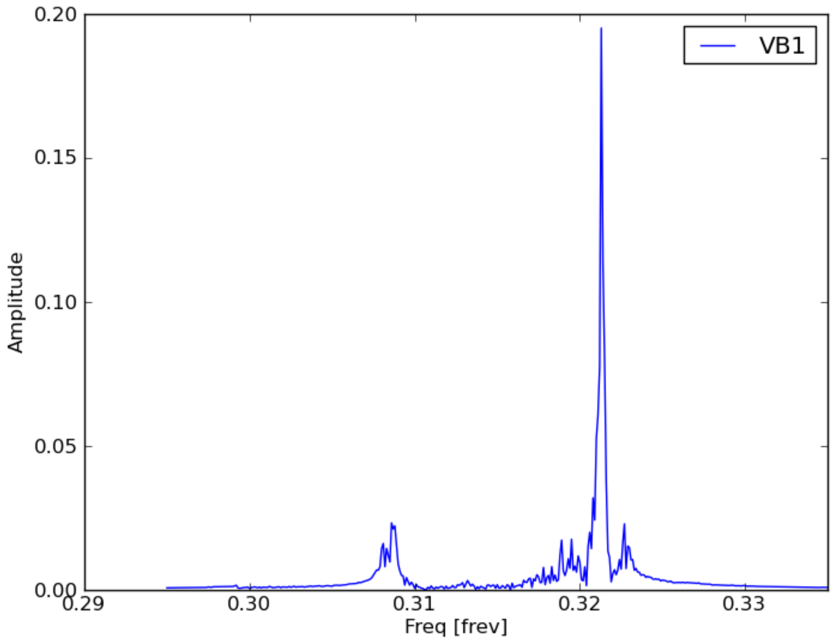
BSRT data, injection, pilot bunches

Similar plots from BLM losses from Belen

NEED a calibration with ADT amplitude kick to have info on amplitude in beam size

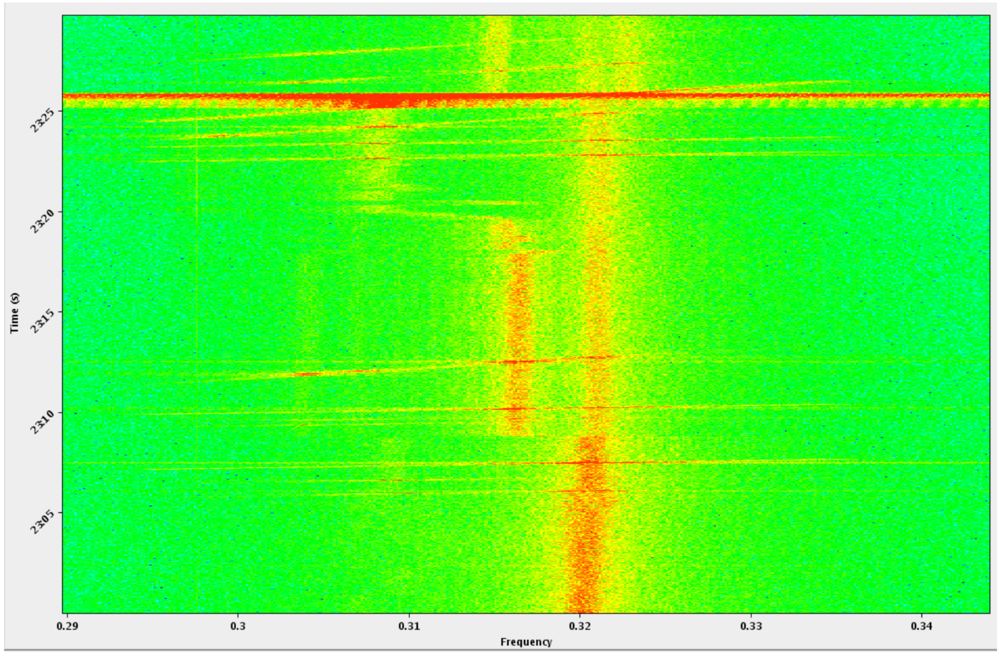
Beams in collision (injection)

BTF signal when beams in collisions in IP1&5: pi and sigma-mode visible



Optimization of the IPs was performed looking at the shift from the BTF

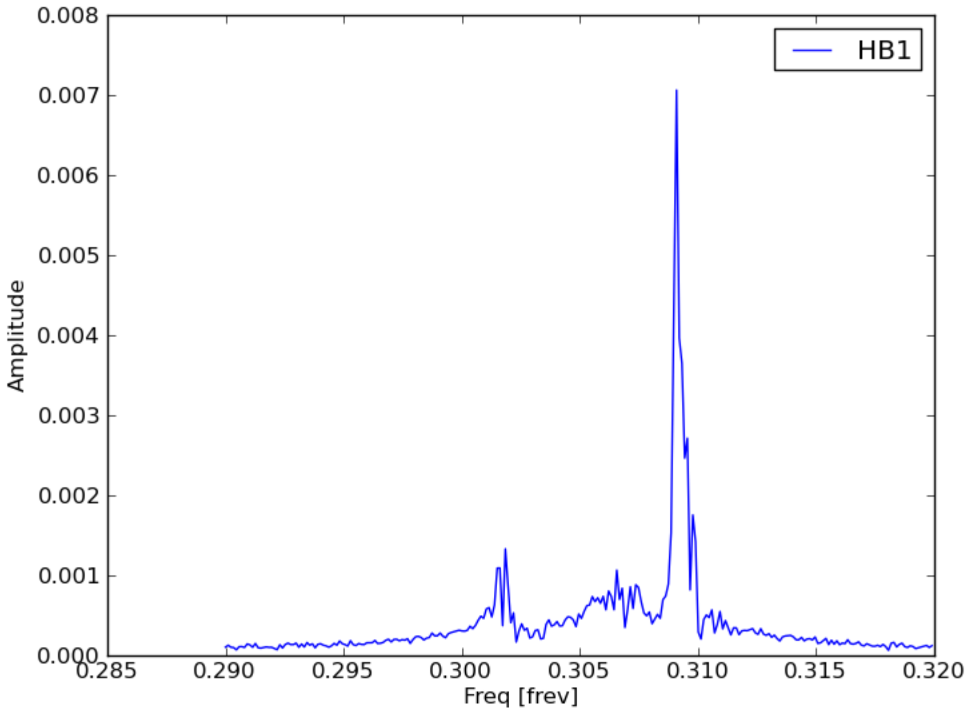
Blow up observed during BTF possibly due to the excitation of the pi mode (ADT off)
Reducing amplitude disappeared!



Measured tune shift by BTF $\Delta Q \sim 0.0129$ (expected $\Delta Q = 0.013$)

Can be used to measure tune shift and BB parameter versus wire current and position

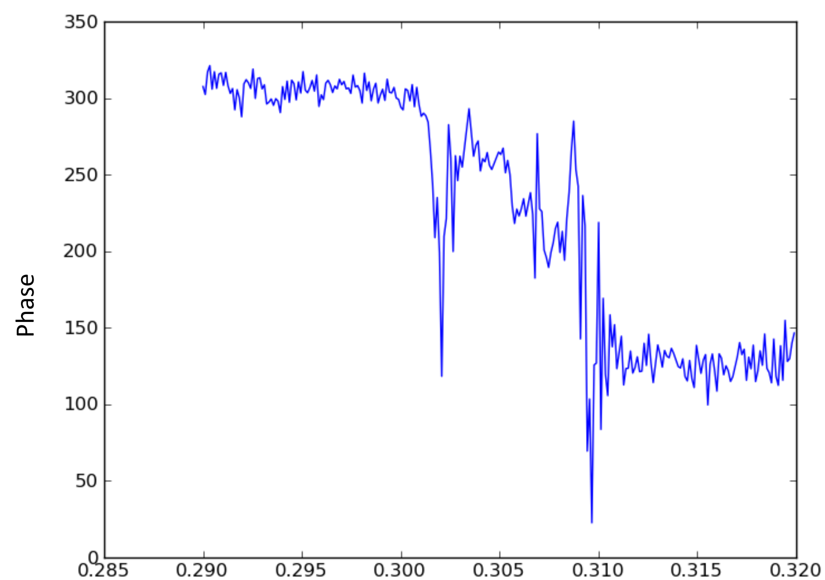
Beams in collision (Flat Top)



Looking at the π-mode position we can optimize collisions

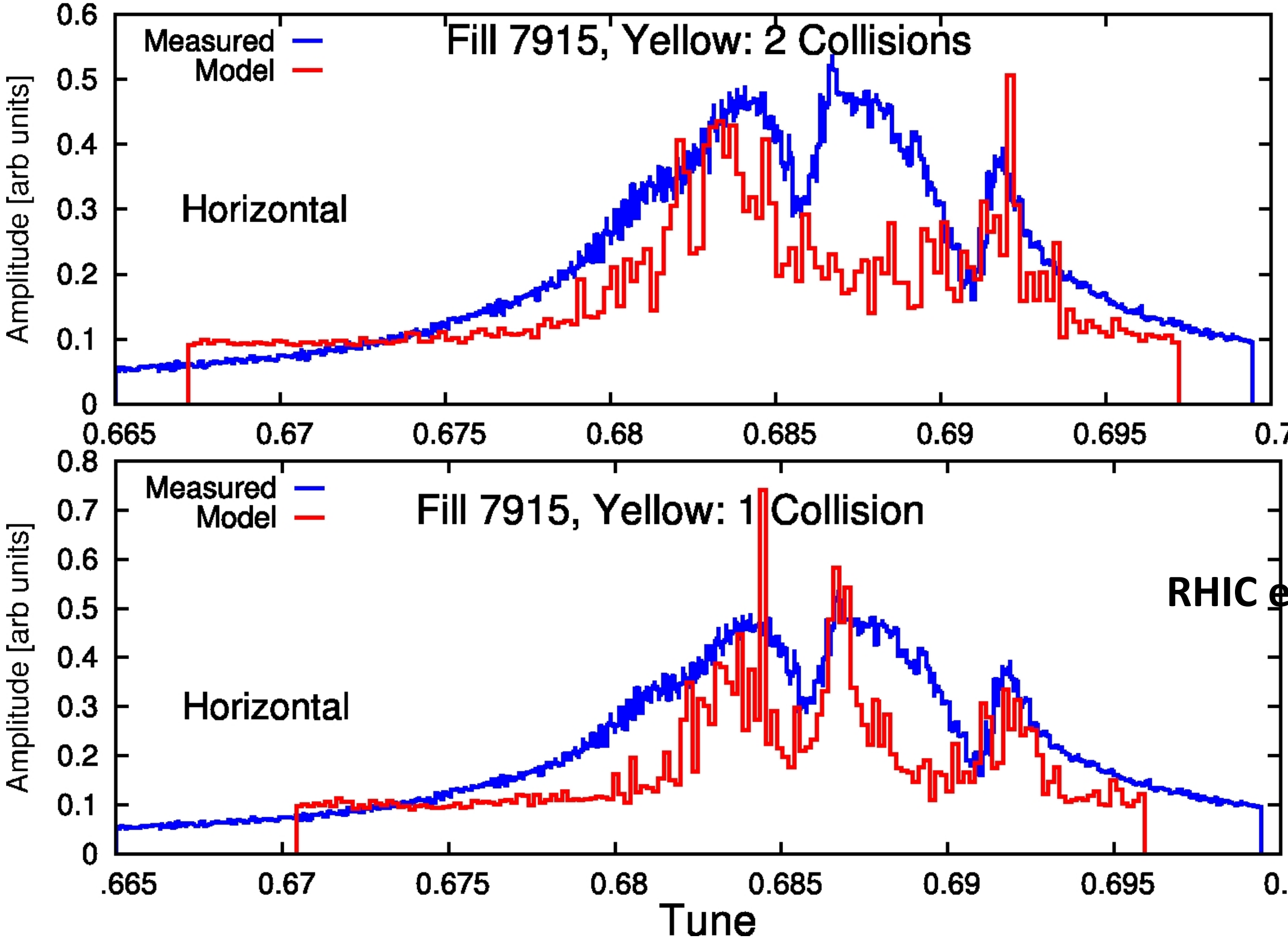
Incoherent spread visible between **σ**-mode and π-mode

No emittance blow up observed (ADT Off)



System is working very well and provides clean measurements of sigma pi modes and BB parameter

Beam-beam coherent modes and Landau Damping

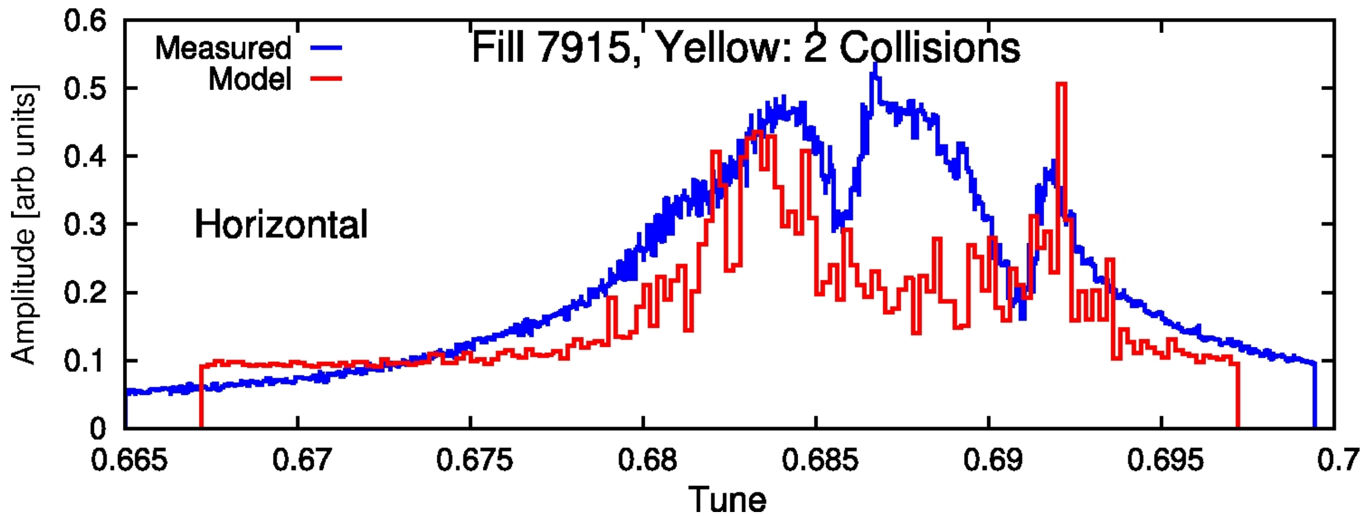


RHIC example only HO

BTF can be used for coherent beam-beam modes measurement normally Landau damped

With LR coherent modes very difficult to see….

Beam-beam coherent modes and Landau Damping



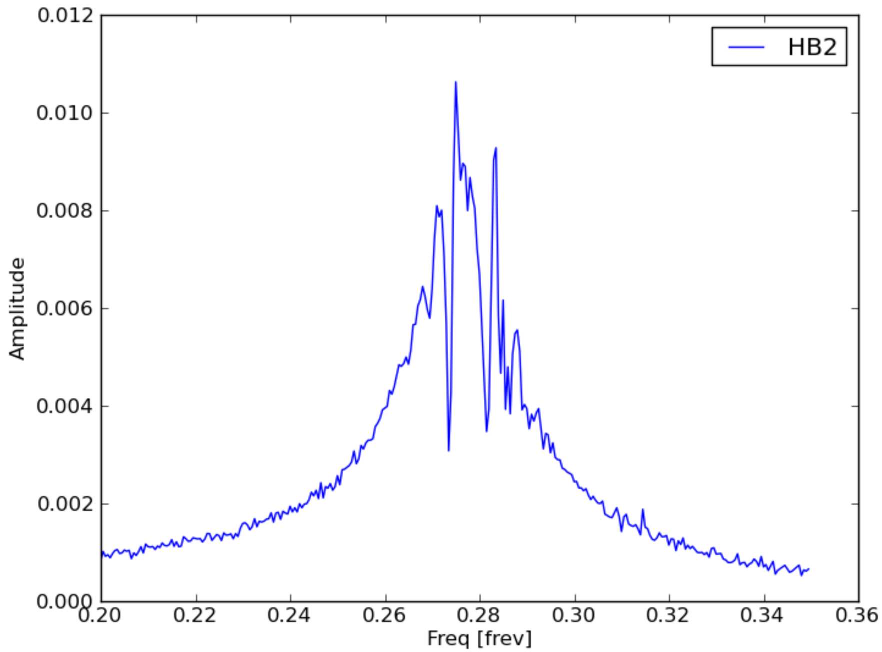
Cross talk BTF measurements (excite beam 1 and measure beam 2) gives also a measurement of the beam-beam force strength → the BB parameter

Long range alone very difficult the many of them break the simmetry and pi modes are so many that is more a continuum

Moreover wire cannot compensate the coherent BBLR effects!

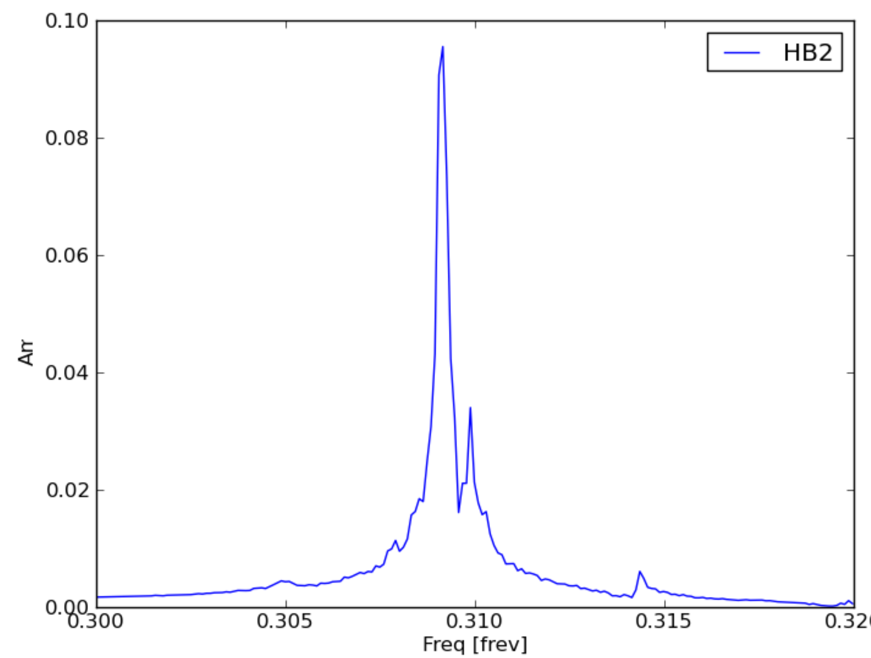
ADT effect on BTF amplitude response

ADT effect on the BTF



Sidebands still visible (Q'~7)

We corrected chromaticity and switched off the ADT (here already collision tunes Q'~2)



Needs to operate with reduced or zero ADT gain

Very easy on reduced intensity bunch (0.6e11 ppb versus 1.2ppb) suppress coherent PI mode

Even simpler on pilot (reduced oct need)

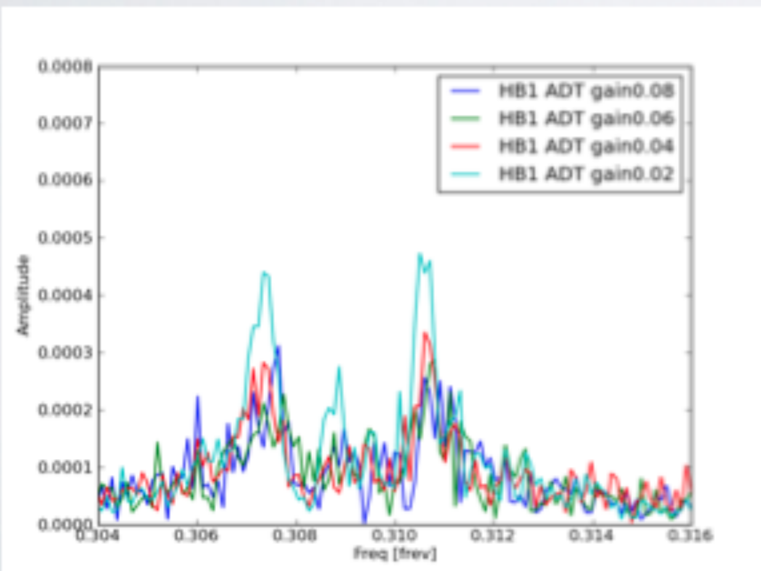
ADT effect on BTF amplitude response

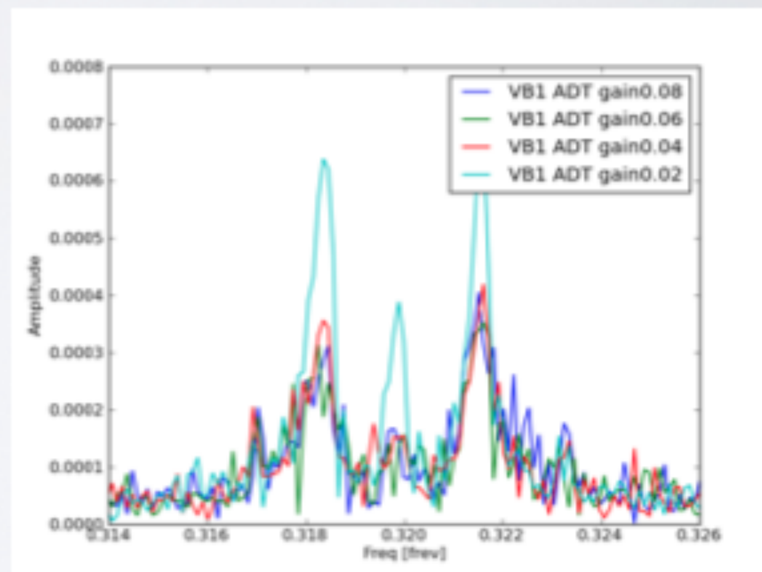
Measurements at flat top

Due to the restricted time we decided to take BTF measurements at flat top

Measurements on **B1** **(single beam)**

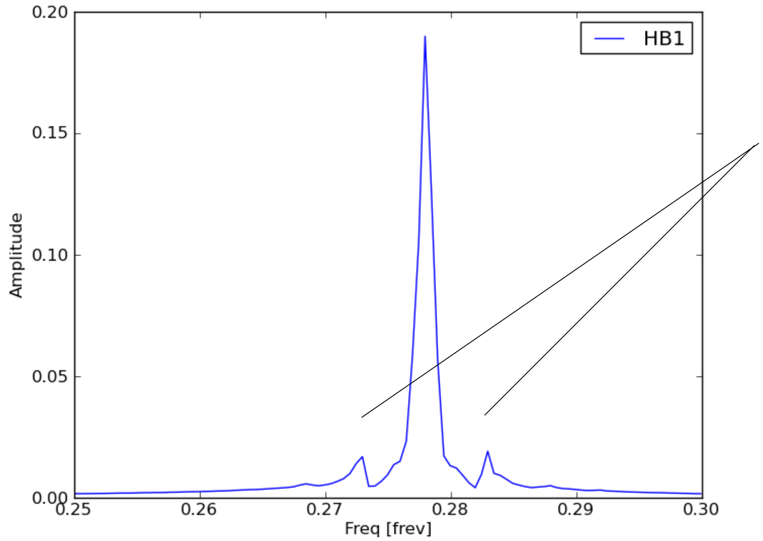
ADT gain scan





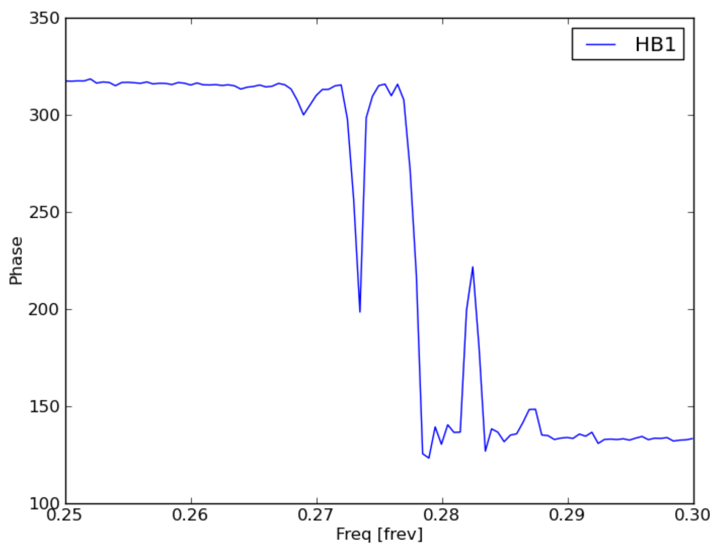
Needs to operate with zero reduced ADT gain

Chromaticity effect on BTF



Synchrotron sidebands visible in the BTF signal

Chromaticity ~7 units

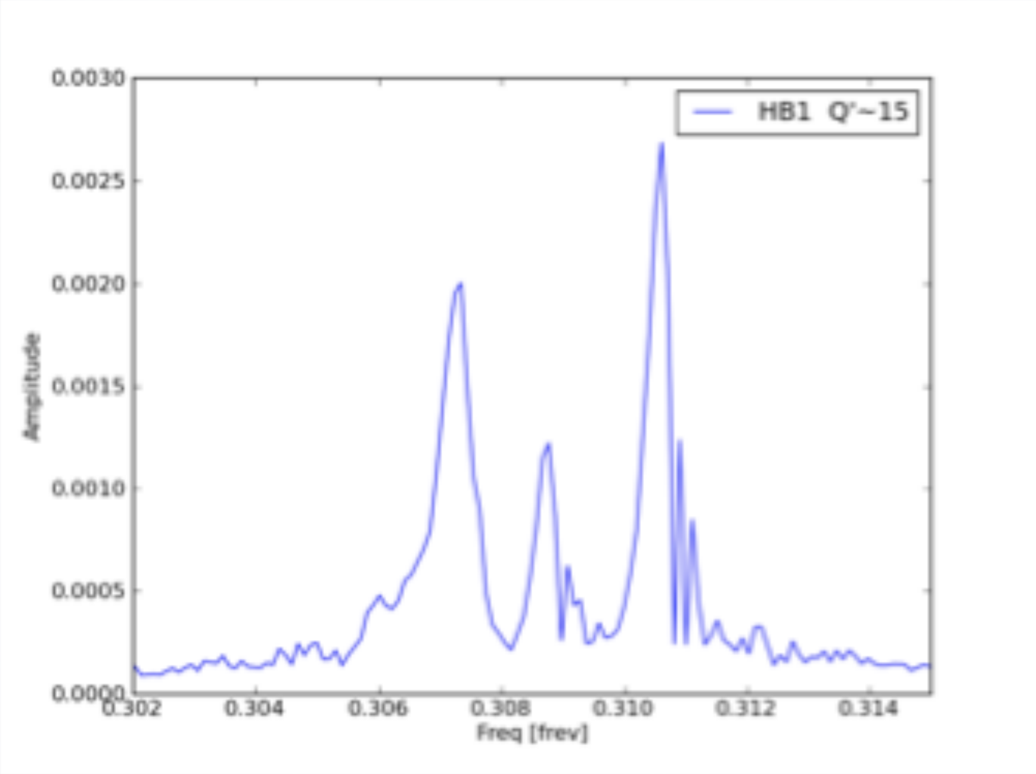


Phase jump clearly visible in correspondence of the synchrotron sidebands

Measurements at flat top

Chromaticity scan

Before the ramp the chromaticity was ~15 we use this value as reference

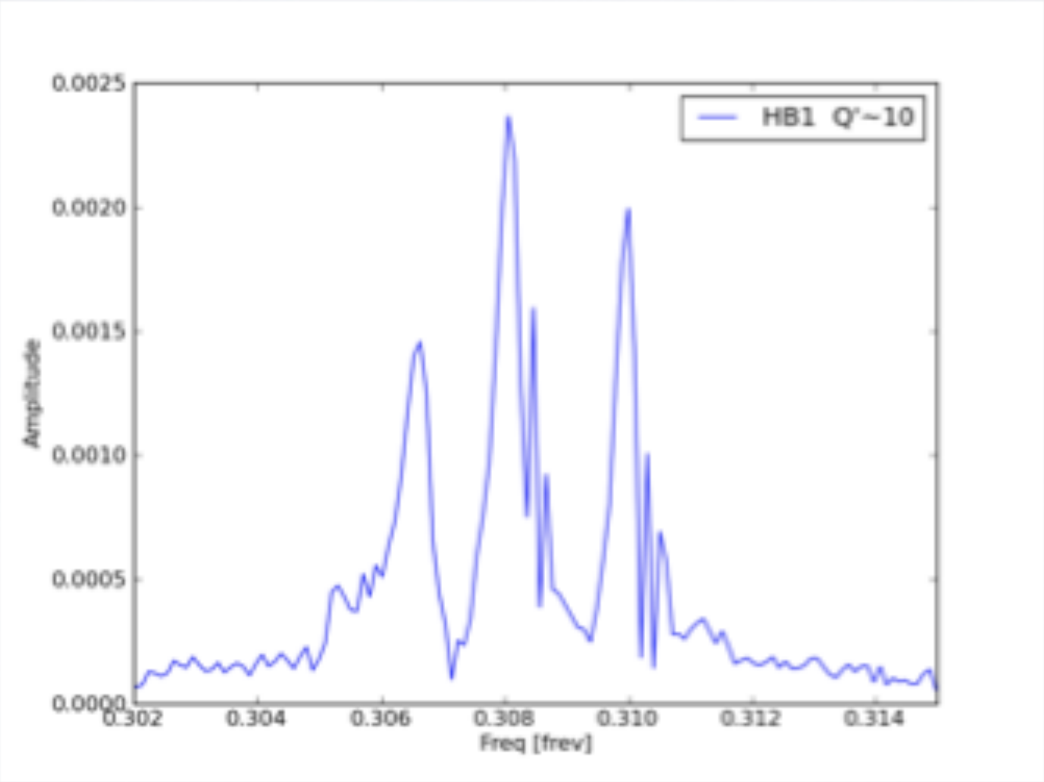


ADT off on single beam

Measurements at flat top

Chromaticity scan

Before the ramp the chromaticity was ~15 we use this value as reference



ADT off on single beam

Measurements at flat top

Chromaticity scan

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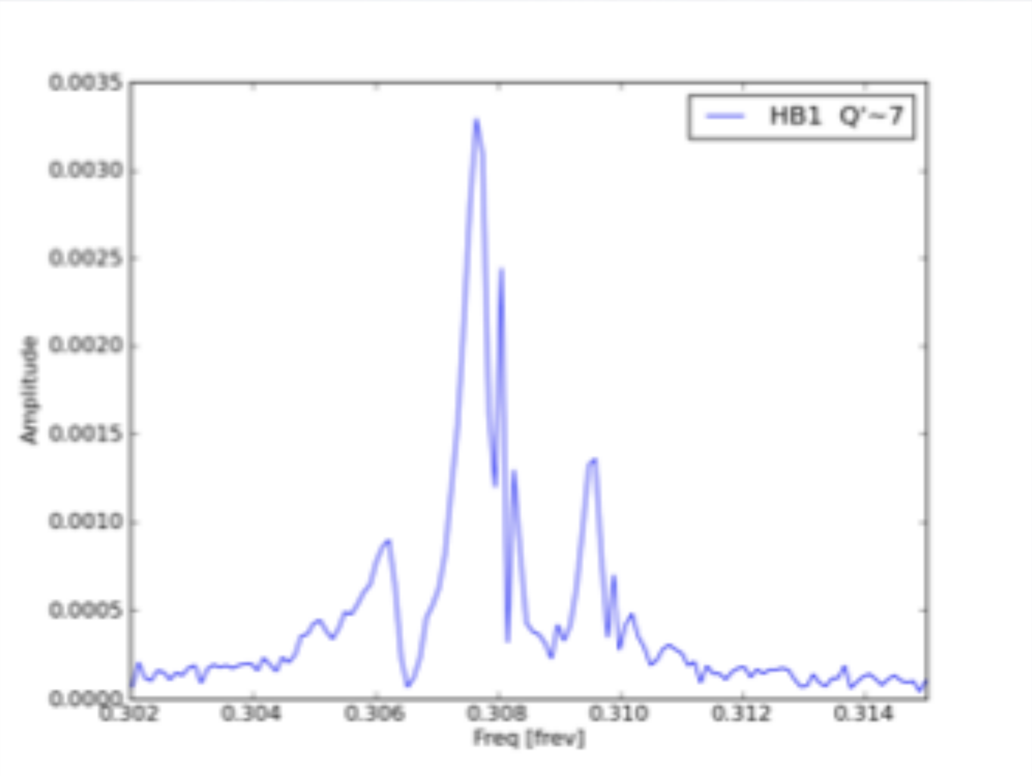

ADT off on single beam

Measurements at flat top

Chromaticity scan

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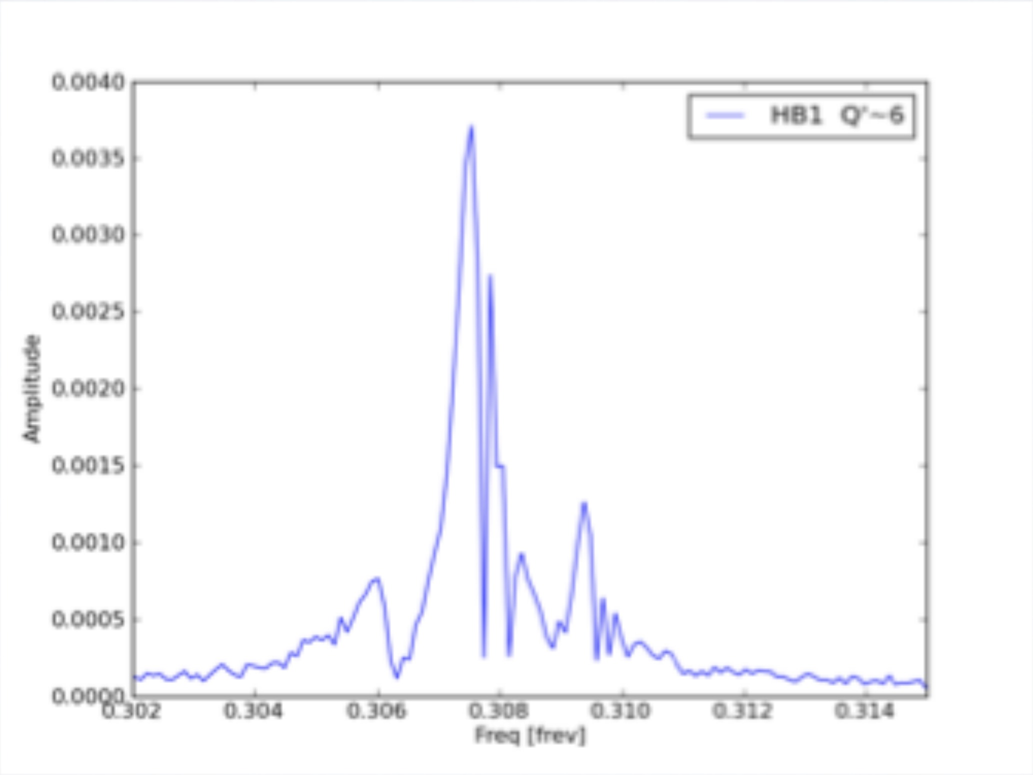

ADT off on single beam

Measurements at flat top

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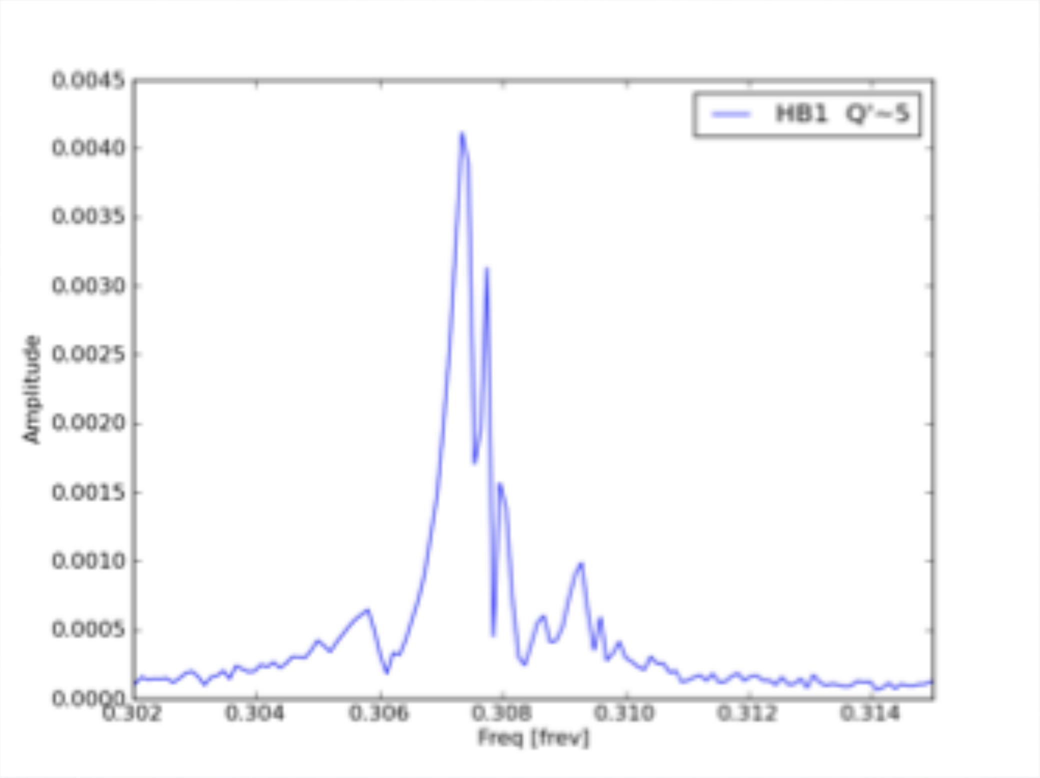
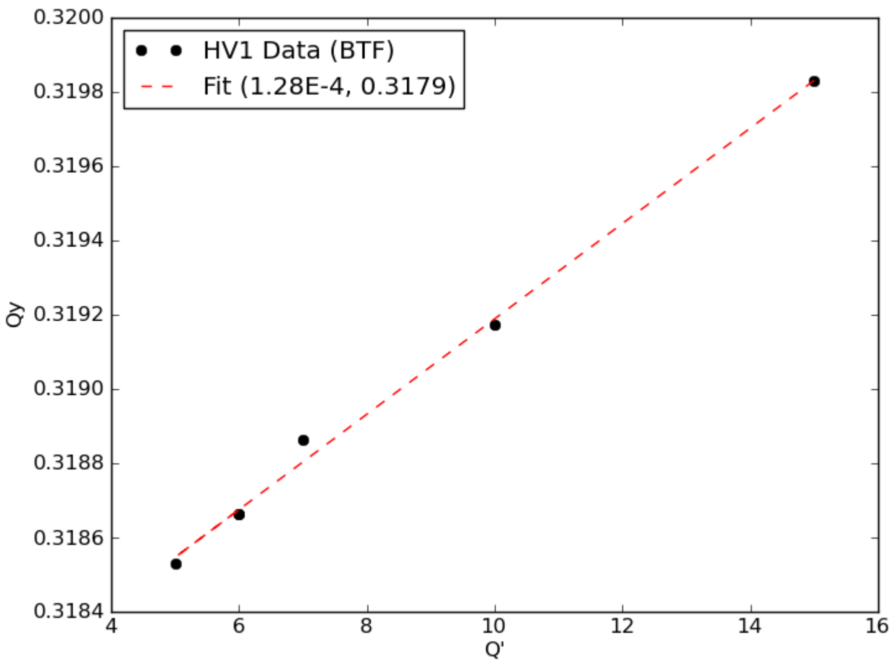
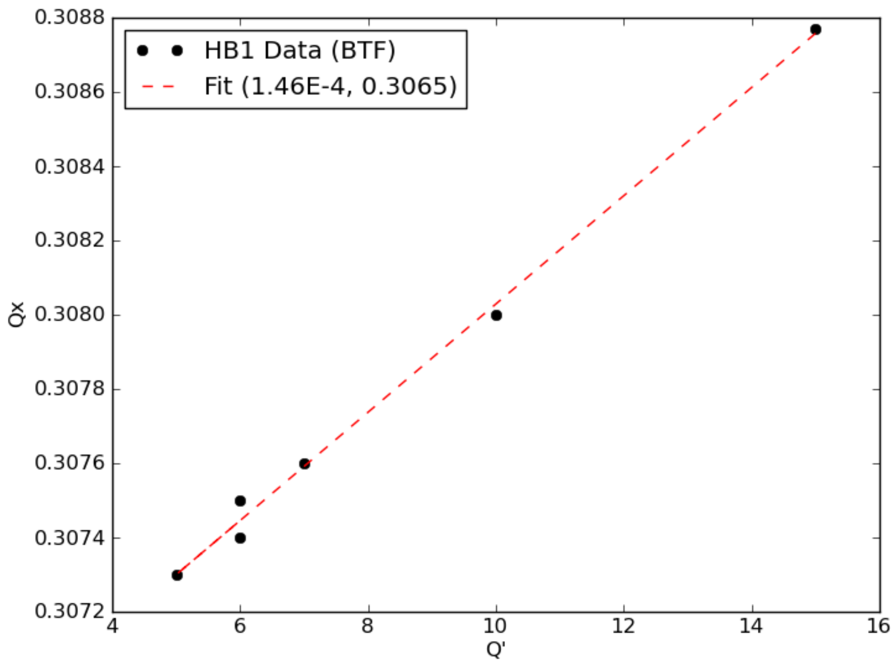


ADT off on single beam

Tune shift versus Chromaticity

Chromaticity change and tune shift:
feed-down effects at 10^{-4} tune units level!!

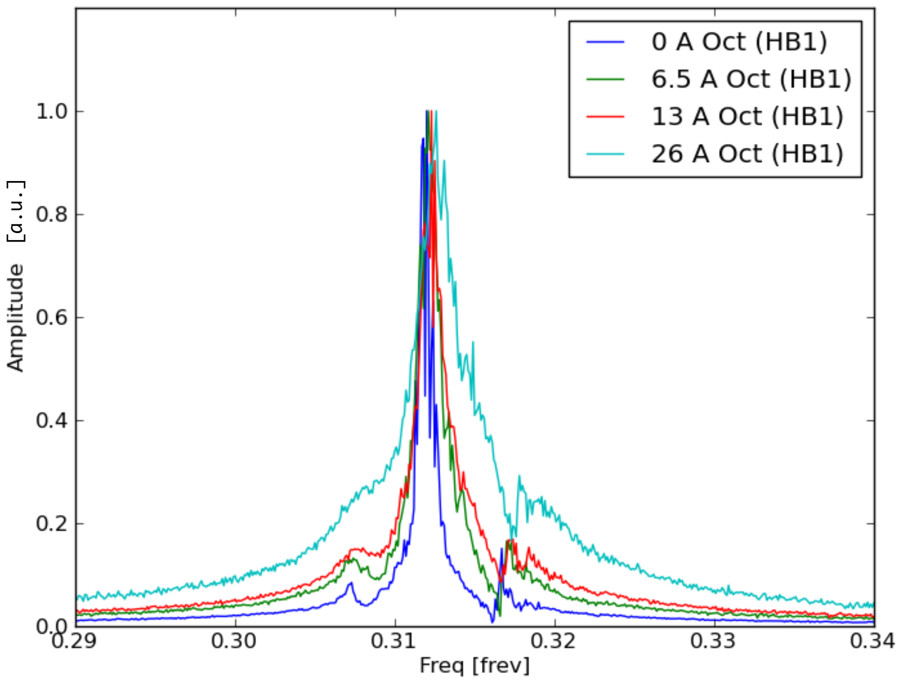


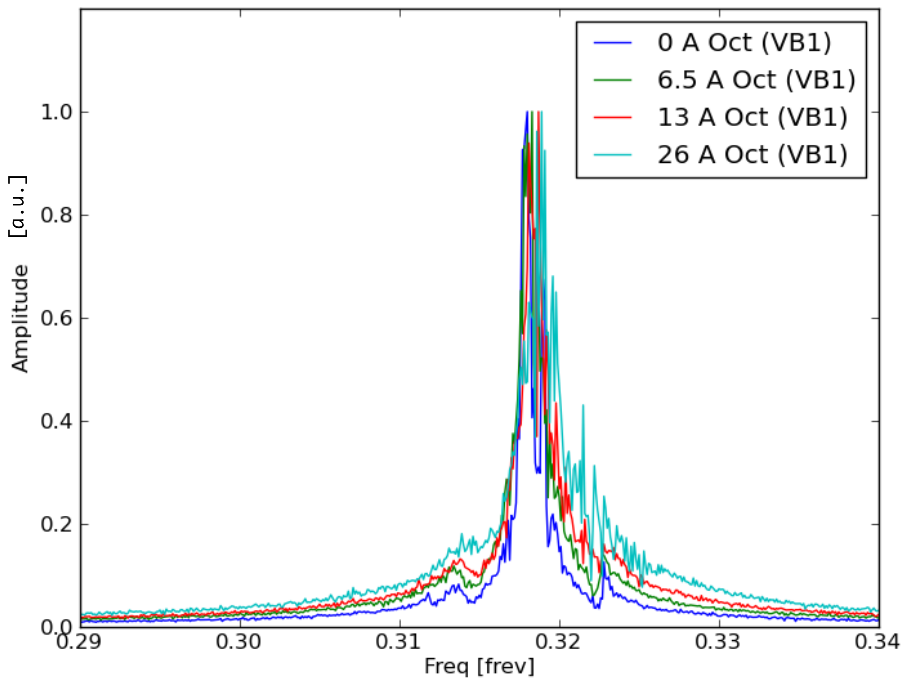


Feed-down of chromaticity change to the tunes 10^{-4} level
Simulations on-going to reproduce the sideband high versus Chromaticity: propose scaling laws

Octupole scan at injection

Octupole scan at injection with nominal bunches at collision tunes

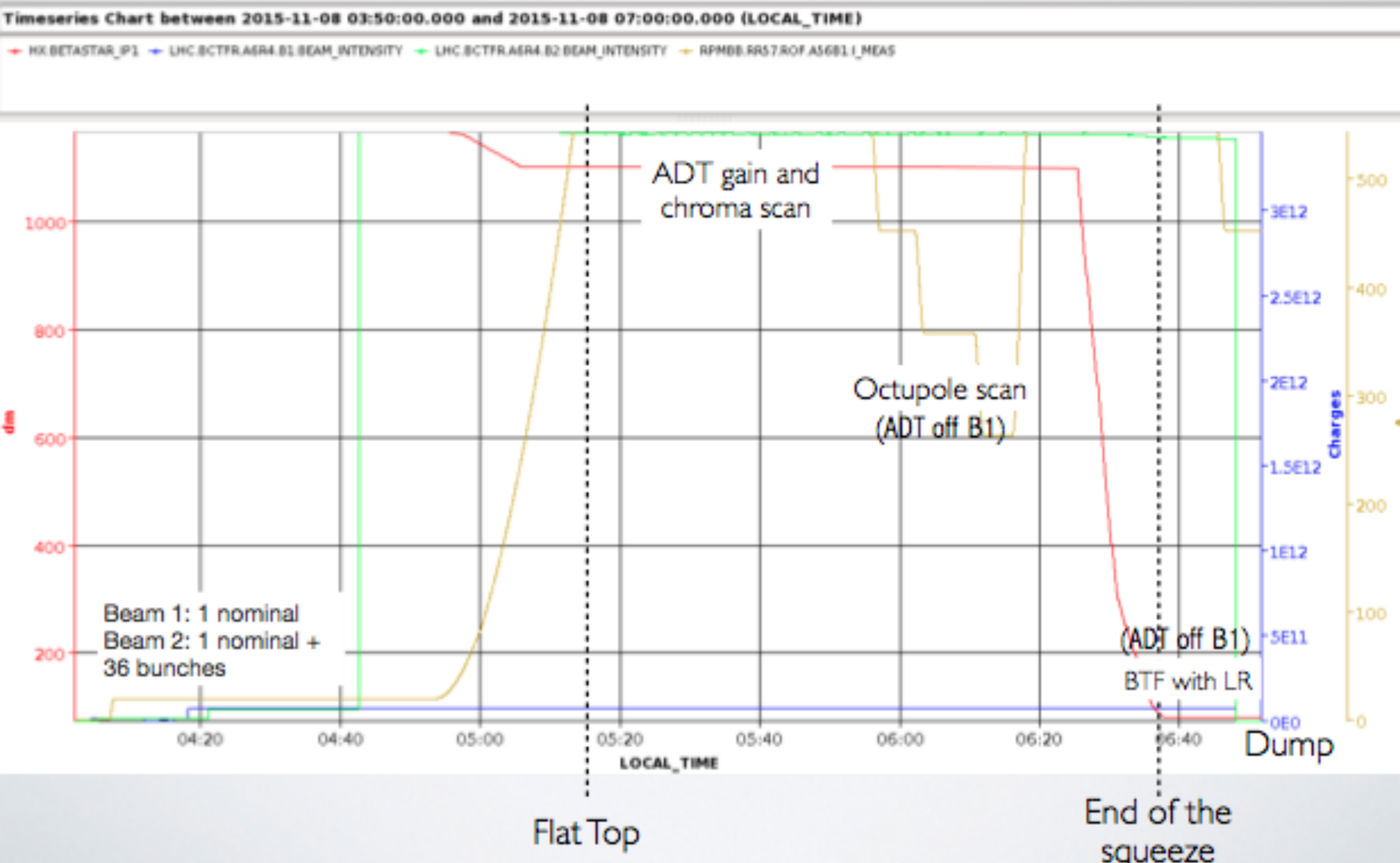




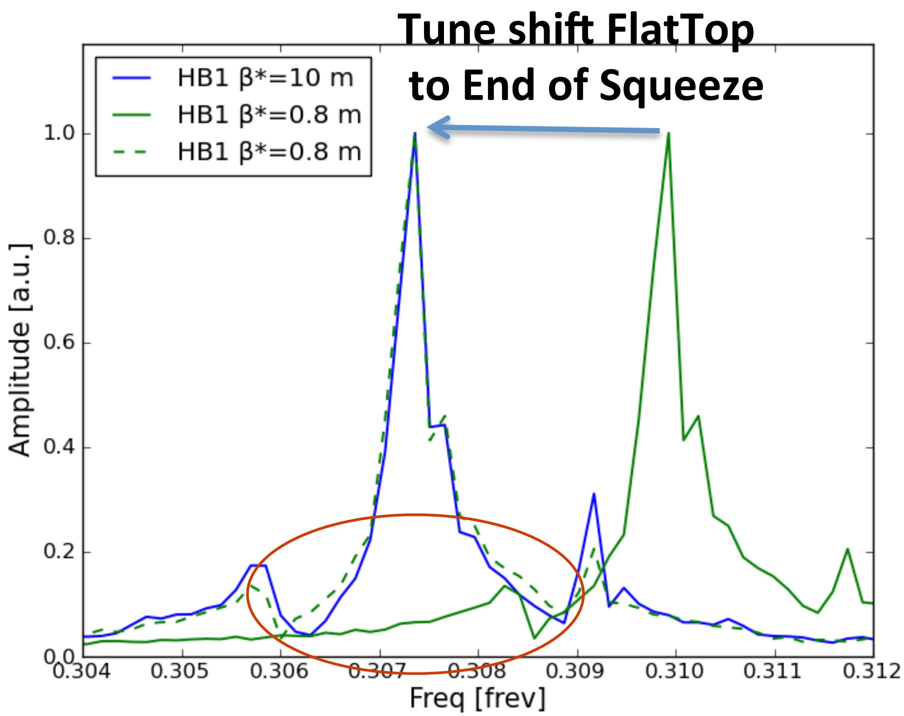
Spread from octupoles clearly visible/measureble

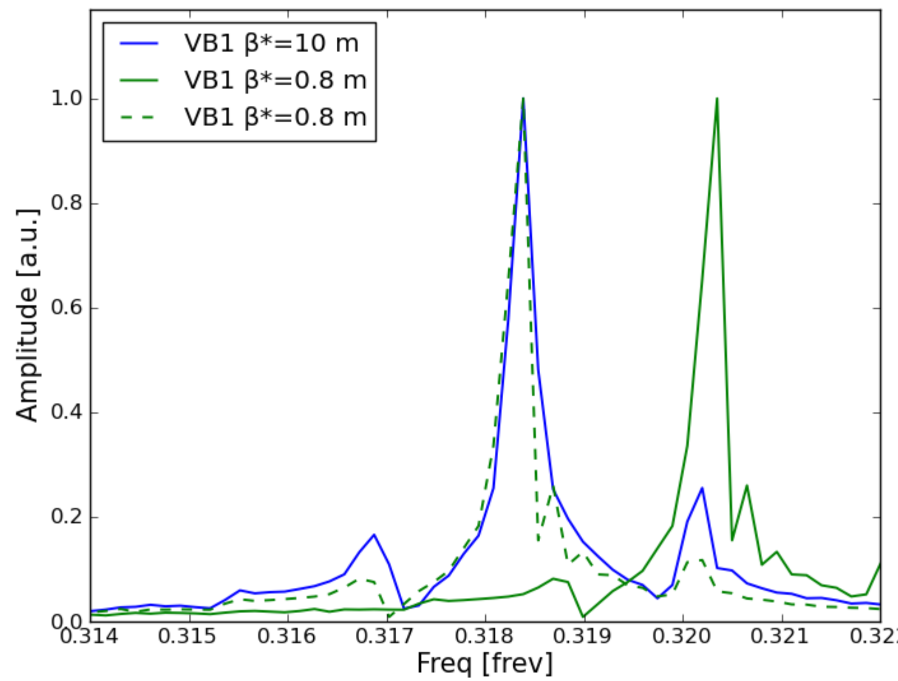
→ Tune spread measurement of LR BB seams feasible!

Summary of the MD procedure



Beam-beam LR contribution in BTF amplitude response





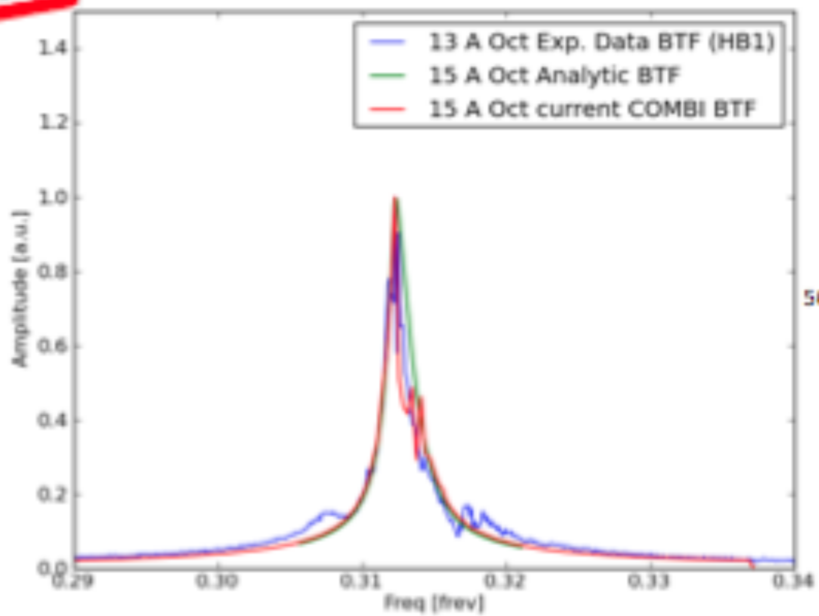
Beam-beam LR at ~14**σ** : spread decreases in vertical plane, spread increases in the horizontal plane

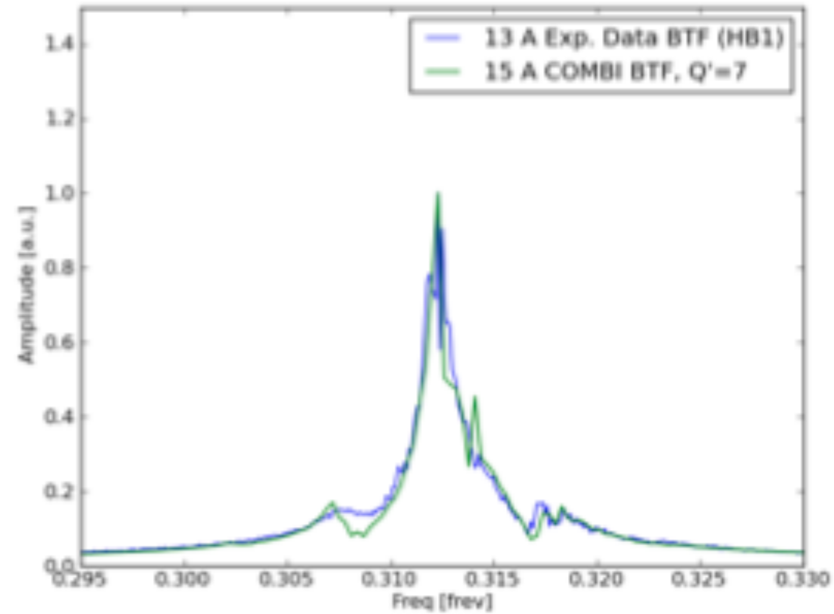
This can be due to some reduution of Vertical emittances and reduced octupole effect (→ less tune spread)

Crossing angle scan needed but no beam time!

COMBI-Measurements comparison with Chromaticity

Preliminary results



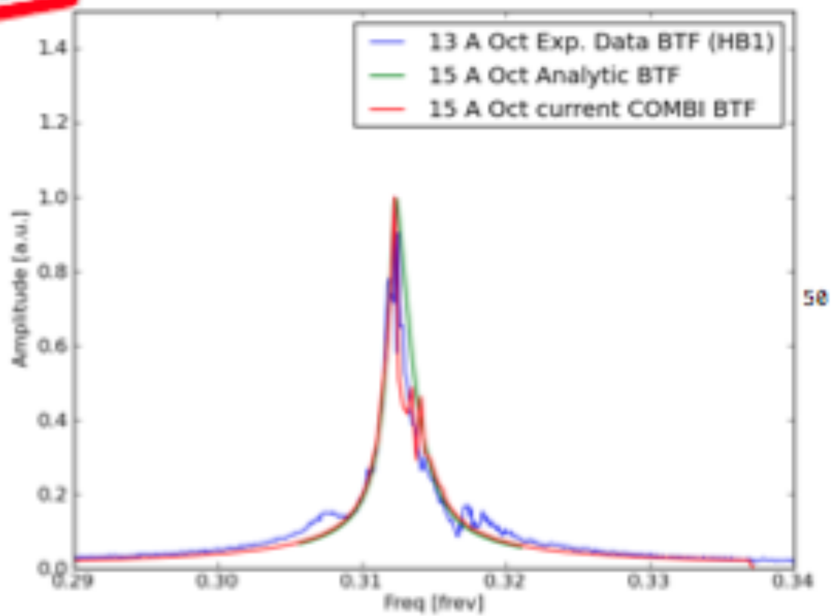


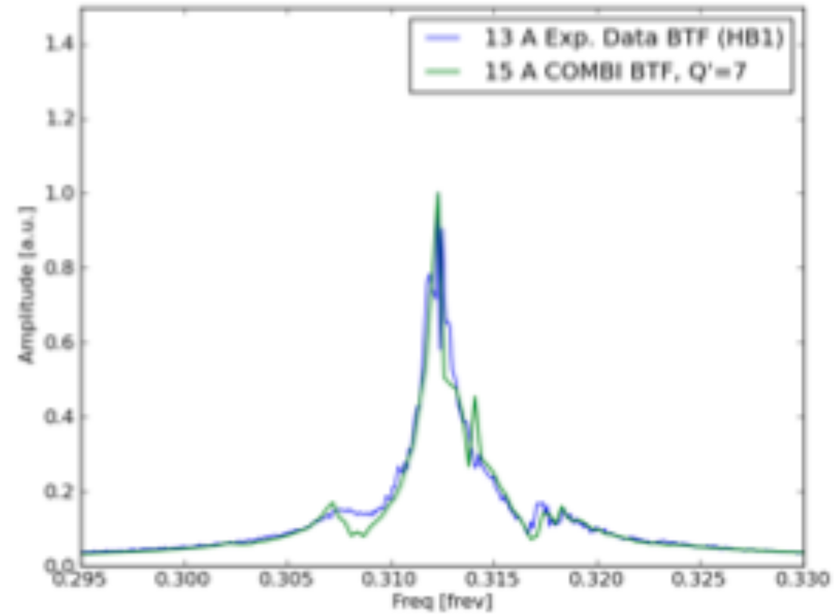
Promising <u>first attempt</u> to reproduce the BTF experimental data
Longitudinal motion "Turned on" in COMBI Simulations

Experimental data are under study and investigation

COMBI-Measurements comparison with Chromaticity

Preliminary results





Simulations versus data have nice agreement
Still many things to characterize before strong beam-beam → present non-linearities in accelerator, feed-down effects, chromaticity precision, LR separations…
On-going modeling DeltaQ vs Q'…DeltaQ vs Octupoles..
Need further data to cross'check our models with BB and resonances excitation (2016 run)!

Summary of 2015 experience:

- **BTF Measurements have been tested successfully in the LHC:**
  - excitation set to be TRANSPARENT to the beam operation (no emittance blow-up, no intensity reductions observed)
  - ADT off for optimum measurement (0.02 maximum gain)
  - Tunes shifts can be measured (10^{-3} level)
  - Tune spread (octupoles scan and non-linearities in the machine)
  - Beam-beam long range effects measured and consistent with expectation means zero effect at 14 sigma separation!

- **Still a lot to be done:**
  - Effects of LR beam-beam on spread: angle scan as usual (2016 MDs)
  - Effect of resonances deformation of BTF? Simulations of distribution evolution and Stability diagram Sixtrack and COMBI
  - Should gain experience on the system during 2016 operation
    - Need to lower intensity and reduced ADT gain (in gated BBQ window?)

Open questions and discussions:

BBLR have impact on tune shift, tune spread, chromaticity, orbit, particle distributions…

Wwhat can be measured with BTF?

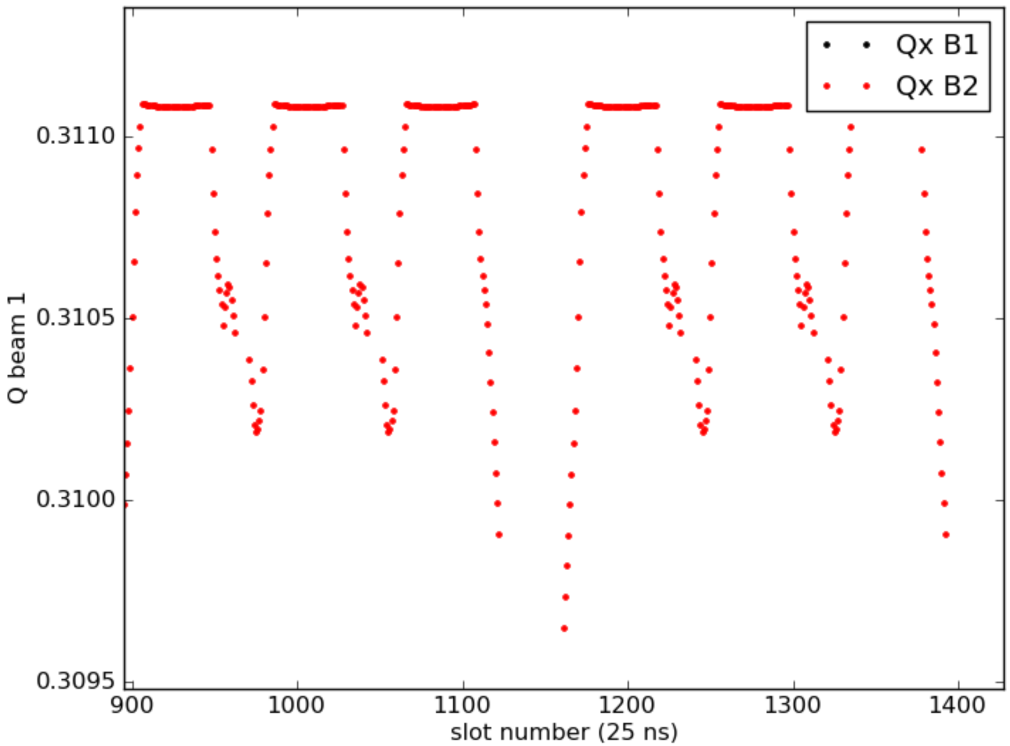
- Can we measure the beam-beam long range spread? Yes
- Can we measure the tune shifts ? Yes
- Can it measure the chromaticity variation due to BBLR? Yes
- Can we measure the resonances excited by BBLRs? To be proved
- Could we measure the compensation of the resonances? To be proved

Need to keep coherent modes weak to see incoherent information
Need to lower/switch off the ADT
Need to Make calibration of ADT amplitude of excitation
Need to have “cross calibration” of chromaticity effect

BBLR effects

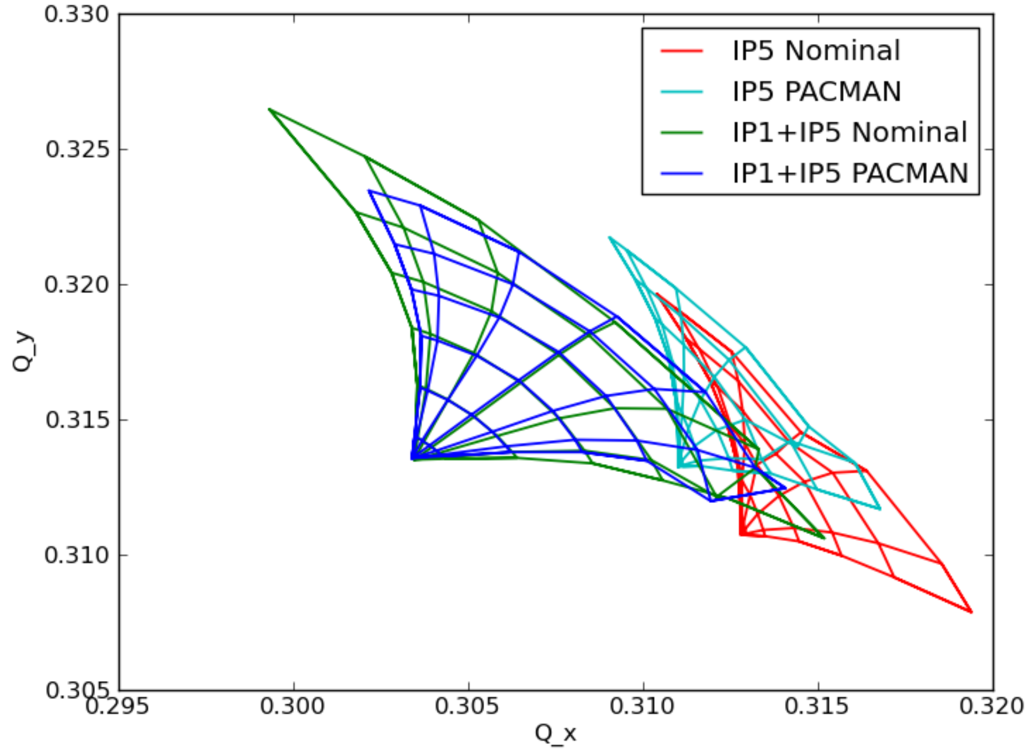
- Tune shifts

Reduced crossing angle 9-8 sigma separation
10^{-3}-10^{-2} tune shift between nominal and PACMAN



BBLR effects

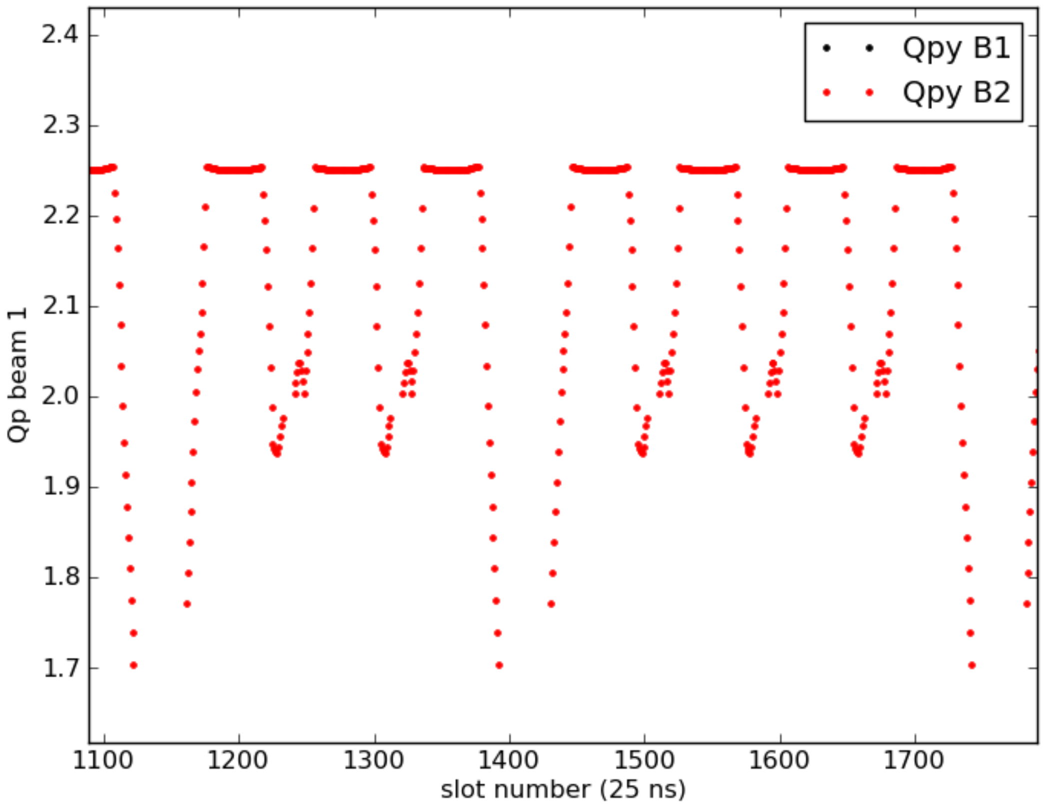
- Tune shifts
- Chromaticity change
- **Tune spread**



BBLR effects

- Tune shifts
- Chromaticity change

Reduced crossing angle 9-8 sigma separation
1-2 units variation on Chromaticity



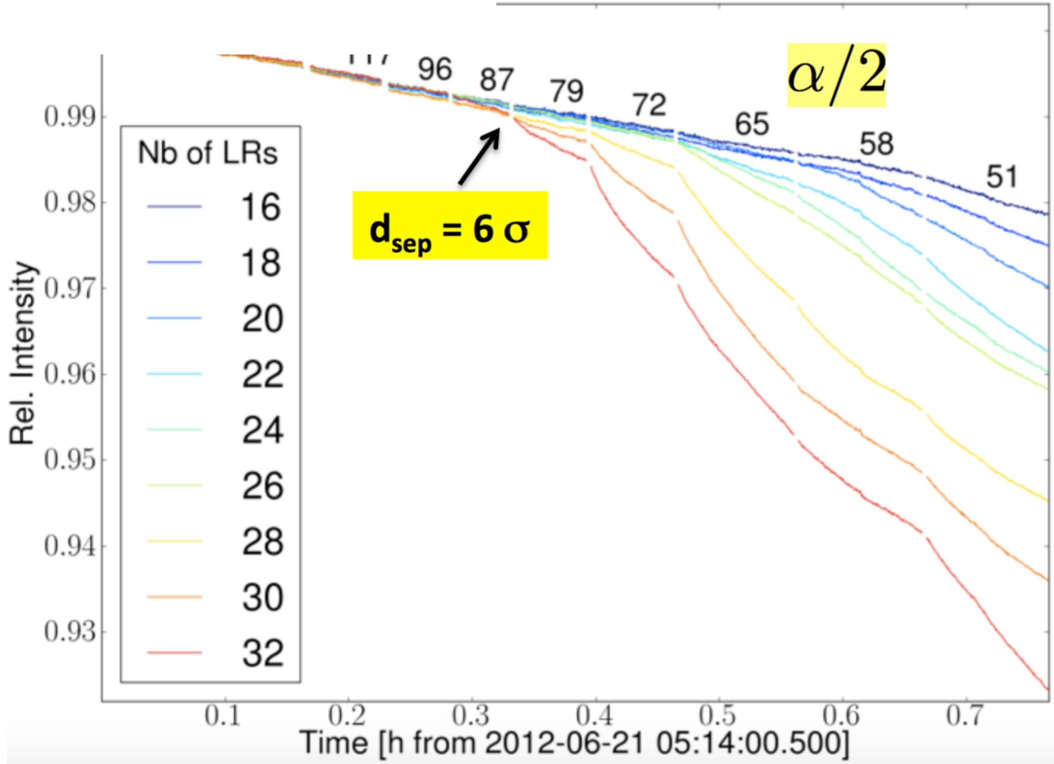
LHC 2012 Instabilities

Beam-Beam separation at first LR

Beam-beam long range experiments 2011-2012:

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

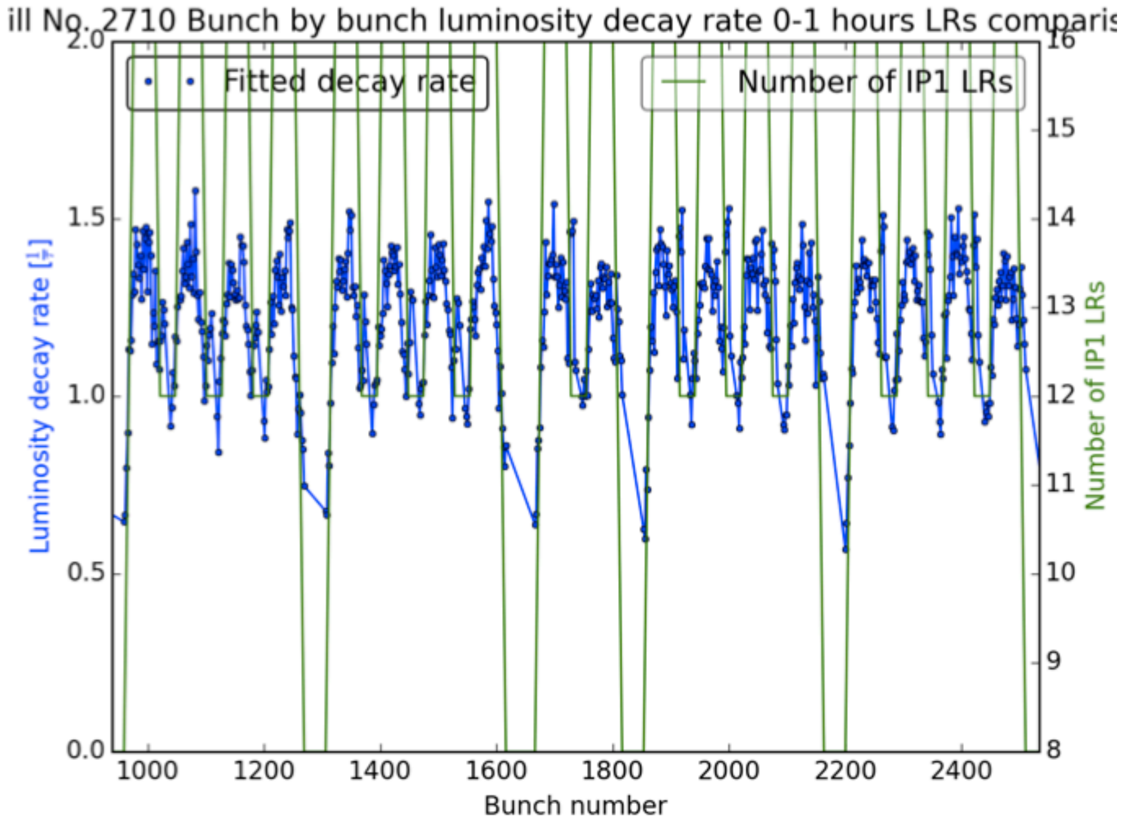
N=1.6e11 ppb
ε=2.2 μm
Q'=2 units
IP1 crossing angle



Beam beam effects determine the beam properties:
➡ must have a role on the instabilities

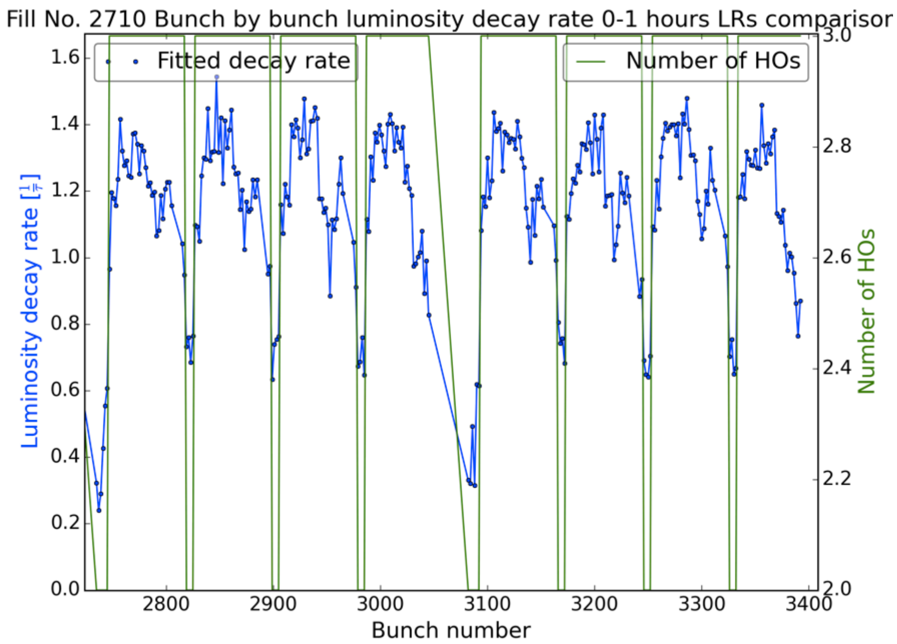
BBLR effects

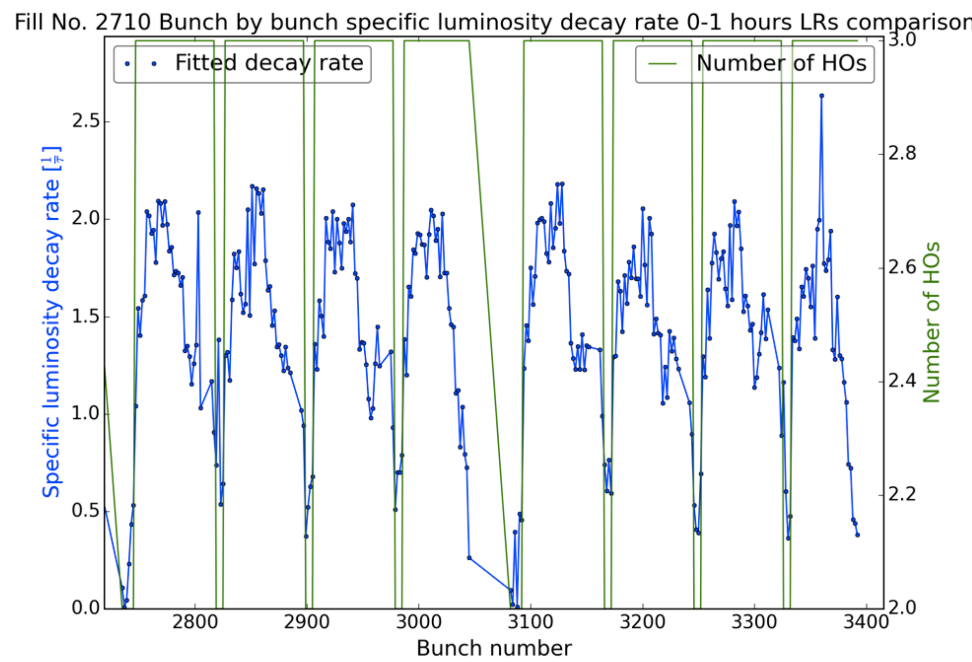
- Luminosity, specific luminosity lifetimes



BBLR effects

- Luminosity, specific luminosity lifetimes





BBLR effects

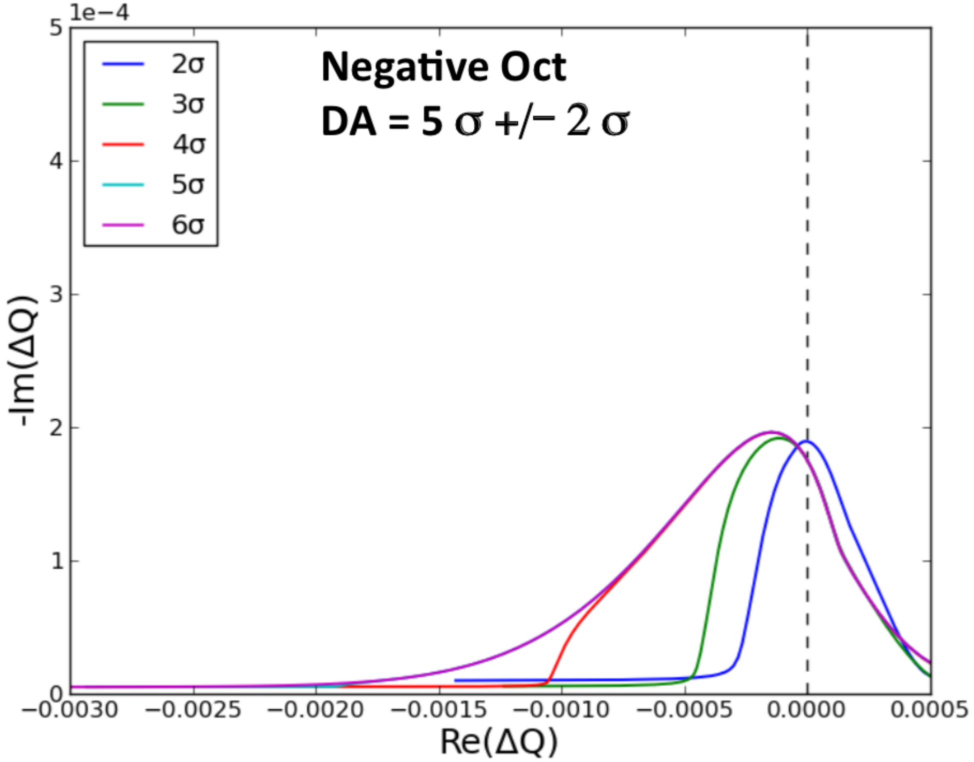
- Luminosity, specific luminosity lifetimes

Stability diagrams with cut distribution

If there is a mechanism that is deteriorating the distribution on the tails of the beam, stability can be reduced

Resonances are also excited differently so could be deteriorated even further

How can we collect information on dΨ/dJ ?



Beam Transfer Function (BTF) are sensitive to density variations (dω/dJ) which can give a loss of Landau damping