Status of noise studies in the LHC and expected impact for HL-LHC

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WP2 26/11/2019

Introduction

PC *,**

1. Dipolar modulation

Thyristor rectifiers (SCR):
comb of 50 Hz harmonics
(not only 600 Hz harmonics)

2. Quadrupolar modulation

SM (Inner triplet):
Mainly switching frequency

*LHC design report, *Chapter 10: Power converter system*
**J. P. Burnet: *Magnet power supplies and Slow extraction*
https://indico.cern.ch/event/639766/contributions/2750925/attachments/1556050/2447340/Power_converter-and_Slow_extraction.pdf

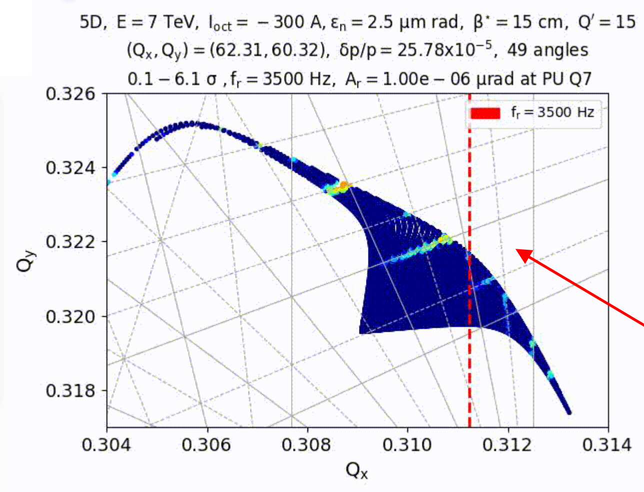
Introduction

→ In both cases, increase of diffusion through **excitation of additional resonances**

5D HL-LHC

1. Dipolar modulation

fr constant, Ar ↑



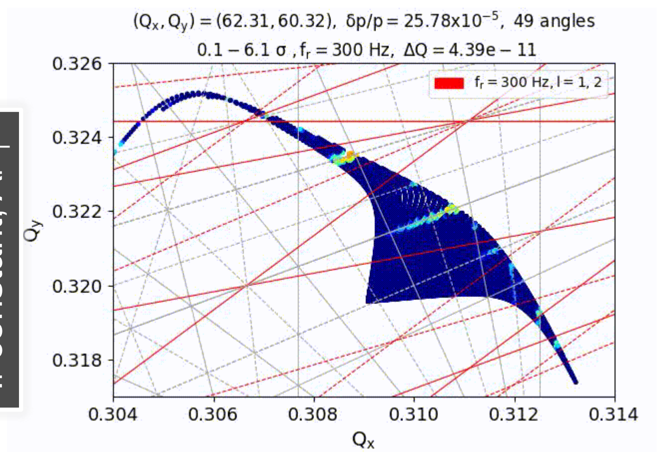
- Largest impact close to the tune
- Observed in the LHC

Excitation frequency

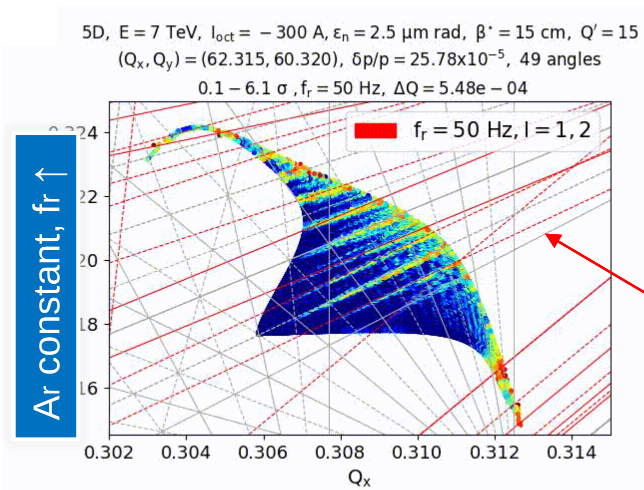
* For 1D FFT without non-linearities see appendix (pg. 38)

2. Quadrupolar modulation

fr constant, Ar ↑



Ar constant, fr ↑



- Impact even at frequencies far away from tune, **depends on WP**.
- Relevant for HL-LHC

Sideband resonances

Part 1: 50 Hz harmonics

Motivation

Observations: Extract information from the beam spectrum in order to define the source of the 50 Hz harmonics.

- Evolution of the 50 Hz (amplitude and phase) during operation.
- Response of the 50 Hz lines during changes in the beam & machine configuration.
  - Betatron motion (tune, phase advance & energy)
  - PC (Active Filters)
  - ADT settings

Simulations: Estimate if the 50 Hz lines impact the beam performance.

- Build a general framework for single-particle noise simulations and make projections for the future.

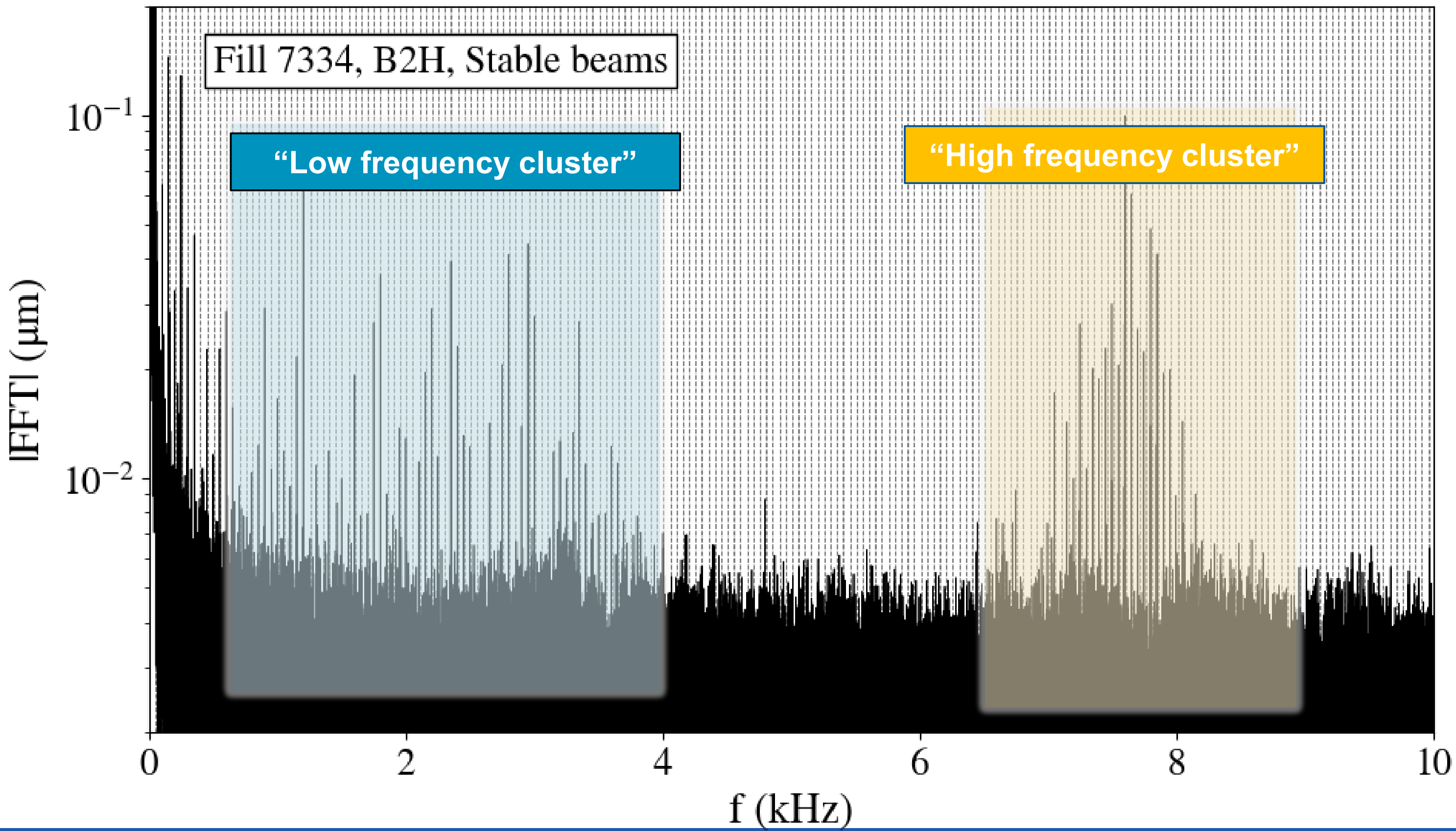
Propose analysis tools and tests for Run 3

LHC beam spectrum: Stable beams

- Beam spectrum mainly from ADTObsBox (bbb, calibrated metric) & sometimes HS-BBQ or MIM (consecutive turns).

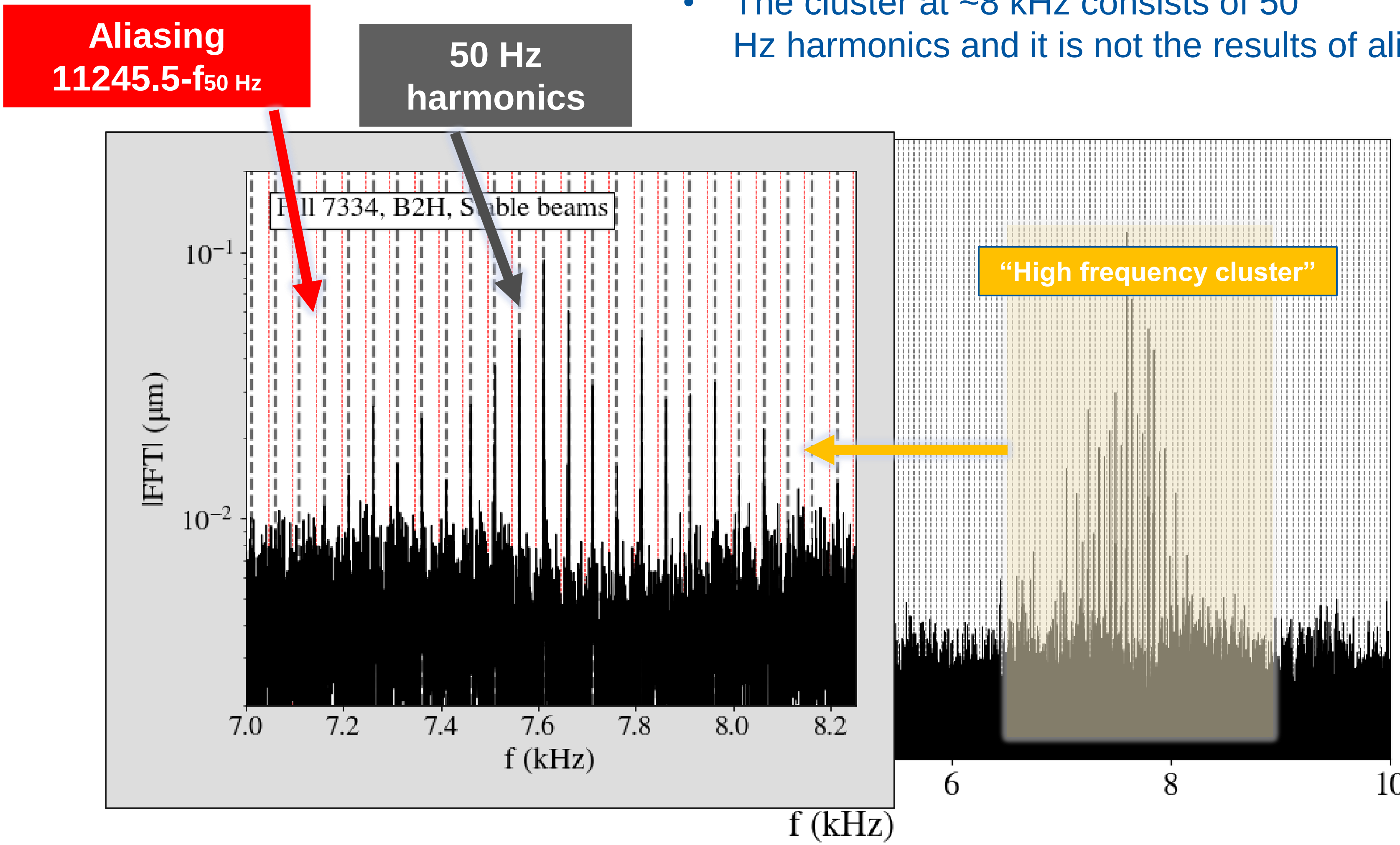
Low-f cluster:
up to 3.6 kHz

High-f cluster:
~7-8 kHz, in the regime f_{rev}-Q

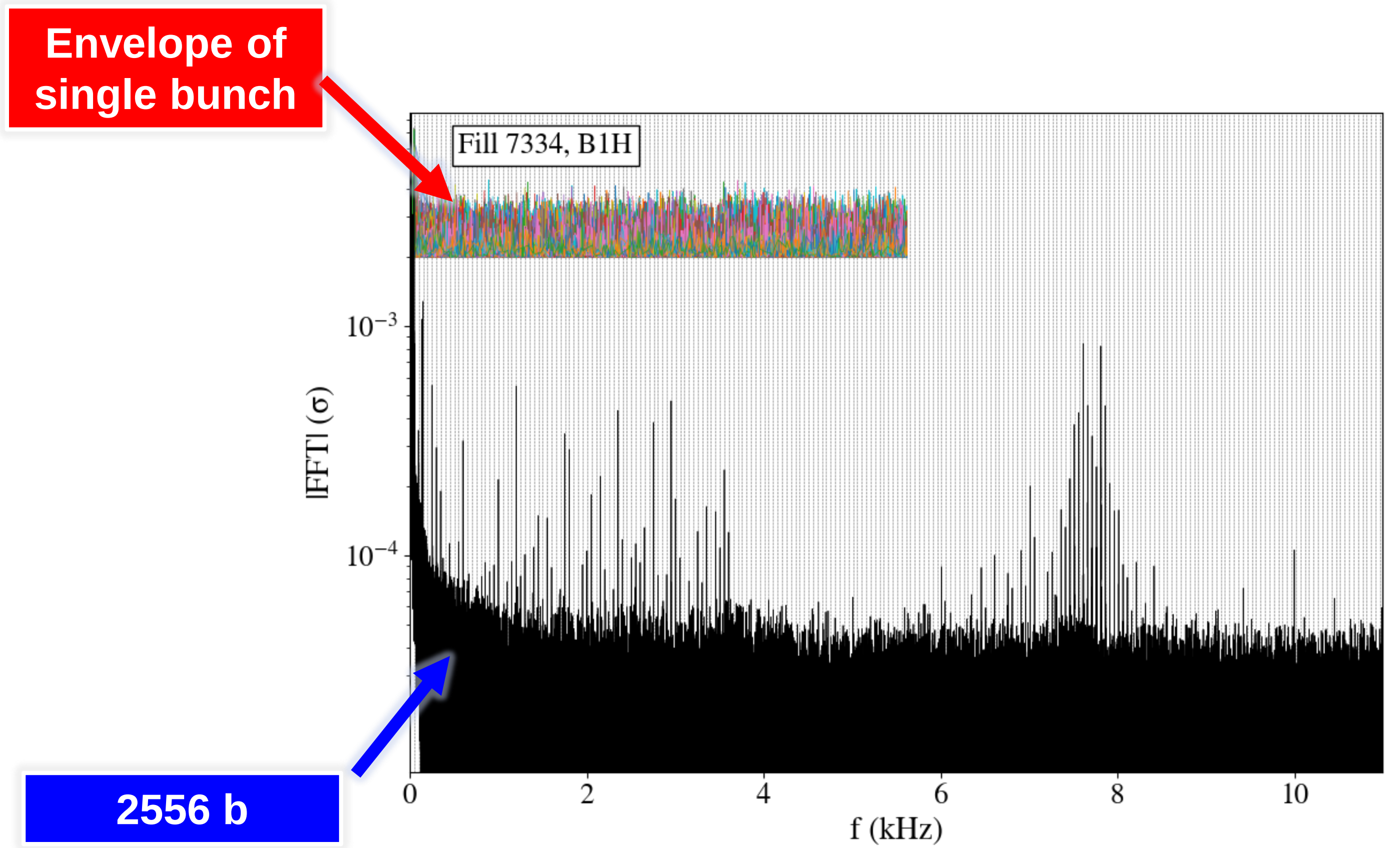


LHC beam spectrum: Stable beams

- As f_{rev} is not a multiple of 50 Hz, we can distinguish aliased frequencies from 50 Hz.
- The cluster at ~8 kHz consists of 50 Hz harmonics and it is not the results of aliasing.



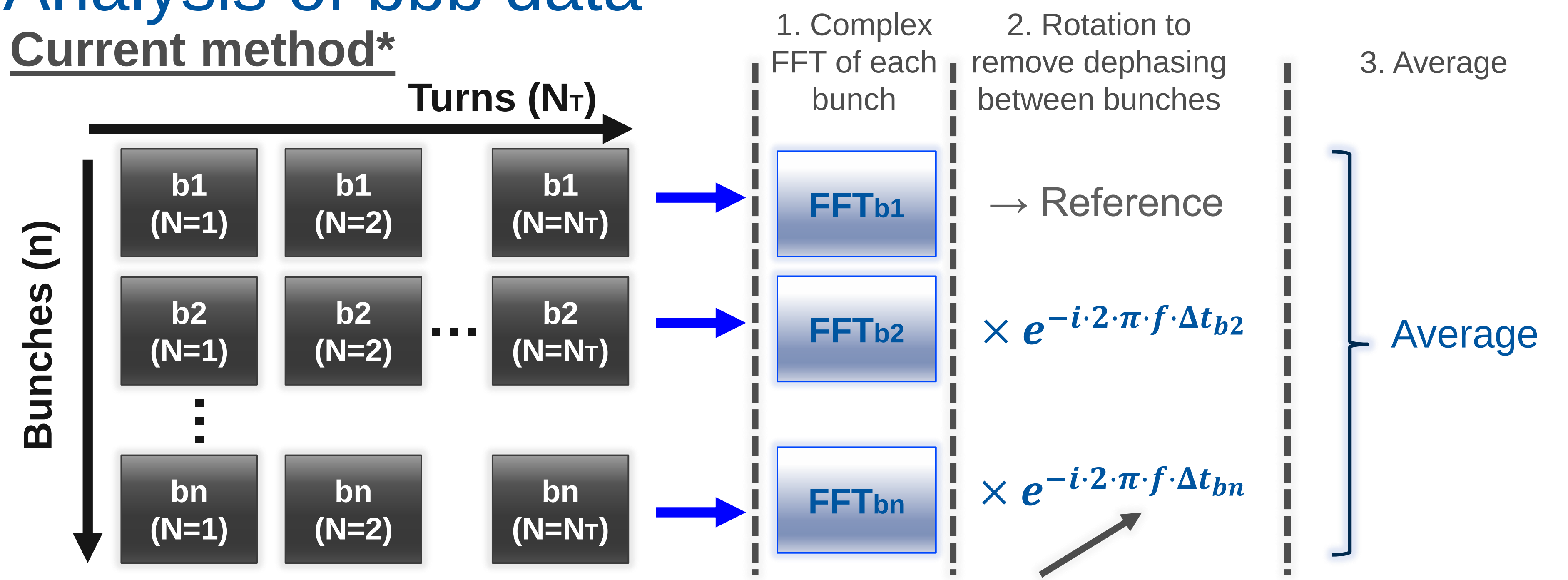
Analysis of bbb data



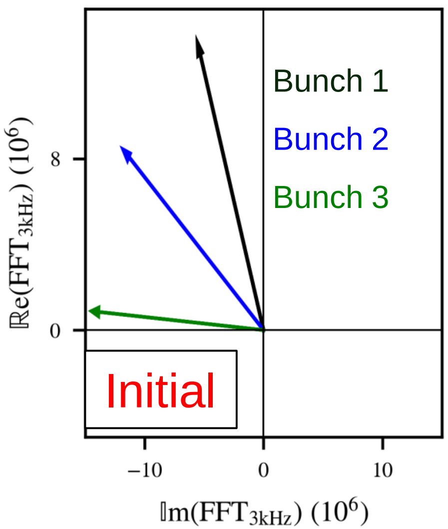
An average over bunches is needed in order to reduce the noise floor compared to the single bunch and access the 50 Hz.

Analysis of bbb data

Current method*



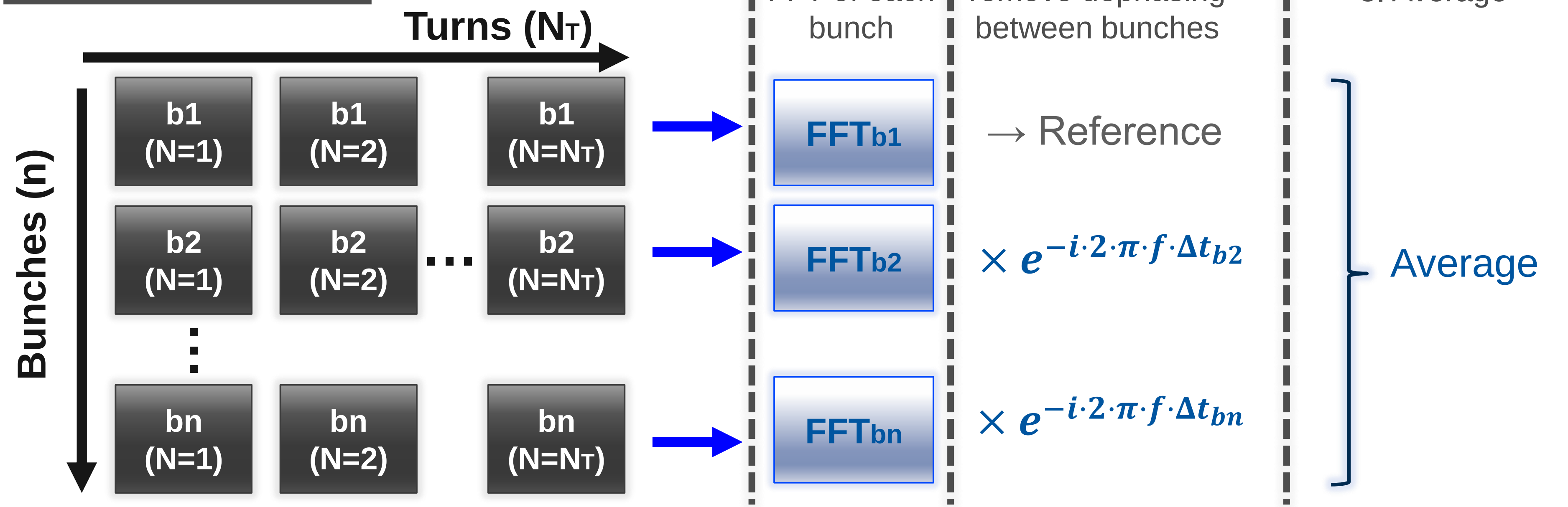
Dephasing proportional to frequency and bunch spacing. For low frequencies can be neglected, for high frequencies (e.g high-f cluster) rotation of the bbb spectra is needed.



*For a comparison with the previous methods used, see appendix (pg. 39)

Analysis of bbb data

Current method*



☑ Accurate metric for high frequencies, no aliasing, >0.5 frev

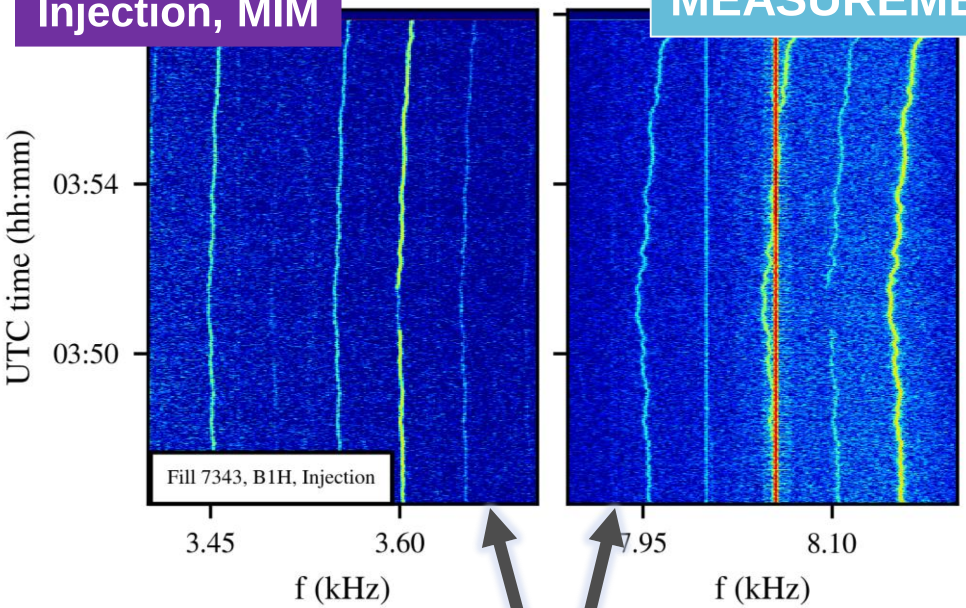
- A regular filling scheme (uniform sampling) is necessary , otherwise there will be errors (best for physics fills or when trains are placed azimuthally symmetric.)
- Online tool to compute spectra instead of storing the bbb TbT data in Run3?

* Example of the analysis in the appendix (pg.40-43)

Frequency evolution of the 50 Hz

Injection, MIM

MEASUREMENT

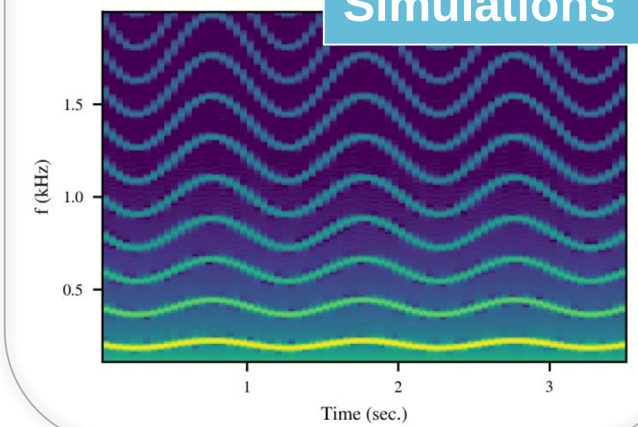


Modulation scales with the order of the harmonics.
Observed in both low and high frequency clusters.

Example:

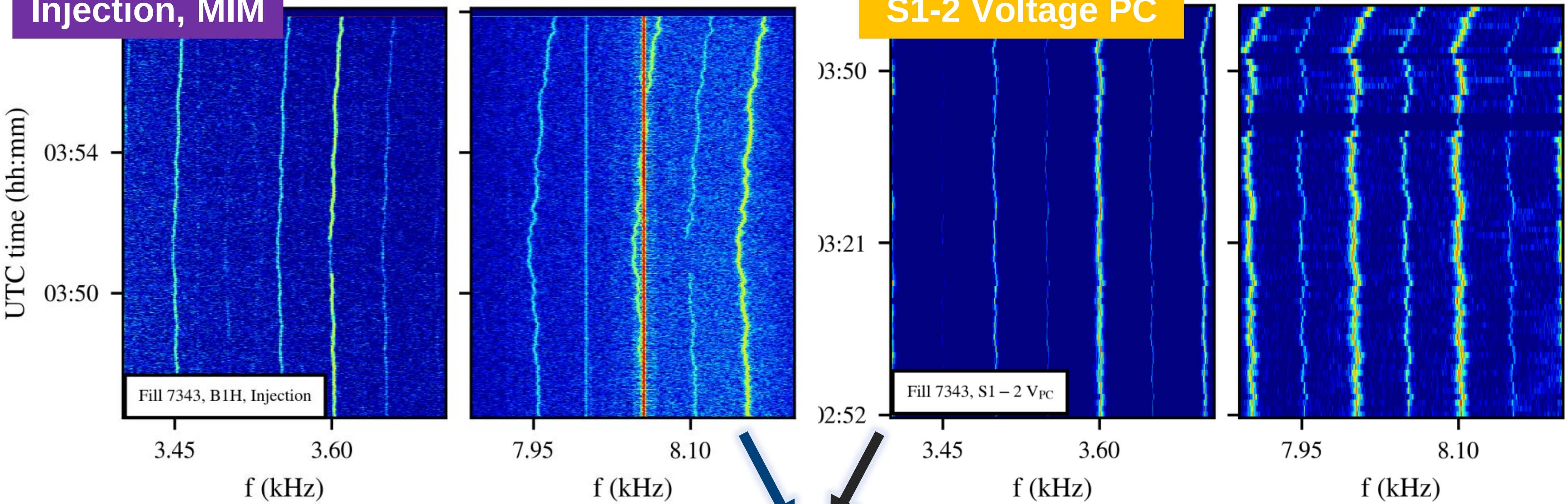
- Dipolar excitation at 200 Hz + non linear transfer function + modulation.
- All harmonics experience a modulation synchronous in phase.
- Amplitude of the modulations proportional to the order of the harmonic.

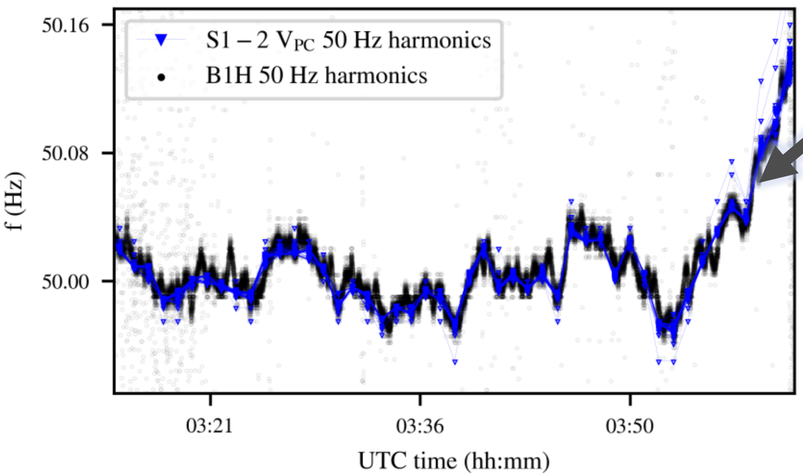
Simulations



Frequency evolution of the 50 Hz

MEASUREMENT



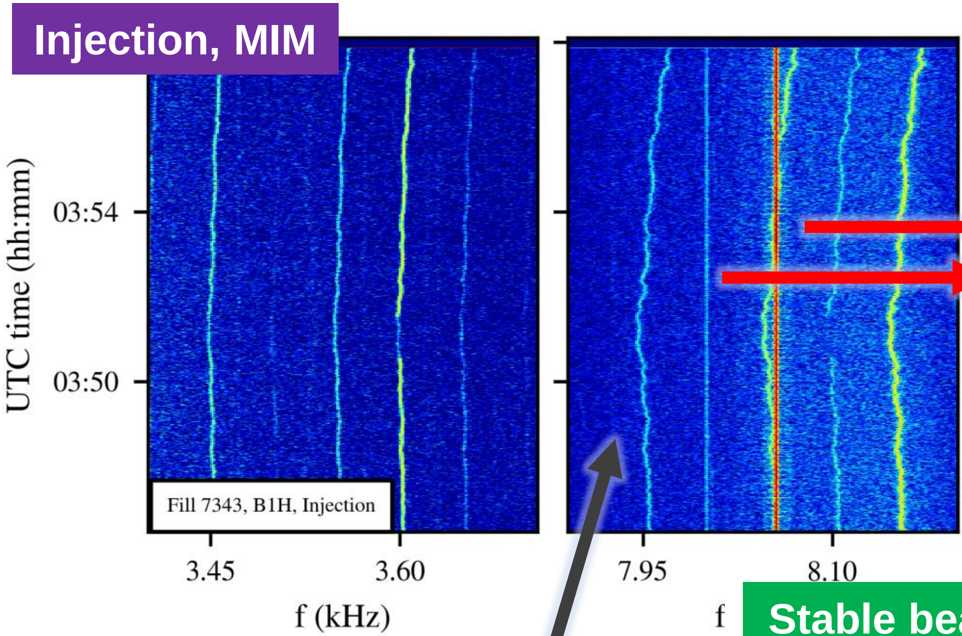


Algorithm that follows each harmonic, normalised with the order of the harmonic to retrieve the common oscillation

- This observation is not used to show a correlation between 50 Hz and dipoles.
- The same oscillaton is observed in LHC harmonics, harmonics of V spectrum of S1-2 MBs PC, PS, SPS, DCCTs.

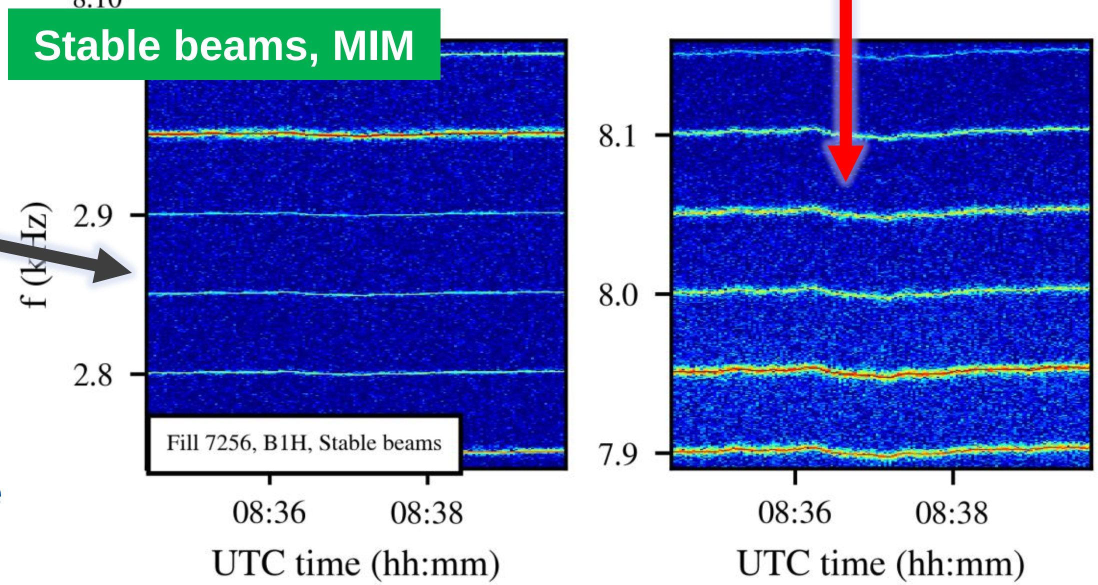
→ 50 Hz mains

Frequency evolution of the 50 Hz



- A different signature from the 50 Hz.
- Possibly a SM power converter or a clock of an acquisition card.
- Affecting mostly the vertical plane.
- Aliased in the BBQ as 3195.5 Hz.
- Attenuates during ramp.

Signature of 50 Hz



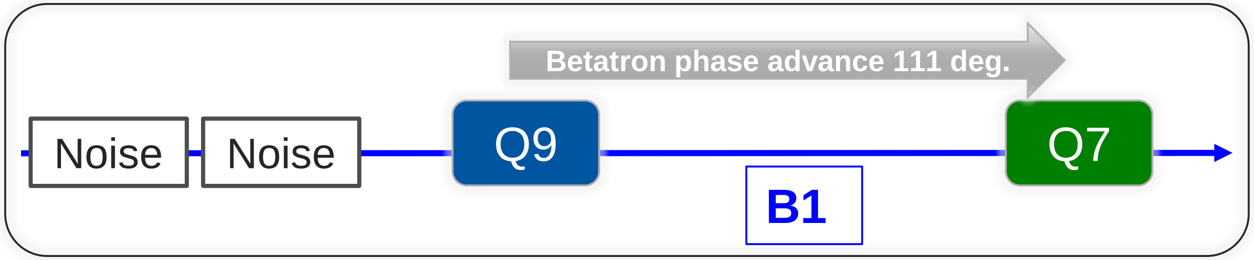
How do we know that they are real?

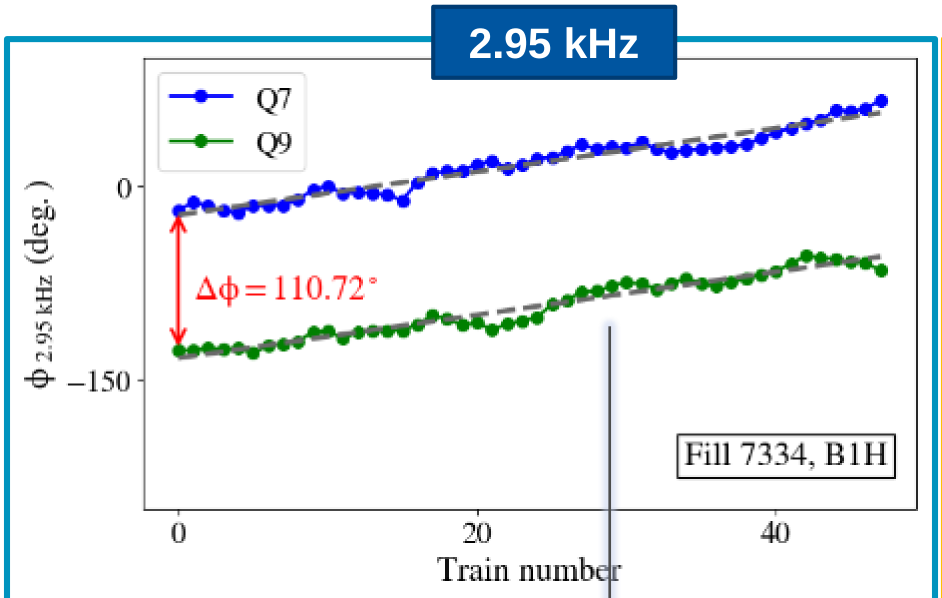
- Observations during operation.
- Observations during changes in the machine configuration.

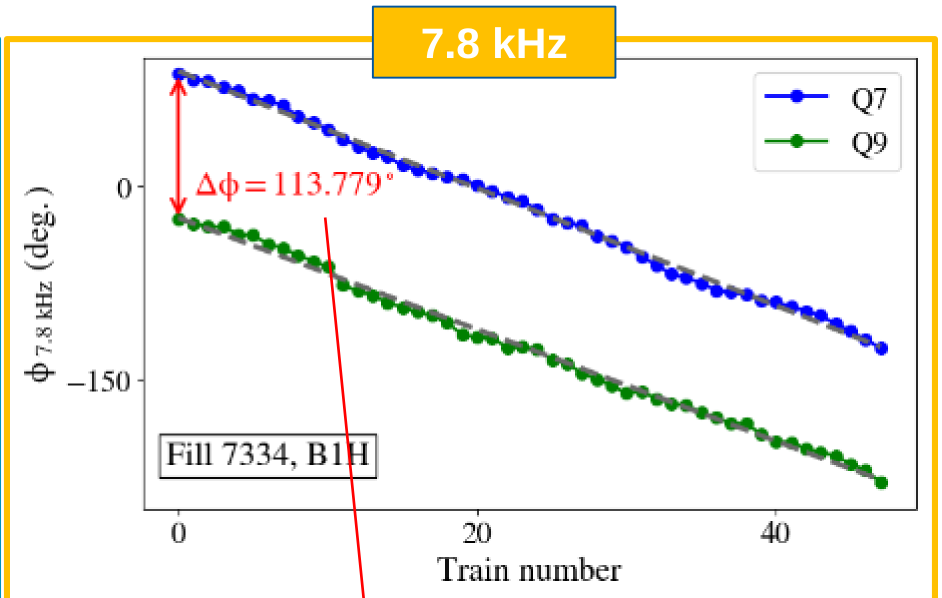
Are these tones an artifact?: Q7-Q9 phase advance

- The phase difference between 2 close-by BPMs (Q7 and Q9) for a given tone corresponds to the betatronic phase advance between Q7-Q9.

→ Reproducible for all harmonics above noise level*.







MEASUREMENT

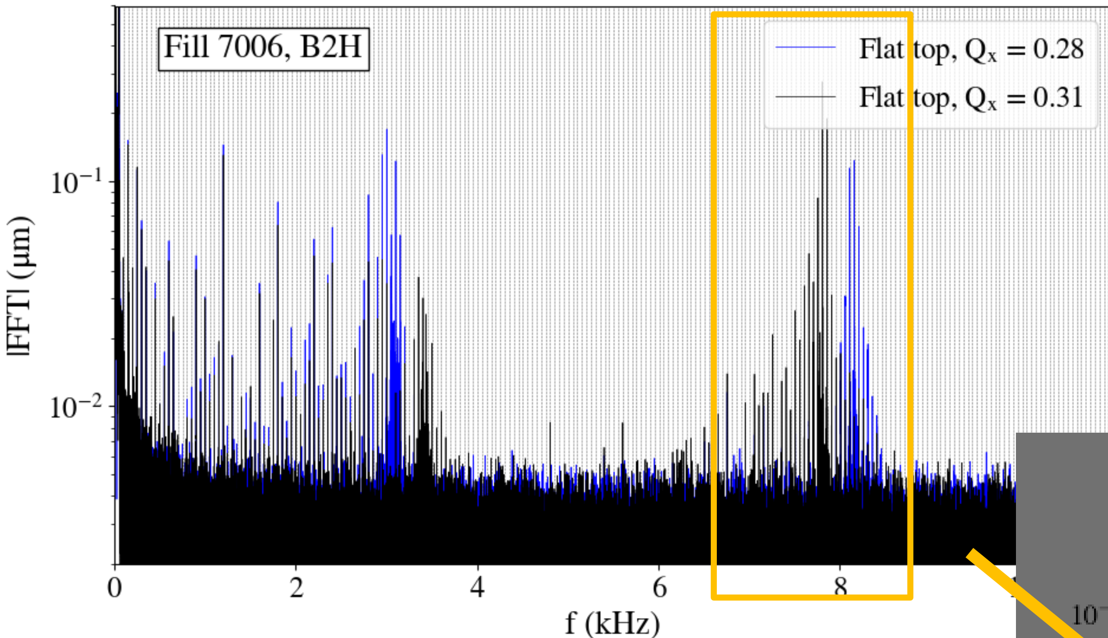
Average over 5 trains

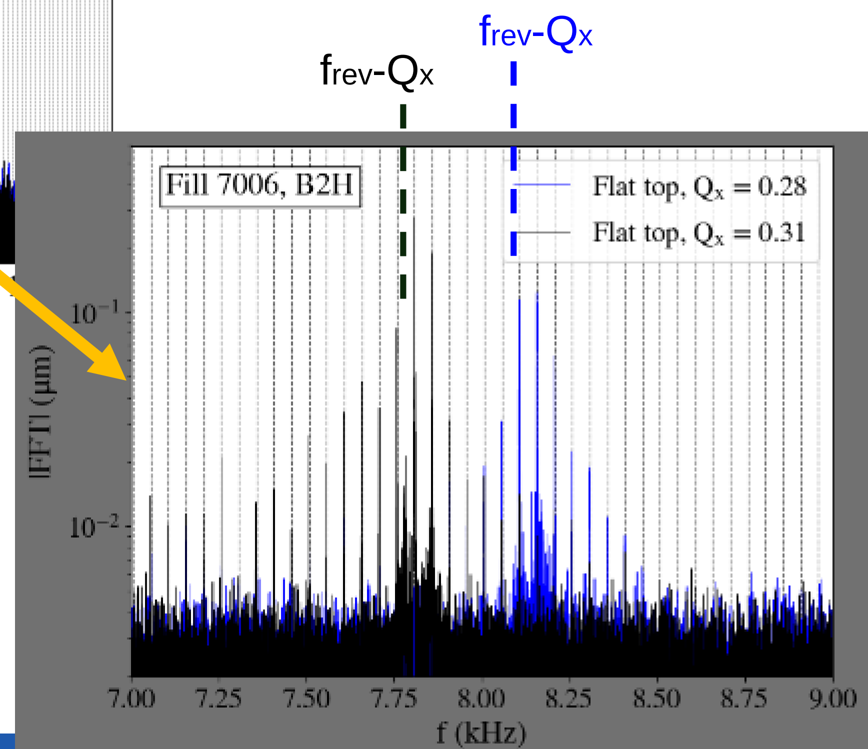
Noise phase advance

* See appendix (pg.44)

Are these tones an artifact?:Change of tune

- Visible impact on the spectrum when changing the tune.

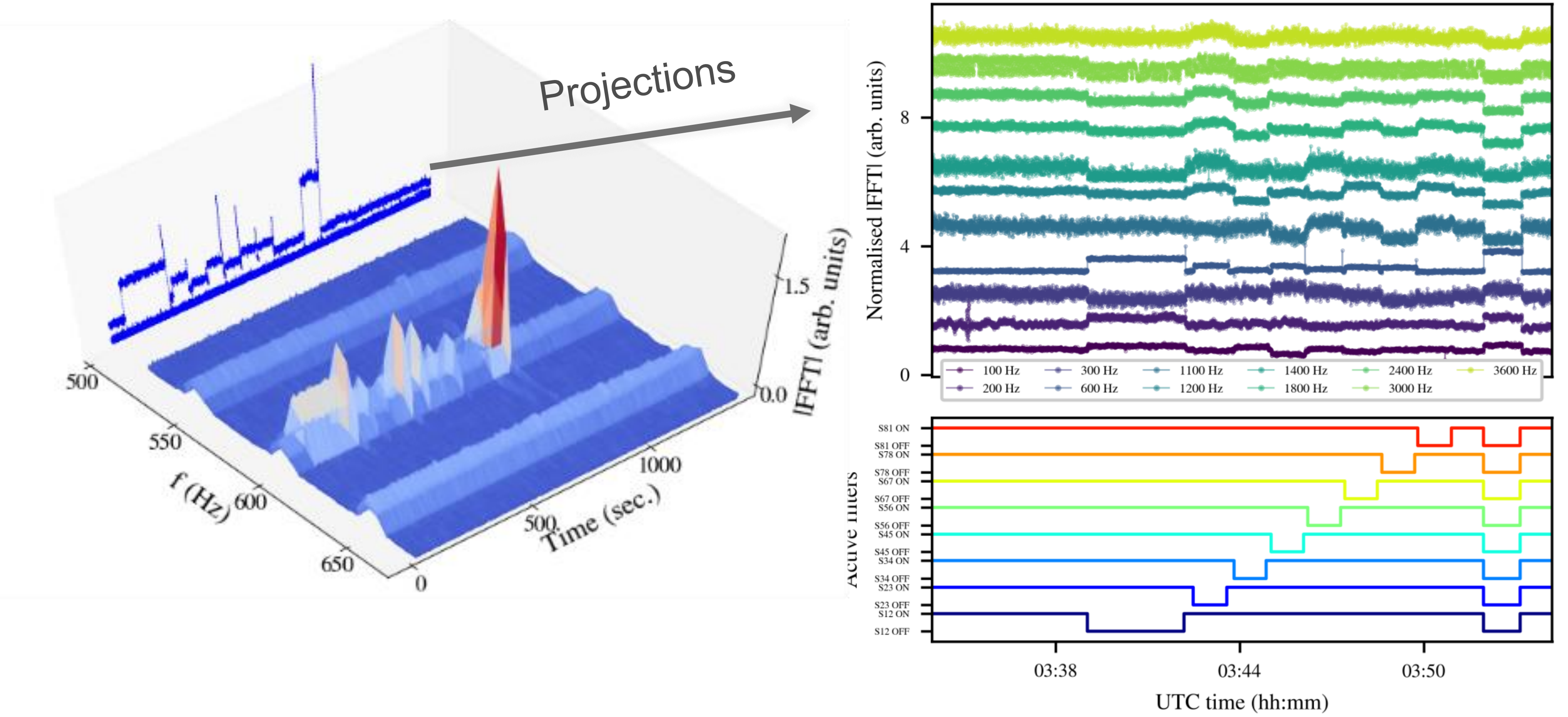




> Also, by keeping the tune constant and changing the phase advance between IP1/5 we see an impact on the low frequency cluster (see appendix), but not in the high frequency cluster (see appendix pg. 45)

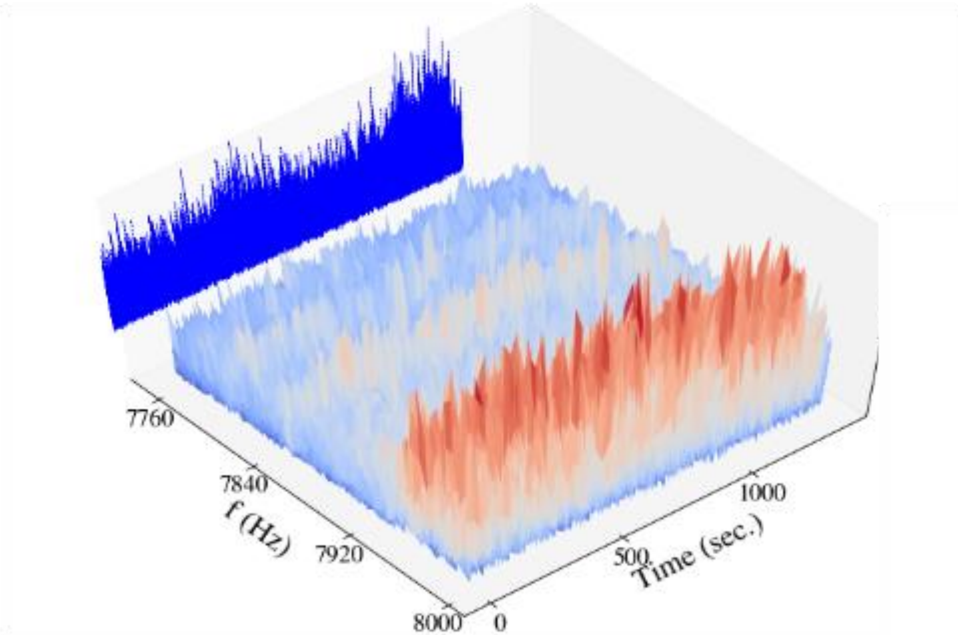
Are these tones an artifact?: Active Filters

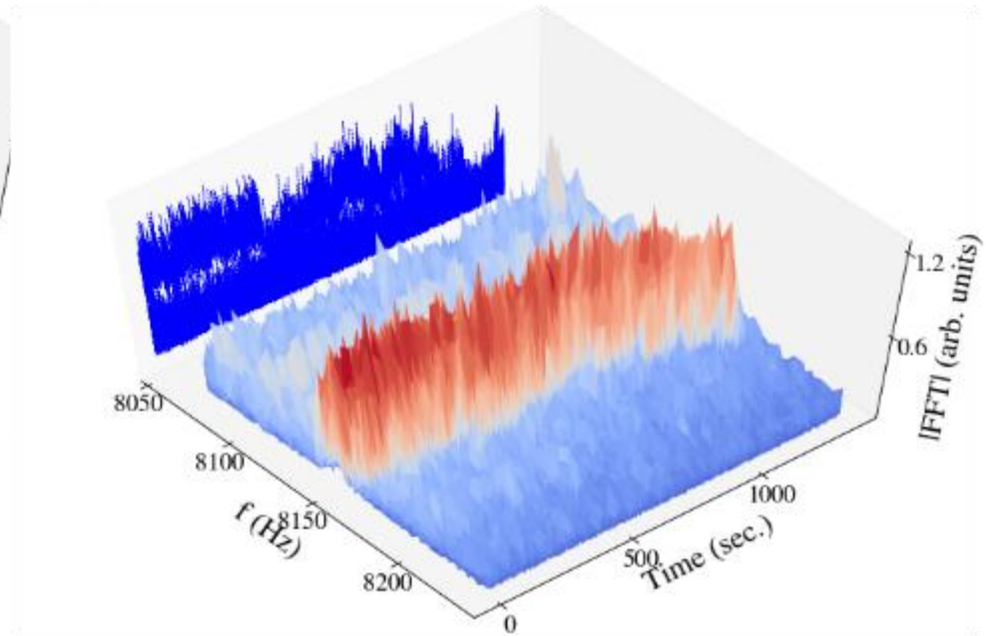
- Active filters tests: The status of the active filters affects the 50 Hz lines in the low frequency cluster→ Main bends are an important contributor.



Are these tones an artifact?: Active Filters

- Active filters tests: No impact in the high frequency cluster.



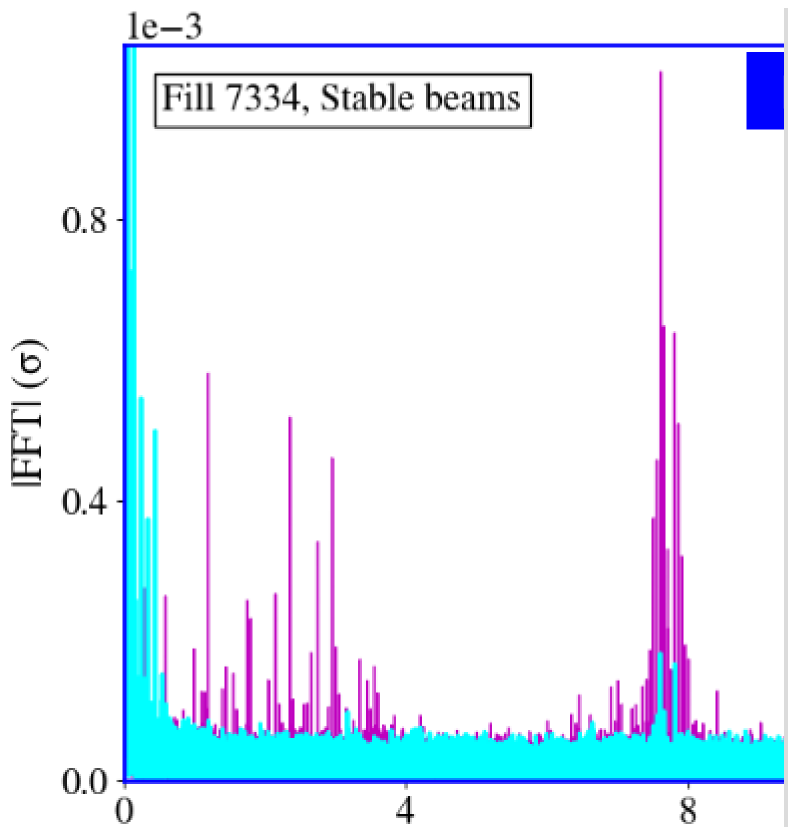


Which beam? Which plane?

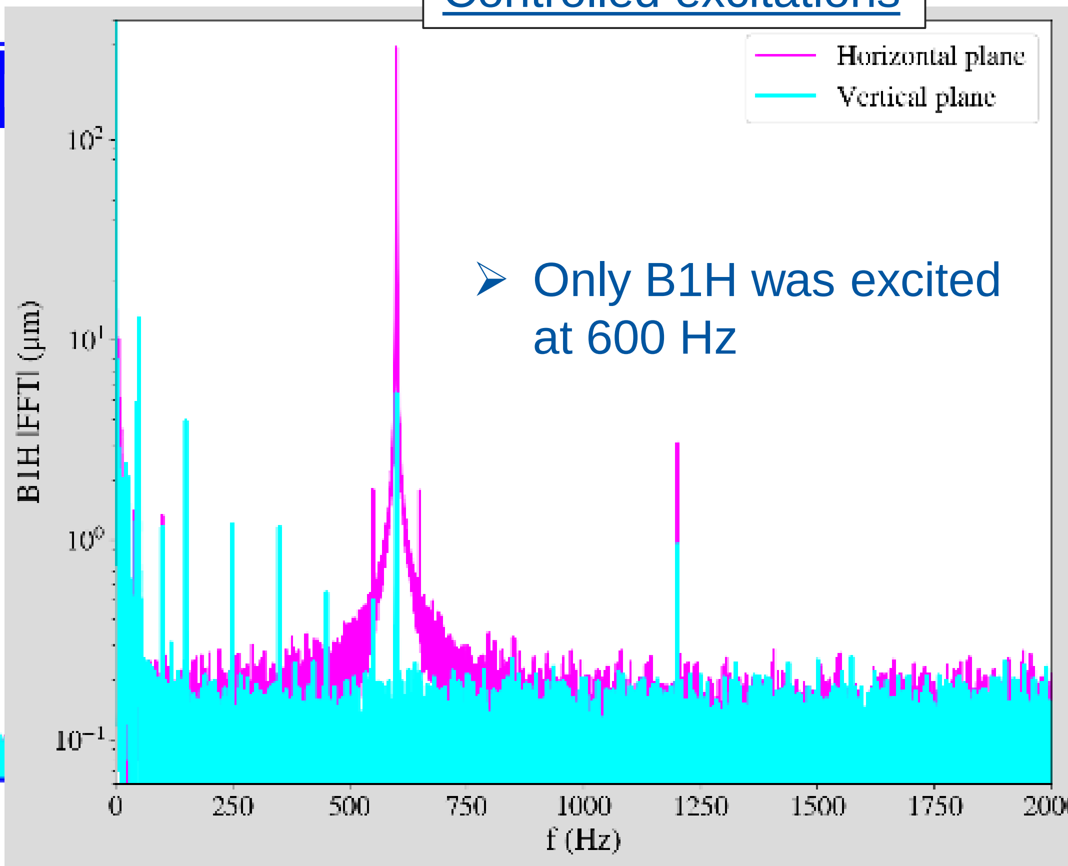
- Mainly in the horizontal plane and larger in B1.

→ The equivalent kick from a single dipole is θ=1e-11 rad (see appendix pg. 55)

→ H-V coupling compatible with observations during MD ADT excitations



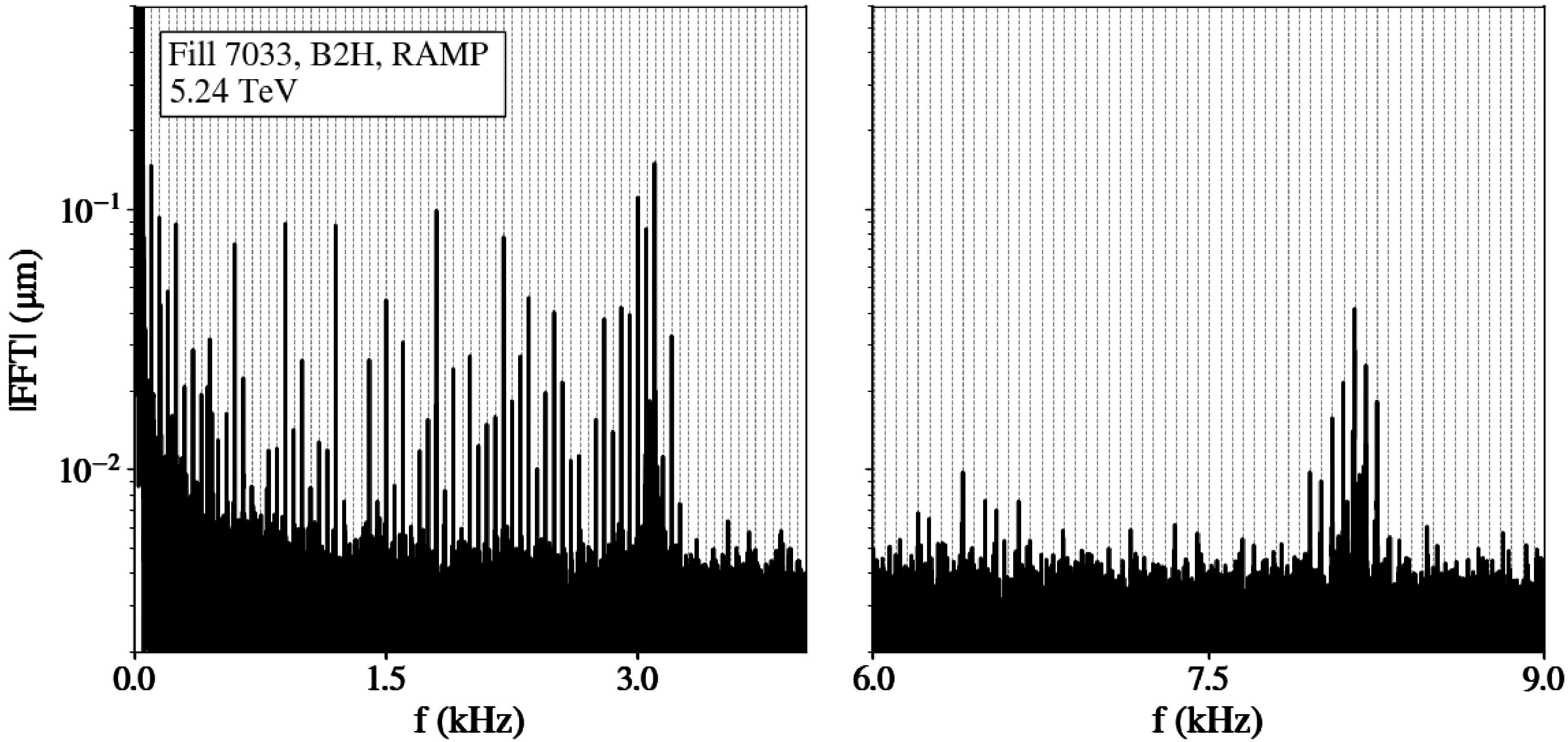
Controlled excitations



➢ Only B1H was excited at 600 Hz

Evolution during the cycle

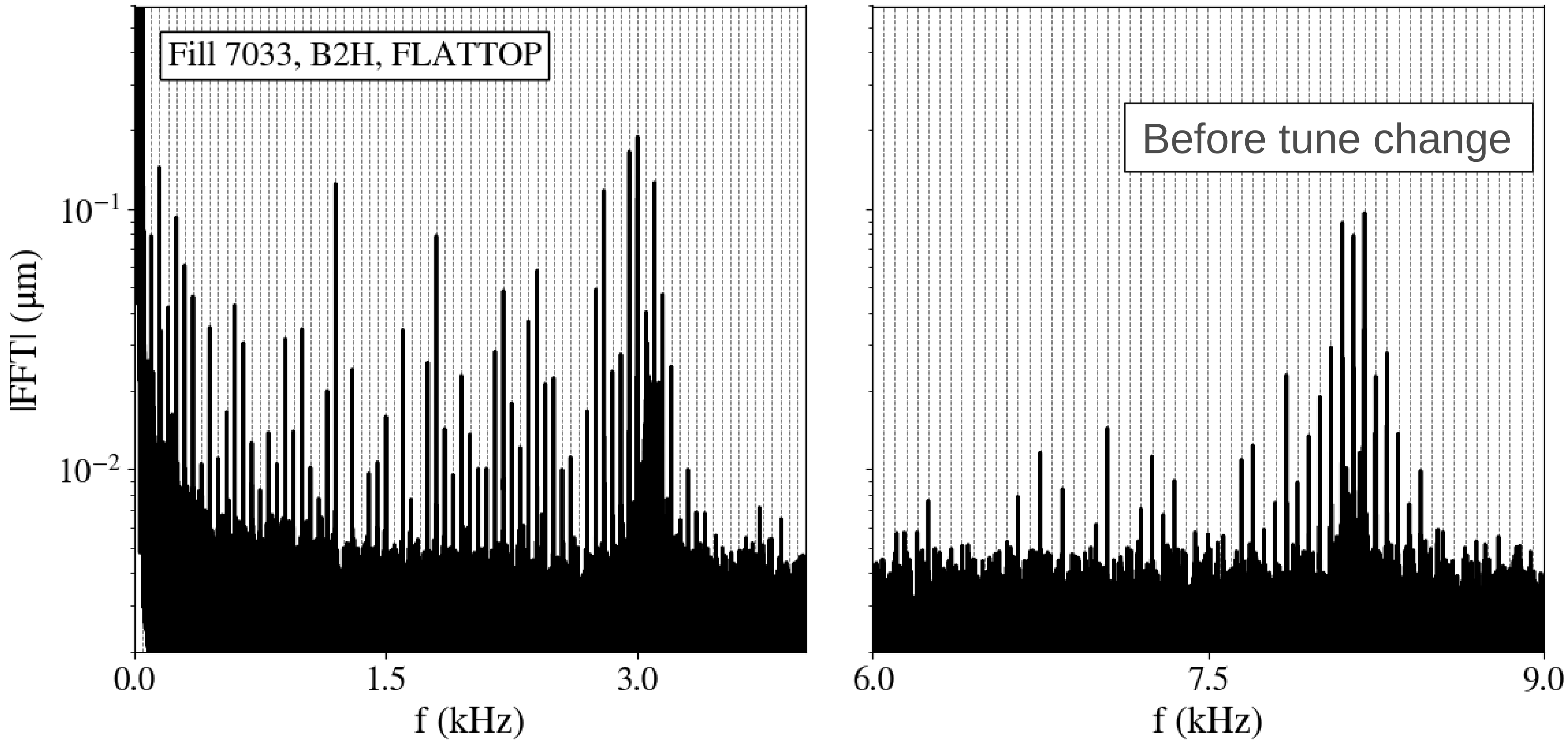
Is the picture beam mode dependent? Mildly.



No significant change on the noise in the MB PCs between flat bottom and top, but also no significant attenuation of the lines with increasing beam rigidity.

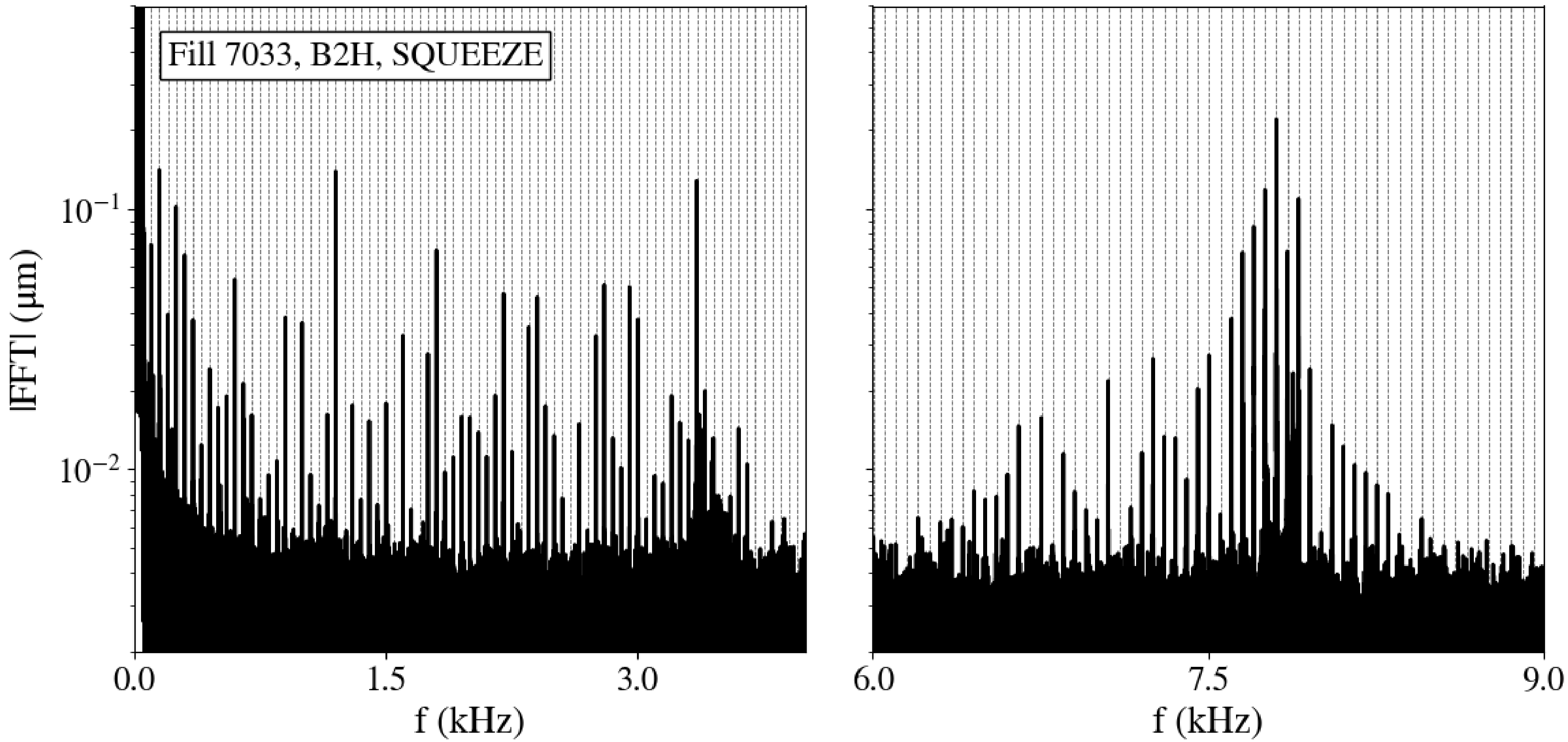
Evolution during the cycle

Is the picture beam mode dependent? Mildly.



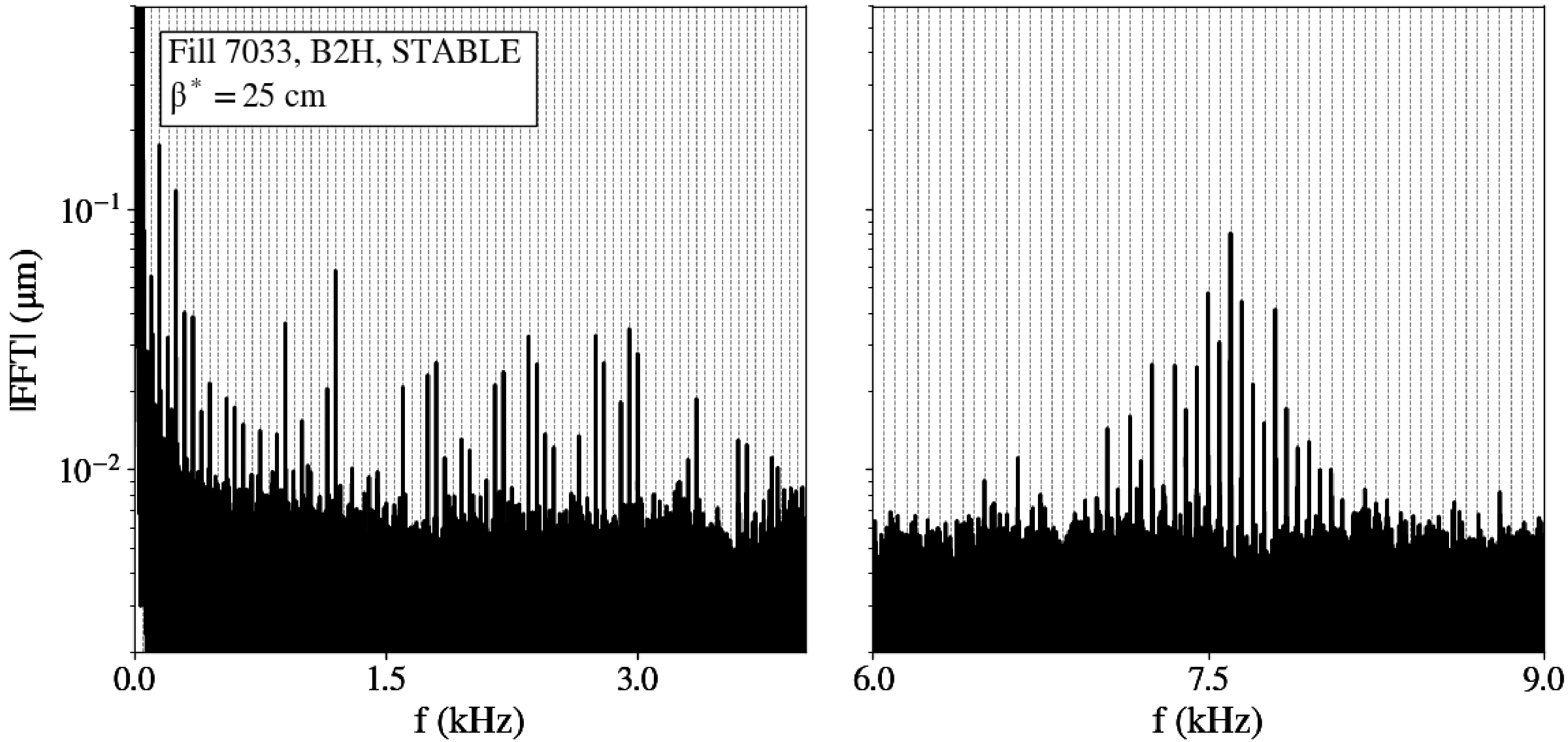
Evolution during the cycle

Is the picture beam mode dependent? Mildly.



Evolution during the cycle

Is the picture beam mode dependent? Mildly.



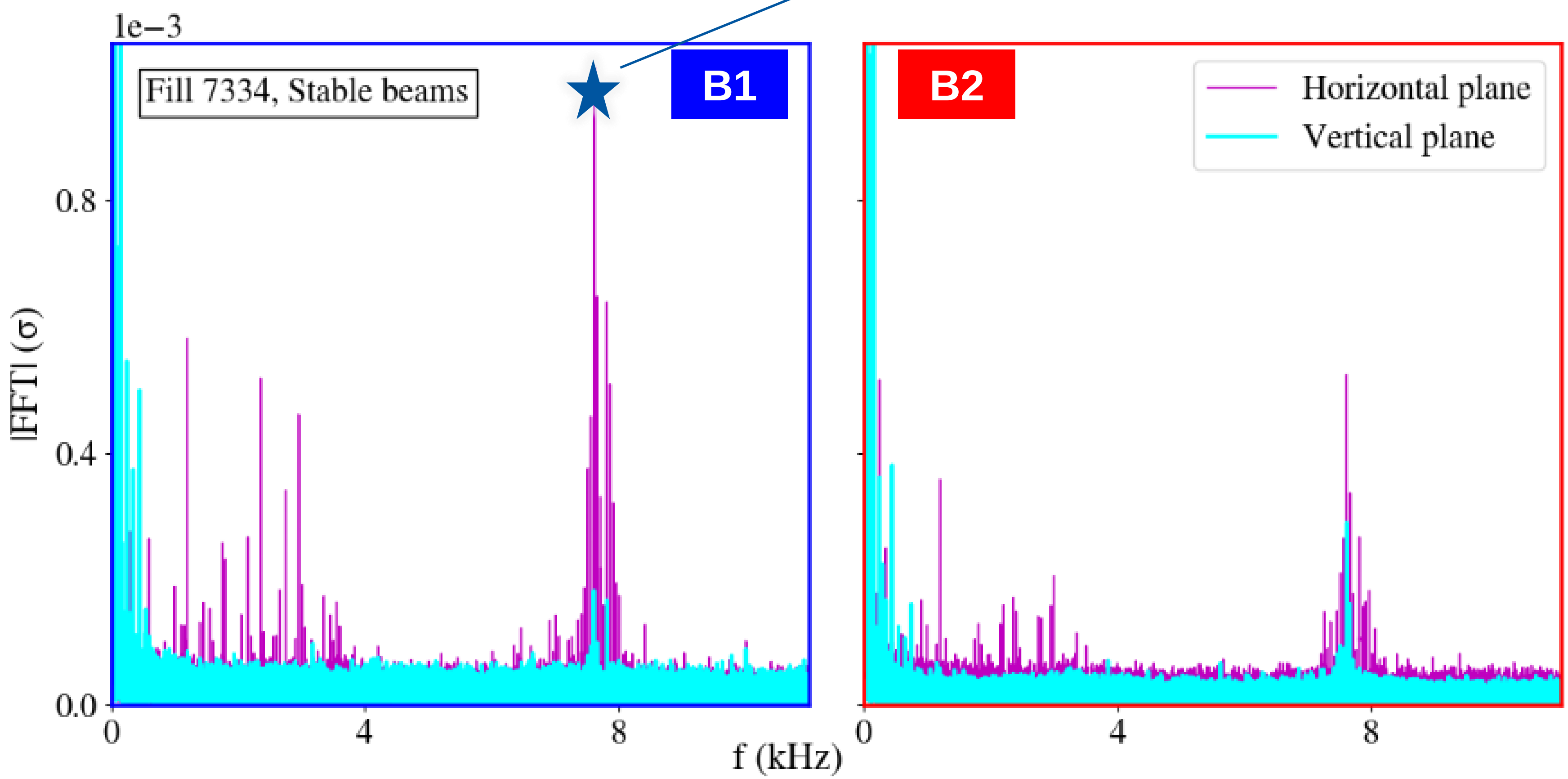
No change during the β* reduction (see appendix pg. 46)

Which beam? Which plane?

- Back to: Mainly in the horizontal plane and larger in B1.

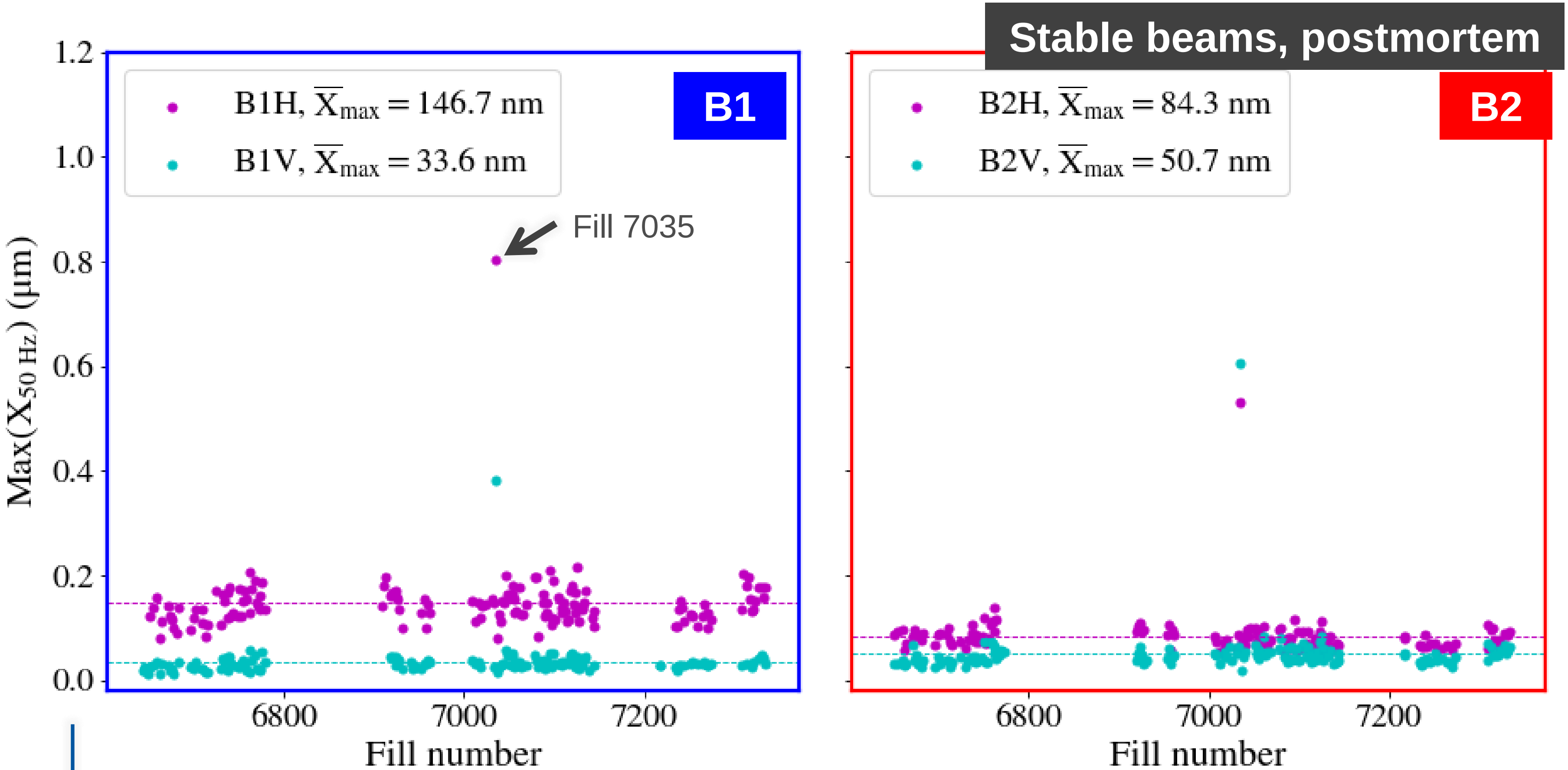
→ Is this reproducible across all fills?

The amplitude of the maximum peak is computed for all fills of 2018, for both beams and planes



Which beam? Which plane?

- Systematically larger for B1H.
- Offsets are very regular during all fills apart from Fill 7035.



Useful information to store for Run 3?

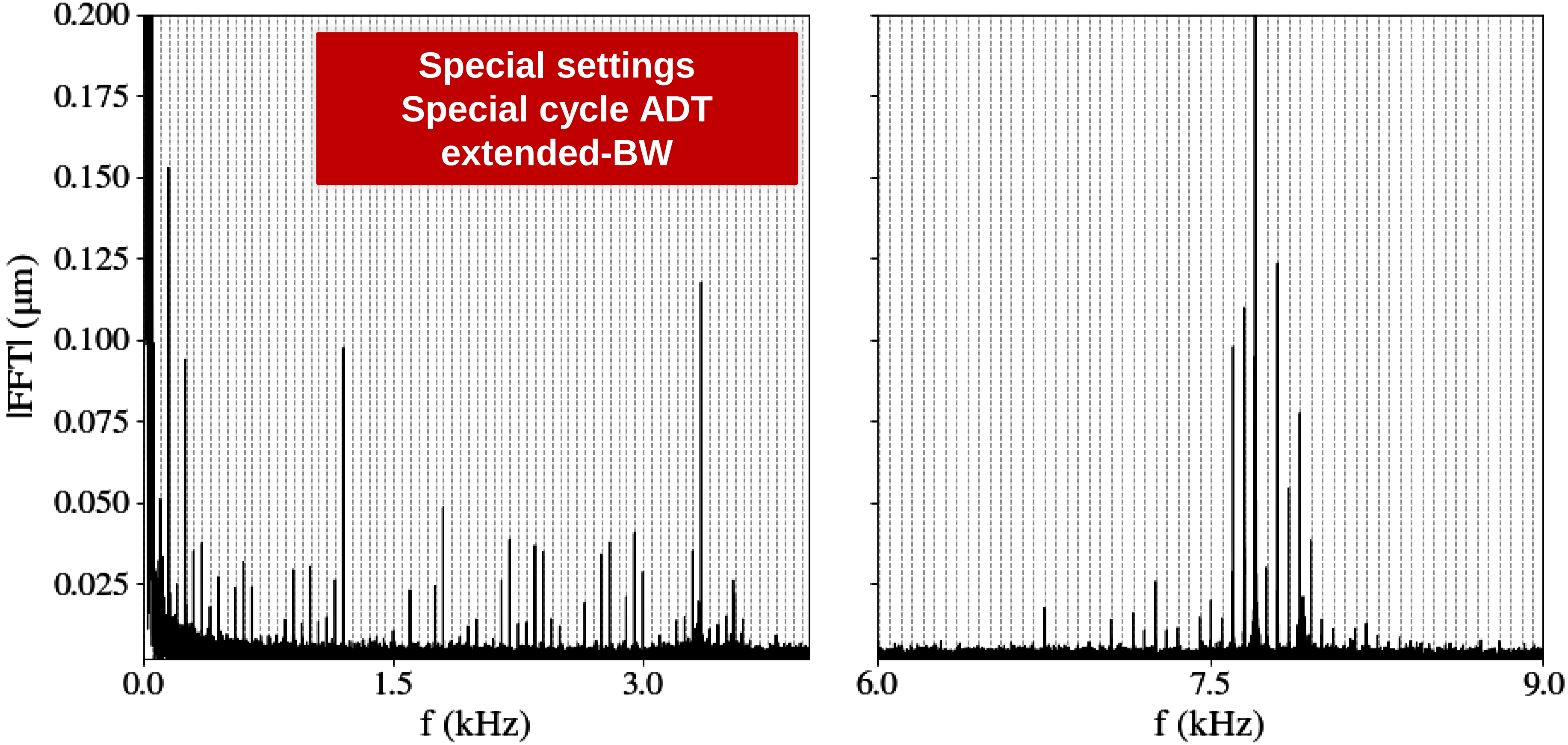
50 Hz harmonics & damper

- In Fill 7035, ADT was set injection BW at SB.

Harmonics > 3kHz are suppressed by the damper.

Fill 7035, Stable beams

➢ No visible impact on losses compared to Fill 7033



* Following the bbb variations of the 7.7 kHz in Fill 7035 indicates LR patterns (see appendix pg. 48)

All observations

Observations per cluster

4. Impact from status of the Active Filters

4. Impact from change of the tune
5. Impact from ADT settings (see appendix pg. 47)

"Low frequency cluster" ⟷ **"High frequency cluster"**

Common observations
1. Comb of 50 Hz harmonics.
2. Jittering from the mains, scaling with the order of the harmonic
3. Real excitation

Source: MBs are an important contributor

Source: ?
High and low cluster asymmetry?

General observations
- Mainly in B1H.
- An attenuation during ramp is not observed (consistent damper suppressing these lines).
- No impact from β* reduction (see appendix pg. 46)
- No change in the spectrum when a single beam is circulating in the machine (see appendix pg. 49)
- H-V coupling compatible with observations during ADT excitations.

What is the source of the 8 kHz cluster?

Still not clear:

- Sampling error? ☒ It is a real excitation.
- Same source? The signature between the low and high frequency cluster is very similar.
  - Direct excitation:
    - If the source is the dipoles, a 8 kHz oscillation is expected to be significantly attenuated by the shielding effect of the beam screen* (see appendix pg. 50-51).
    - Does not explain why the location of the cluster is at f_{rev}-Q.
    - Does not explain the asymmetry in terms of offset between the low & high frequency cluster.
  - **Present <u>hypothesis</u>**: Interplay between a mechanism on the beam, noise from the dipoles and damper:
    - Could explain why a higher sensitivity is observed at f_{rev}-Q.
    - Is it related to impedance (resistive wall **, first unstable mode at f_{rev}-Q for Q<0.5)?

* M. Morrone *et al*: *Magnetic frequency response of High-Luminosity Large Hadron Collider beam screens.*
** F.Ruggiero: *Single-Beam Collective Effects in the LHC*
D. Brandt and L. Vos*: Resistive Wall Instability for the LHC: Intermediate review*
P. Baundrenghien et al*: LHC Transverse Feedback System and its Hardware Commissioning*

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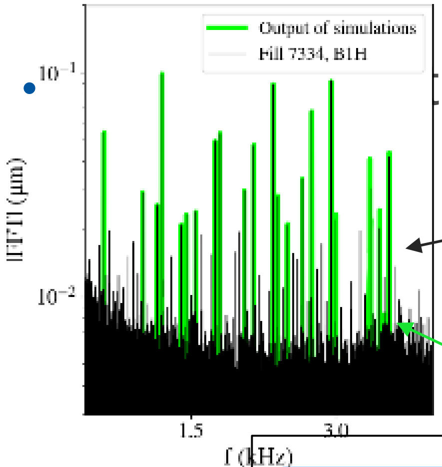
    - Could explain why a higher sensitivity is observed at f_{rev}-Q.
    - Is it related to impedance (resistive wall **, first unstable mode at f_{rev}-Q for Q<0.5)?

<u>Ideas for tests in Run 3:</u>

- Observations indicate that the ADT is suppressing the high frequency cluster:
  - Remove the damping around a single 50 Hz harmonic with a notch filter?
  - Increase the ADT gain only around the 50 Hz with a comb filter?

Simulating the effect of the observed spectrum

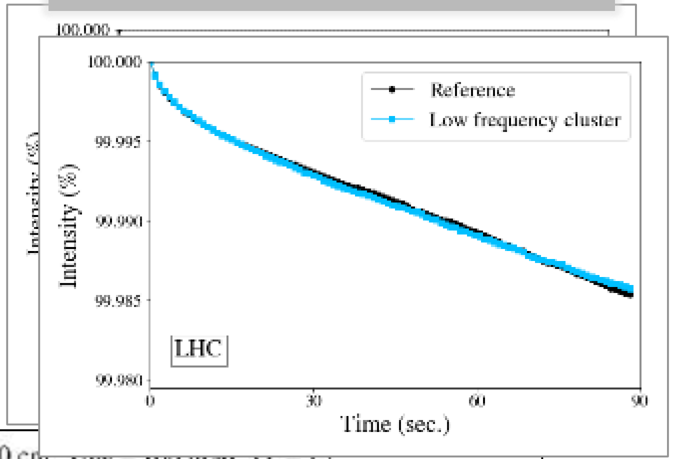


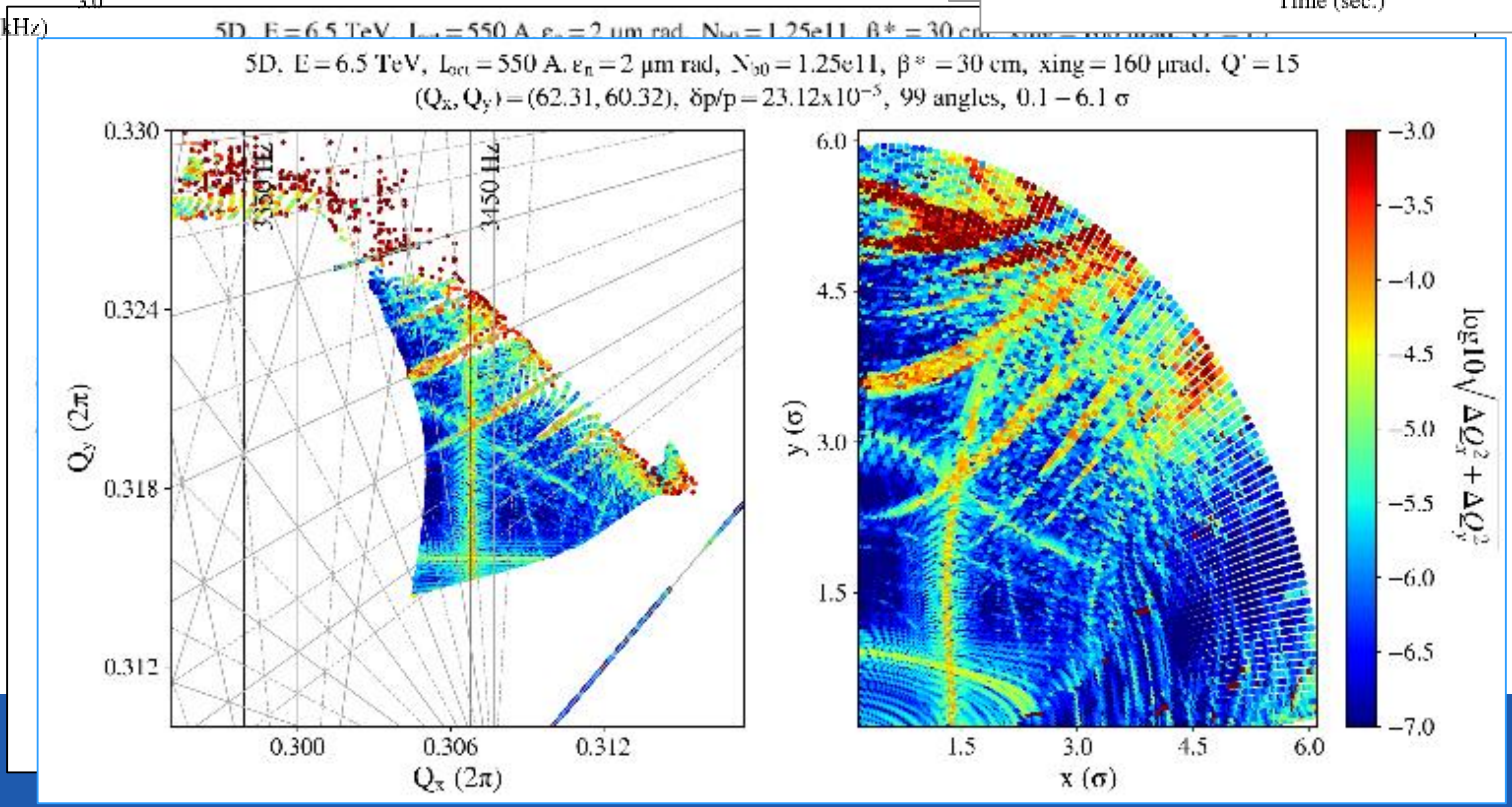
Considering "Low frequency cluster" Lumped in the ADT PU Q7

Real spectrum

Output of simulations (the largest harmonics have been selected)

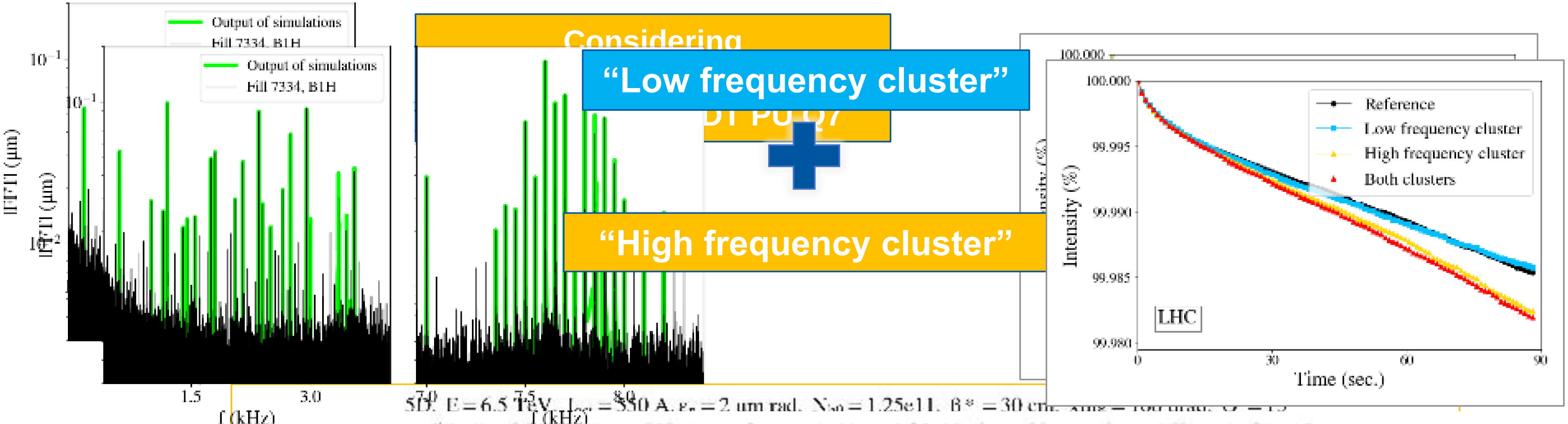
Losses with weighted distribution



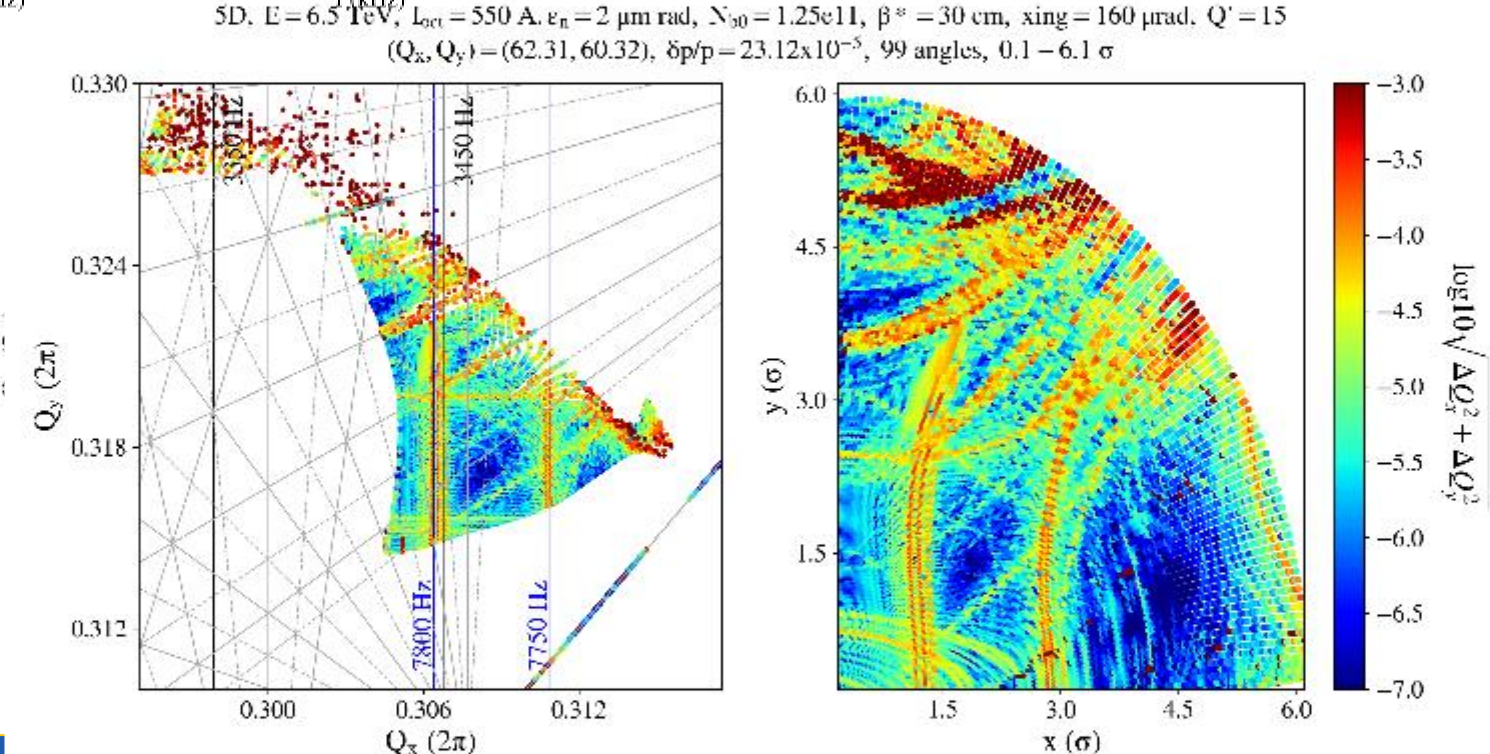


* Losses for HL-LHC see appendix pg.54

Simulating the effect of the observed spectrum



There is some increase on diffusion especially due to the high frequency cluster (-0.31 σ in DA). However, in Fill 7035, the increase of the lines by a factor of 2 did not lead to increased losses.



MD with controlled excitation and DA

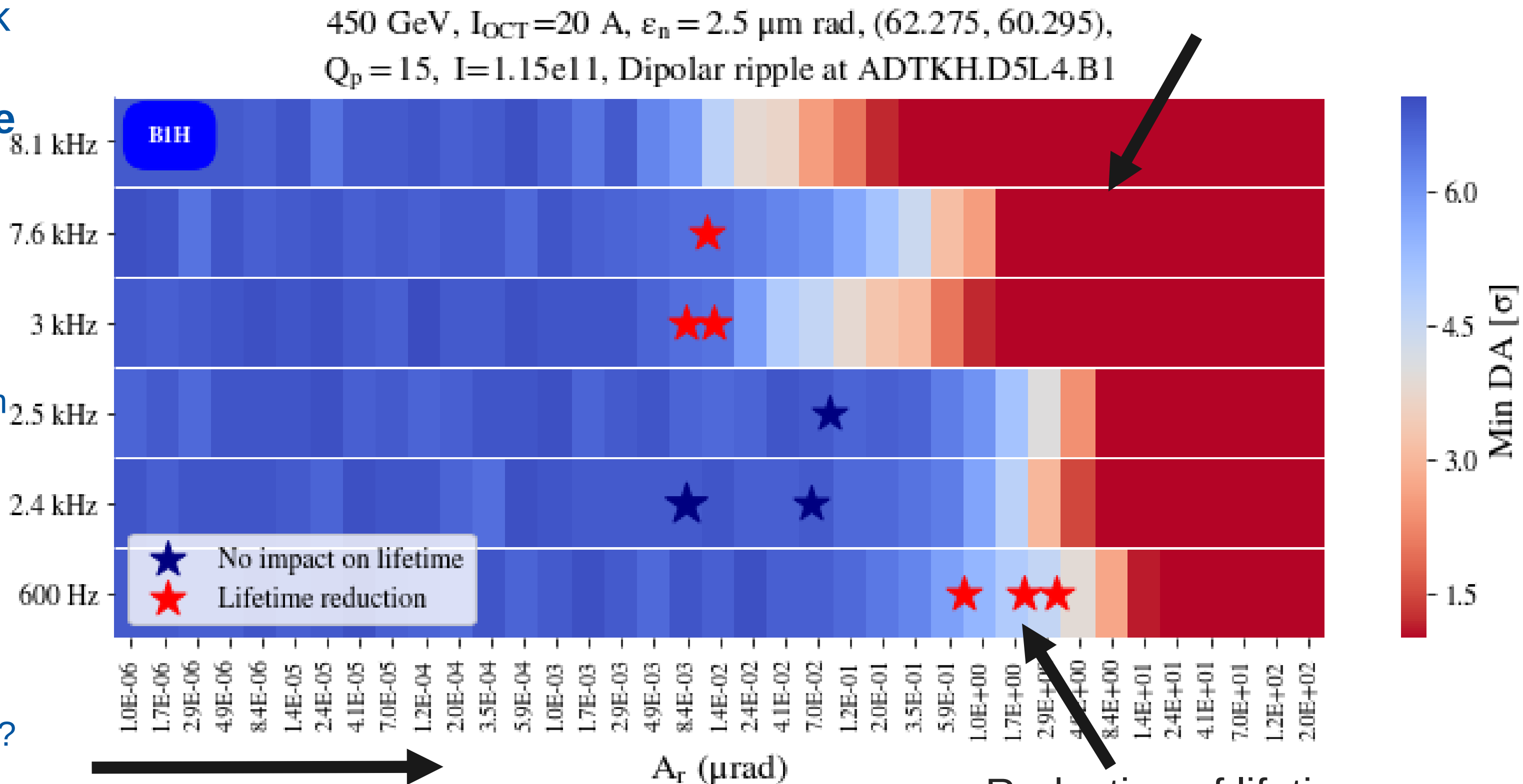
- During 2018, MD were performed and a **qualitative agreement** was found between observation and simulation.

DA reduction expected from simulations

The equivalent kick from the ADT is computed **from the beam spectrum**

The equivalent kick at 600 Hz exceeds the maximum ADT strength (2 μrad at injection)

The excitations were much larger than expected based on the ADT parameters → interplay of excitation with pre-existing 50 Hz?



Increasing amplitude of the noise

Reduction of lifetime during ADT excitations

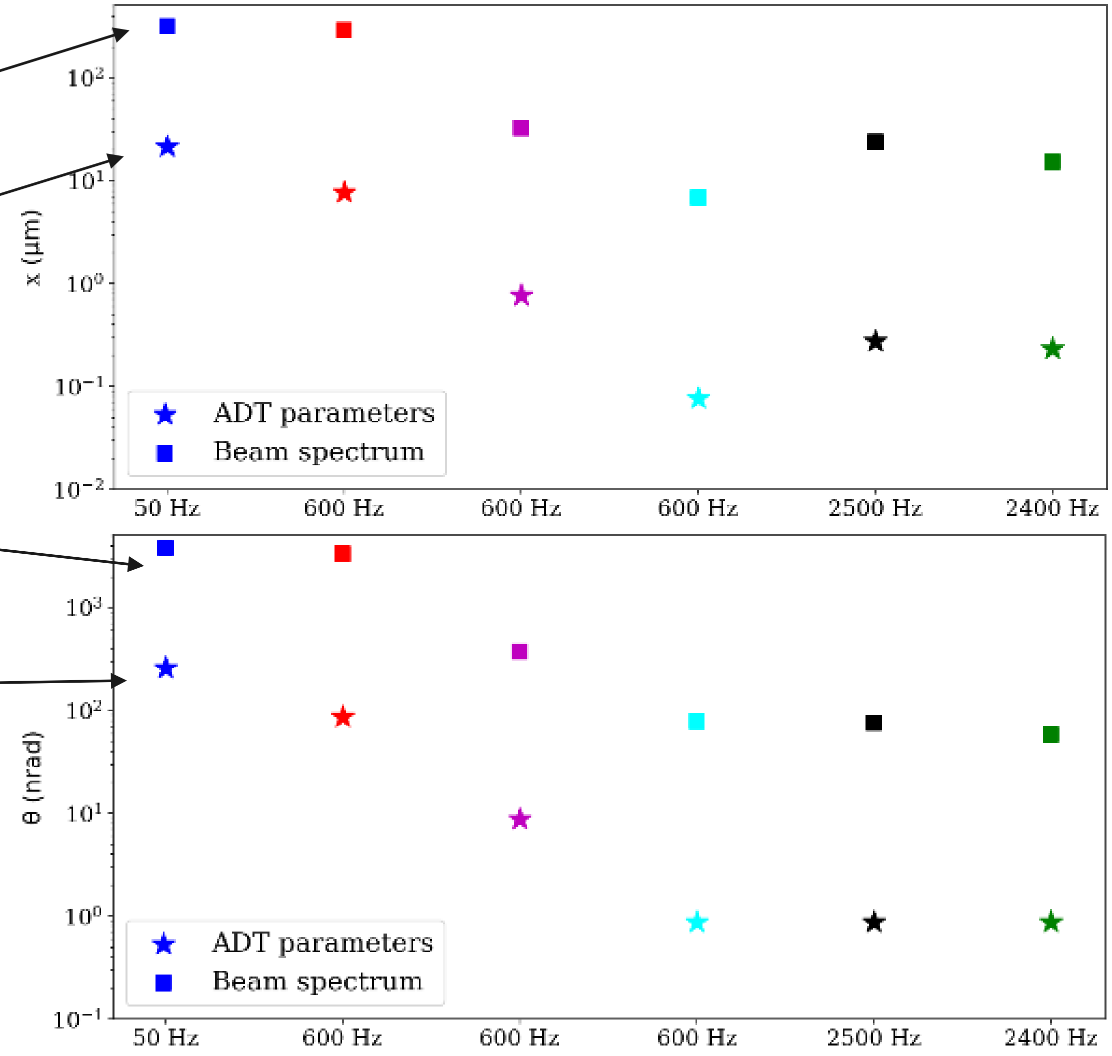
A note on controlled excitation

Offsets in beam spectrum

Equivalent offsets from kick computed from ADT parameters

Equivalent kicks from beam spectrum.

Kicks from ADT parameters.



* Also, during controlled ADT excitations, B1-B2 coupling through LR encounters in the presence of trains in appendix pg. 52-53

Part 2: Inner triplet simulations for HL-LHC

Inner Triplet studies for HL-LHC

1. Considering Q1, Q2a, Q2b, Q3 left and right of IP1 & 5.
2. Scan individual frequencies for different strengths in order to define threshold of DA reduction.
3. Compare with PC specifications.

<u>Power converters</u>

- Switching frequency from **50-200 kHz***

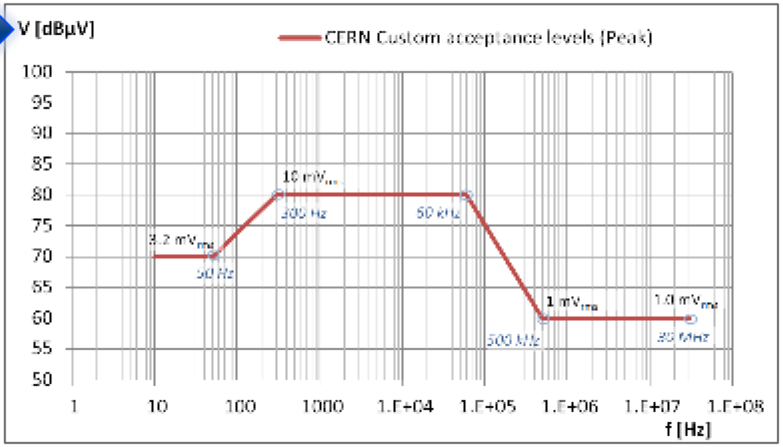
<u>Transfer function</u>

- **Maximum** output voltage
- Impact from beam screen, cold bore **not included**.

<u>Simulations</u>

- Scan up to 10 kHz
- Not optimized working point
- Conservative approach**: same phase of noise in all locations** leads to maximum modulation

<u>Maximum</u> output voltage



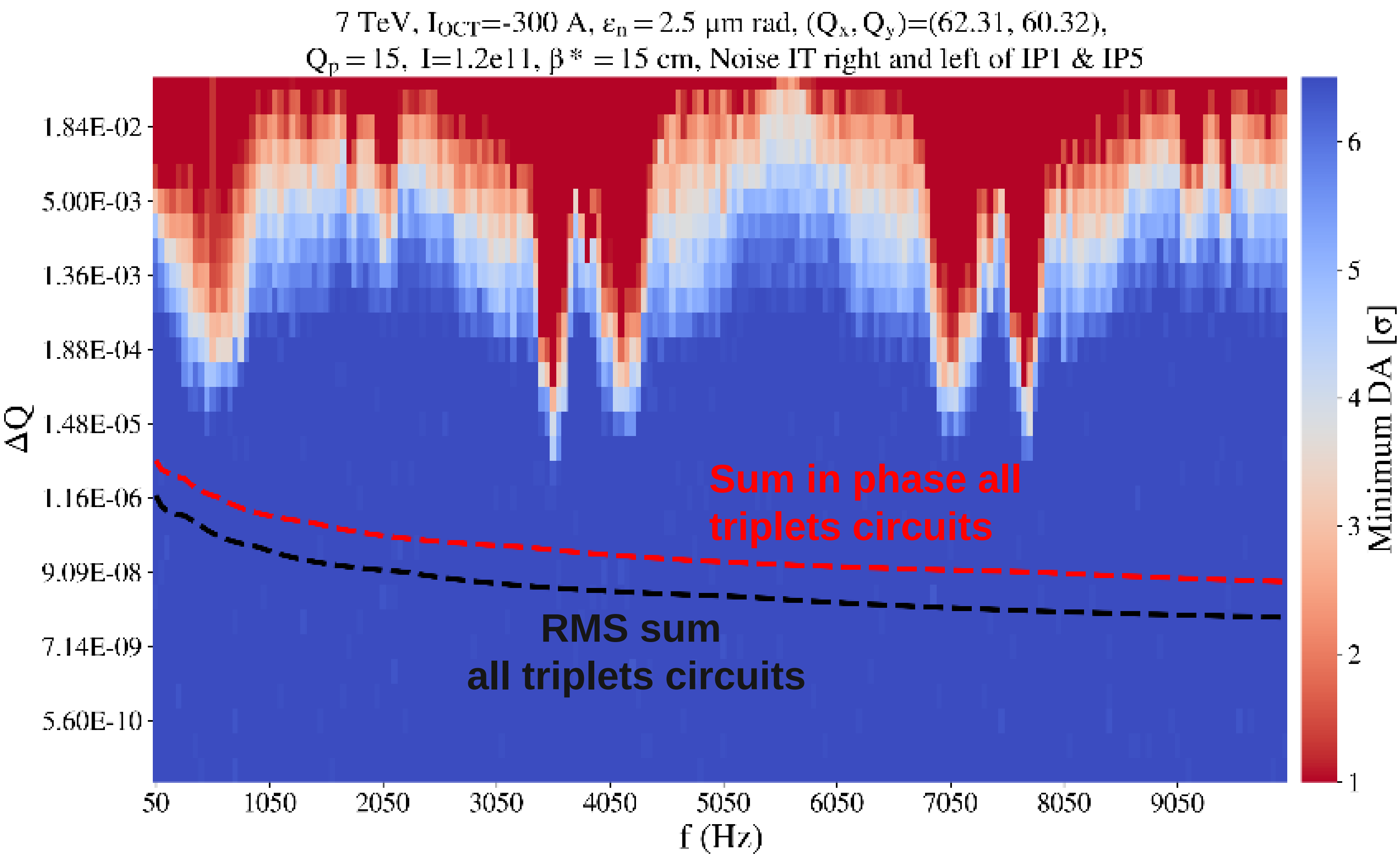
Simulation parameters
HLLHC.v13
ε_n=2.5 µm rad
I=-300 A
(Q_x, Q_y)=(62.31,60.32)

7 TeV
I=1.2e11
$\theta_{crossing}$=250 µrad
V_{RF} = 16 MV
Δp/p=25.78e-5

* D. Gamba *et al*: *Update of beam dynamics requirements for HL–LHC electrical circuits*

Inner Triplet: DA studies

Similar results for nominal & ultimate scenario



Conclusions & next steps

Harmonics of 50 Hz:

- 2 regimes of interest have been identified: **the low** (up to 3.6 kHz) and **high** (7-8 kHz) frequency cluster.
- Larger impact on **B1H and in both cases the effect is dipolar in nature.**
- Both regimes are the result of a **real beam excitation**.
- A correlation of the 8 power converters of the **Main Bends and the low frequency cluster** has been identified. The studies concerning the source of the **high frequency cluster** are inconclusive: the present hypothesis is that is due to an **interplay between noise, damper and a mechanism from the beam.**
- Simulations in the LHC & HL-LHC (assuming the same spectrum) with a realistic beam spectrum (lumped dipolar perturbation in a single location) indicate that the **harmonics lead to an increase of diffusion and eventually losses,** especially due to the **high frequency cluster**.
- **These harmonics will also be present in the future.**
- **Future planes and tests:**
  - Online tool for ADTObsBox FFT analysis and storage.
  - Suppress the damping only around the 50 Hz with a notch filter in the ADT.
  - Change the gain only around the 50 Hz with a comb filter in the ADT.

Inner triplet:

- Switching frequencies at **50-200 kHz**
- Even with a conservative approach (no beam screen, maximum output voltage, same noise phase in all location, not optimized working point), **orders of magnitude below the threshold of DA reduction.**

Backup slides

Dipolar excitation vs tune modulation

1D FFT

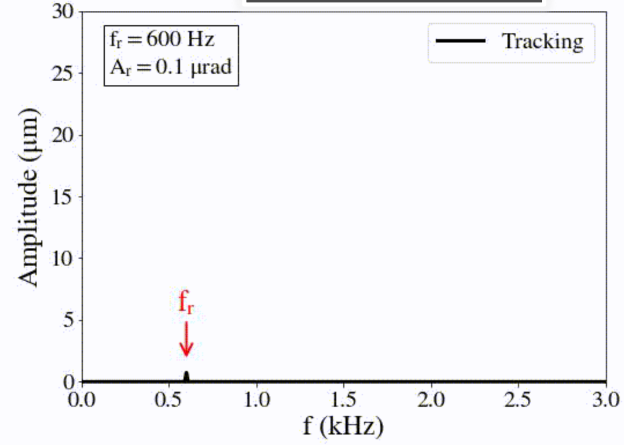
fr constant, Ar ↑

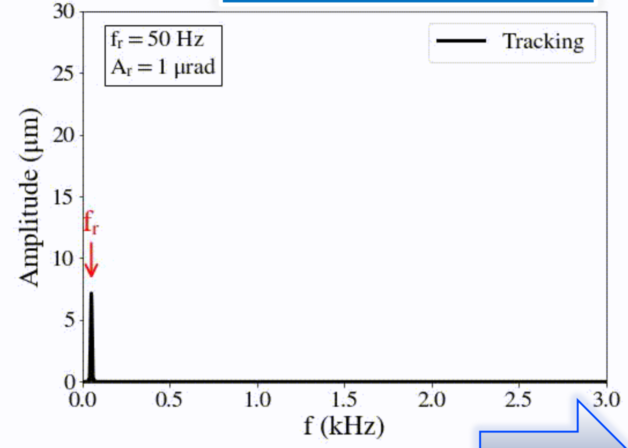
Ar constant, fr ↑ or ↓

1. Dipolar modulation

$$x_{max} = \left| \frac{\sqrt{\beta_{noise}\beta_s}\,\Theta_{noise}\sin(2\pi Q)}{2(\cos(2\pi Q_{noise}) - \cos(2\pi Q))} \right|$$

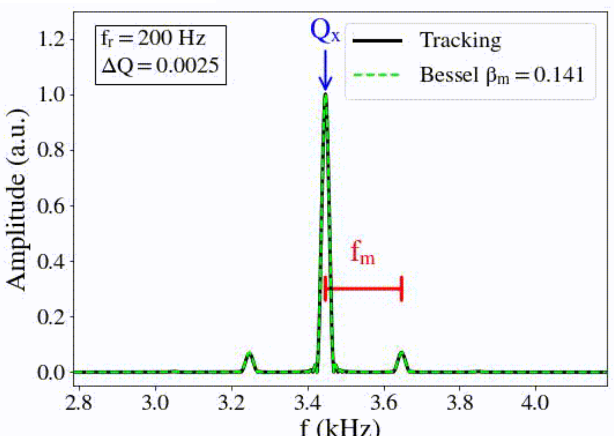
Offset from frequency & kick

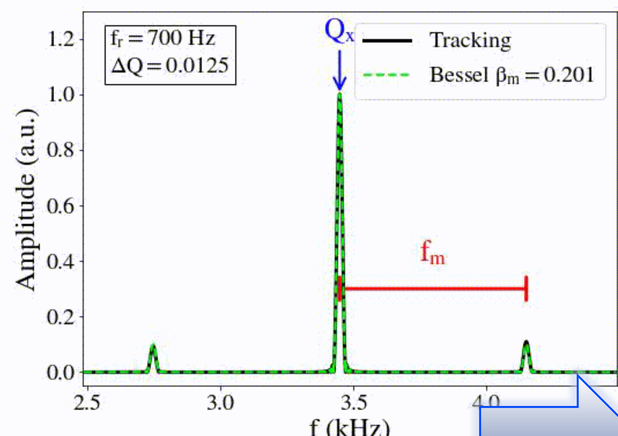




2. Quadrupolar modulation

FM /Strong sideband regime*: Order of sidebands and relative amplitude depends on:
$J(\beta)$ with $\beta = \frac{\Delta Q}{Q_m}$





*T. Satogata, *Nonlinear resonance islands and modulational effects in a proton synchrotron*

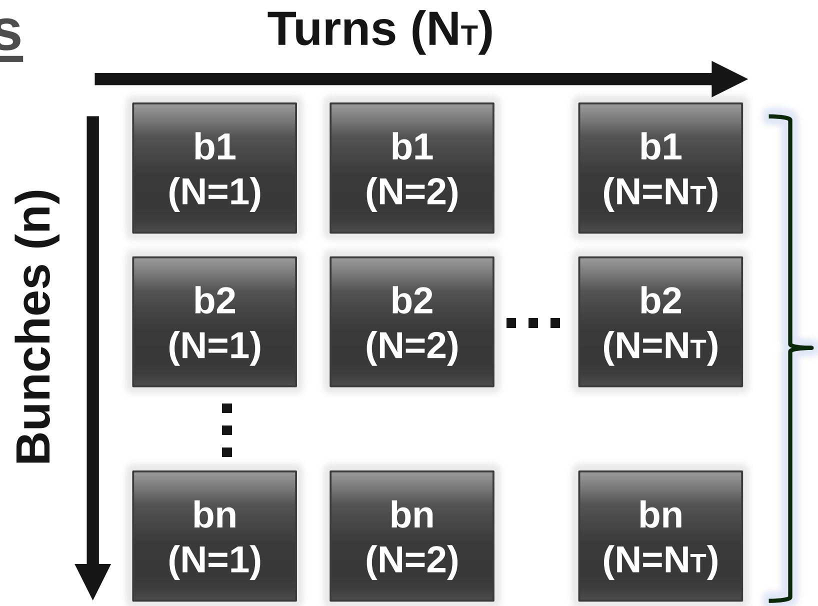
Analysis of bbb data

Previous methods

Average in time domain/ Average in complex frequency domain

= 0.5 frev

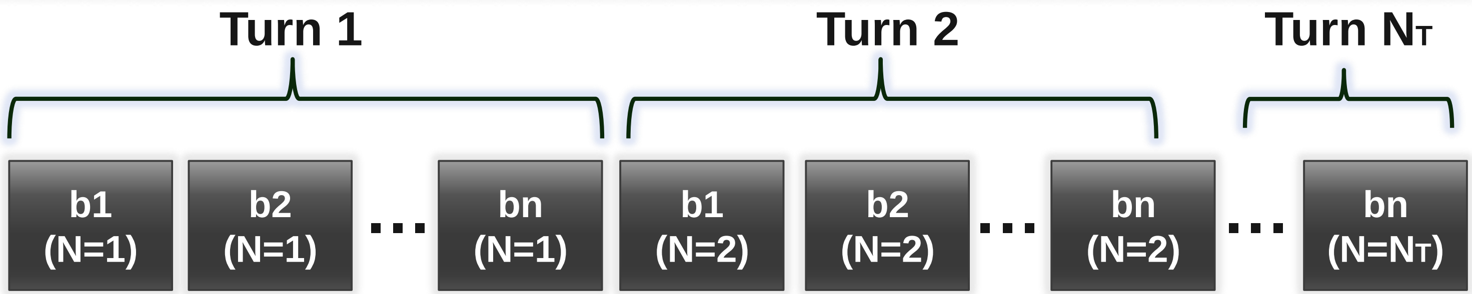
(Frequencies >0.5 frev will be aliased)



For frequencies close to frev (e.g high-f cluster) it leads to an error in the metric ✗

Concatenate bunches per turn

> 0.5 frev



For frequencies close to frev (e.g high-f cluster) it leads to aliasing and in an error in the metric ✗

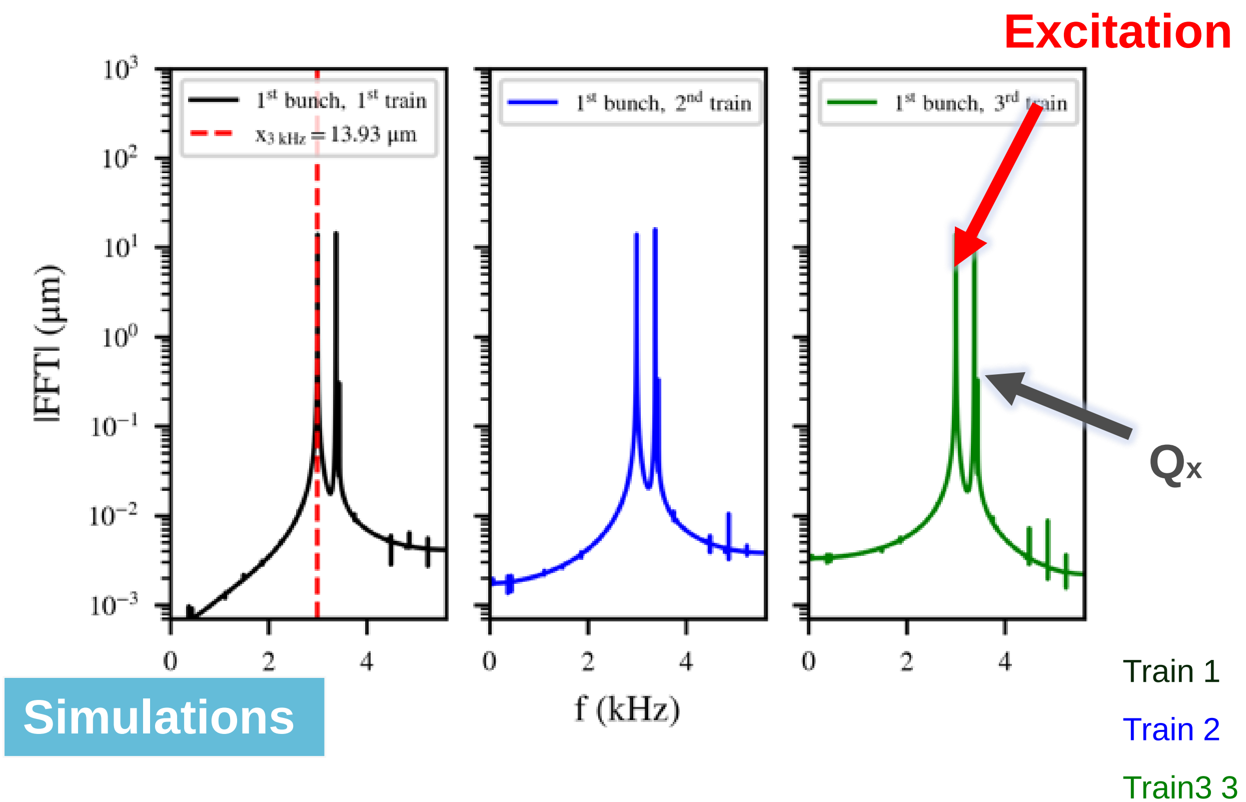
(Not important, can be distinguished) (Important)

Analysis of bbb data

Example:

- A dipolar kick at **3 kHz** which produces an offset of **13.93 μm**.
- Simulate 3 trains in azimuthally symmetric positions with a 25 ns bunch spacing (similar filling scheme to the 50 Hz MD).

Spectrum of 1st bunch of each train

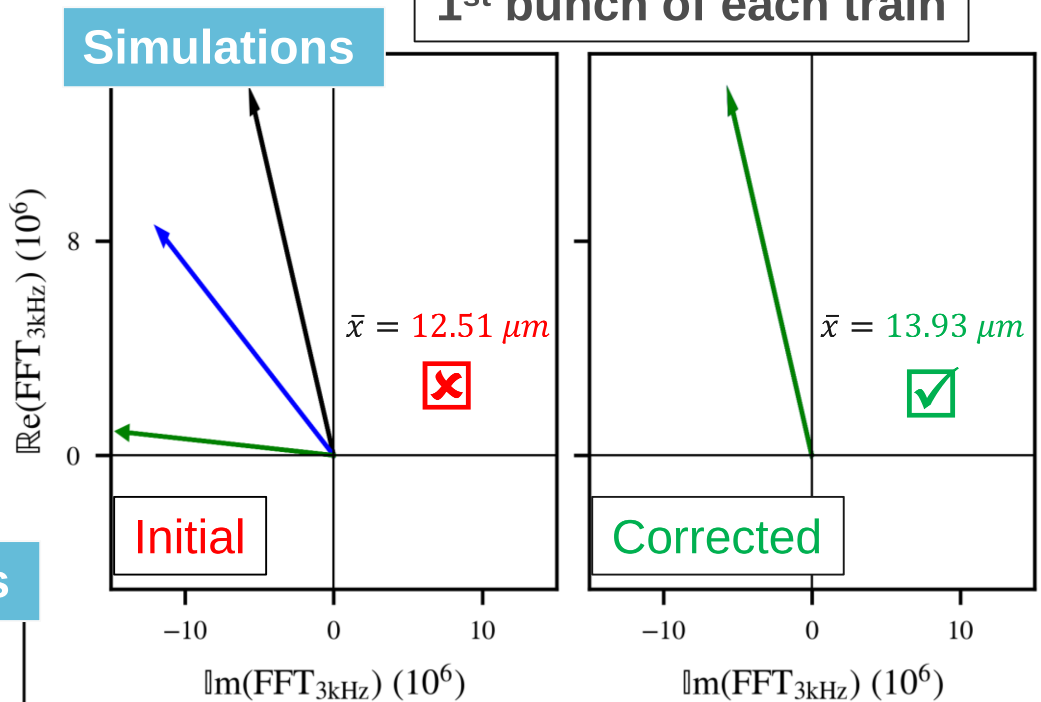


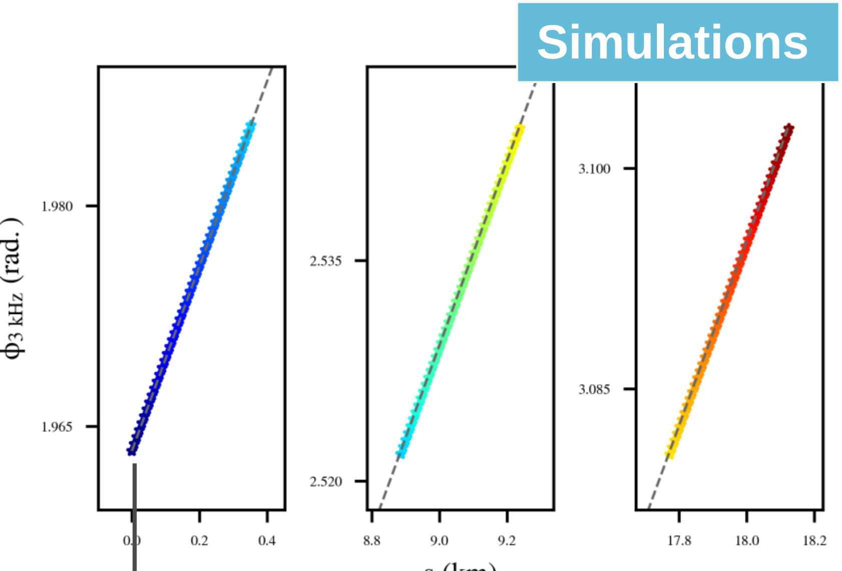
Analysis of bbb data

Before averaging, a rotation of the spectra to remove the dephasing between the bunches must be applied:

$$F(\omega) = \frac{1}{N_b}\sum_{n=1}^{N_b} F_n(\omega)e^{-i\omega\Delta\tau_n}$$

1st bunch of each train





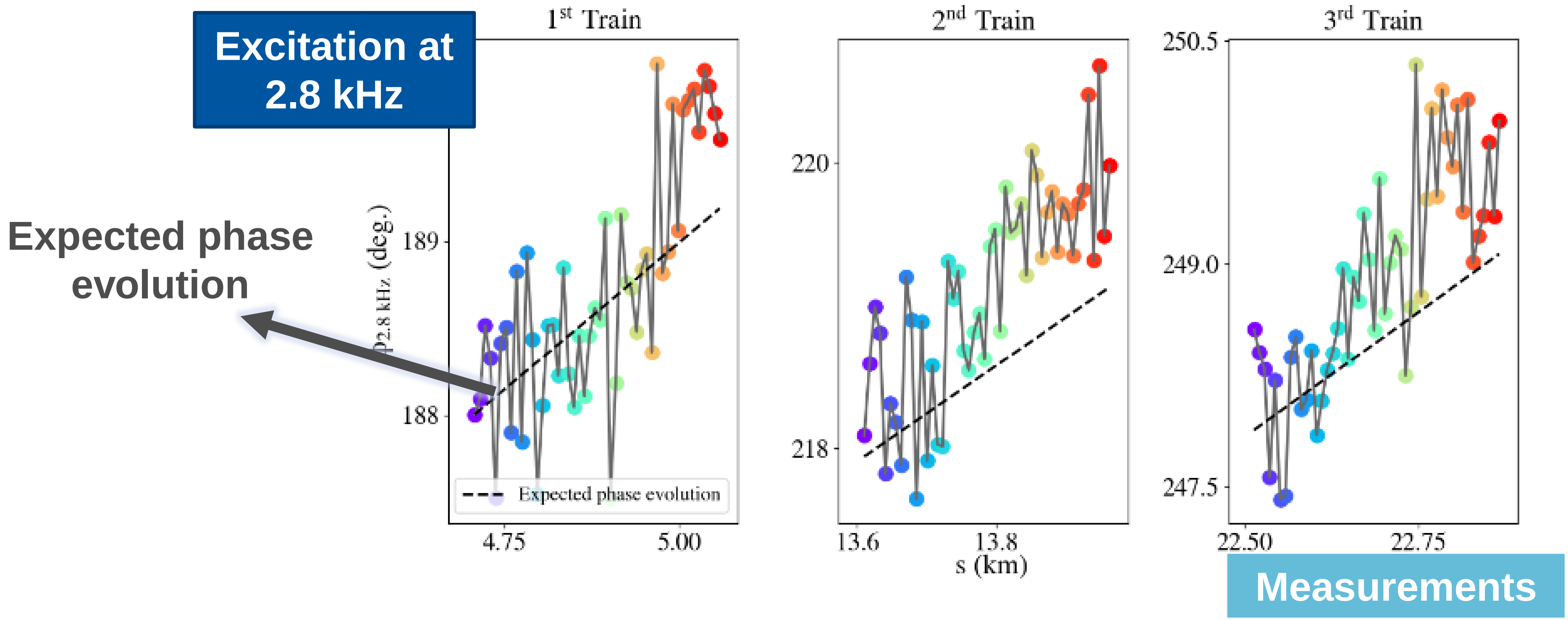
Reference bunch

Dephasing of each bunch of the 3 trains at f=3 kHz equal to 2·π·f·Δτ.

By applying this correction, we retrieve the correct offsets and a spectrum >0.5 frev is achieved (in the presence of a regular filling scheme such as a physics fill).

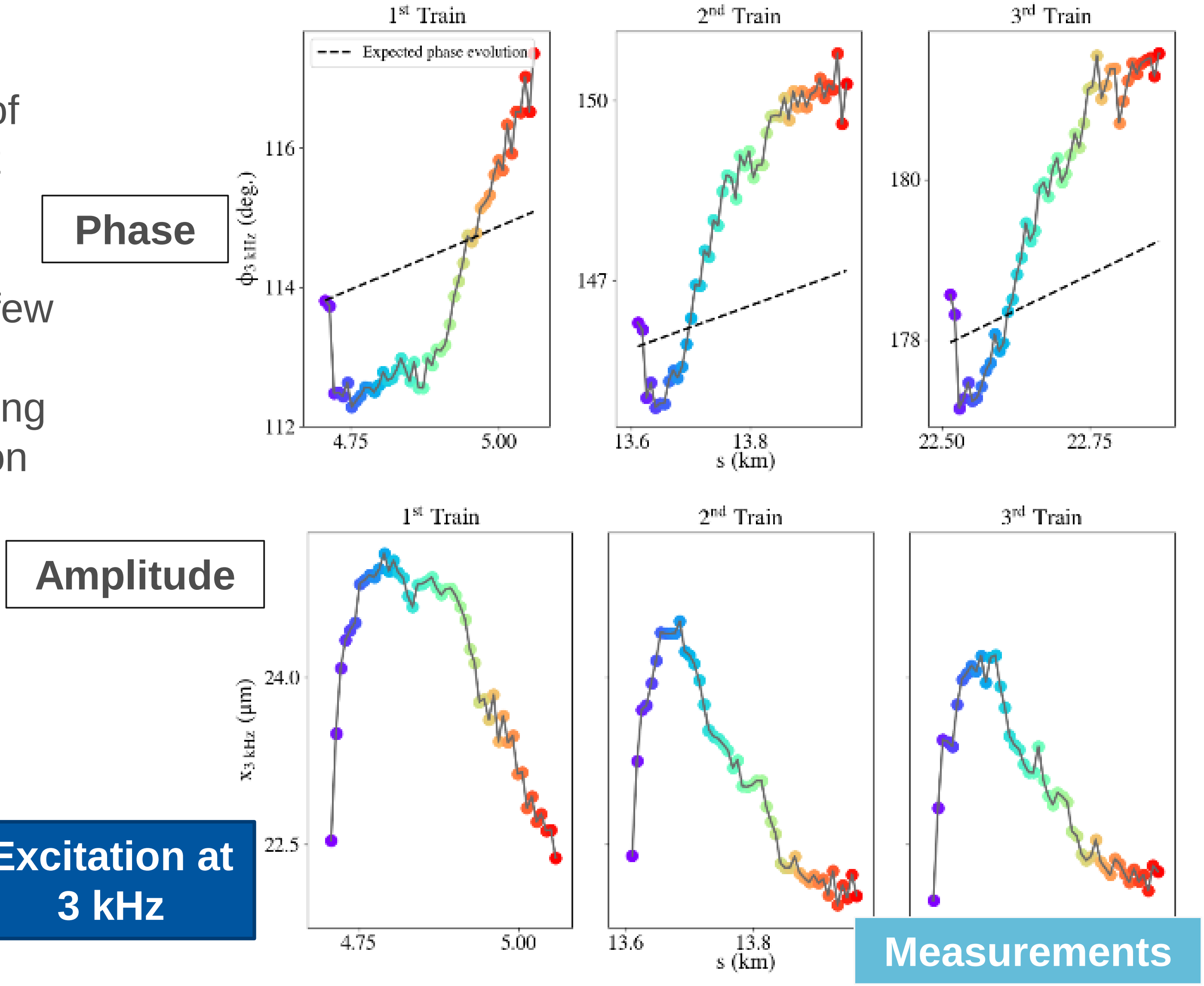
Analysis of bbb data: experimental observations

- Verify if there is an agreement between the predicted dephasing from simulations and experimental measurements:
  - ❑ In the bbb spectrum for 65 K turns (ADTObsBox) the 50 Hz lines are below the noise level.
  - ❑ Controlled excitations during the 50 Hz MD above single bunch noise level: agreement between the expected dephasing and experimental observations.



Analysis of bbb data: experimental observations

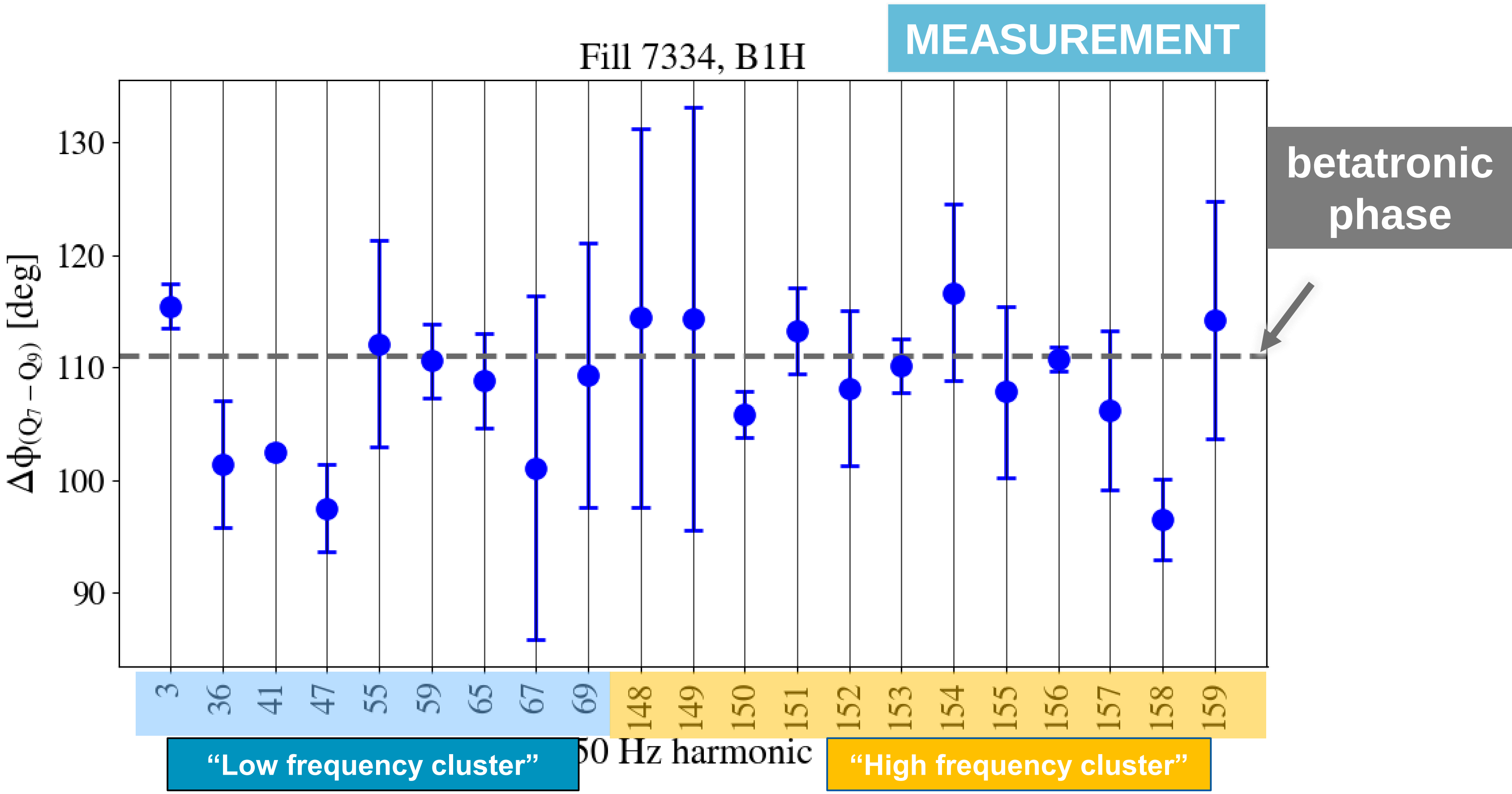
- For large values of the excitation that lead to a large offset: a discrepancy of a few degrees from the expected dephasing and a bbb variation of the excitation amplitude is observed.
- 50 Hz lines are below ~0.2 μm.



Are these tones an artifact?: Q7-Q9 phase advance

- The phase difference between 2 close-by BPMs (Q7 and Q9) for a given tone corresponds to the betatronic phase advance between Q7-Q9

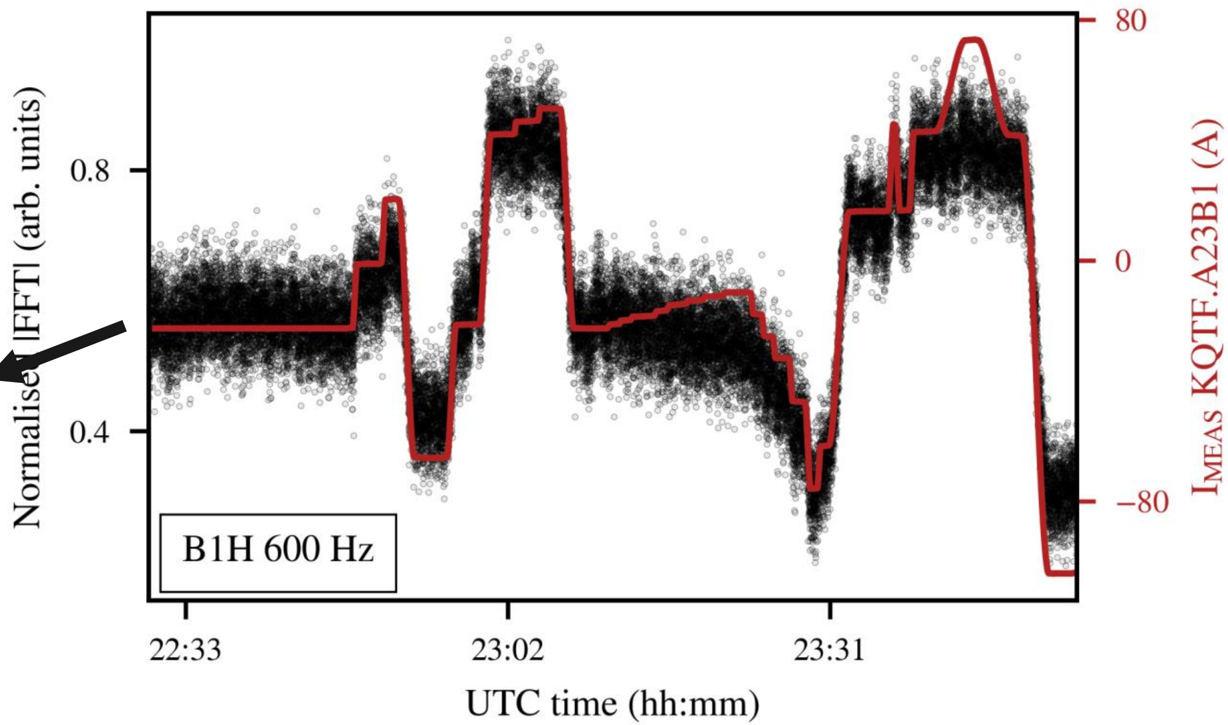
→ Reproducible for all harmonics above noise level.



Are these tones an artifact?: IP1/5 phase scan

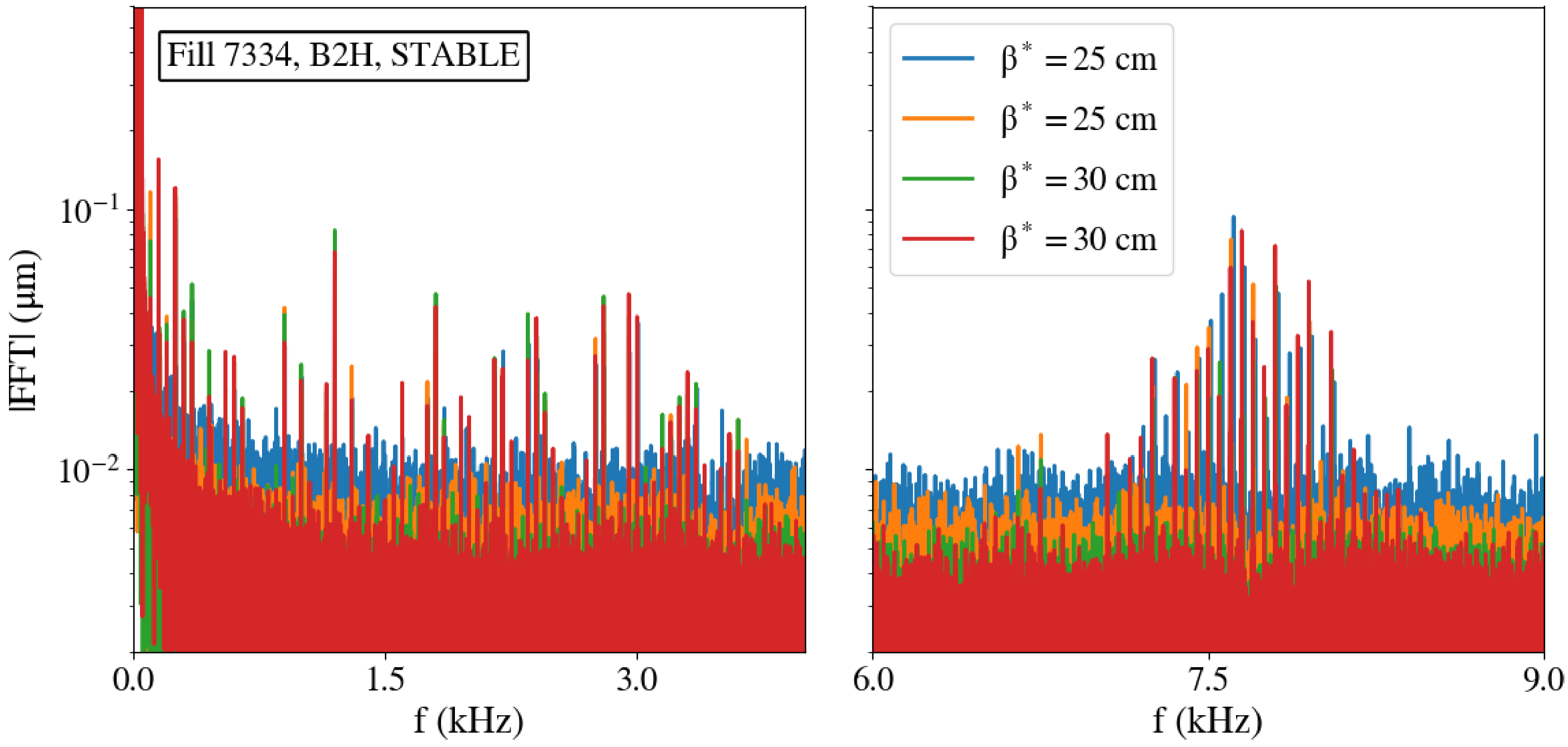
- IP1/5 phase scan: changing the phase advance between the two IPs has an impact on the low frequency cluster.
- No impact on the high frequency cluster.

Amplitude of 600 Hz line



Trim for IP1/5 phase scan

Spectrum evolution during β* reduction



- No impact from the β* reduction.
- There is an increase of the noise floor with decreasing intensity.

50 Hz harmonics & damper

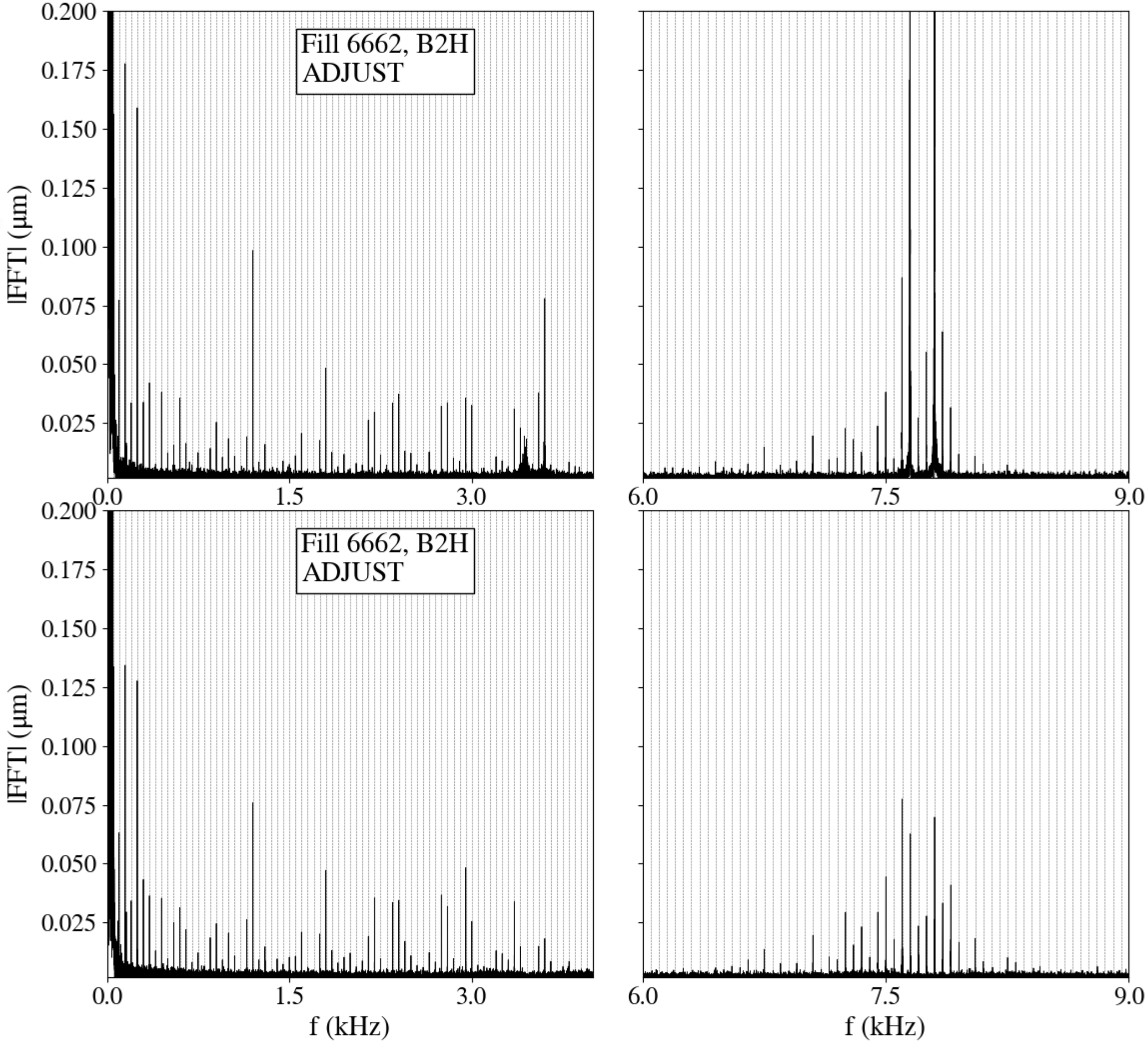
At the end of Adjust, the BW is changed with a visible impact on the lines

2018-05-09 20:40:37

ADT BW to standard at 2018-05-09 20:43:35

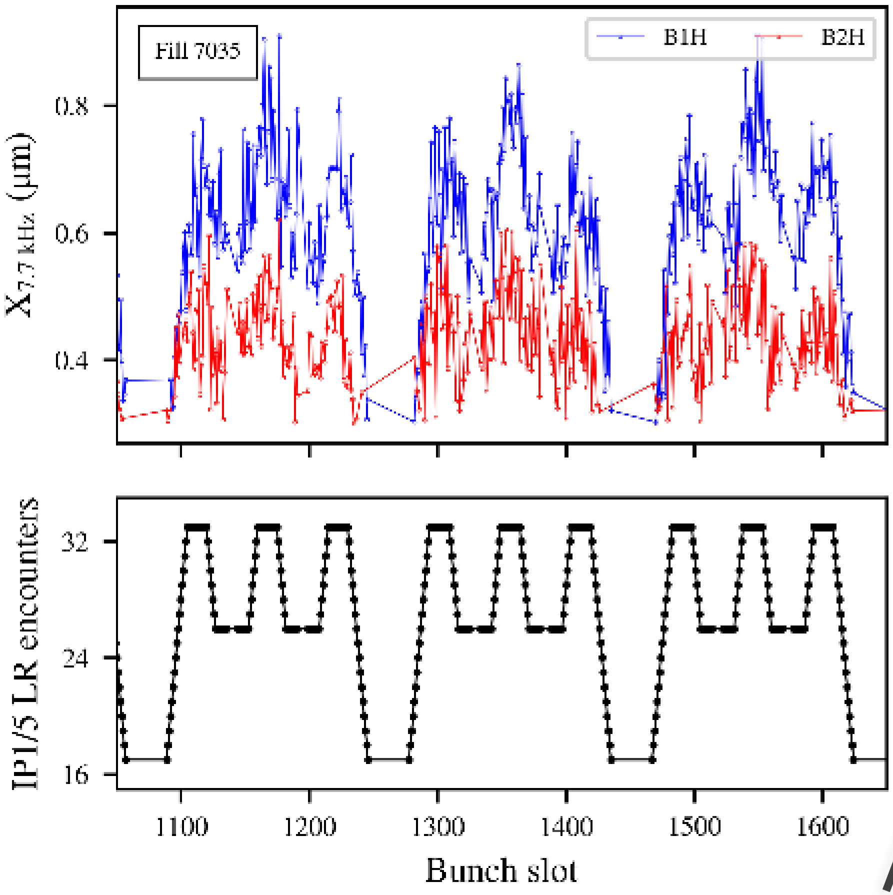
2018-05-09 20:44:09

Harmonics > 3kHz are suppressed by the damper

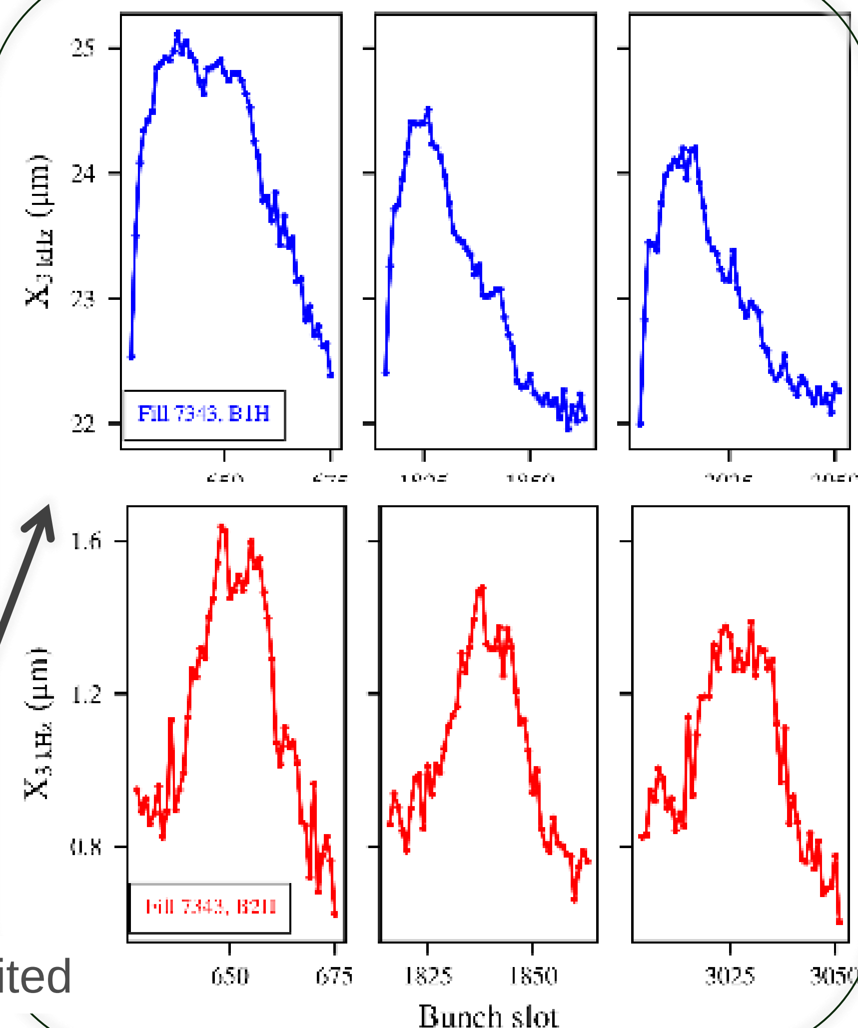


Fill 7035: 7.7 kHz & bbb evolution

Fill 7035



ADT controlled excitations

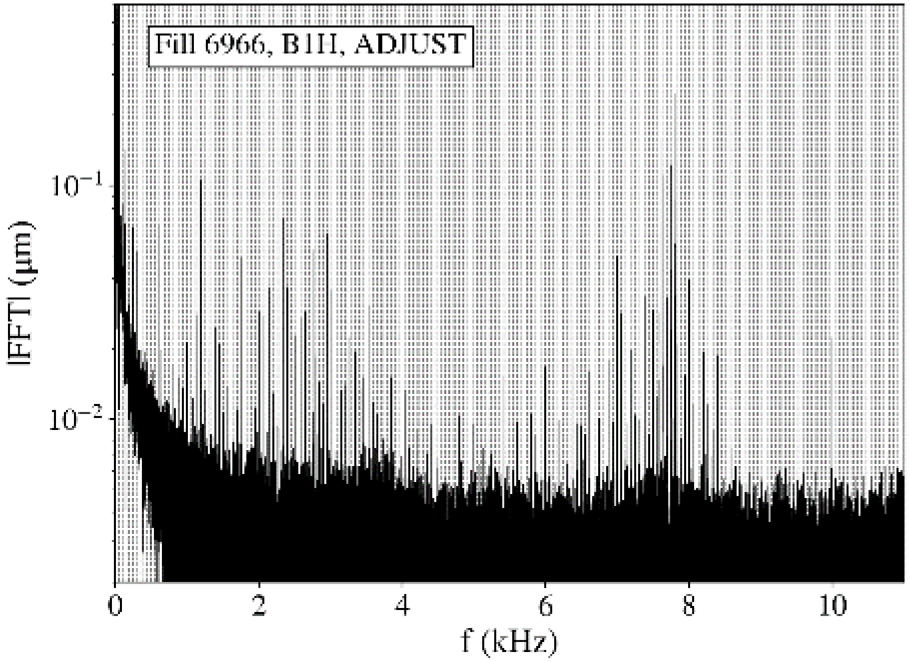


Only B1H was excited

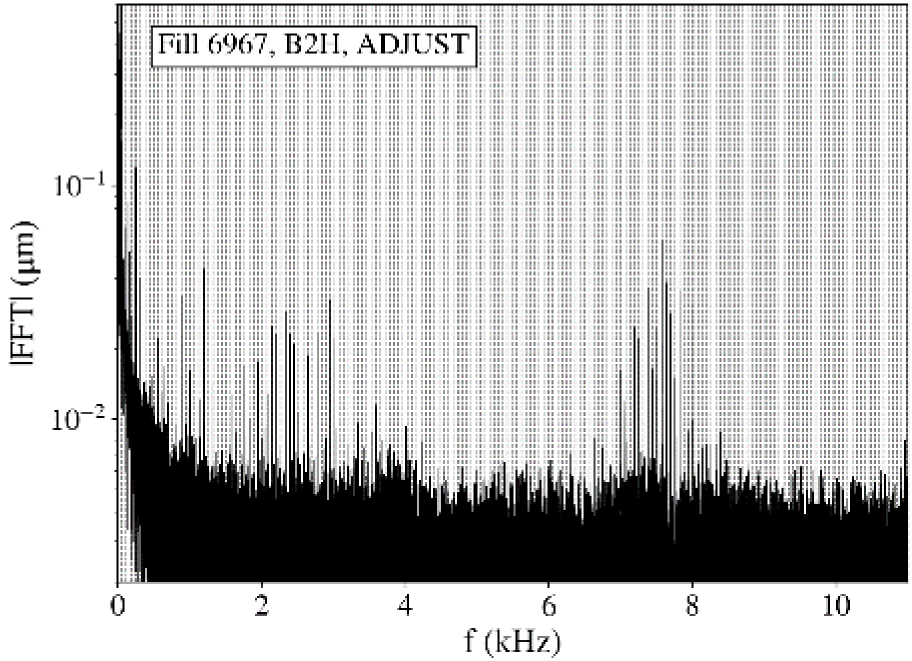
Spectrum with single circulating beam

- In Fill 6966 (MD for heatloads) only **B1** was circulating in the machine.
- In Fill 6967 (MD for heatloads) only **B2** was circulating in the machine.
- No change in the spectrum when a single beam is circulating in the machine.

2556 b in B1, 24 b in B2



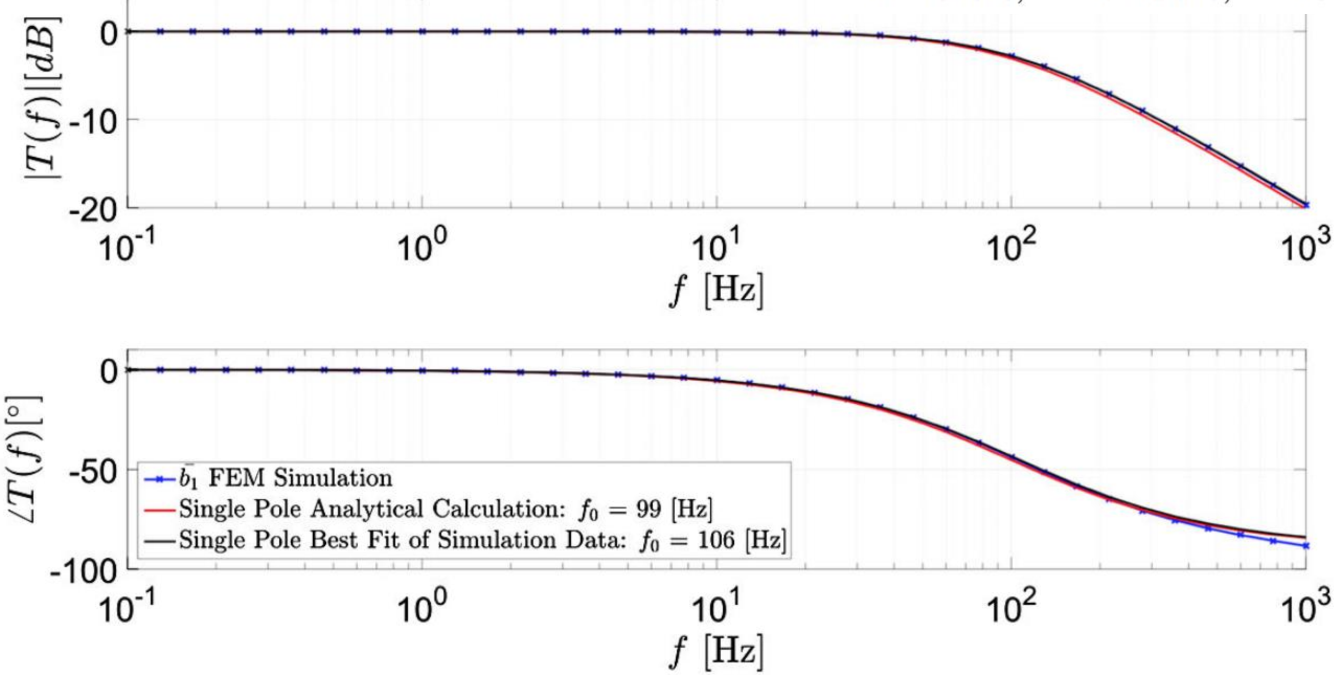
24 b in B1, 2556 b in B2



What is the source of the 8 kHz cluster?

Magnetic frequency response of High-Luminosity Large Hadron Collider beam screens

M. Morrone,[1,2,*] M. Martino,[1] R. De Maria,[1] M. Fitterer,[3] and C. Garion[1]



(a) LHC Main Dipoles at 20 K

- A 8 kHz oscillation is expected to be significantly attenuated by the vacuum chamber.

What is the source of the 8 kHz cluster?

METHODS AND RESULTS OF MODELING AND TRANSMISSION-LINE CALCULATIONS OF THE SUPERCONDUCTING DIPOLE CHAINS OF CERN'S LHC COLLIDER

F. Bourgeois and K. Dahlerup-Petersen

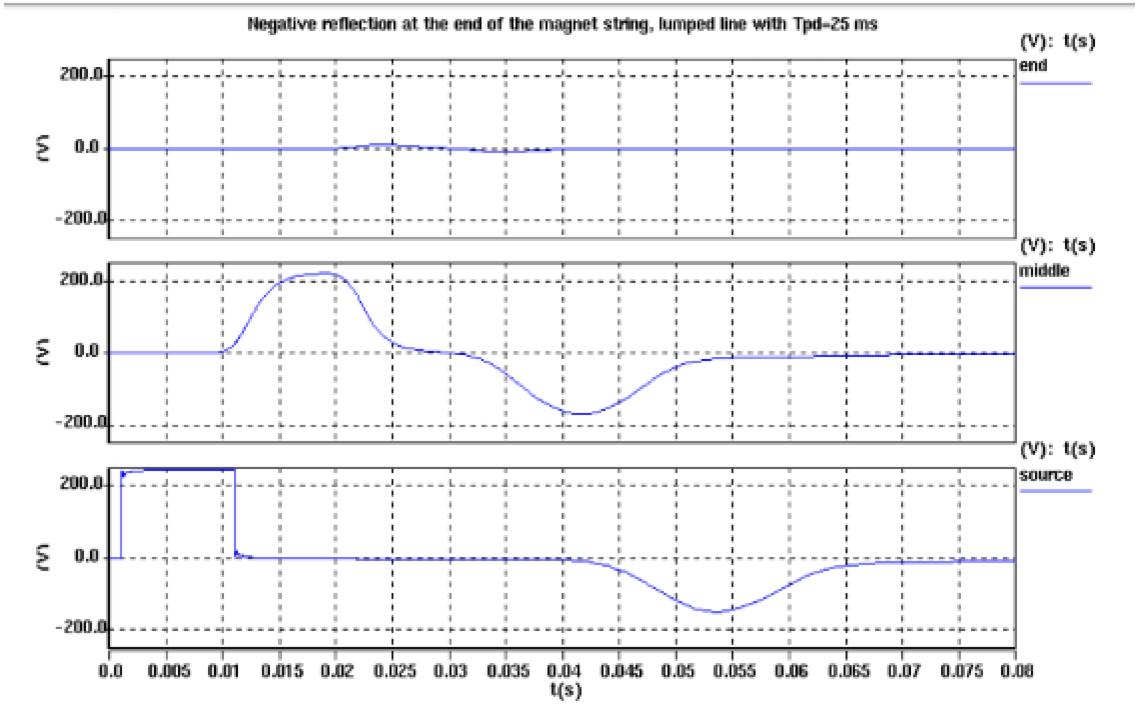


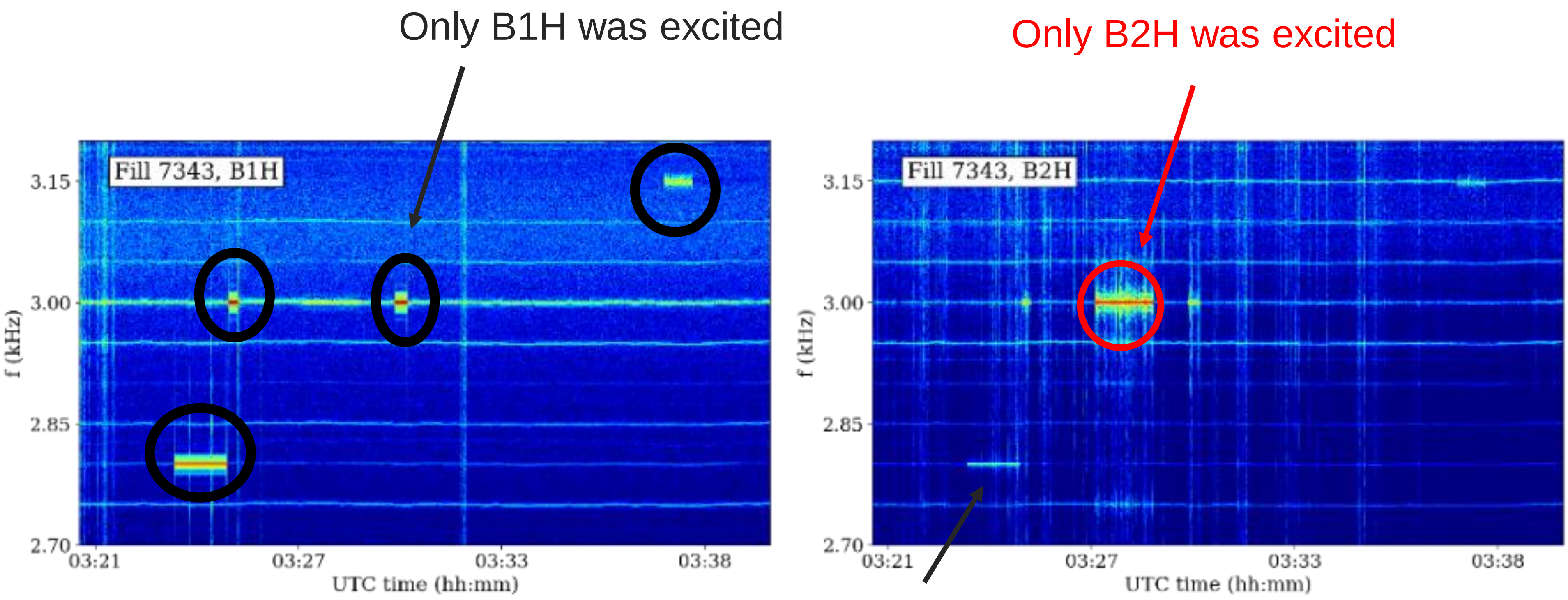
Figure 4: Reflection of a 1A, 10 ms current pulse

Propagation of a 1 A, 10 ms, current pulse in the LHC dipole chain

A note on controlled excitation

Fill with 3 trains of 48b:

- Only one beam is excited, but the excitation is also seen on the other.

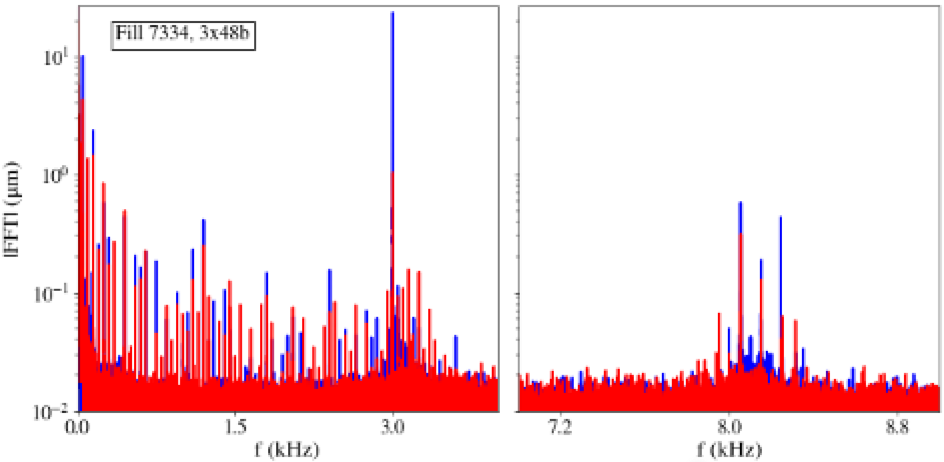


A note on controlled excitation

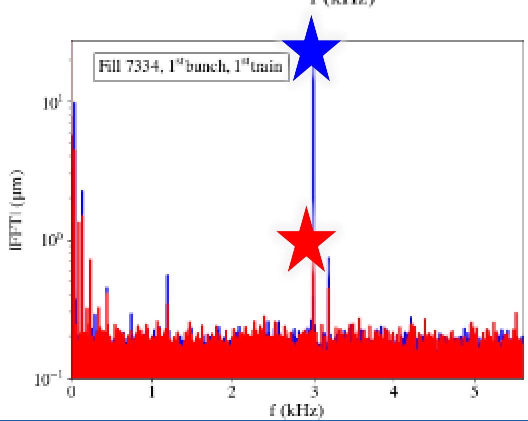
Fill with 3 trains of 48b:

- **Only B1H was excited at 3 kHz**
- The excitation is seen in B2.

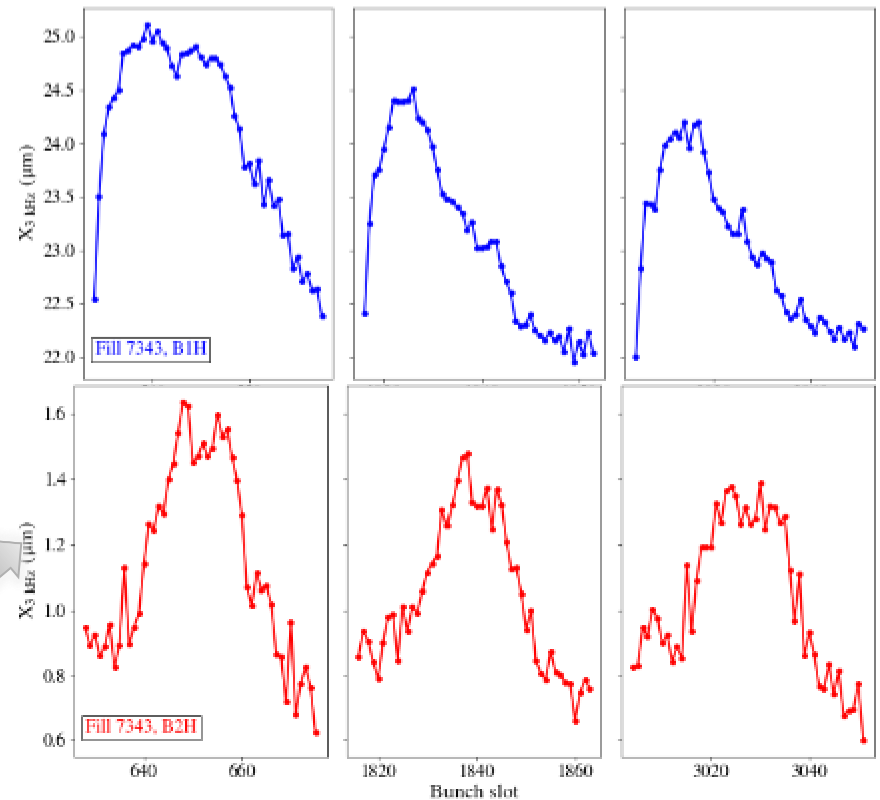
Average over all trains



Single bunch

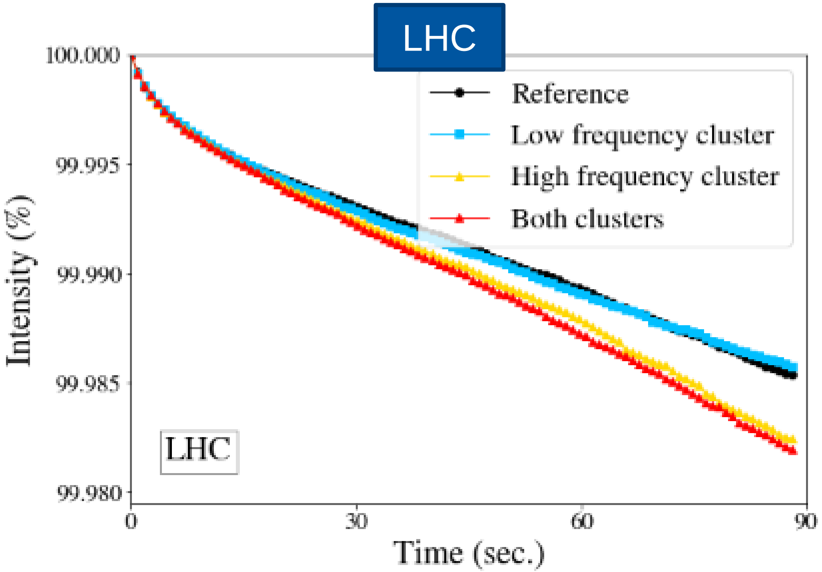


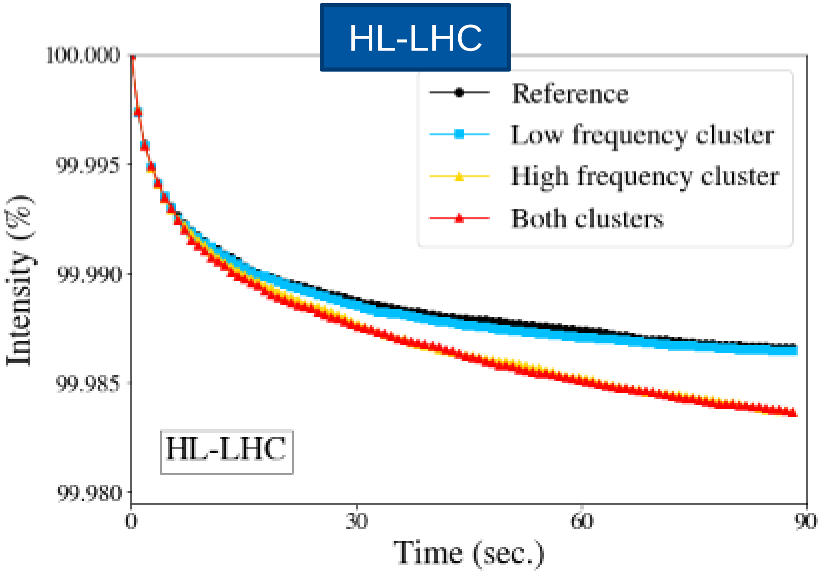
bbb amplitude of 3 kHz



Simulating the effect of the observed spectrum: Losses

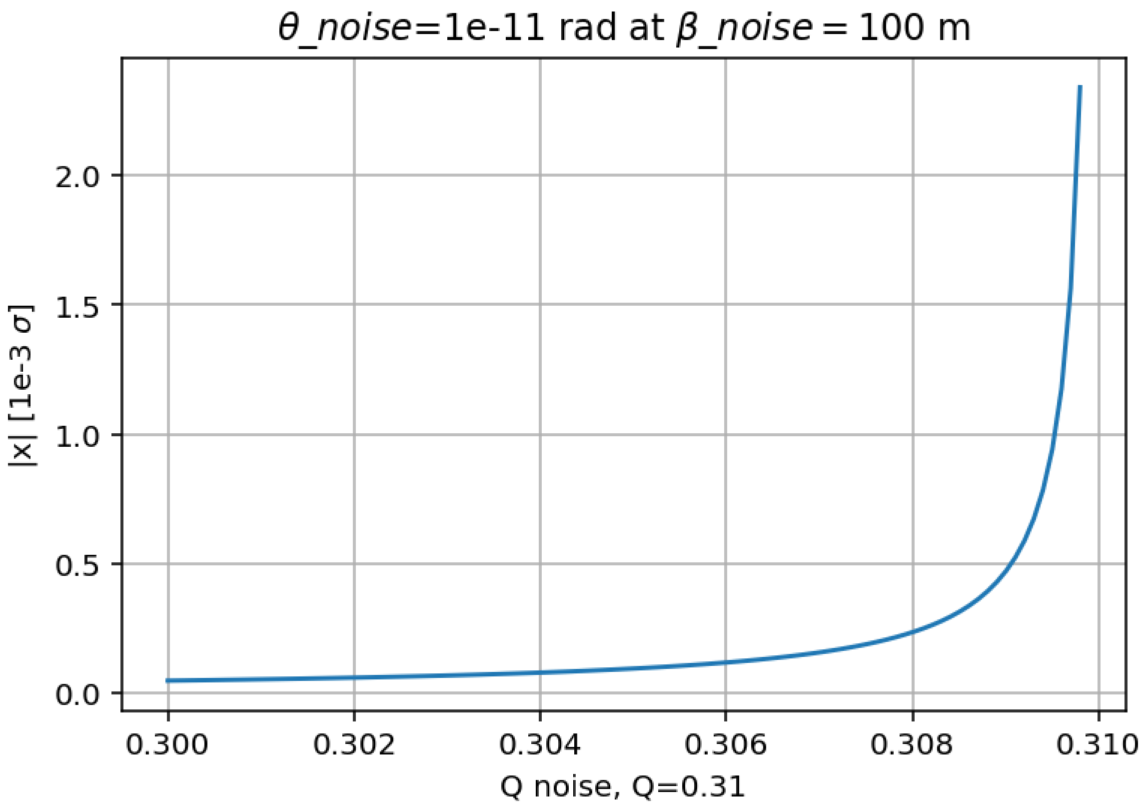
Weighted distributions, collimator at 5 σ_{beam}





Assuming that the spectrum remains the same

What is the equivalent kick?



- As reference, a single kick of **θ = 1e-11 rad** at β=100 m gives oscillation in the order of **1e-3 σ** (as observed).
- 1e-11 rad has to be compared with the kick of the main bend (~5 mrad)
- It would be equivalent to 2e-9 stability of one single MB at a frequency 1e-3 apart from the tune.