Latest on noise effect on the beam

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Thanks to HL-LHC WP2 and WP6

9th HL-LHC Collaboration Meeting, Fermilab, USA, 15 October 2019

OUTLOOK

- Motivation
- What we see in LHC beams
- Simulation benchmarking in LHC
- Prediction for HL-LHC
- Conclusions

Introduction

GOAL

- estimate if/when the noise from the power converters impact the **HL-LHC beam performance**

METHOD

- analyze the effect of the power converter noise in LHC
- build a general framework for simulations and benchmark against LHC observations
- make predictions for HL-LHC

WORKING FOCUS

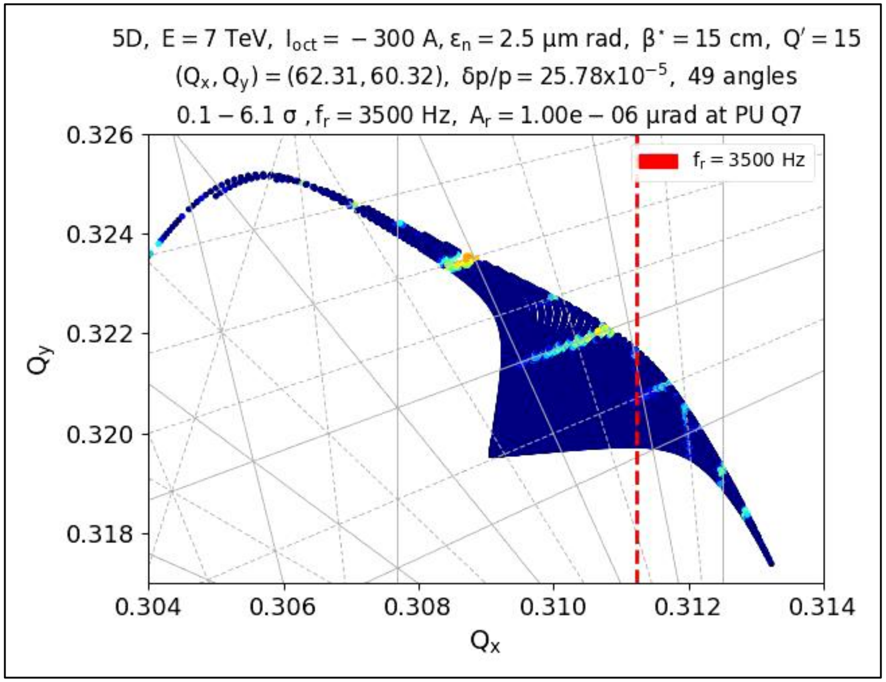
- We will address the **dipolar and quadrupolar** noise.

Introduction

1. Dipolar modulation

largest impact close to the tune

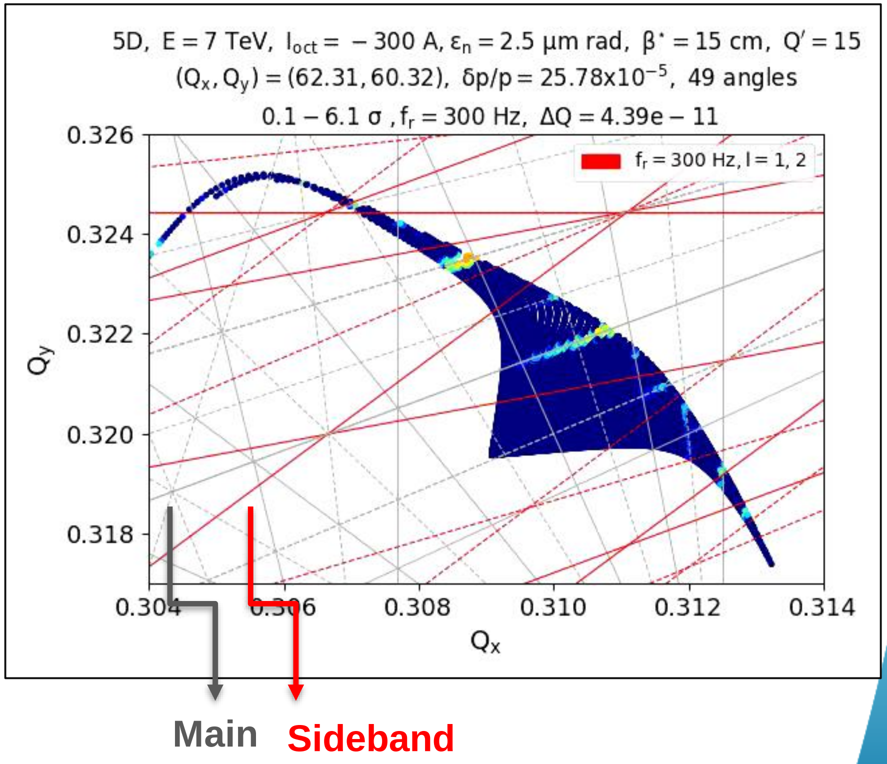
3.5 kHz



2. Quadrupolar modulation

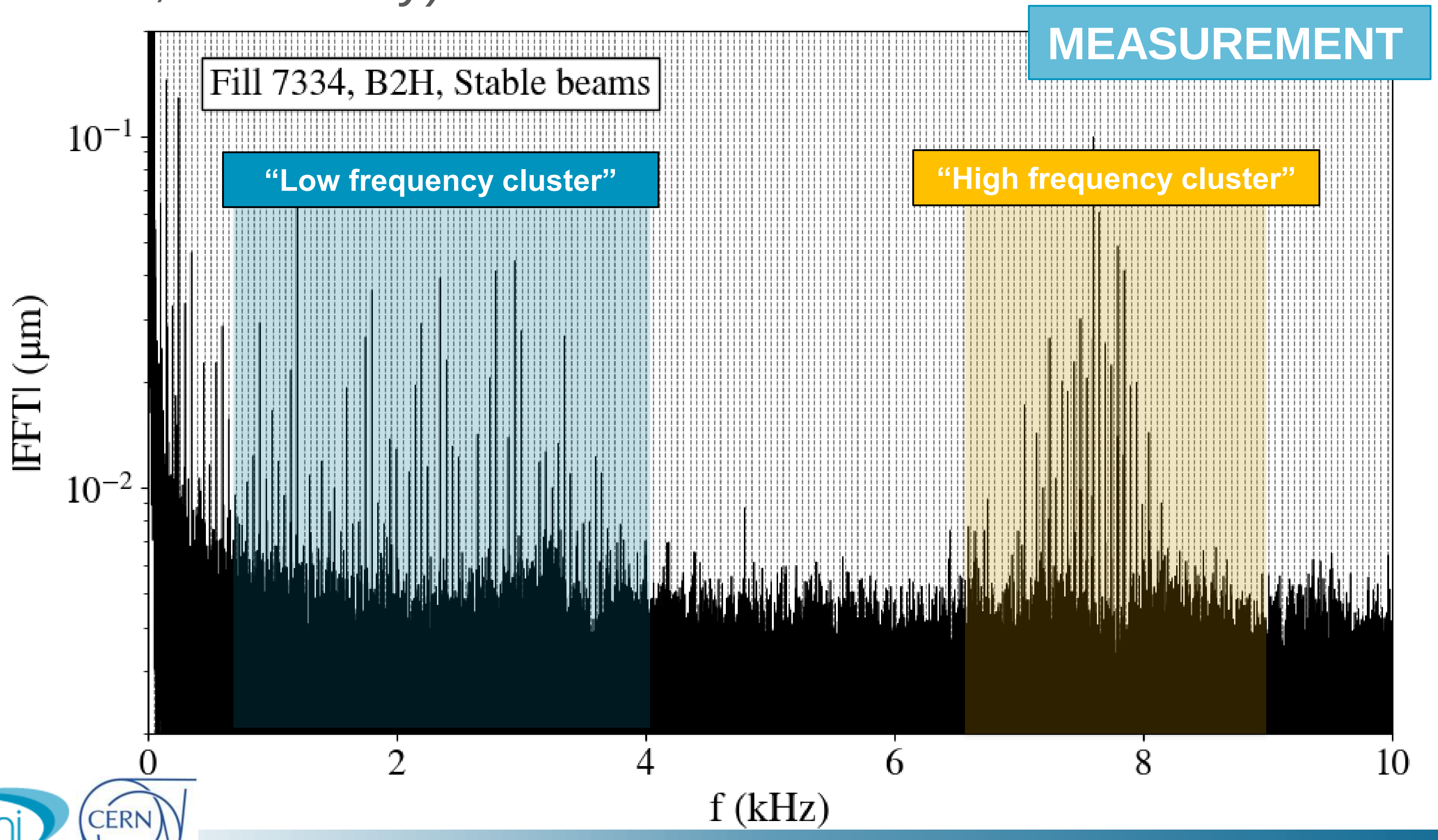
possible large impact even at frequencies far away from the tune

300 Hz



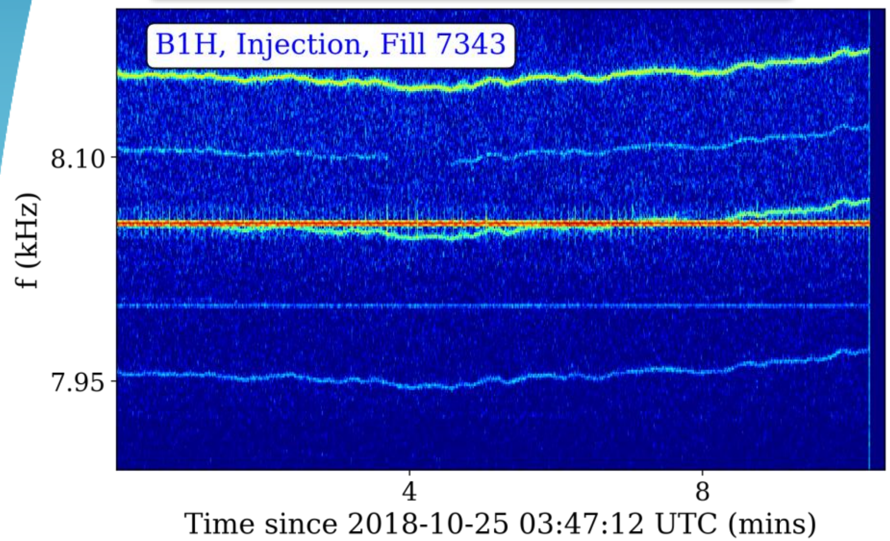
Observations in LHC beam spectrum

- In the LHC we see **only dipolar oscillations**
- Those tones are dominated by **50 Hz harmonics.** Visible in several instruments (BBQ, MIM, DOROS, ADTObsBox).
- **ADTObsBox** will be our privileged system (bbb, calibrated metric, sensitivity).

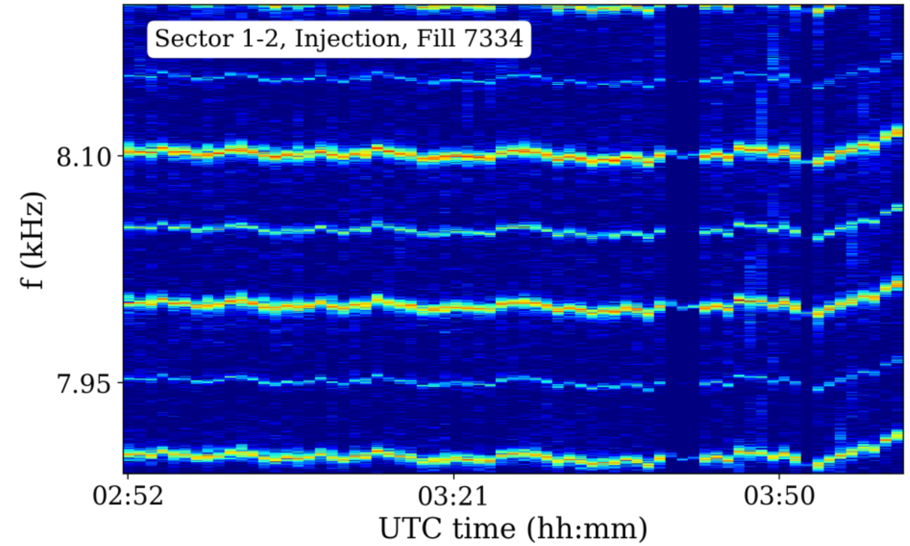


50 Hz harmonics

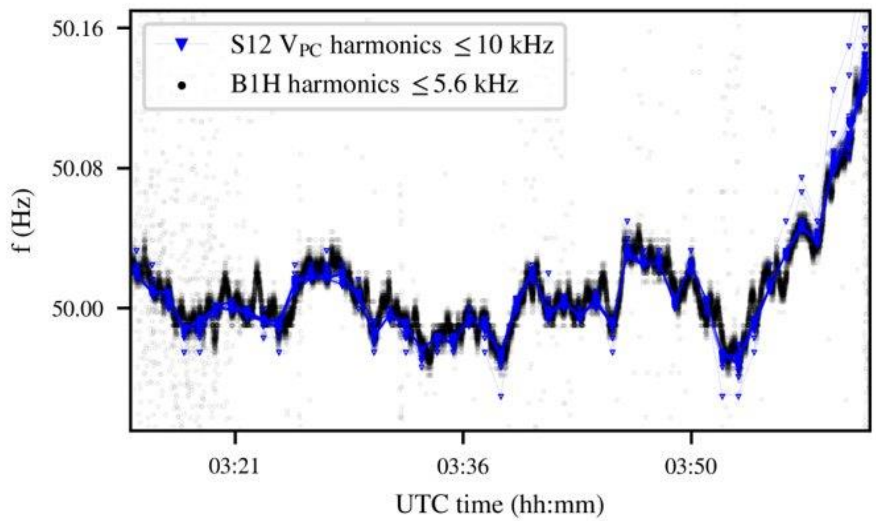
B1H, Injection



MB Power converter V S1-2

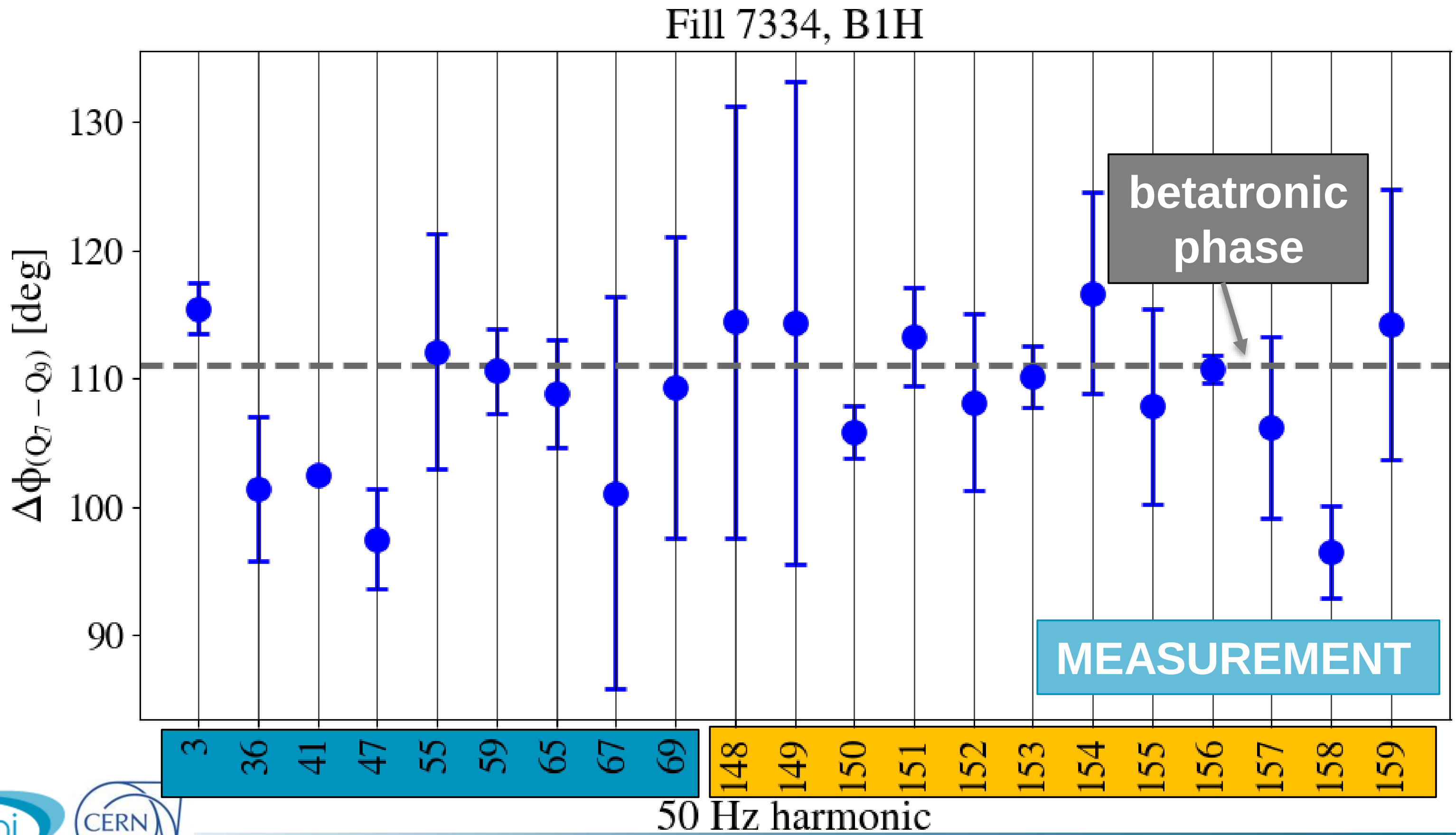


- Clear correlation between the 50 Hz harmonics.



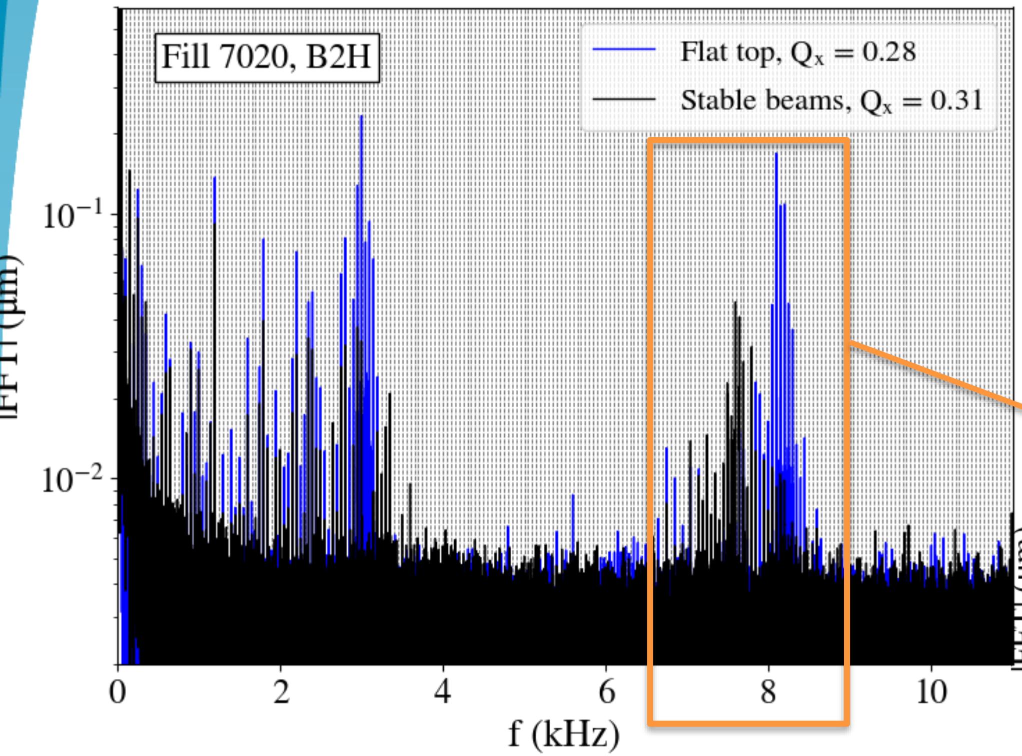
Are these tones an artefact? No.

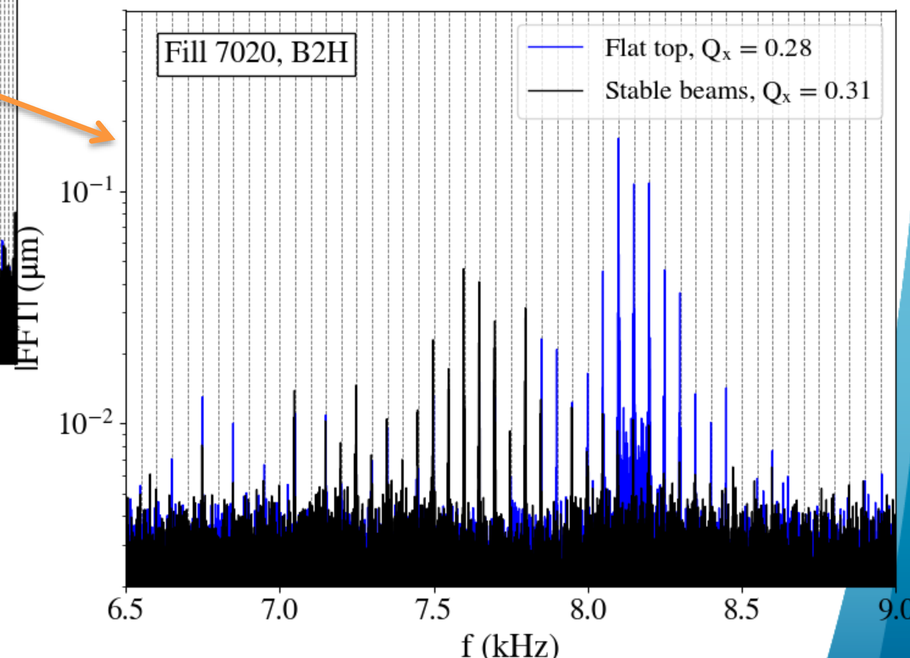
- The phase difference between 2 close-by BPMs (Q7 and Q9) for a given tone corresponds to the betatronic phase advance between Q7-Q9.



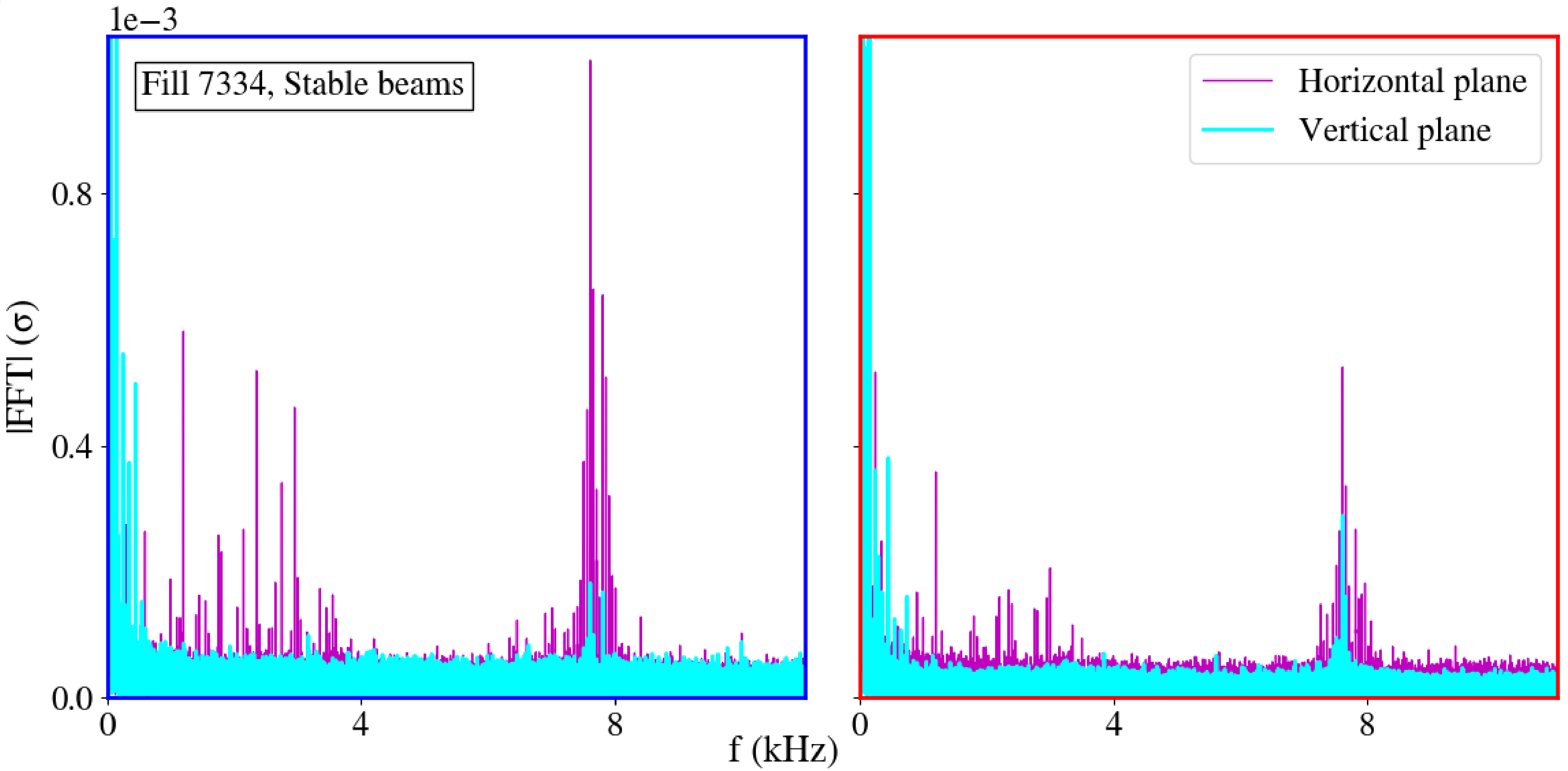
Are these tones an artefact? No.

- Changing the tune there is a visible impact on the spectrum.





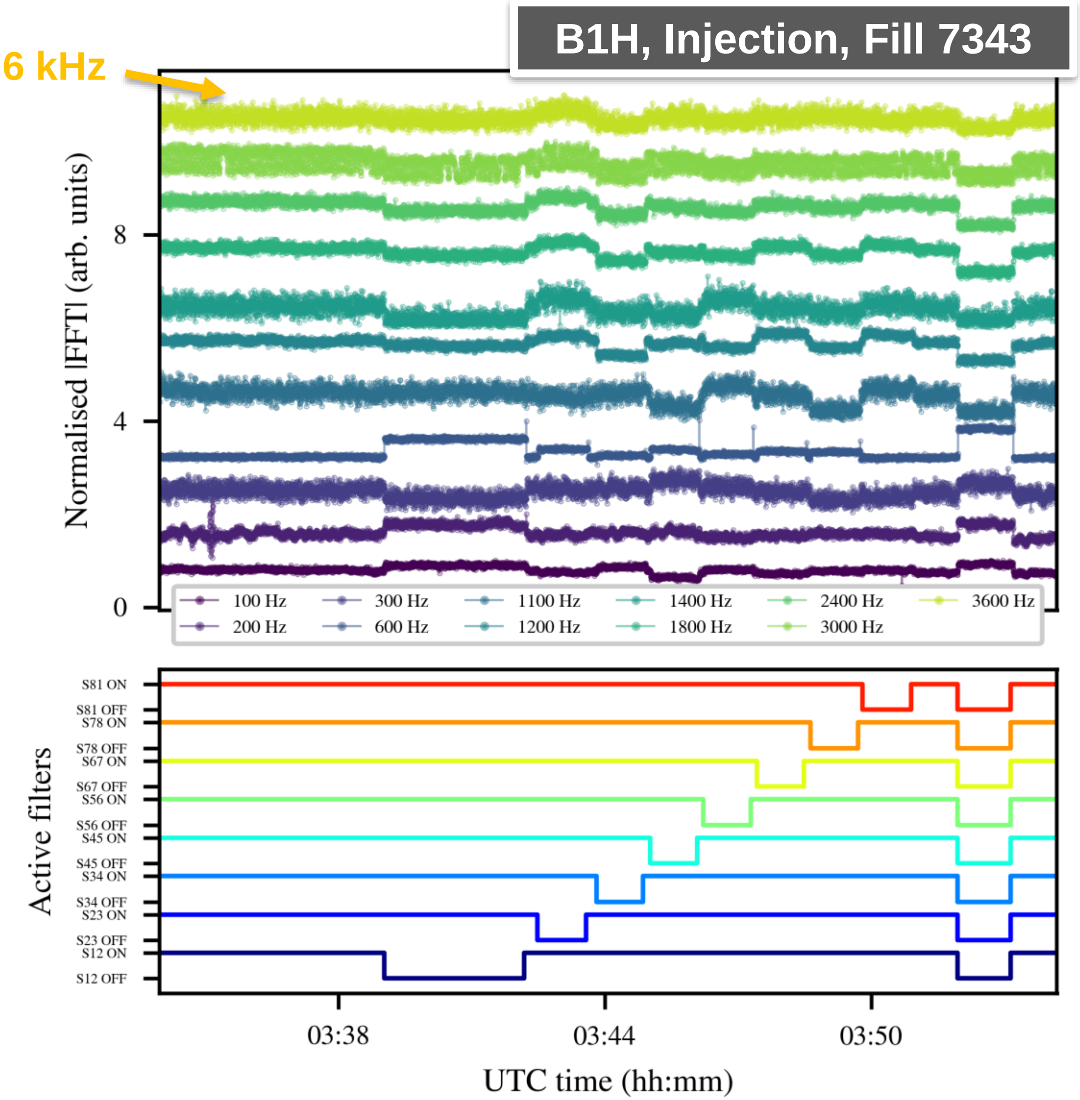
Which beam? which plane?



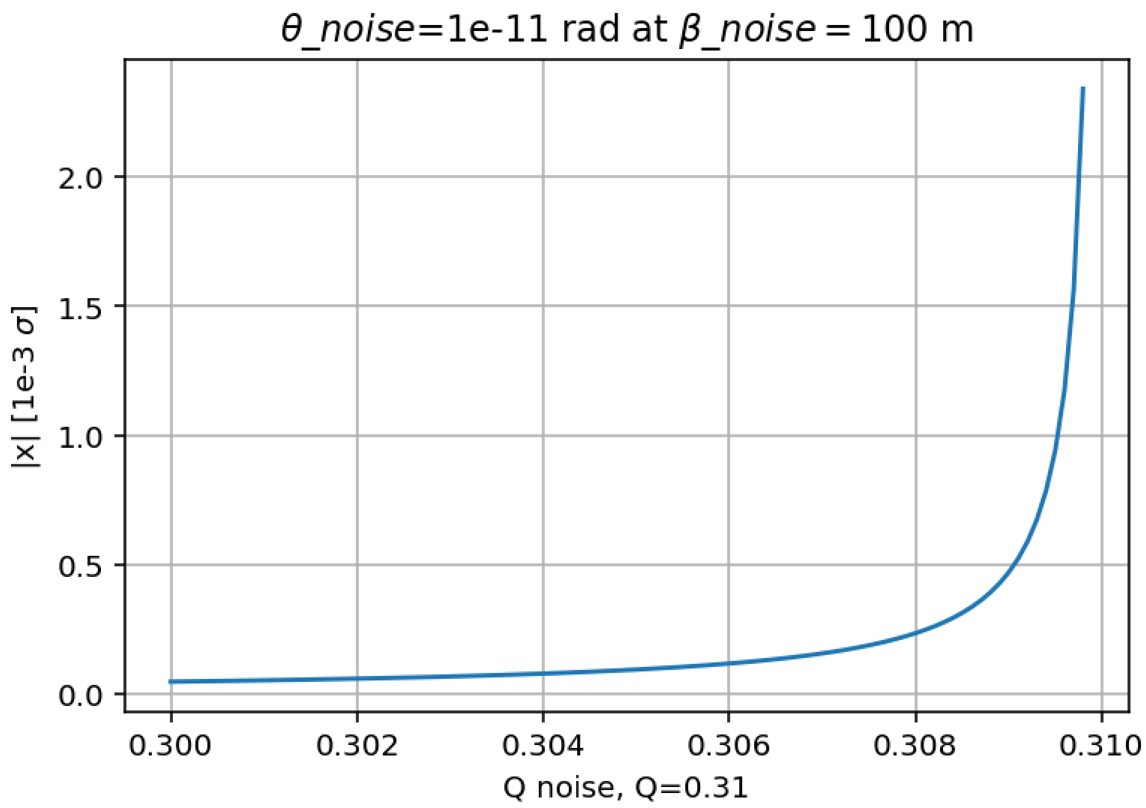
- B1 more excited than B2.
- H-plane more than V-plane (→ **main bends**).
- **High frequency cluster (surprisingly) strong.**

Impact of the main bends power supplies

- For **lower frequencies**, effect of the Sector Dipoles Active filters.
- → **main dipoles are clearly a contributors**.

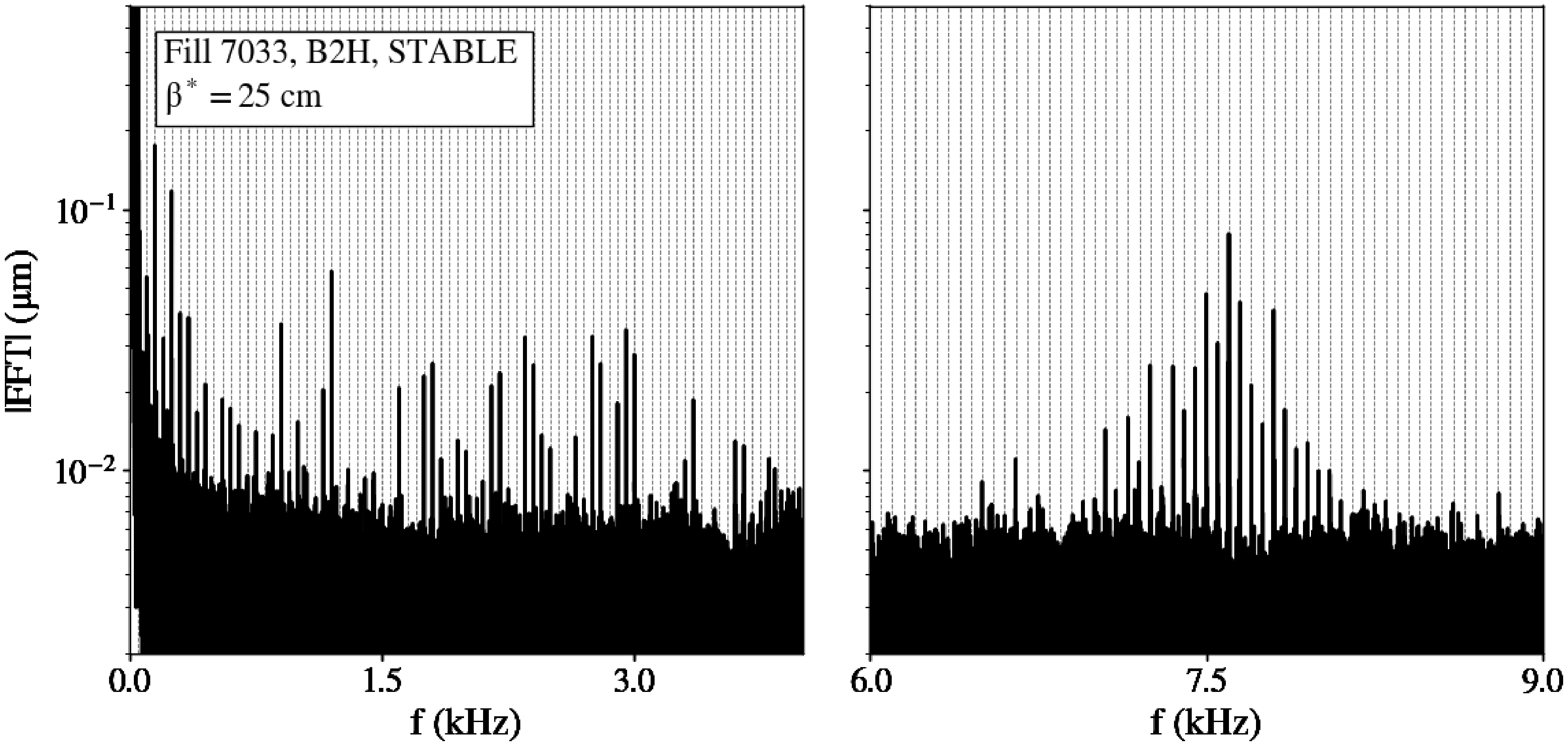


What is the equivalent kick?



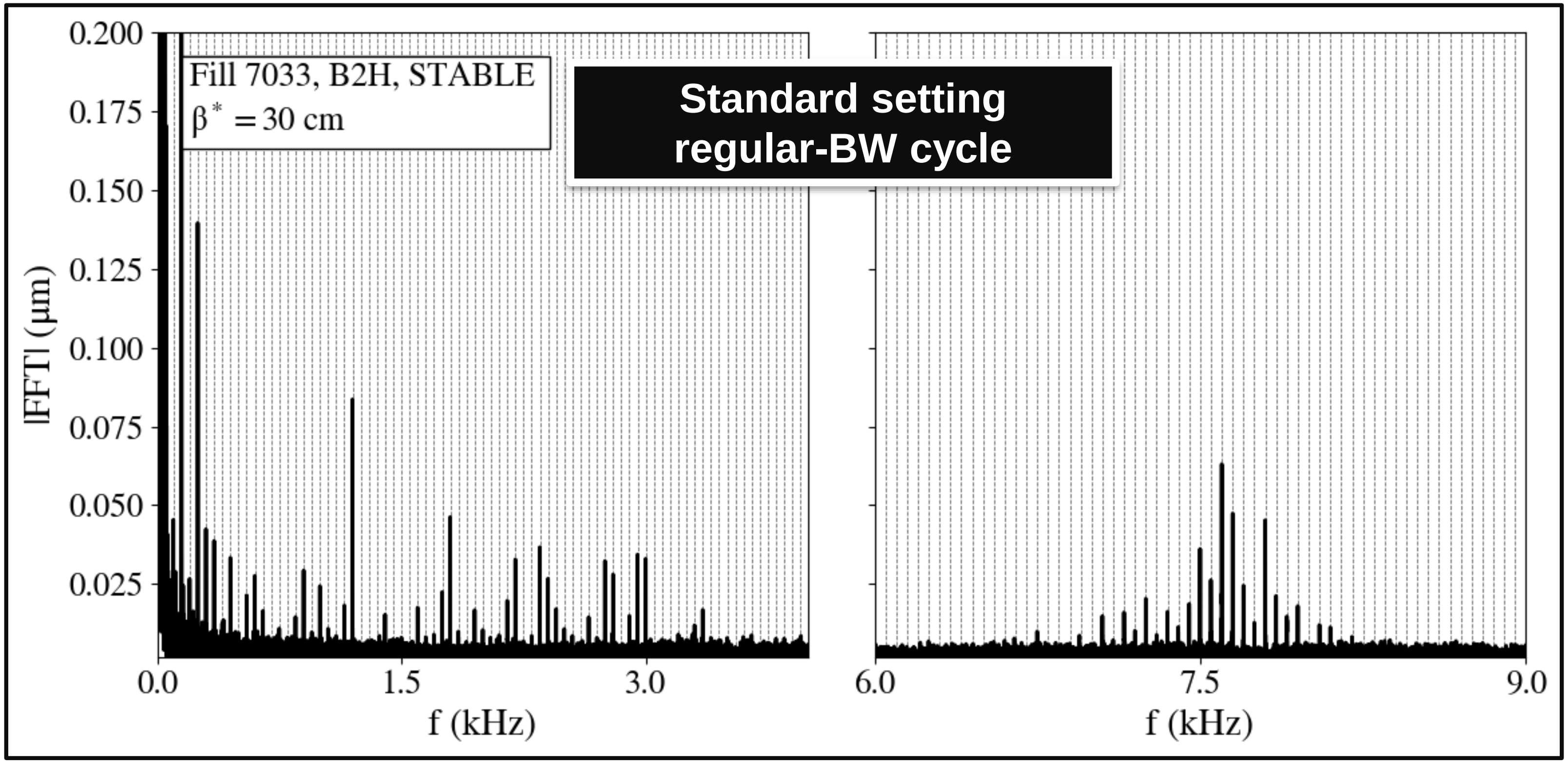
- As reference, a single kick of **θ = 1e-11 rad** at β=100 m gives oscillation in the order of **1e-3 σ** (as observed).
- 1e-11 rad has to be compared with the kick of the main bend (~5 mrad)
- It would be equivalent to 2e-9 stability of one single MB at a frequency 1e-3 apart from the tune.

Is the picture beam mode dependent? Mildly.



Does the damper enter in the game? Yes.

- Beam spectrum could be further attenuated by the damper.
- Reducing the damper affect 50 Hz harmonics.



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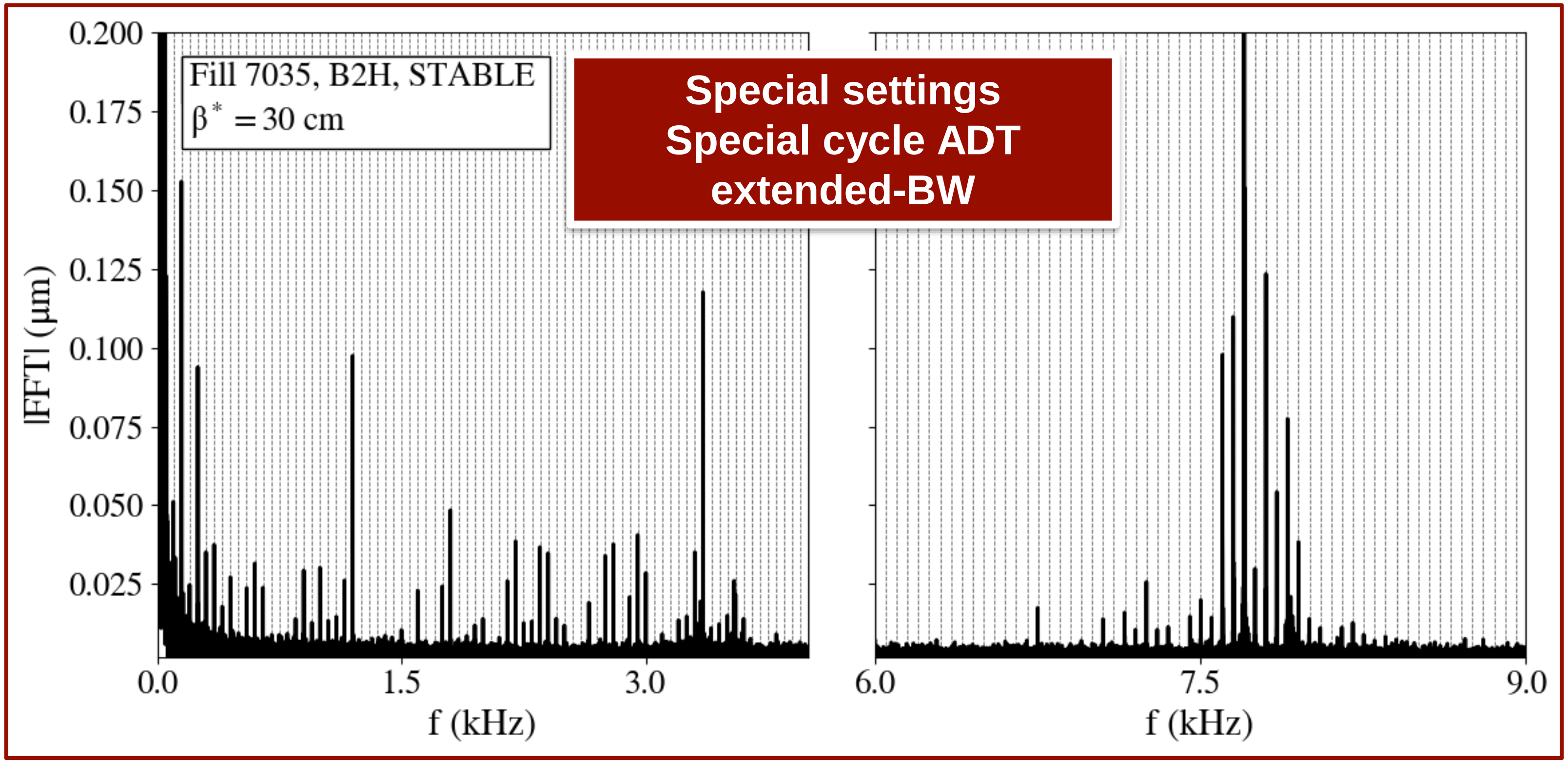
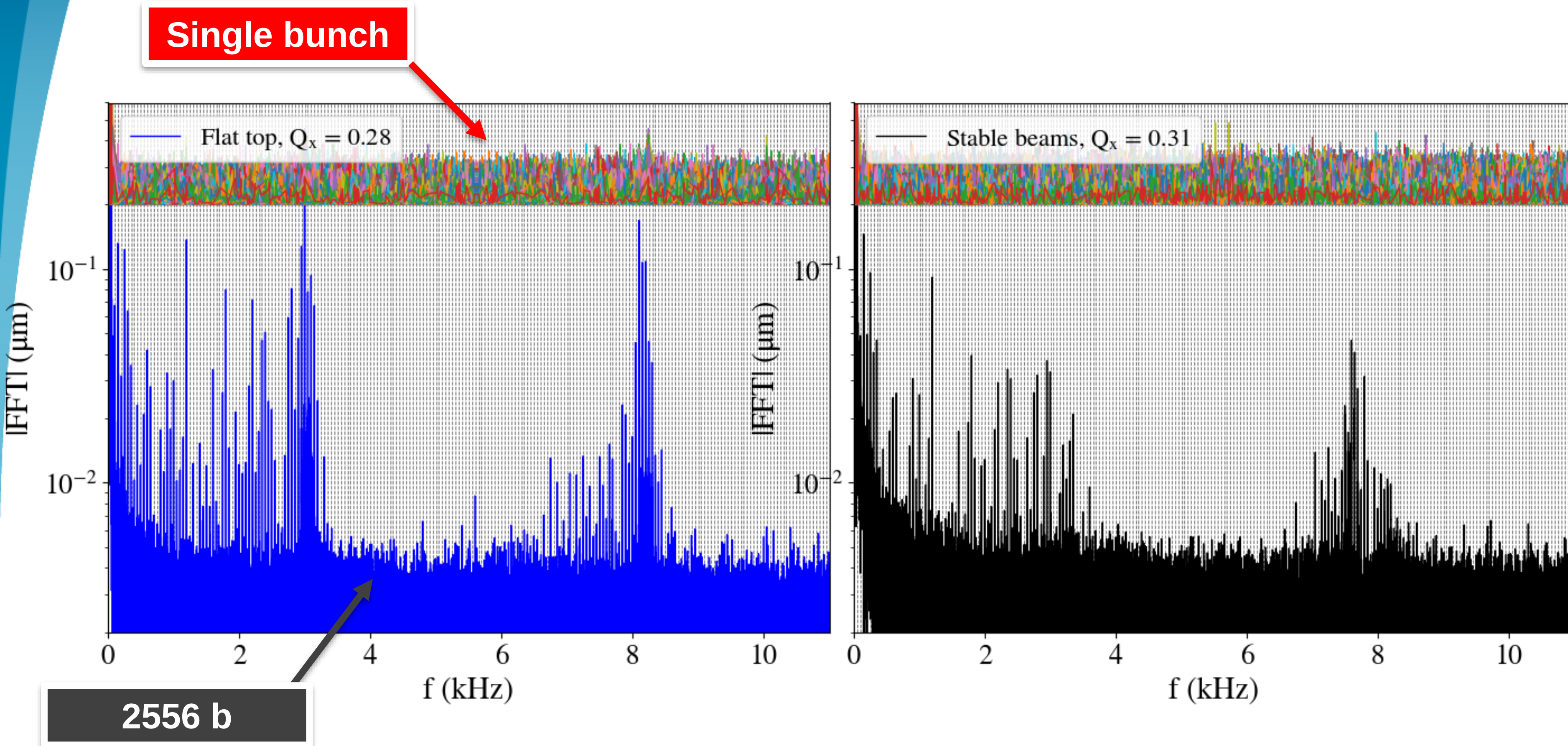
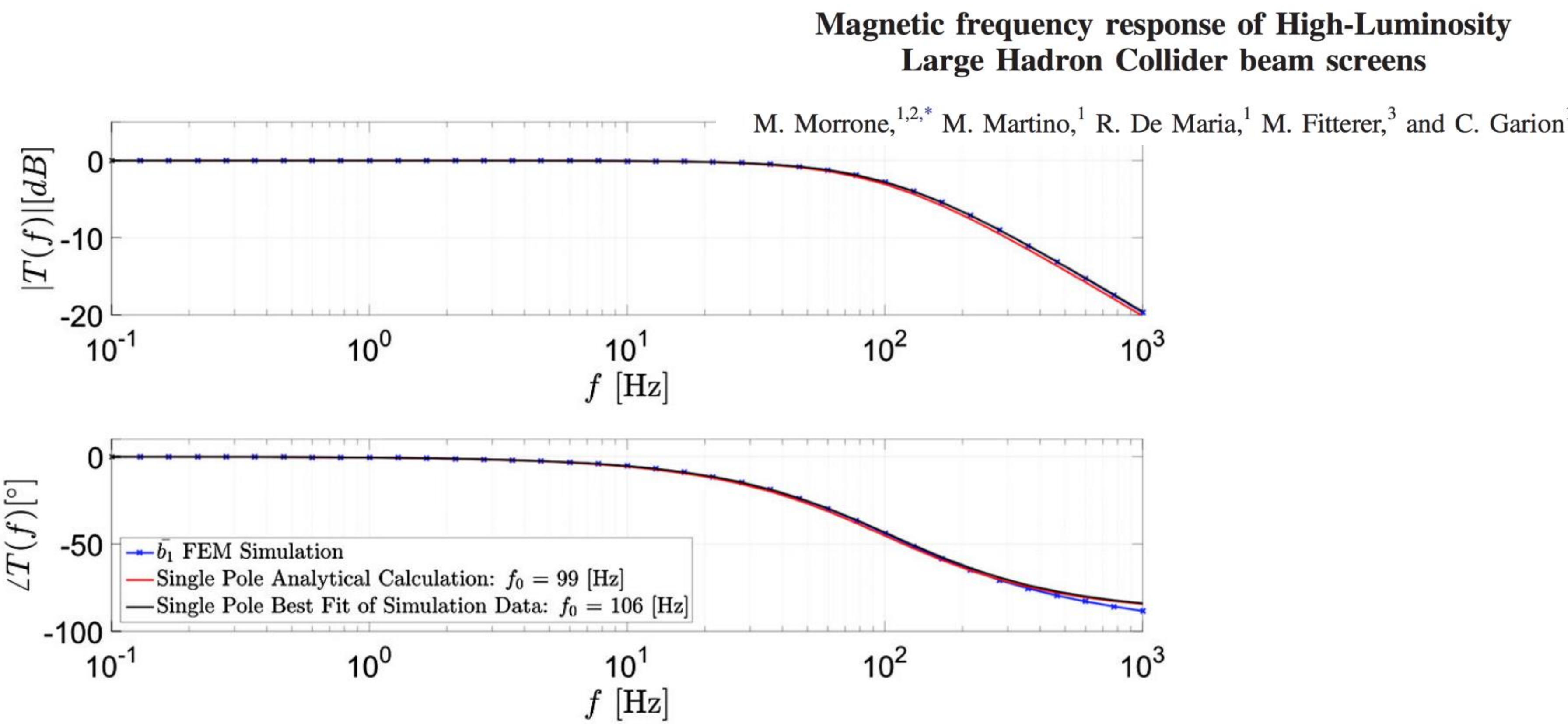


Single-bunch spectrum vs beam-spectrum



- The measured beam spectrum is below the single bunch spectrum (input for the damper).

What is the source of the 8 kHz oscillations?



(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 oscillations?

- **Still not clear**: the **present hypothesis** is that it could be related first unstable mode of the resistive wall coupled-bunch instability (frev-Q). See [1-3].

- Following this hypothesis the 8 kHz cluster of tones is an interplay between noise from the main bends circuit, impedance (resistive wall) and damper.

- **Multi-bunch simulations** with noise, impedance, damper are **still needed to verify it**.

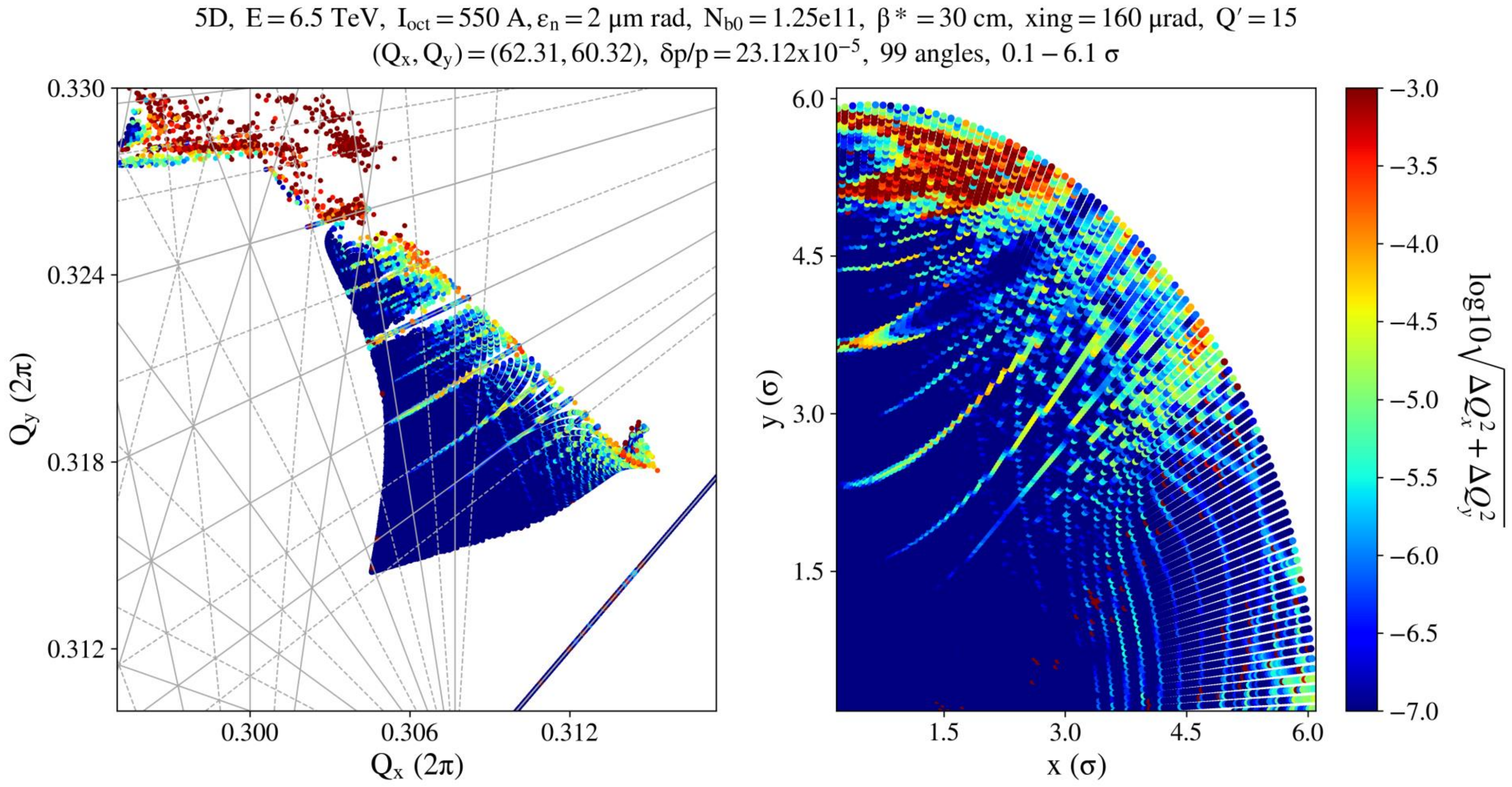
[1] F. Ruggiero, Single-Beam Collective Effects in the LHC, LHC Note 313
[2] D. Brandt and L. Vos, Resistive Wall Instability for the LHC: intermediate review, LHC Project Note 257
[3] P. Baudrenghien et al., LHC Transverse Feedback System and Its Hardware Commissioning, EPAC08

OUTLOOK

- Motivation
- What we see in LHC beams
- **Simulation benchmarking in LHC**
- Prediction for HL-LHC
- Conclusions

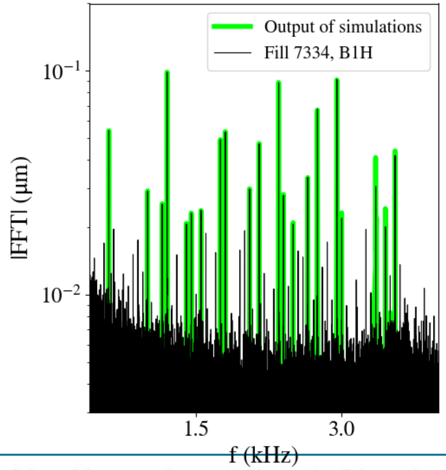
Simulating the effect of the observed spectrum

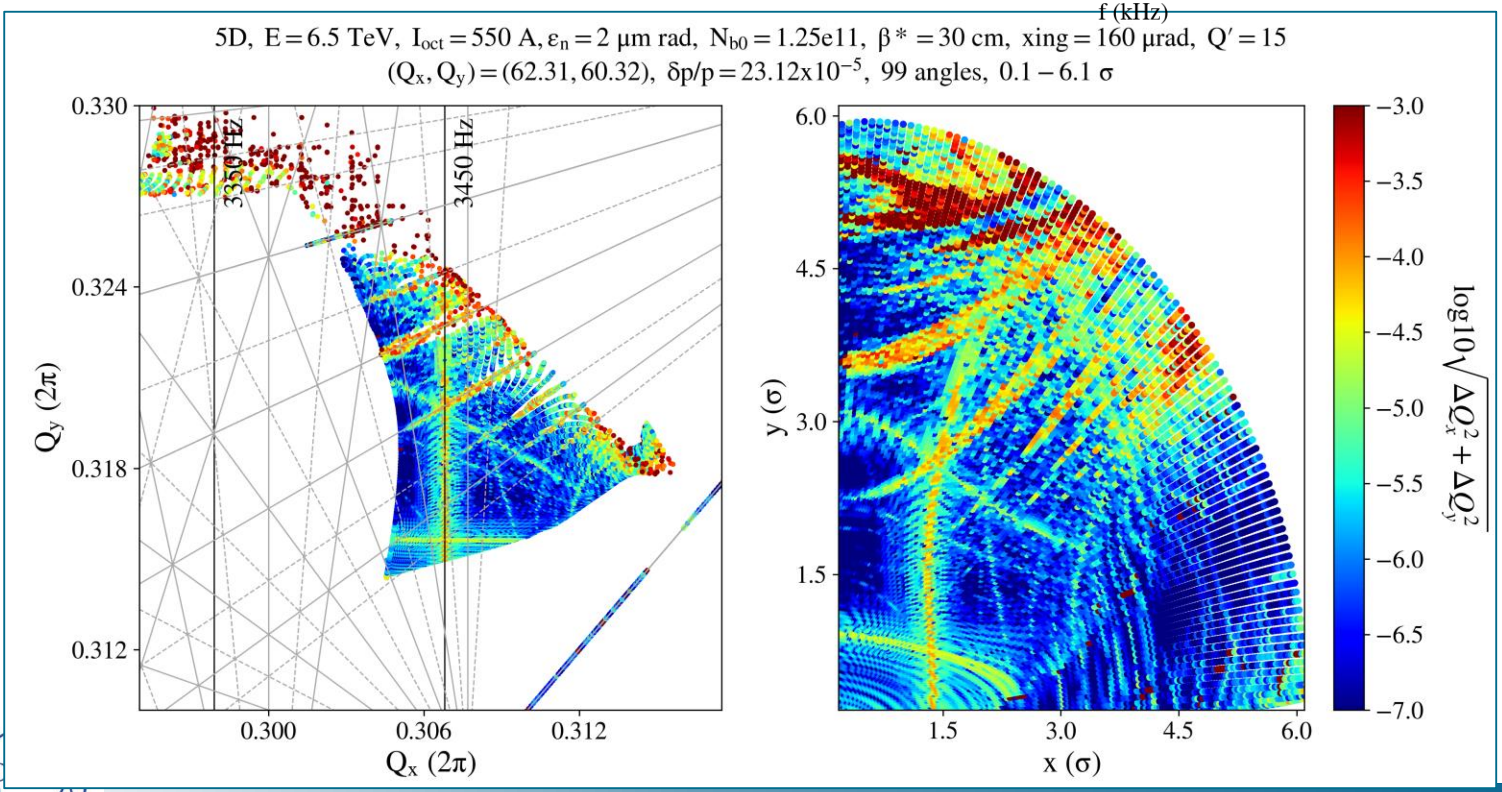
- FMA without noise in LHC (reference)



Simulating the effect of the observed spectrum

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





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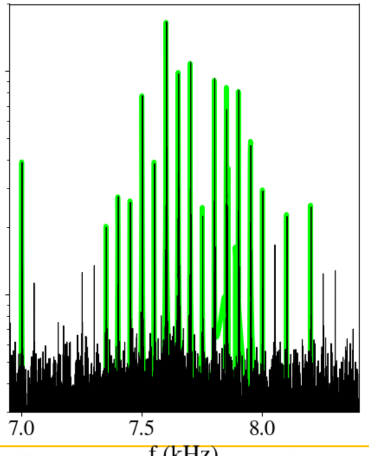
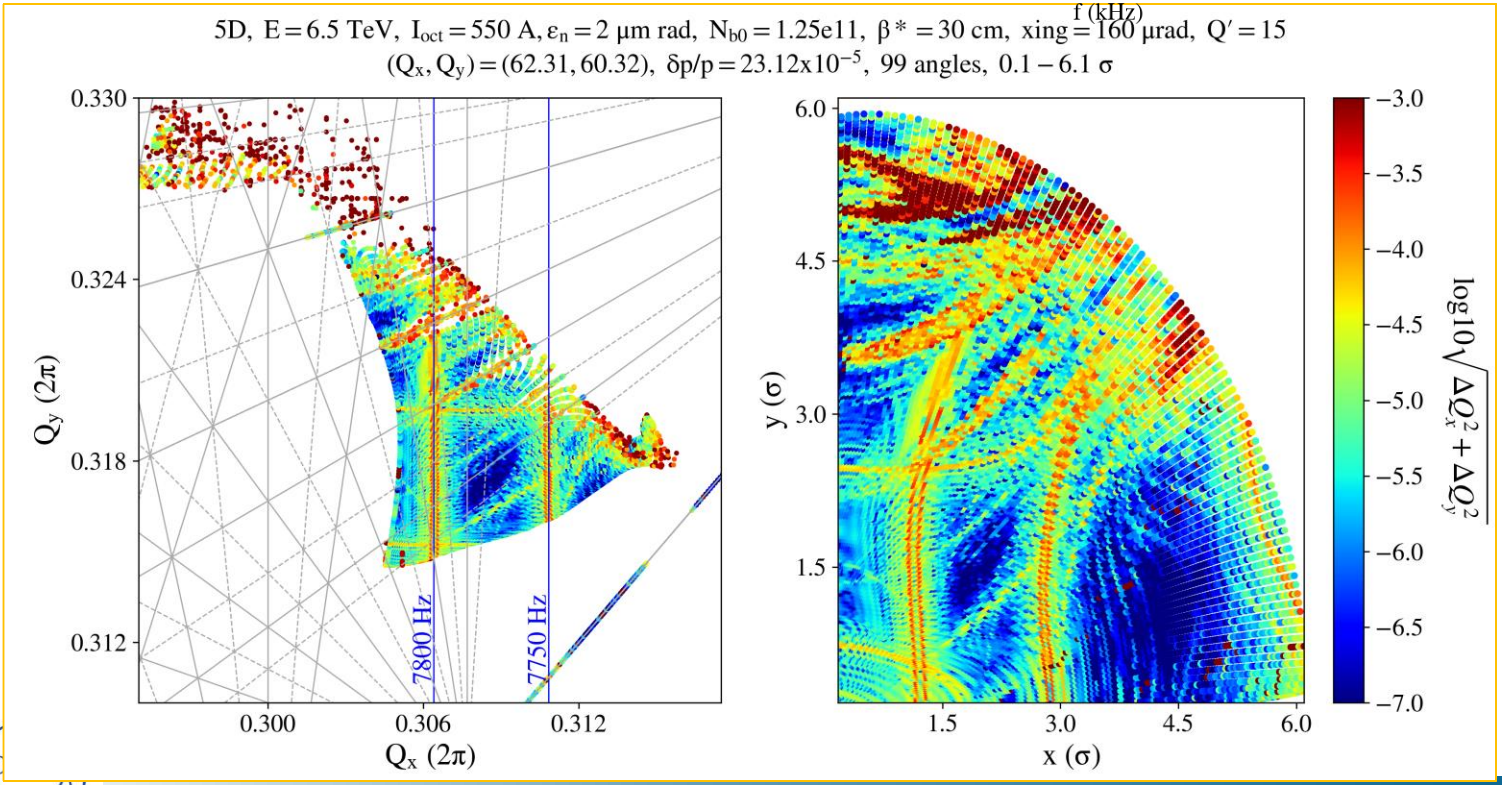


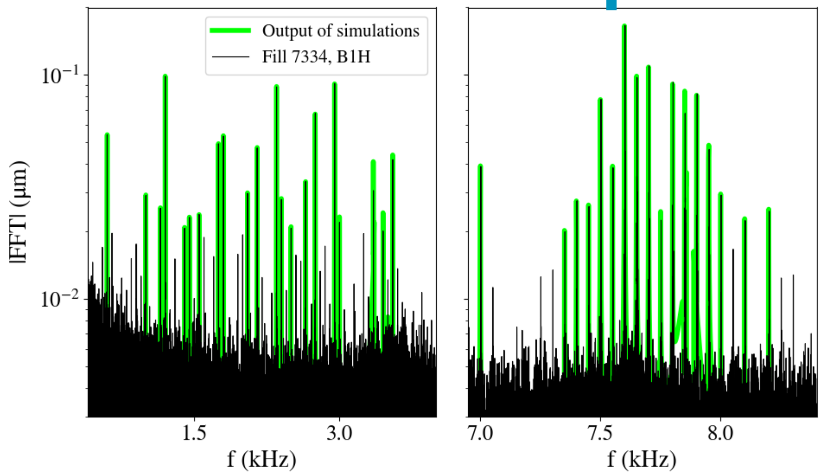


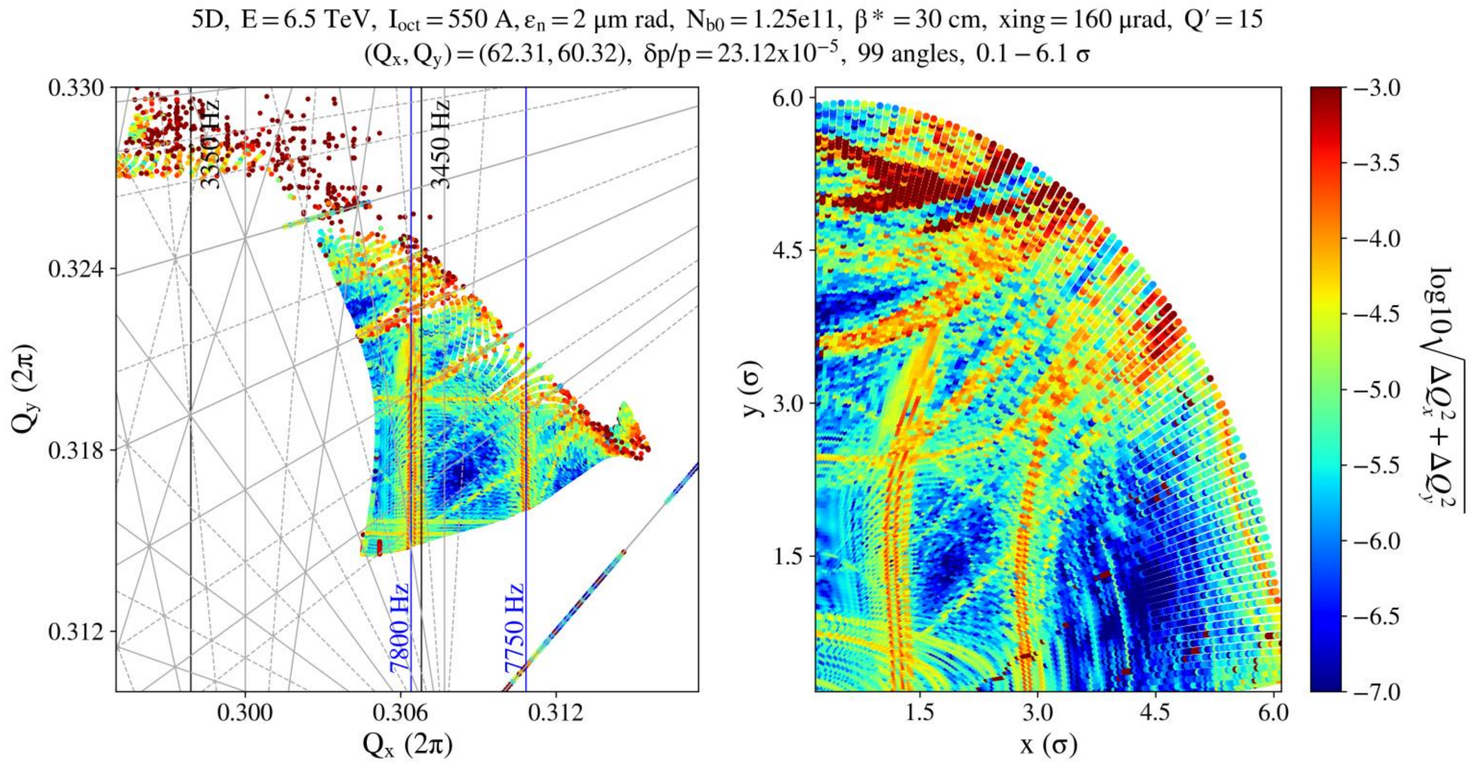
Simulating the effect of the observed spectrum

"Low frequency cluster"

+

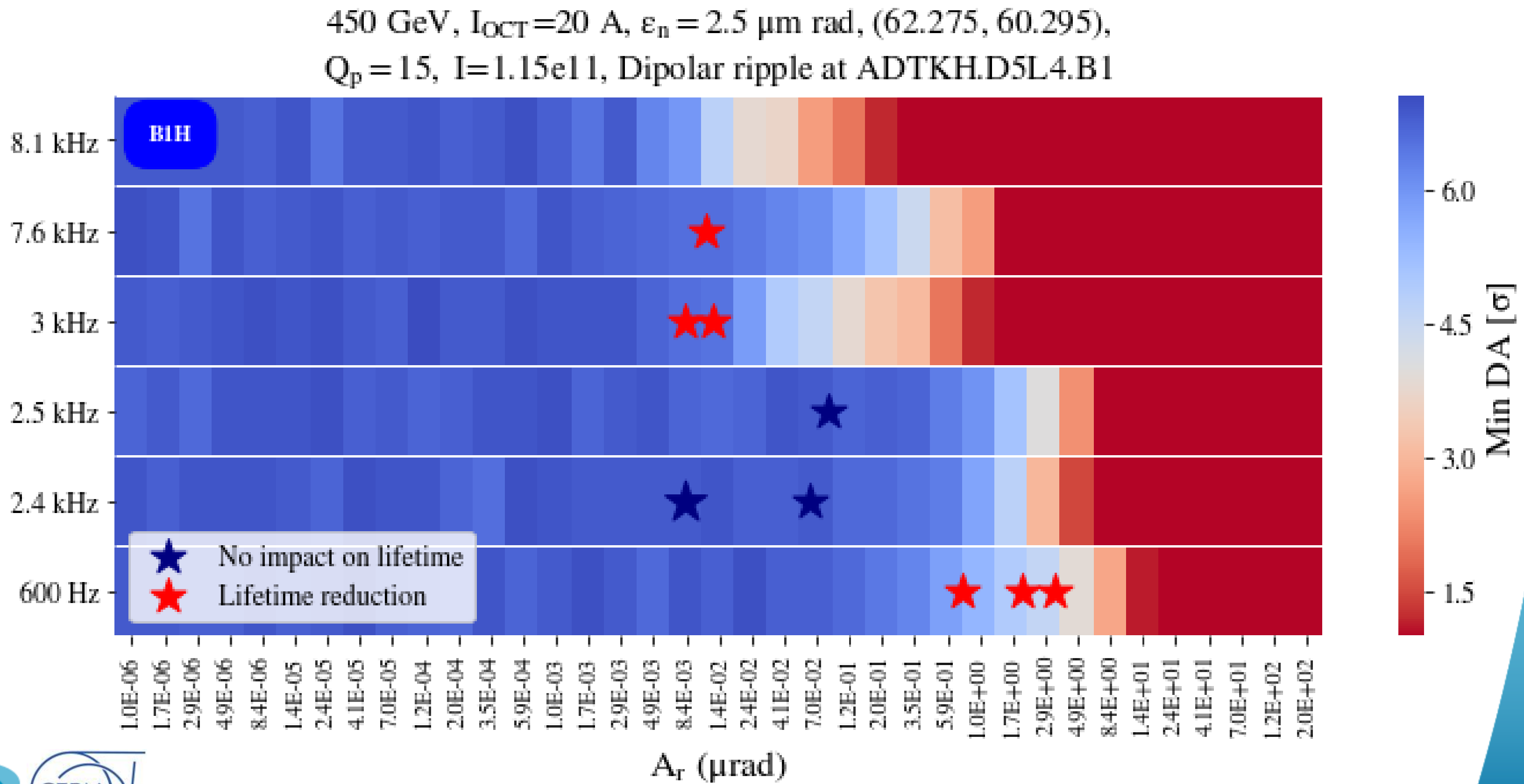
"High frequency cluster"





MD with controlled excitation and DA

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



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- **Prediction for HL-LHC**
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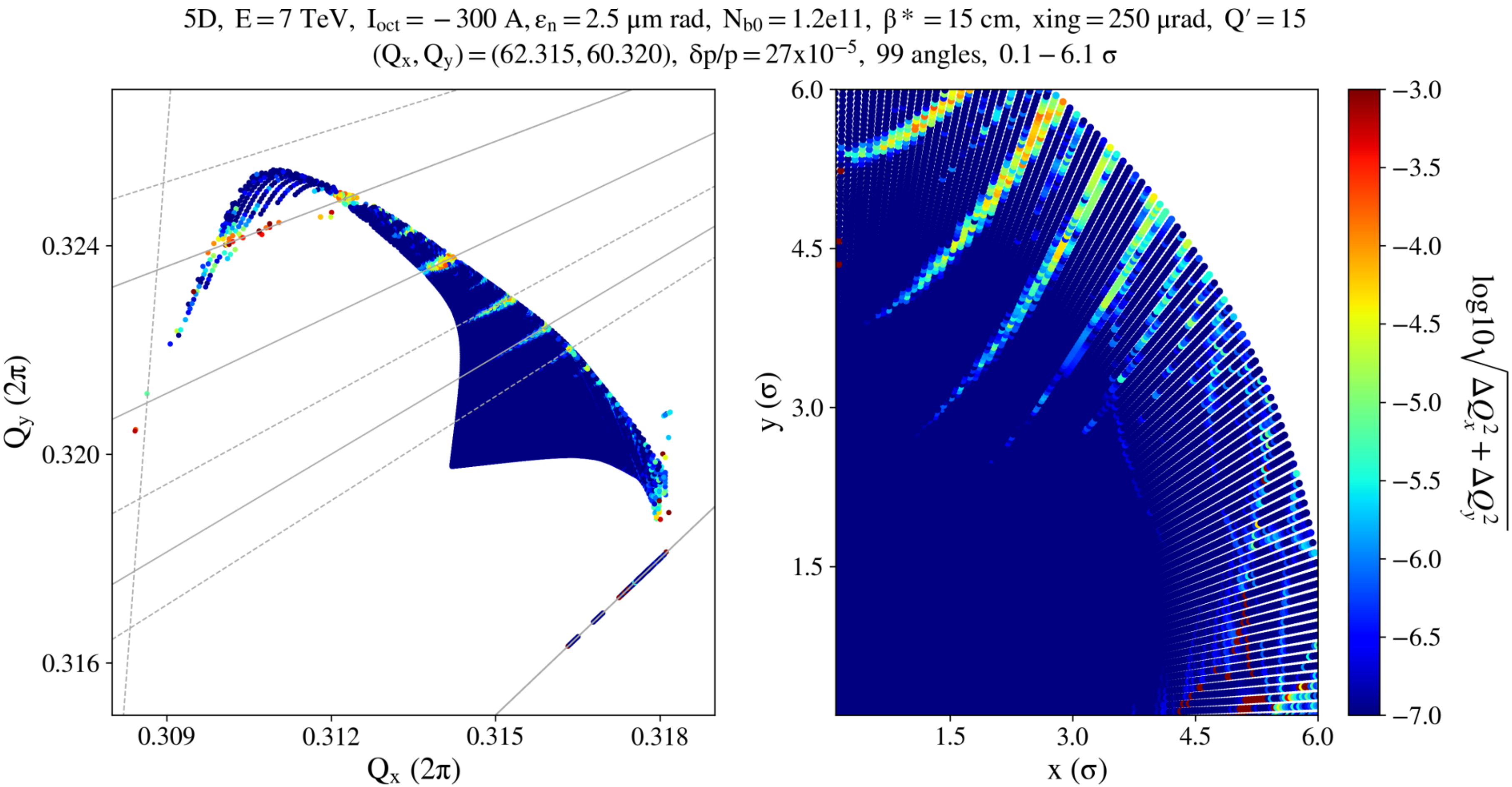
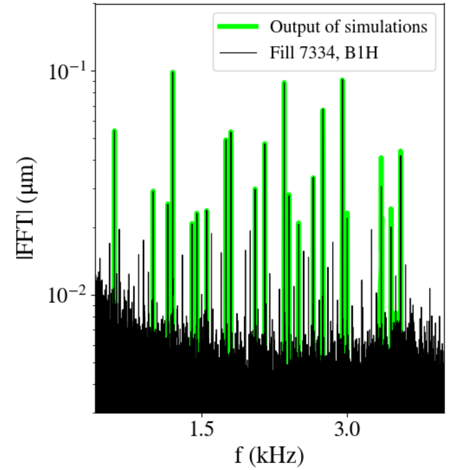
Projections for dipolar perturbations in HL-LHC

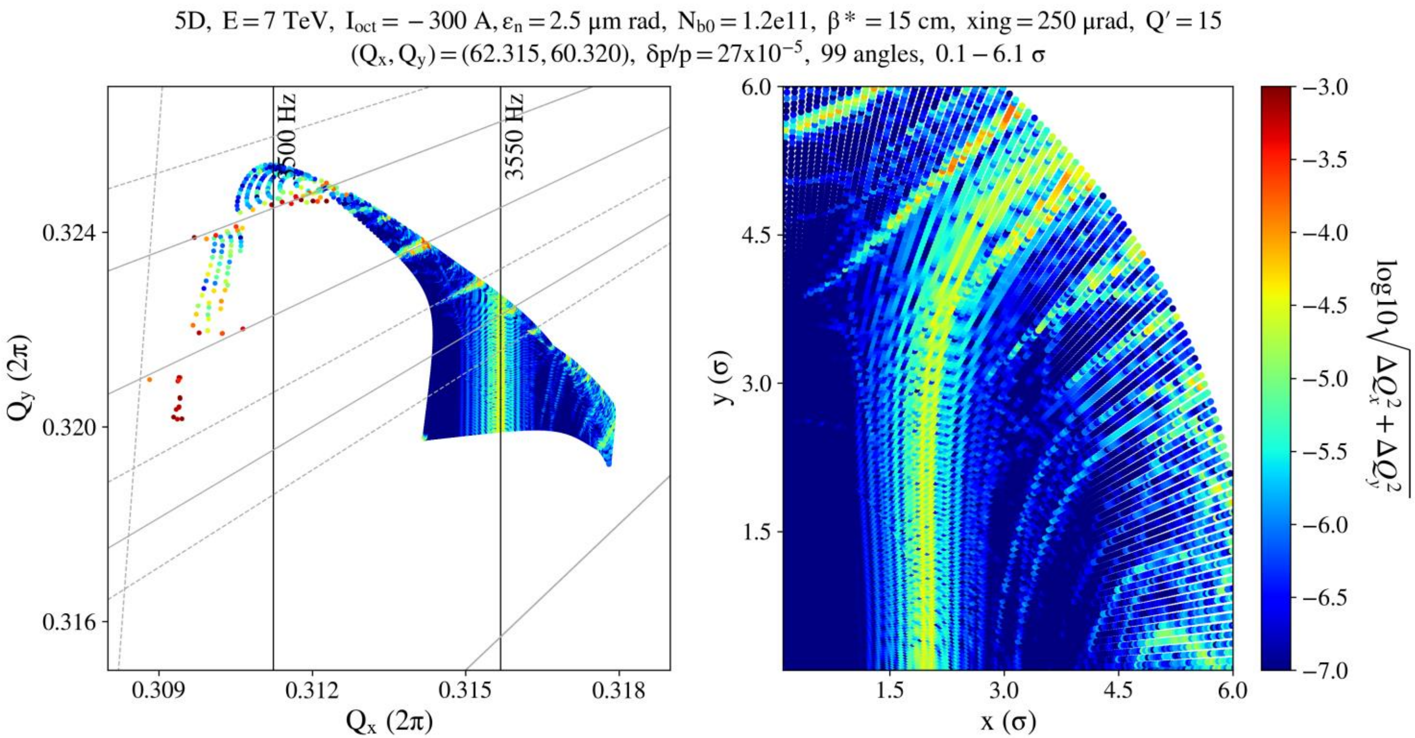
- FMA without noise in **HL-LHC** (reference)



Projections for dipolar perturbations in HL-LHC

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





Projections for dipolar perturbations in HL-LHC

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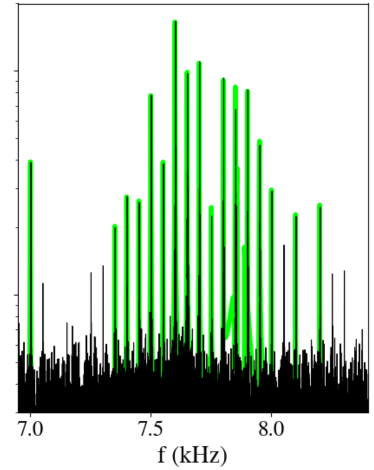
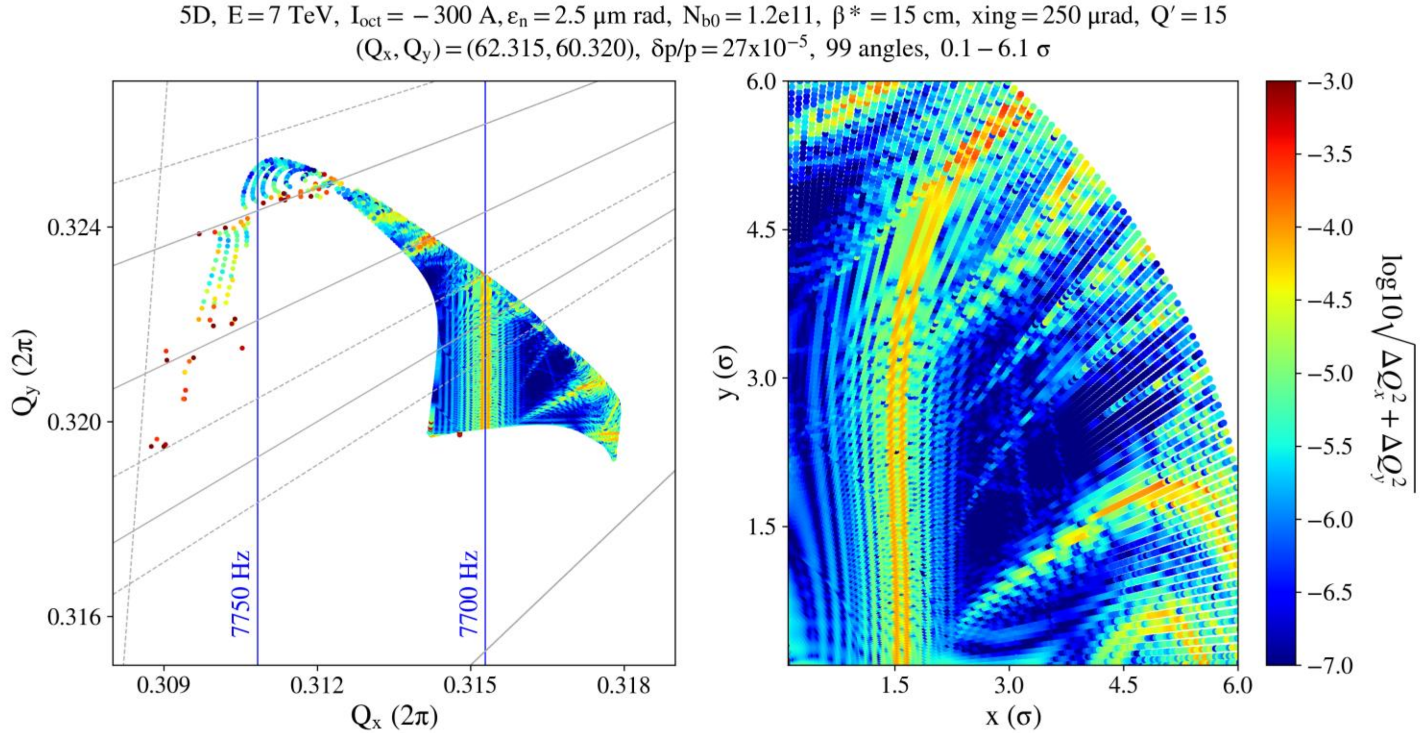


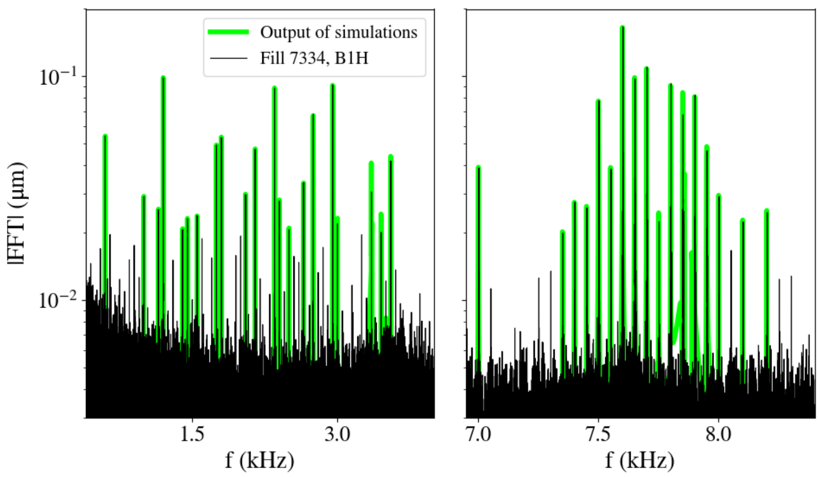


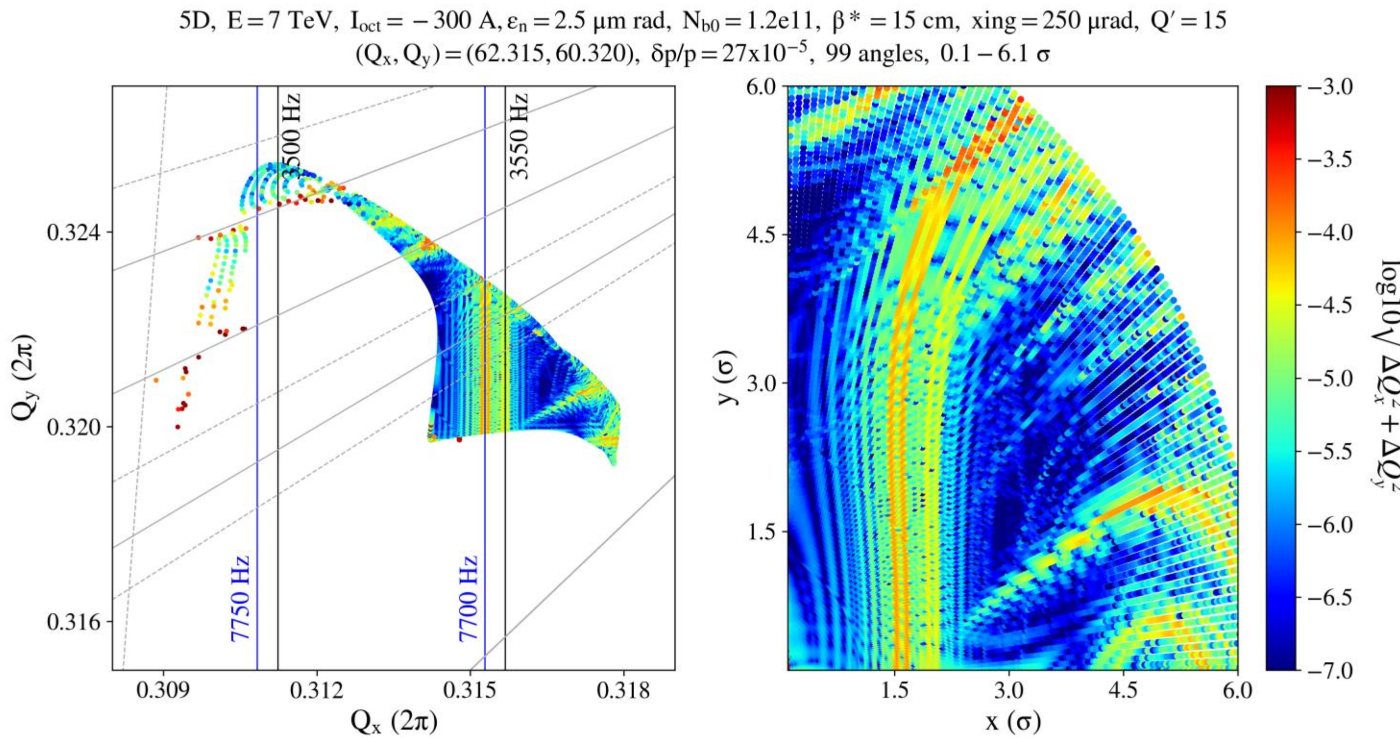
Projections for dipolar perturbations in HL-LHC

“Low frequency cluster”

+

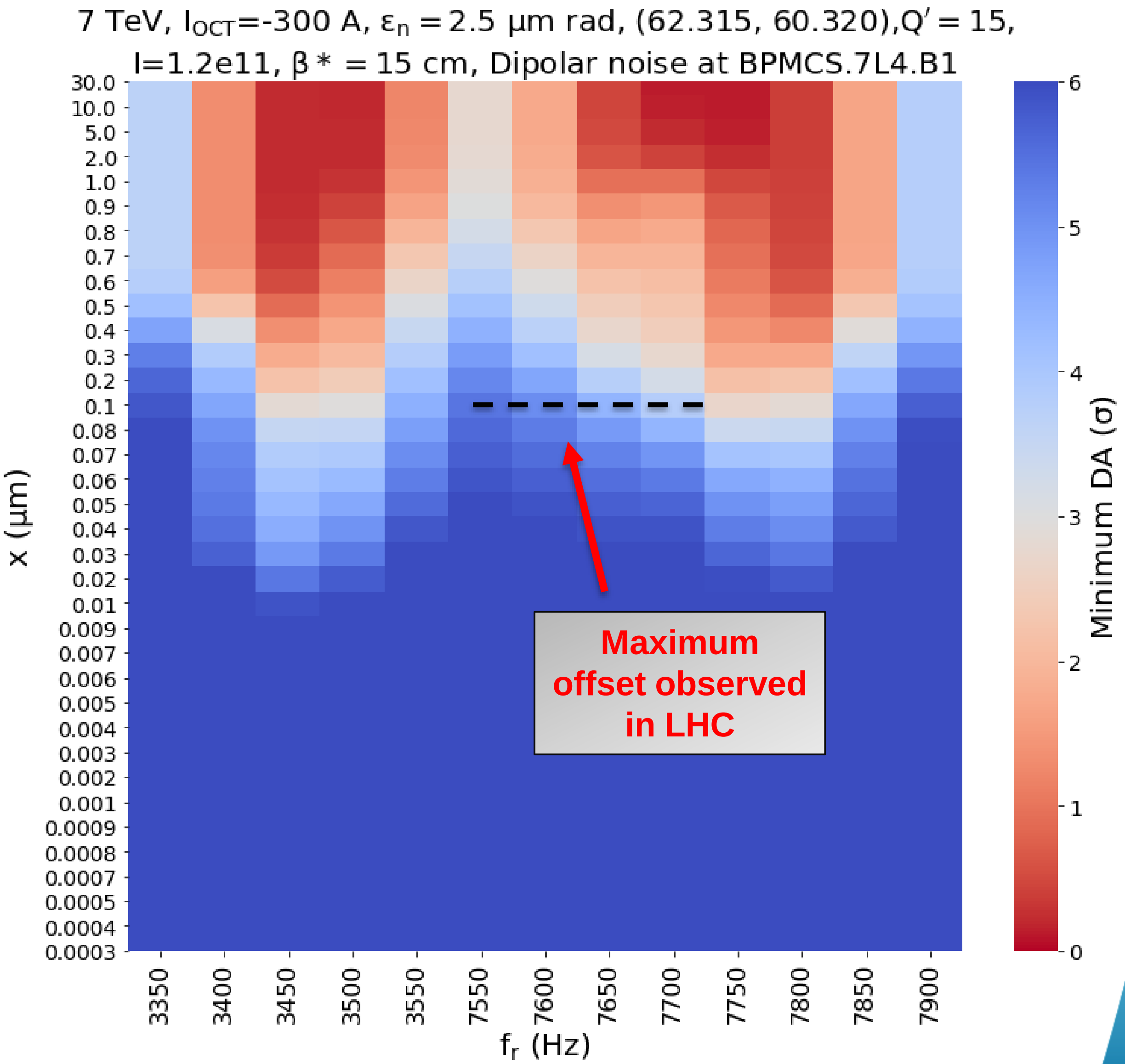
“High frequency cluster”





Projections for dipolar perturbations in HL-LHC

- Assuming a **lumped dipolar perturbation** in the ADT PU in Q7.
- Simulations shows that **0.1 um** level of excitation **can degrade the machine DA.**



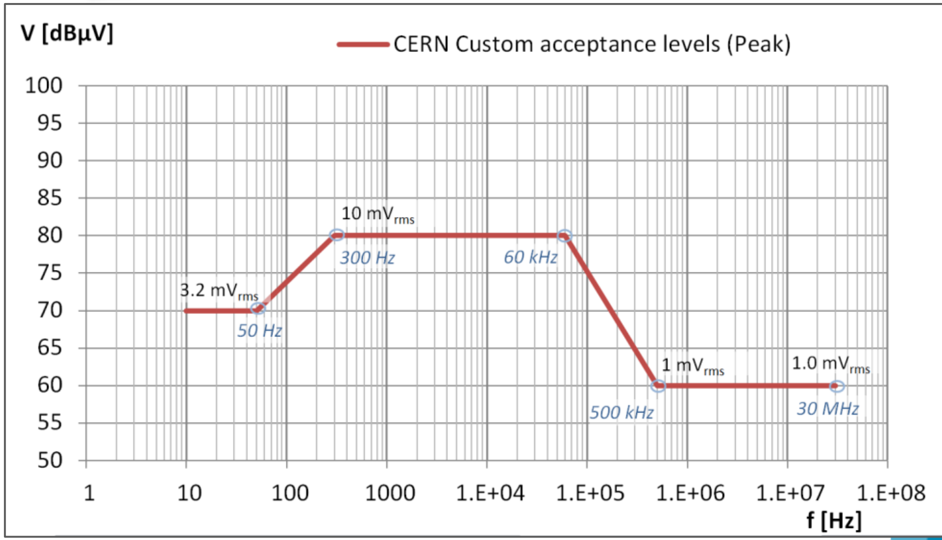
From dipolar to quadrupolar noise: the Inner Triplet simulations for HL-LHC

Inner Triplet: Voltage-control regime

- Based on previous studies [4], scan **individual frequencies** for **different strengths** in order to determine where reduction of DA is observed.
- Compare with PC specifications [5].

Approximations:

- Impact from beam screen, cold bore **not included**.
- **Inductance** considered **constant vs f**.
- Impact from **individual frequencies**, not multiple harmonics.

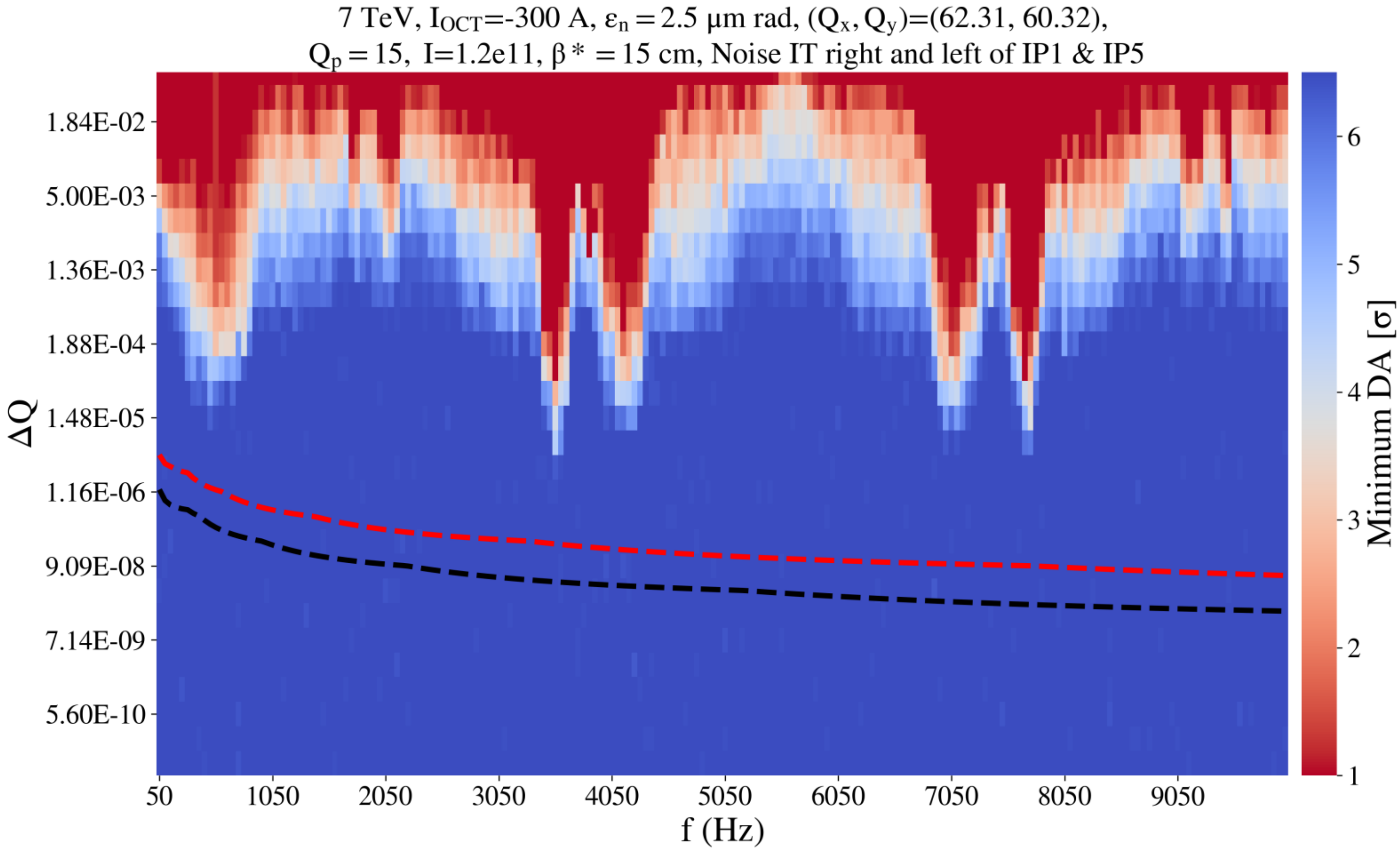


Simulation parameters
HLLHC.v13
ε_n=2.5 μm rad
I=-300 A
(Q_x, Q_y)=(62.31,60.32)

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

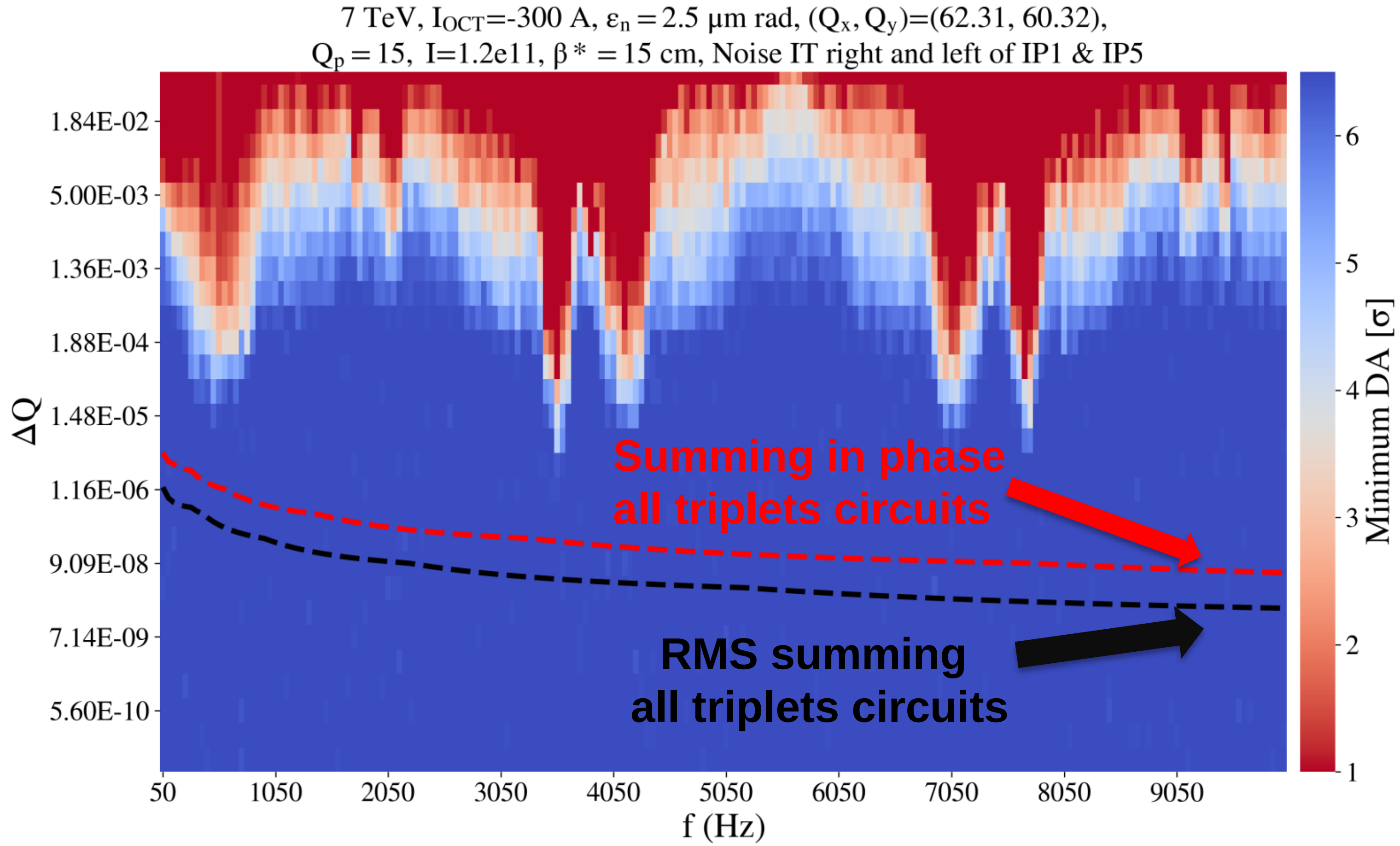
[4] M. Fitterer, R. De Maria, S. Fartoukh and M. Giovannozzi, Beam Dynamics Requirements for the Powering Scheme of the HL-LHC Triplets
[5] D. Gamba et al., Beam Dynamics Requirements for HL–LHC Electrical Circuits

Inner Triplet: DA studies



- Frequency scan as a function of ΔQ with ripples in all circuits of IP1 & IP5. Each point is an individual study
- Conservative approach: same phase of noise in all locations. Switching frequency of the 18 kA circuit will be at 50-200 kHz.

Inner Triplet: DA studies



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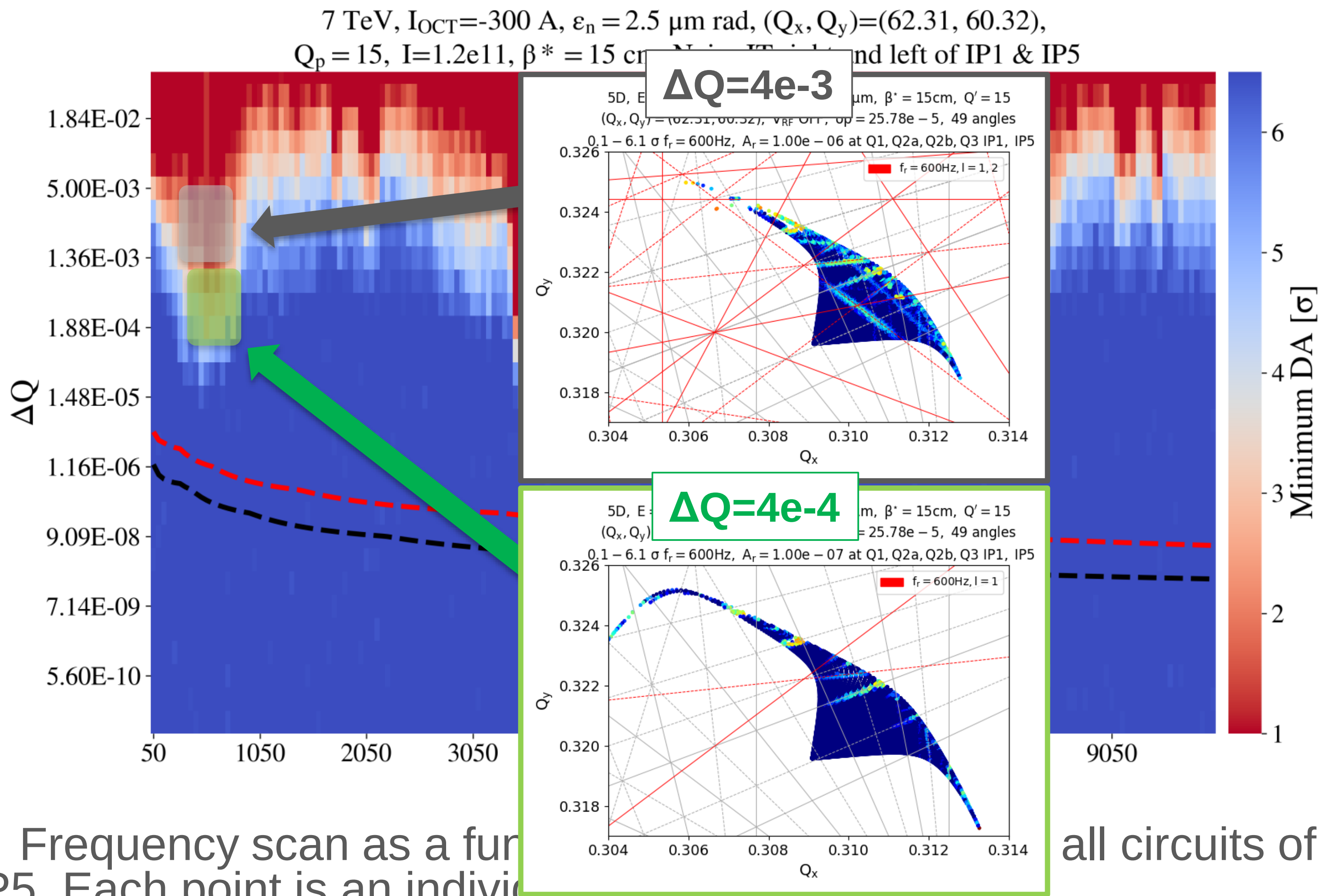

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HL-LHC PROJECT

Conclusions

- **Dipolar excitation:**
  - Harmonics of 50 Hz have been observed in the beam spectrum. 2 regimes have been identified: **the low** (up to 3.6 kHz) and **high** (7-8 kHz) frequency cluster.
  - 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 (larger impact on **B1H**). The **high** frequency cluster is not affected by the status of the Active Filters: the present hypothesis is that is due to an **interplay between noise, damper and impedance (first unstable couple bunch mode at 8 kHz)**.
  - Simulations in the LHC with a realistic beam spectrum (lumped dipolar perturbation in a single location) indicate that these **harmonics lead to an increase of diffusion and can harm the beam lifetime**.
  - **These harmonics will also be present in the HL-LHC and, assuming the same noise spectrum, the impact on DA is significant, especially due to the high frequency cluster.**

- **Quadrupolar excitation (Inner Triplet):**
  - Maximum output voltage is below the level where reduction of DA is expected.
  - Switching frequencies are expected to be heavily attenuated and do not pose a limitation to the beam performance.

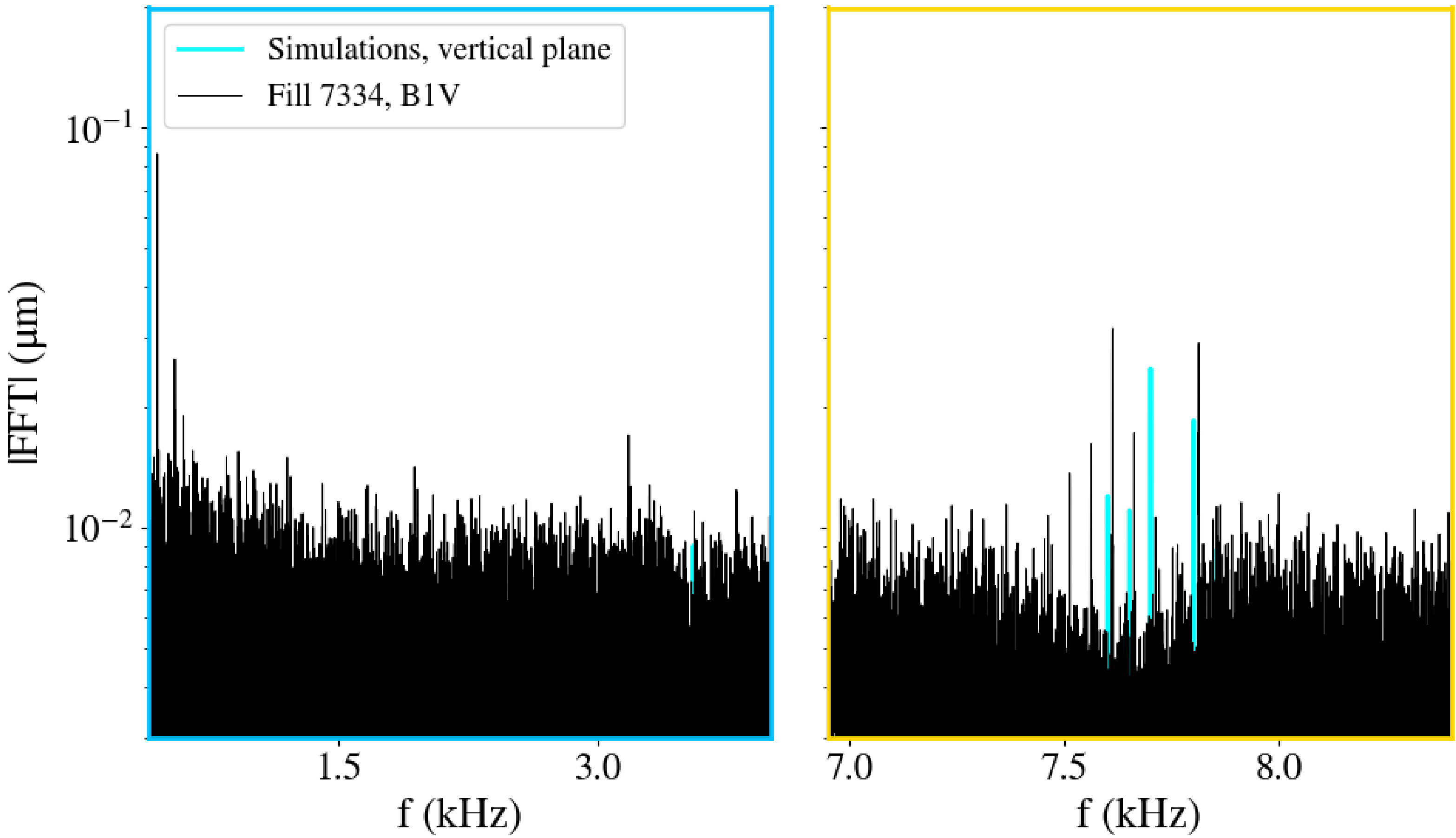
HiLumi
HL-LHC PROJECT

Thank you!

CERN

Backup

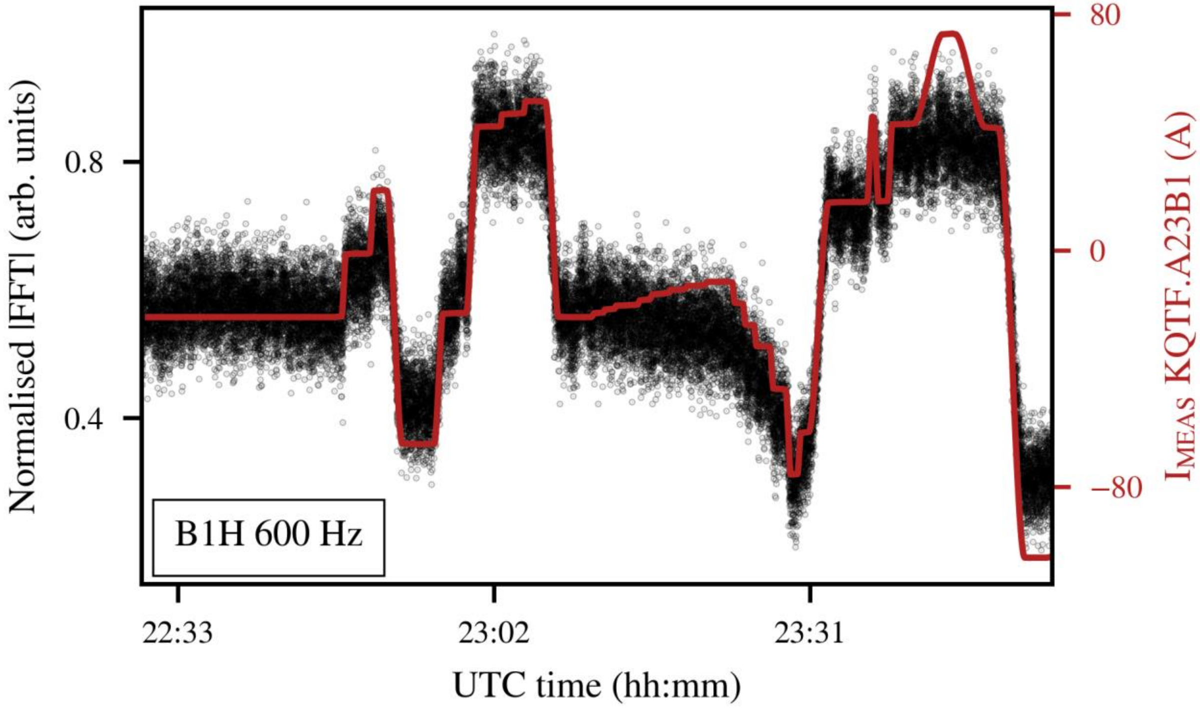
Coupling of H/V plane in simulation



- Vertical motion observed in simulations.

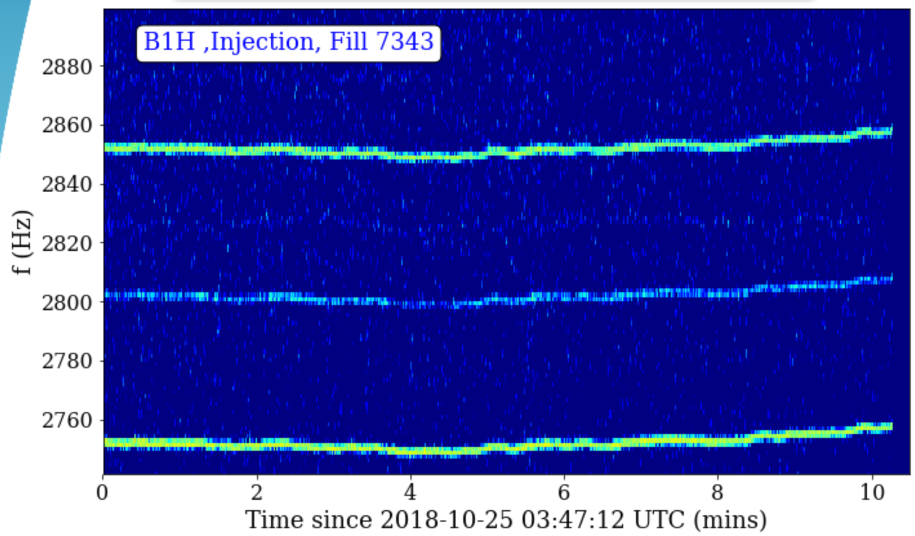
Are these tones an artefact? No.

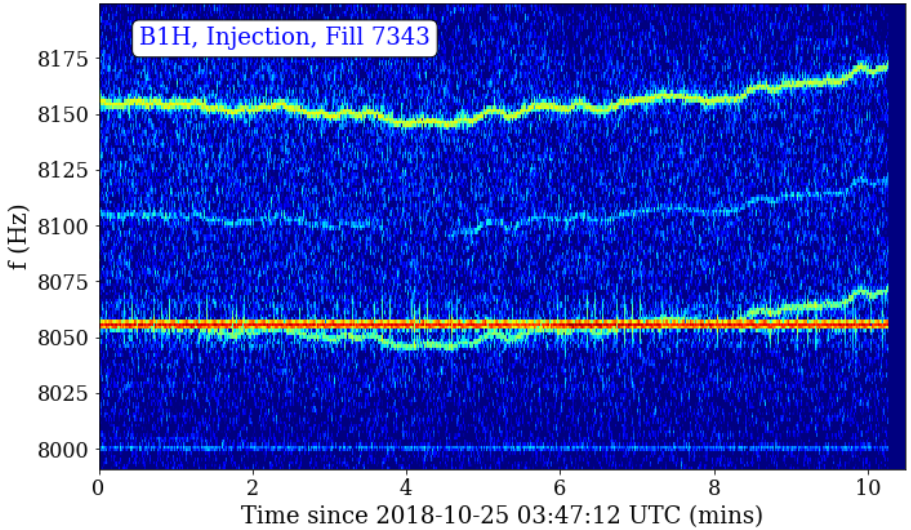
- For **lower frequencies** (<4 kHz) impact of the IP1/IP5 phase advance.



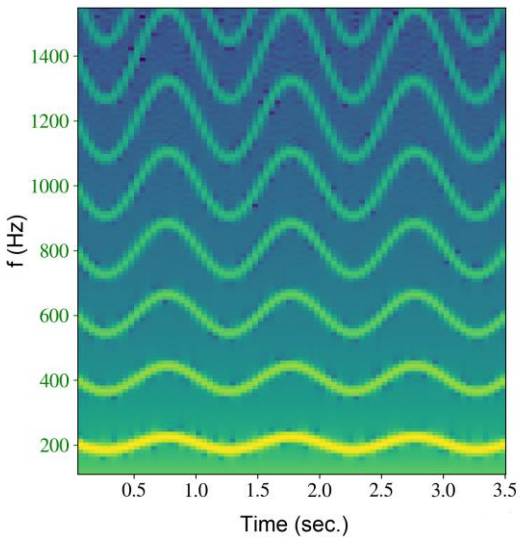
Harmonics of 50 Hz

B1H, Injection





Simulations



Appendix

$\frac{\Delta Q}{\Delta I / I_{rated}}$			
RQX.L1	80.500	RTQX3.L1	4.490
RQX.R1	62.790	RTQX3.R1	9.070
RQX.L5	79.160	RTQXA1.L5	0.060
RQX.R5	61.620	RTQXA1.R5	0.060
RTQXA1.L1	0.060	RTQX1.L5	2.670
RTQXA1.R1	0.060	RTQX1.R5	2.000
RTQX1.L1	2.700	RTQX3.L5	4.470
RTQX1.R1	2.010	RTQX3.R5	8.970

	L [mH]	I_{rated} $[kA]$
Q1/Q2a/Q2b/Q3	255	18
Trim Q1	69	2
Trim Q1a	34.5	0.035
Trim Q3	69	2

$$\frac{\mathrm{d}B(f)}{B_{nom}} = \begin{cases} \frac{\mathrm{d}I(f)}{I_{nom}} & \text{for } f \leq f_0 \\ T_{Vacuum}(f) \times T_{VtoB}(f) & \text{for } f > f_0 \end{cases}$$

$$\text{with: } T_{VtoB}(f) = T''_{VtoB}(f) \times \frac{\mathrm{d}V(f)}{2\pi f L_{DC} I_{nom}}$$

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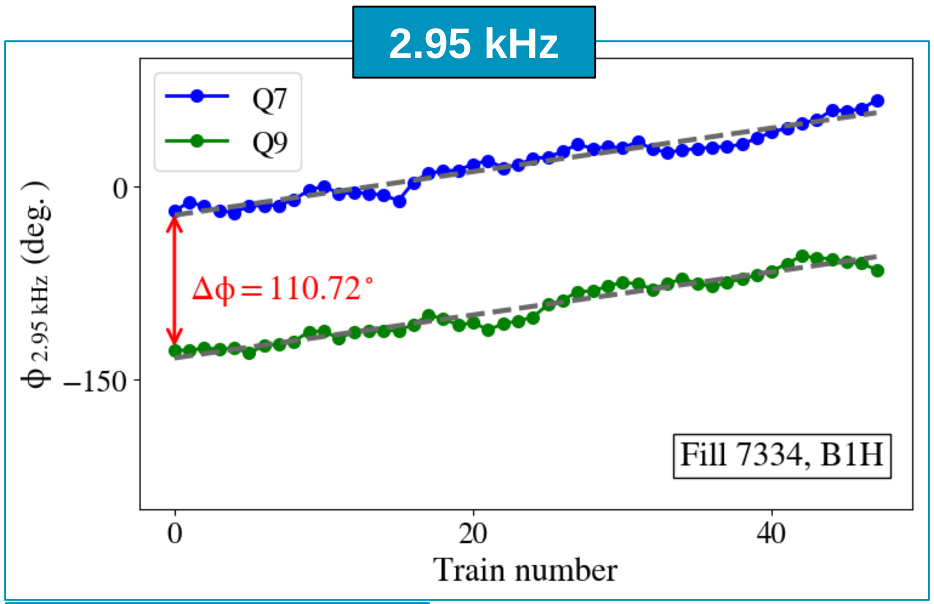

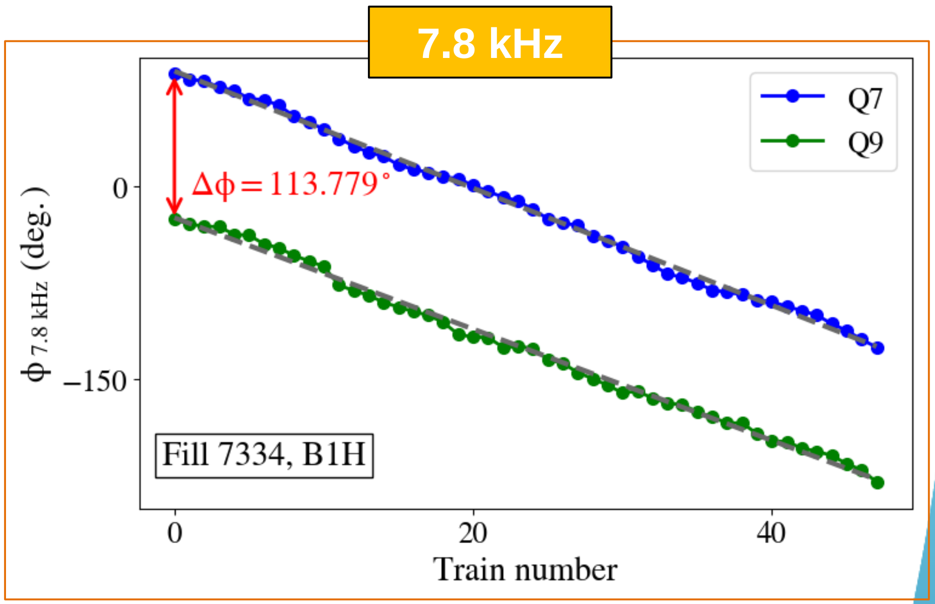

MEASUREMENT