Summary of power supply ripple observations in the LHC and impact on the HL-LHC

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63rd TCC 13/12/2018: https://indico.cern.ch/event/779650/contributions/3244747/attachments/1770859/2877607/TCC_noise_131218.pdf

WP2, 05/05/2020

Motivation

- LHC performance during Run I & II: proton losses and emittance growth ↑ than anticipated [1-4] → mechanism that enhances diffusion → **Noise effects**

[1] F. Antoniou, et al. Can we predict luminosity? 7th Evian Workshop on LHC beam operation 2016
[2] S. Papadopoulou, et al. Emittance, intensity and luminosity modeling and evolution, 8th Evian Workshop on LHC beam operation 2017
[3] S. Papadopoulou S, et al. What do we understand on the emittance growth? 9th Evian Workshop on LHC beam operation 2019
[4] S. Kostoglou, et al. Luminosity and lifetime modeling and optimization, 9th Evian Workshop on LHC beam operation 2019

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- LHC performance during Run I & II: proton losses and emittance growth ↑ than anticipated → mechanism that enhances diffusion → **Noise effects**
- Power supply ripple in dipoles and quadrupoles:

  Observed in LHC & expected in HL-LHC

  - 50 Hz harmonics
    - What is the source? Summary of 2018 observations.
    - What will be the impact in HL-LHC?
    - How can we mitigate?

  Expected in HL-LHC

  - Inner Triplet
    - Do we expect an impact on the HL-LHC beam performance?
  - Open questions and next steps.

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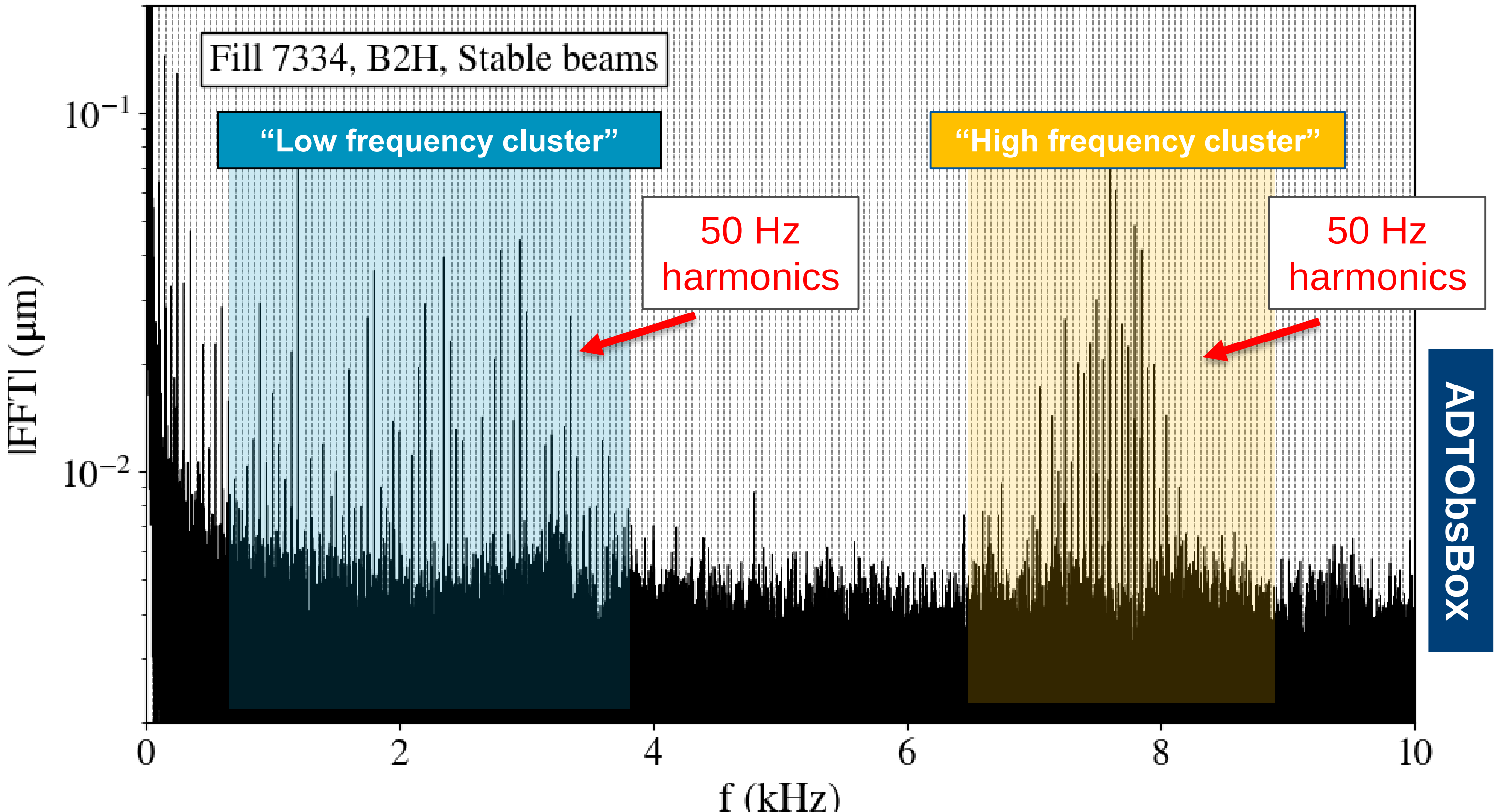
Beam spectrum at SB

Low-f cluster up to 3.6 kHz.

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

- Not aliases due to sampling error.
- Not an artifact of the instrumentation system.
- The effect is dipolar.

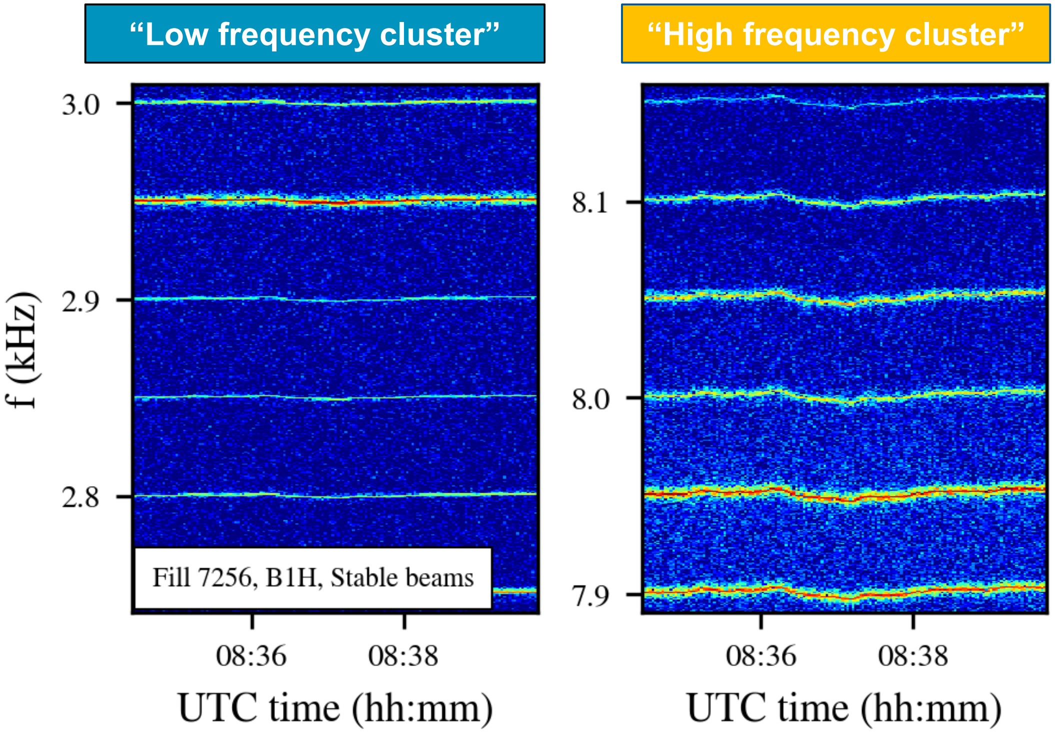
Status of noise studies in the LHC and expected impact for the HL-LHC, WP2 26/11/2019

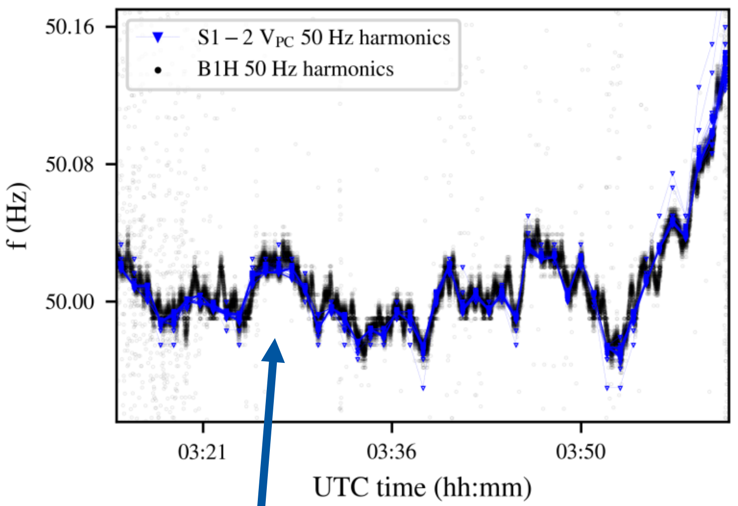


Beam spectrum at SB

Low-f cluster + **High-f cluster**:

1. Multiple 50 Hz harmonics
2. Similar phase modulation from the mains, with an amplitude proportional to the order of the harmonic.

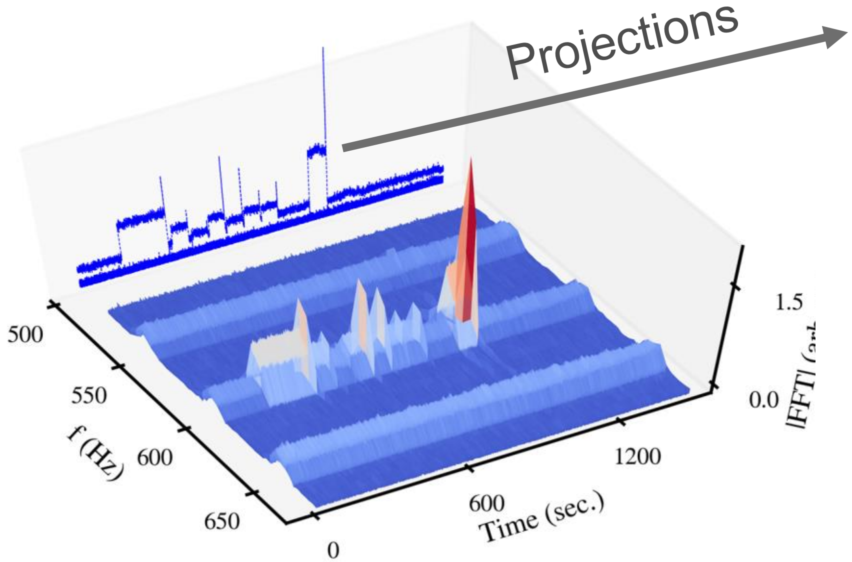




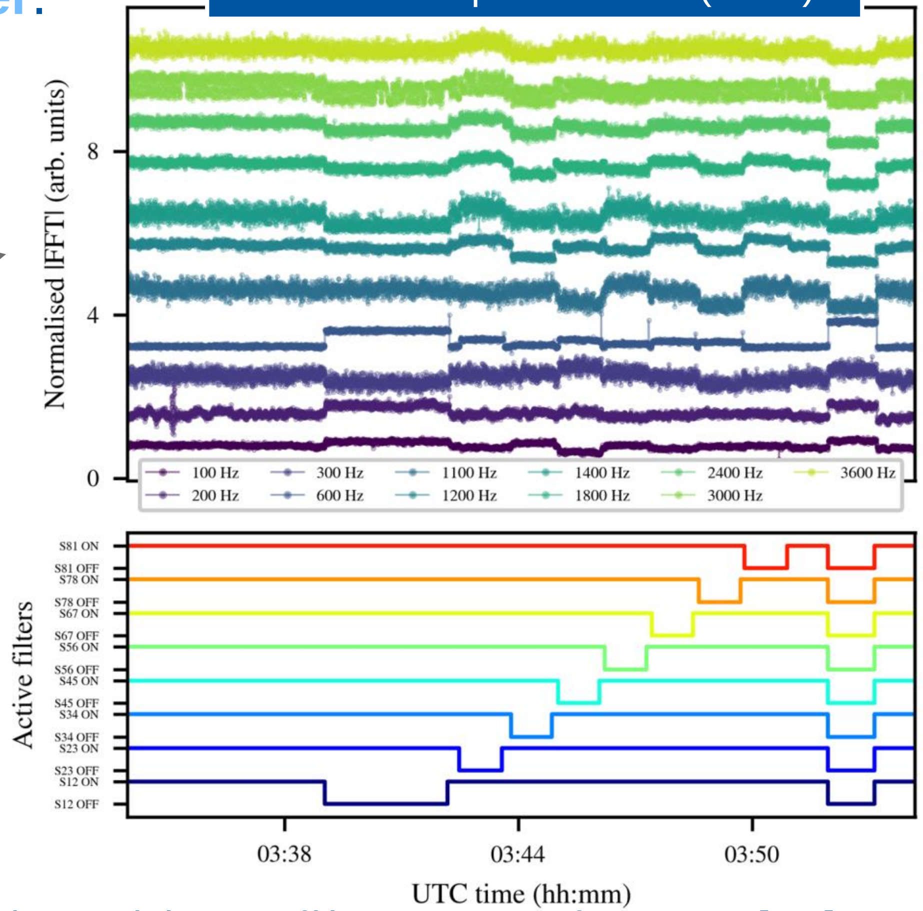
Frequency evolution of all harmonics normalized with the order of the harmonic.

Experiments with active filters

- ON/OFF active filters MB PC: impact on the harmonics of the **low-f cluster**.
- All eight sectors contribute to this effect.



Amplitude evolution of beam harmonics up to **3.6 kHz** (h=72)



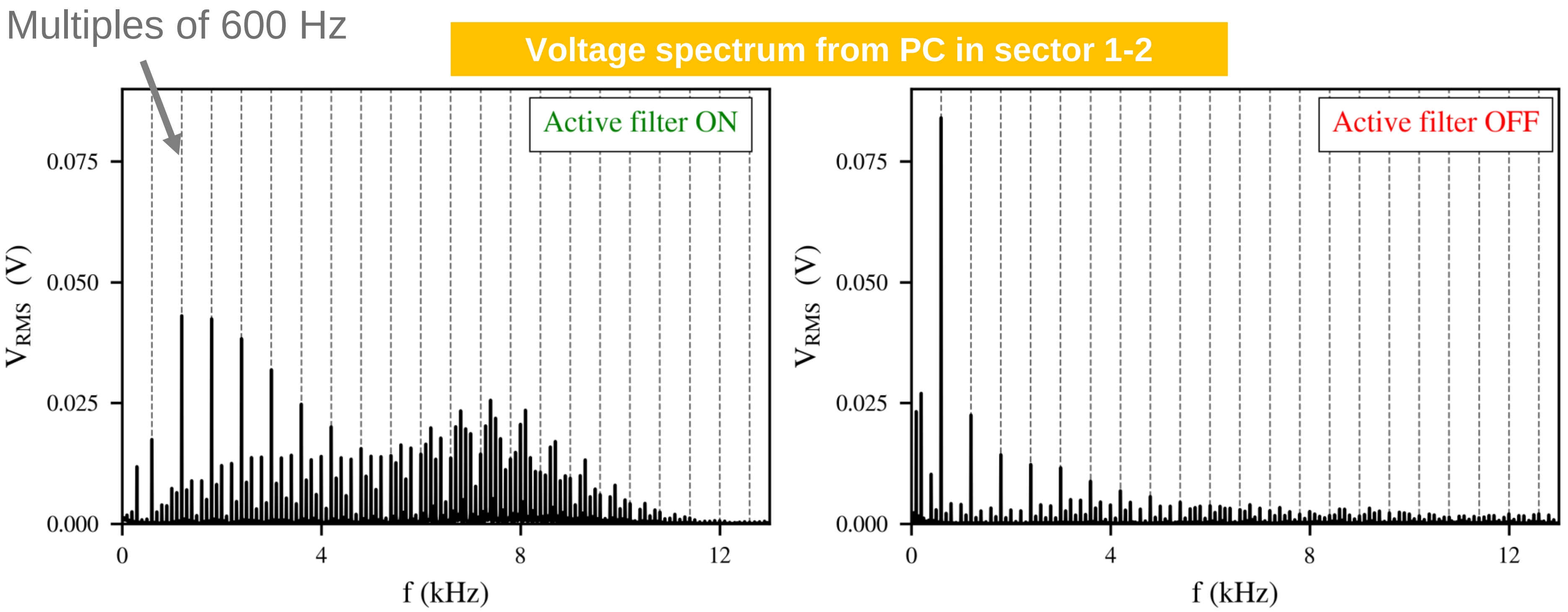
3.6 kHz is clearly passing to the beam, although way beyond the cutoff beam screen frequency [1,2].

[1] R. De Maria et al, Field fluctuation and beam screen vibration measurements in the LHC magnets

[2] M. Morrone M. Martino, et al, Magnetic frequency response of High-Luminosity Large Hadron Collider beam screens., Phys. Rev. ST Accel. Beams

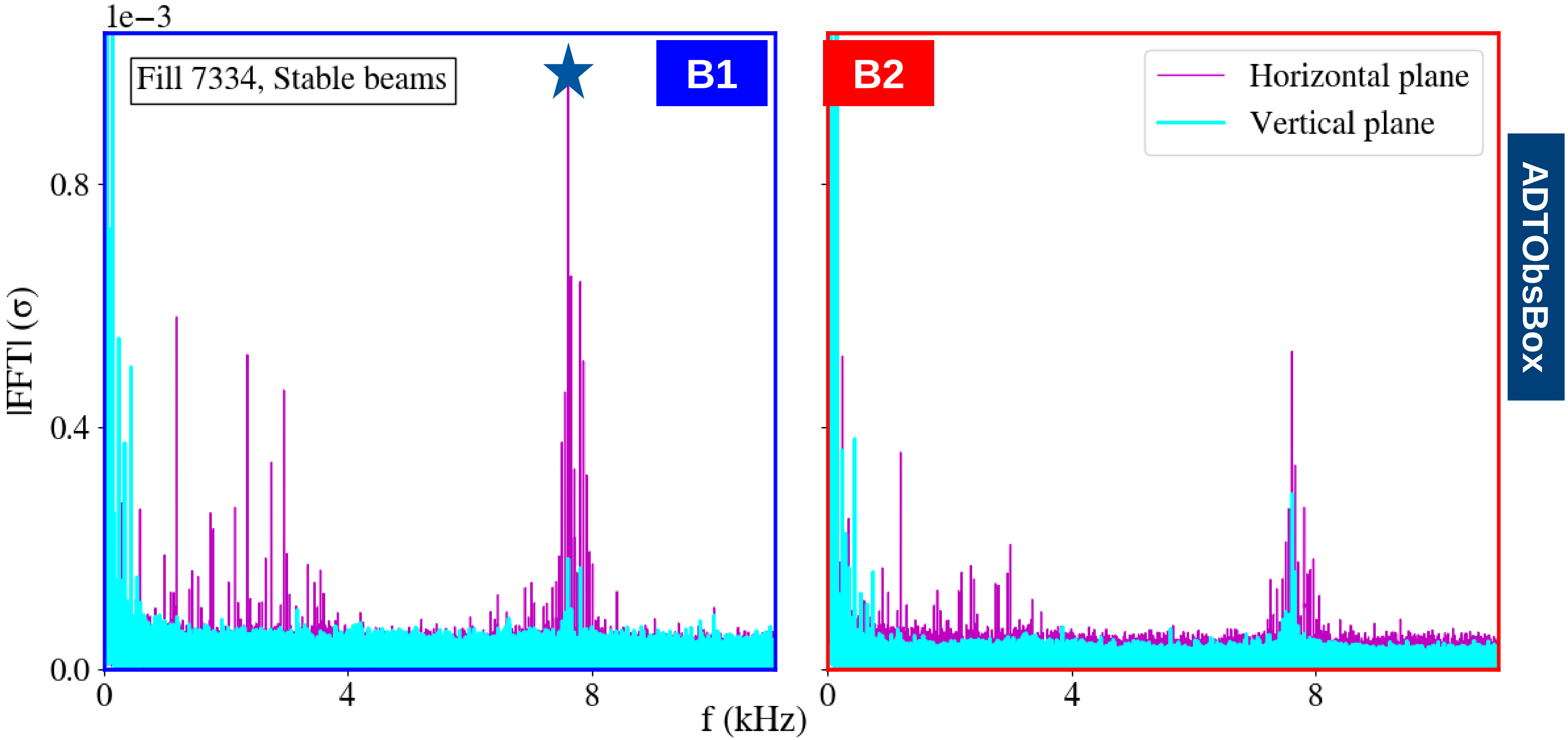
Experiments with active filters

1. Active filters enhance the high-order harmonics [1].
2. Amplitudes of the high-f cluster still lower than low-f cluster.
3. There is also the shielding from beam screen, vacuum chamber.
4. No impact on the high-f cluster in the beam was observed during AF tests but strong mitigation from ADT, see next slides.



[1] J.P Burnet, Test results of RPTE LHC thyristor rectifier with active filter.

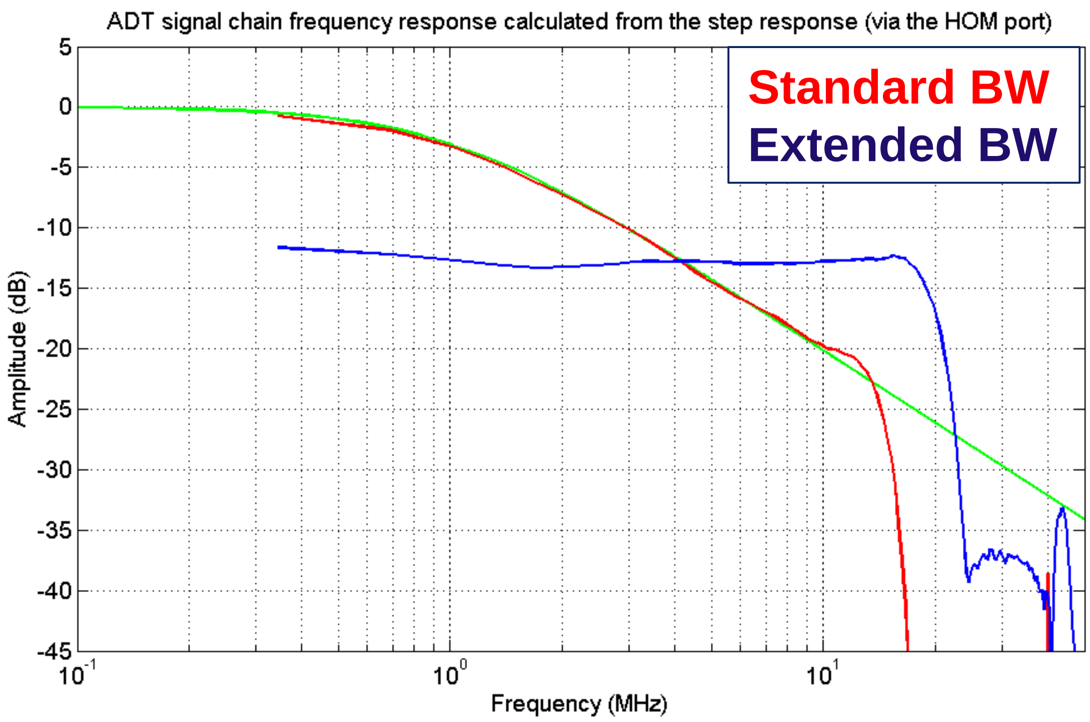
Comparison between beams & planes



- The horizontal plane of **B1** is mainly affected.
- Asymmetry between **low** & **high** f-cluster.
- ★ maximum beam offset, equal to ~**0.1 μm** or **10^{-3} σ** → Equivalent kick **0.09 nrad** from single dipole at β=105 m, 1e-3 distance from tune **(in the absence of a damper),** corresponds to stability of **2e-9** for a single main bend.

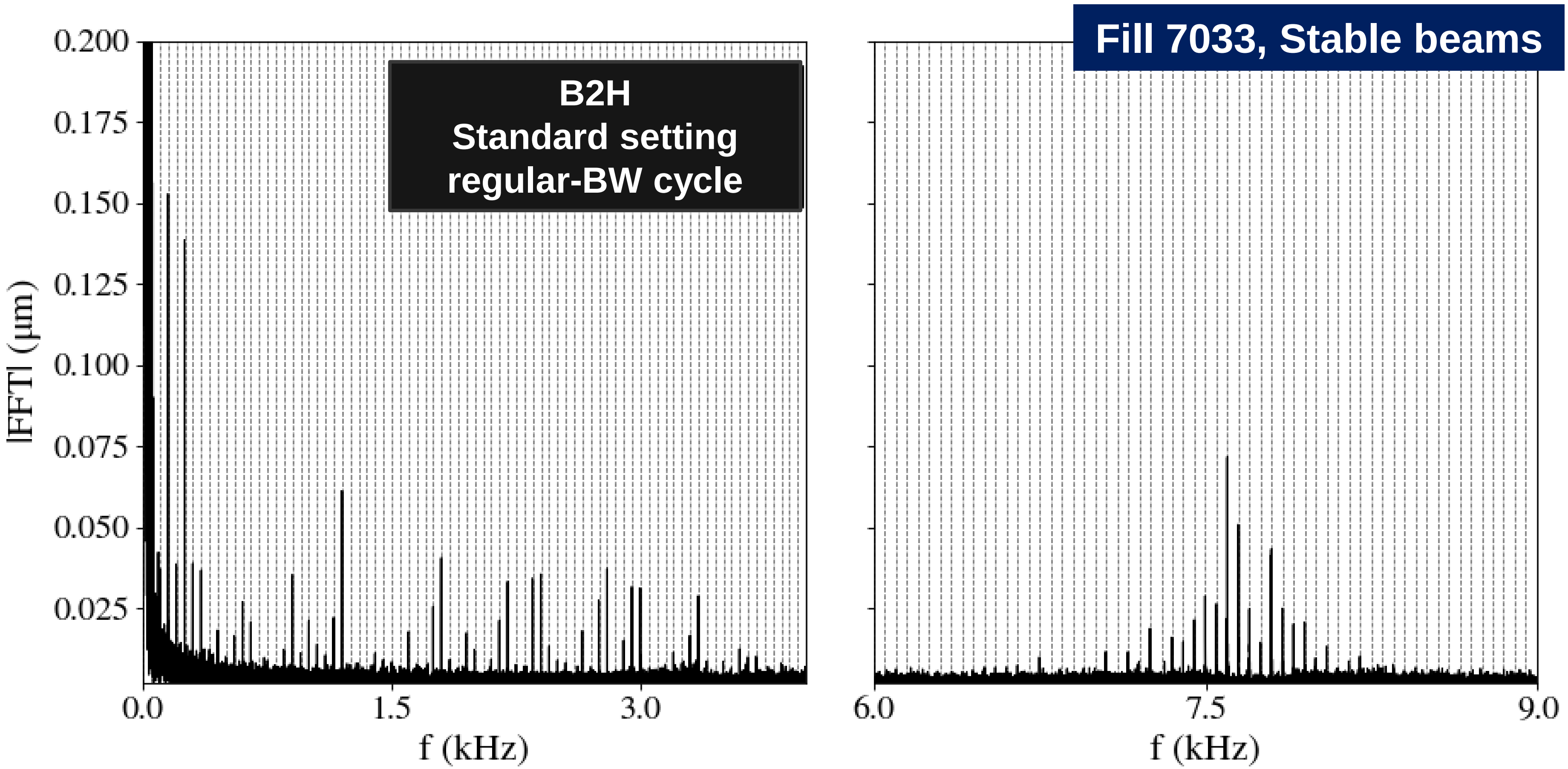
Impact of ADT BW on 50 Hz

1. Impact of high-f cluster when the ADT BW is changed from extended to standard.
2. Change in the ADT BW during Adjust, reduction of high-f cluster.
3. Fill 7035 no change of ADT BW in Adjust. SB with extended BW.

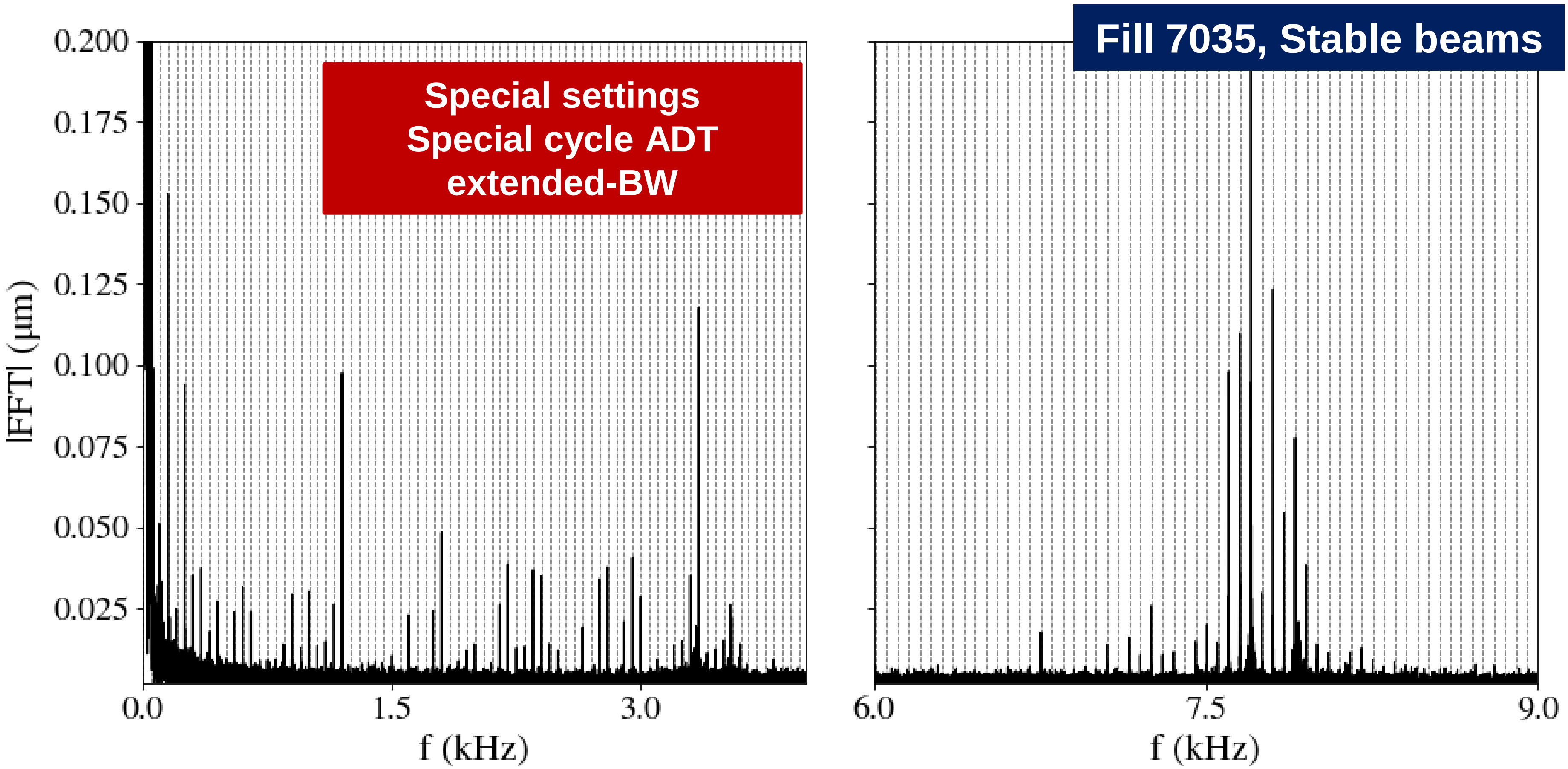


LBOC, 30/10/2012, D. Valuch

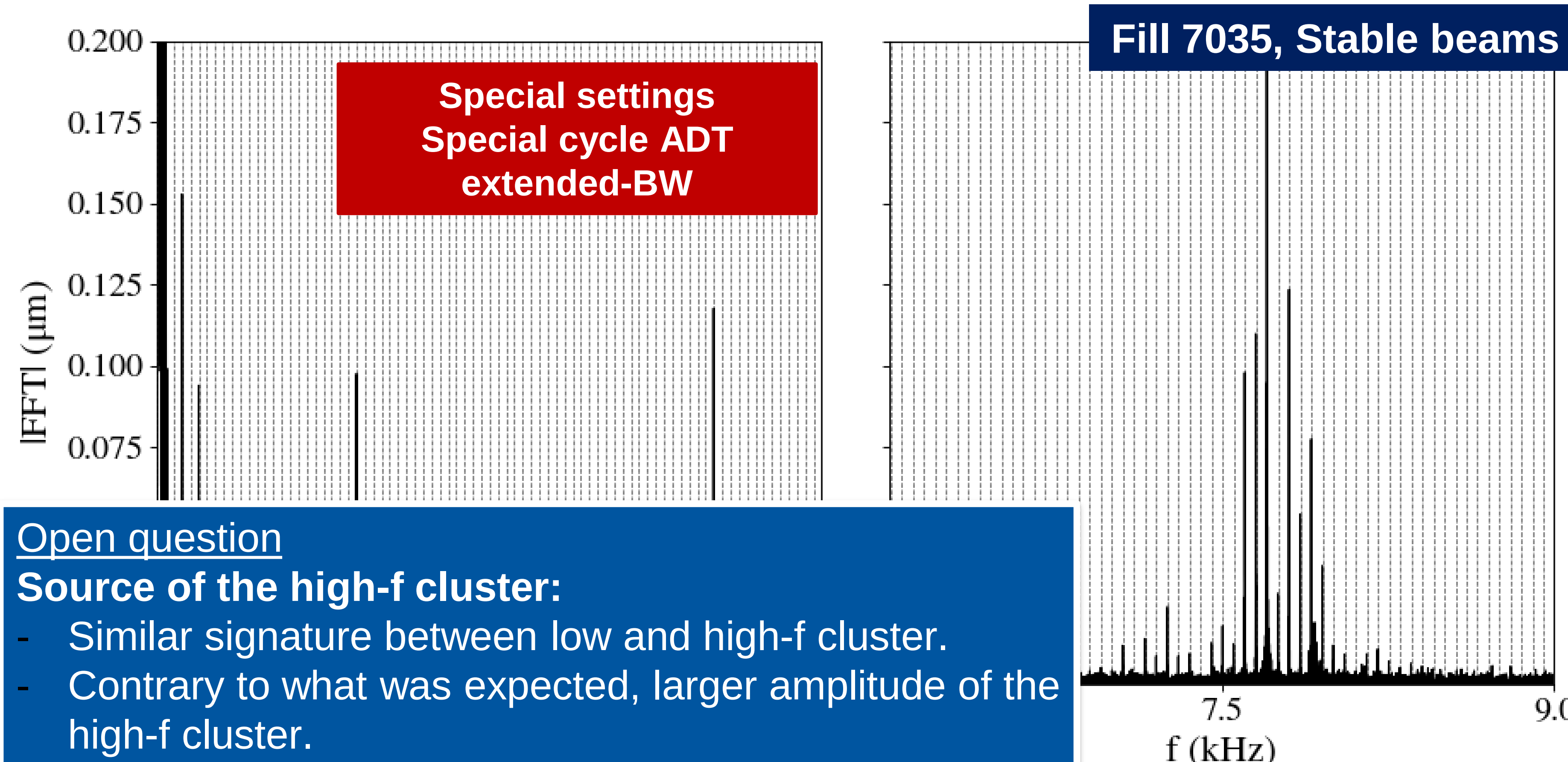
Impact of ADT BW on 50 Hz



Impact of ADT BW on 50 Hz



Impact of ADT BW on 50 Hz



Open question

Source of the high-f cluster:

- Similar signature between low and high-f cluster.
- Contrary to what was expected, larger amplitude of the high-f cluster.
- Higher sensitivity of the beam’s response to f_{rev}-f_x compared to f_x?

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- Power supply ripple in dipoles and quadrupoles:

  Observed in LHC and expected in HL-LHC

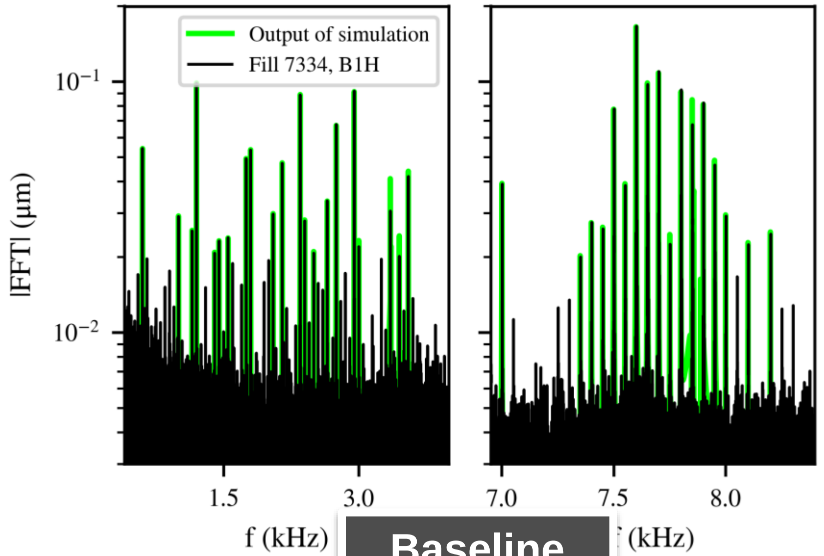
  - 50 Hz harmonics
    - What is the source? Summary of 2018 observations.
    - **What will be the impact in HL-LHC?**
    - How can we mitigate?

Based on the source and that no modification is foreseen for the MB PC for HL-LHC, the 50 Hz harmonics will be present in the future.

    - Do we expect an impact on the HL-LHC beam performance?
  - Open questions and next steps.

Intensity evolution with a realistic spectrum

“Low frequency cluster” **“High frequency cluster”**

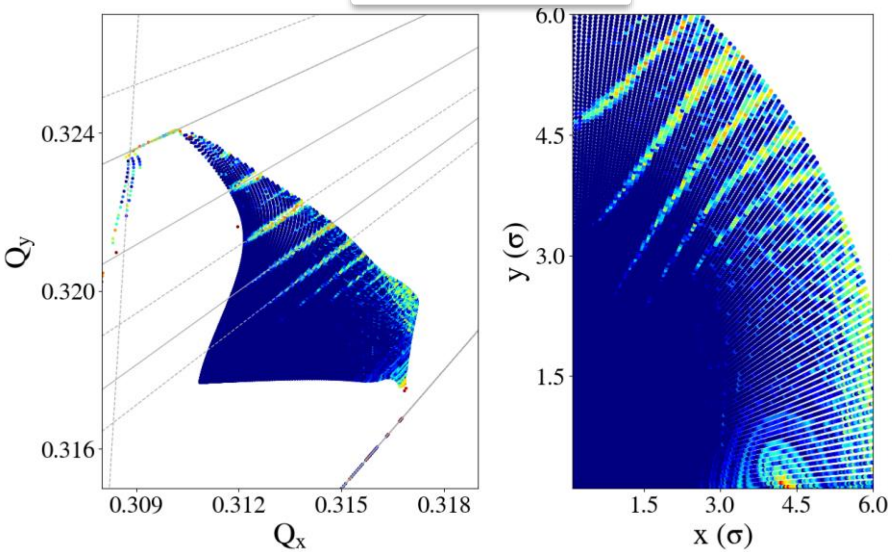


Spectrum in SB (considering the LHC spectrum).

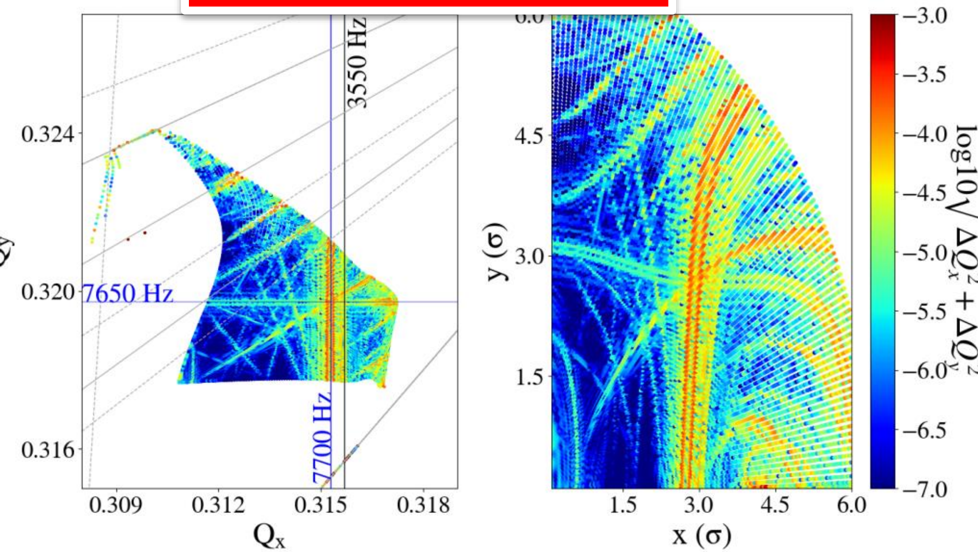
Spectrum in simulations end of β* leveling and nominal scenario.

HL-LHC

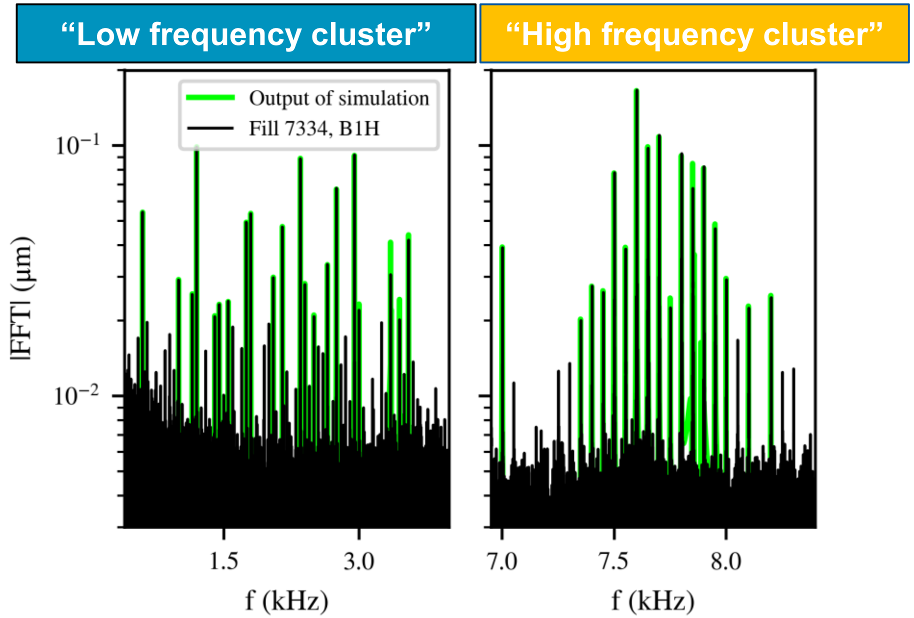
Baseline



Realistic spectrum



Intensity evolution with a realistic spectrum

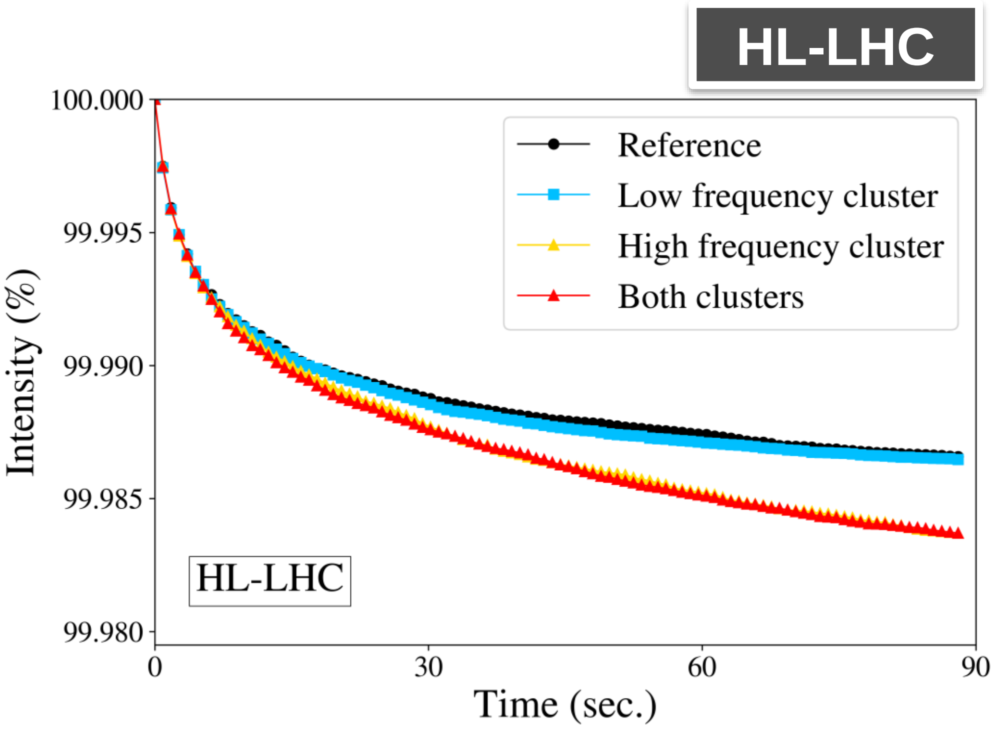


Baseline

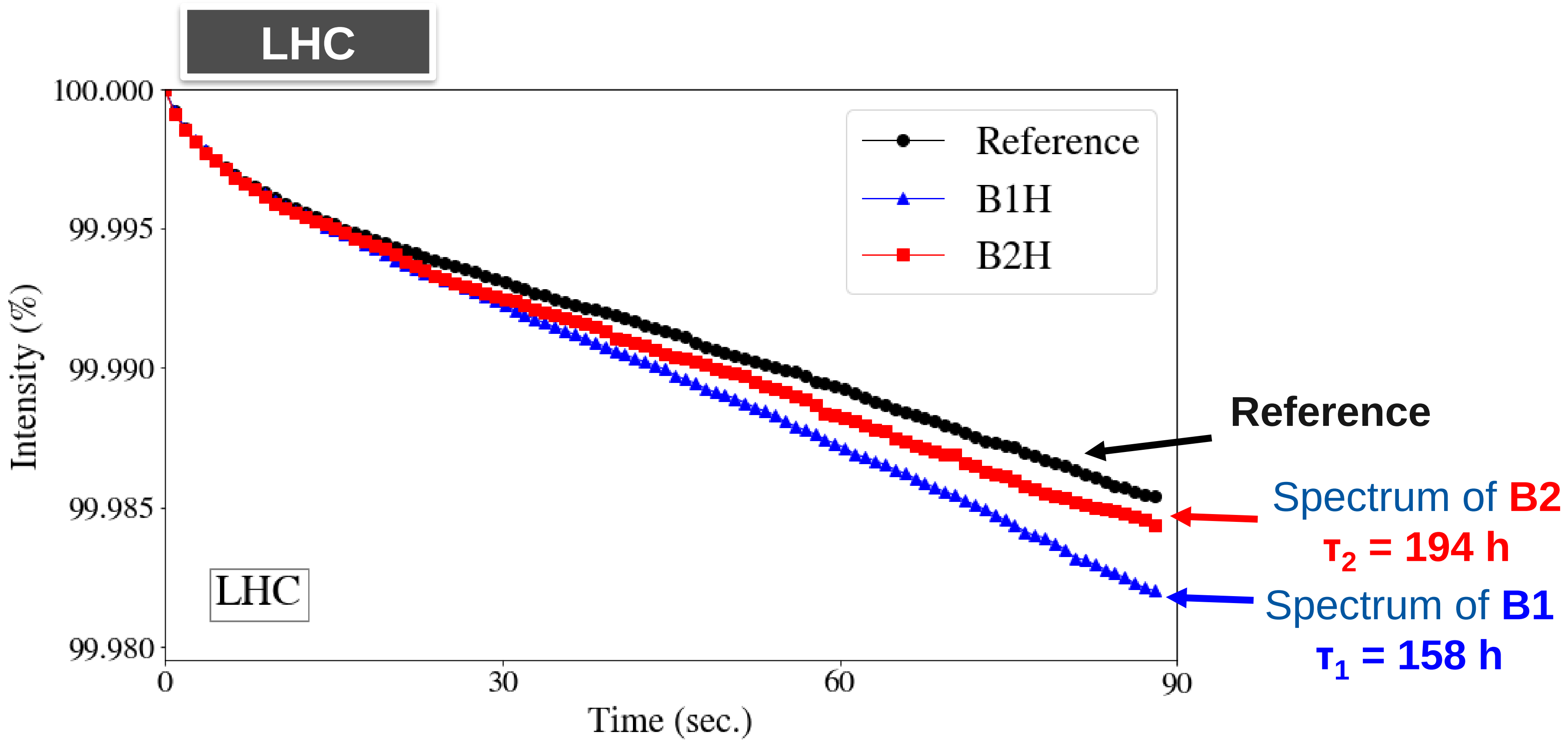
Including the low-f cluster

Including the high-f cluster

Including both



Intensity evolution of B1 & B2



- Considering the spectrum of **B1** or **B2** in simulations leads to an asymmetry in the intensity evolution for the two beams.

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- Power supply ripple in dipoles and quadrupoles:

  Observed

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    - What is the source? Summary of 2018 observations.
    - What will be the impact in HL-LHC?
    - **How can we mitigate?**

  Expected

  - Inner Triplet
    - Do we expect an impact on the HL-LHC beam performance?
  - Open questions and next steps.

Mitigation

- Attenuation of 50 Hz harmonics is expected due to upgrade of ADT system for Run 3.

- ADT comb filter to increase the gain only around the most important 50 Hz harmonics instead of whole BW.

Main objectives for Run 3:

Better understanding of the source of the **high-f cluster** in Run 3 (Inject noise in a warm dipole?, impact of ADT gain,..)

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  Expected in HL-LHC
  - Inner Triplet
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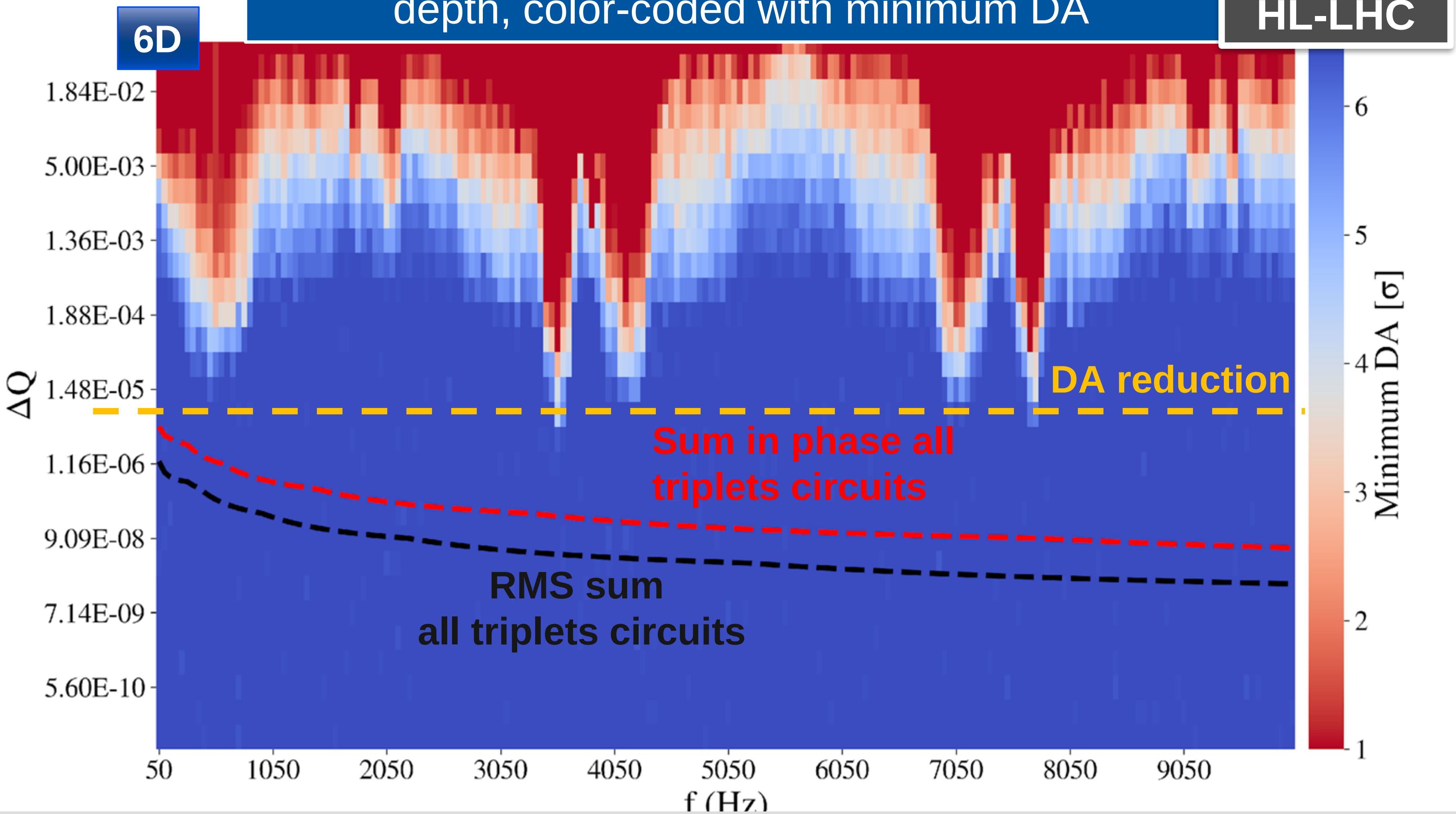
Noise thresholds with DA scans

Modulation frequency as a function of modulation depth, color-coded with minimum DA



No impact even when considering multiple voltage tones simultaneously with amplitudes as derived by PC specifications

Open questions & next steps

50 Hz

What is the source?

- Source of the **low-f cluster** are rectifier MB PC. Although the source and signature is the same, the mechanism driving the **high-f cluster**'s amplitude to be clearly identified with dedicated experiments in Run 3.

Do we expect an impact on the HL-LHC?

- If the spectrum remains the same, impact on intensity evolution especially due to **high-f cluster**. LHC simulations show that the factor of 2 between the spectra of **B1** and **B2** can lead to a different intensity evolution of the two beams.

How can we mitigate?

- Expecting amplitude reduction of harmonics due to higher sensitivity ADT pickups.
- If not the case, more refined ADT filter configuration.

- ❑ Inject noise in a warm dipole.
- ❑ MB PC instrumentation in sector 1-2 very important to these studies. If possible, deploy in all sectors or to be cycled around the sectors after technical stops.
- ❑ Shielding not as effective as expected: Study voltage vs magnetic field transfer function in the 0-10 kHz regime for LHC MB and its vacuum chamber in SM18?

Open questions & next steps

Inner triplet

Do we expect an impact on the HL-LHC?

- The threshold of DA reduction (ΔQ = 1e-5, depending on the frequency) orders of magnitude above PC specifications → **no impact is expected** (including both tune modulation due to power supply ripple and operation with high-chromaticity).

- However, important non-linearities <u>not included in the simulations</u> → test limits by injecting noise in a single warm quadrupole e.g. Q4/Q5.

Backup

SCR power converters in LHC

Low-f cluster + **High-f cluster**:

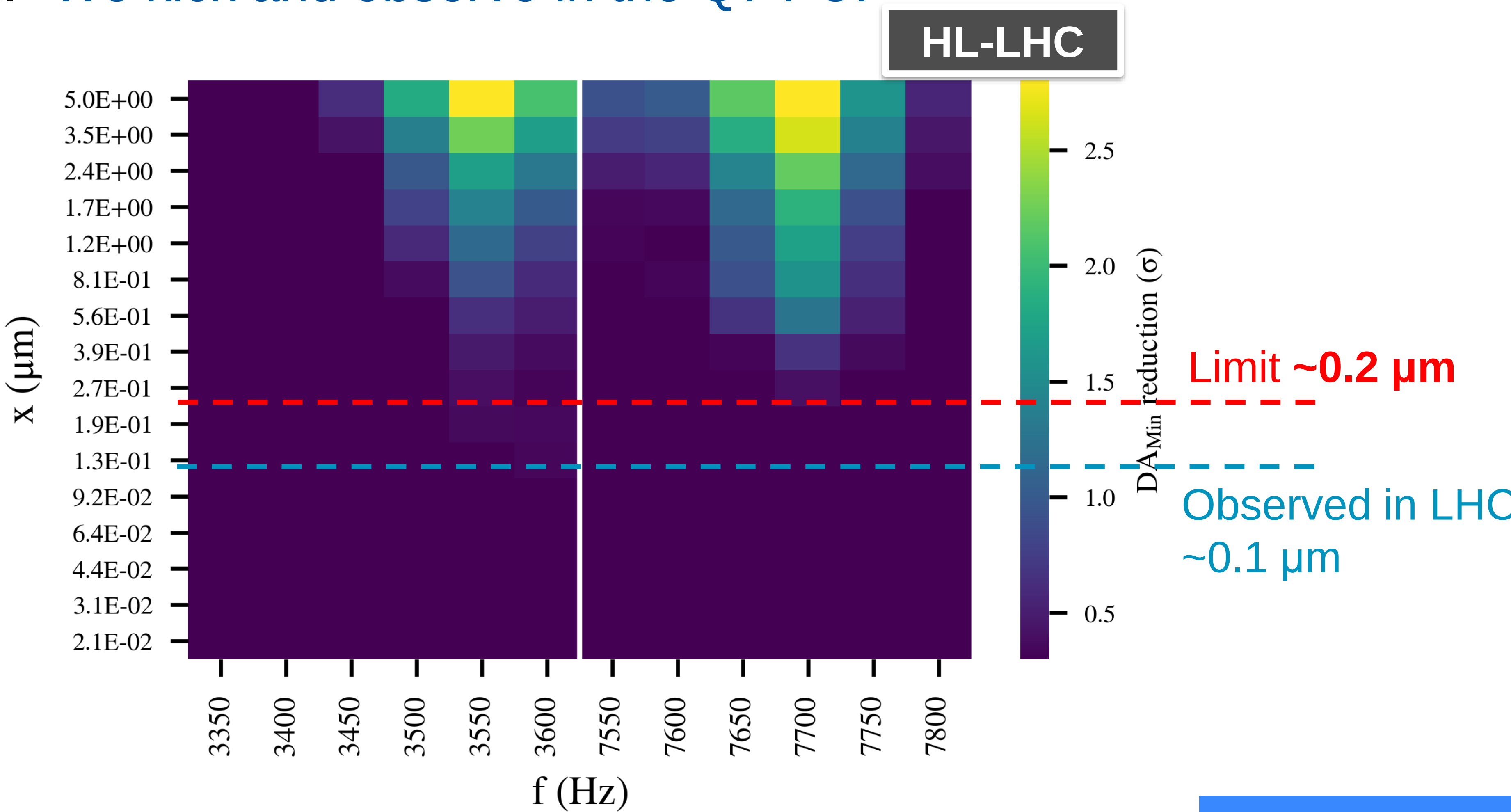
1. Multiple 50 Hz harmonics
2. Similar phase modulation from the mains, with an amplitude proportional to the order of the harmonic.

TABLE I. The SCR power converters in the LHC [36, 43].

Power converter type	Use
RPTE	Main dipoles
RPTF	Warm quadrupoles (Q4, Q5)
~~RPTG~~	~~Dogleg dipoles (D1, D3, D4, spare)~~
~~RPTL~~	~~Alice compensator~~
~~RPTM~~	~~Septa~~
~~RPTI~~	~~Alice and LHCb dipoles~~
~~RPTN~~	~~LHCb compensator~~
~~RPTJ~~	~~CMS Solenoid~~
~~RPTH~~	~~Alice Solenoid~~
~~RPTK~~	~~RF Klystron~~

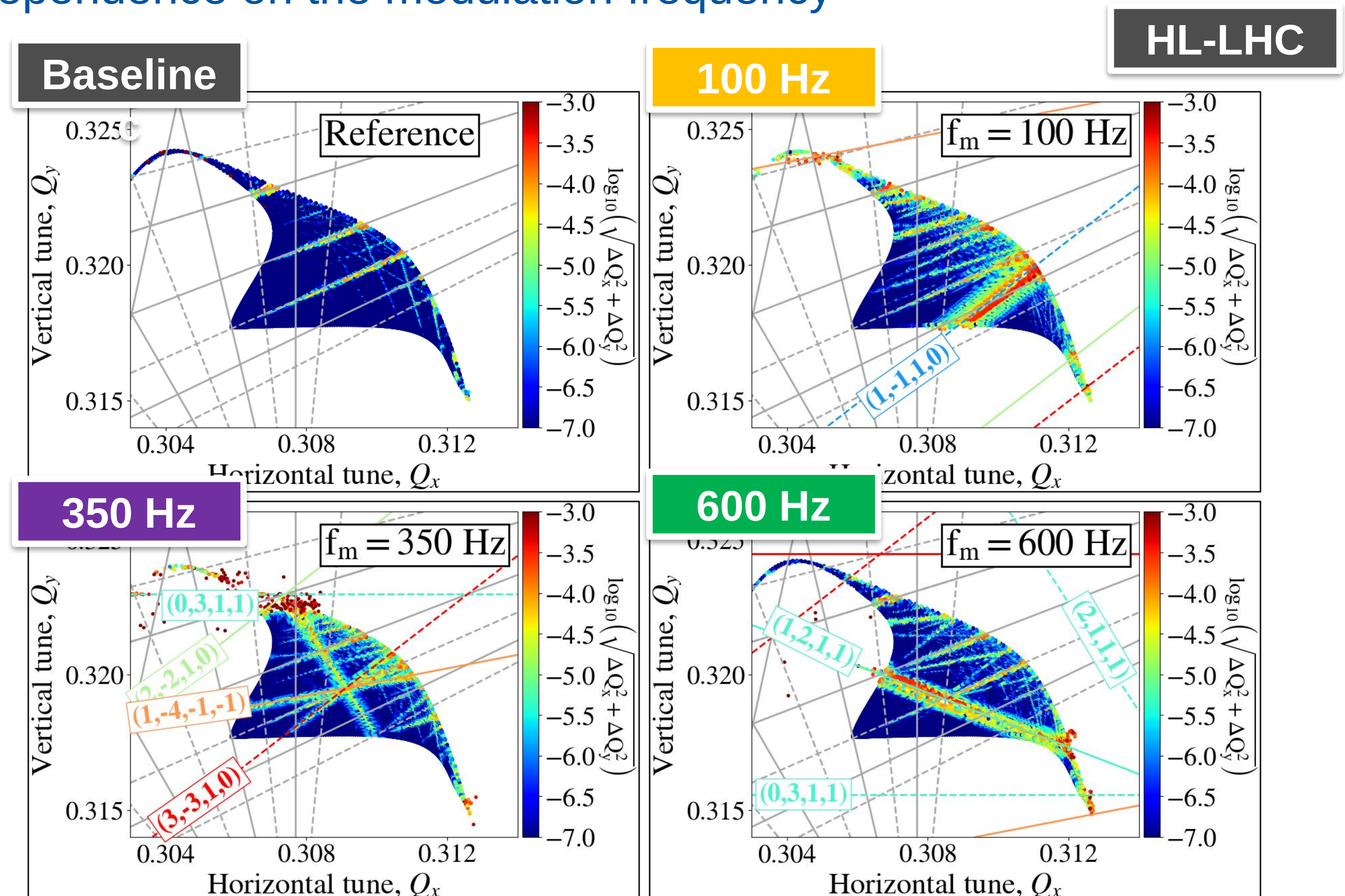
Single tones and DA

1. To set a power supply ripple threshold, we scan **single tones** for increasing deflections.
2. We kick and observe in the Q7 PU.

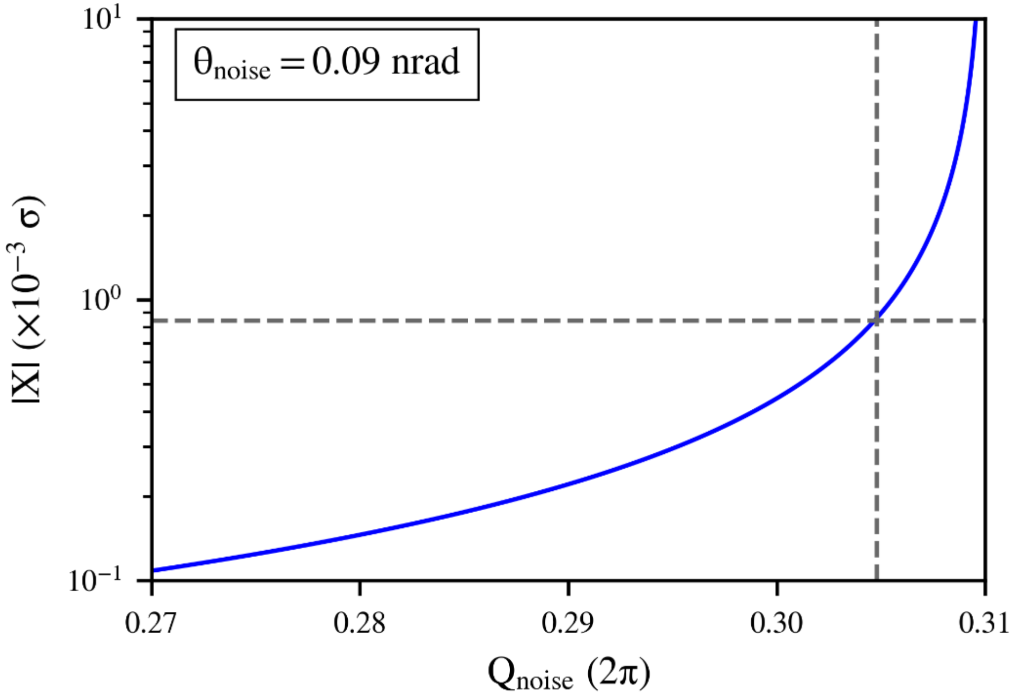


FMAs with power supply ripple in the IT

- Dependence on the modulation frequency



Equivalent deflection

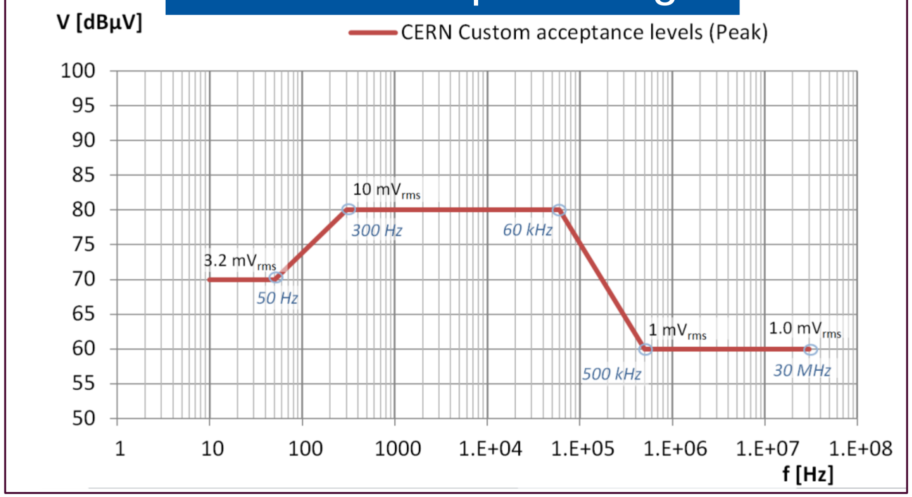


- ★ (maximum 50 Hz offset) is equal to ~**0.1 μm** or **10^{-3} σ_{beam}**
- As a reference, considering a **single dipole** at β=105 m corresponds to an equivalent kick of **0.09 nrad**
- Comparing with the kick of the main dipoles (~5 mrad), it would be equivalent to a stability of 2e-9 for a single main bend at a frequency 1e-3 apart from the tune **(in the absence of a damper).**

Simulation setup

- Simulated parameters at end of β*-levelling, nominal scenario.
- Noise in Q1, Q2a, Q2b, Q3 IR1 & 5 (Simulating the worst case scenario).
- Comparison with PC specifications.

Maximum output voltage



Limits from previous studies: Maximum tolerated ΔQ

TABLE I. The critical modulation depth due to power supply ripple as reported from previous studies [10, 13, 18, 19].

Study	Modulation depth	Study	Modulation depth
RHIC	$< 10^{-3}$	HERA	$< 10^{-4}$
SPS	$< 10^{-3}$	LHC	$< 5 \times 10^{-4}$
HL-LHC	$< 10^{-4}$		