Capricious beam jitters: power supply ripple & beam performance

S. Kostoglou, G. Sterbini, Y. Papaphilippou, G. Arduini, C. Baccigalupi, H. Bartosik, M. C. Bastos, X. Buffat, J. P. Burnet, R. De Maria, D. Gamba, L. Intelisano, T. Levens , M. Martino, V. Montabonnet, N. Mounet, M. Soderen, H. Thiesen, Y. Thurel, D. Valuch, J. Wenninger

Mitigation Approaches for Storage Rings and Synchotrons
30.06.2020

Motivation

- LHC performance during Run I & II: proton losses and emittance growth ↑ than anticipated [1-4]

[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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http://noisestudies.web.cern.ch/

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- **Power supply ripple** in dipoles & quadrupoles:

  Observed in LHC & expected in HL-LHC

  - Harmonics of the **mains power frequency** (50 Hz)
    I. What is the source? Summary of 2018 observations.
    II. What is the impact on the LHC beam lifetime?

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- **Power supply ripple** in dipoles & quadrupoles:

Observed in LHC & expected in HL-LHC

- Harmonics of the **mains power frequency** (50 Hz)
  I. What is the source? Summary of 2018 observations.
  II. What is the impact on the LHC beam lifetime?

Expected in HL-LHC

- Quadrupoles of the Inner Triplet
  - Do we expect an impact on the HL-LHC beam performance?

Power supply ripple spectra

Main dipoles

→ Silicon Controlled Rectifier (SCR)

Inner Triplet quadrupoles

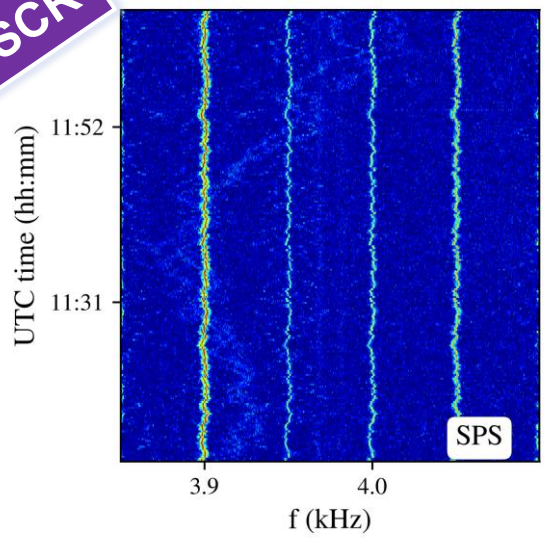
→ Switch-Mode (SM)

Power supply ripple spectra

Main dipoles

→ Silicon Controlled Rectifier (SCR)

Example of SCR

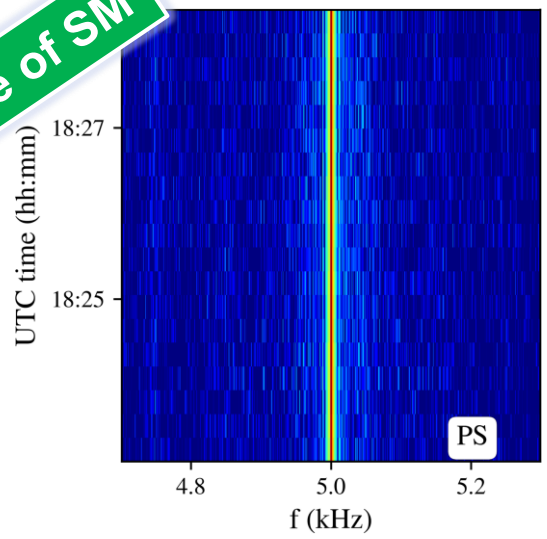


- Multiple 50 Hz harmonics
- Frequency modulation (see next slides)

Inner Triplet quadrupoles

→ Switch-Mode (SM)

Example of SM



- Switching frequency & its harmonics

Power supply ripple spectra

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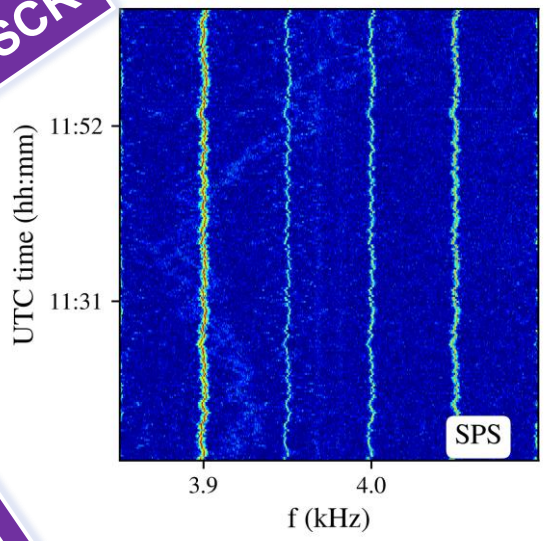
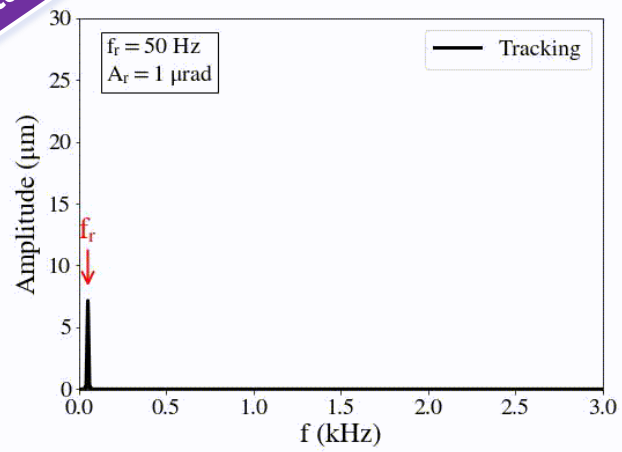


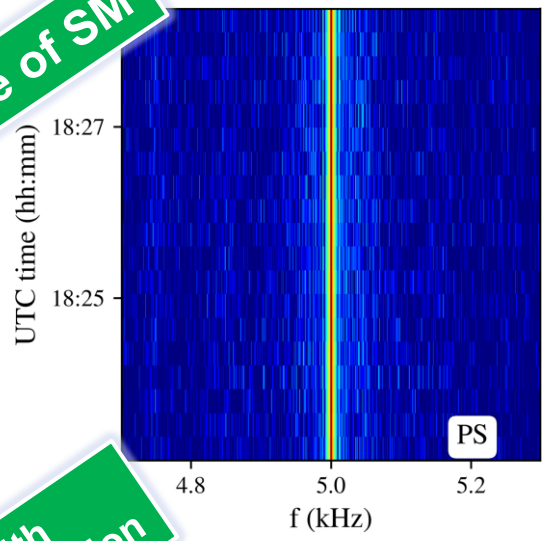
Spectrum with dipolar excitation



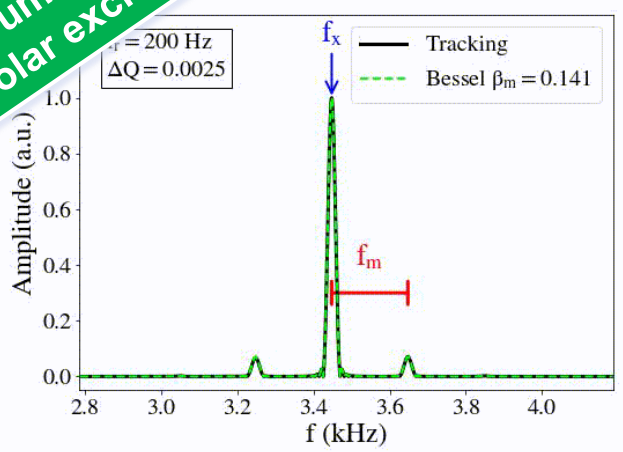
Inner Triplet quadrupoles

→ Switch-Mode (SM)

Example of SM



Spectrum with quadrupolar excitation



Power supply ripple spectra

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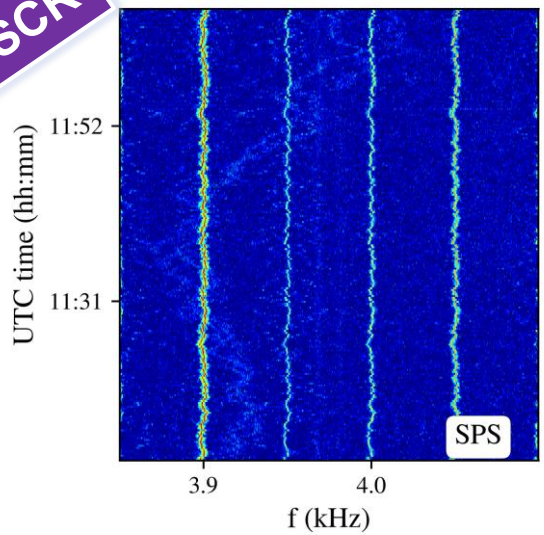

⚠ Observed in:

SPS, RHIC, Tevatron, **LHC**..

Inner Triplet quadrupoles

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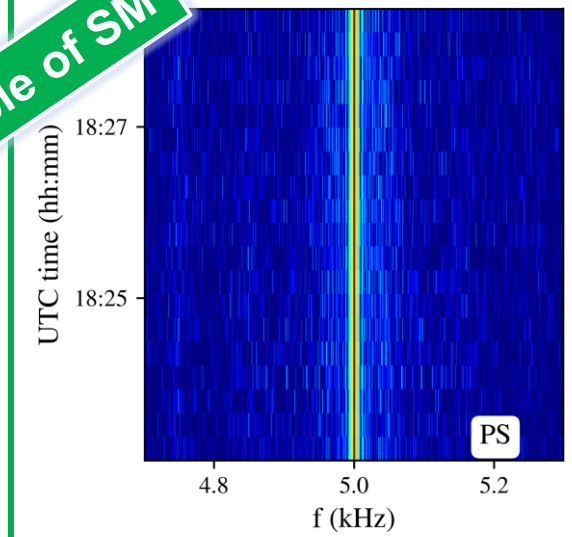


⚠ Observed in:

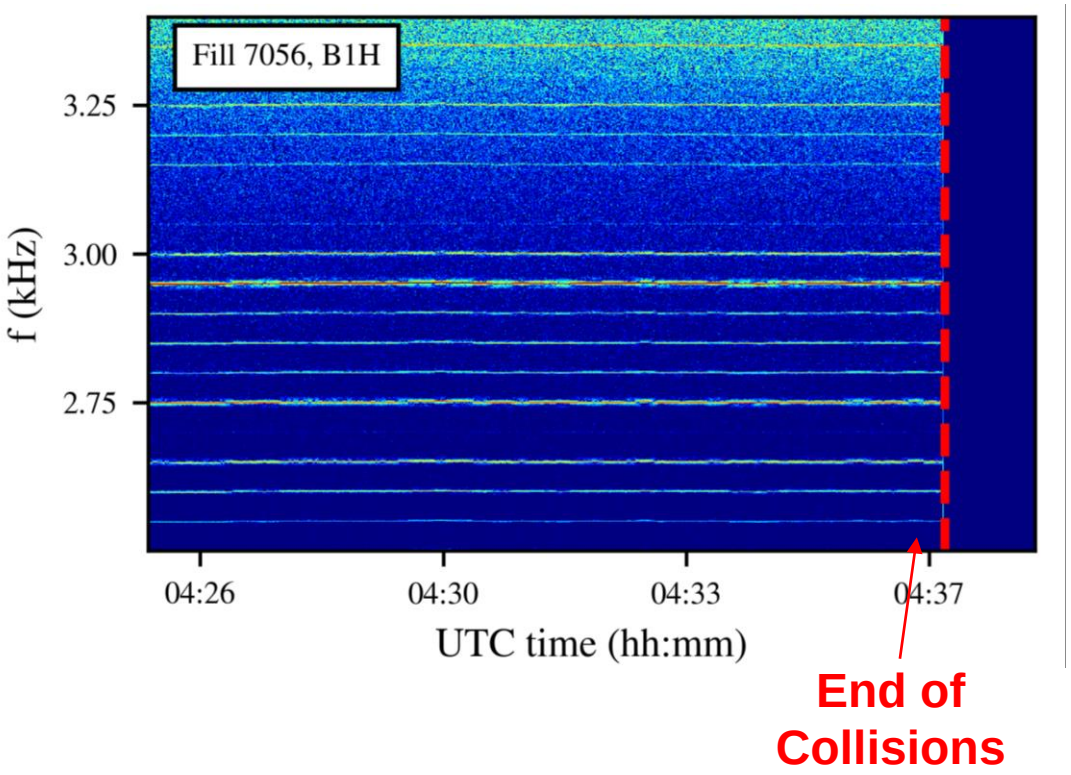
RHIC, SPS, HERA..

Part 1: Harmonics of the mains frequency on the beam spectrum

Introduction

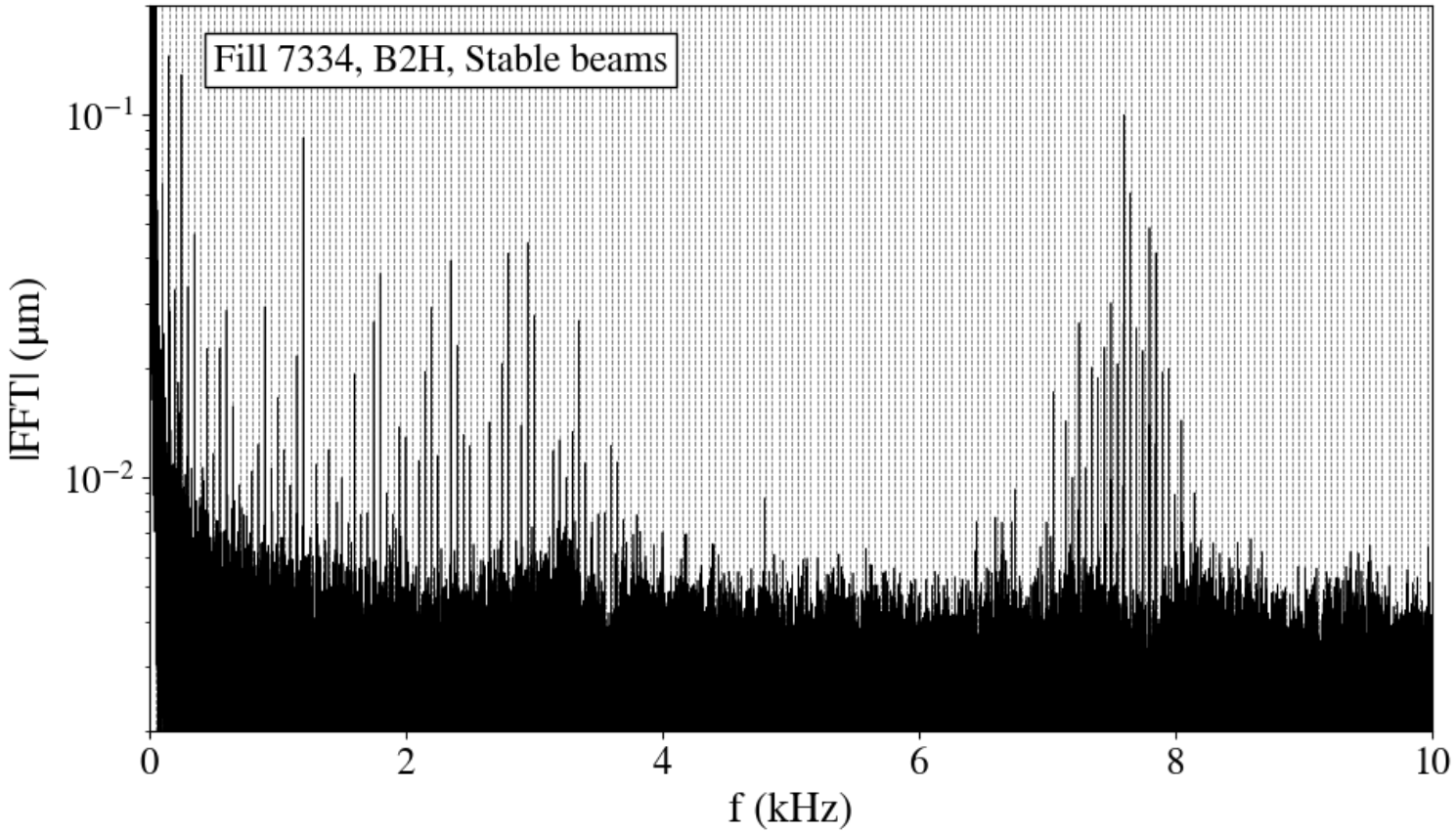
Harmonics of 50 Hz in the transverse beam spectrum **since the start of the LHC operation**.

- Observed in several unrelated instruments.
- Visible in all beam modes and planes.
- Not present without beam.



The low and high-f clusters

Computed with **bunch-by-bunch** calibrated position measurements.



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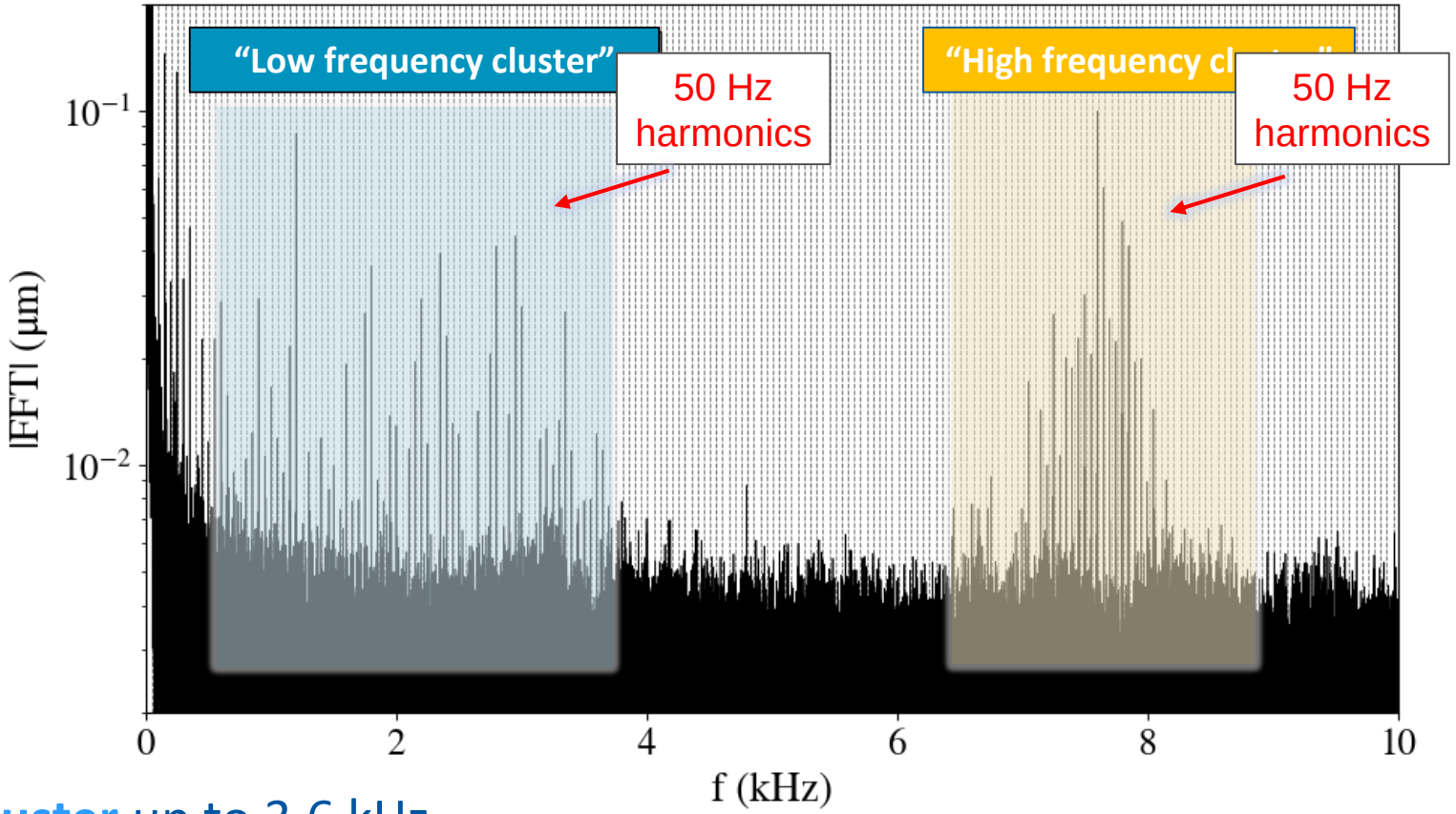


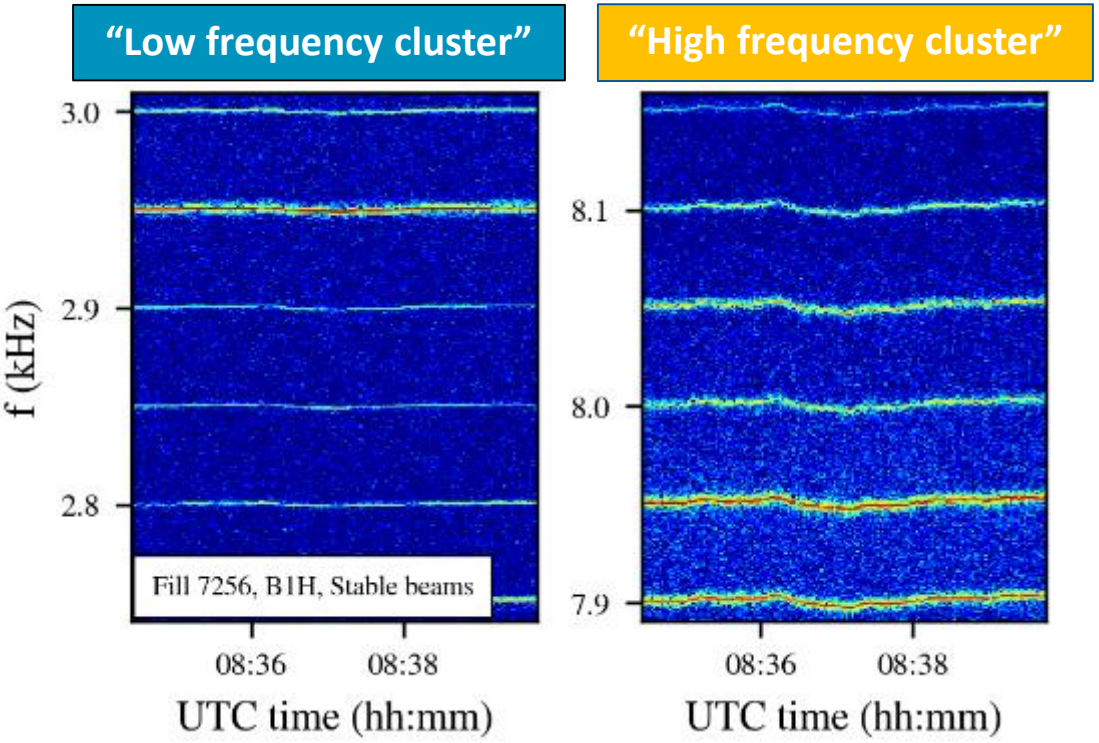
Low-f cluster up to 3.6 kHz.

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

Signature of low and high-f cluster

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

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



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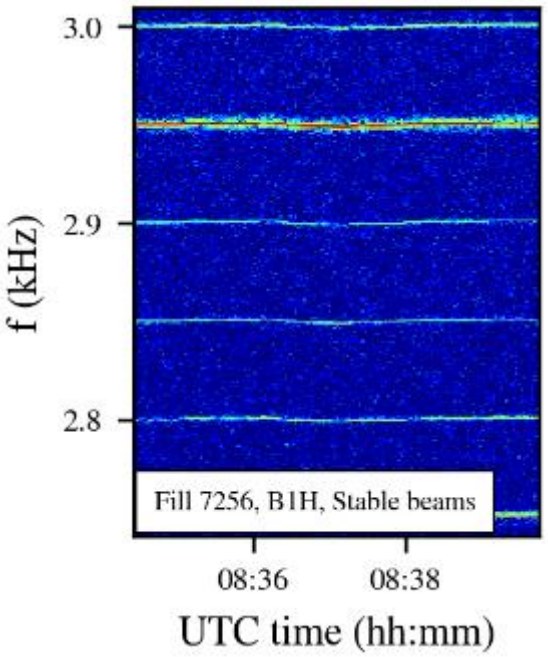
50 Hz in the beam

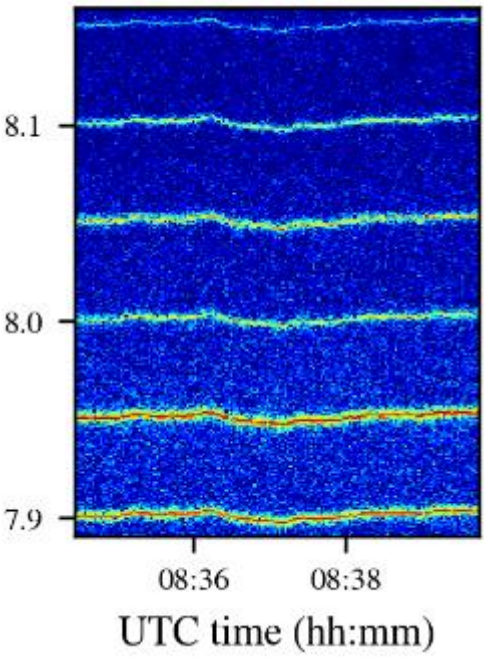
50 Hz in the voltage spectrum of the MB power converter in S12

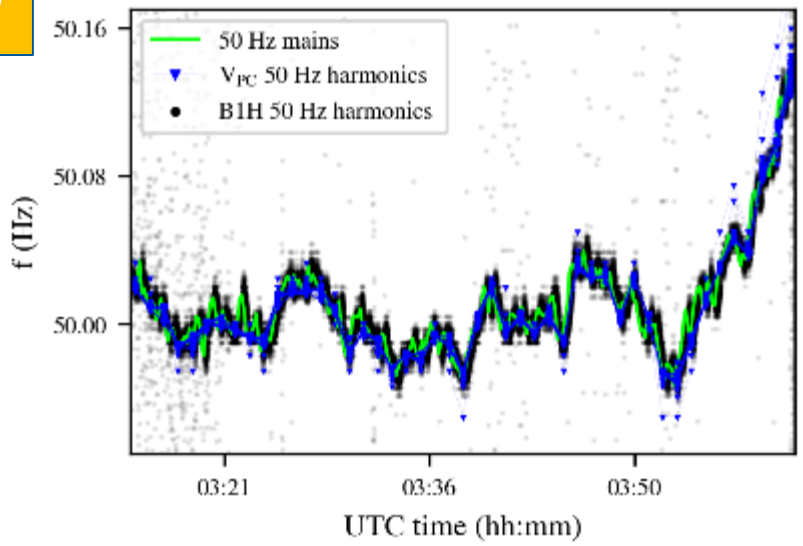
50 Hz mains*

"Low frequency cluster"



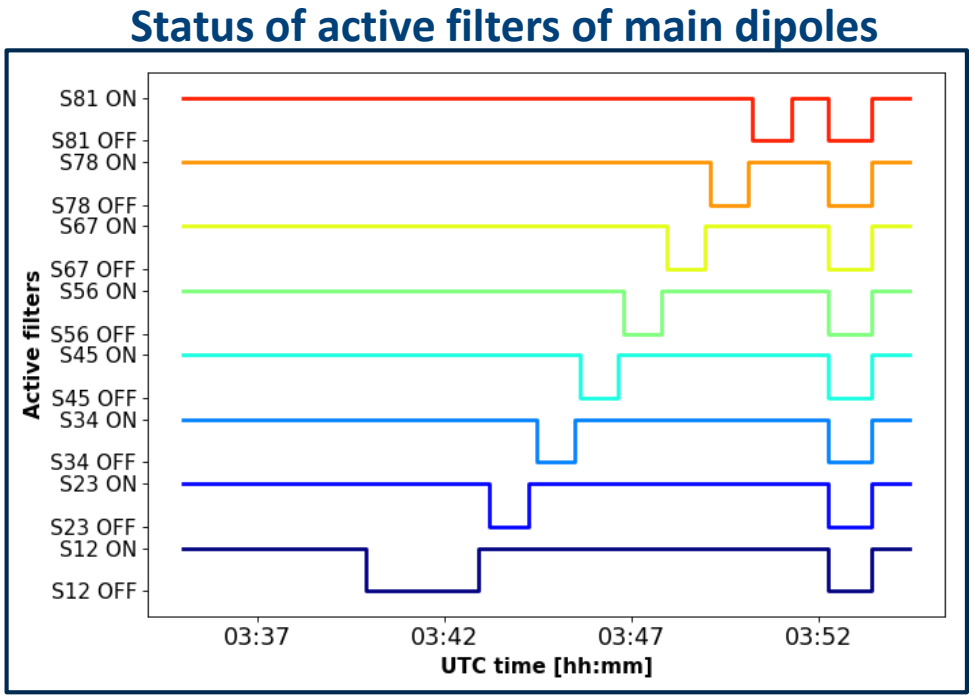
"High frequency cluster"





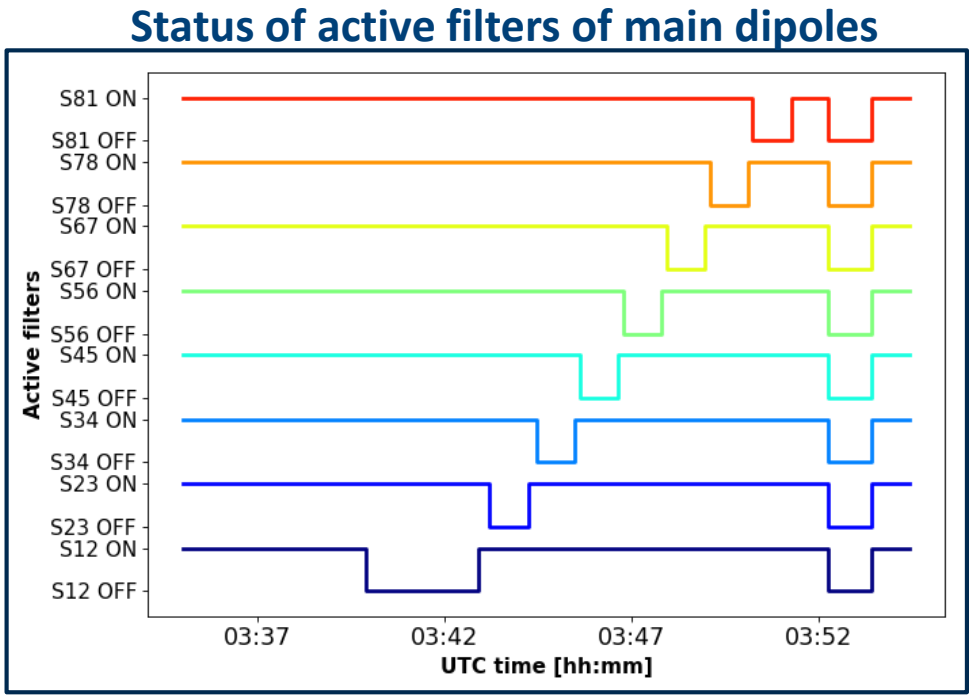
*RTE, thanks to A. Bland

Source of the low-f cluster



Active filters to reduce 50 Hz harmonics from pc output (although they enhance the high-order harmonics).

Source of the low-f cluster



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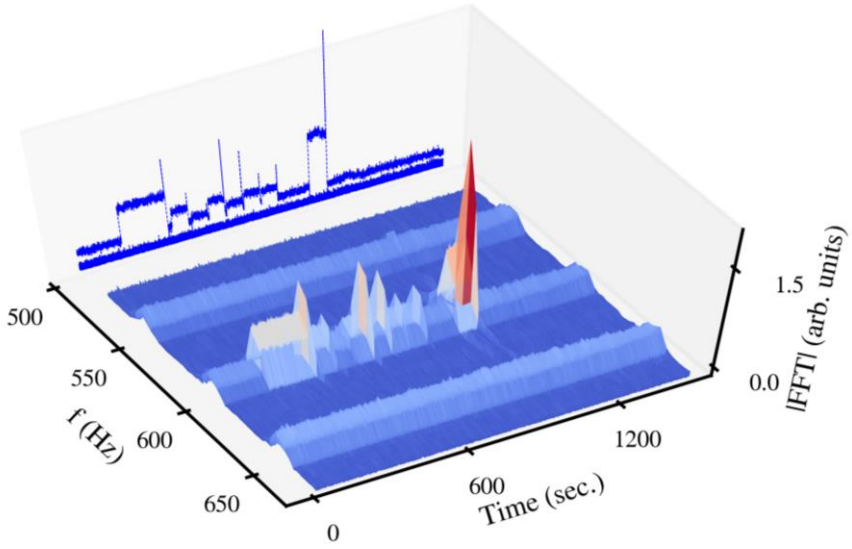
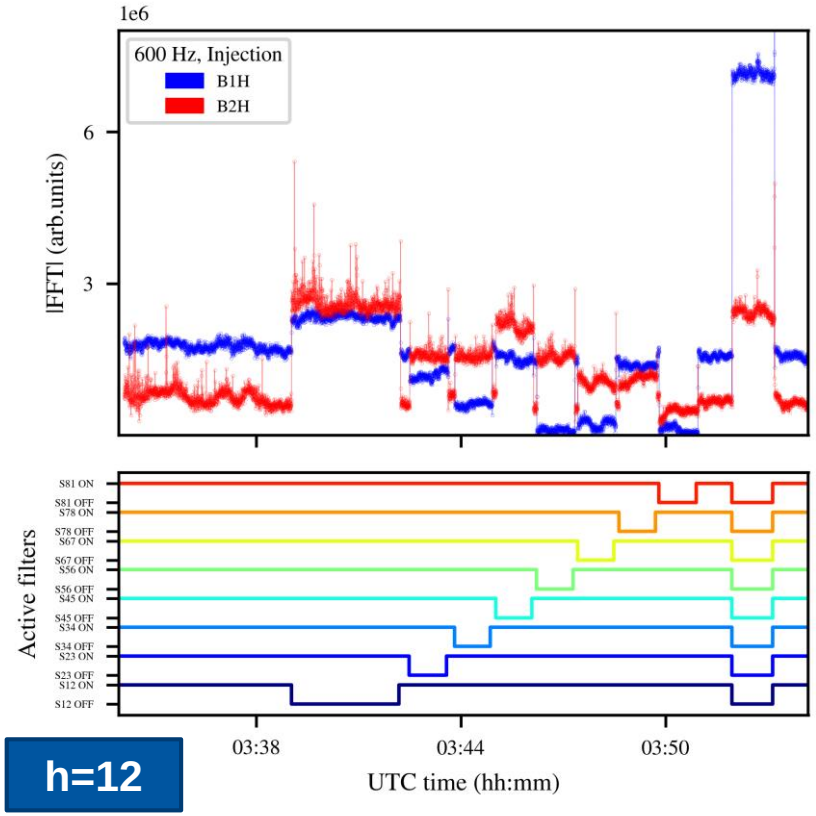
Beam's response during AF tests

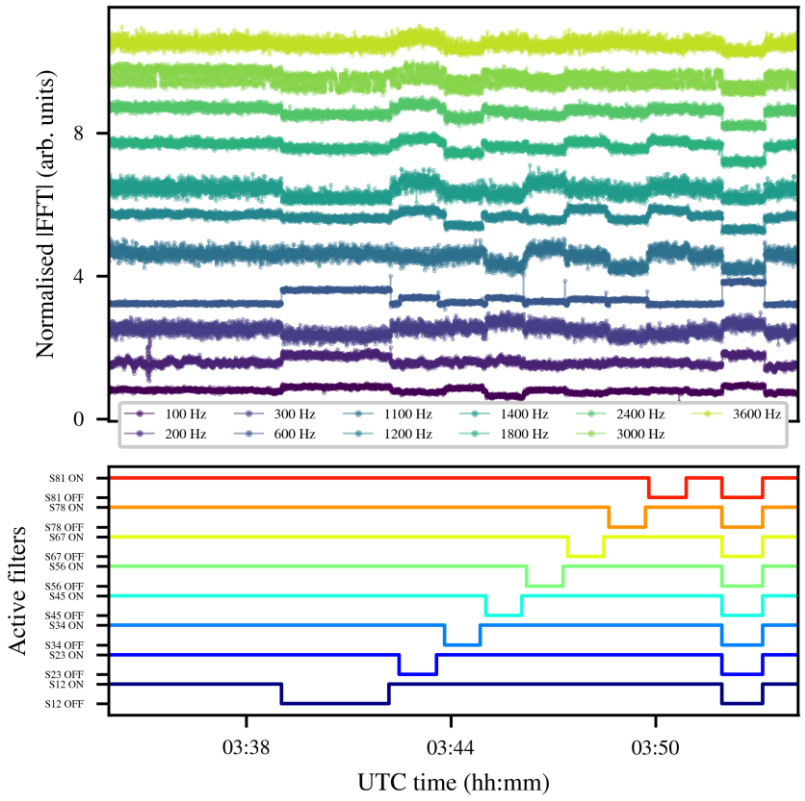


Source of the low-f cluster

- ON/OFF active filters MB PC: impact on the harmonics of the **low-f cluster**.
- All eight sectors contribute to this effect.
- For the same harmonics, **different response** between Beam 1 & Beam 2

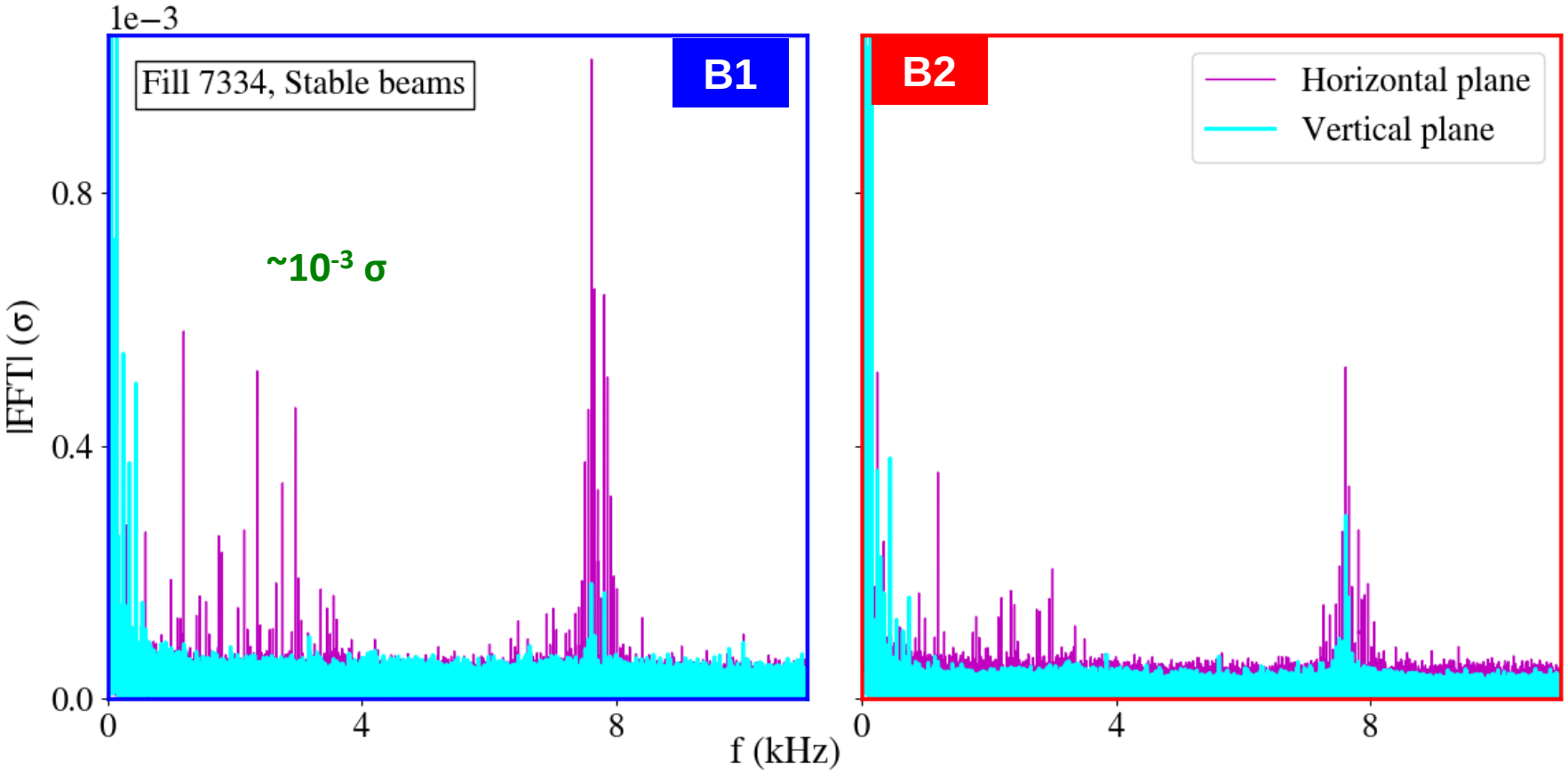


h=12



Comparison of Beam 1 & Beam 2

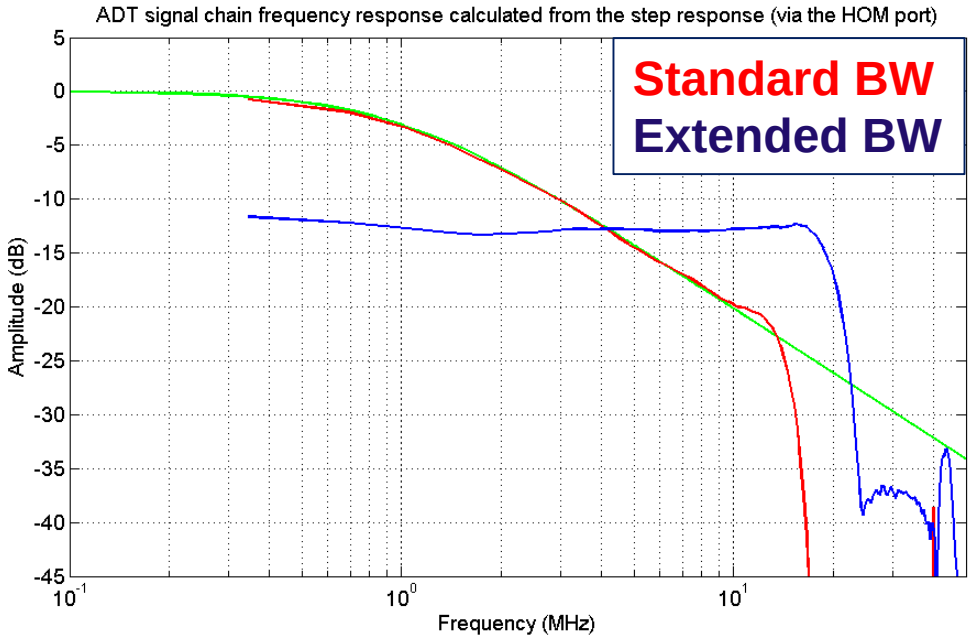
The impact of 50 Hz is higher in Beam 1 by a factor of **2** as compared to Beam 2.



- The horizontal plane of **B1** is mainly affected.
- Asymmetry between **low** & **high** f-cluster.

Impact of transverse damper on high-f cluster

Impact of high-f cluster when the ADT BW is changed from “extended” to “standard”.



LBOC, 30/10/2012, D. Valuch

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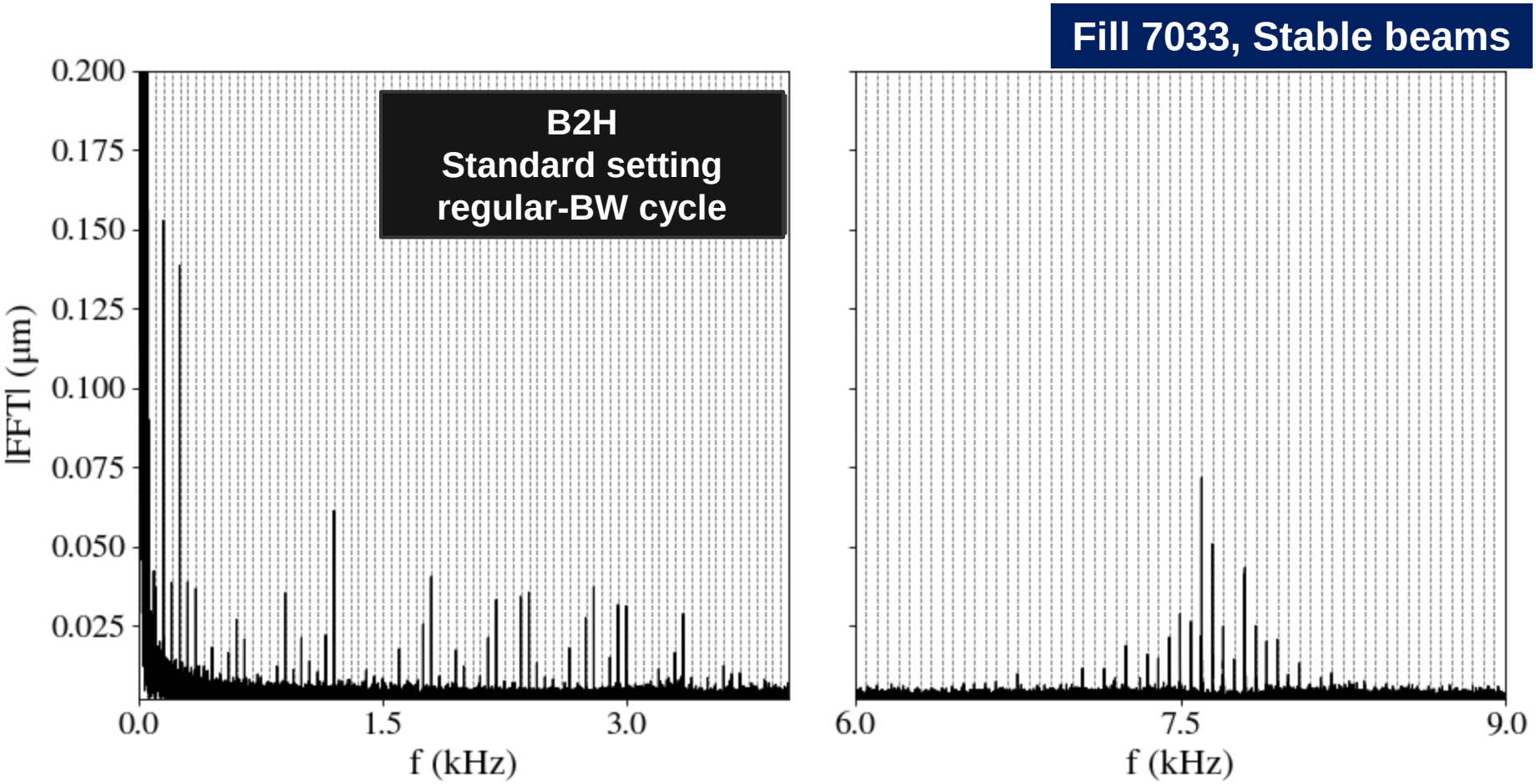

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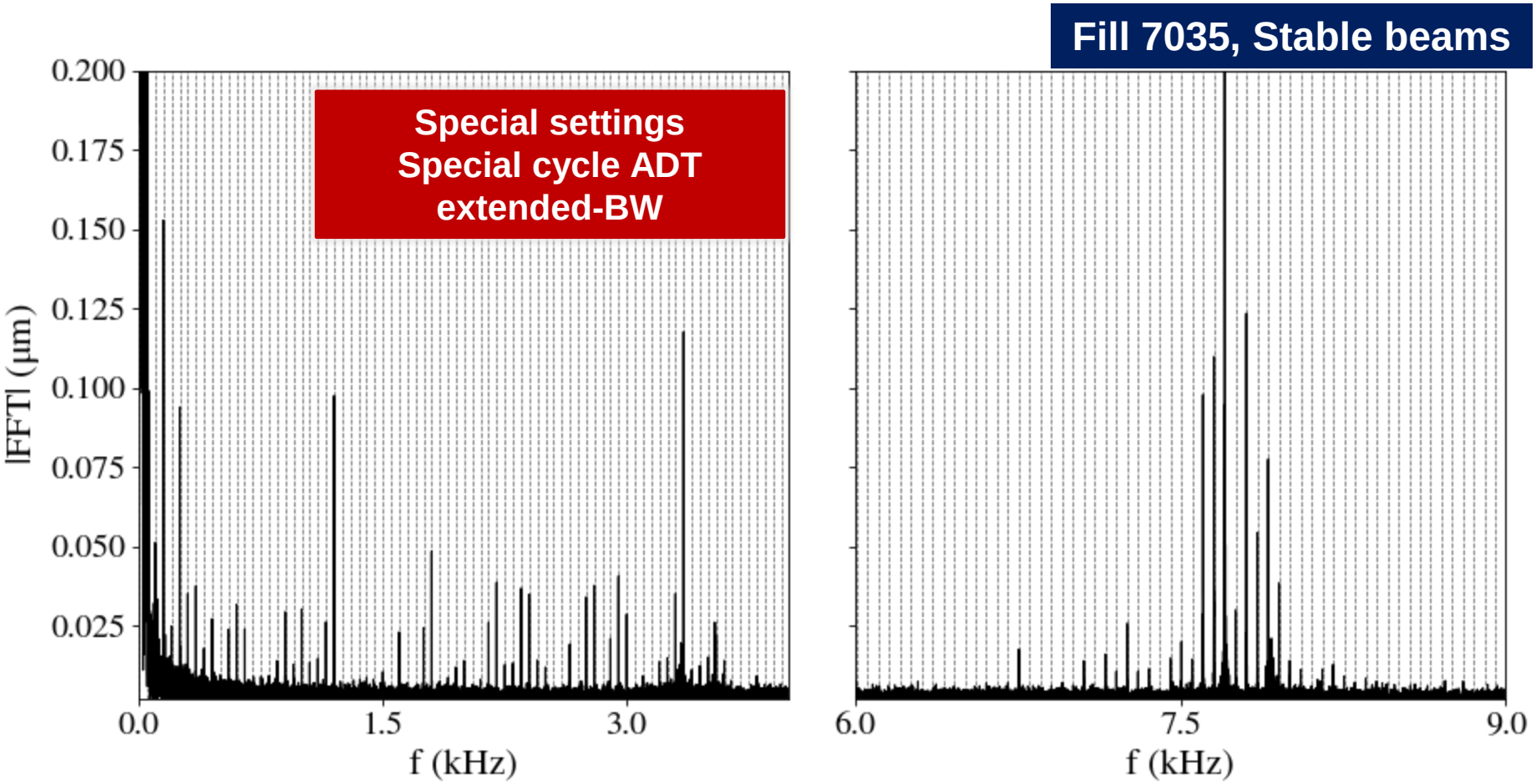

Main unresolved issue in Run 2: The high-f cluster

Expected

- From the transfer function of the voltage ripple to the magnetic field seen by the beam*: **factor of 2 attenuation** of the high-f cluster compared to the low-f cluster.

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

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- In the beam spectrum, **larger amplitudes** are observed in the high-f cluster, while also **strongly mitigated** by the ADT.

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- In the beam spectrum, **larger amplitudes** are observed in the high-f cluster, while also **strongly mitigated** by the ADT.

Possible explanation

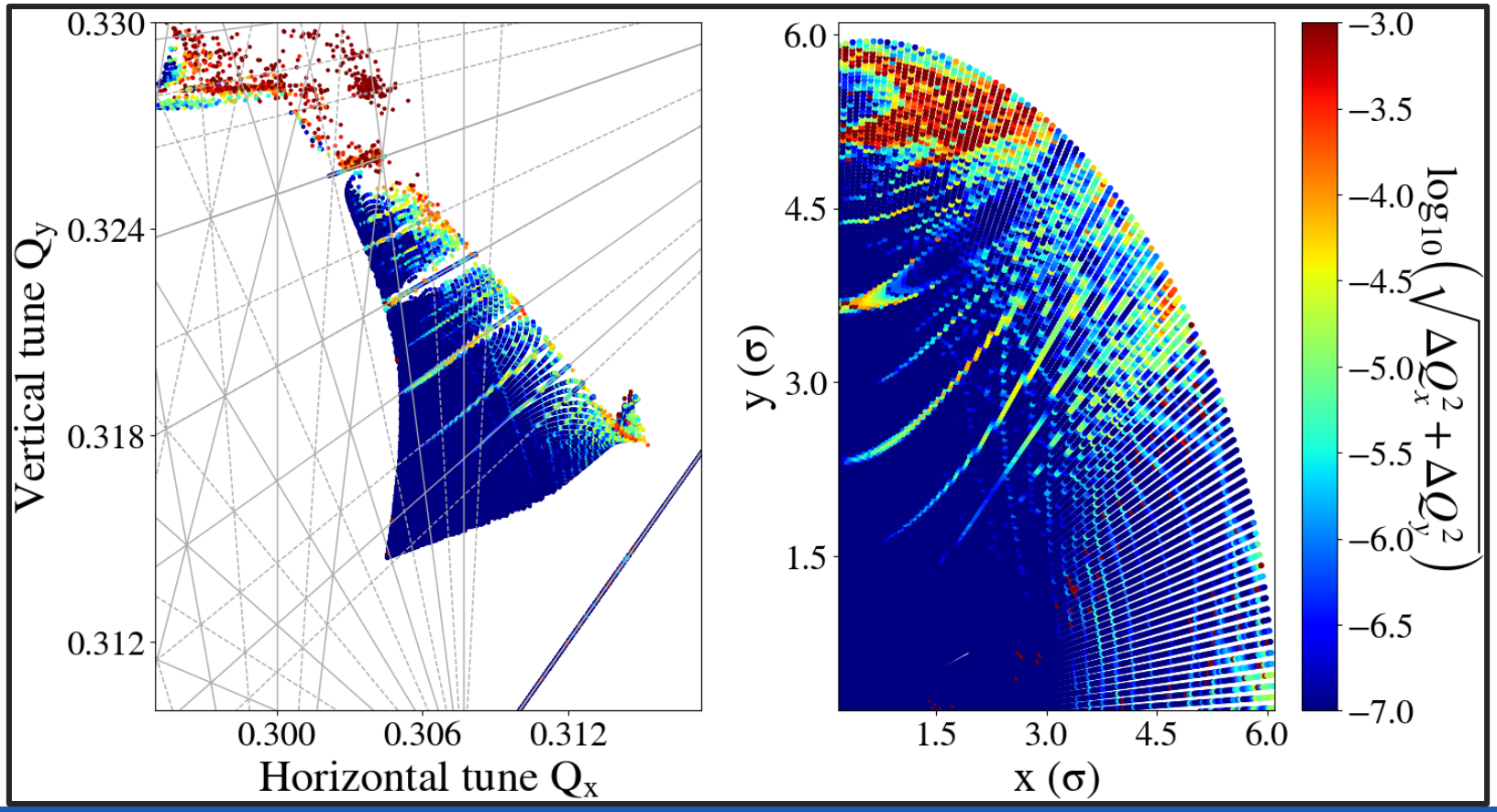
- Similar signature between the low & high-f cluster indicates that the source is the same. Two directions of study:
  1. A **higher sensitivity** of the beam's response to f_{rev}-f_x compared to f_x.

     or
  2. Interplay with additional circuit resonances or other system (**UPS***).

* V. Chareyre. Assessment of the High Frequency Noise Produced by the UPS Systems in the LHC Machine.

FMA with 50 Hz harmonics

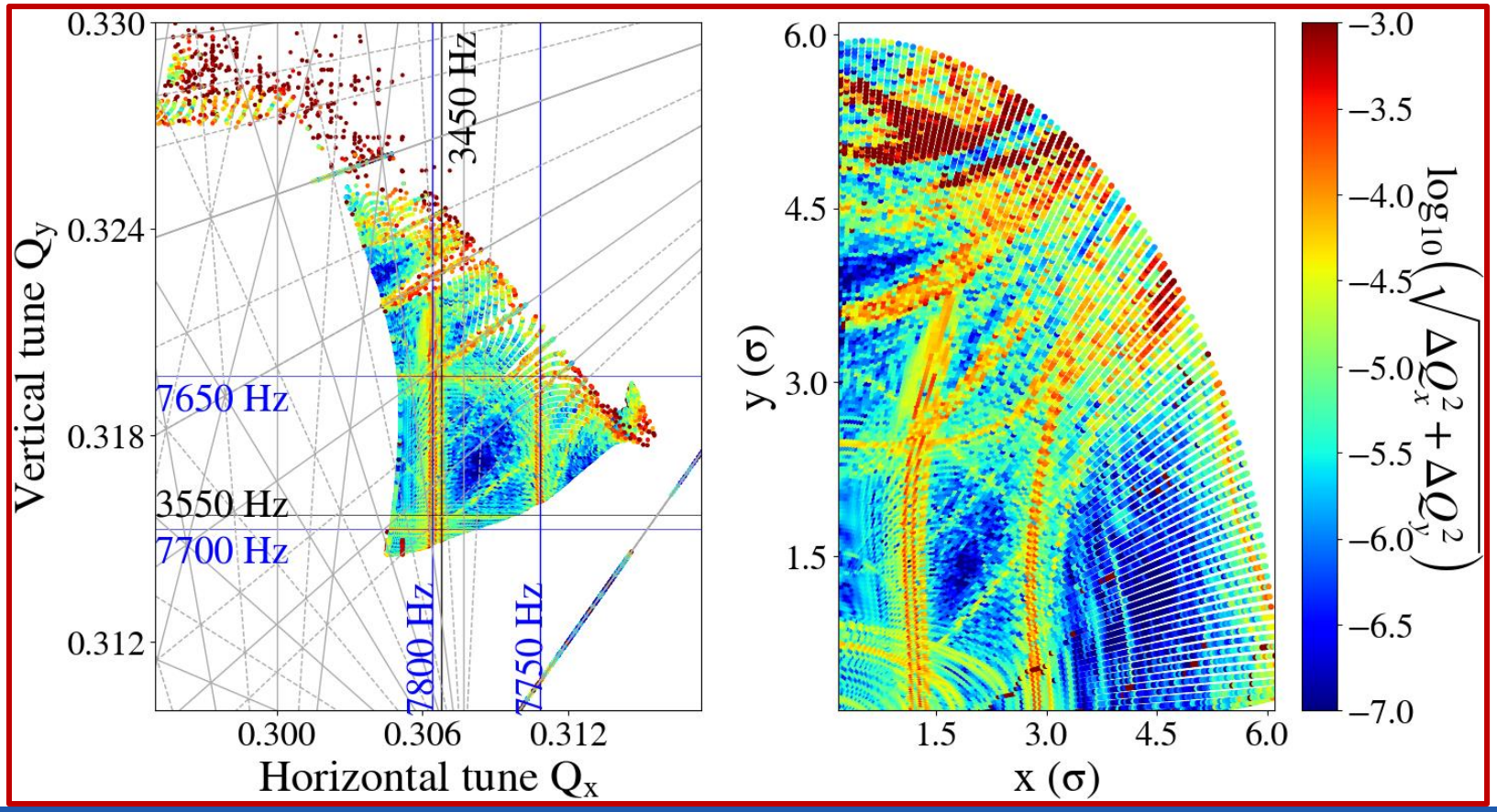
Ideal machine without ripple



FMA with 50 Hz harmonics

"Low frequency cluster" + "High frequency cluster"

$Q_x = Q_r$ & $Q_x = 1-Q_r$



Simulations including 50 Hz

Estimation of **beam lifetime** with **weighted distributions** in simulations including:

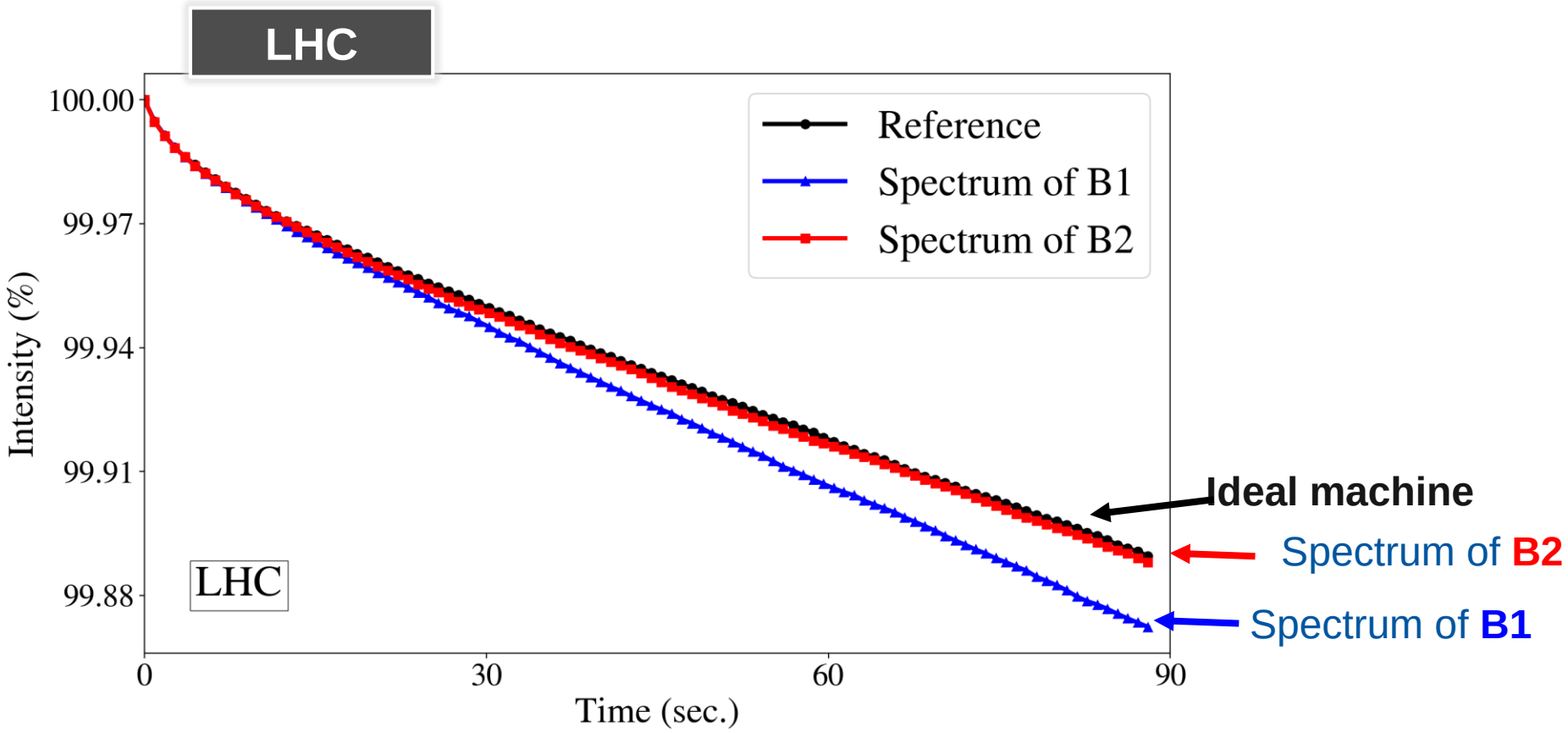
I. **Realistic 50 Hz spectrum** as extracted from ADTObsBox.

II. **Non Gaussian beam profiles**: overpopulated tails in the transverse plane[*,**] & underpopulated in the longitudinal[**].

III. "Collimator"/Aperture at 5 σ (for 3.5 μm).

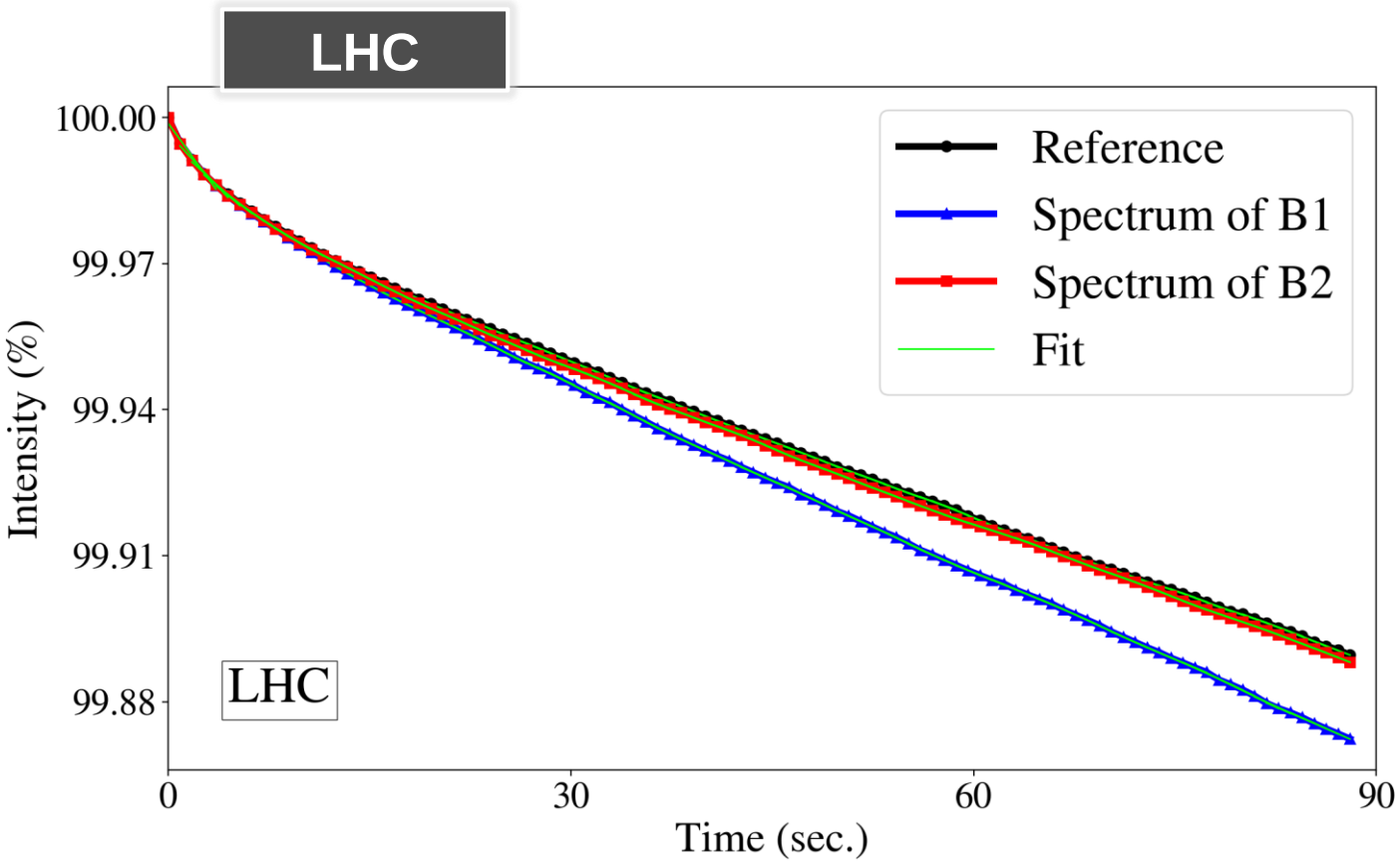
* H. Garcia Morales: WP2 16/06/2020, Halo measurements using collimator scans
** S. Papadopoulou: HSI lumi meeting 18/5/2018 BSRT calibration Fill 6699

Beam lifetime simulations



- Impact on Beam 1 intensity evolution especially due to high-f cluster.

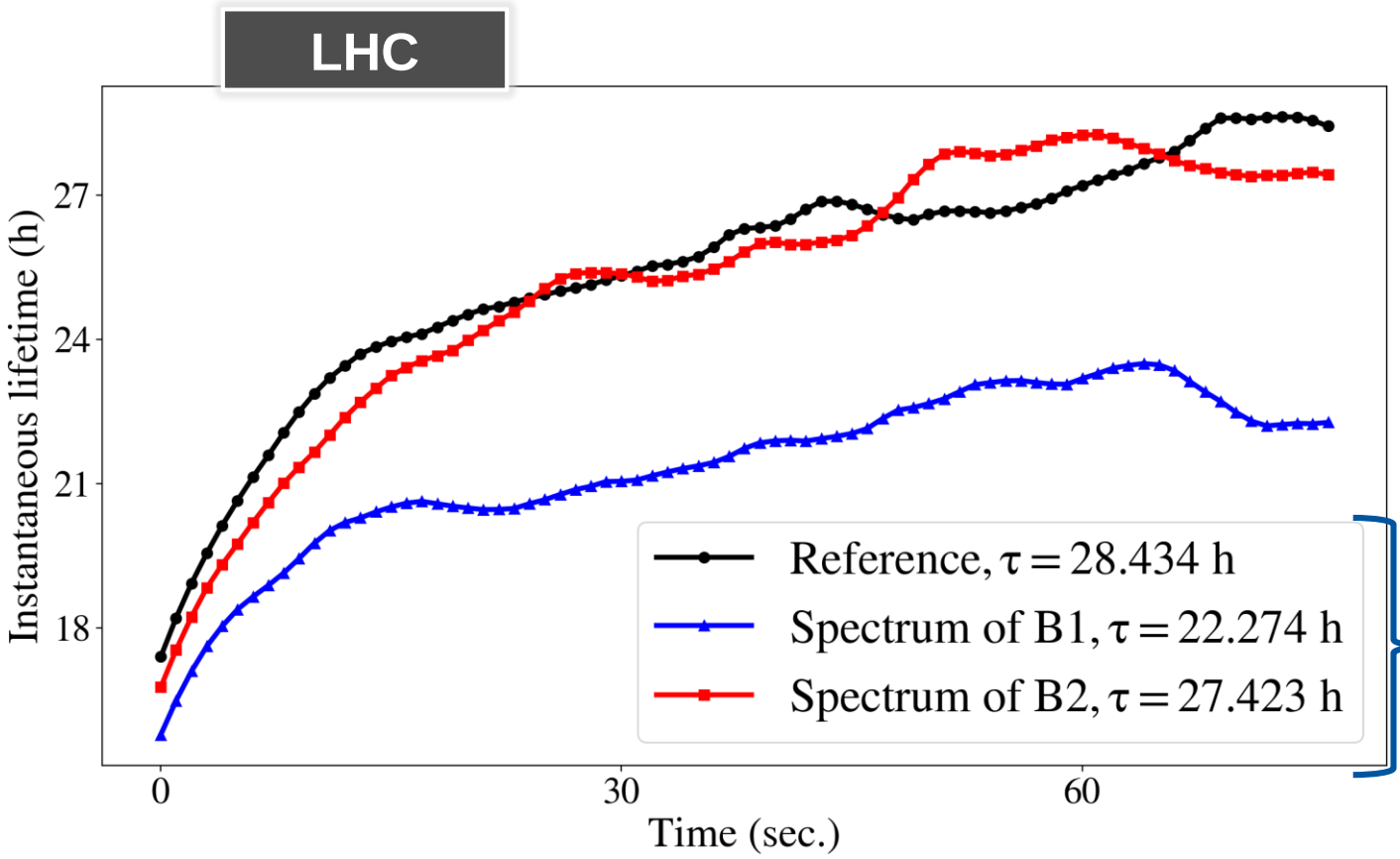
Beam lifetime simulations



Instantaneous lifetime from **fit** + moving average →

- Impact on Beam 1 intensity evolution especially due to high-f cluster.

Beam lifetime simulations



Instantaneous lifetime at 90 s.

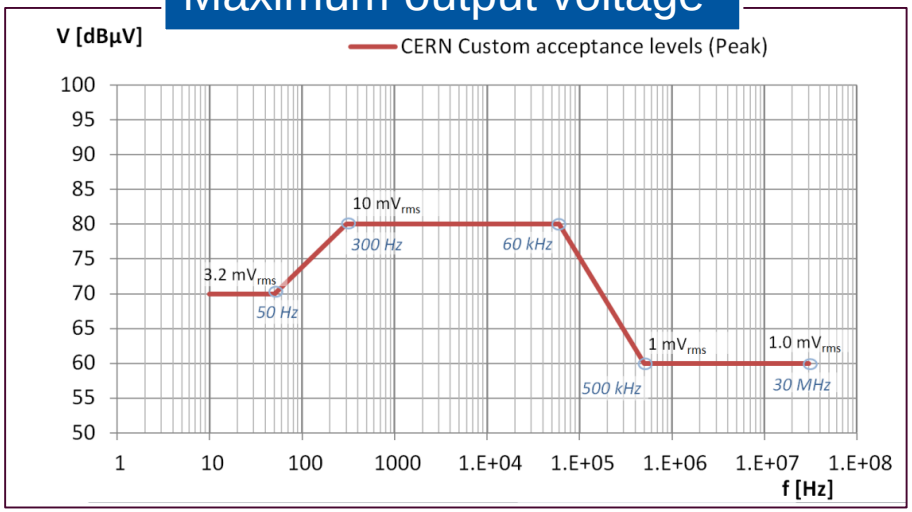
- The 50 Hz contribute to the asymmetric beam lifetime of Beam 1 & Beam 2
- **20% reduction of Beam 1 lifetime** compared to the ideal machine.

Part 2: Power supply ripple in the IT quadrupoles of HL-LHC

Simulation setup

- Simulated parameters at end of β*-levelling (β*=15 cm)
- Ripple in Q1, Q2a, Q2b, Q3 IR1 & IR5
- Comparison with PC specifications.

Maximum output voltage



Limits from previous studies: Maximum tolerated ΔQ

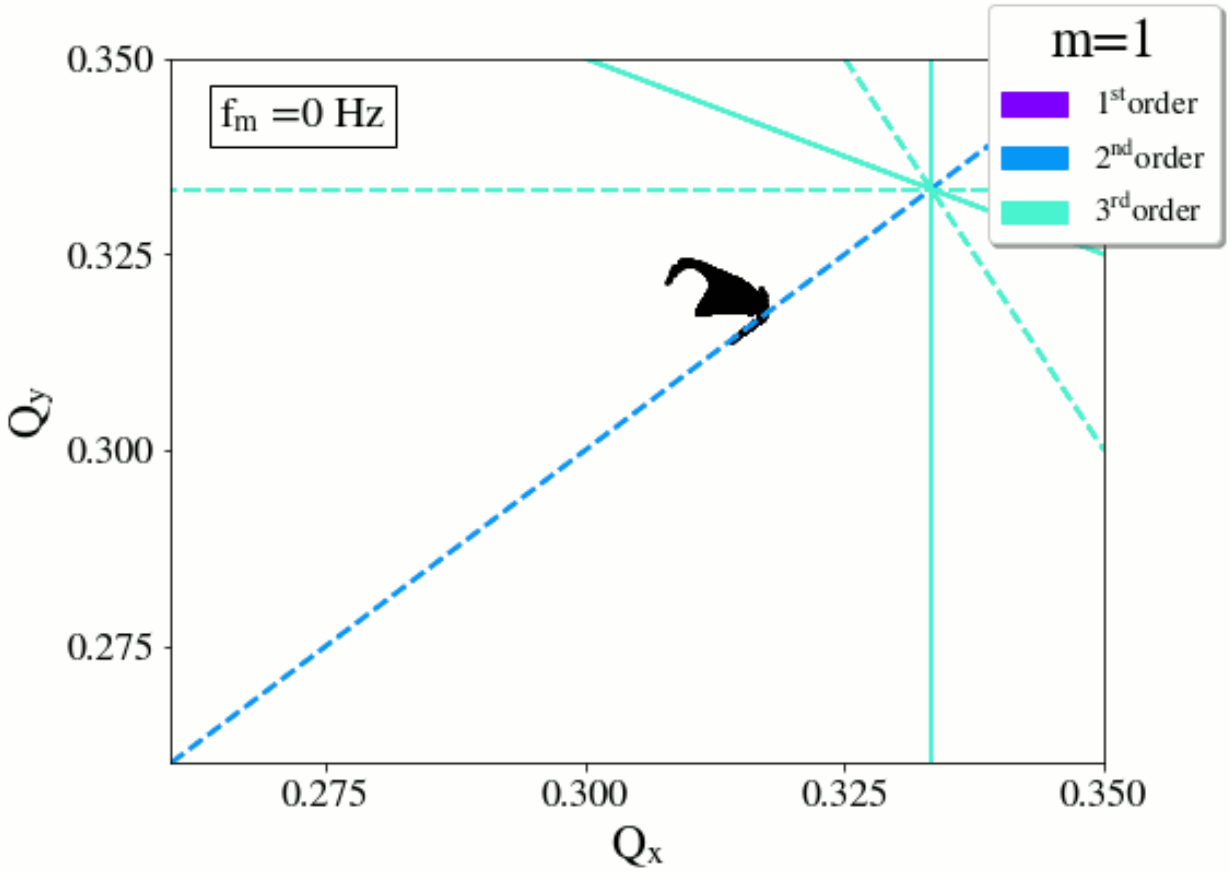
TABLE I. The critical modulation depth due to power supply ripple as reported from previous studies [10, 13, 18, 19].

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

Tune modulation

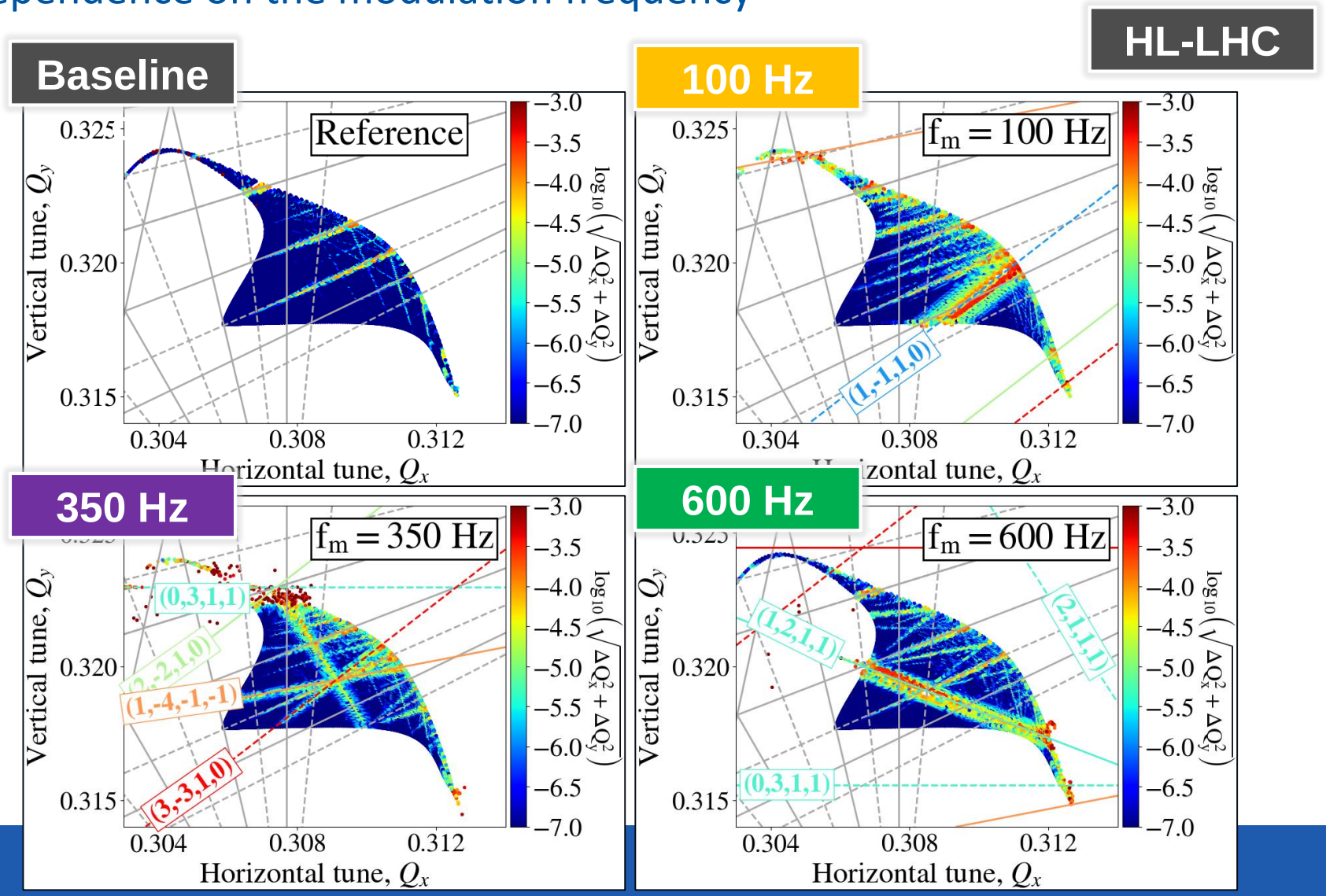
- Dependence on the modulation frequency

$$k \cdot Q_x + l \cdot Q_y + \mathbf{1 \cdot Q_m} = n,\ \mathbf{Q_m} \uparrow [1]$$

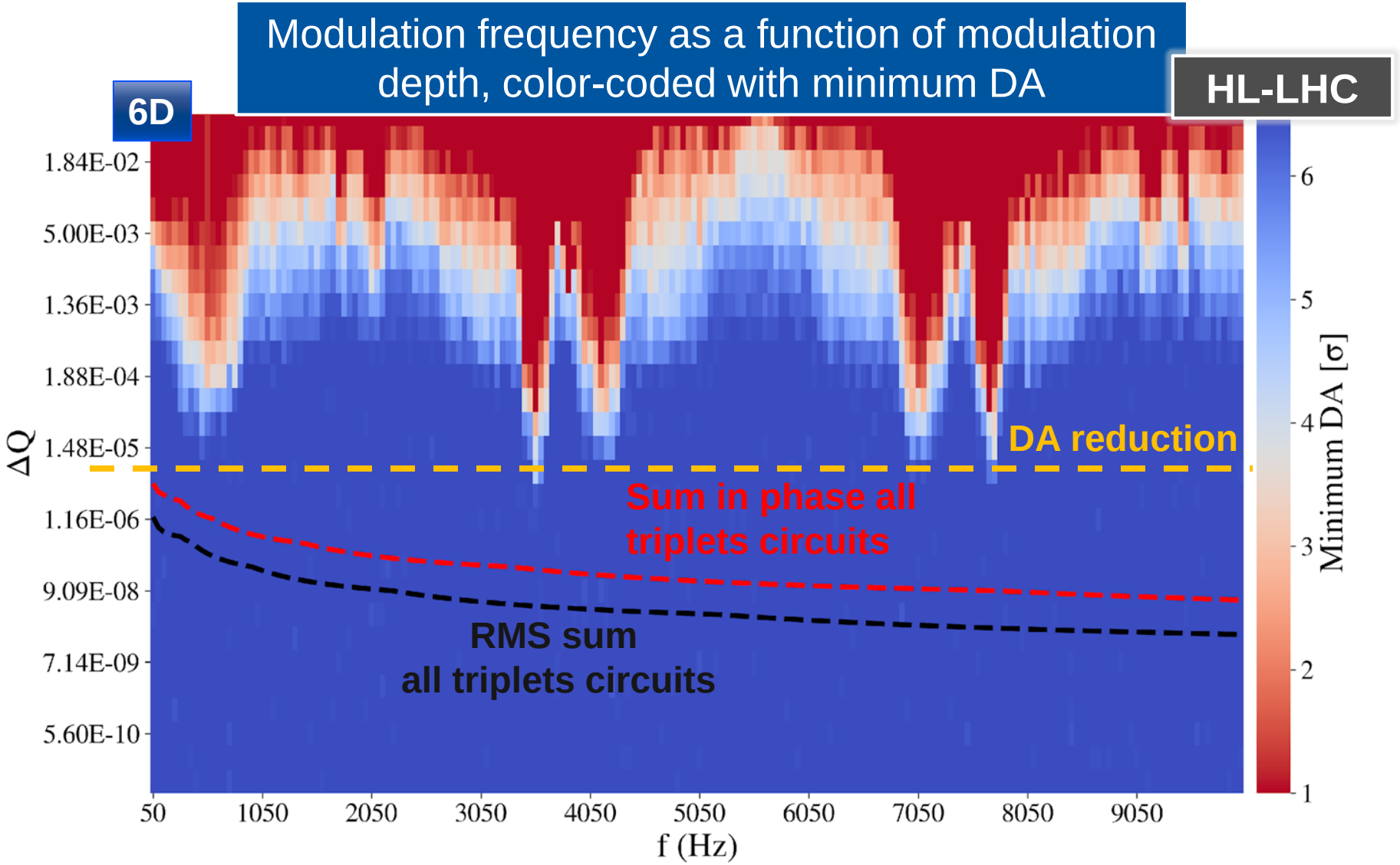


FMAs with power supply ripple in IT

- Dependence on the modulation frequency



Ripple thresholds with DA scans



Conclusions: 50 Hz harmonics

- **What is the source?**
- **Do they have an impact on the beam performance?**

Experimental observations

- 2 clusters of 50 Hz in beam spectrum: **low** (up to 3.6 kHz) and **high** (f_{rev}-f_x) frequency clusters.
- Both **real beam excitations,** both **dipolar** effect.
- **Low-f cluster** source: **8 Main Bends power converters,** ripple in all LHC dipoles.
- **High-f cluster** source: exact mechanism to be identified.

Simulations

- Contribute to the **lifetime asymmetry** of Beam 1 and Beam 2, observed since start of Run 2.
- Including realistic beam profiles & realistic power supply ripple spectra, **20% beam lifetime reduction** compared to ideal machine, especially due to high-f cluster.
- Expected to be present in the future operation → mitigation measures.

Conclusions: Inner triplet HL-LHC

- **Will tune modulation effects pose a limitation in the luminosity production of HL-LHC?**

Simulations

- Simulations at the end of β* leveling, most critical scenario for power supply ripple studies.
- Critical HL-LHC power supply ripple **modulation depth 10^{-5}**
- Comparison of DA reduction limit and power converter specifications, possible ripple **orders of magnitude below the limit of DA reduction.**
- Tune modulation in HL-LHC from power converter noise & chromatic tune modulation **not expected to impact the beam performance**.

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Two different types of power converters, different mechanisms of coupling to the beam → **same analysis tools**, can be used to address other beam jitter effects.

Thank you for your attention