Impact of power supply ripple on the beam performance of the Large Hadron Collider & the High-Luminosity LHC

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Motivation

- LHC performance in Run1 (2009-2013) & Run2 (2015-2018): proton losses & emittance growth ↑ than anticipated→ mechanisms that enhance diffusion → **noise effects**.

- Understanding & mitigating noise effects: **essential for LHC future operation** to reach unprecedented values of integrated luminosity:
  - **Strong non-linearities:**
    - ↓ emittances, ↑ intensities, ↓ β^*, strong beam-beam effects (incoherent effects)
    - ↑ chromaticity, ↑ octupole current (for coherent effects)
  - **↑ β-functions (arcs, Inner Triplet)**

- Focusing on **power supply ripple** in **transverse beam spectrum** since start of LHC operation:

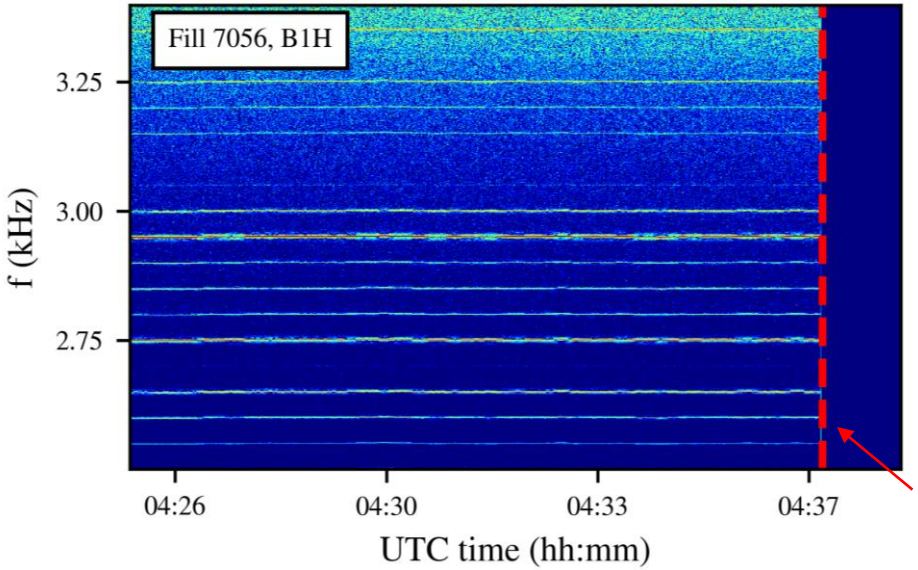
I. Determine if resulting from instrumentation system artifacts.

II. If not, identify source.

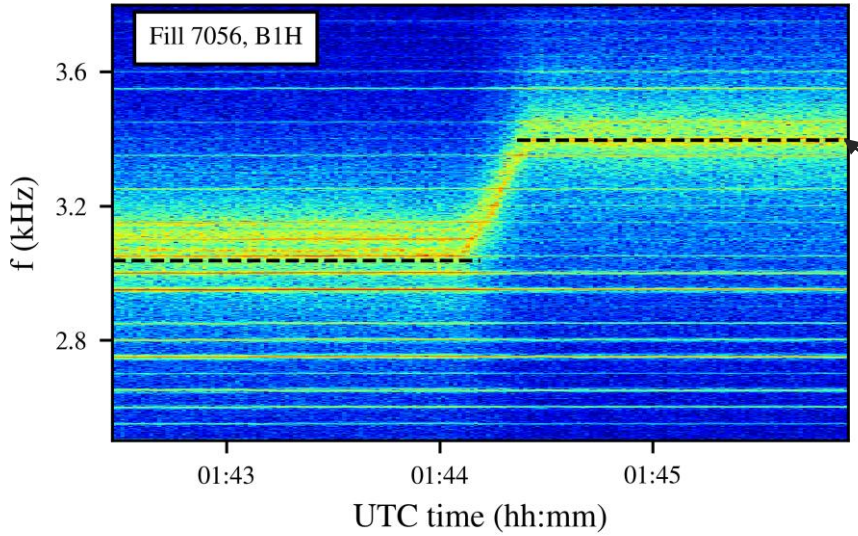
III. Evaluate impact on beam performance.

Introduction

- **Harmonics** of mains power frequency (**50 Hz**):
  - I. Observed in **several unrelated instruments**.
  - II. Visible in all beam modes, fills, planes & both beams.
  - III. Not present without beam (noise of instruments).
  - **IV. Dipolar excitations**, not sidebands around betatron tune.
  - V. Similar observations of high-order harmonics in the form of dipolar excitations in other accelerators (Tevatron, RHIC).
  - VI. Several observations: **real beam excitations**, not an instrumentation artifact.



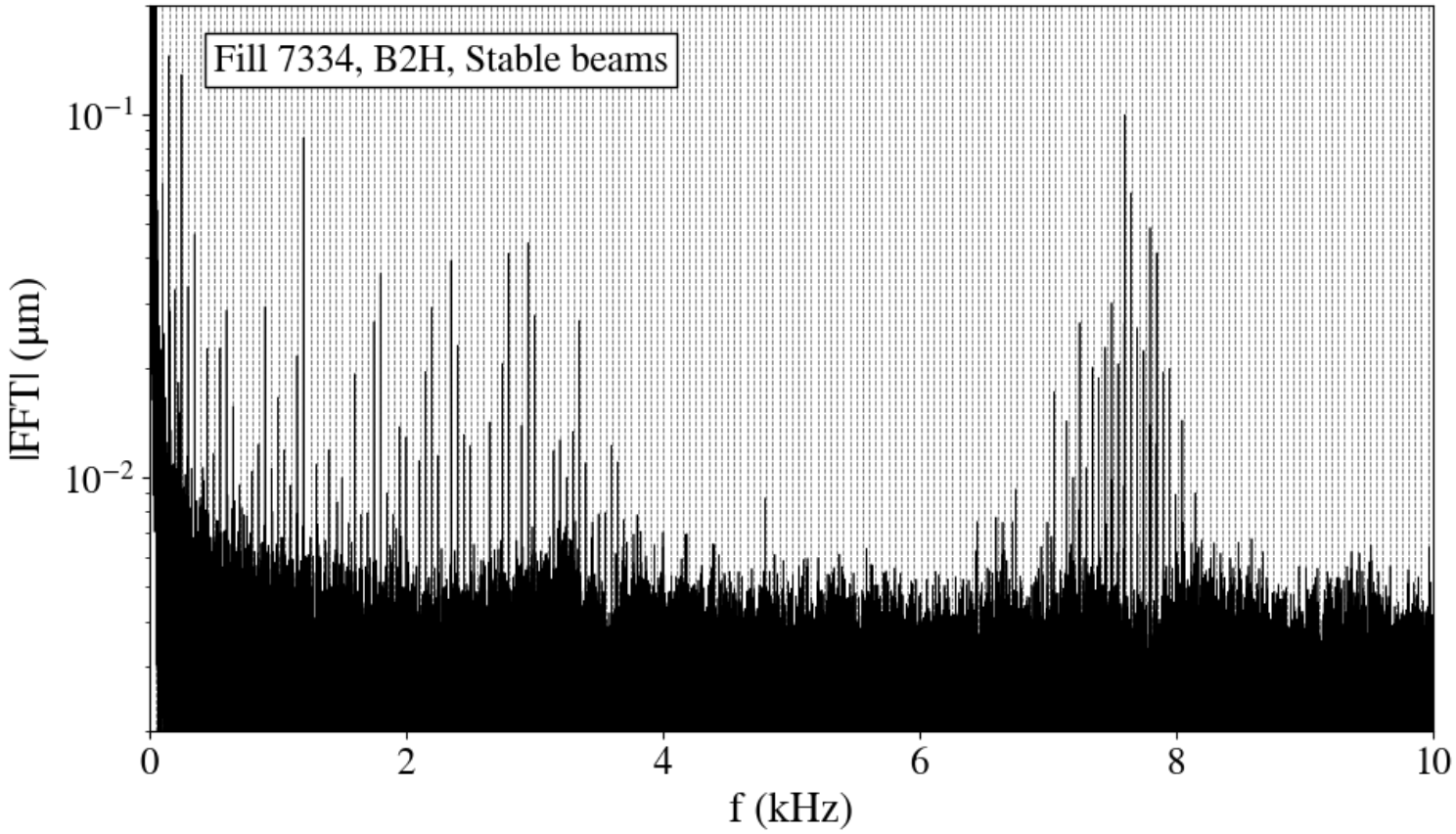
Beams dumped



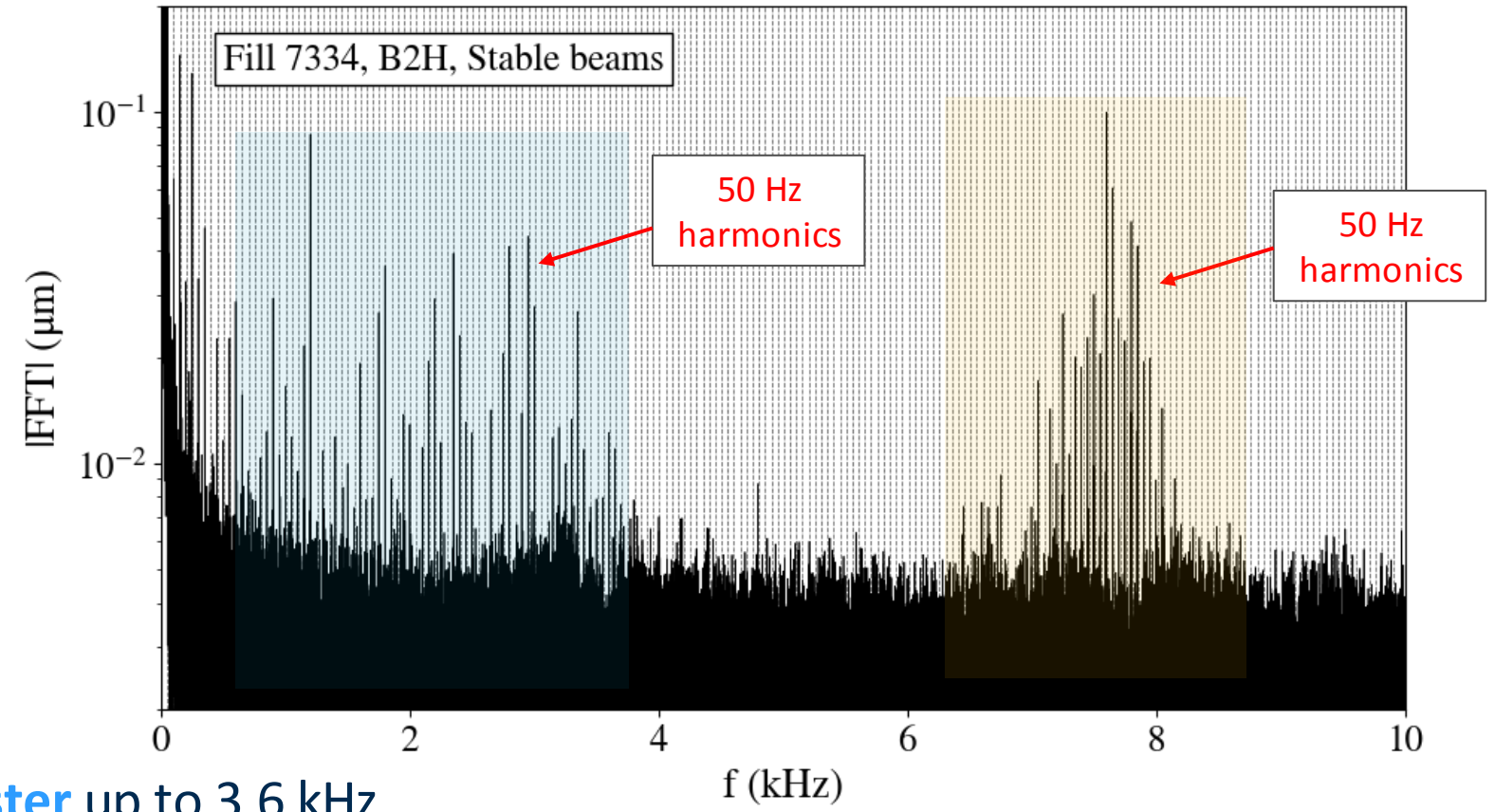
Betatron tune

The low and high-frequency clusters

- Computed using bunch-by-bunch & turn-by-turn calibrated position measurements from transverse damper high-sensitivity pickups (ADTObsBox).



The low and high-frequency clusters



Low-frequency cluster up to 3.6 kHz.

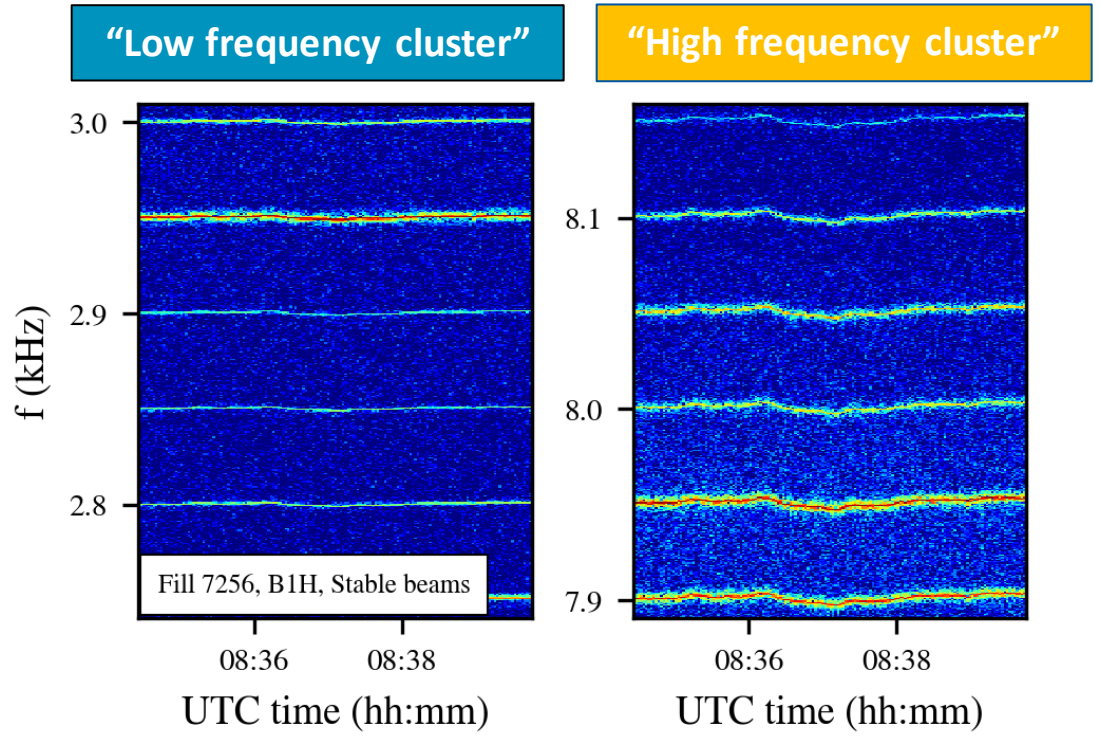
High-frequency cluster ~7-8 kHz, in the regime f_{rev}-f_x

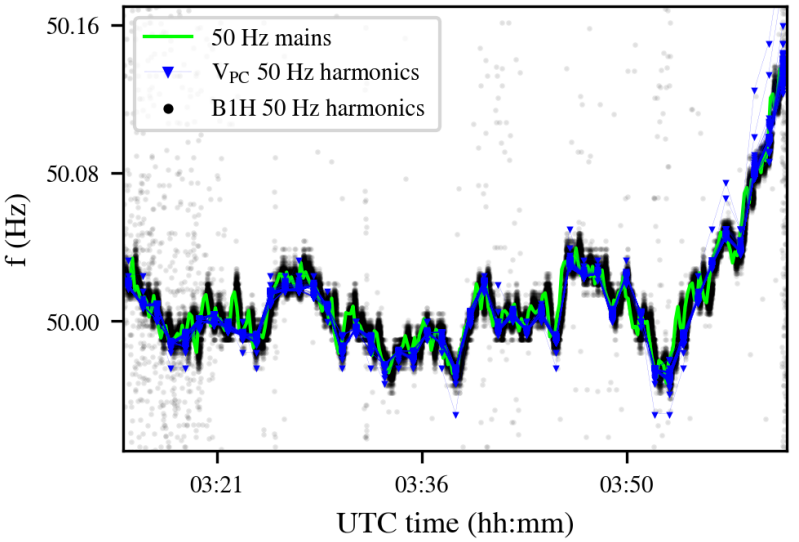
Signature of low and high-frequency cluster

Low-frequency cluster & **High-frequency cluster**:

I. Multiple 50 Hz harmonics.

II. Similar **frequency modulation from the mains**, with f-modulation amplitude proportional to the order of harmonic.





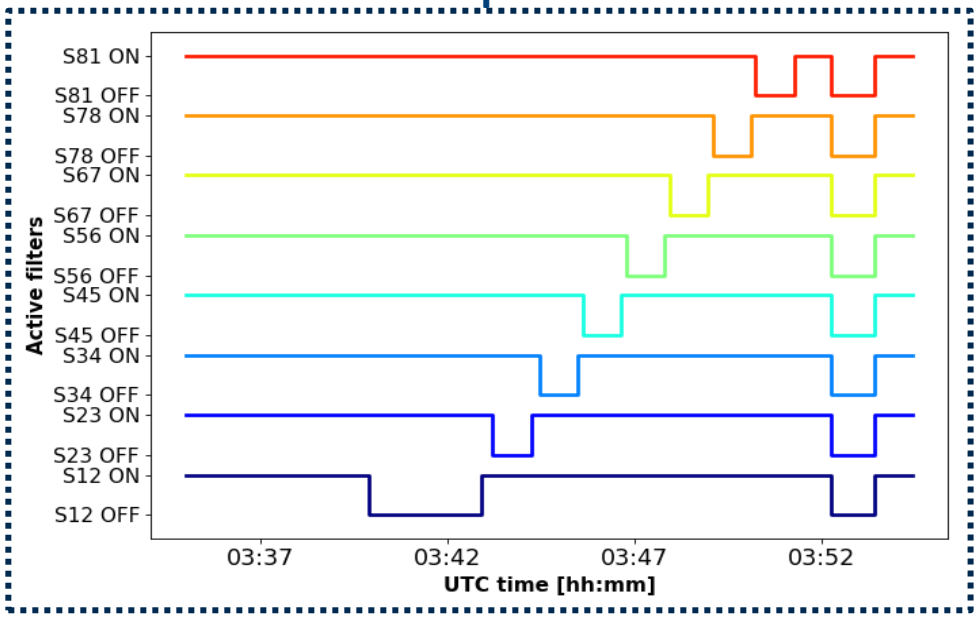
50 Hz in the beam, normalized

50 Hz mains

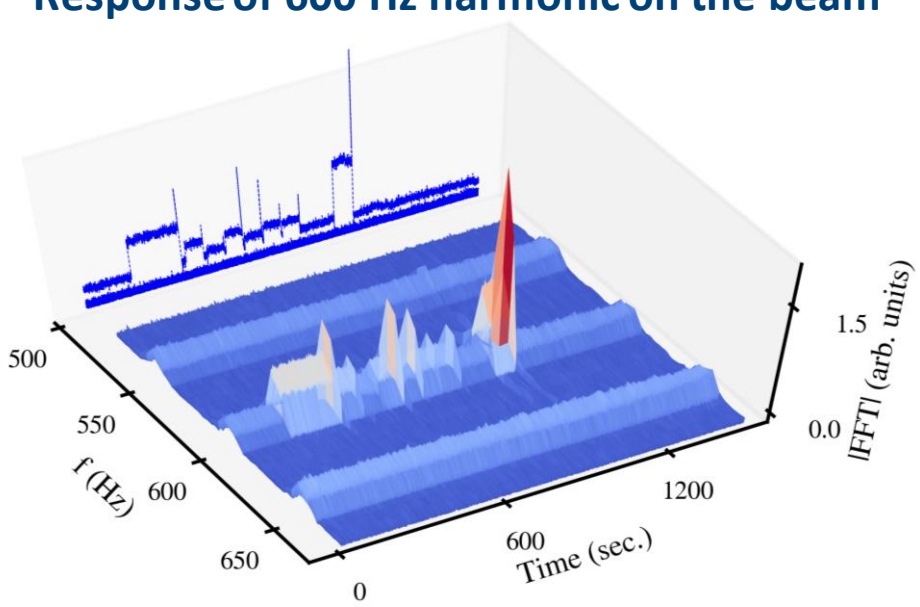
Source of the low-frequency cluster

- Based on signature→ Silicon Controlled Rectifier (SCR) **power supplies of main dipoles.**
- Simple modifications of main dipole power supplies combined with beam measurements → Experiments with **main dipole active filters**:
  - Responsible for attenuation of 50 Hz ripple.
  - Enabling & disabling active filters sector by sectors and observing beam's response.

Status of main dipole active filters

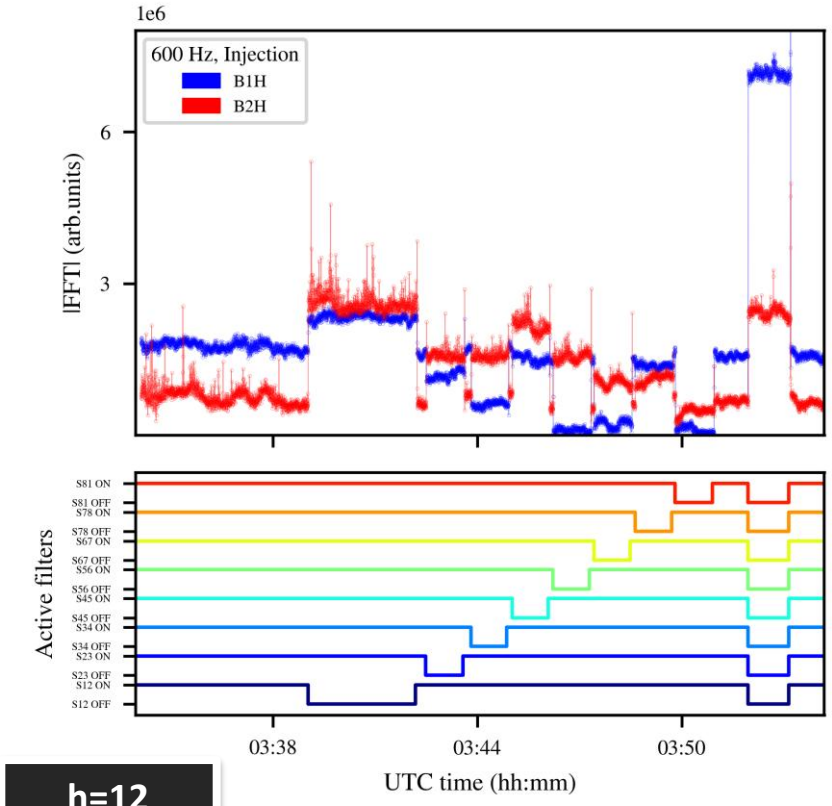


Response of 600 Hz harmonic on the beam



Source of the low-frequency cluster

- Clear impact on low-frequency cluster when enabling & disabling active filters.
- All eight power supplies contribute to this effect → power supply ripple **distributed in the whole ring**.
- For the same harmonics, **different response between Beam 1 & Beam 2**→ attributed to their different phase advances.



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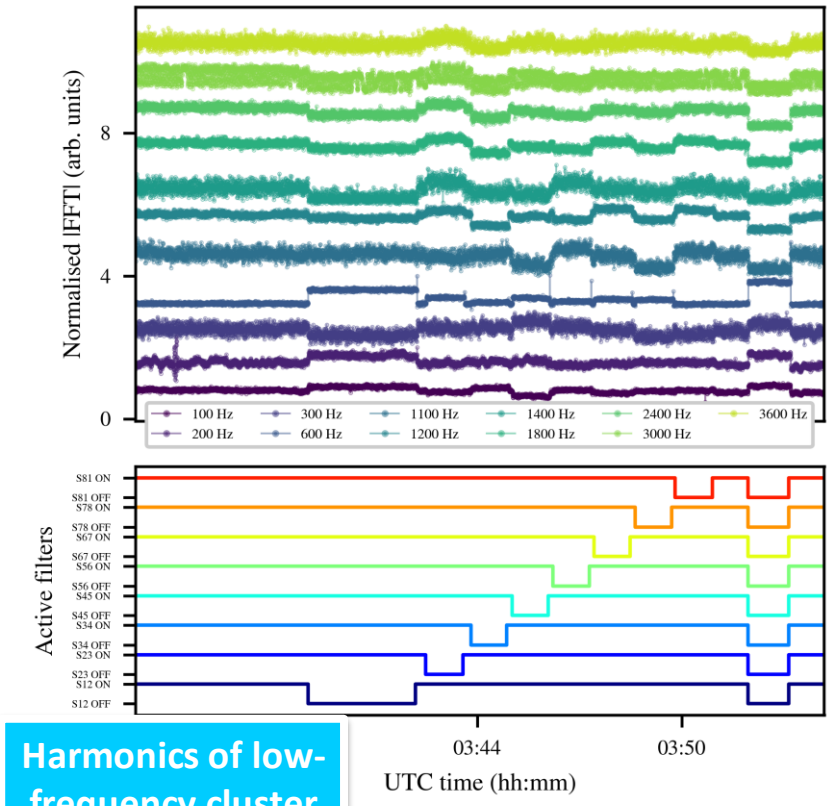
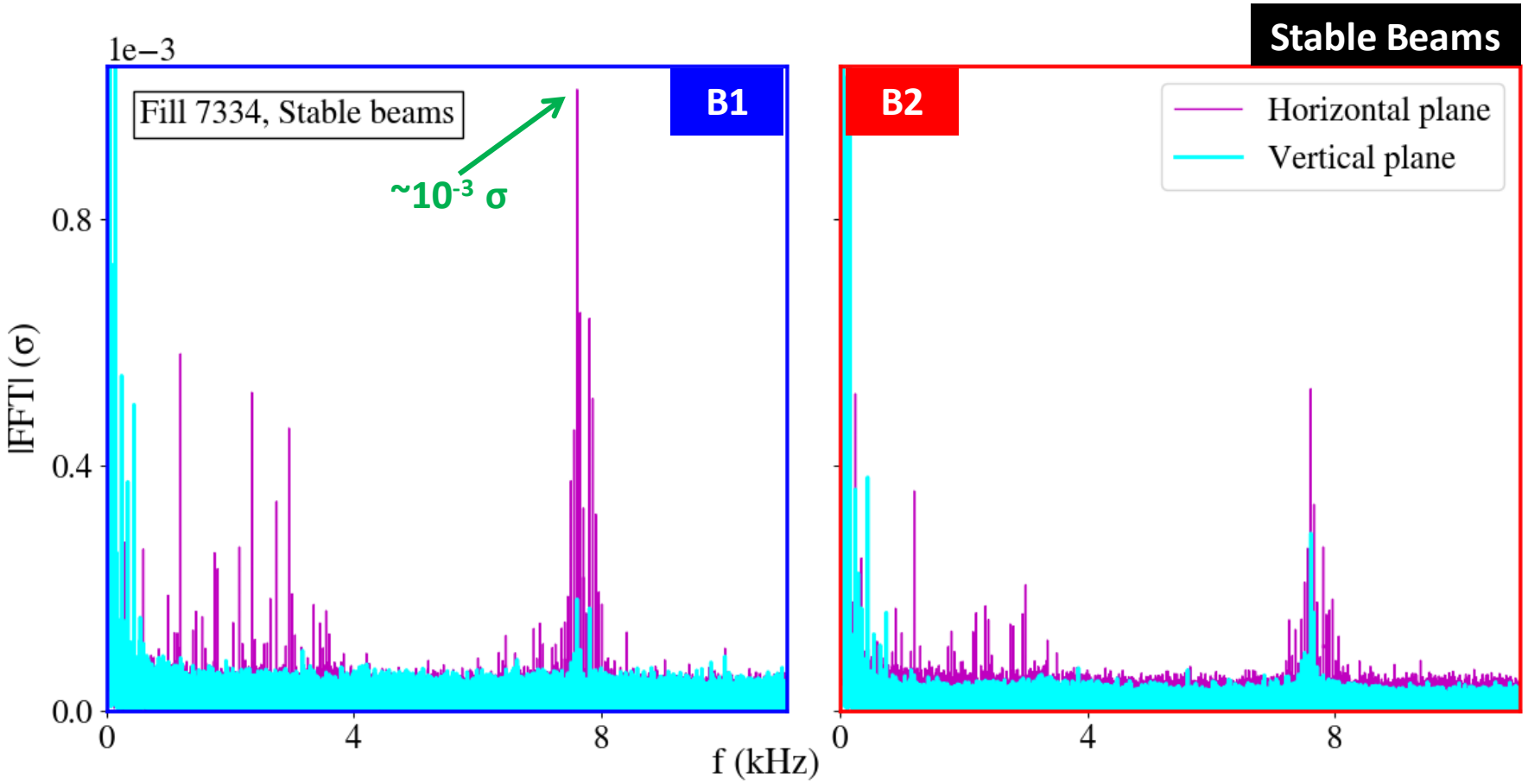


Harmonics of low-frequency cluster

Comparison of Beam 1 & Beam 2 spectra

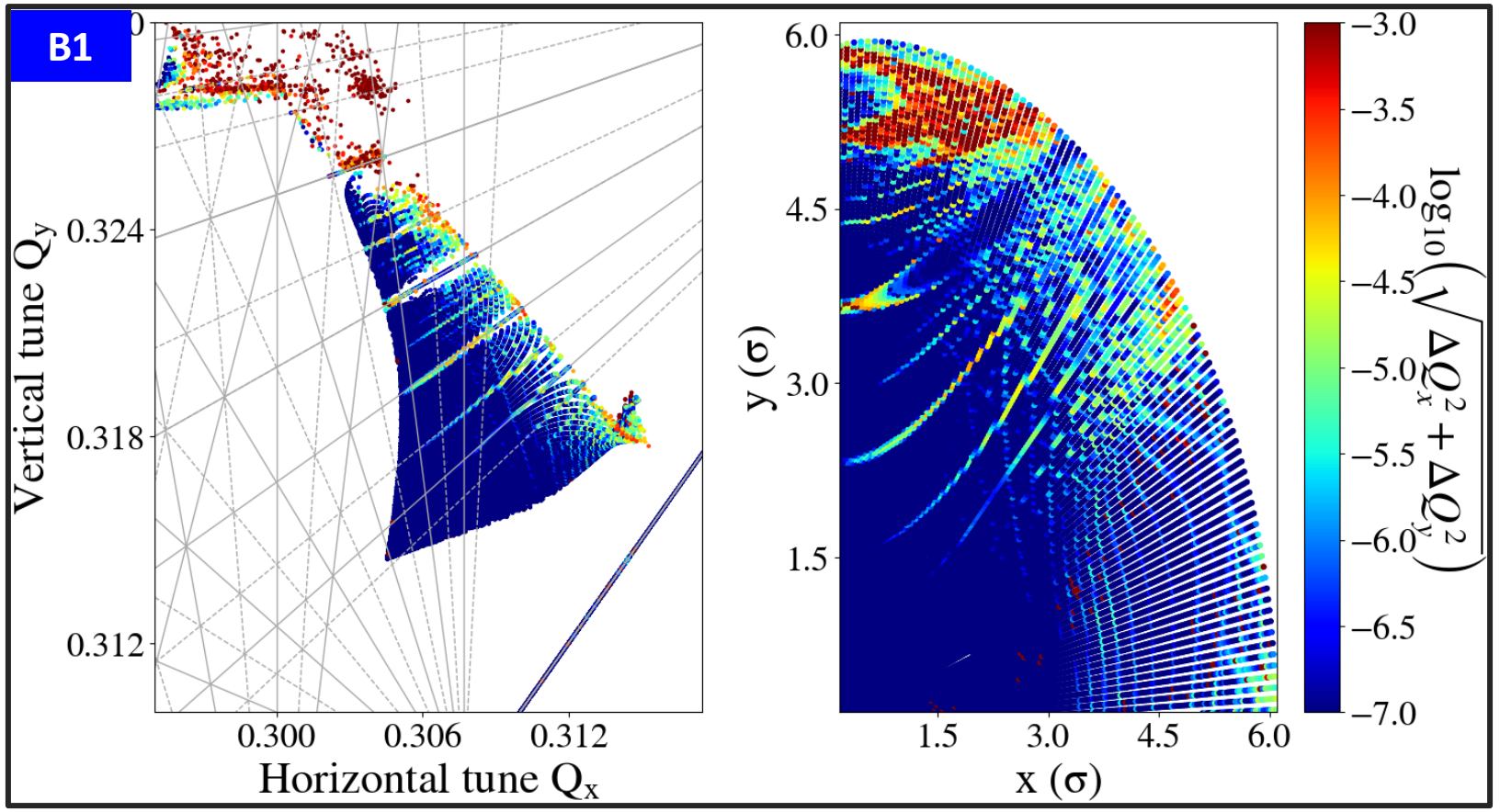


- Larger amplitudes of 50 Hz harmonics **by factor of two in Beam 1 compared to Beam 2**.
- Main impact on the **horizontal plane** → consistent with dipolar field error.
- Maximum amplitude of high-frequency cluster **~10^{-3} σ**.

Frequency Map Analysis with 50 Hz harmonics

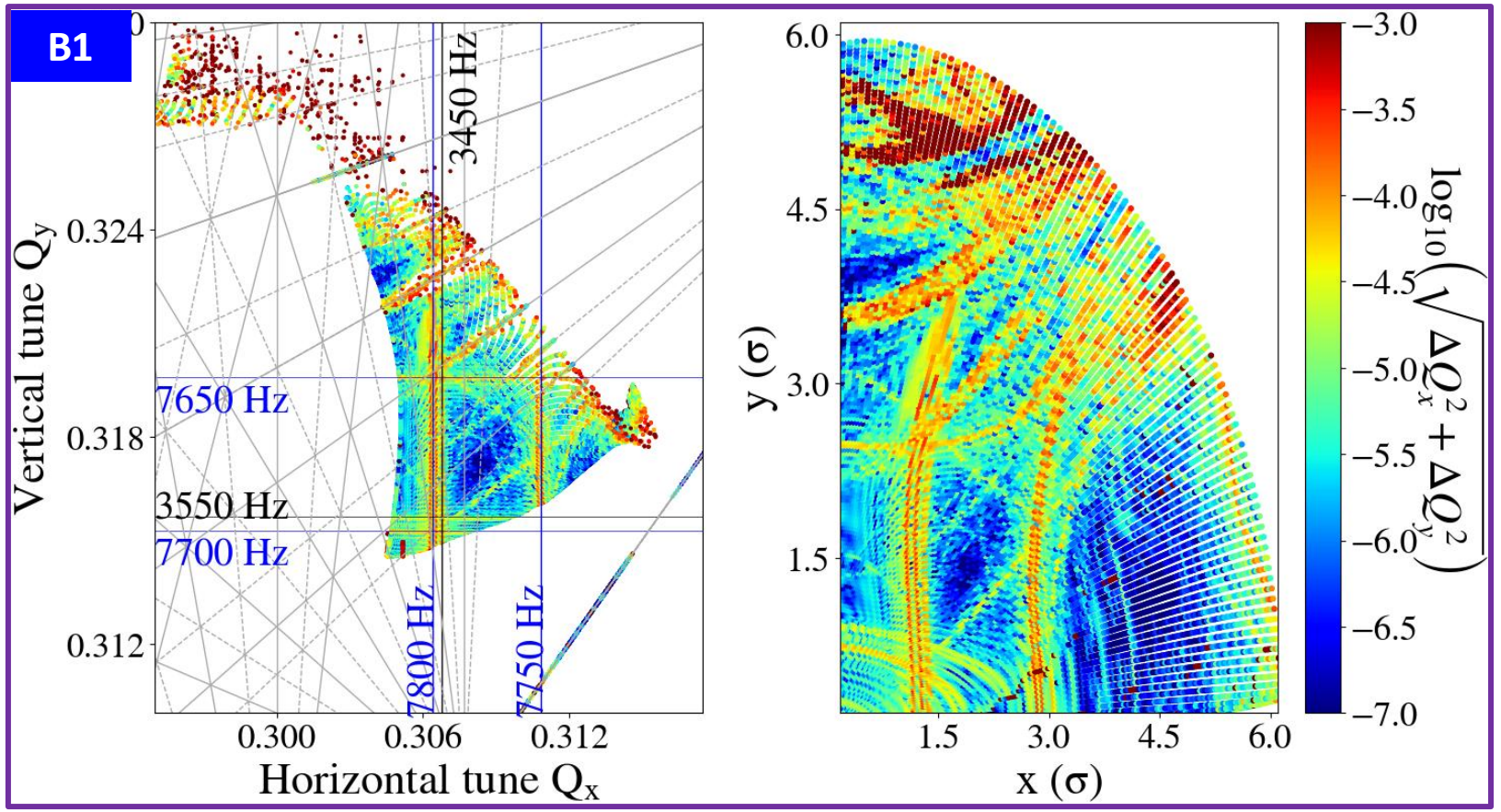
- Single particle tracking simulations in element-by-element LHC lattice during collisions including beam-beam interactions.

Ideal machine without ripple



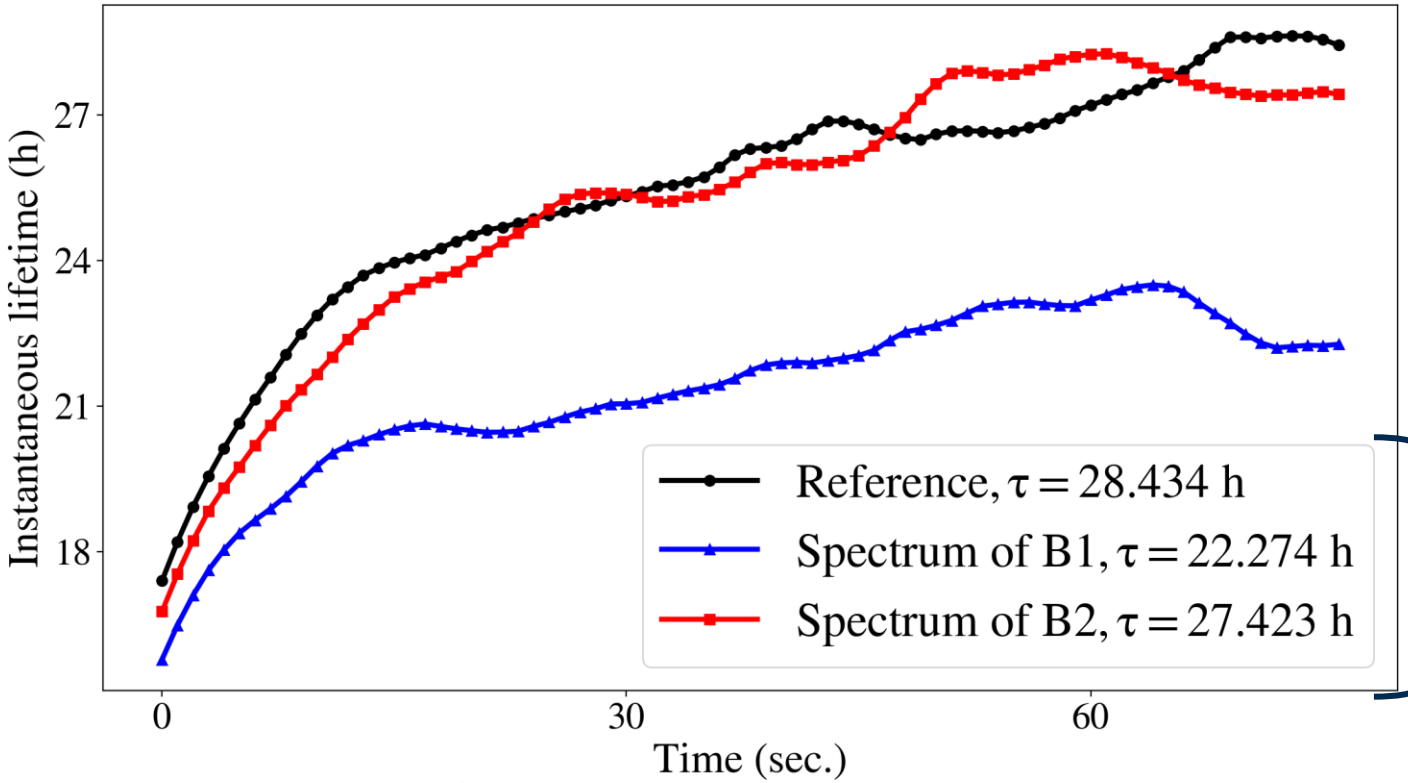
Frequency Map Analysis with 50 Hz harmonics

"Low frequency cluster" + "High frequency cluster"



Beam lifetime simulations

- Estimations of beam lifetime with tracking simulations (10^6 turns / 90 seconds operational time) including realistic power supply ripple spectra & non-Gaussian beam profiles.



Instantaneous lifetime at 90 s.

As a reference, **LHC burn-off life time 25 h**.

- The 50 Hz contribute to the asymmetric beam lifetime of Beam 1 & Beam 2
- **20% reduction of Beam 1 lifetime** compared to ideal machine especially due to high-frequency cluster → consistent with losses beyond burn-off observed in Run2

Summary

Experimental observations

- 50 Hz harmonics in the transverse beam spectrum since the start of the LHC operation.
- 2 clusters of 50 Hz in beam spectrum: **low** (up to 3.6 kHz) & **high** (7-8 kHz) frequency clusters.
- Both **real beam excitations** rather than artifact of instrumentation system, both **dipolar effect**.
- **Low-frequency cluster** source identified through dedicated experiments with main dipole active filters: **8 main dipole SCR power supplies**, ripple distributed in all LHC dipoles.
- **High-frequency cluster** source: exact mechanism to be identified. Currently investigating other potential sources (e.g. Uninterruptible Power Supply, transverse damper).

Summary

Single-particle tracking simulations

- **Tune diffusion increase** when including power supply ripple spectrum as observed experimentally.
- Including realistic beam profiles & realistic power supply ripple spectra, **20% beam lifetime reduction** compared to ideal machine, especially due to **high-frequency cluster**.
- 50 Hz harmonics contribute to **lifetime asymmetry of Beam 1 & Beam 2**, observed since the start of Run 2.
- Based on observations, expected to be **present in the future LHC operation** → mitigation measures are necessary for HL-LHC era.

Detailed overview of LHC power supply ripple observations:

Origin of the 50 Hz harmonics in the transverse beam spectrum of the Large Hadron Collider, Phys. Rev. Accel. Beams 24, 034001

Impact of the 50 Hz harmonics on the beam evolution of the Large Hadron Collider, Phys. Rev. Accel. Beams 24, 034002

Thank you for your attention