Observations of high frequency noise in turn-by-turn spectra of LHC beams

BE-ABP, SY-EPC, EN-EL and many more..

234th WP2, 13/02/2025

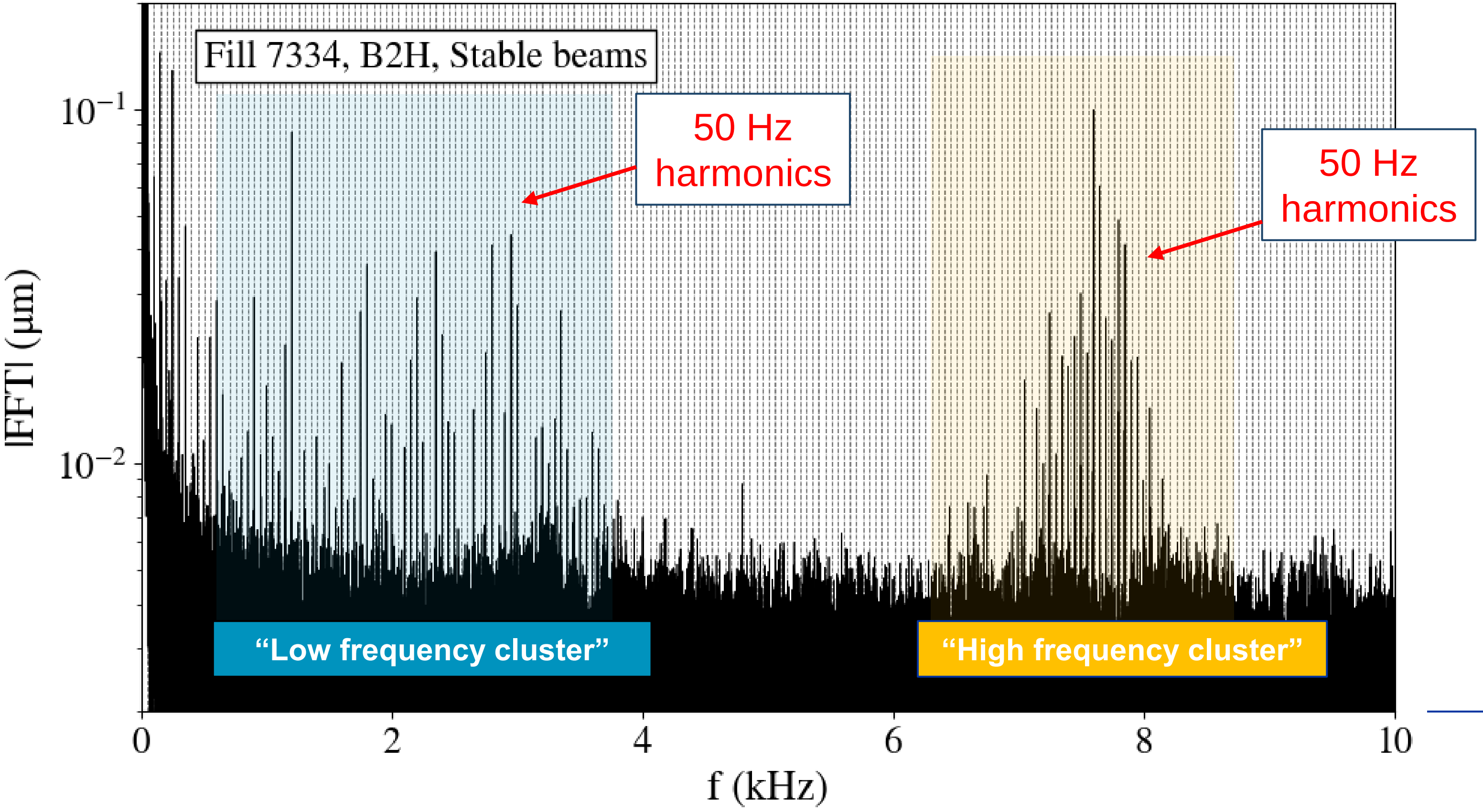
Overview

- **Observations from the LHC:**
  - Power supply ripple in transverse beam spectrum
  - Source of emittance growth with unknown origin both at injection and top energy
- **Tests with main dipole power supply active filters**
- **Impact of transverse damper**
- **Measurements of UPS noise & tests with beam**
- **Impact on beam performance**

LHC observations: Power supply ripple

- **50Hz power supply ripple** systematically observed in the transverse LHC spectrum in **both beams** and planes (mainly in **H-plane**).
- Several studies confirm that it is a **real beam excitation** in the form of **dipolar perturbations**.
- Very high frequencies also present (~8 kHz while ~11 kHz LHC revolution frequency)

Spectrum from bunch-by-bunch and turn-by turn position measurements

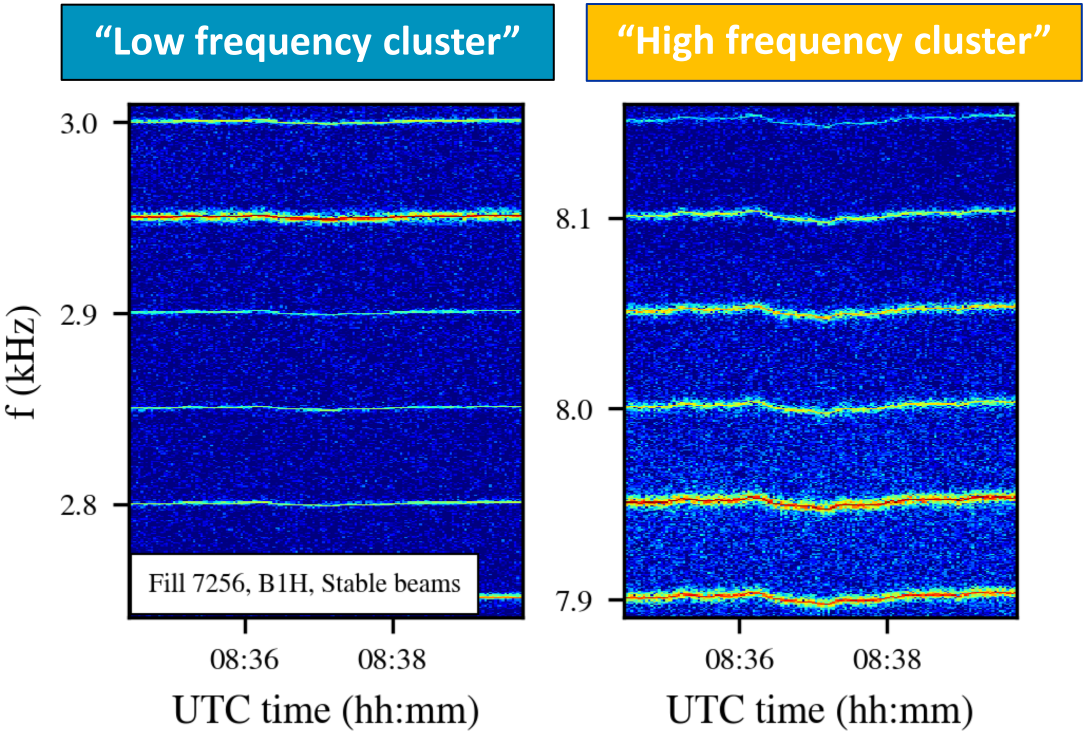


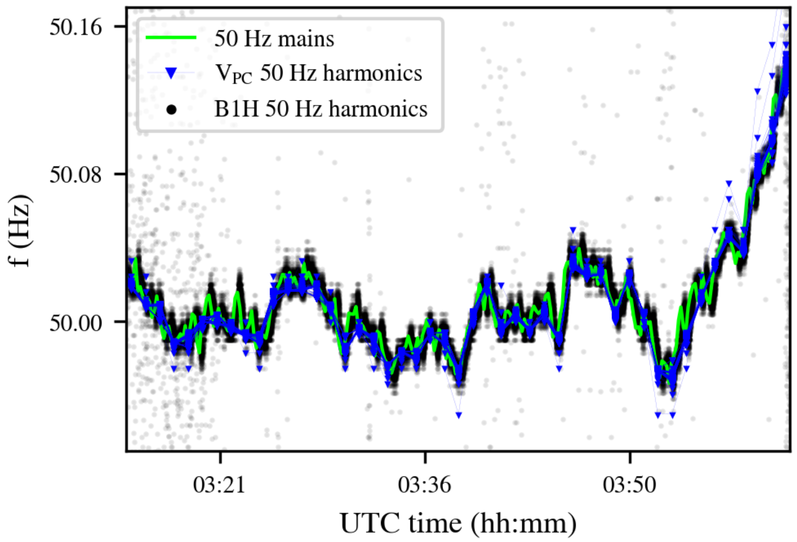
LHC observations: Power supply ripple

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.



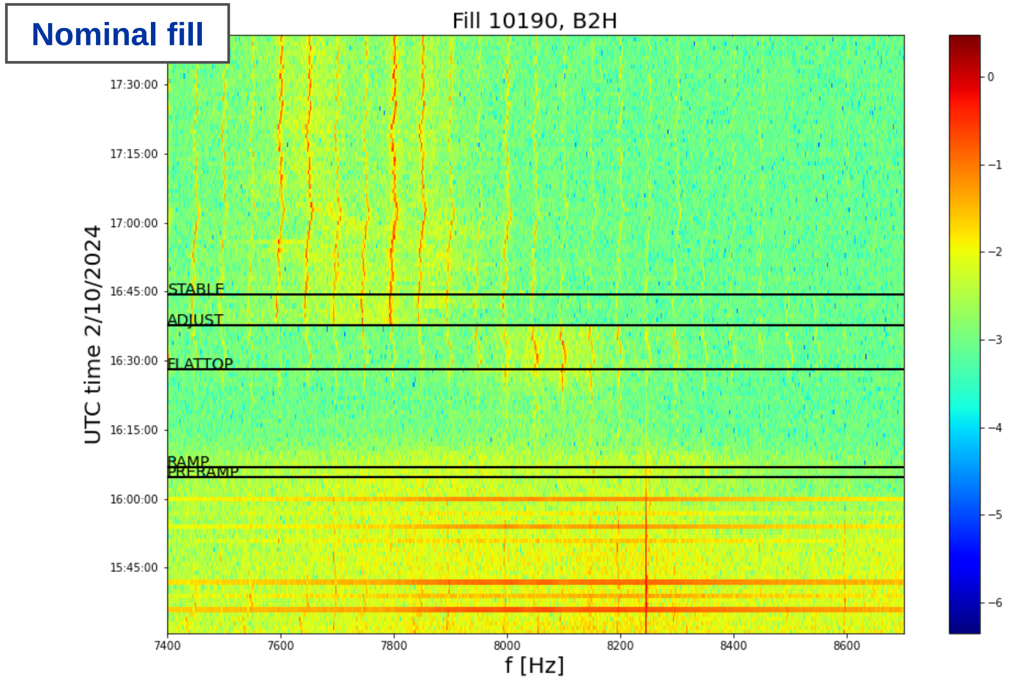


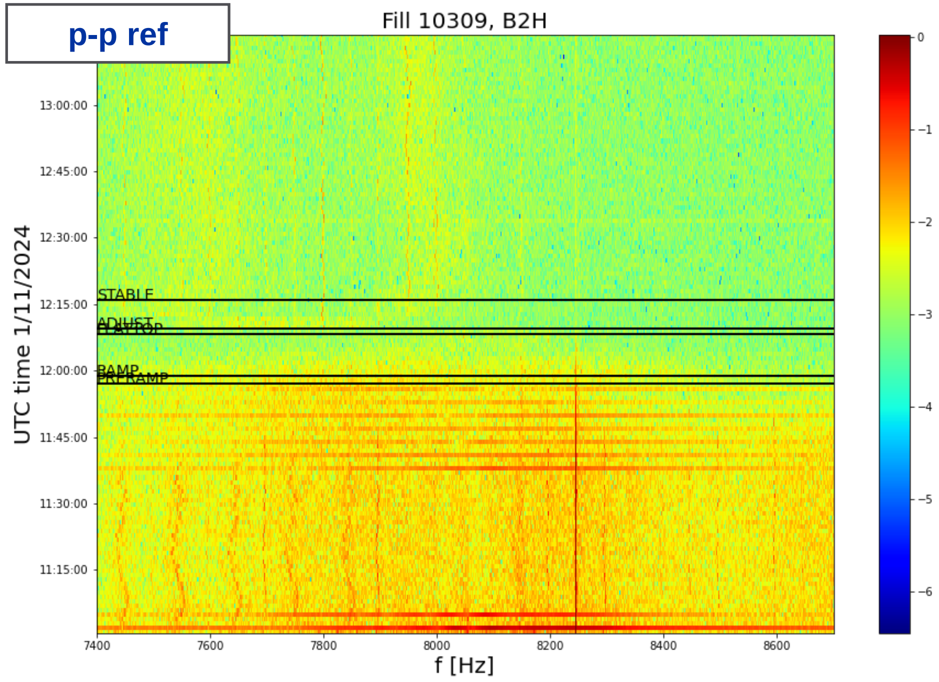
50 Hz in the beam, normalized

50 Hz mains

LHC observations: Power supply ripple

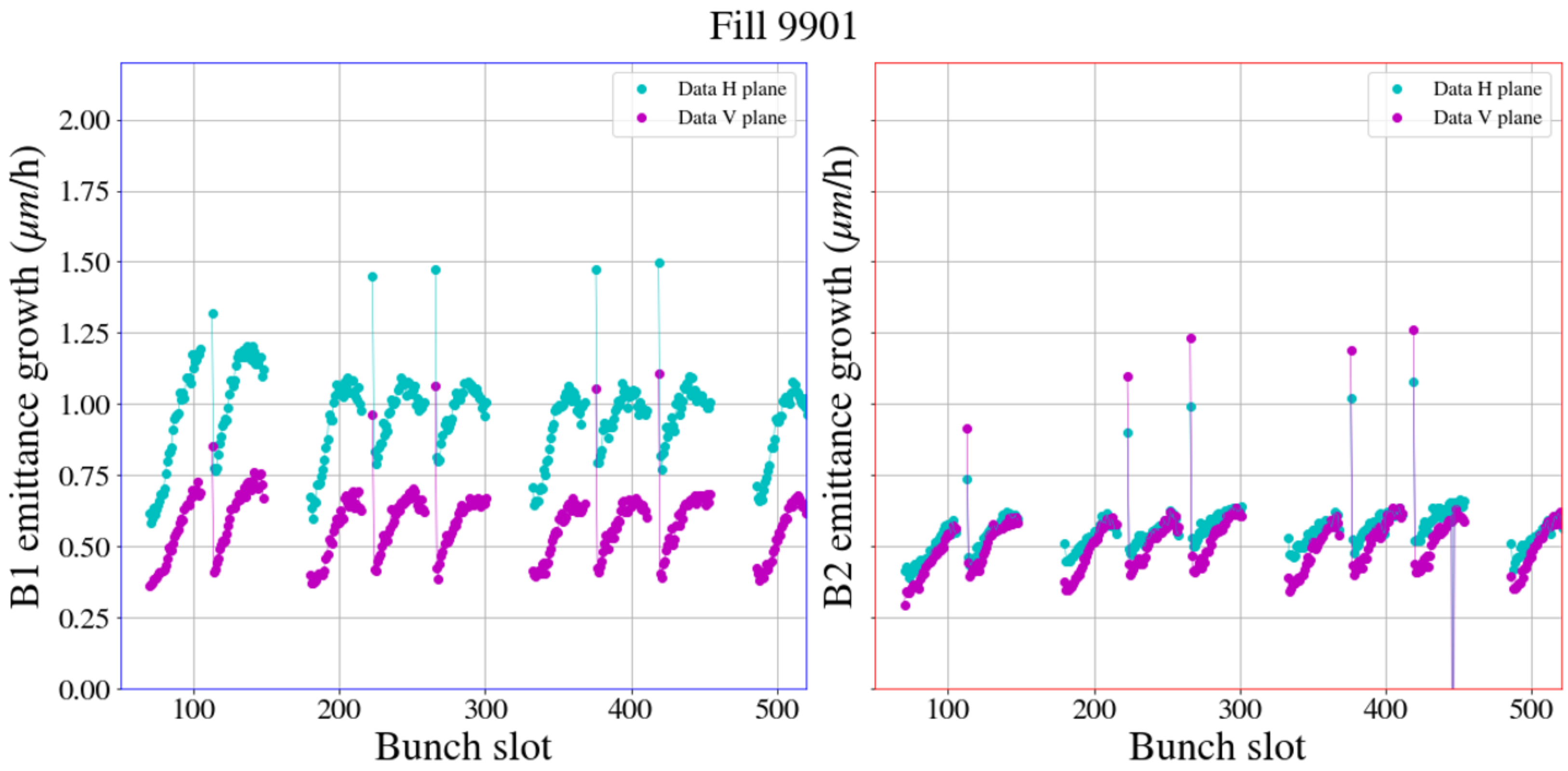
- Origin of high-frequency 8 kHz cluster is **not understood**:
  - Clear **amplitude increase at the end of the ramp** when reaching 6.8 TeV.
  - Sensitivity to tune trims consistent with dipolar excitations.
  - Significantly attenuated amplitude during p-p ref Run (2.68 TeV).
  - Impact on performance is unclear, reproducible fill-by-fill.





LHC observations: Emittance growth at injection

- Emittance growth mechanism at injection **not fully understood**:



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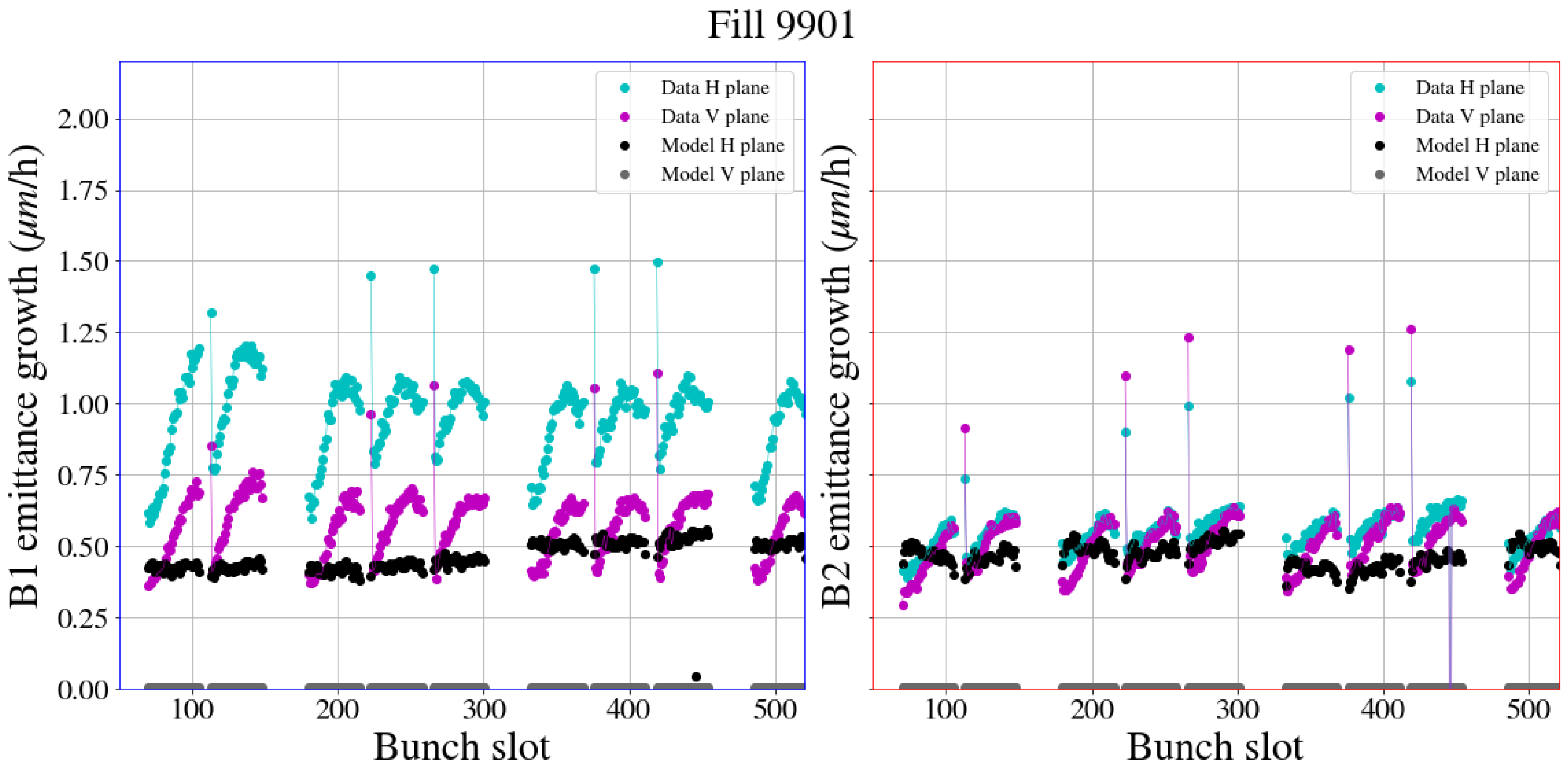


LHC observations: Emittance growth at injection

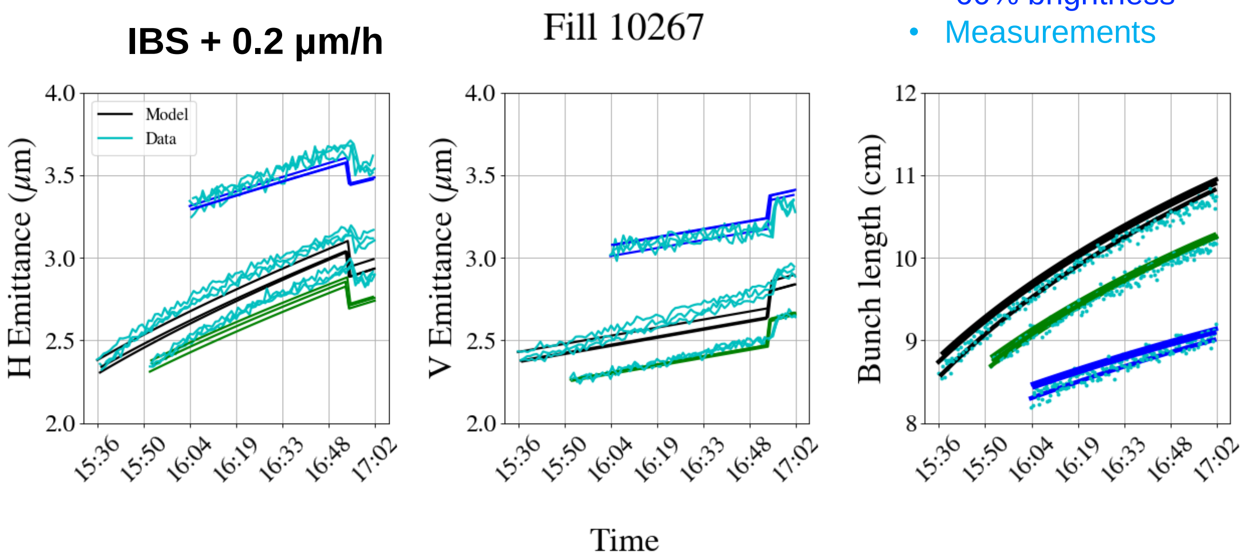
- Emittance growth mechanism at injection **not fully understood**.
  - Comparison of measured emittance growth & bunch length evolution against theoretical IBS model.

<u>Horizontal plane:</u>

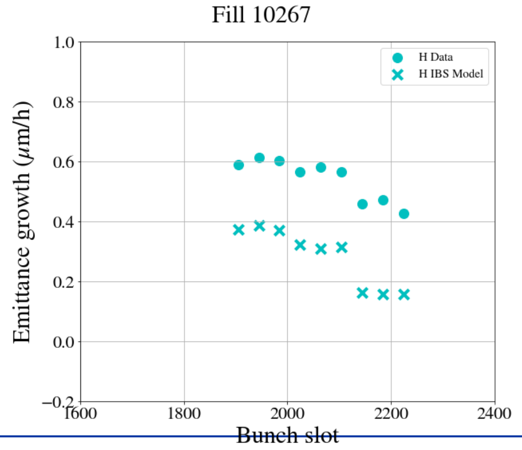
- Systematically larger in B1H: ~0.6 μm/h in addition to e-cloud:
  - 0.4 μm/h from IBS.
  - 0.2 μm/h of unknown origin:
    - even with single bunches.
    - brightness independent.

- Max. brightness
- -20% brightness
- -60% brightness
- Measurements

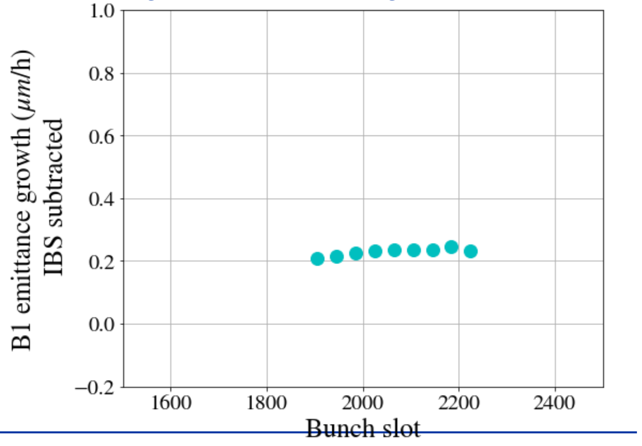
IBS + 0.2 μm/h



o Measured emittance growth for H & V
x IBS model emittance growth for H & V



Emittance growth in H with unknown origin after subtracting IBS contribution



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Horizontal plane:

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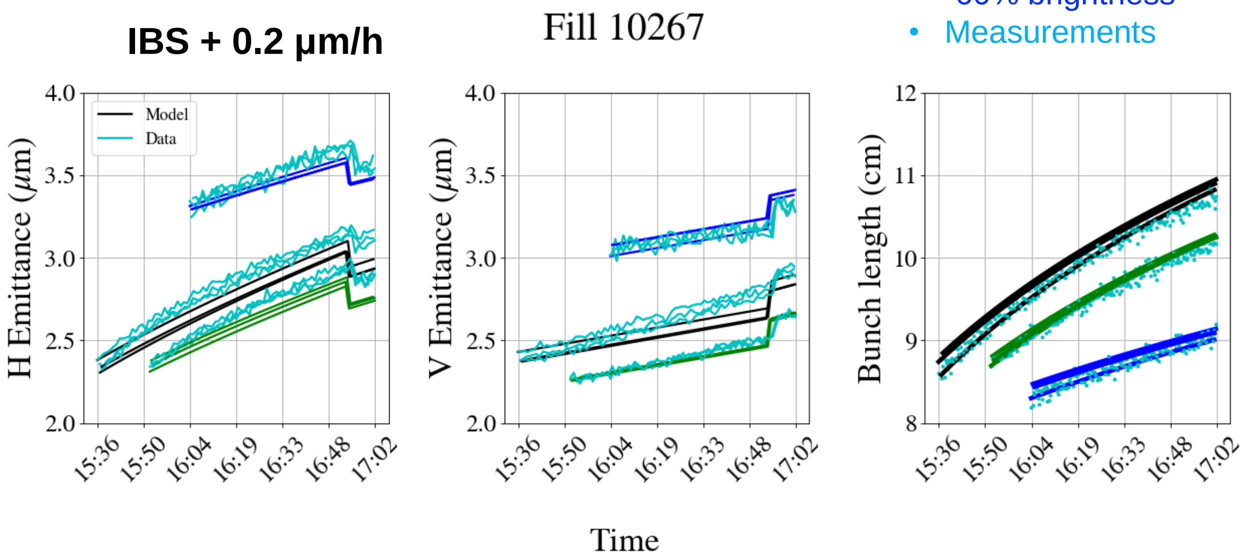
  - 0.4 μm/h from IBS.
  - 0.2 μm/h of unknown origin:
    - even with single bunches.
    - brightness independent.

Vertical plane:

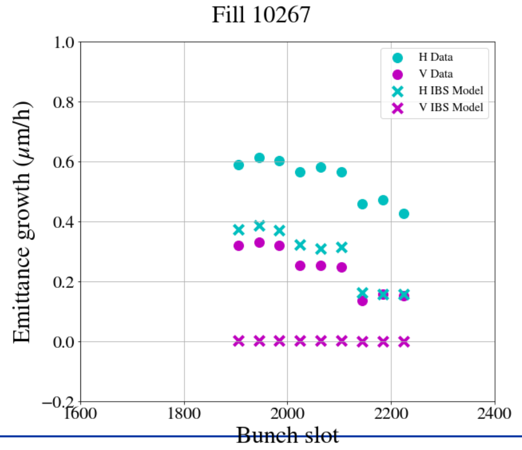
- ~0.1-0.3 μm/h in addition to e-cloud (B1 & B2).
  - Low vertical dispersion & good coupling control → small IBS contribution.
  - Measurements suggest some brightness dependence → possibly underestimating IBS or emittance exchange with horizontal in the modeling.
  - Linear increase of emittance over time.

IBS + 0.2 μm/h

- Max. brightness
- -20% brightness
- -60% brightness
- Measurements



o Measured emittance growth for **H** & **V**
x IBS model emittance growth for **H** & **V**



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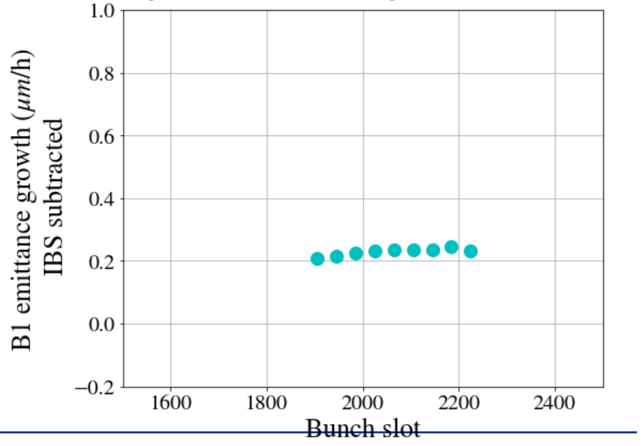
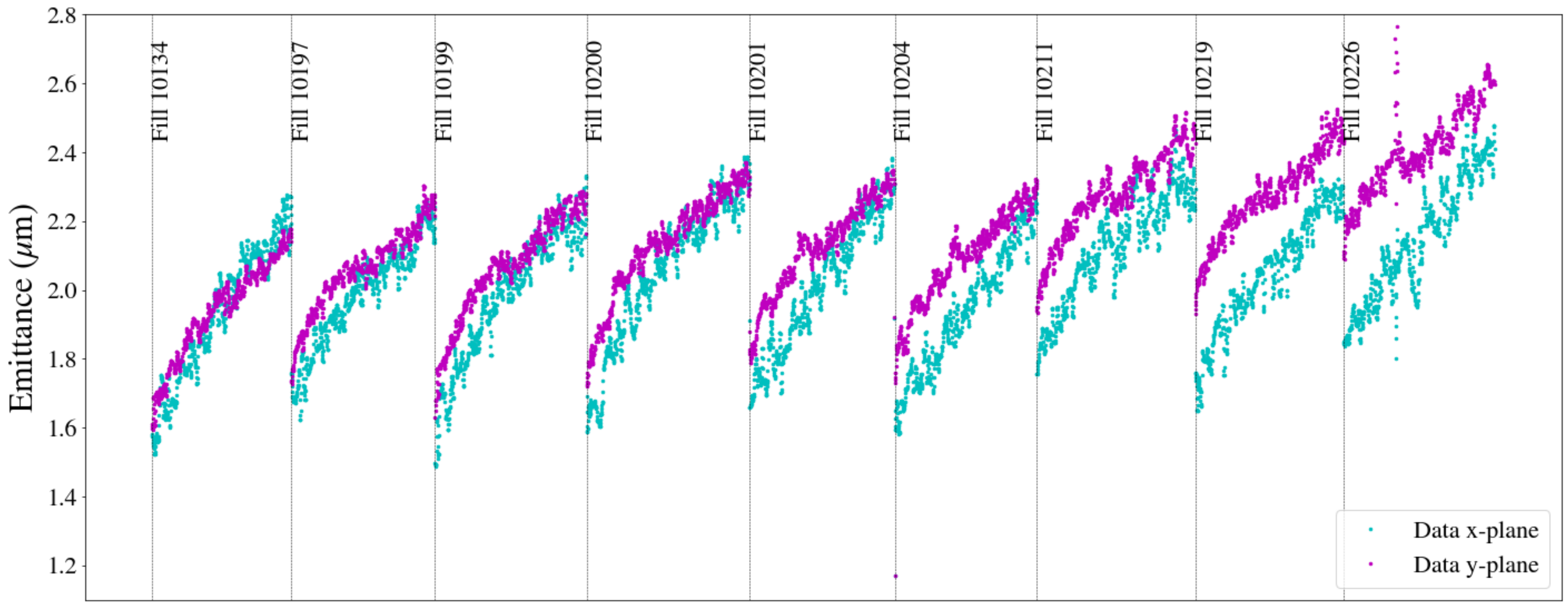


LHC observations: Emittance growth at collisions

- Emittance growth of unknown origin also during collisions:
  - Cannot be fully explained by IBS models.
  - Vertical emittance expected to be shrinking due to SR.



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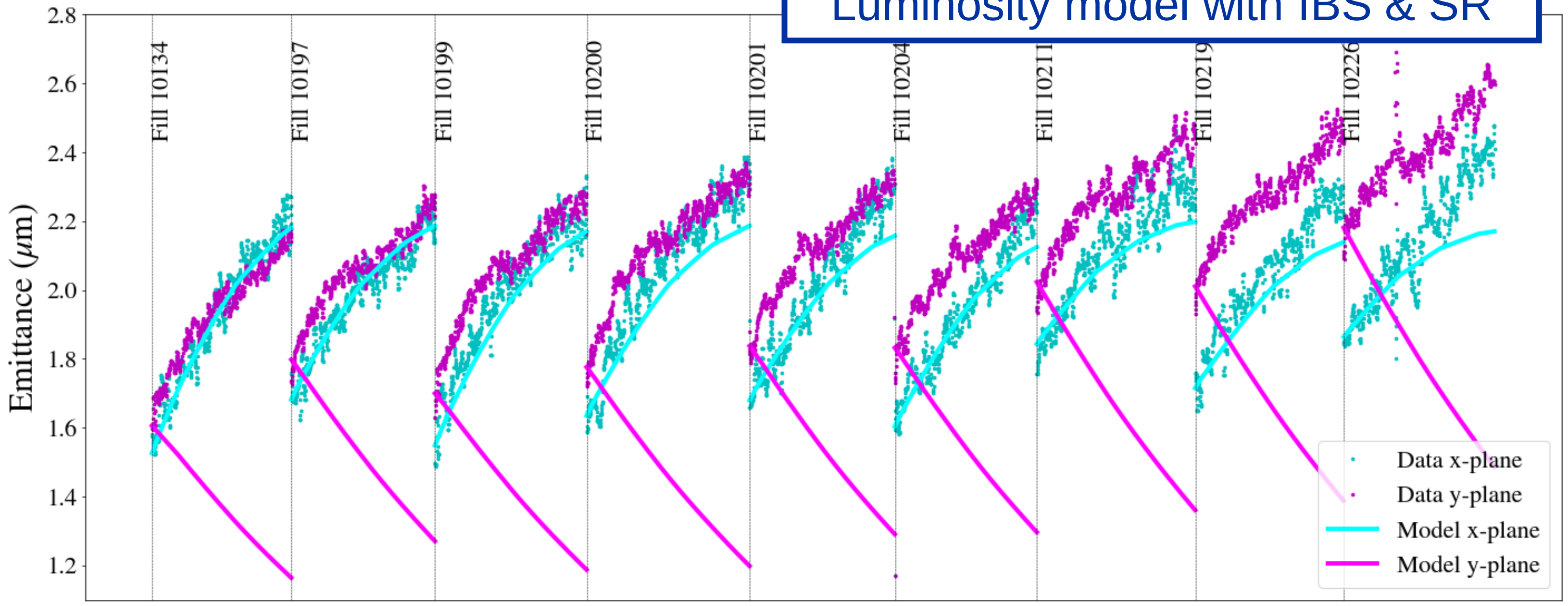
Luminosity model with IBS & SR



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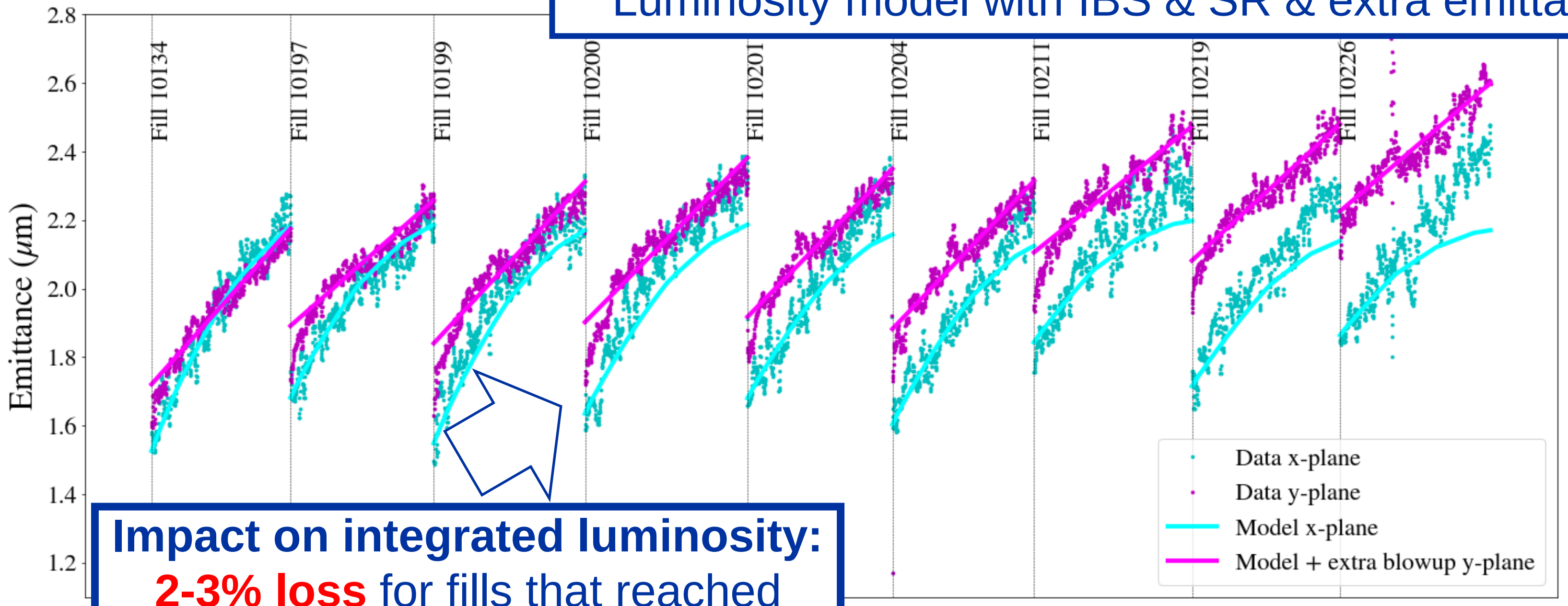
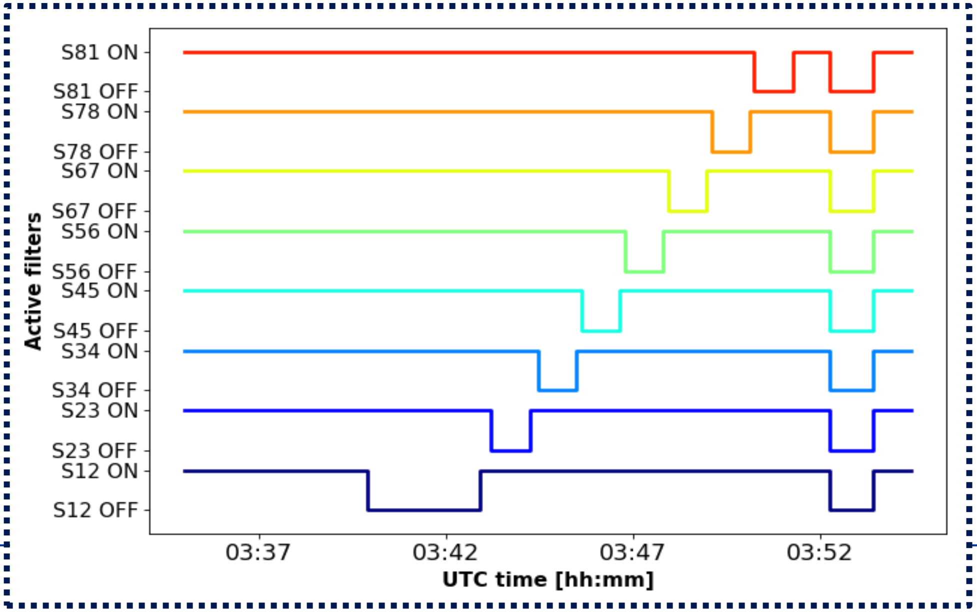
Luminosity model with IBS & SR & extra emittance growth



Impact on integrated luminosity:
2-3% loss for fills that reached optimal fill length & τ=2.5 h

Tests with main dipole PC active filters

- 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.



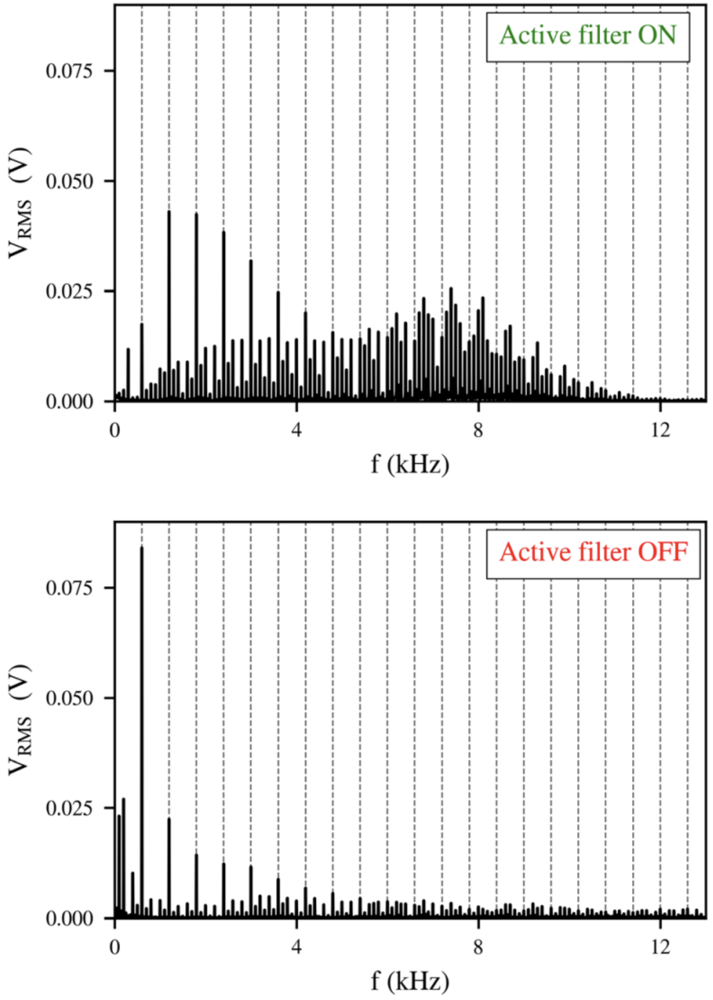
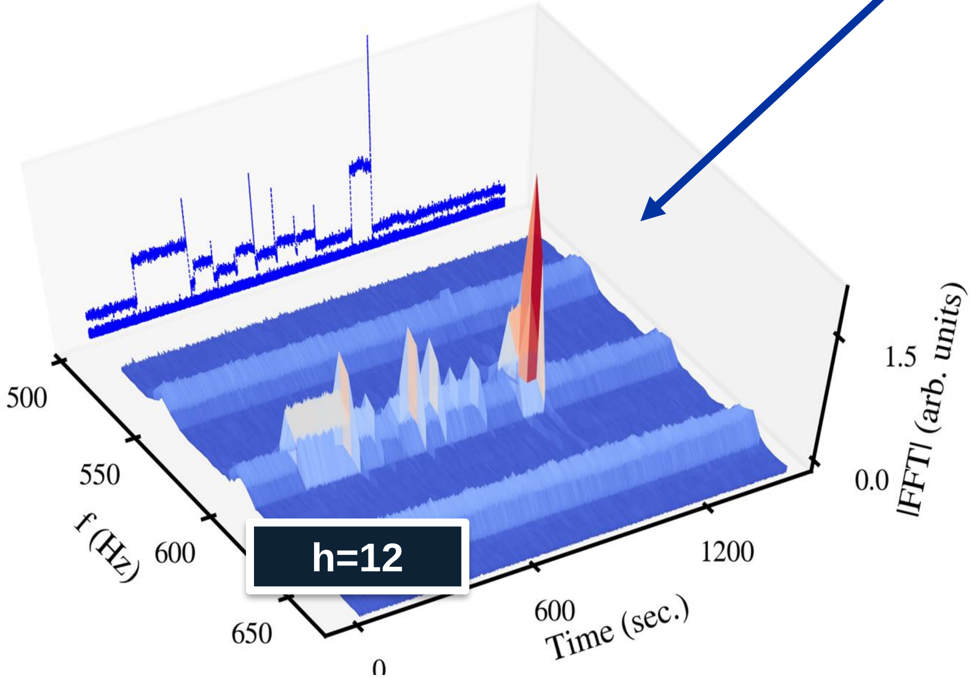
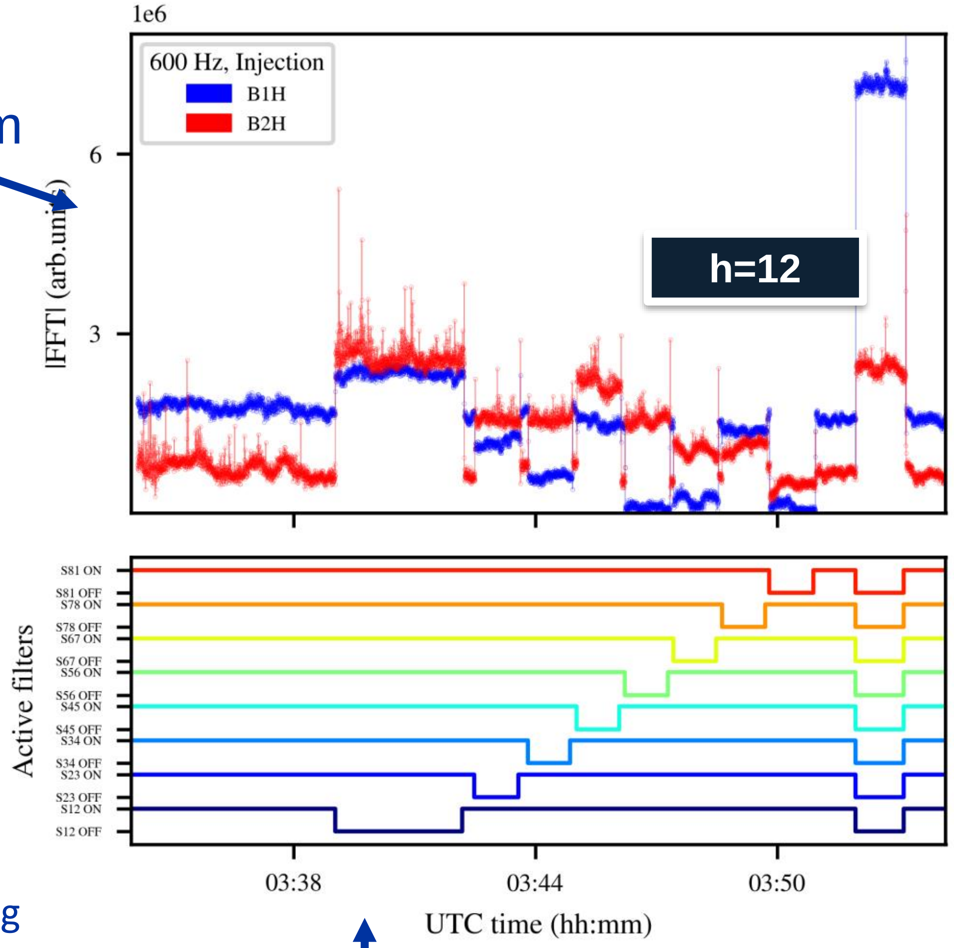


FIG. 16. Voltage spectrum of the power supply of the main dipoles in the LHC arcs (Sector 1-2) with the active filter enabled (top) and disabled (bottom). The vertical gray lines represent the multiples of 600 Hz.

Tests with main dipole PC active filters

Beam spectrum



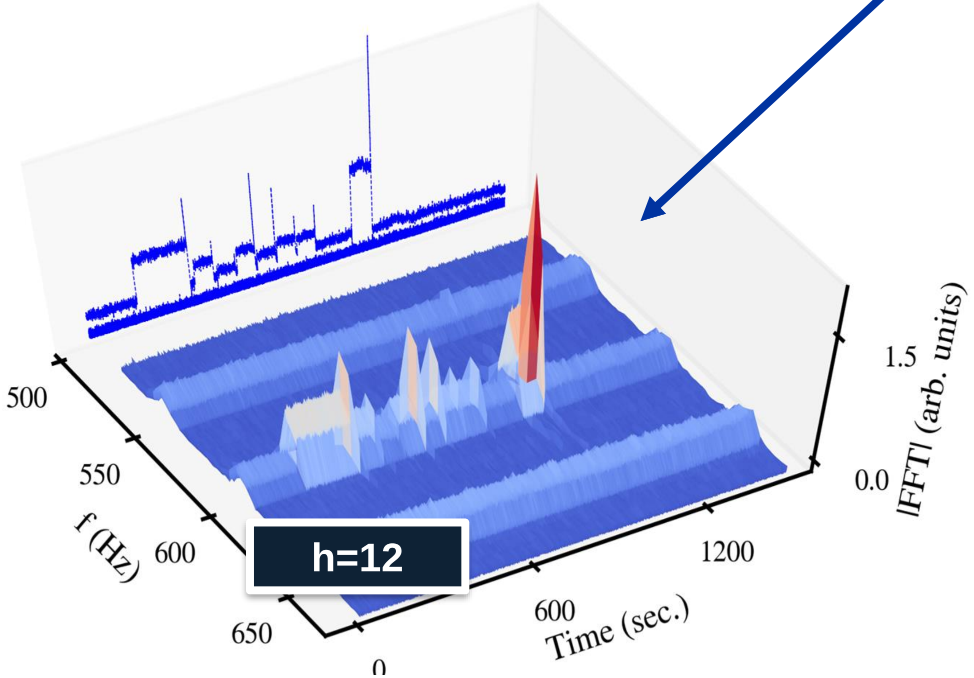


Status of active filter per sector

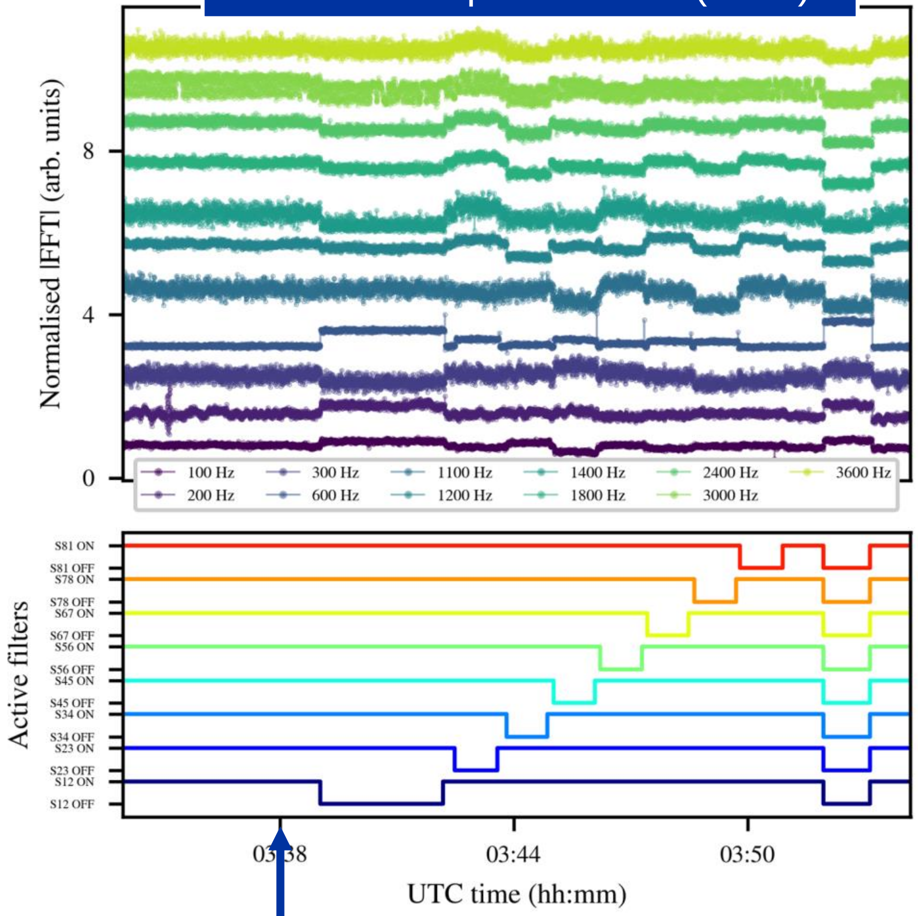
- Clear impact on low-frequency cluster when enabling & disabling active filters.
- All eight power supplies contribute to this effect → power supply ripple distributed in the whole ring.
- For the same harmonics, different response between Beam 1 & Beam 2→ attributed to their different phase advances.

Tests with main dipole PC active filters

Beam spectrum



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



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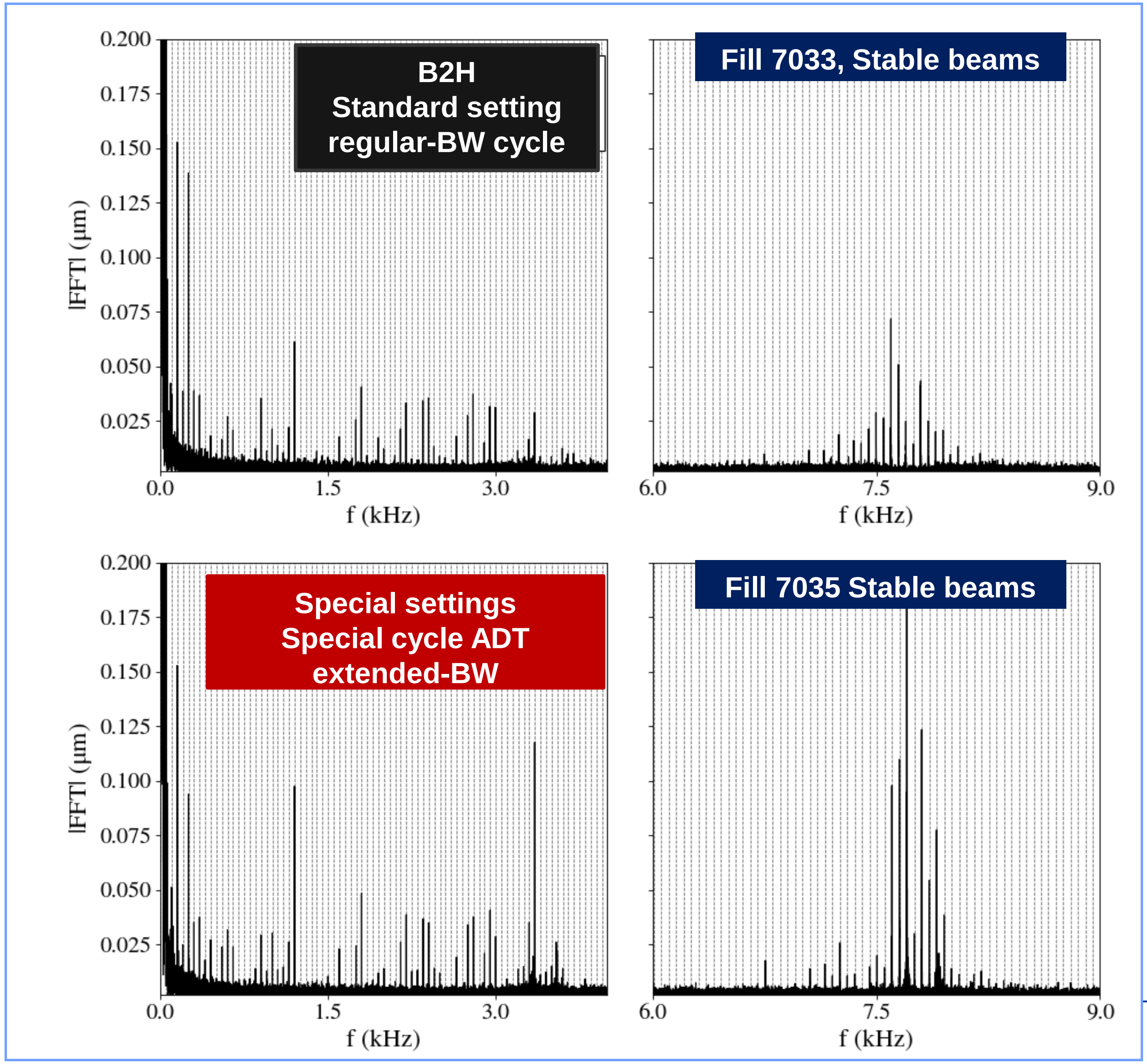
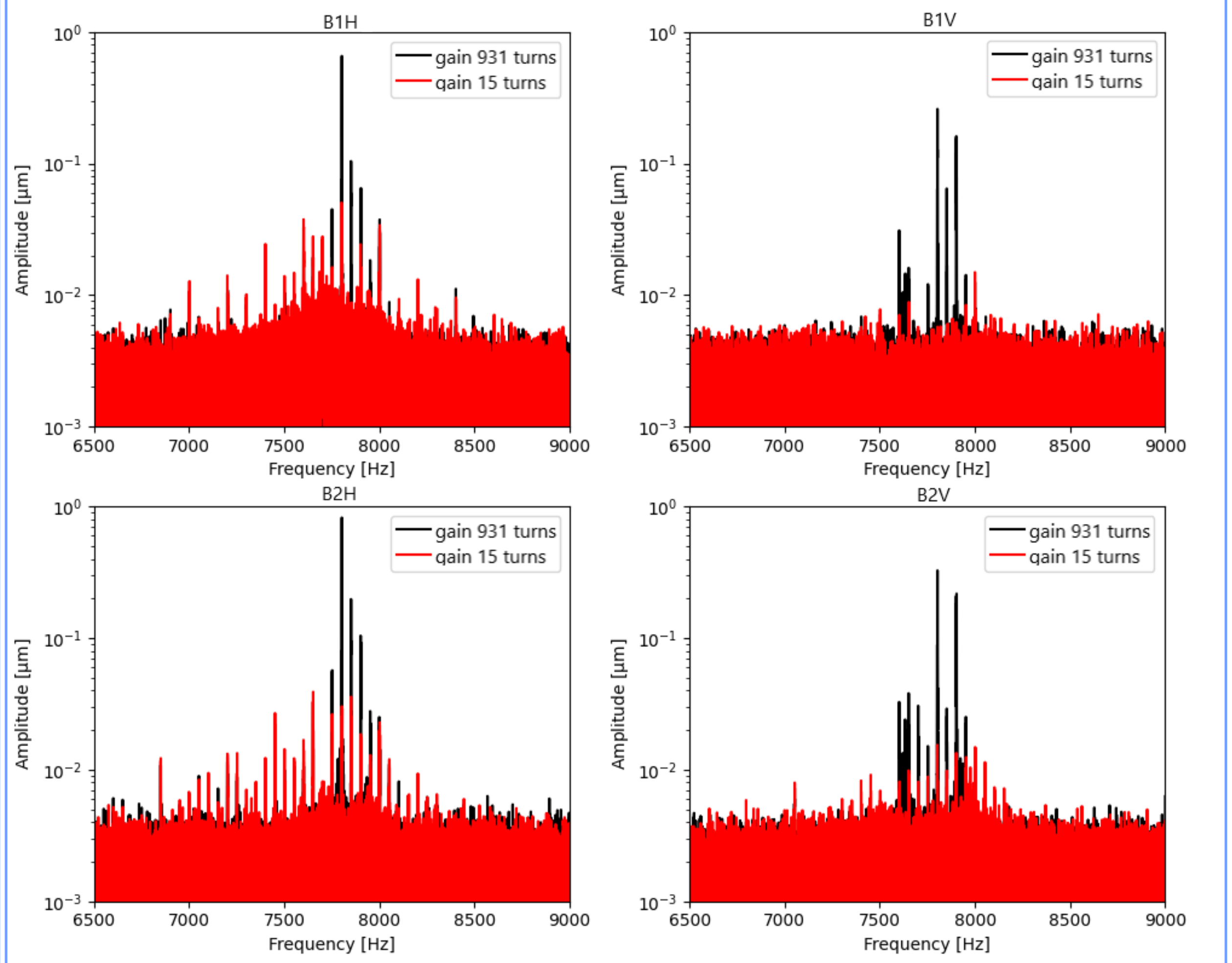
Impact of transverse damper

Run 2



Run 3

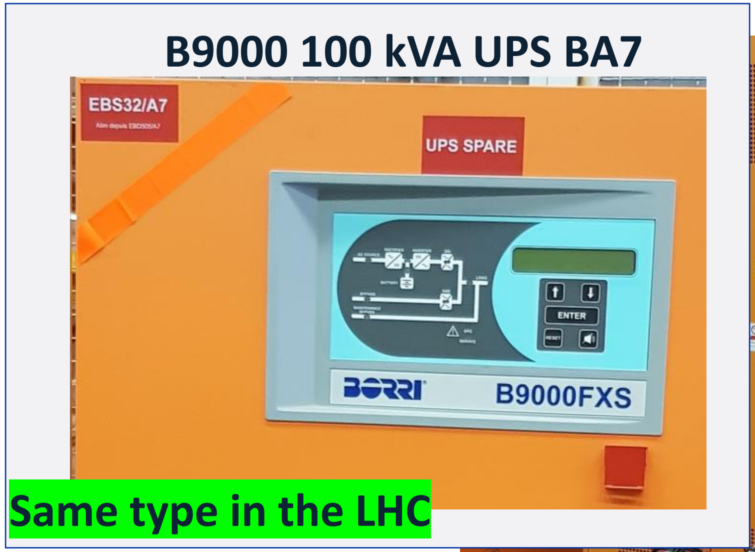


- Increasing the transverse damper gain is beneficial: Clear reduction of harmonics’ amplitude

Measurements of UPS noise

1. Measurements of UPS output spectrum (same type as the ones in the LHC) to determine if possible candidate for high-f cluster:
   I. To determine if UPS noise spectrum contains 50 Hz harmonics around 8 kHz as observed on the LHC beam spectrum.
   II. To determine if spectral components are synchronized to the mains as observed on the LHC beam spectrum.

2. Changed mode of operation of a few UPSs during dedicated measurements in the LHC with beam.



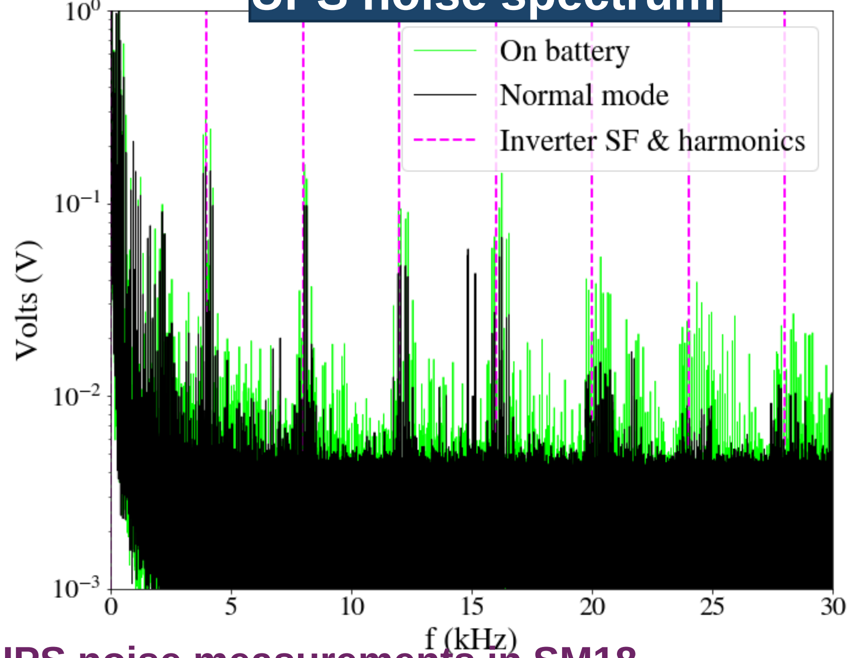
Measurements of UPS noise

Measurements of spare UPS in SM18 thanks to EN/EL: UPS output voltage spectrum very similar to transverse LHC beam spectrum in terms of ripple→ **good candidate to study**

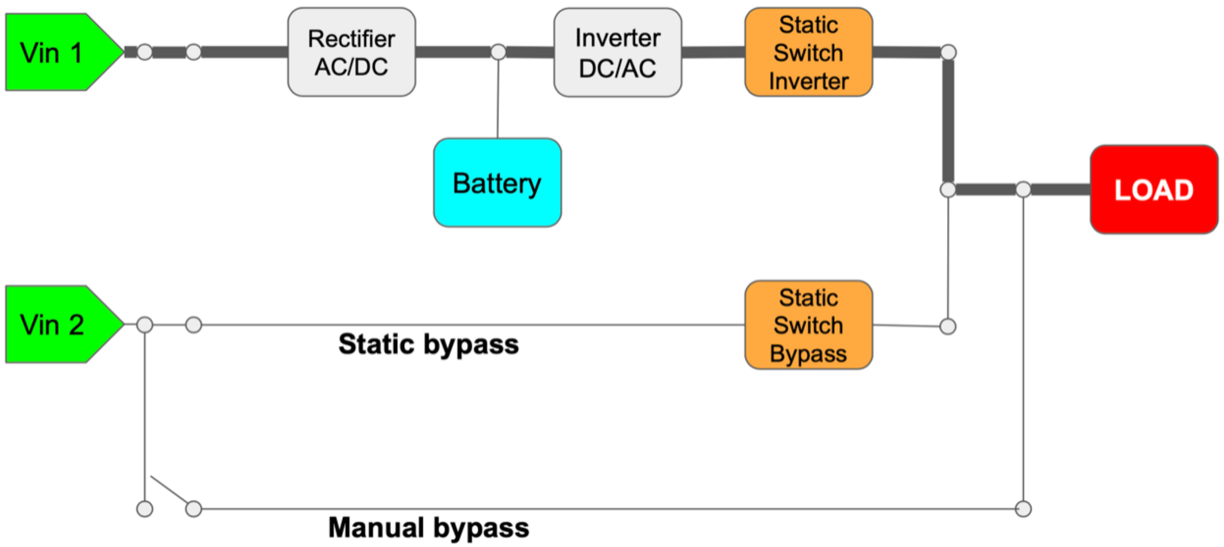
Different modes of UPS operation:

1. Nominal
2. On battery
3. Static & manual bypass

UPS noise spectrum



UPS modes of operation



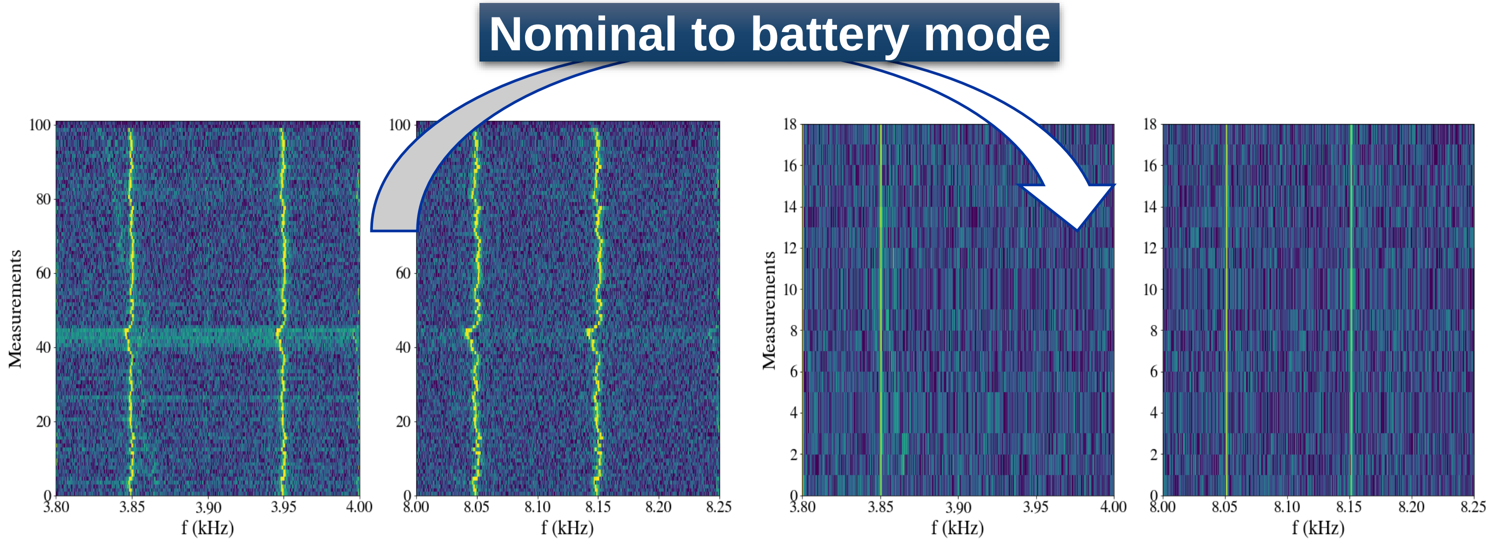
Link for UPS noise measurements in SM18

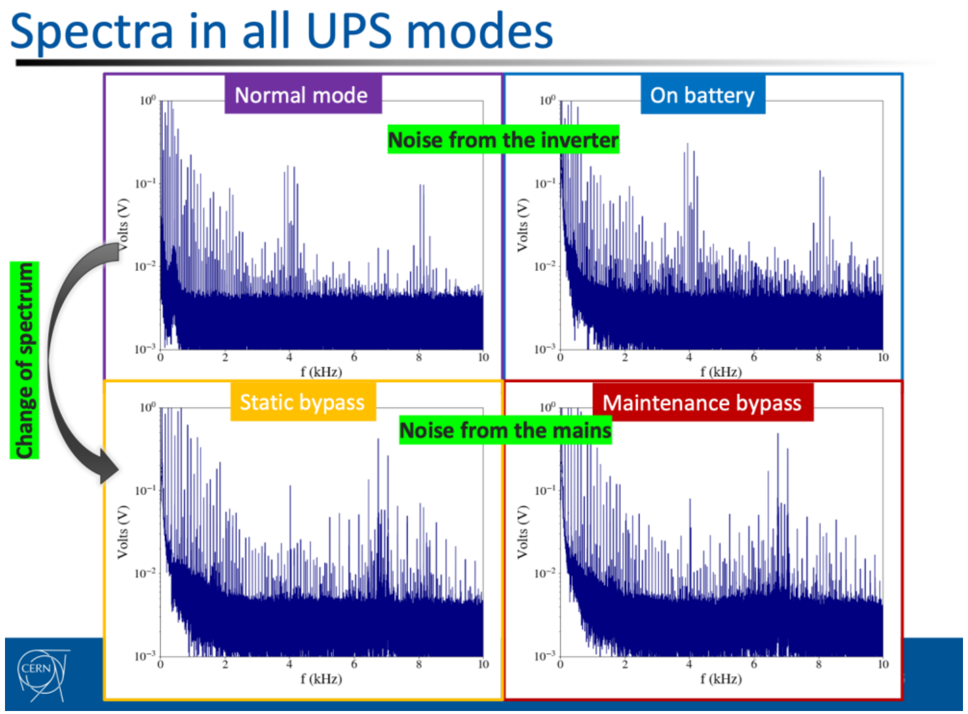
Measurements of UPS noise

Changing mode of UPS operation → different UPS output voltage spectrum → **Can these changes be detected on the beam spectrum as well?**

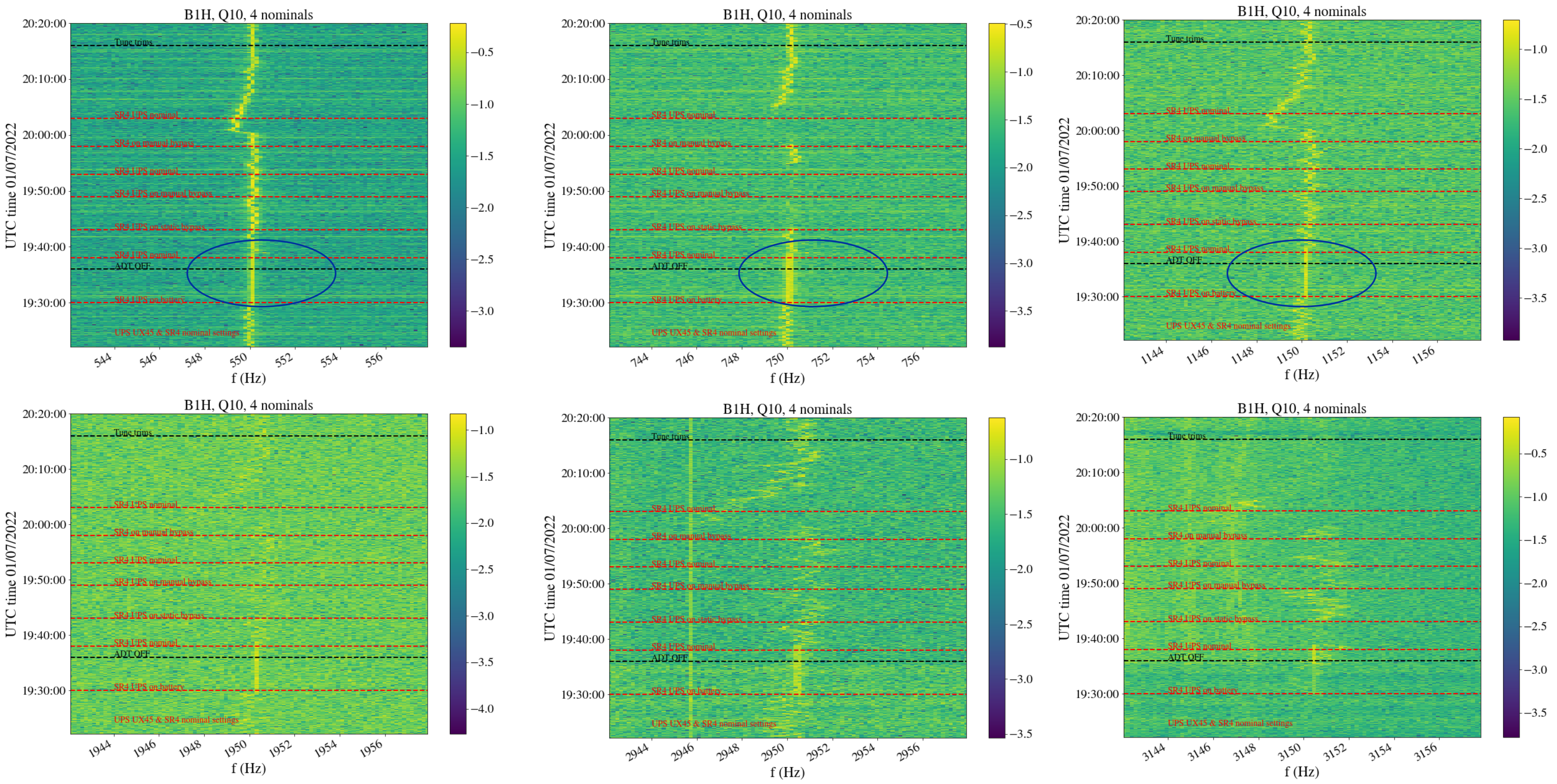
On battery: Clear change of UPS spectrum (**loss of synchronization with mains**), **can be easily detected**.

Bypass: Change of UPS spectrum (change of harmonics' amplitude), **not so easy to detect**.



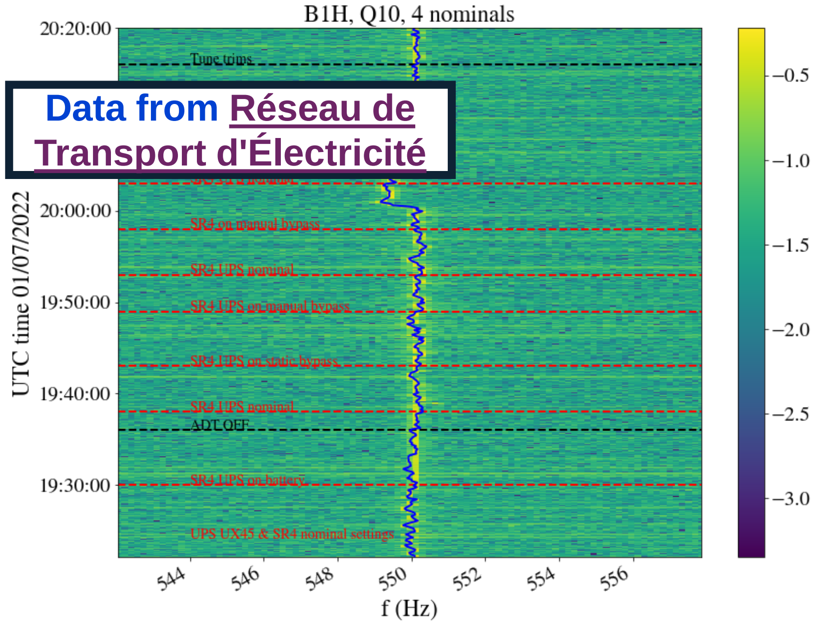


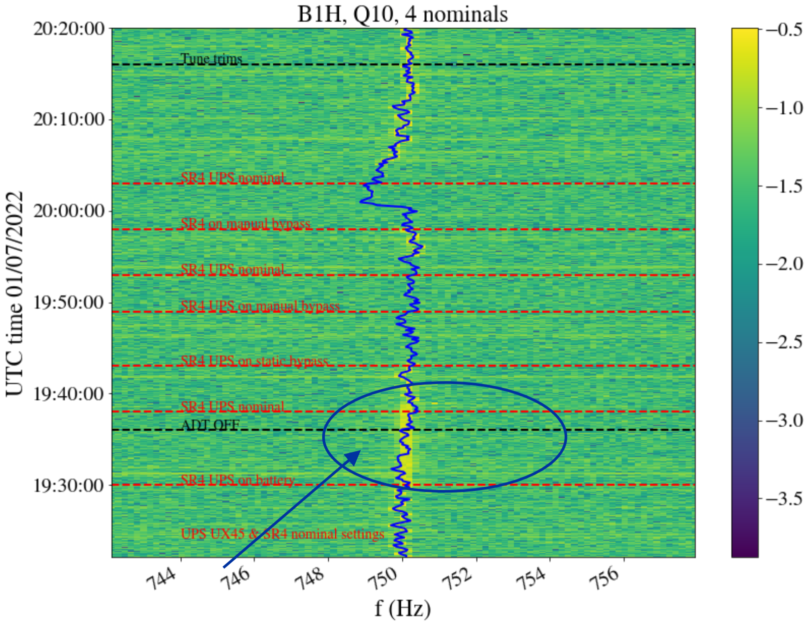
Beam spectrum during SR4 UPS modifications

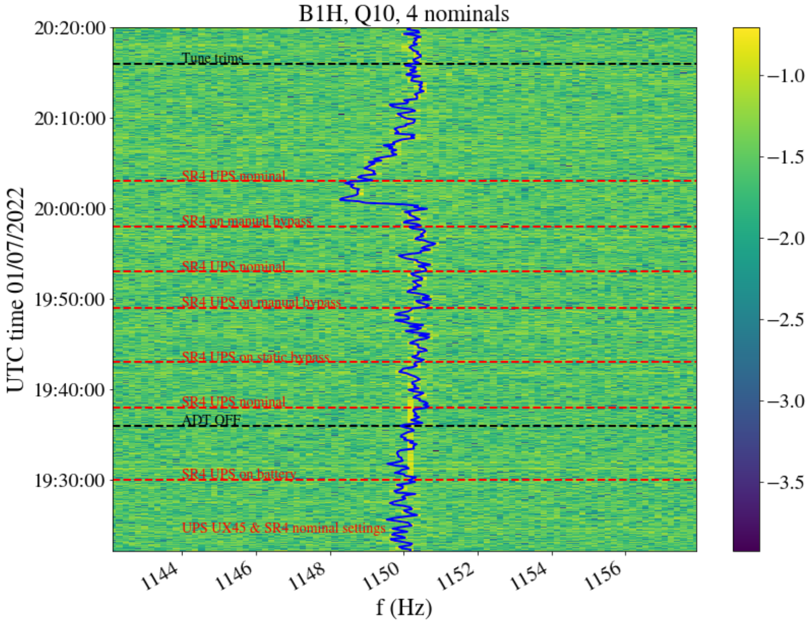


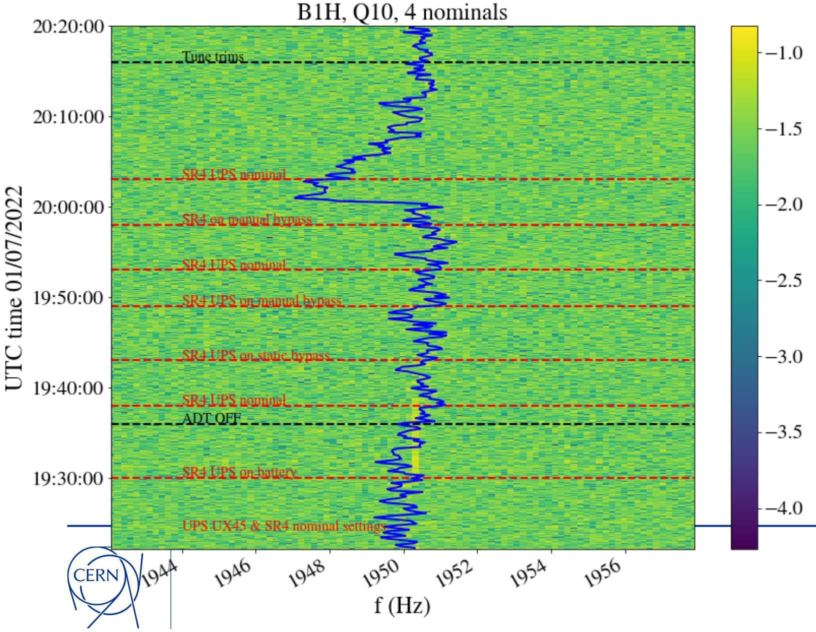
Beam spectrum during SR4 UPS modifications

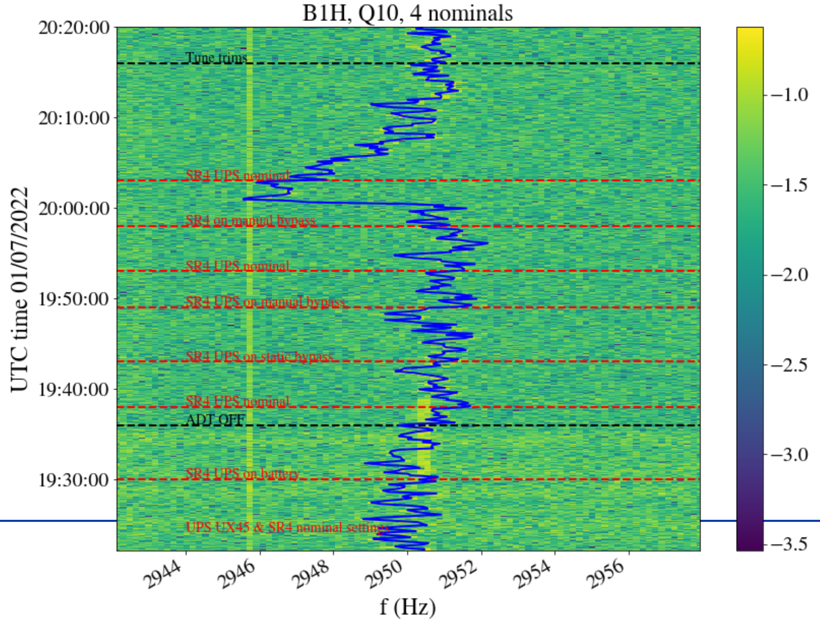
Data from Réseau de Transport d'Électricité

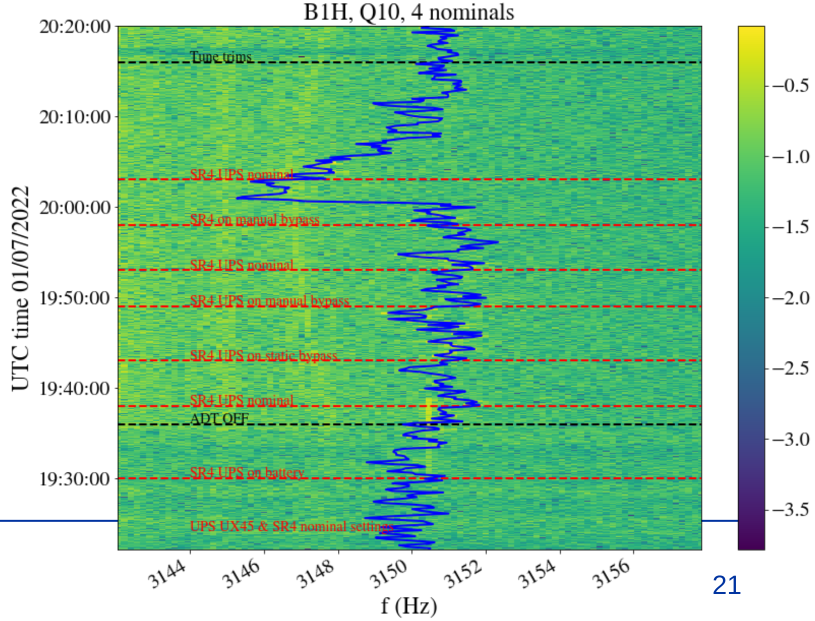






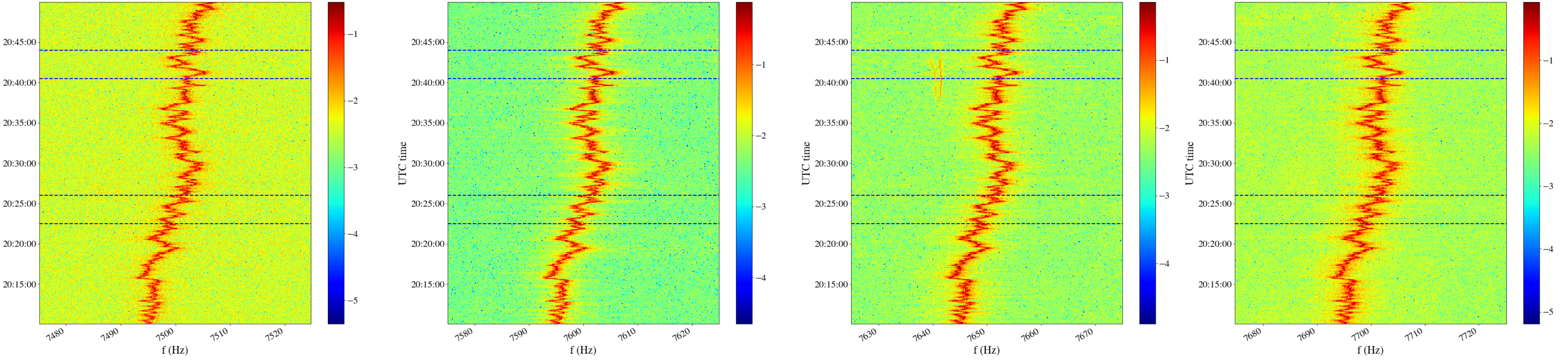






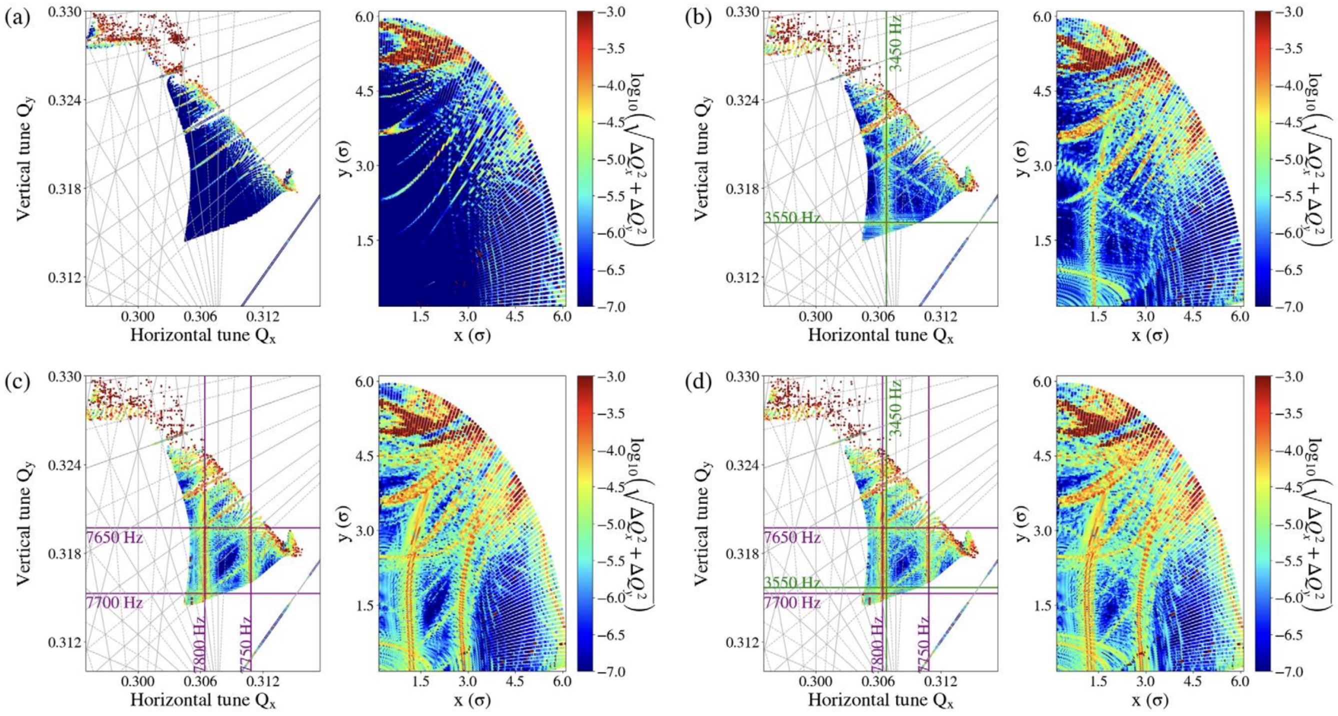
Beam spectrum during SR4 UPS modifications

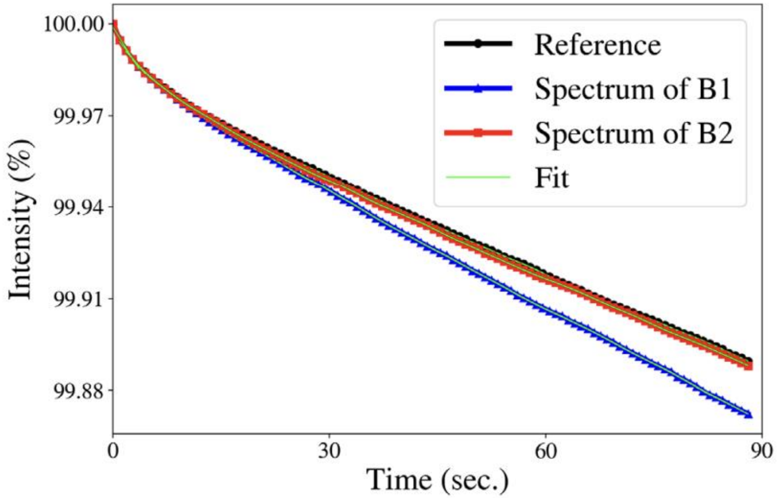
- No loss of synchronization during tests



Impact on beam performance

- Simulations reproducing the ripple spectrum observed in operation indicate that the high-f cluster has an impact on performance.



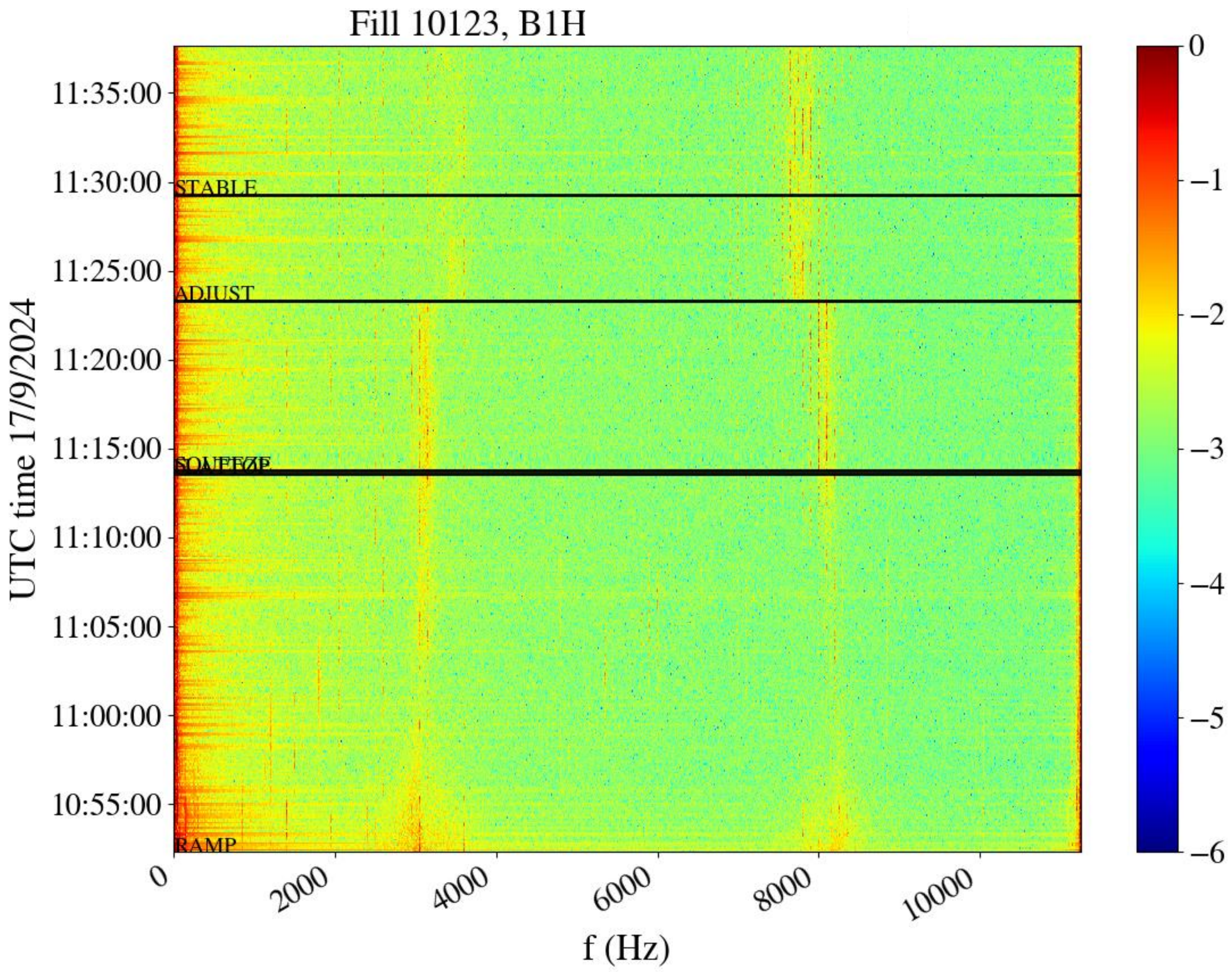


Conclusions

- **50 Hz dipolar power supply ripple** systematically observed in **transverse LHC beam spectrum** up to high frequencies (~8 kHz).
- Origin of harmonics **up to 3.6 kHz** are the **power converters of the main dipoles**. Active filters tests demonstrated that frequencies up to 3.6 kHz are passing from the power converter to the beam.
- Source of high-frequency harmonics (~8 kHz) remains unknown. Their amplitude significantly increases at the **end of the ramp** and spectrum is reproducible fill-by-fill. Did not observe **any "atypical" behavior that could pinpoint to the source.** A lower amplitude was only observed during special runs (2.7 TeV instead of 6.8 TeV)
- **UPS** noise signature matches beam observations: 50 Hz harmonics around 4 kHz & 8 kHz. Dedicated experiments switching some UPS in SR4 to "battery" mode affected only a few low-order harmonics (550, 750, 1150, 1950, 2050, 3150 Hz) only on B1, no impact (loss of synchronization to the mains) on high-f cluster. Testing all UPSs at top energy cannot be done without **remote control for UPSs** that require access. Switching to battery mode is the clearest signature to detect in the beam spectrum.
- Increasing the **transverse damper gain** reduces amplitude of harmonics.
- There is an unknown source of emittance growth at injection (brightness-independent) and during collisions, which cannot be explained by current models. It remains unclear whether this is related to power supply ripple.

Backup

LHC observations: Power supply ripple



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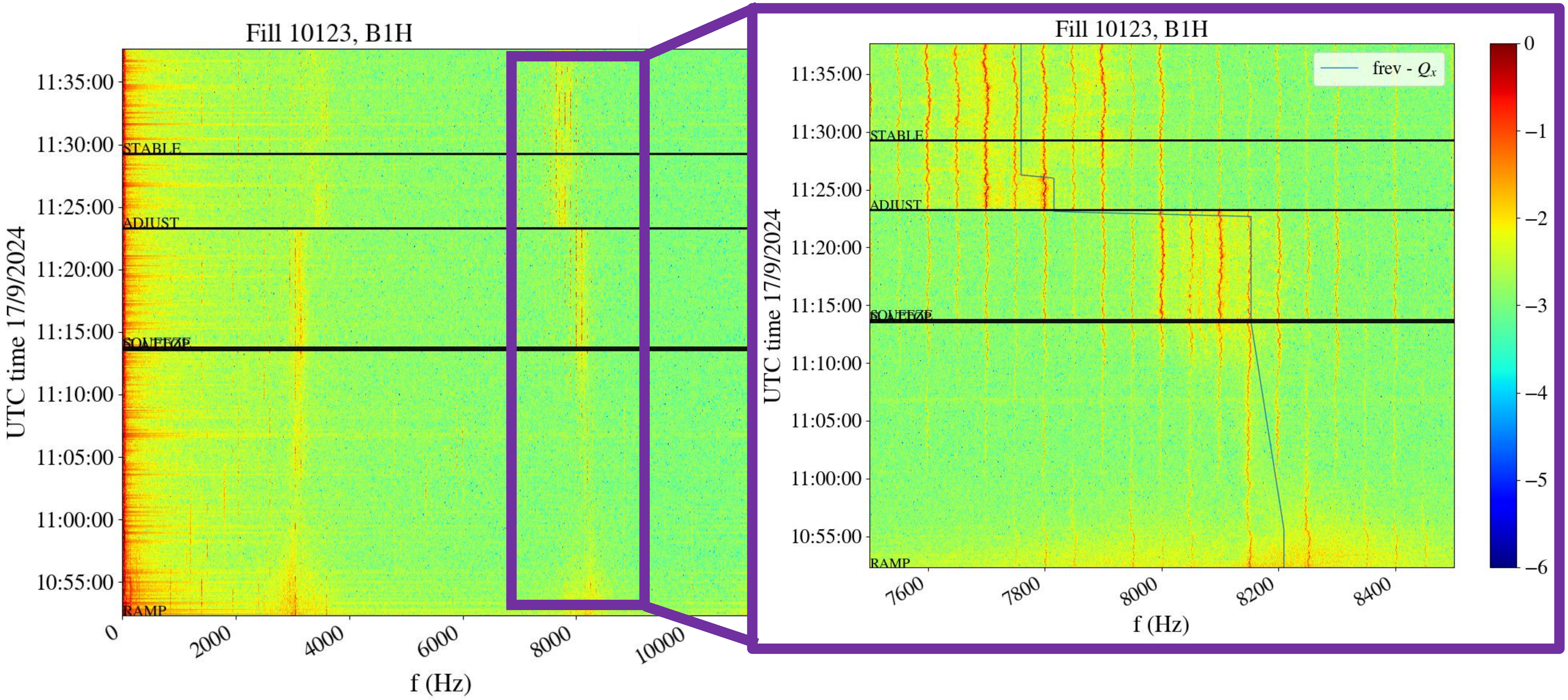
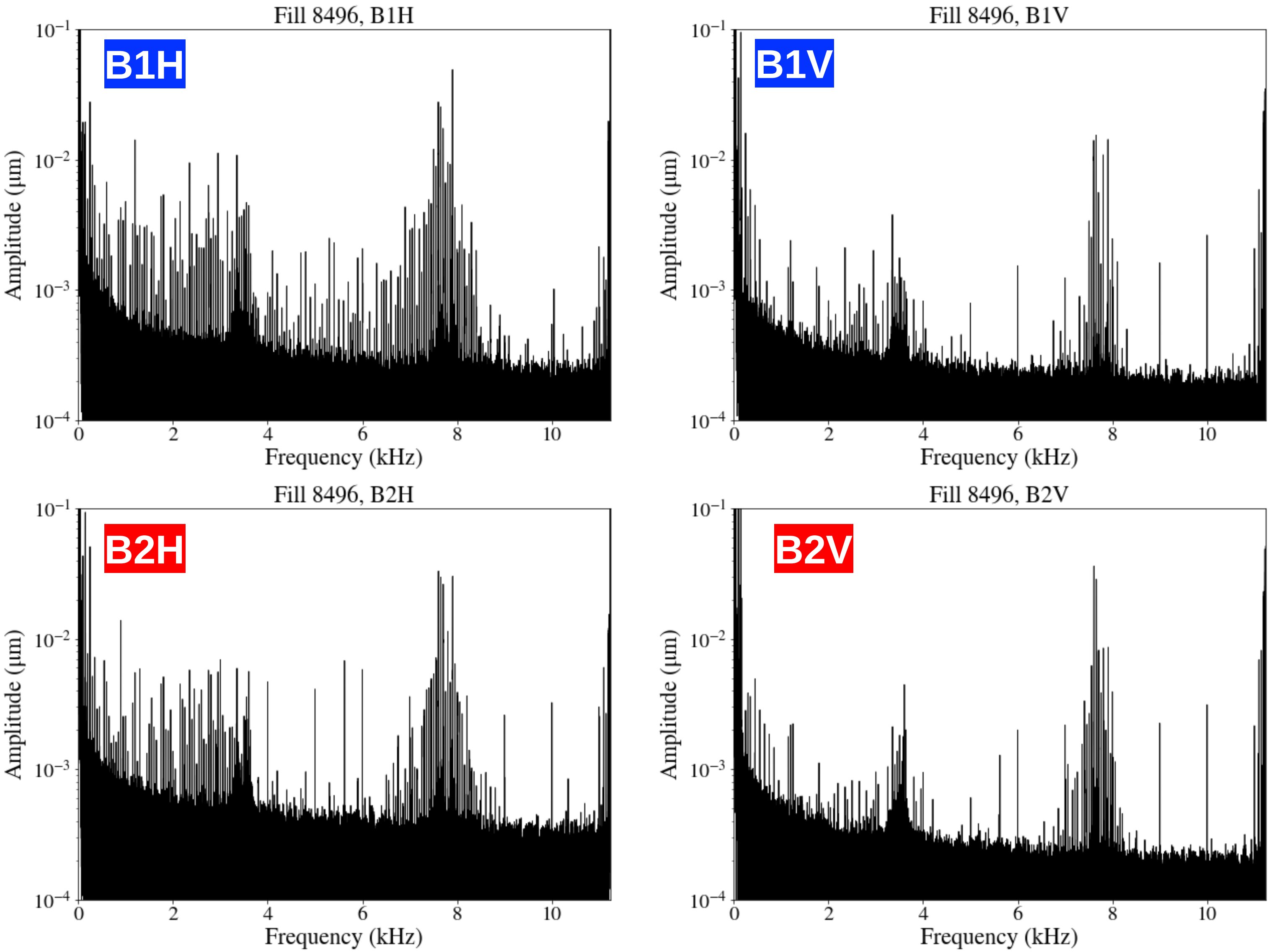


Observations in Run 3

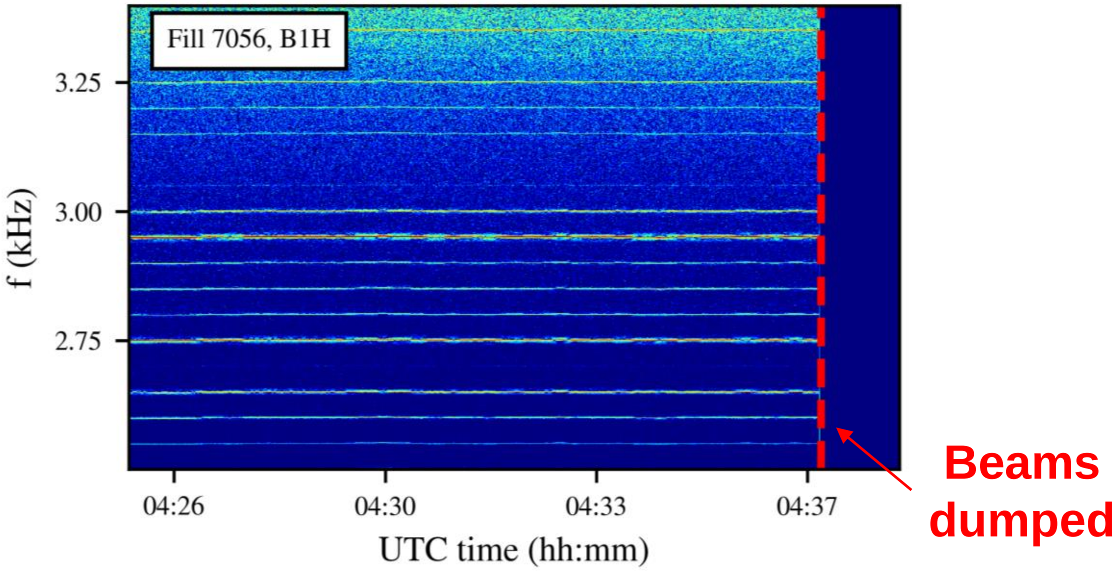
Calibrated spectrum for fill 8496, 2390 bunches, Stable beams: similar to what was considered for Run 2.

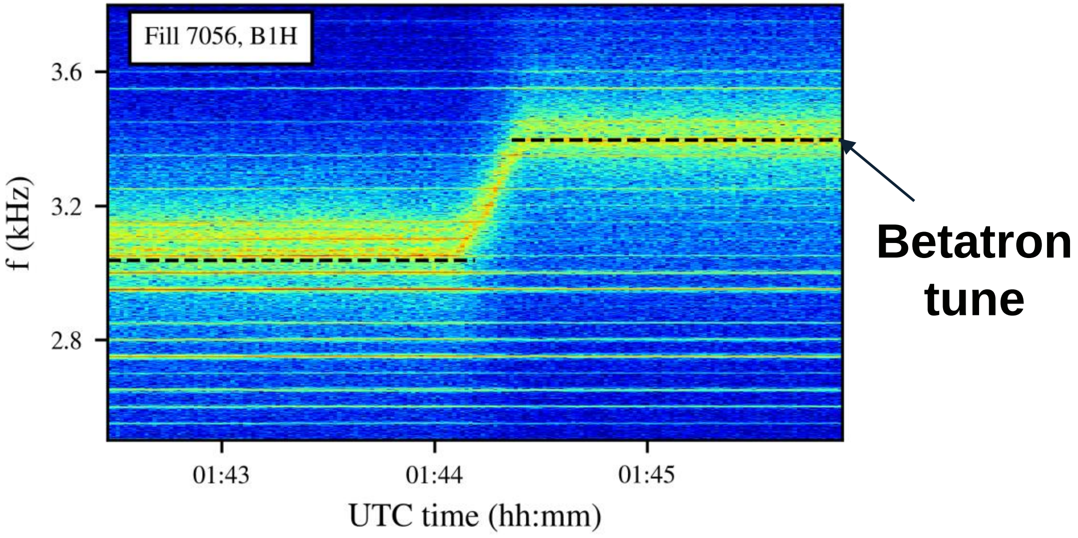


Steps for calibration:
https://codimd.web.cern.ch/s/V1pL7RIBp

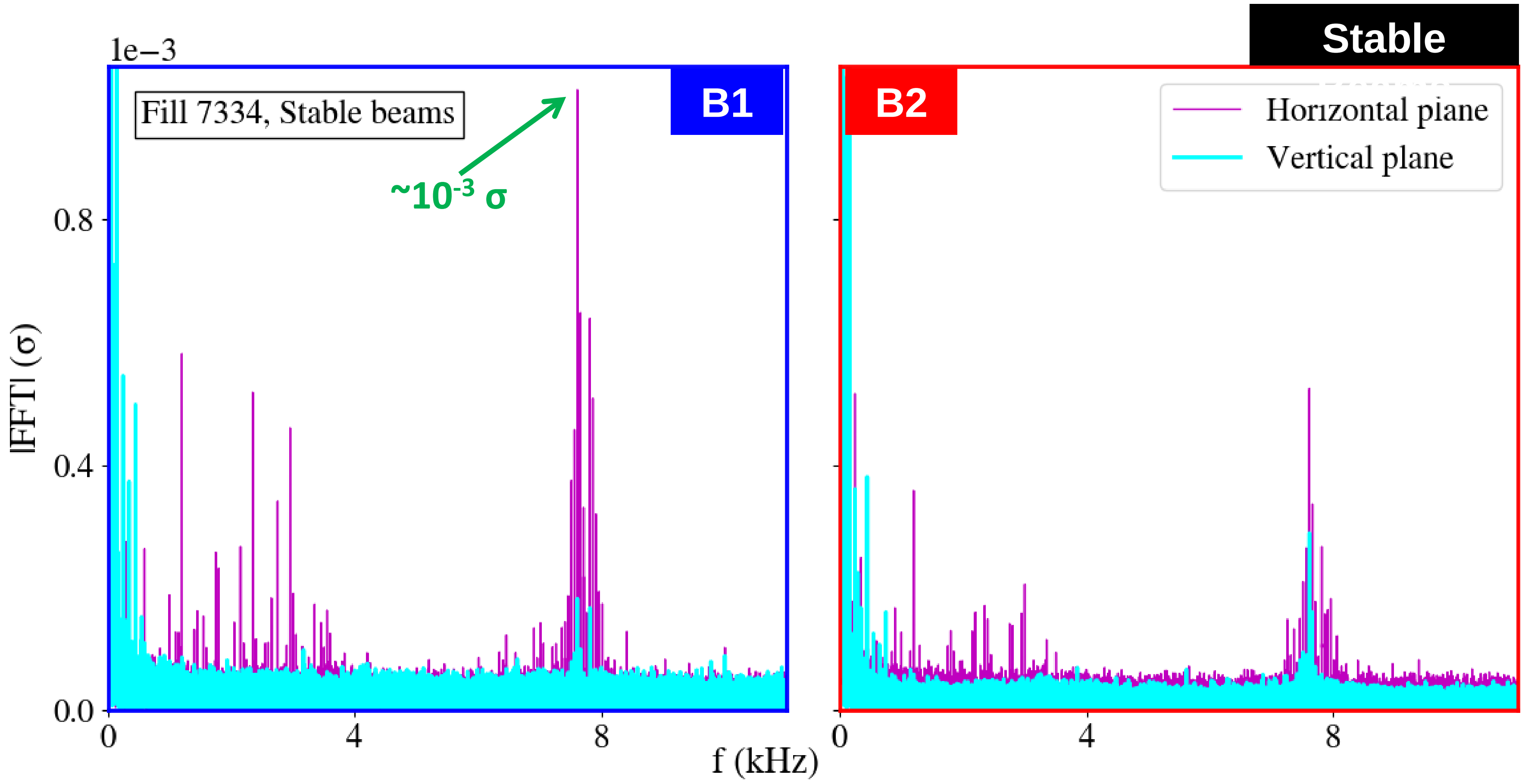
Introduction

- **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.





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**.

UPS modes

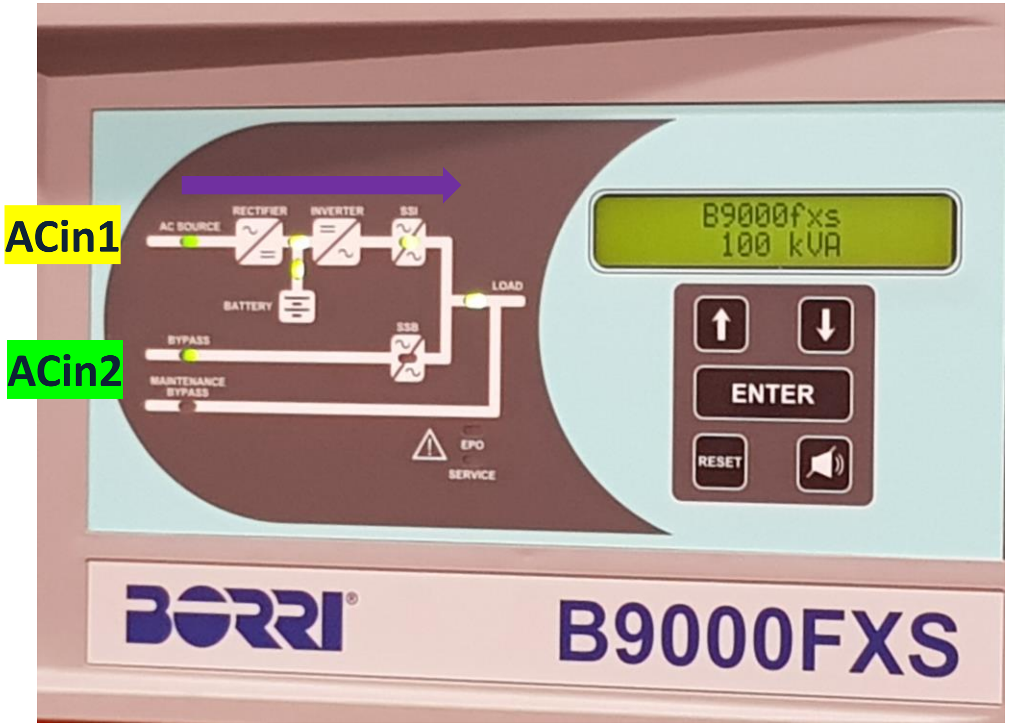
Normal mode: ACin1 → Rectifier→ Inverter→ Load

- **Synchronized** to bypass (ACin2) through internal inverter PLL.

Switching frequency (info from Borri)

Inverter: 4 kHz

Rectifier: 7.5 kHz



UPS modes

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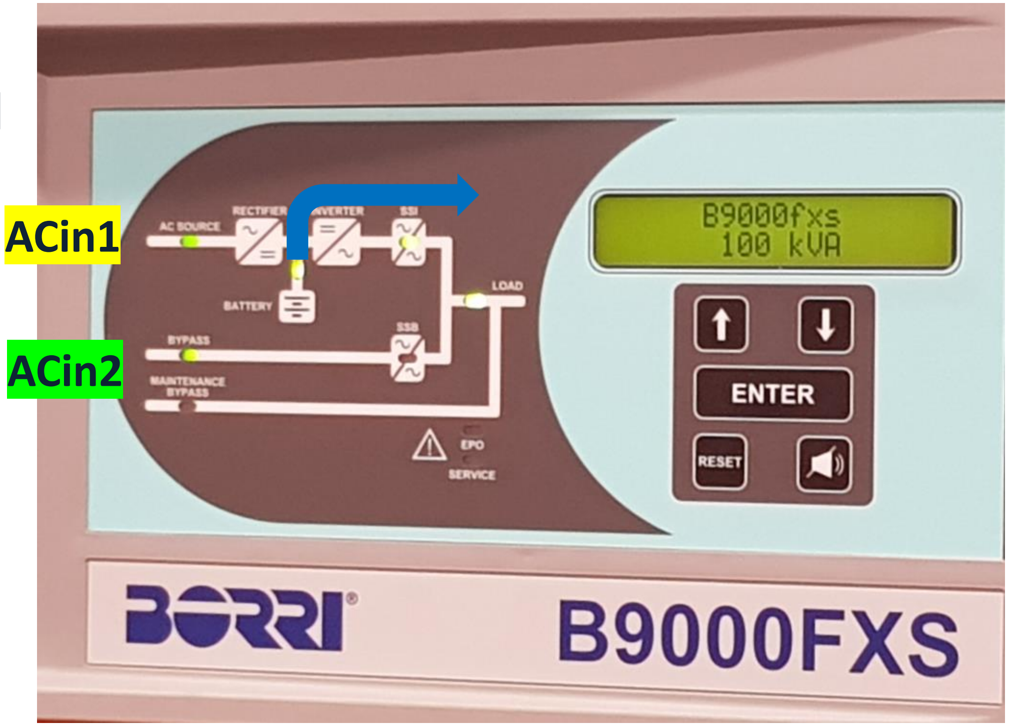
- **Synchronized** to bypass (ACin2) through internal inverter PLL.

On battery: Battery→ Inverter→ Load

- In case of **power failure**.
- In our measurements, no synchronization with ACin1 and ACin2.



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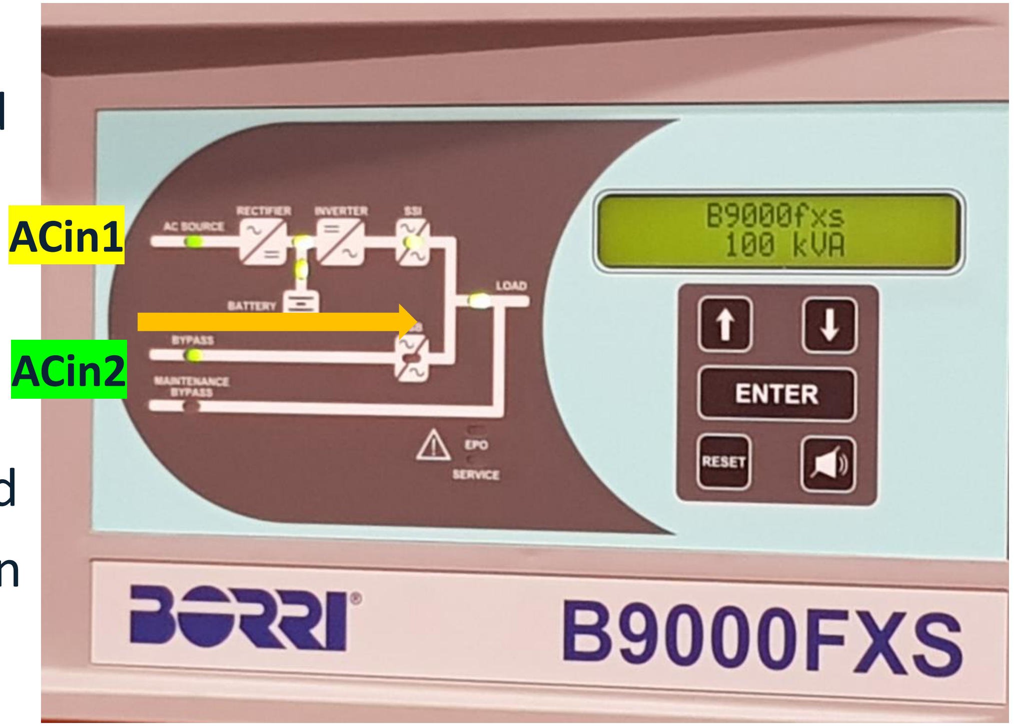
Static bypass: ACin2 → Switch → Load

- Switches **automatically** to maintain power continuity in case of **inverter failure.**



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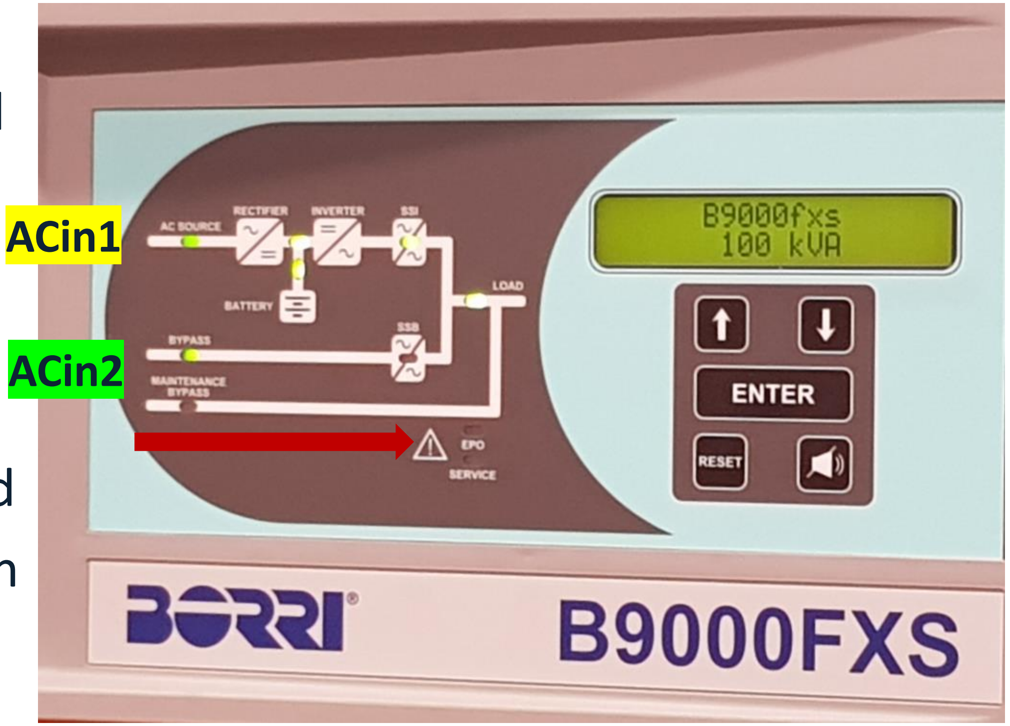
Static bypass: ACin2 → Switch → Load

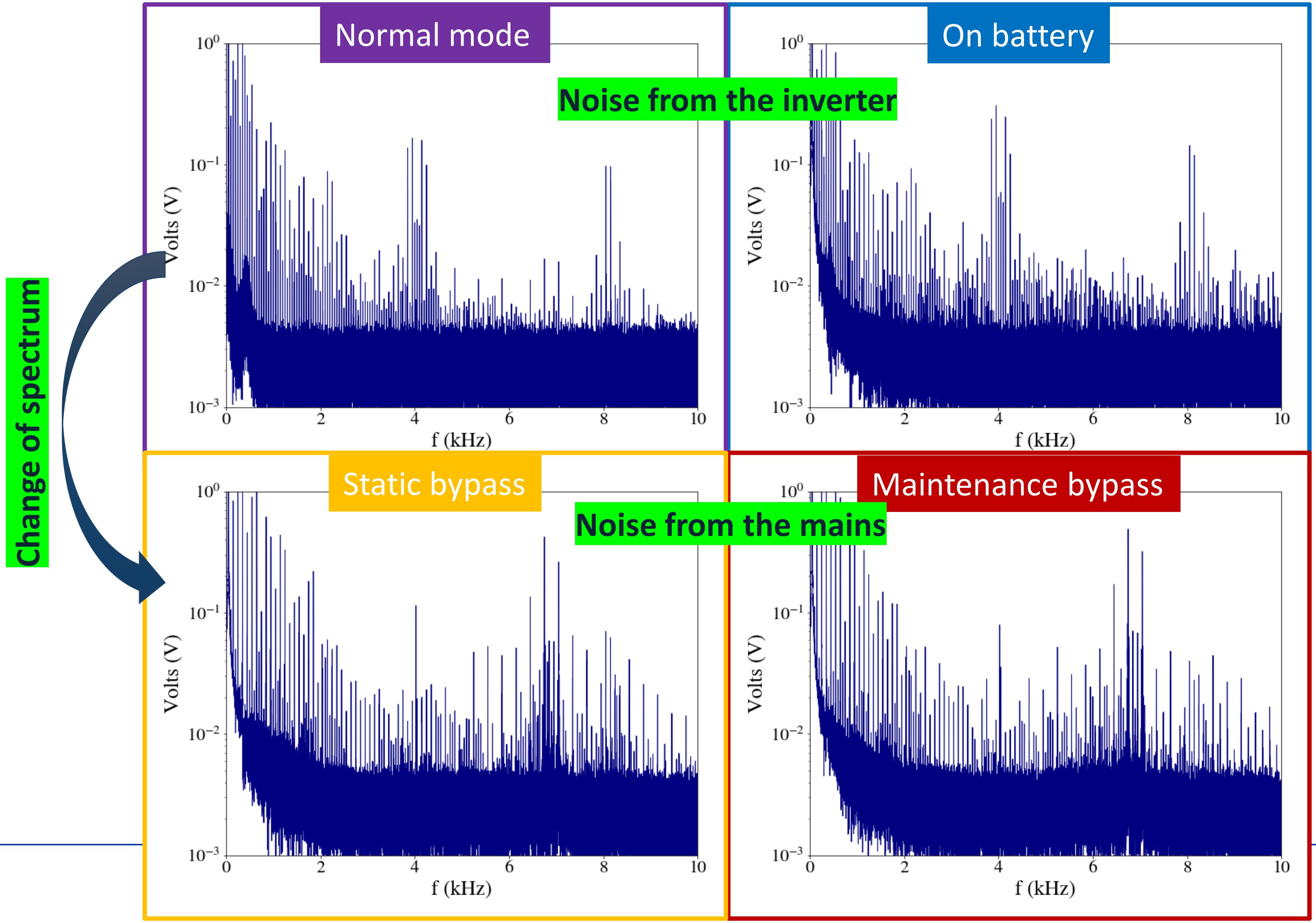
- Switches **automatically** to maintain power continuity in case of **inverter failure.**

Maintenance bypass: Acin2 → Load

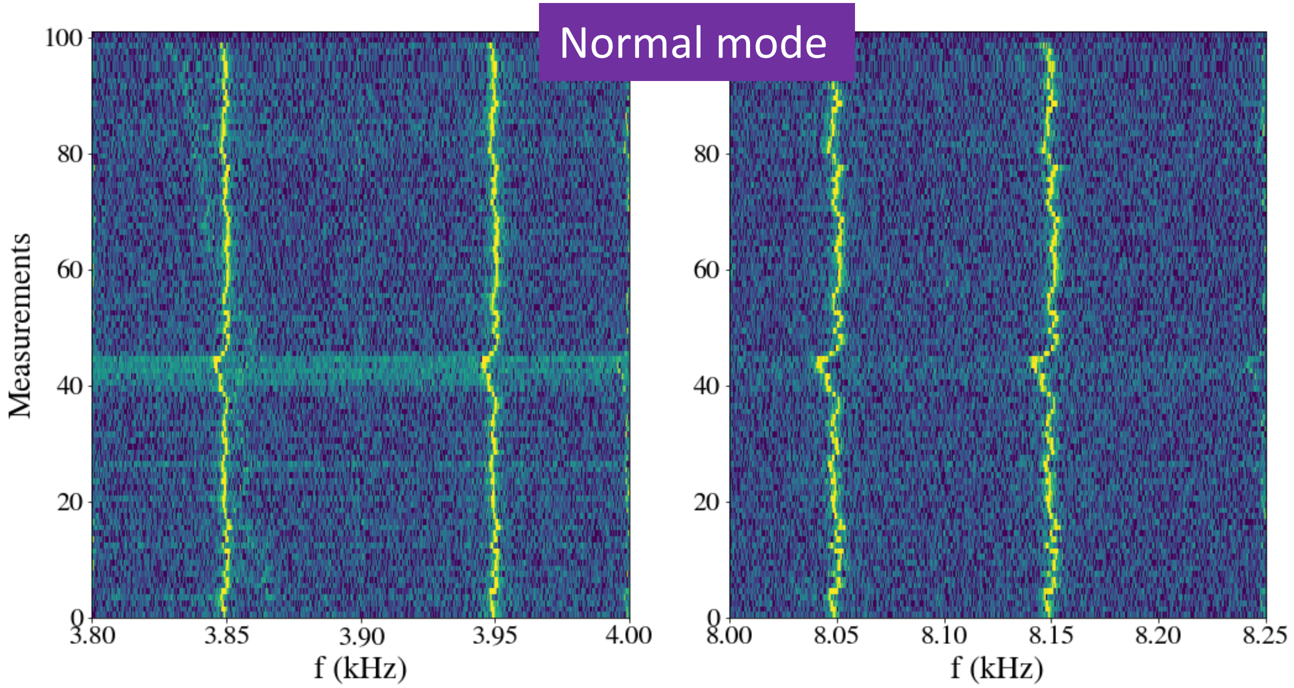
- **Manual** action required.



Spectra in all UPS modes

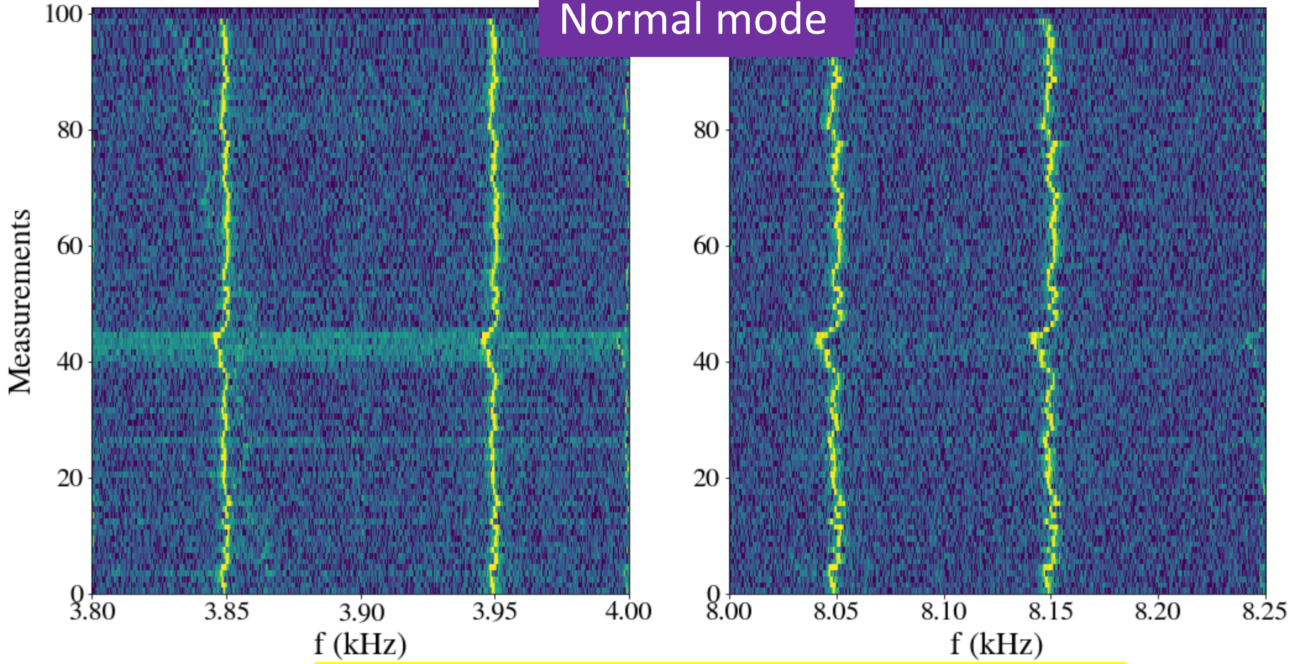


Spectrogram in normal mode

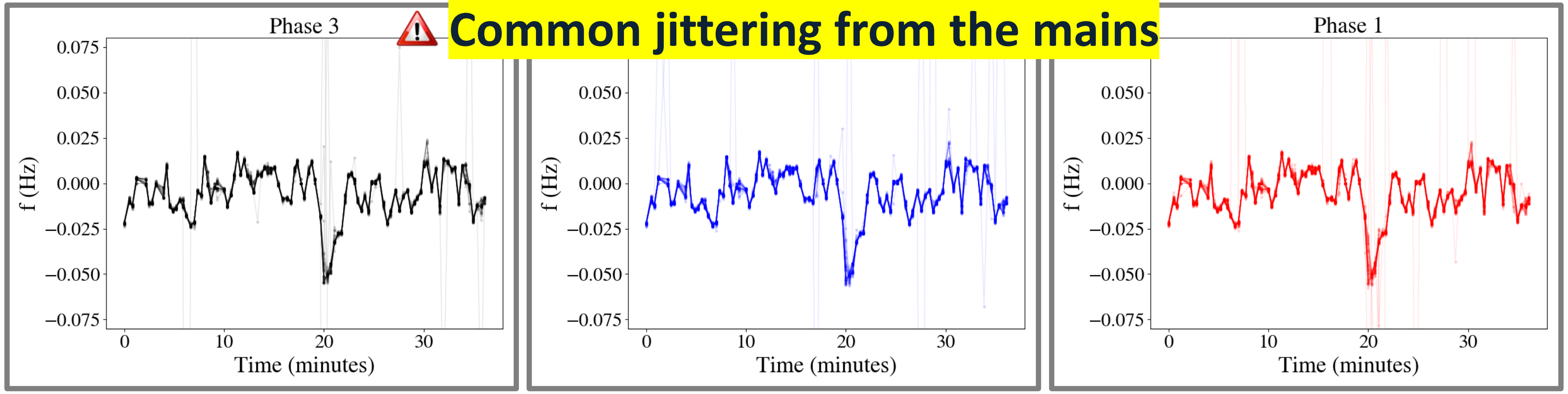


Spectrogram in normal mode

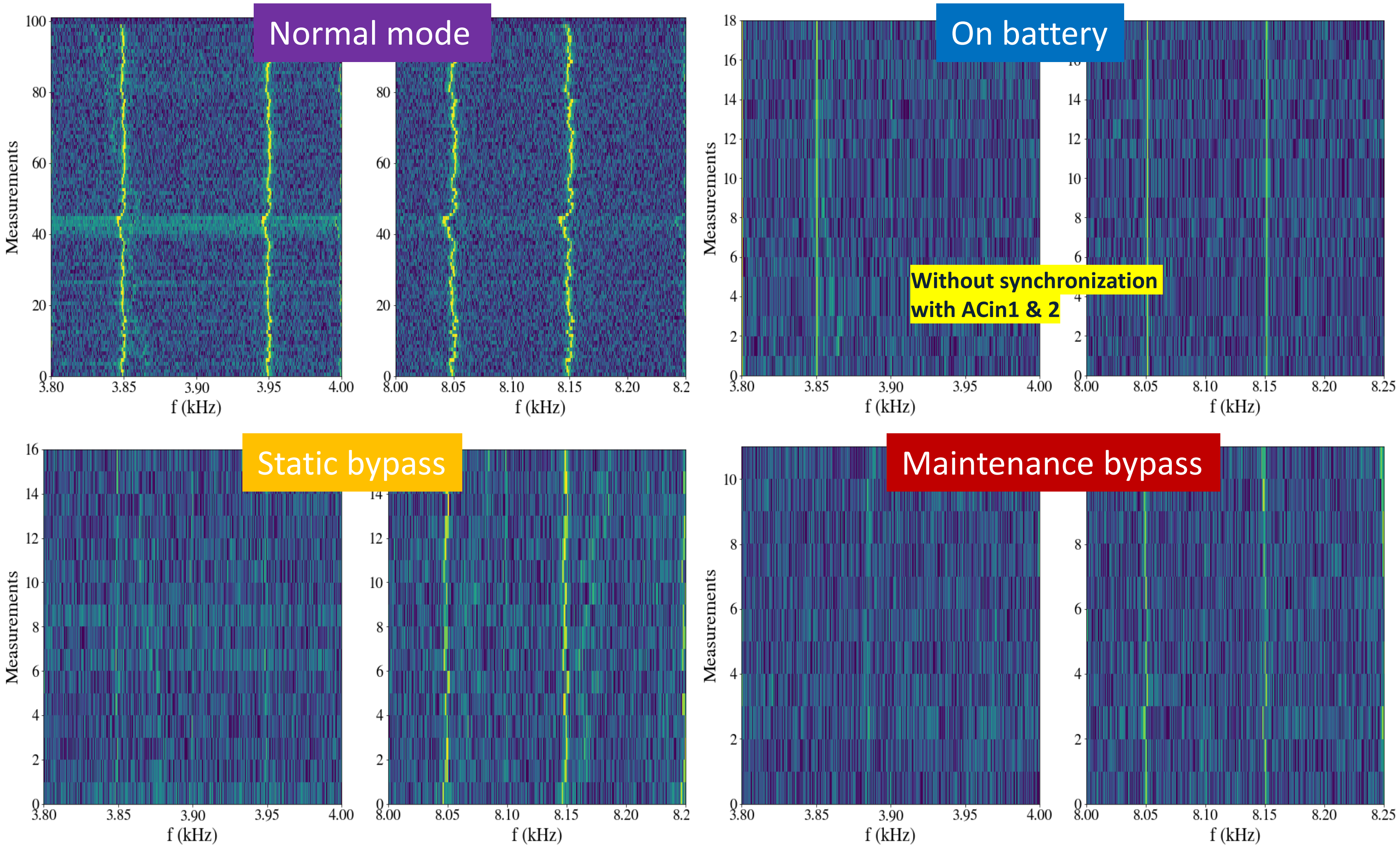
Normal mode



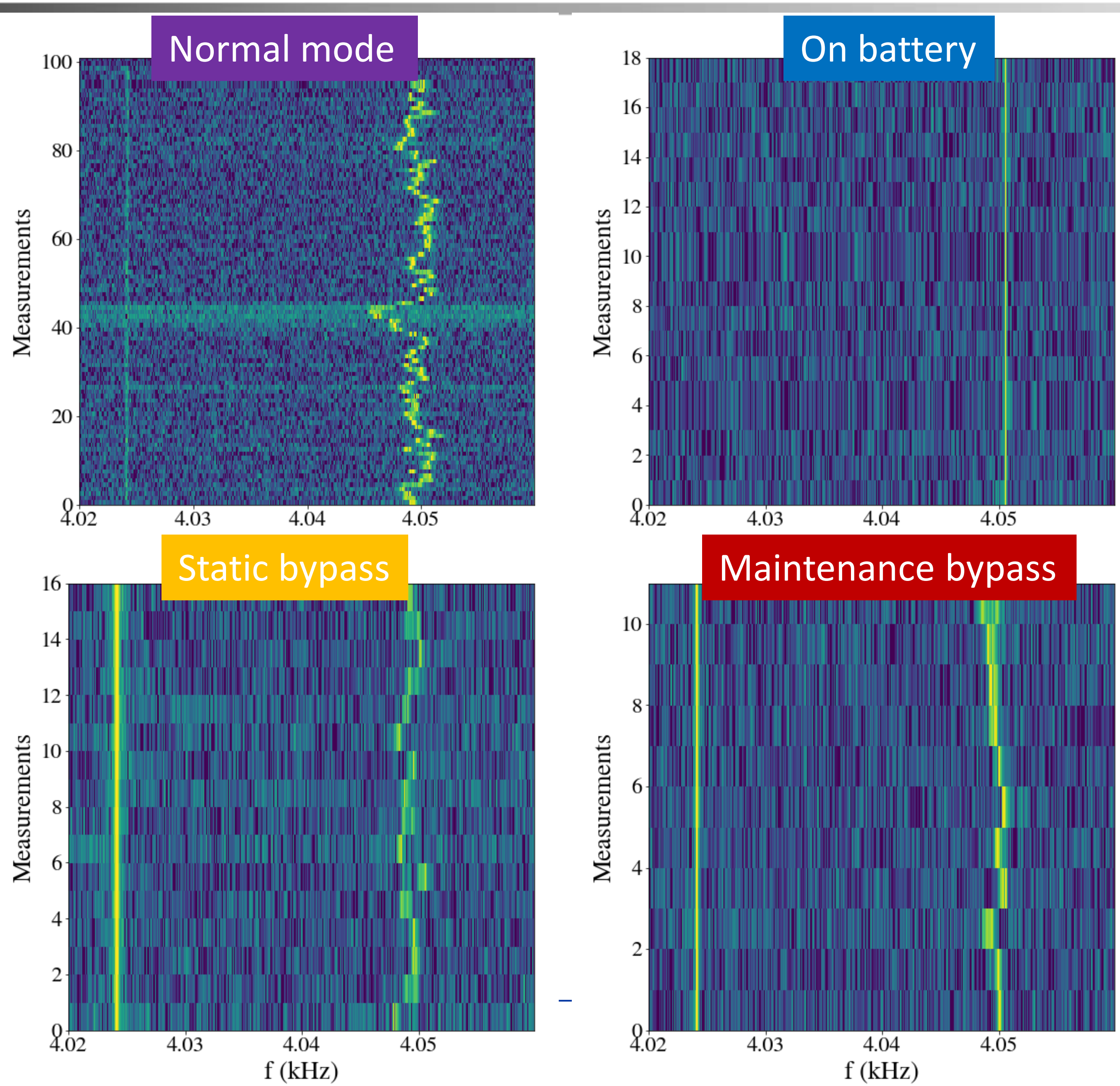
Common jittering from the mains



Spectrograms in all UPS modes

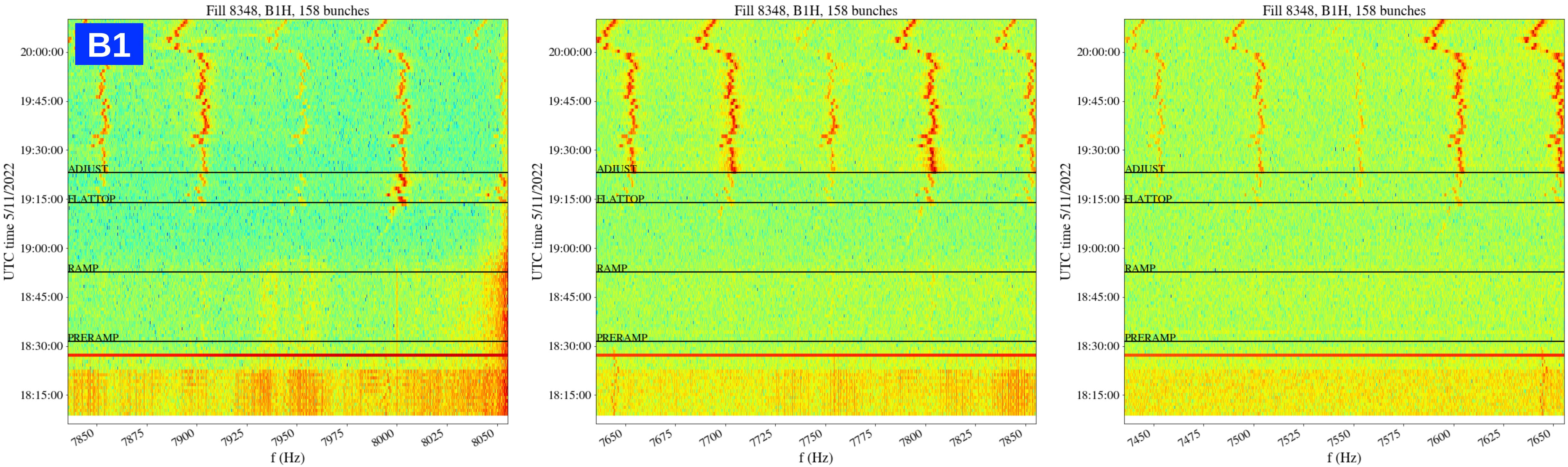


Spectrograms in all UPS modes



MD overview

- Second MD:
  - At top energy so that the 8 kHz cluster is clearly visible.
  - With 3 trains of 48 bunches to have a symmetrical filling scheme.
  - UPS in SR4 switched twice to battery mode and back to nominal operation



MD overview

- **2 MDs (July & November)**

- **First MD:**
  - at injection, with 6 pilots and then 4 nominals
  - UPS modifications from EN/EL:
    1. First, EZS1/45X and EZS11/45X (in cascade) in UX45 (access needed) switched from “nominal” configuration to “manual bypass” and then back to “nominal”. Not possible to switch to “battery mode” without remote control.
       - UPS connected to (H. Timko): ADT, racks for klystrons, LLRF crates for cavity control and longitudinal diagnostics in UX45.
    2. Then, EBS11/4R in SR4 (no access needed) switched from “nominal” configuration to “battery”, “static bypass”, “manual bypass” and back to “nominal”.
       - UPS connected to (H. Timko): ADT, LHC beam control (RF frequency generation, beam phase loop, synchronisation etc.), longitudinal diagnostics in SR4 (APWL, beam spectra, longitudinal ObsBox)