# Do we need a Wide-Band Transverse Feedback in the LHC/HL-LHC?

K. Li, W. Hofle, J. Kamppolou, E. Metral

WP2 Meeting, 23. August 2016, CERN

# Context & Outline

## Context:

The HL-LHC upgrade features a **doubling of the nominal LHC intensity together with reduced emittances** with the goal of delivering higher brightness beams to considerably increase the luminosity. **Intensity effects and possible limitations** are likely to become **more pronounced**. For this it will be important to draw up **adequate mitigation measures**. One of the potential options is a **wideband feedback system** which will be discussed more closely here.

## Outline:

1. Introduction
2. Instabilities from impedance
3. Instabilities from electron cloud
4. Performance of demonstrator system
5. Specification together with need, capabilities and cost

# Context & Outline

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Brief outline of what is meant by **wideband feedback system**.

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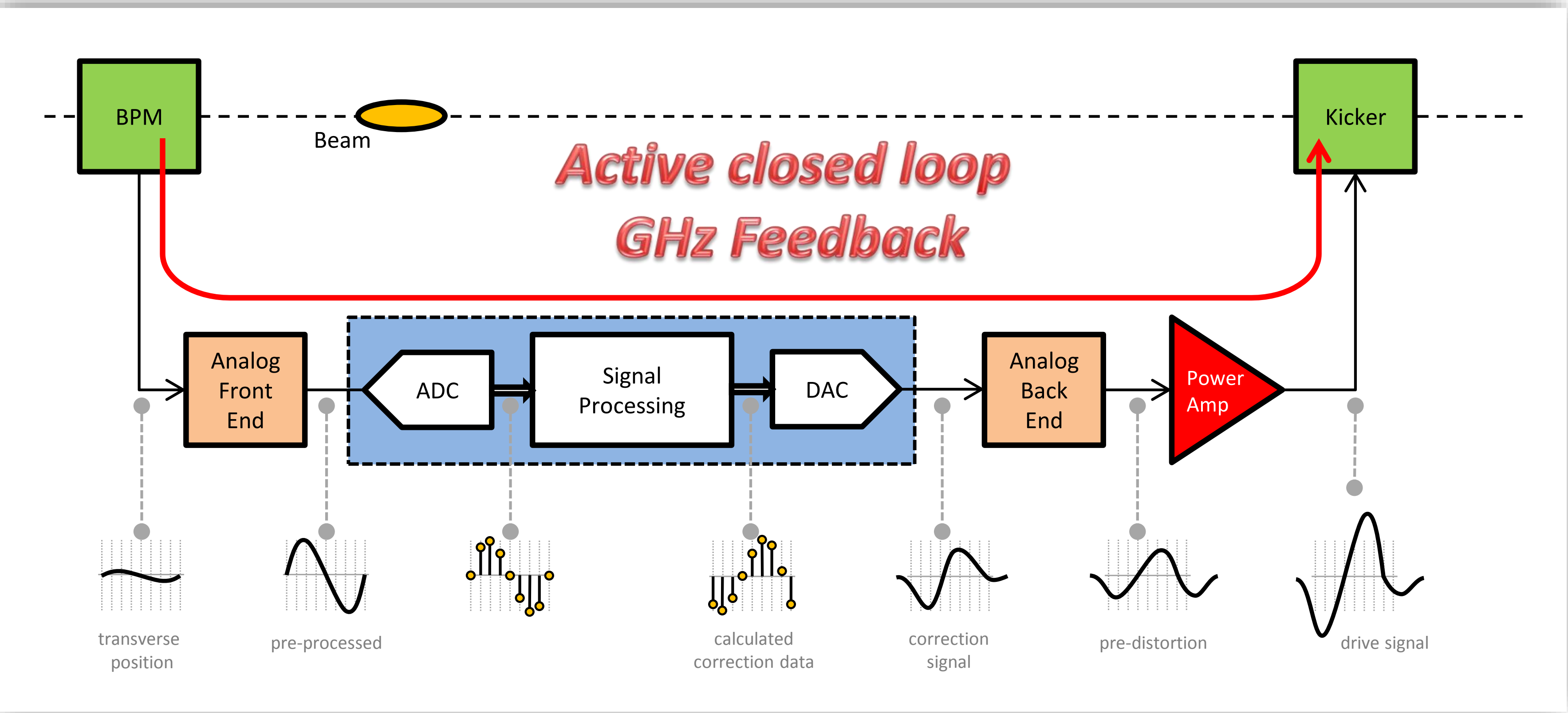
# Brief description of a wideband feedback system




Courtesy W. Hofle

- Active damping of single or coupled bunch instabilities
- High frequency allows damping of intra bunch motion
- No introduction of additional tune spread
- No introduction of additional non-linearities

- Technically challenging and complex system → close follow-up required during operation
- Imperfections can lead to loss of stabilization (i.e. noise or saturation)
- Impedance contribution of kickers must be addressed

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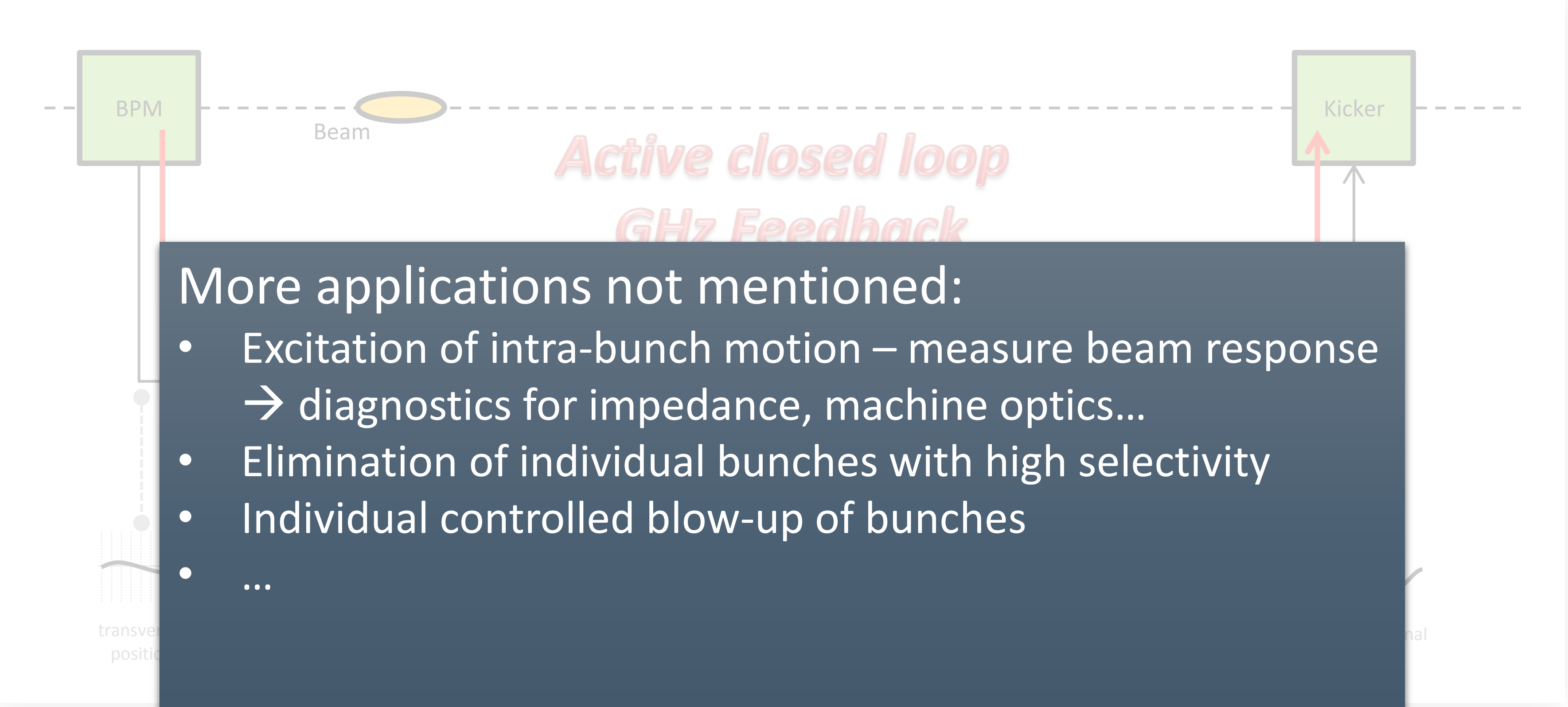


Courtesy W. Hofle

## More applications not mentioned:

- Excitation of intra-bunch motion – measure beam response → diagnostics for impedance, machine optics…
- Elimination of individual bunches with high selectivity
- Individual controlled blow-up of bunches
- …

- Active damping of s… instabilities
- High frequency allows damping of intra bunch motion
- No introduction of additional tune spread
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- … complex system → close follow-up required during operation
- Imperfections can lead to loss of stabilization (i.e. noise or saturation)
- Impedance contribution must be addressed

# The present transverse feedback system – "ADT"

- Primarily designed for:
  - Damping of injection oscillations
  - Damping of oscillations driven by coupled bunch instability
  - Important role in preservation of the beam's transverse emittance
- Since the LHC start in 2008 it grew into (view from the CCC):

Injection oscillation damping

Injection cleaning

Abort gap cleaning


Transverse blow-up (used for loss maps)

Instabilities detection (with the damper PU)

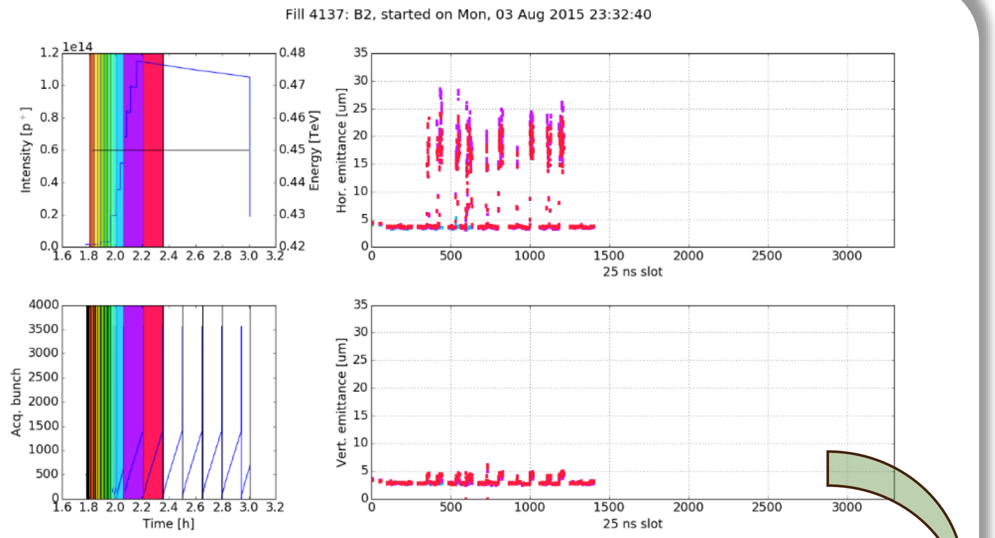
Tune measurement

Slide: Delphine Jacquet, LHC Beam Operation Workshop, Evian 2012

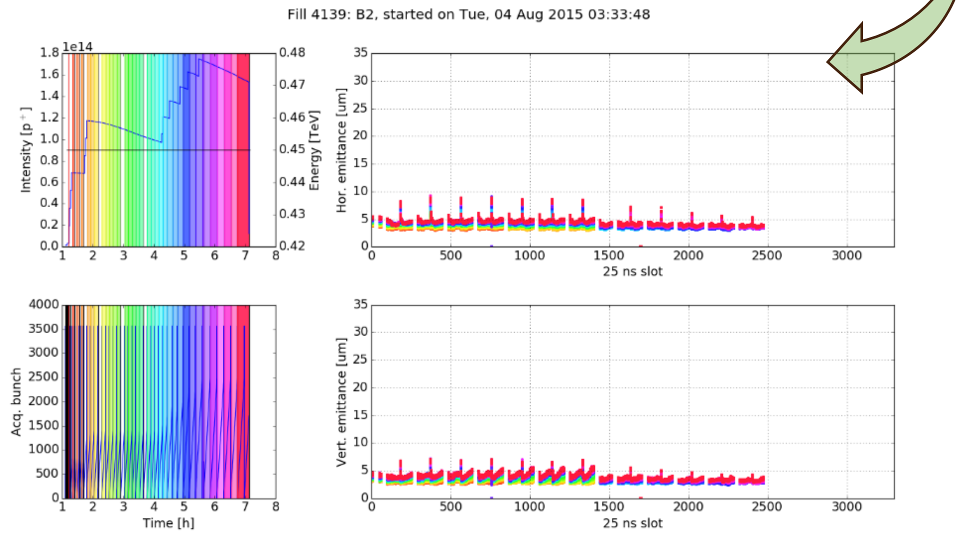
**From D. Valuch, EVIAN 2014**

# The present transverse feedback system – "ADT"

- **Transverse damper:**
  operational experience has also shown, it is also absolutely essential for control of instabilities and emittance blow-up for coupled as well as single bunches




- After switching to optimized settings of the transverse damper – impeccable fill



# HL-LHC challenges

- HL-LHC targets for high luminosity:
  - Intensity 1.15e11 → 2.2e11
  - Emittance 3.75um → 2.5 um
- Intensity effects are detrimental for performance:
  - Instabilities
  - Beam-beam tune spread
  - IBS
- Can HL-LHC sustain the high brightness beams without loss of performance?
- Do we require means of additional beam stabilization?

# HL-LHC predictions

- Impedances:
  - Simulations based on the present HL-LHC impedance model predict that the present means of stabilization (i.e. Landau octupoles and transverse damper) are sufficient to ensure beam stability
- E-cloud:
  - Simulation work is ongoing
  - E-cloud in dipoles: main source of instabilities (at least at flat top) – ‘scrubbable?’
  - E-cloud in quadrupoles: less crucial for instabilities
  - E-cloud in triplets: triplets are coated
- Incoherent effects:
  - Tune spread significant due to high chromaticities and octupoles
  - In addition enhanced by LR and HO collisions
  - Means of compensation are under investigation (i.e. wires)

# HL-LHC predictions

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Wideband feedback:

- Do we need it? Let’s tackle this at the end…
- Can it work? We look at this first…

# Context & Outline

## Context:

We investigate instabilities expected from **pure impedance** effects and identify whether a **wideband feedback system could theoretically provided sufficient cure**.

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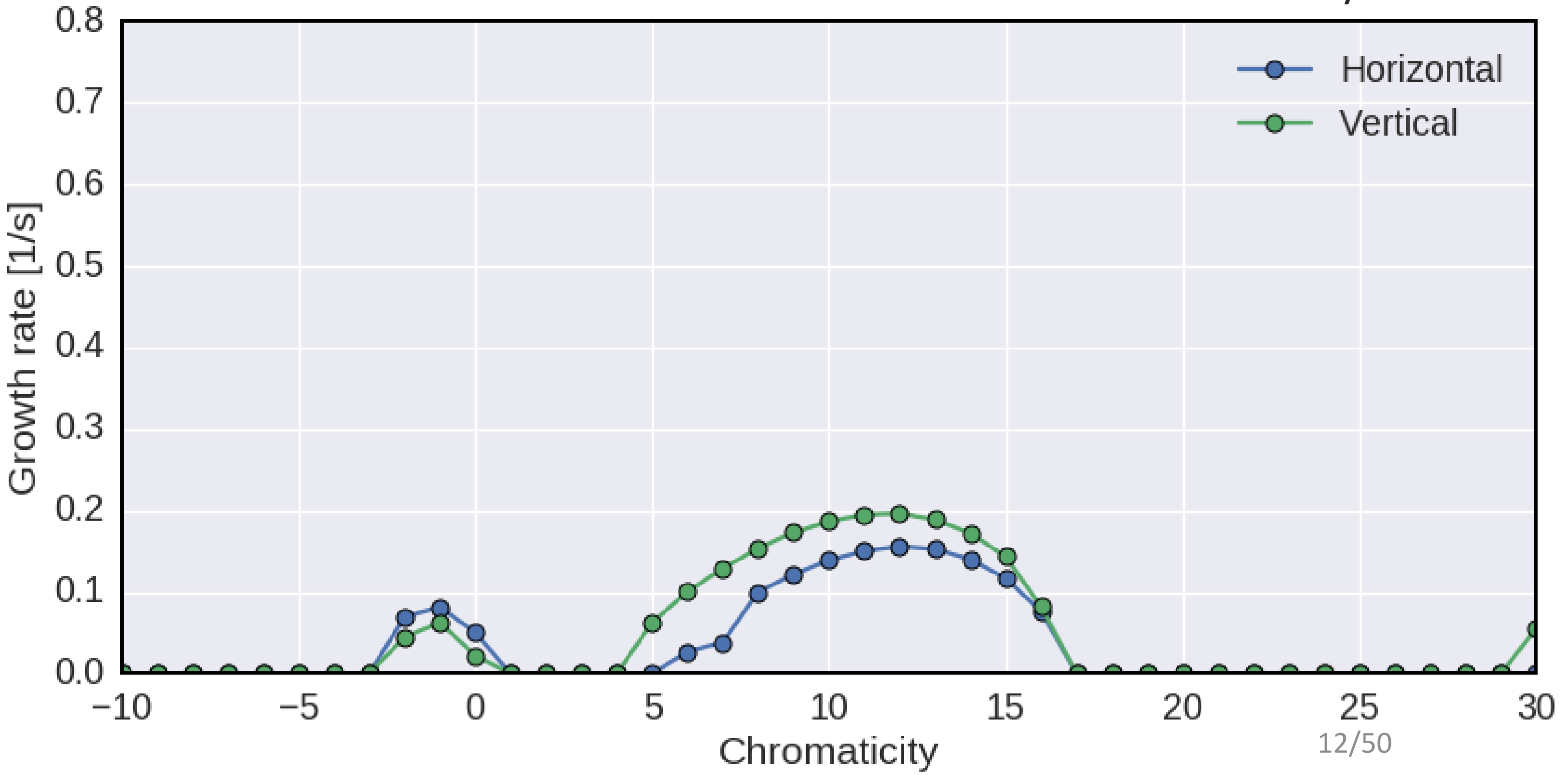
# Impedance and instabilities

- The **HL-LHC impedance model**
  - 7 TeV
  - 15 cm beta*
  - 5um Mo and MoC coated TCTs
- Predictions on **single bunch stability** from **PyHEADTAIL simulations**
  - 7 TeV with present impedance model
  - Perfect transverse damper – damping rate 50 turns, single bunch

Intensity: 2.3e11



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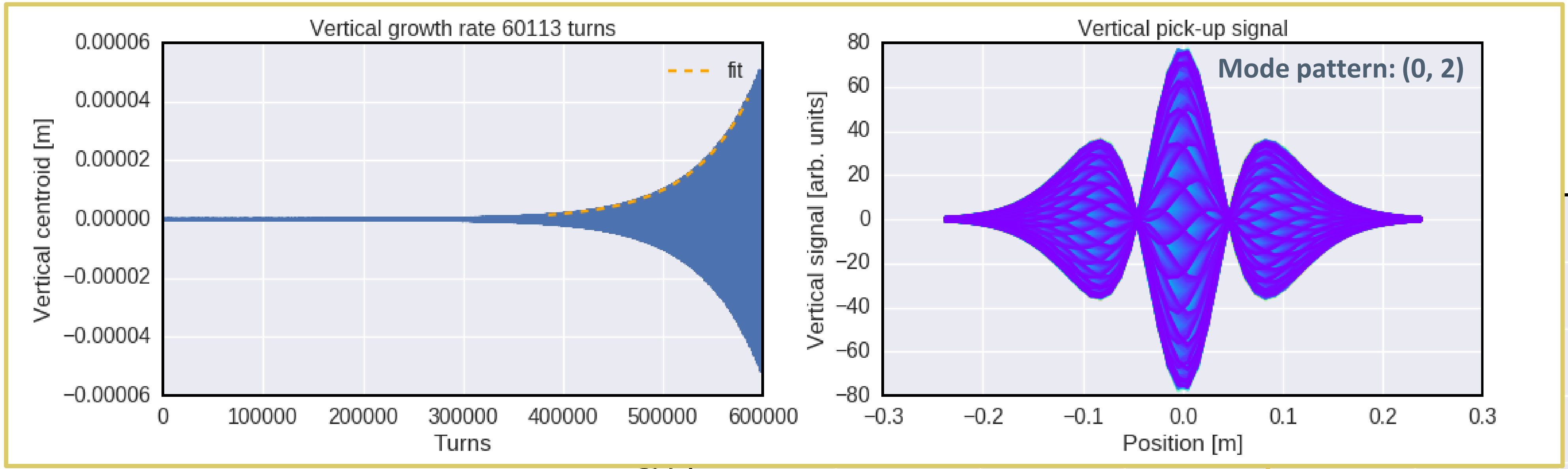


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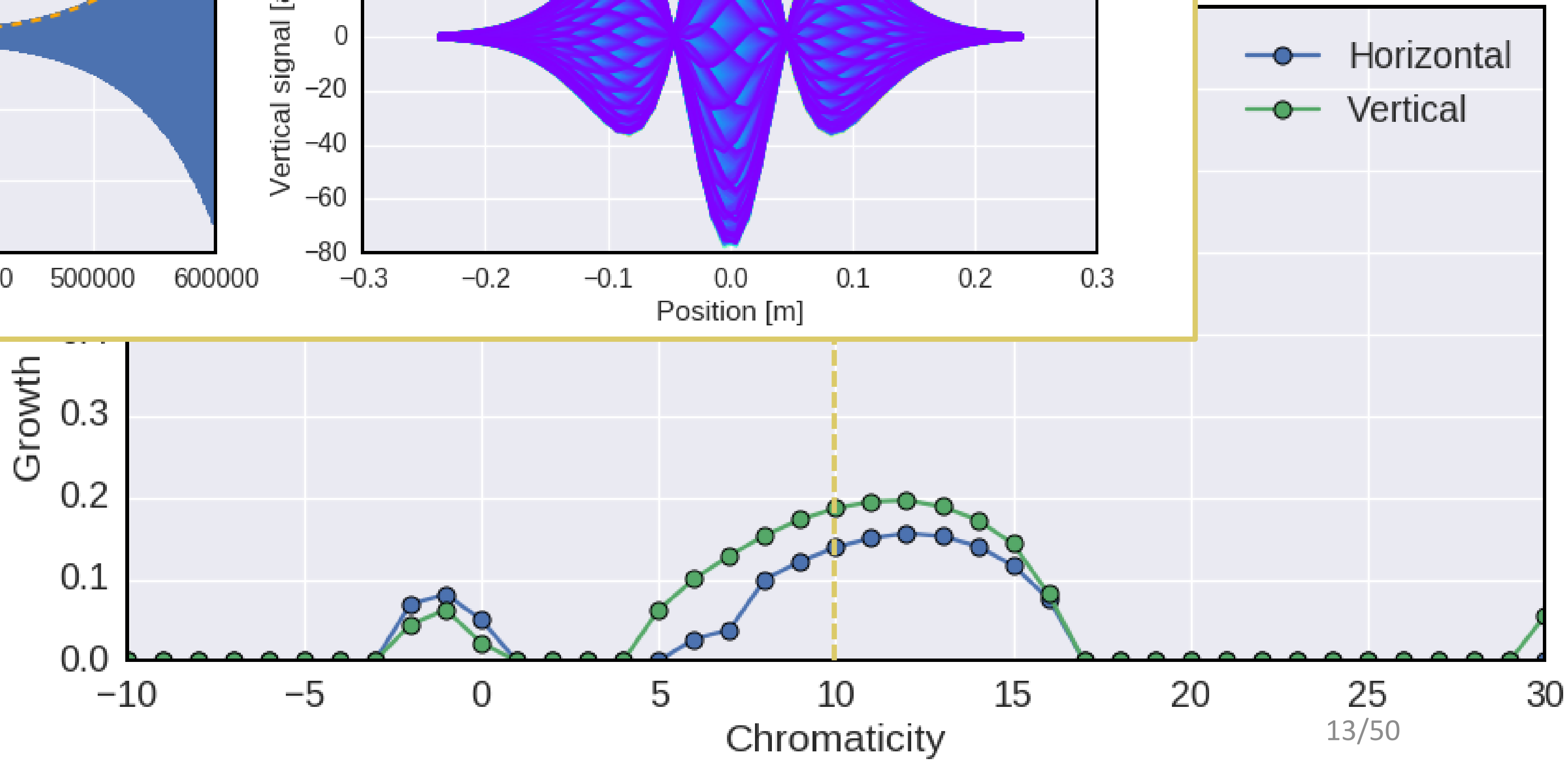

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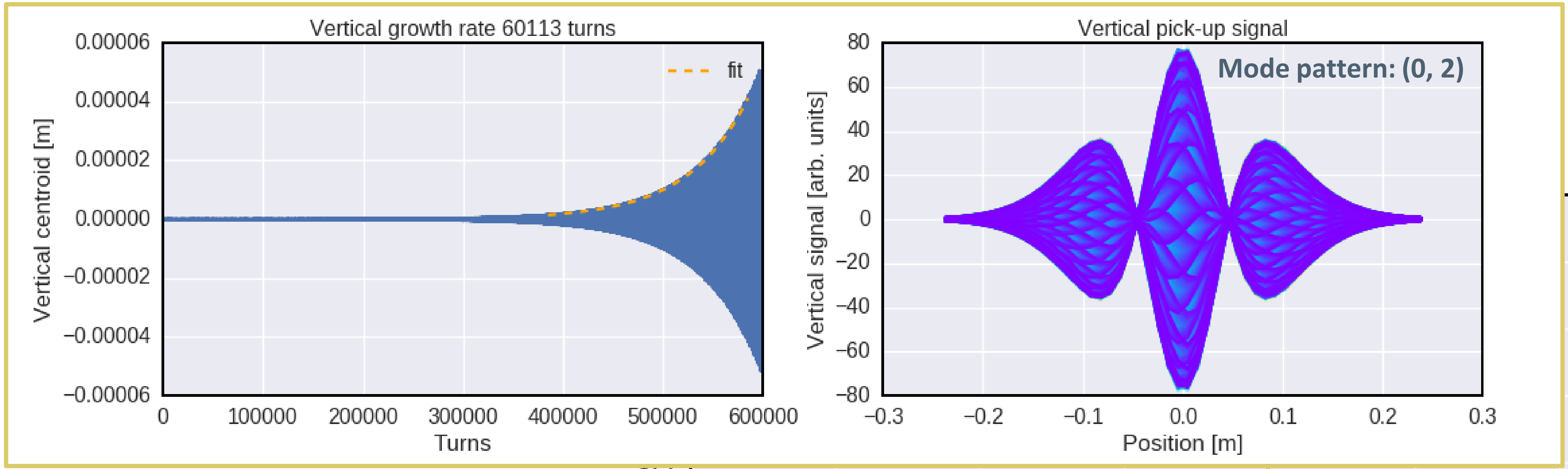


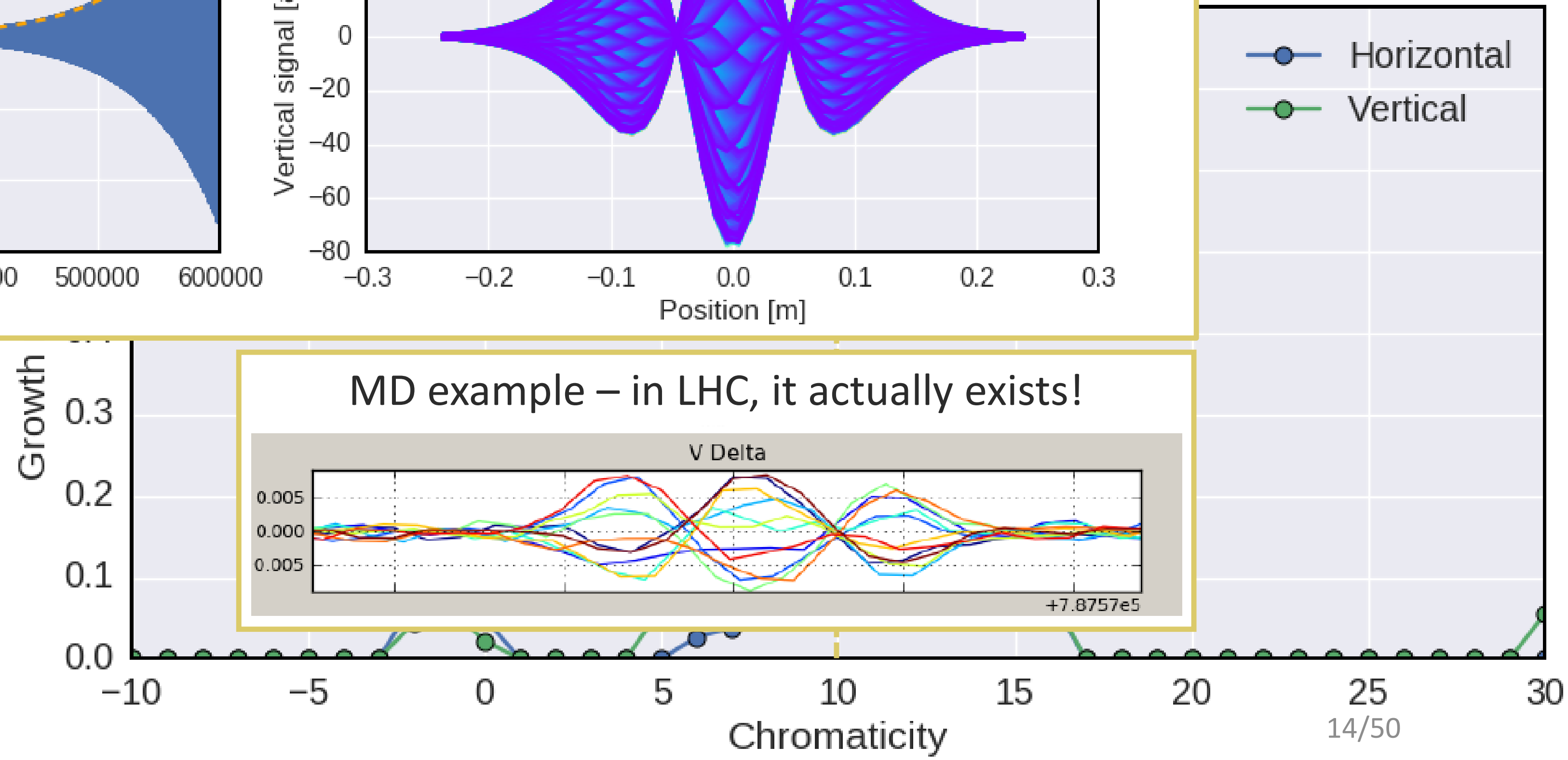

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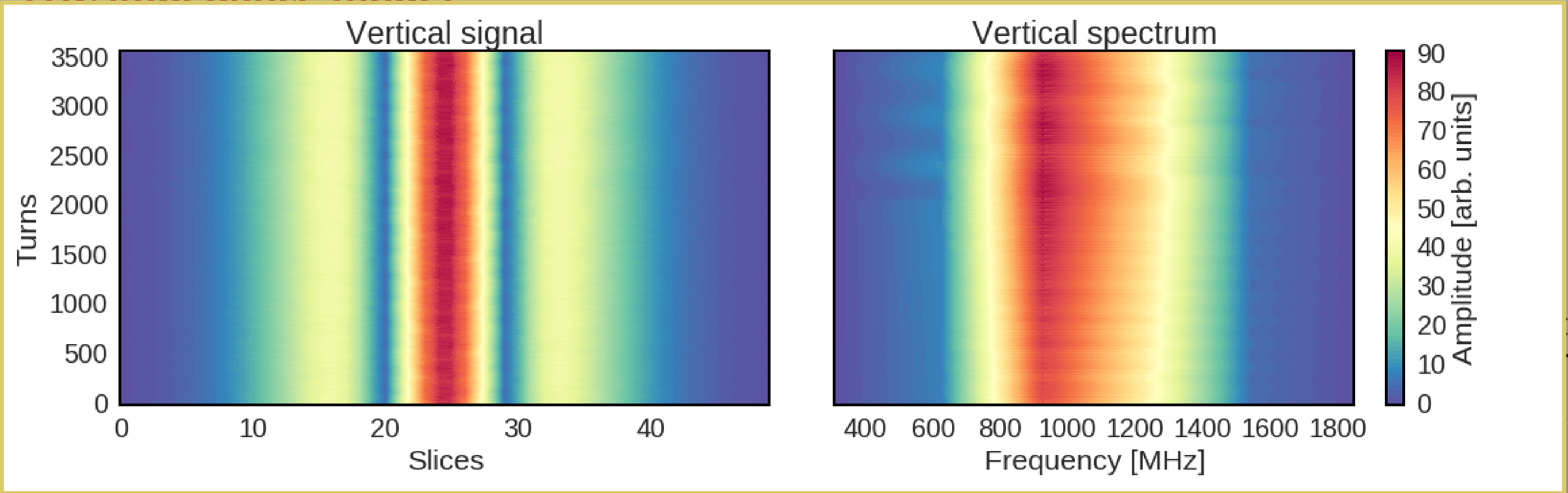
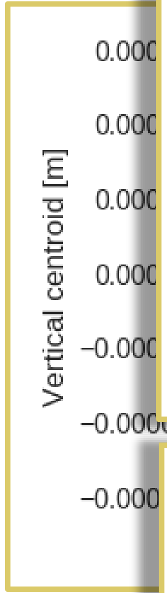
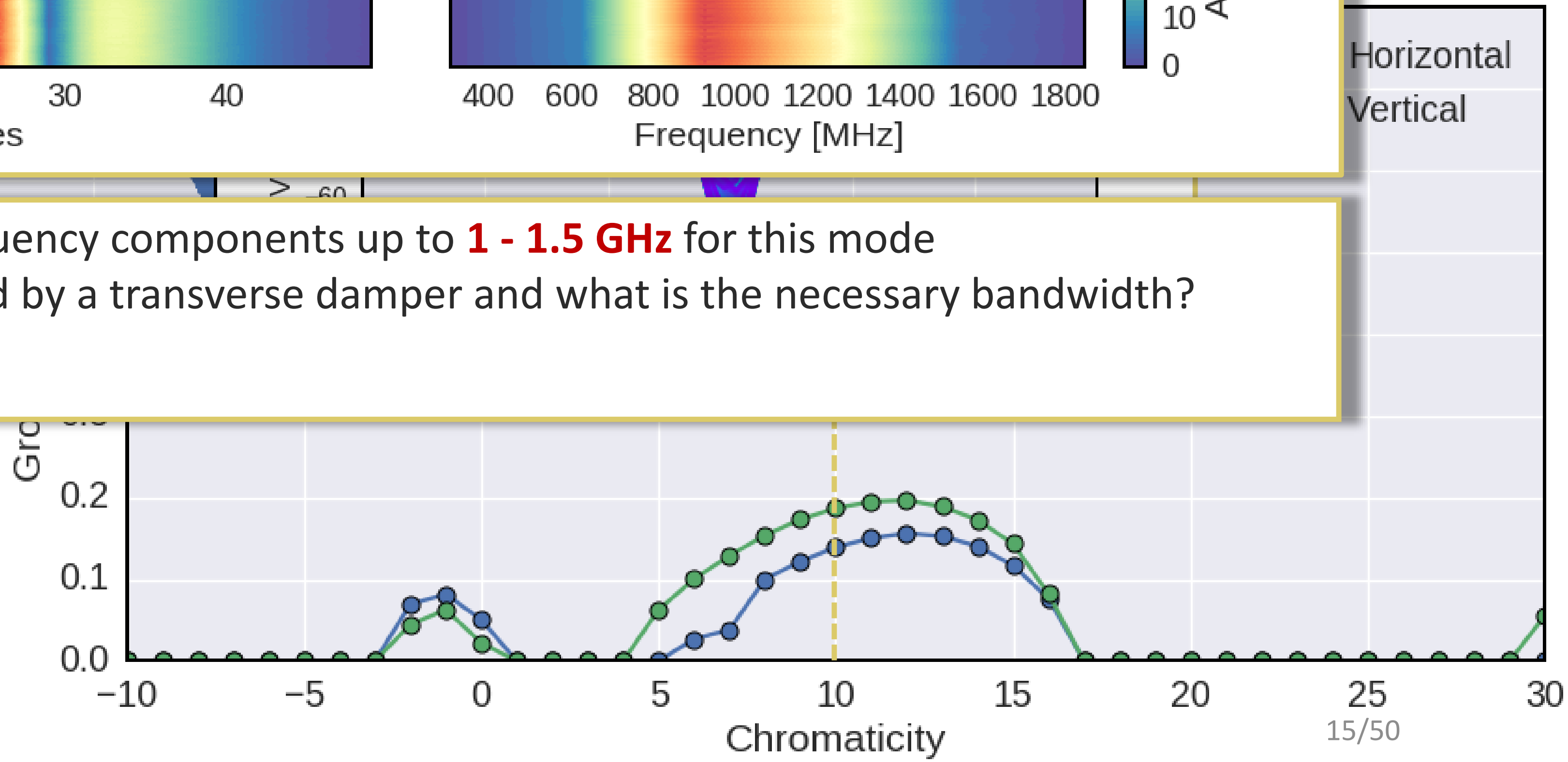
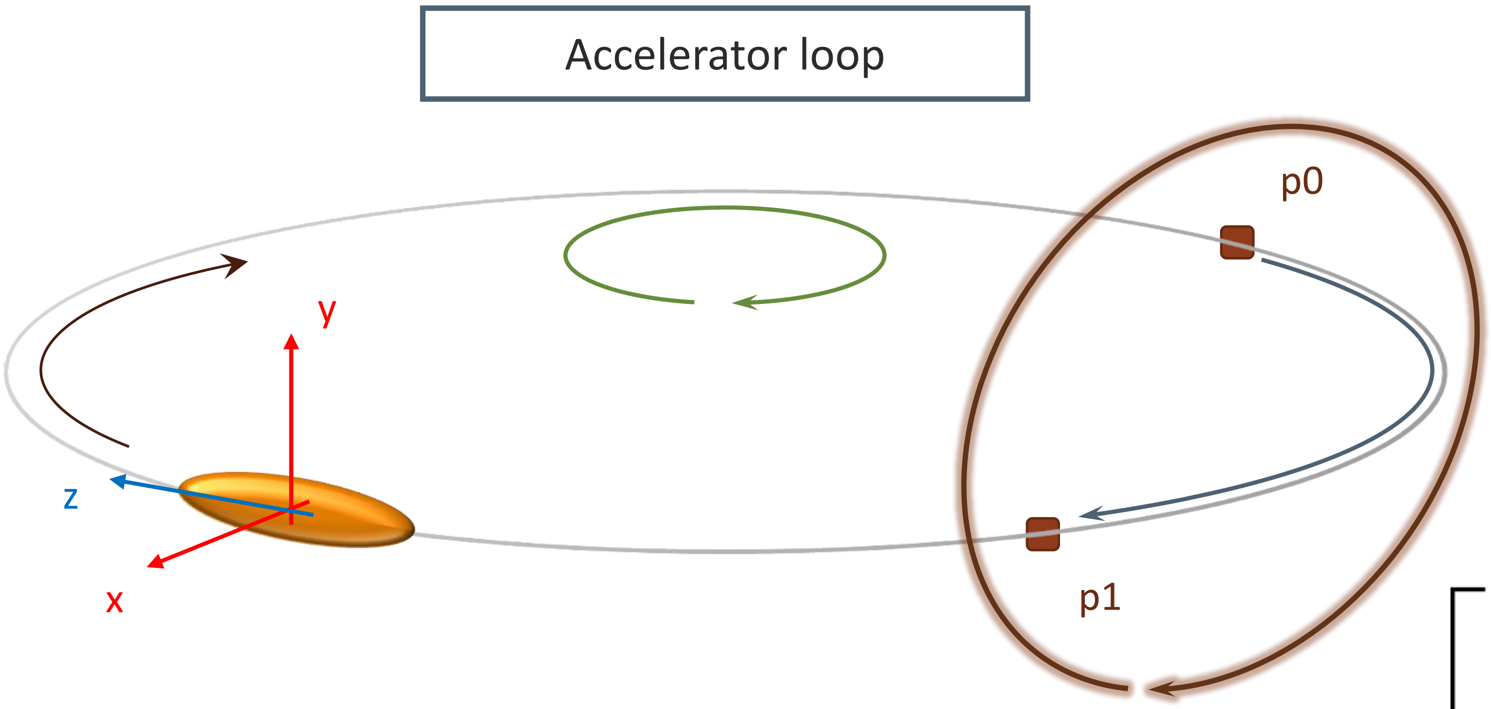


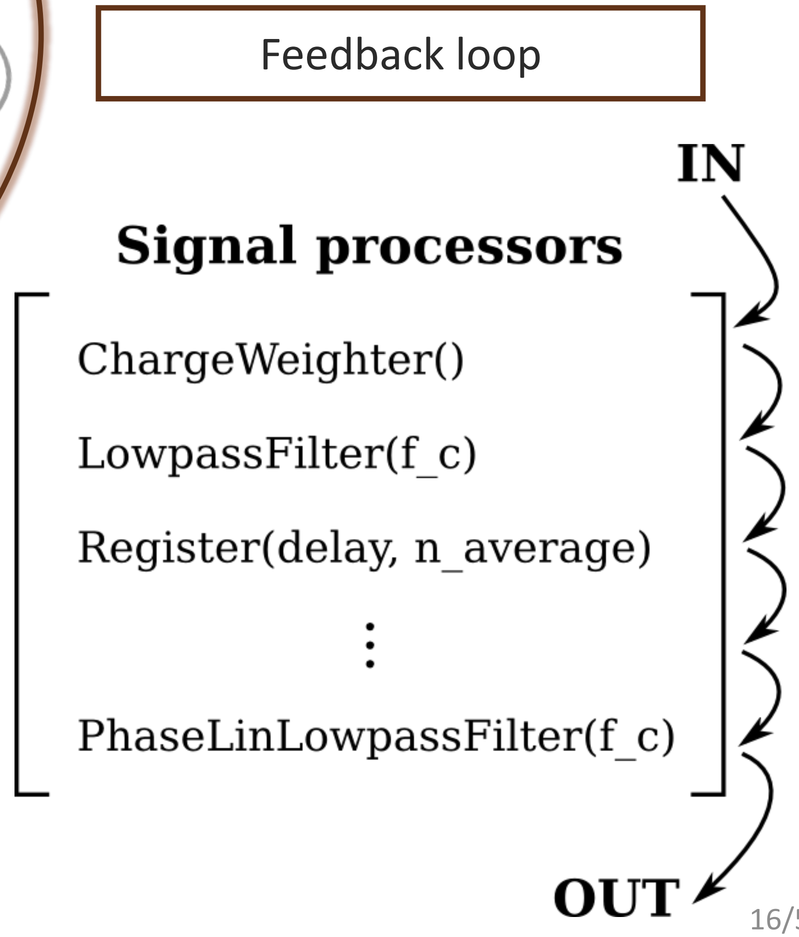




- Spectrogram reveals frequency components up to **1 - 1.5 GHz** for this mode
- Can this mode be damped by a transverse damper and what is the necessary bandwidth?

# New PyHEADTAIL Feedback module

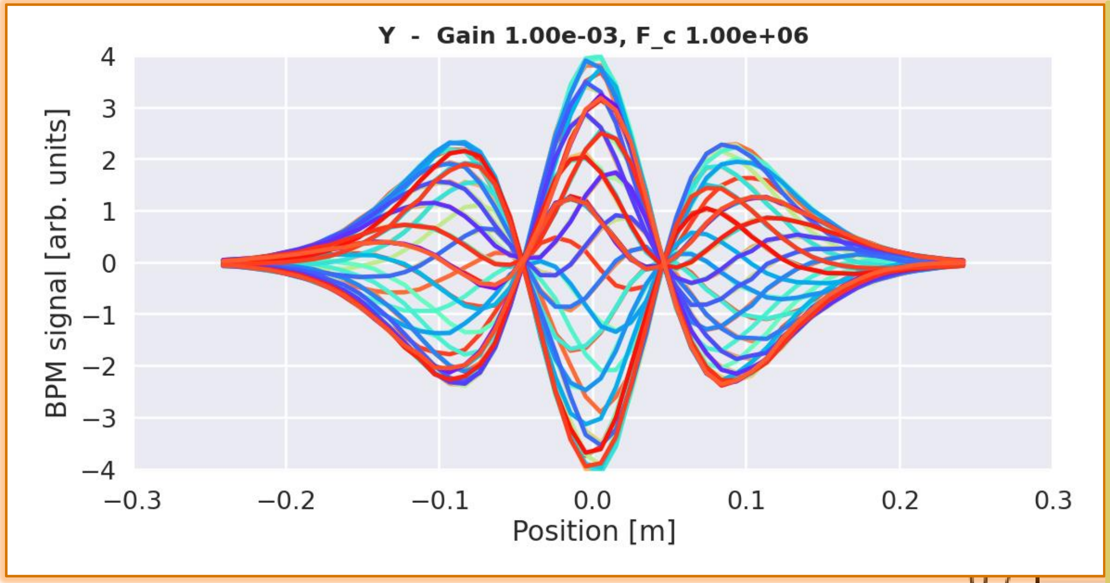


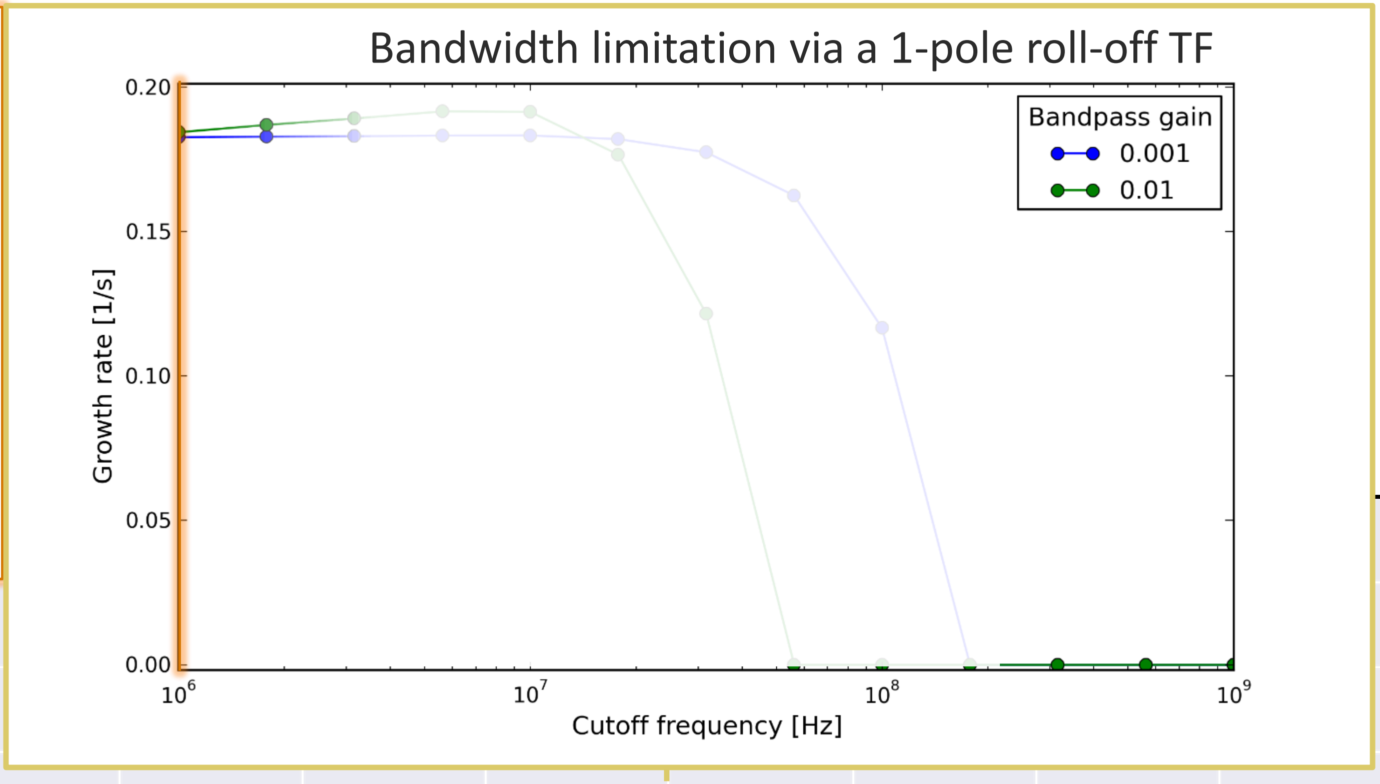



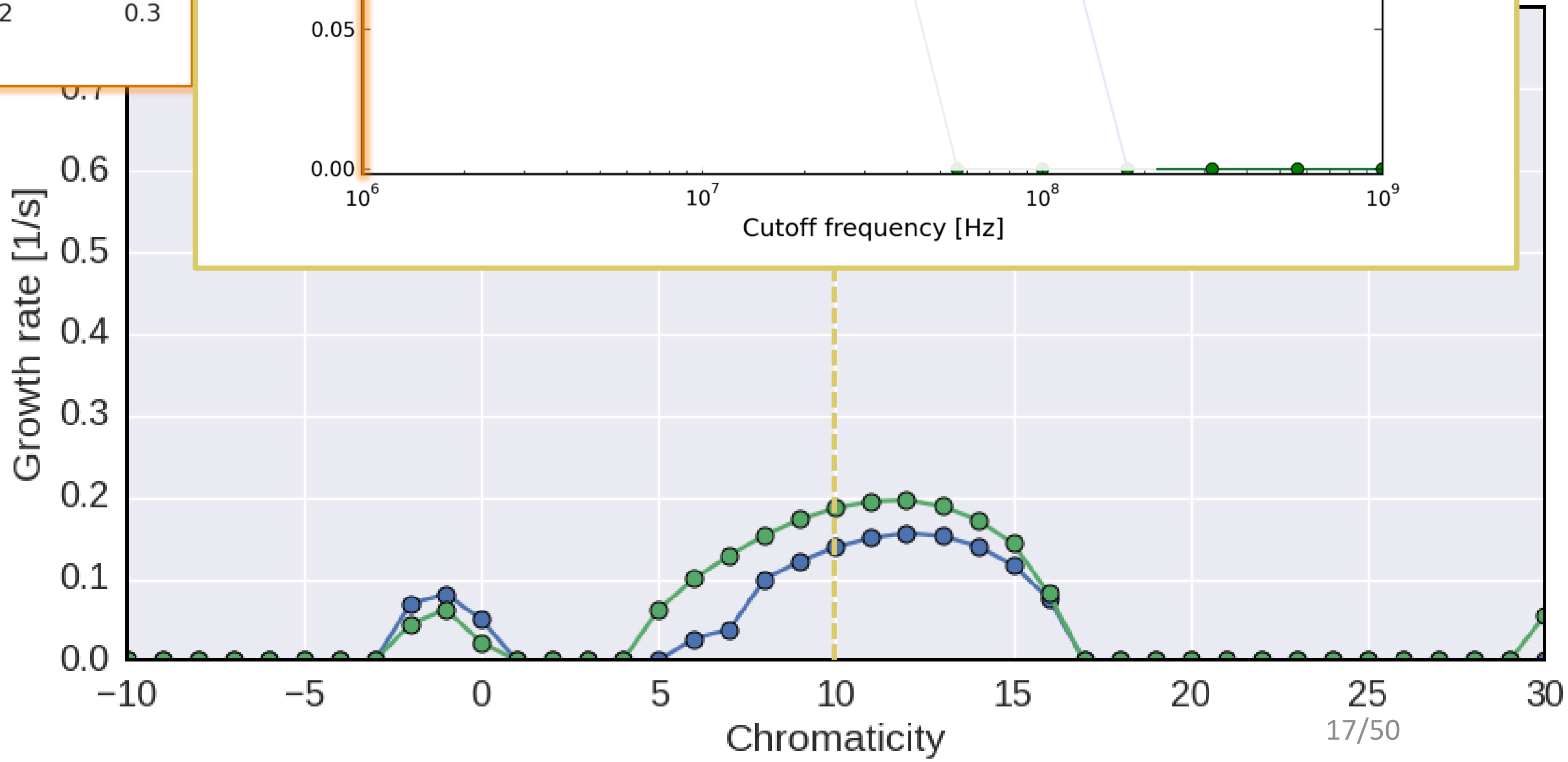

- New module to handle the feedback loop.
- Concept of **list of abstract signal processors**.
- Several pickups and kickers at different positions possible.
- To date – filter functions, delay/registers, noise, gain functions.

J. Komppula

# Impedance and instabilities

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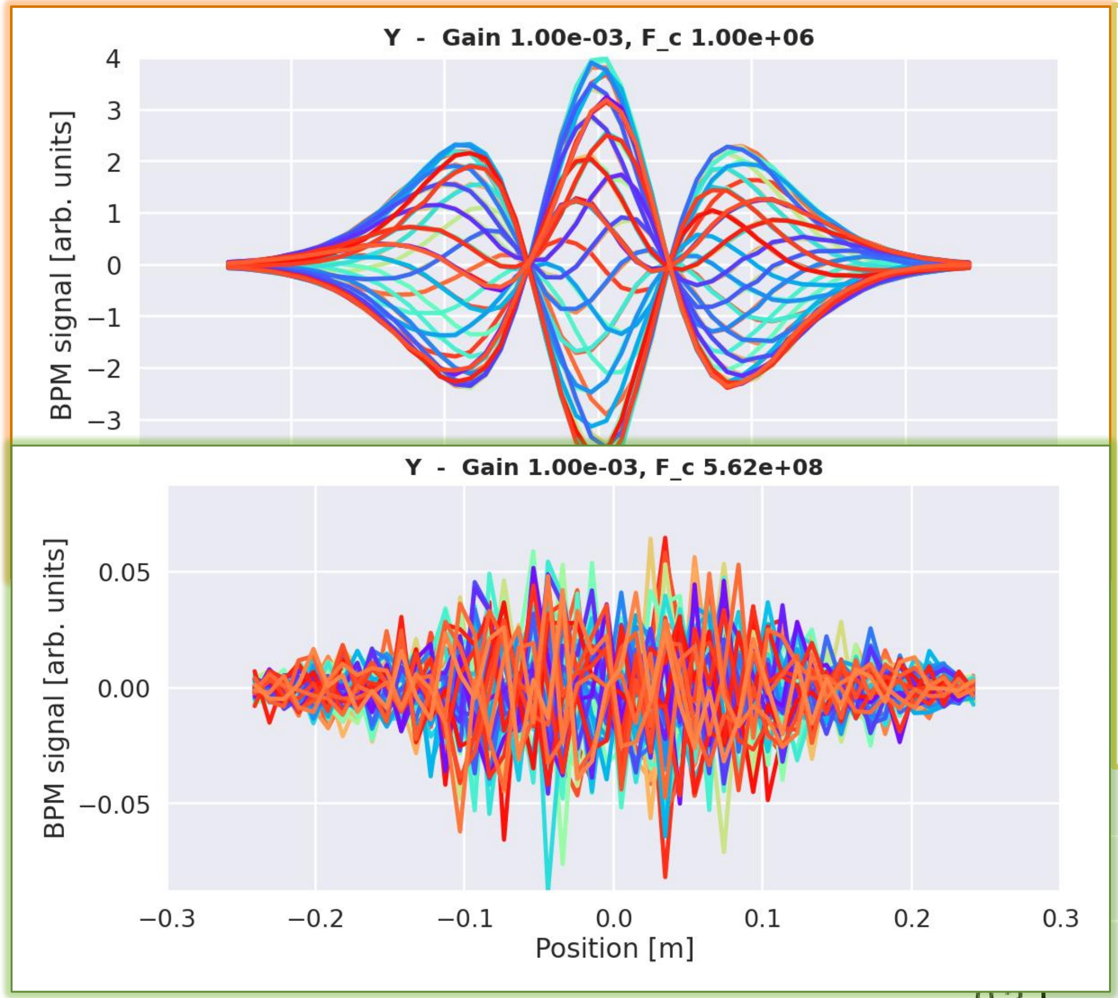
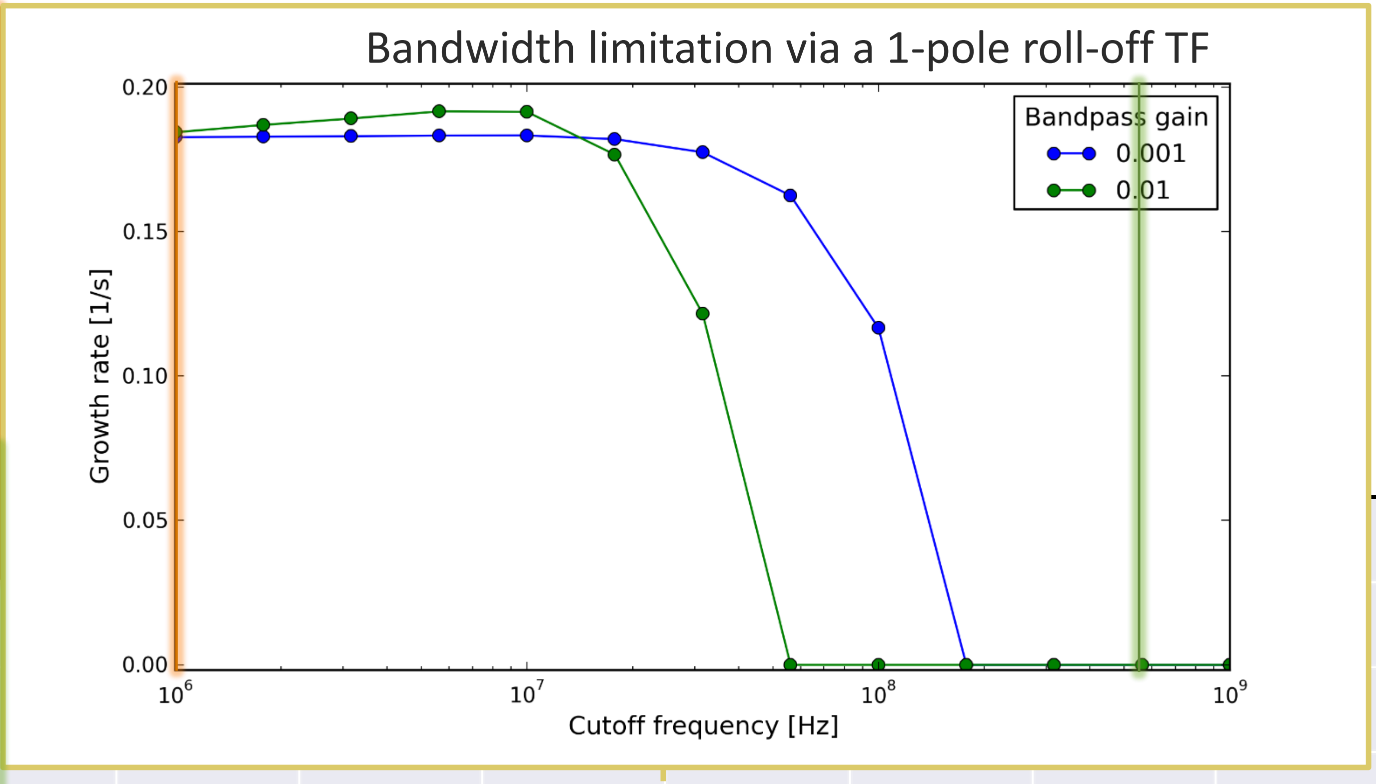
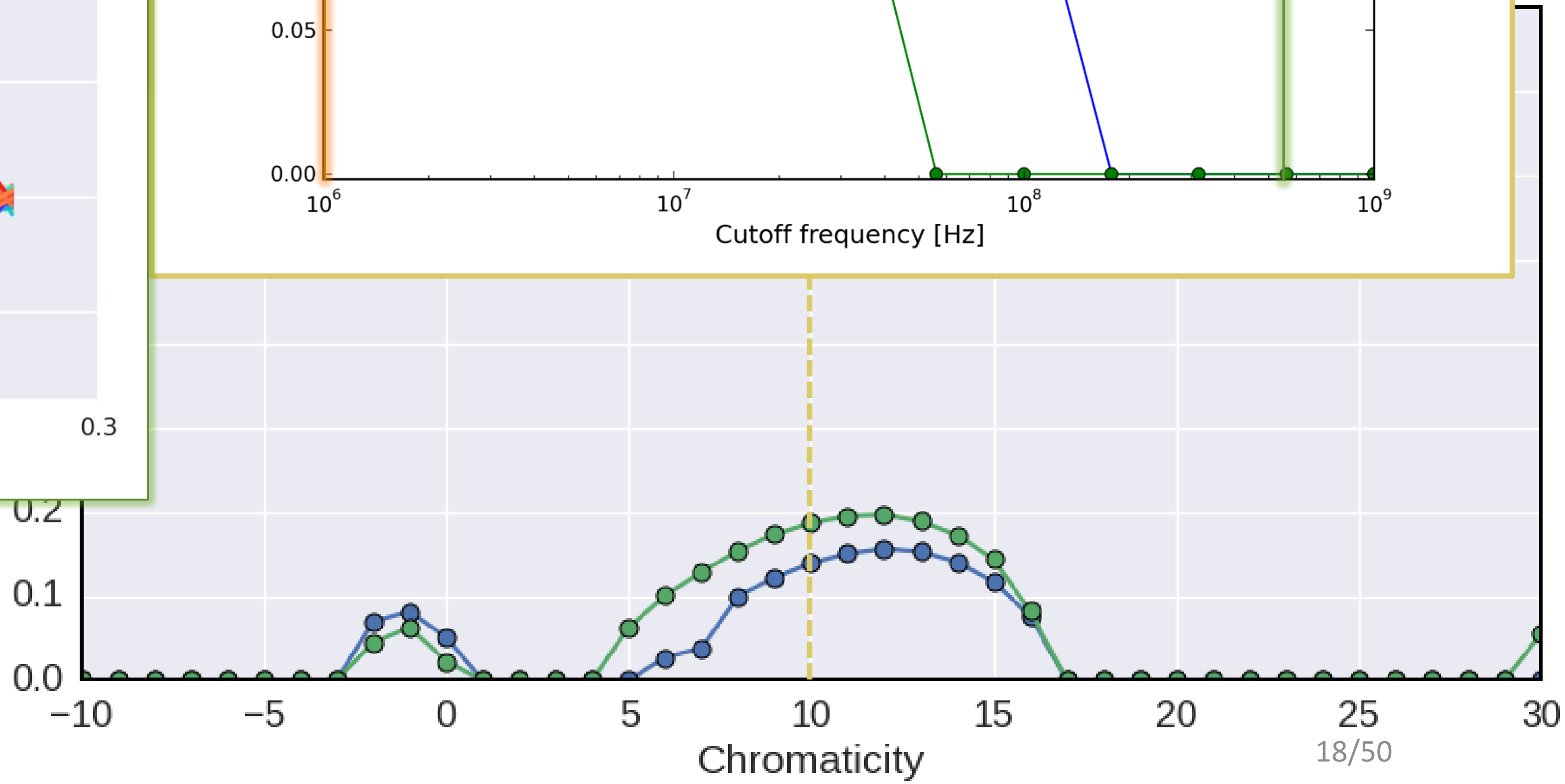
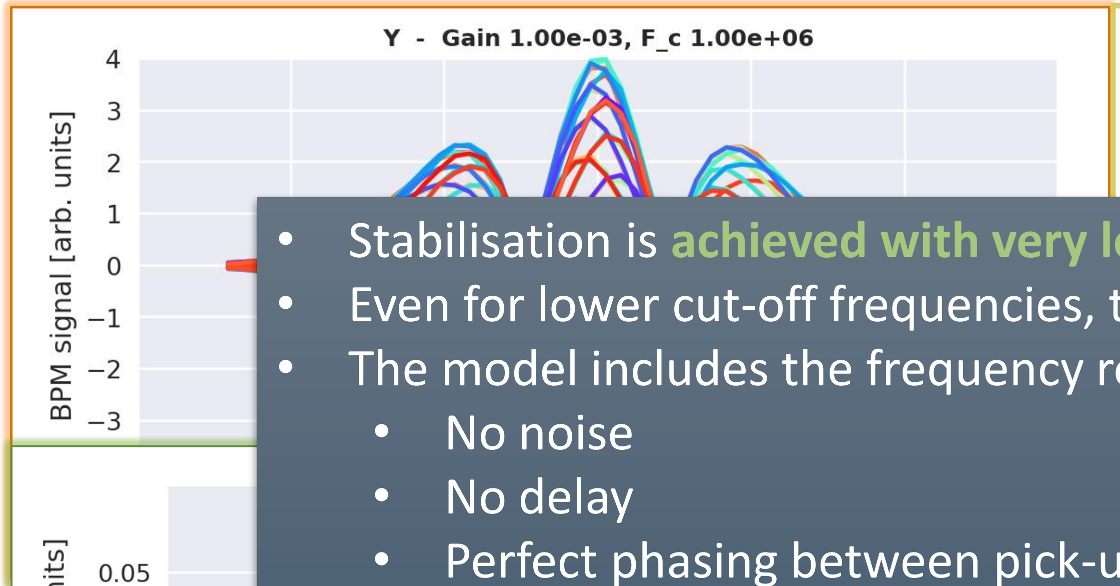


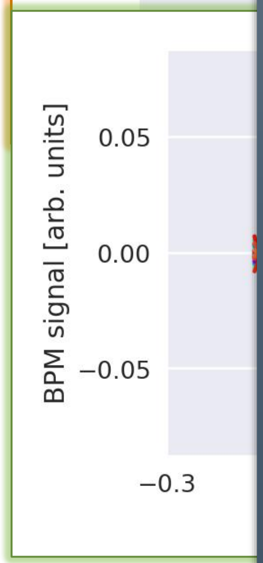



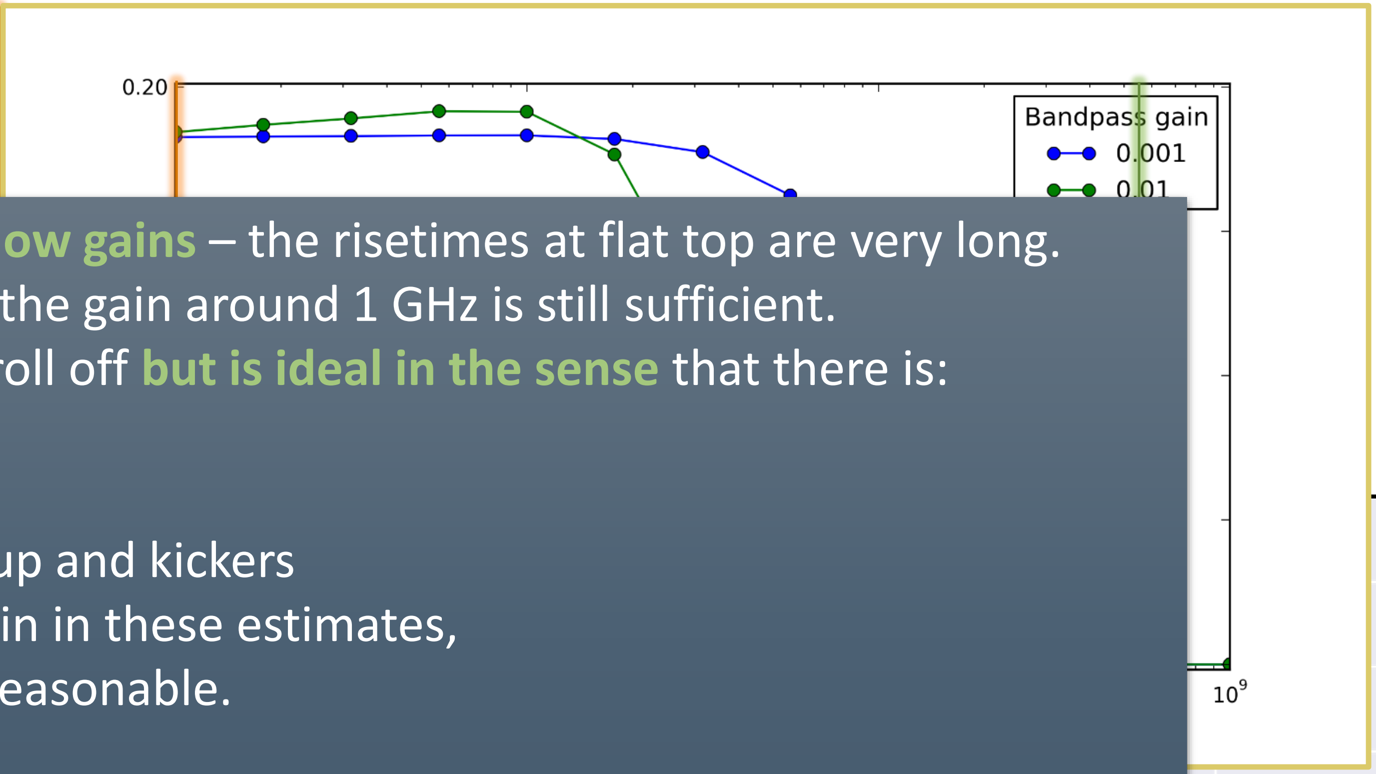



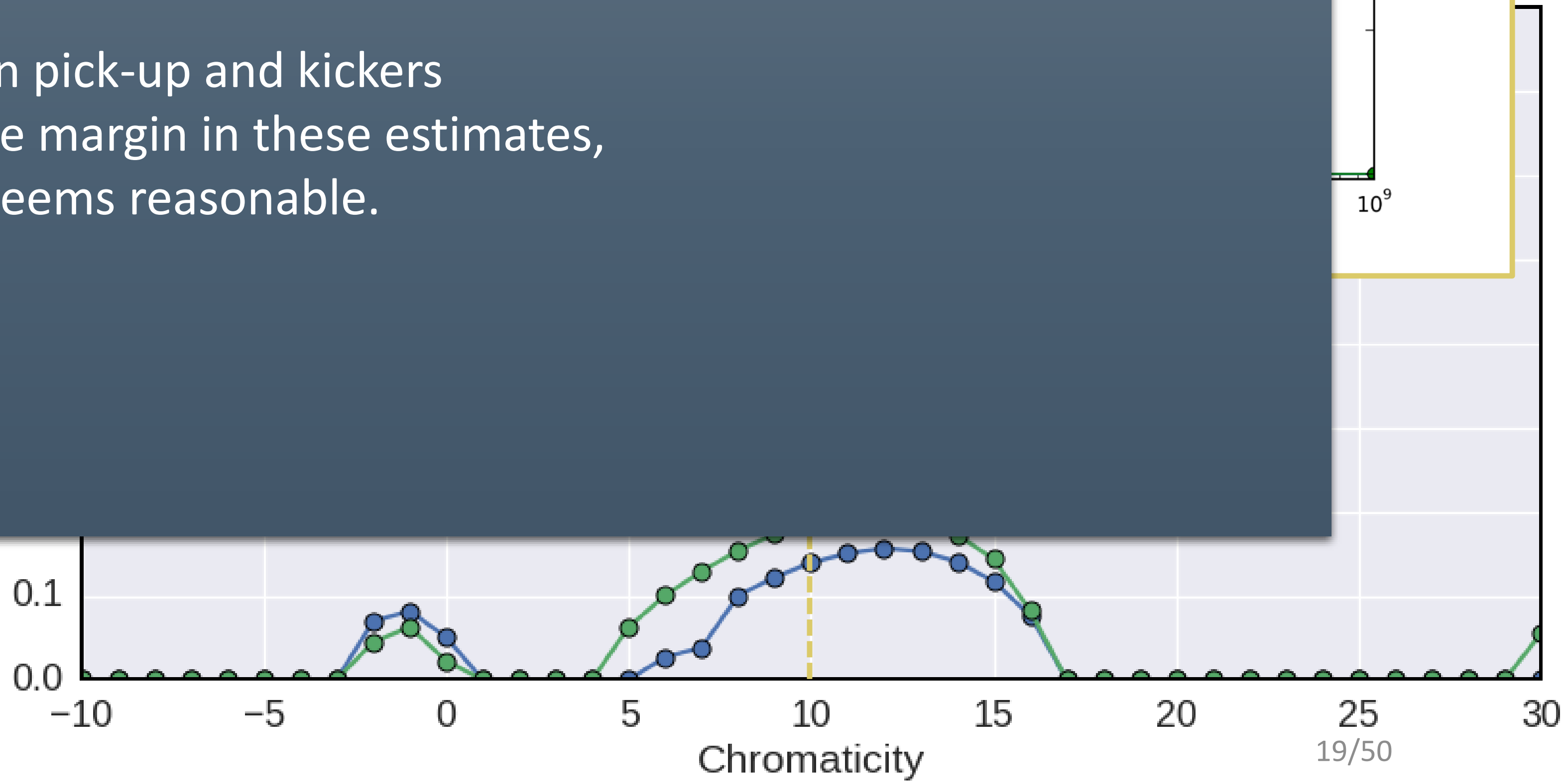

**J. Komppula**

# Impedance and instabilities




- Stabilisation is **achieved with very low gains** – the risetimes at flat top are very long.
- Even for lower cut-off frequencies, the gain around 1 GHz is still sufficient.
- The model includes the frequency roll off **but is ideal in the sense** that there is:
  - No noise
  - No delay
  - Perfect phasing between pick-up and kickers
- We still need to include some margin in these estimates, but a bandwidth of <2 GHz seems reasonable.

**J. Komppula**

# Context & Outline

## Context:

We outline the status and plans for investigating the **impact of electron cloud on beam stability** and how we want to include a **wideband feedback system** into the model.

## Outline:

# E-cloud and instabilities

- Ongoing **simulation campaign with PyHEADTAIL + PyECLOUD** (G. Iadarola, A. Romano)
- Studying stability limits in **dipoles, quadrupoles** and the impact of **chromaticity, octupoles** and, new, also the **transverse damper**

# E-cloud and instabilities

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- Studying stability limits in **dipoles, quadrupoles** and the impact of **chromaticity, octupoles** and, new, also the **transverse damper**
- Simulations in the past have shown **chromaticity to be the main stabilizing parameter** with octupoles virtually ineffective (K. Li, G. Rumolo, IPAC 2012)

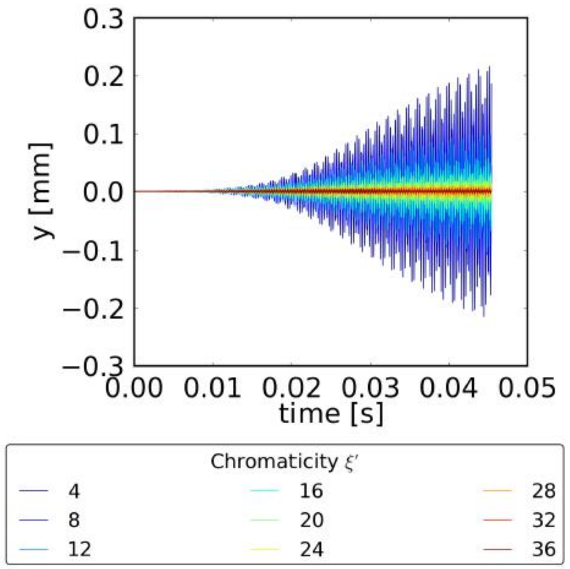


Figure 2: The vertical coherent motion under the influence of electron clouds at an energy of 3.50 TeV for different chromaticities.

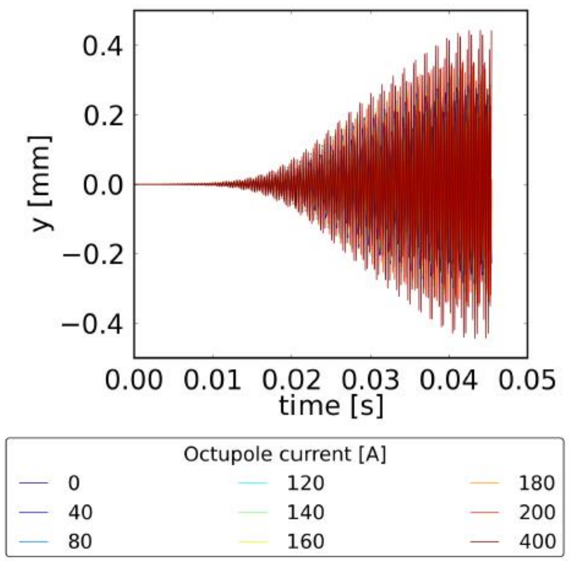


Figure 5: The vertical coherent motion under the influence of electron clouds at an energy of 3.50 TeV for different octupole currents.

# E-cloud and instabilities

- Ongoing **simulation campaign with PyHEADTAIL + PyECLOUD** (G. Iadarola, A. Romano)
- Studying stability limits in **dipoles, quadrupoles** and the impact of **chromaticity, octupoles** and, new, also the **transverse damper**
- Simulations in the past have shown **chromaticity to be the main stabilizing parameter** with octupoles virtually ineffective at high energies (K. Li, G. Rumolo, IPAC 2012)
- What do we want to learn from these simulations?
  - Identify a possible scenario with limitation from e-cloud
  - Include new feedback module and make a bandwidth – gain study

# E-cloud and instabilities

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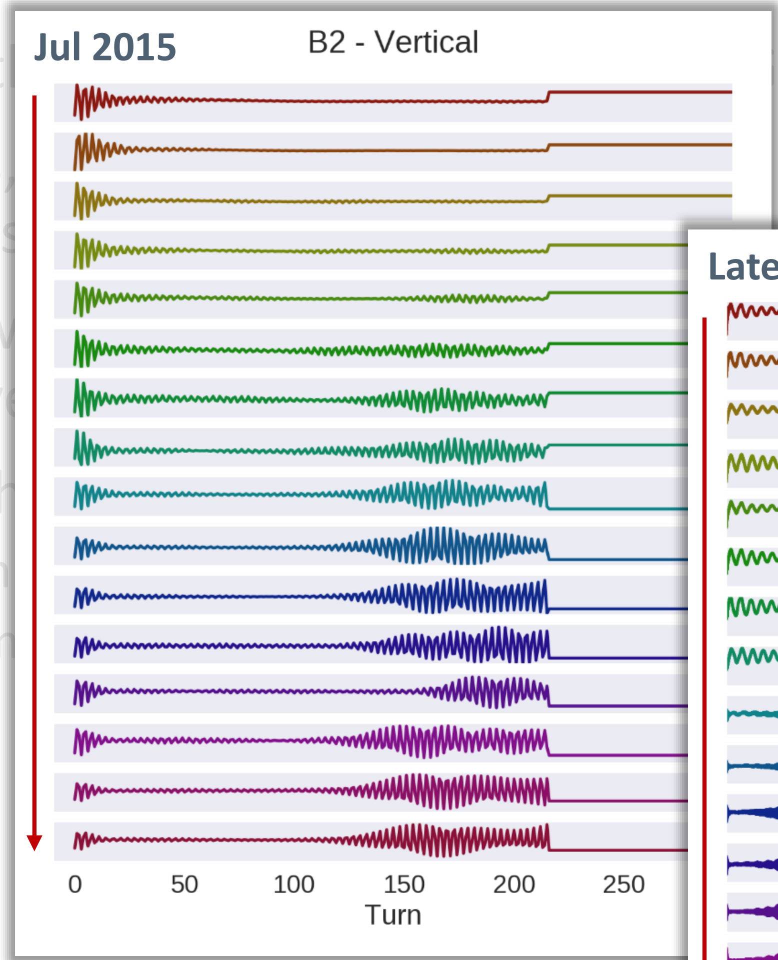
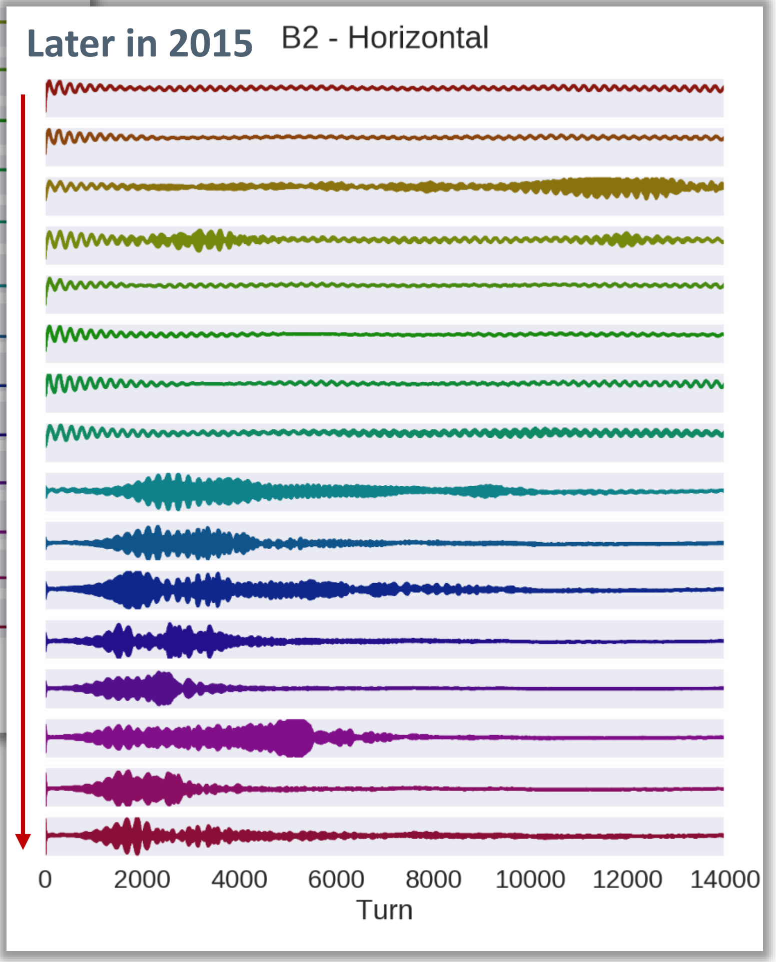
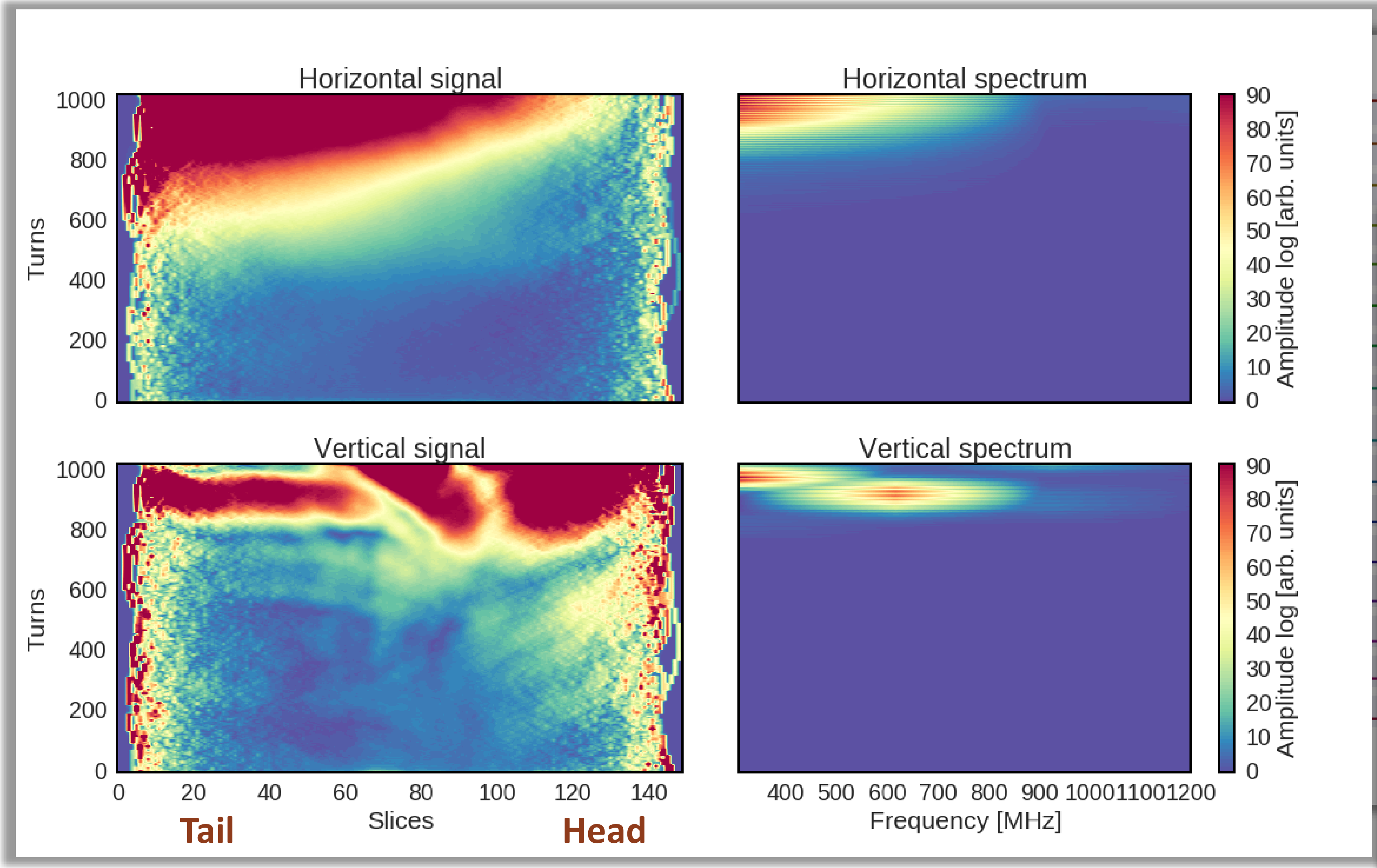


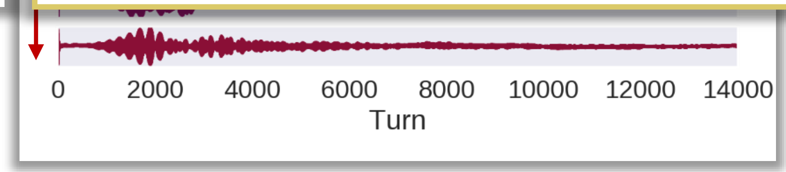

Example from scrubbing runs: in the LHC, it is real!

# E-cloud and instabilities




Simulations:

- E-cloud in dipoles with chromaticity
- Horizontal shows **strong centroid motion** – this **can be damped by the conventional system**
- Vertical motion shows **higher frequency content at ~600 MHz** – this **cannot be damped by the conventional system**
- We will **identify a representative scenario** and add the new feedback to investigate **bandwidth requirements**




A. Romano, G. Iadarola

# Context & Outline

## Context:

We briefly describe the **wideband feedback demonstrator system** developed **in collaboration with SLAC (within the US-LARP)** and highlight some recent MD results that indicate **successful damping of intra-bunch** as an **experimental proof-of-principle**.

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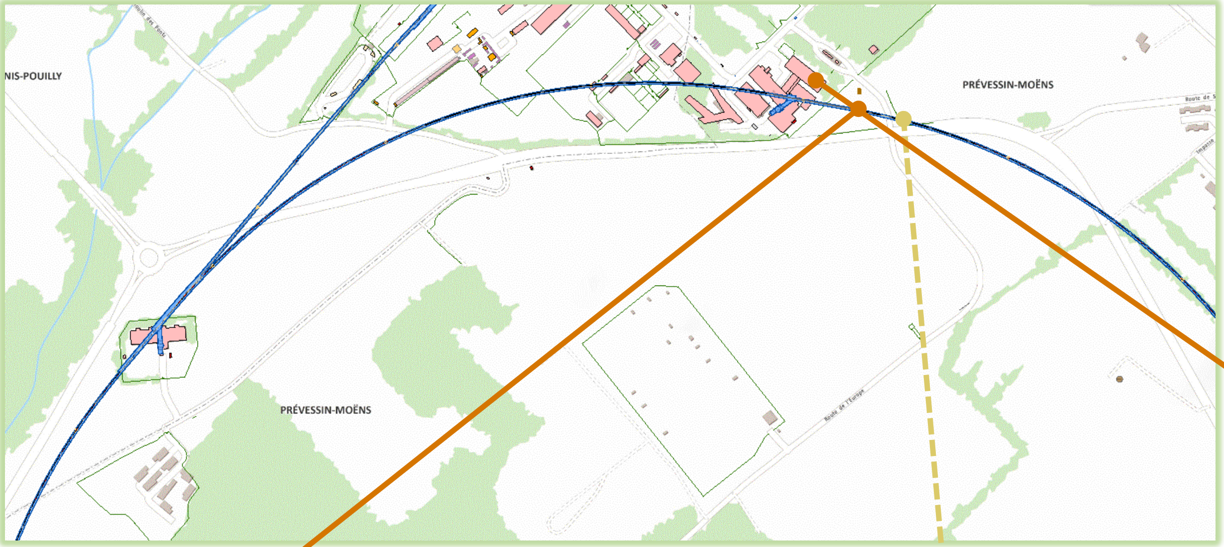
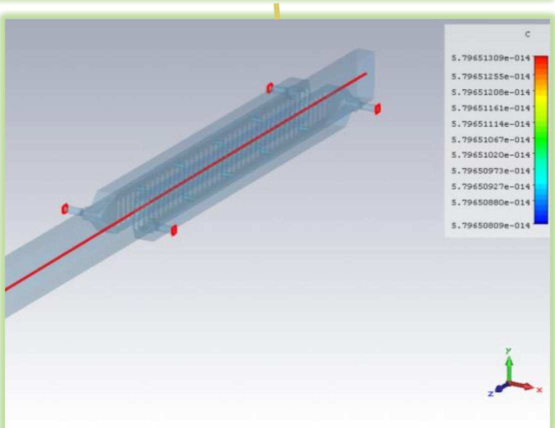
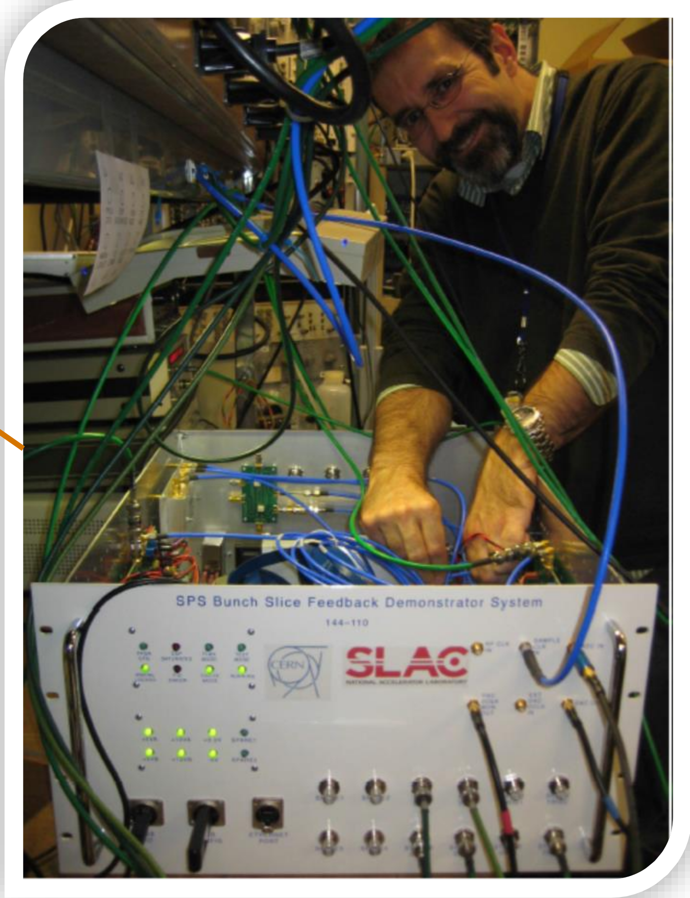
# Can it work in practice?



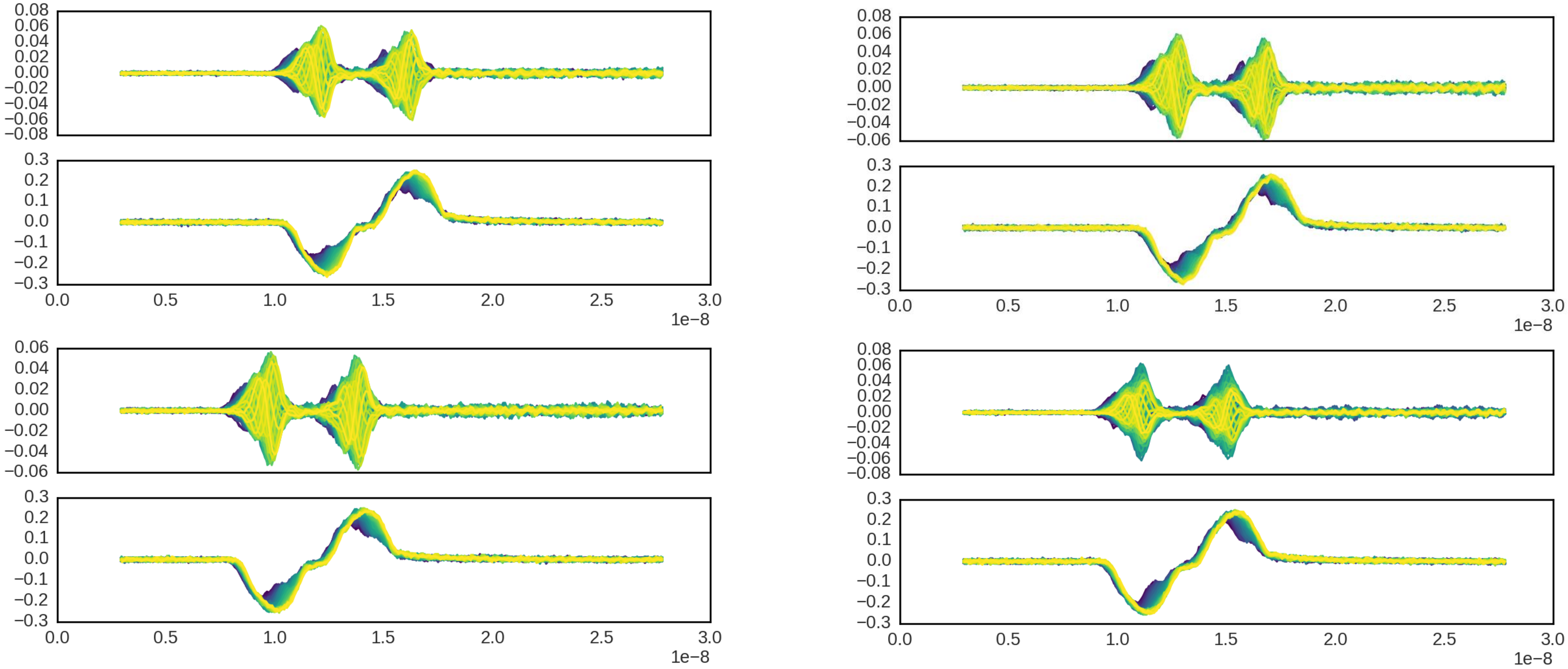



2 stripline kickers + 2 x 2 power amplifiers
Power: 250 W
Frequency range: 5 – 1000 MHz

"The Box":
Complete processing channel from pickups through kicker, running a digital **reconfigurable system** up to **4 GS/s** is installed and ready for use at 3.2 Gs/s. Now includes **multi-bunch processing** of up to 64 bunches in any configuration.

# Observation in the SPS for Q26 single bunch MDs

- Different shorts:
  - Top: delta signal – bottom: sum signal
  - Yellow: early turns – blue: late turns



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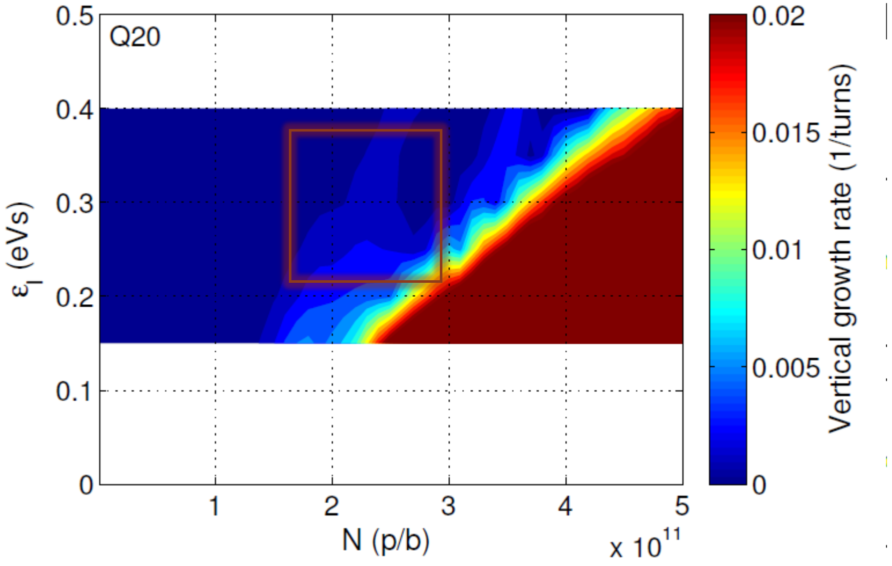
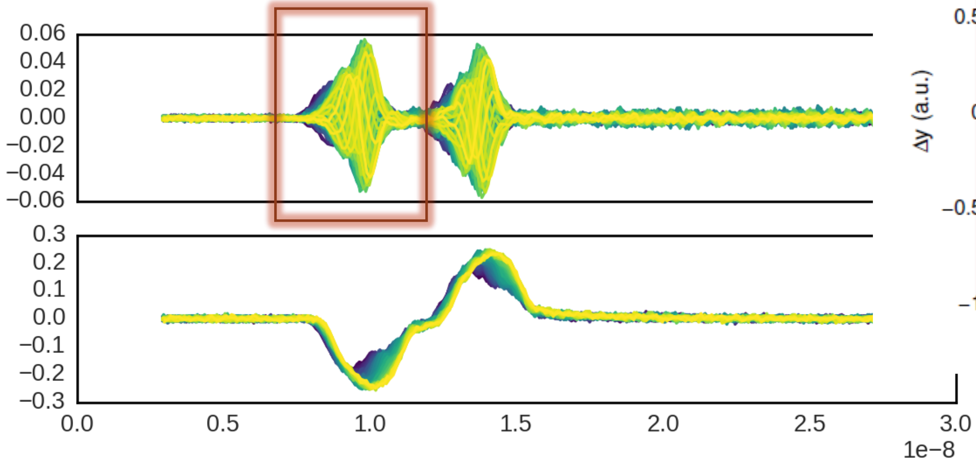
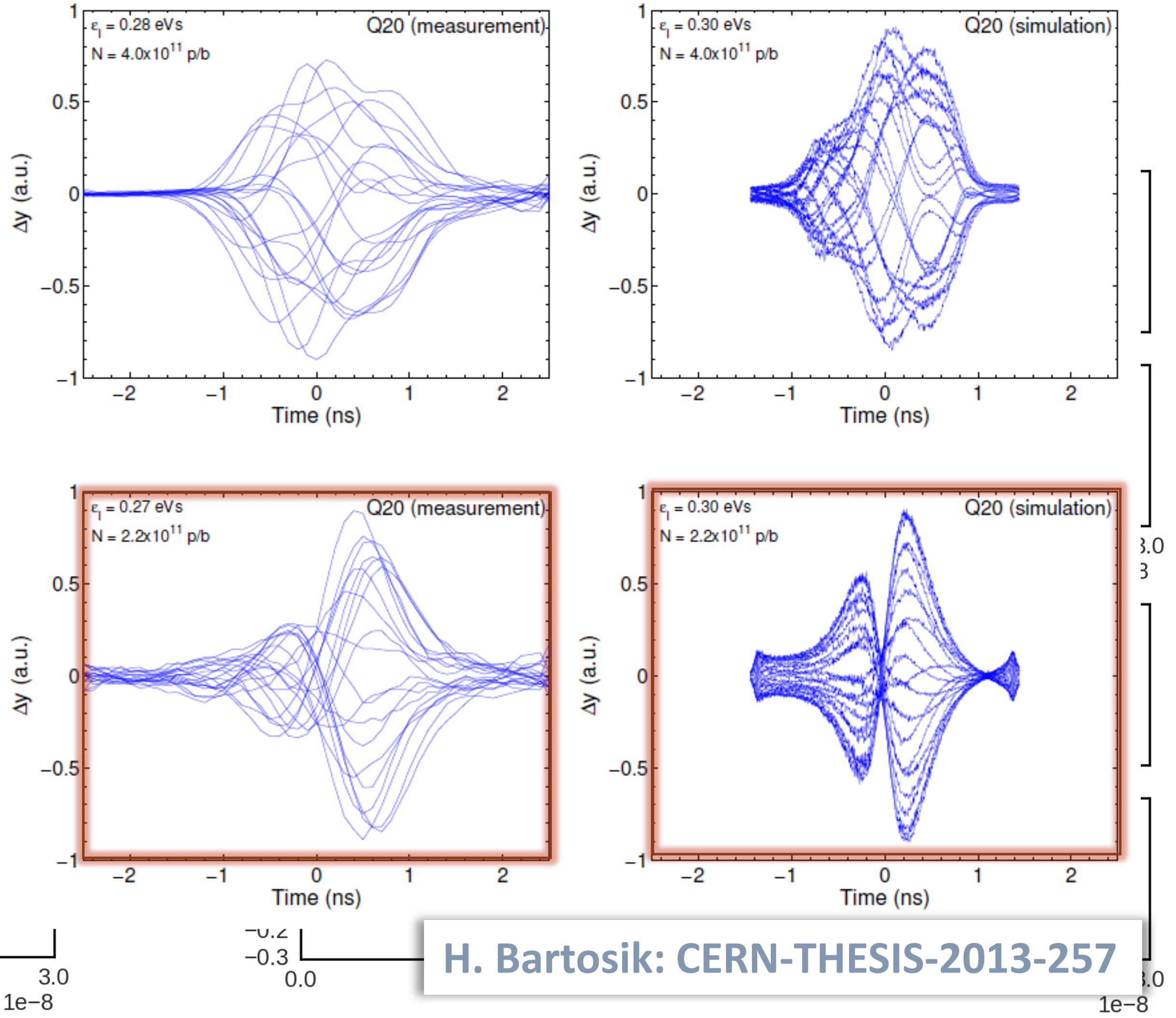


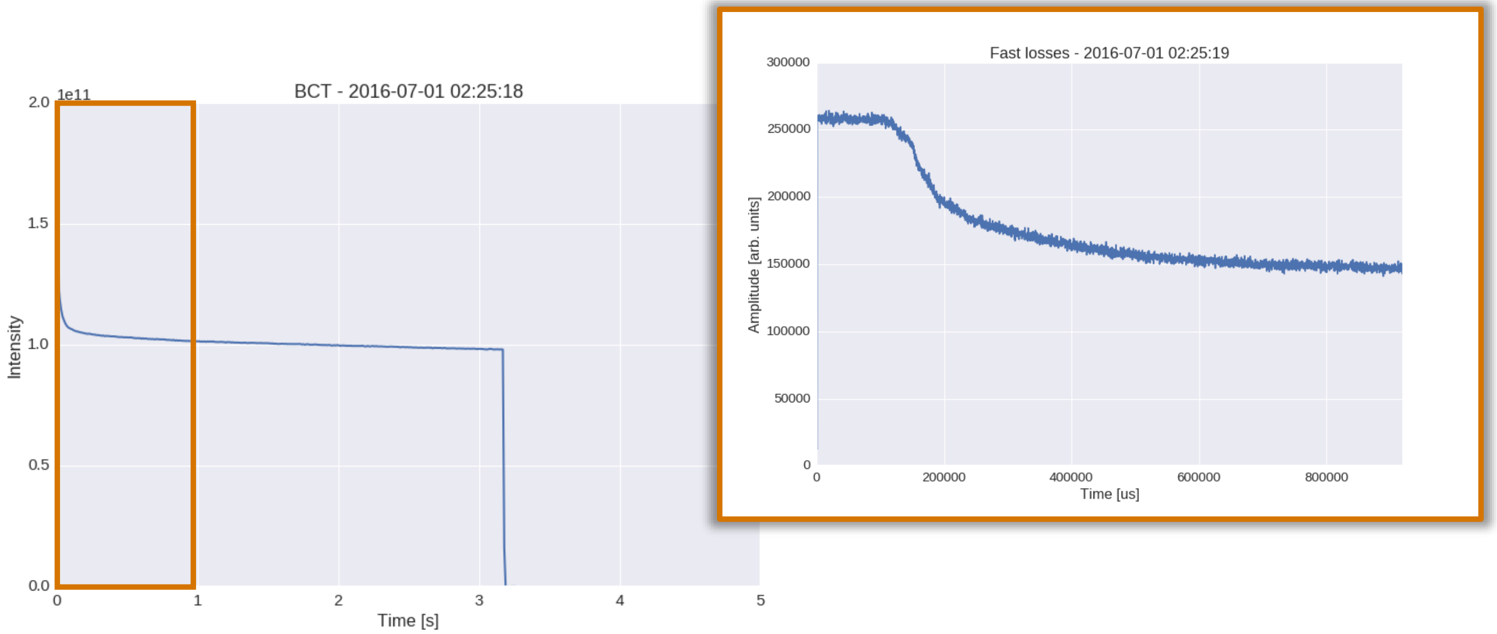




**H. Bartosik: CERN-THESIS-2013-257**

# Data from the ADC of the Box

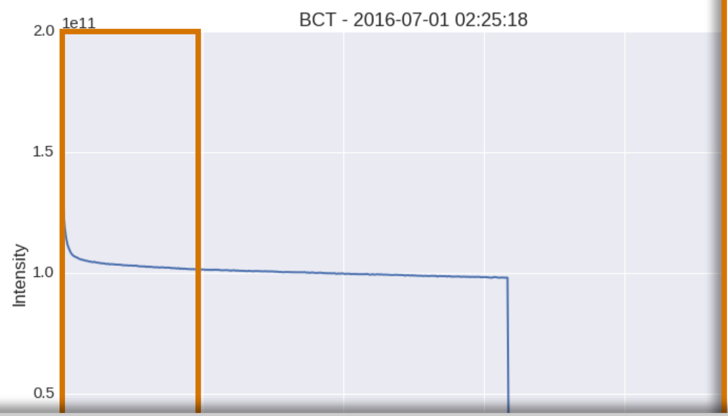
**Open loop**

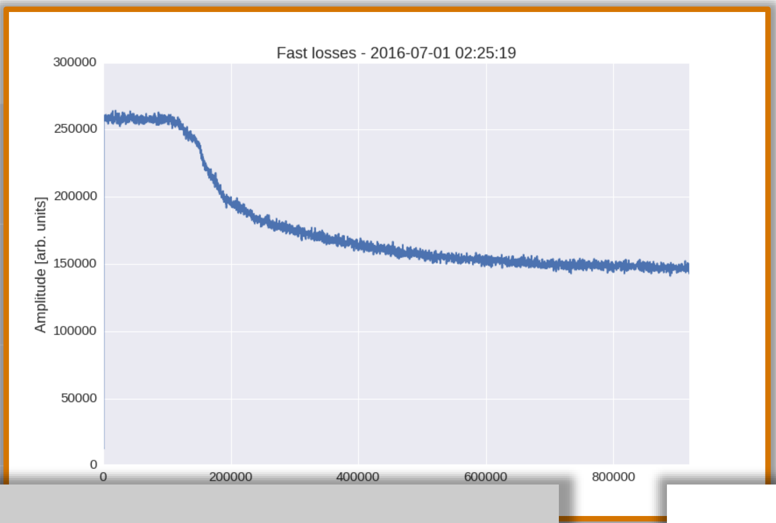


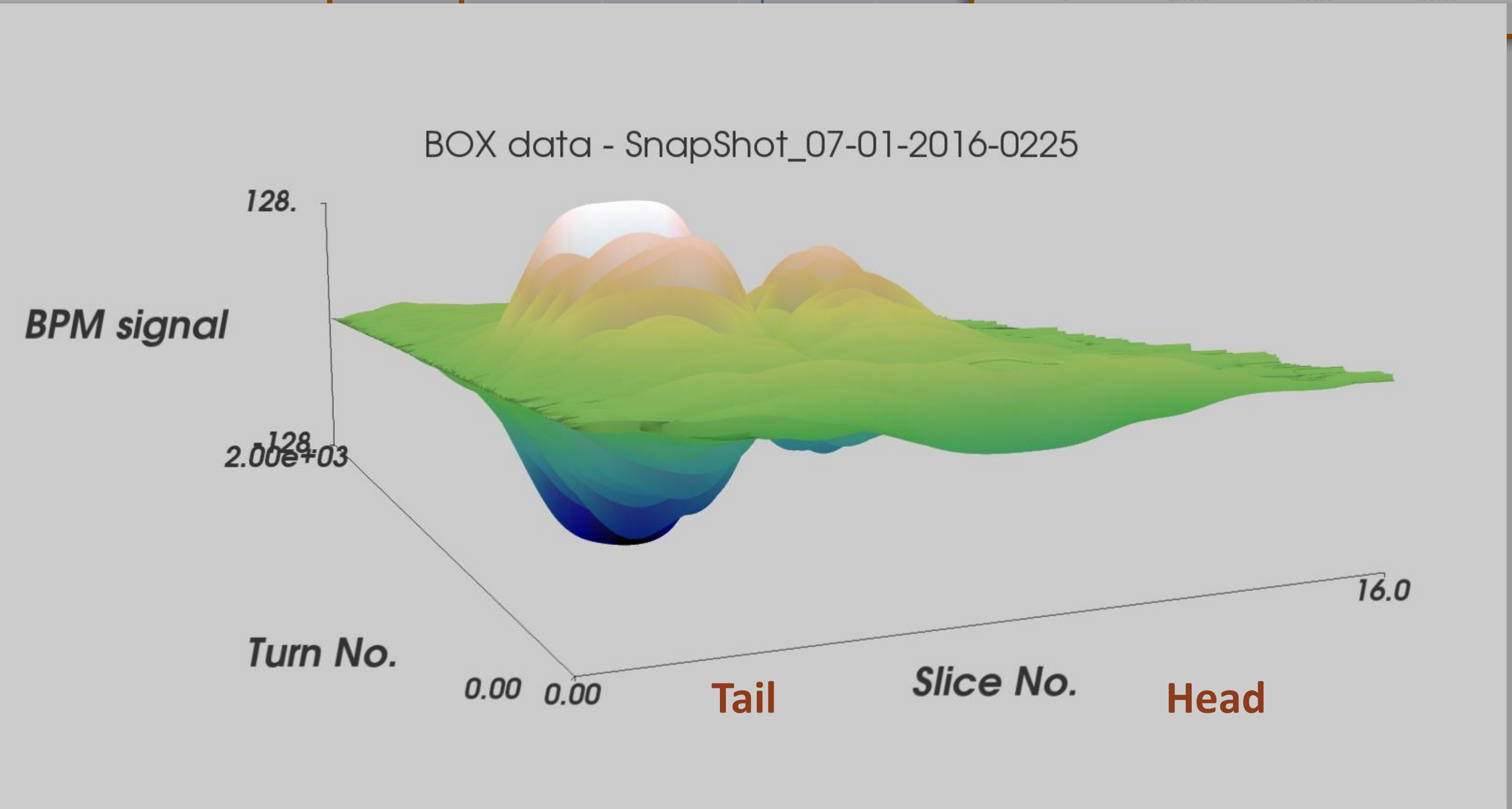

- Intensity ~1.6e11 – 1.8e11
- Low vertical chromaticity
- Low 200 MHz voltage
- Transverse damper active to remove injection oscillations

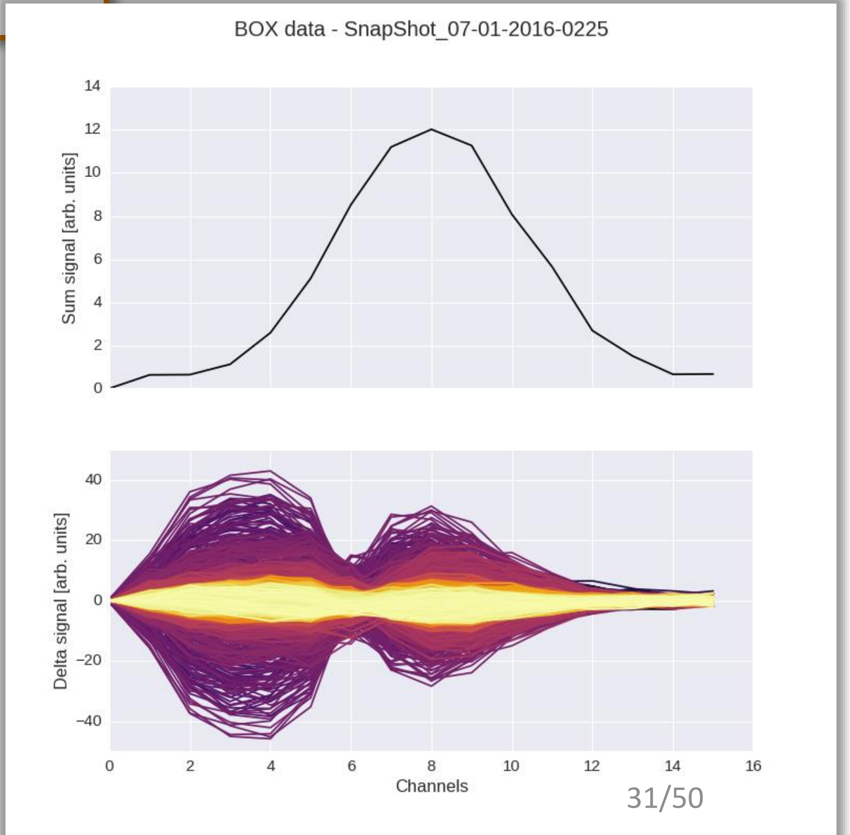
# Data from the ADC of the Box

**Open loop**



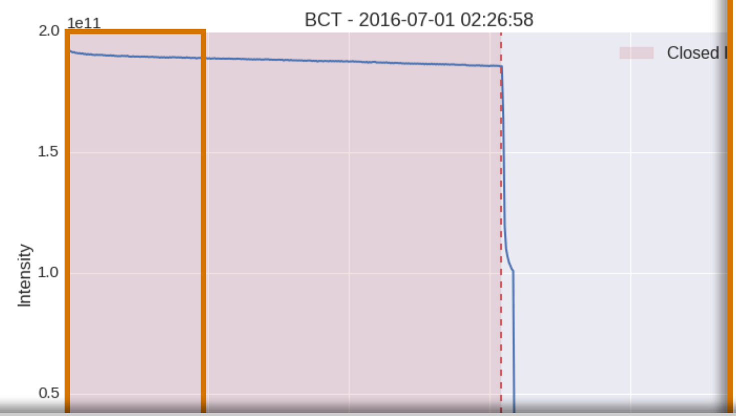



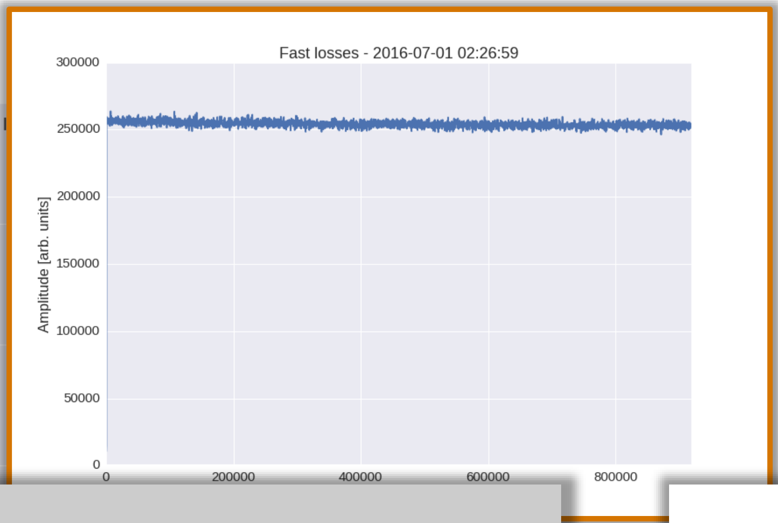



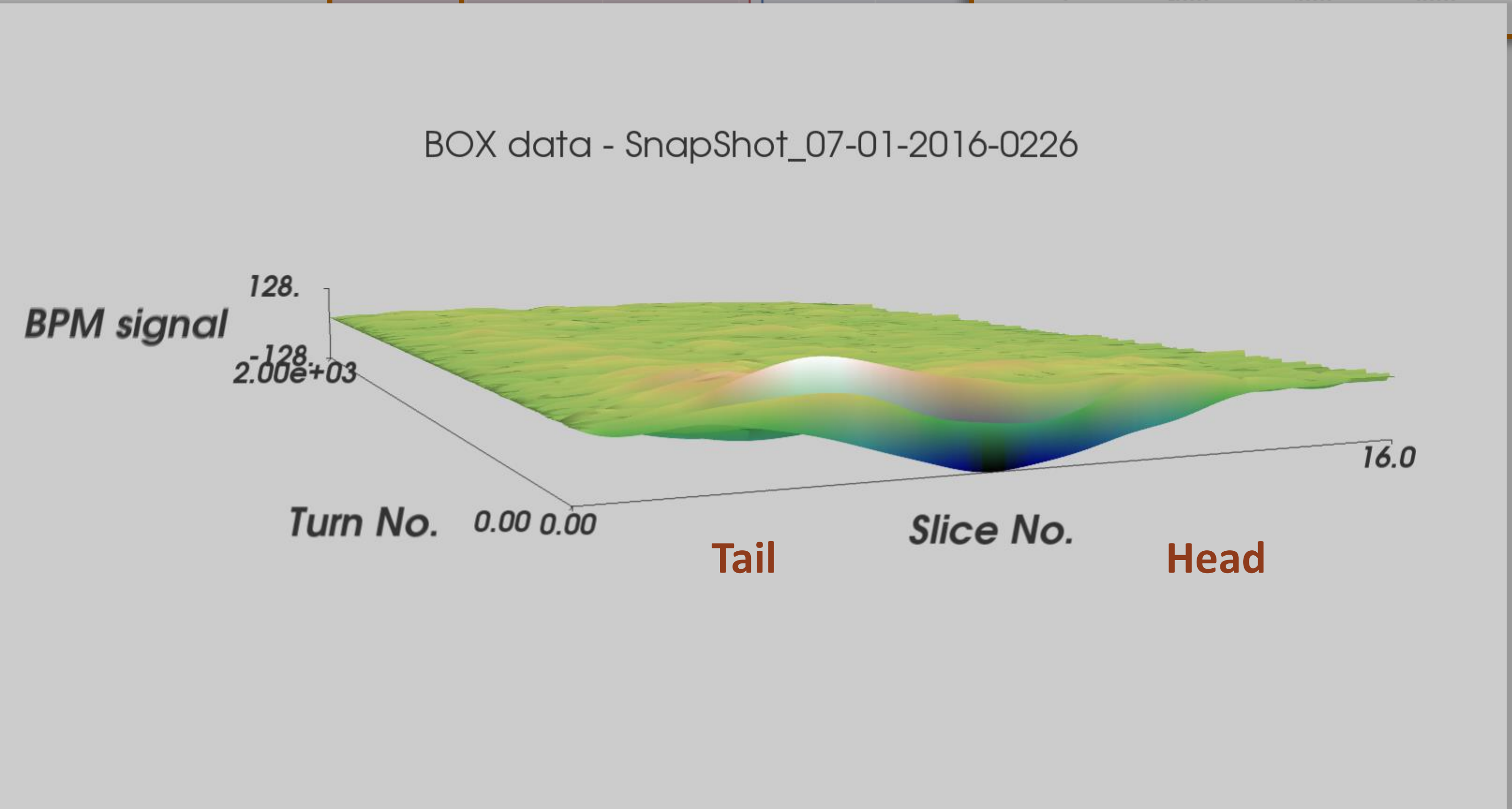



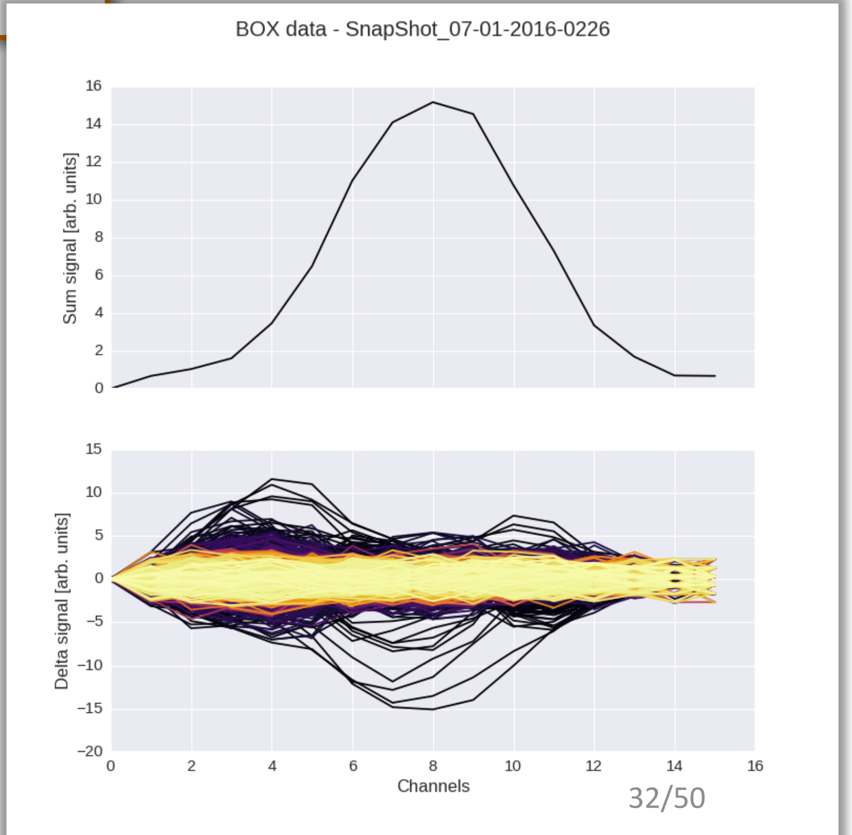
# Data from the ADC of the Box

**Closed loop**



# Context & Outline

## Context:

Based on what we have learned so far, we investigate **specifications and options for wideband feedback system configurations which are suitable for HL-LHC**.

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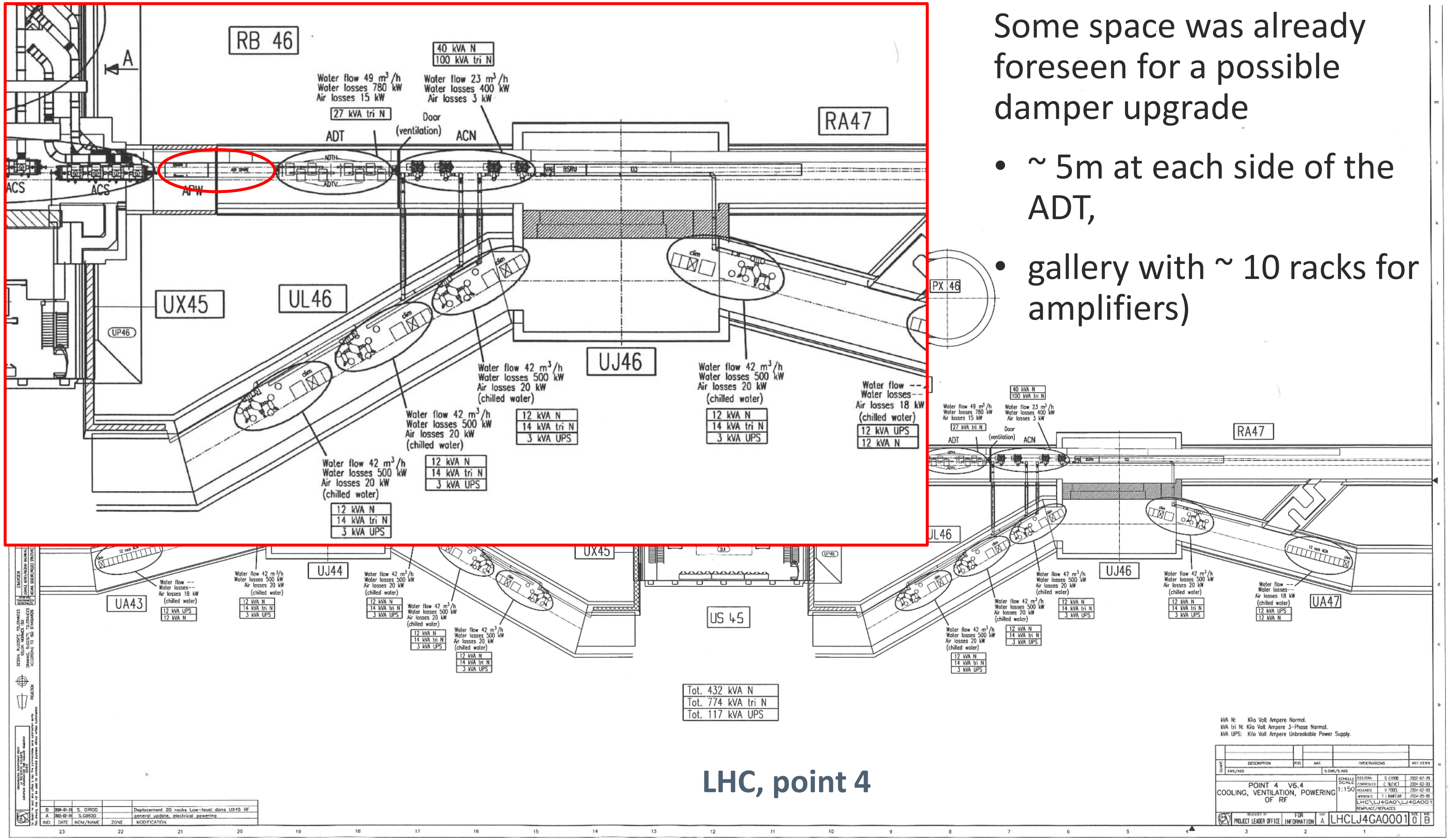
# Potential location in HL-LHC




**LHC, point 4**

Some space was already foreseen for a possible damper upgrade

- ~ 5m at each side of the ADT,
- gallery with ~ 10 racks for amplifiers)

# Kicker specs – examples from the SPS

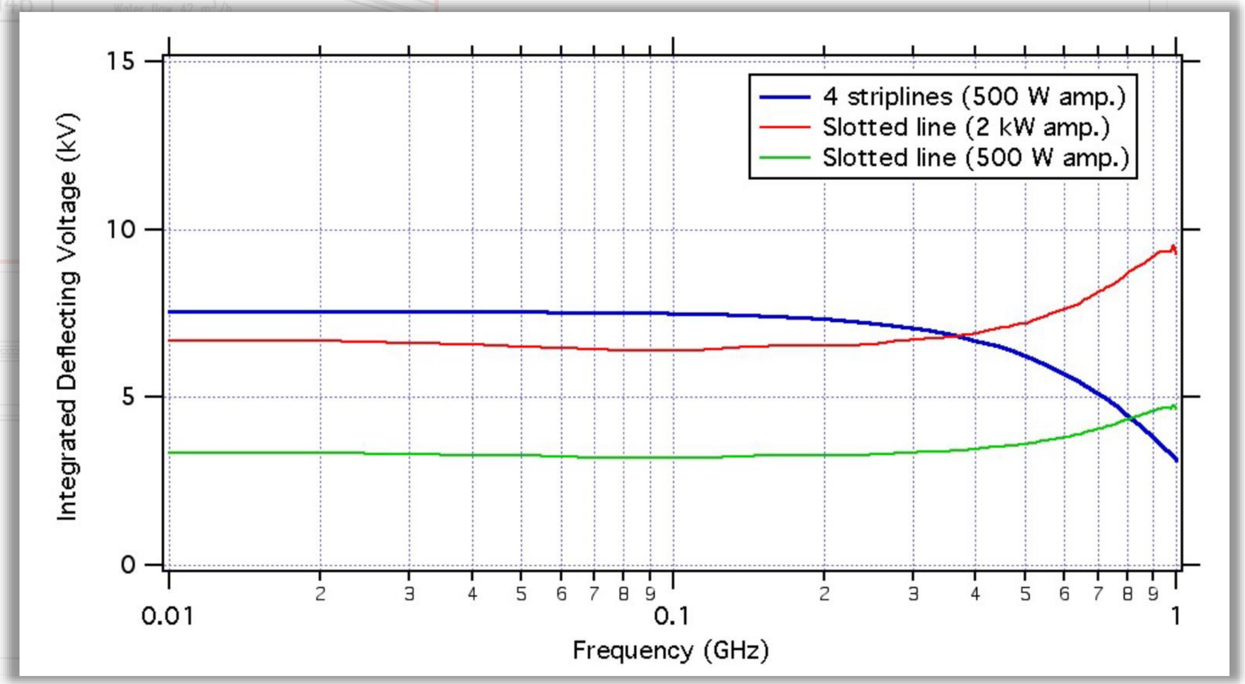
| | $N_{mod}$ | $N_{amp}$ | $P_{amp}$ (W) | $P_{tot}$ (W) | $V_\perp$ (kV) 100 MHz | 250 MHz | 500 MHz | 750 MHz | 1000 MHz |
|---|---|---|---|---|---|---|---|---|---|
| Striplines | 4 | 8 | 500 | 4000 | 7.6 | 7.3 | 6.3 | 4.9 | 3.2 |
| Striplines | 44 | 88 | 100 | 8800 | 37.3 | 35.9 | 31.1 | 23.9 | 15.5 |
| Slotline | 1 | 2 | 500 | 1000 | 3.2 | 3.3 | 3.6 | 4.2 | 4.6 |
| Slotline | 1 | 2 | 2000 | 4000 | 6.4 | 6.6 | 7.2 | 8.4 | 9.3 |
| Slotline | 6 | 12 | 300 | 3600 | 14.8 | 15.3 | 16.7 | 19.4 | 21.5 |

$$\Delta x' \propto \frac{eV_\perp}{E}$$

- Stripline – 10 cm
- Slotline – 1 m
- +- 5 m on each side

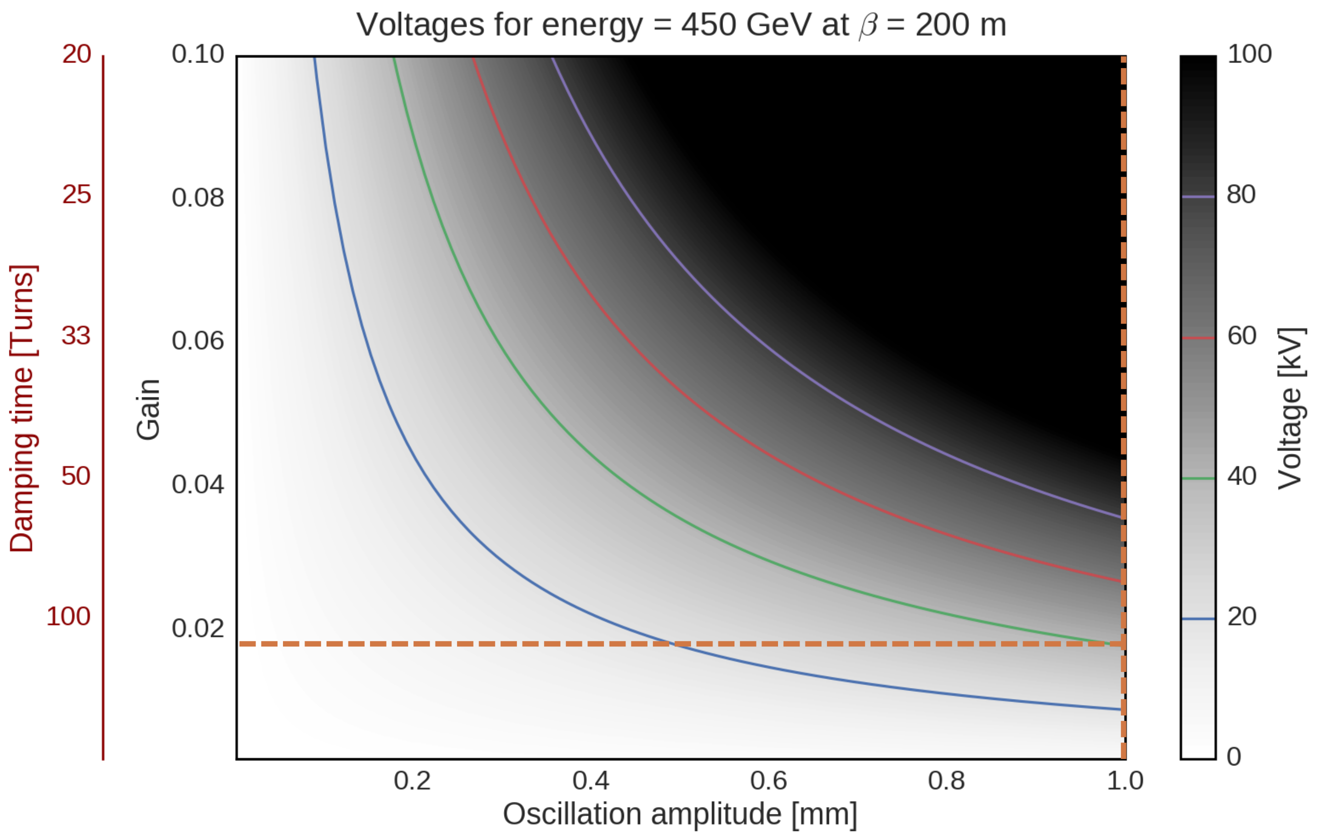
**J. Cesaratto et al.:**
***SPS Wideband Transverse Feedback Kicker: Design Report,***
**CERN-ACC-NOTE-2013-0047**

LHC would of course require a re-design, that could, however, build on the SPS designs



# Wideband feedback system – scaled to LHC

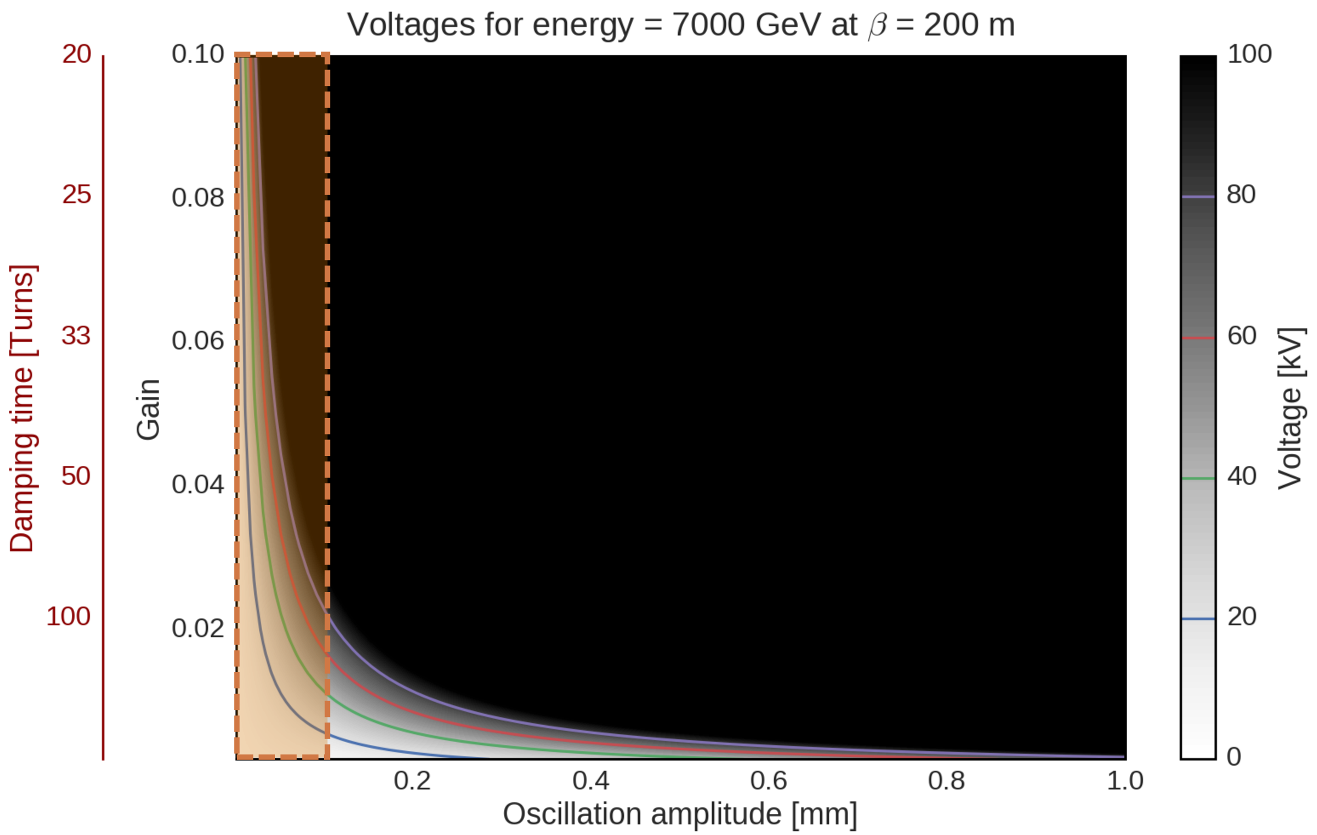
- Damper kick strength/voltage:
  - With 5 m space – consider installation of 4 slotline kickers → **V ~ 37 kV with 2 kW amplifiers at 1 GHz**
  - Slotline dimensions are smaller for LHC – can gain **a factor 2 in kick strength**




**Millimetre oscillations can still be damped at reasonable rates.**

# Wideband feedback system – scaled to LHC

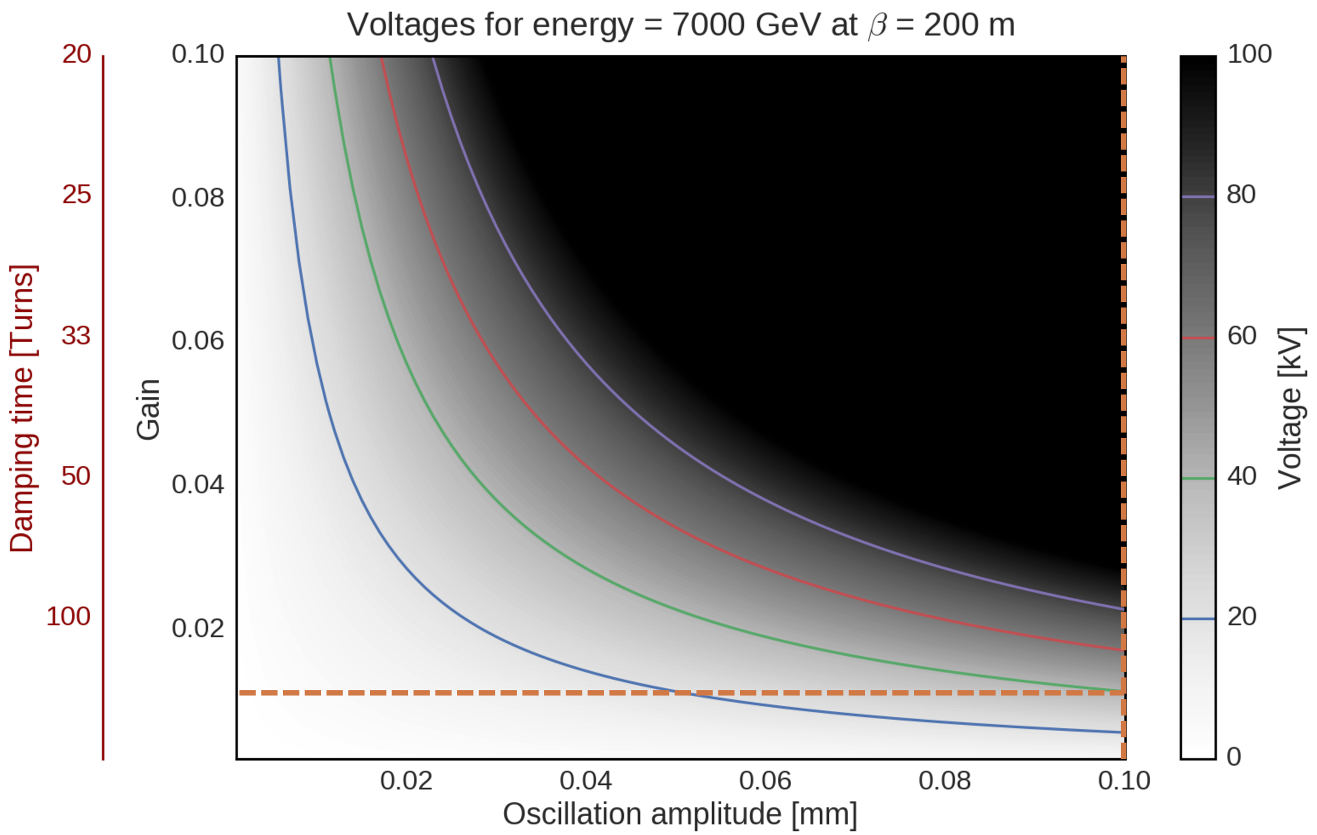
- Damper kick strength/voltage:
  - With 5 m space – consider installation of 4 slotline kickers → **V ~ 37 kV with 2 kW amplifiers at 1 GHz**
  - Slotline dimensions are smaller for LHC – can gain **a factor 2 in kick strength**




**Beam gets more rigid at flat-top, where…**

# Wideband feedback system – scaled to LHC

- Damper kick strength/voltage:
  - With 5 m space – consider installation of 4 slotline kickers → **V ~ 37 kV with 2 kW amplifiers at 1 GHz**
  - Slotline dimensions are smaller for LHC – can gain **a factor 2 in kick strength**



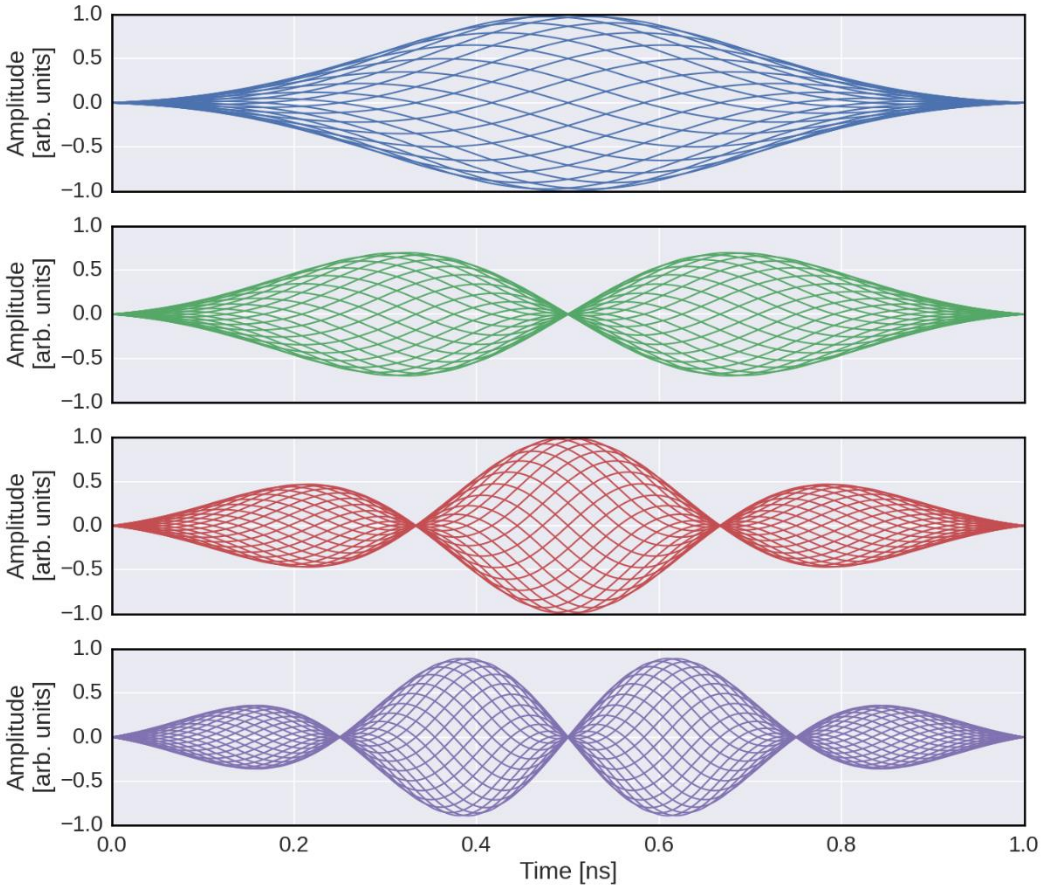

**… transient effects are usually less critical. If detection level is at the <100 um range, we still get reasonable damping rates.**

# Wideband feedback system – scaled to LHC

- Damper kick strength/voltage:
  - With 5 m space – consider installation of 4 slotline kickers → **V ~ 37 kV with 2 kW amplifiers at 1 GHz**
  - Slotline dimensions are smaller for LHC – can gain **a factor 2 in kick strength**
- Bandwidth:
  - Slotline dimensions are smaller for LHC – can gain **a factor 2 in frequency reach**

  Options:

  1. **Extension of current system:**
     long stripline at 40 MHz for true bunch-by-bunch damping
  2. **Band-by-band approach:**
     Stripline at 400 MHz in combination with slotlines at 800, 1200, 1600, 2000, 2400,… MHz



# Wideband feedback system – scaled to LHC

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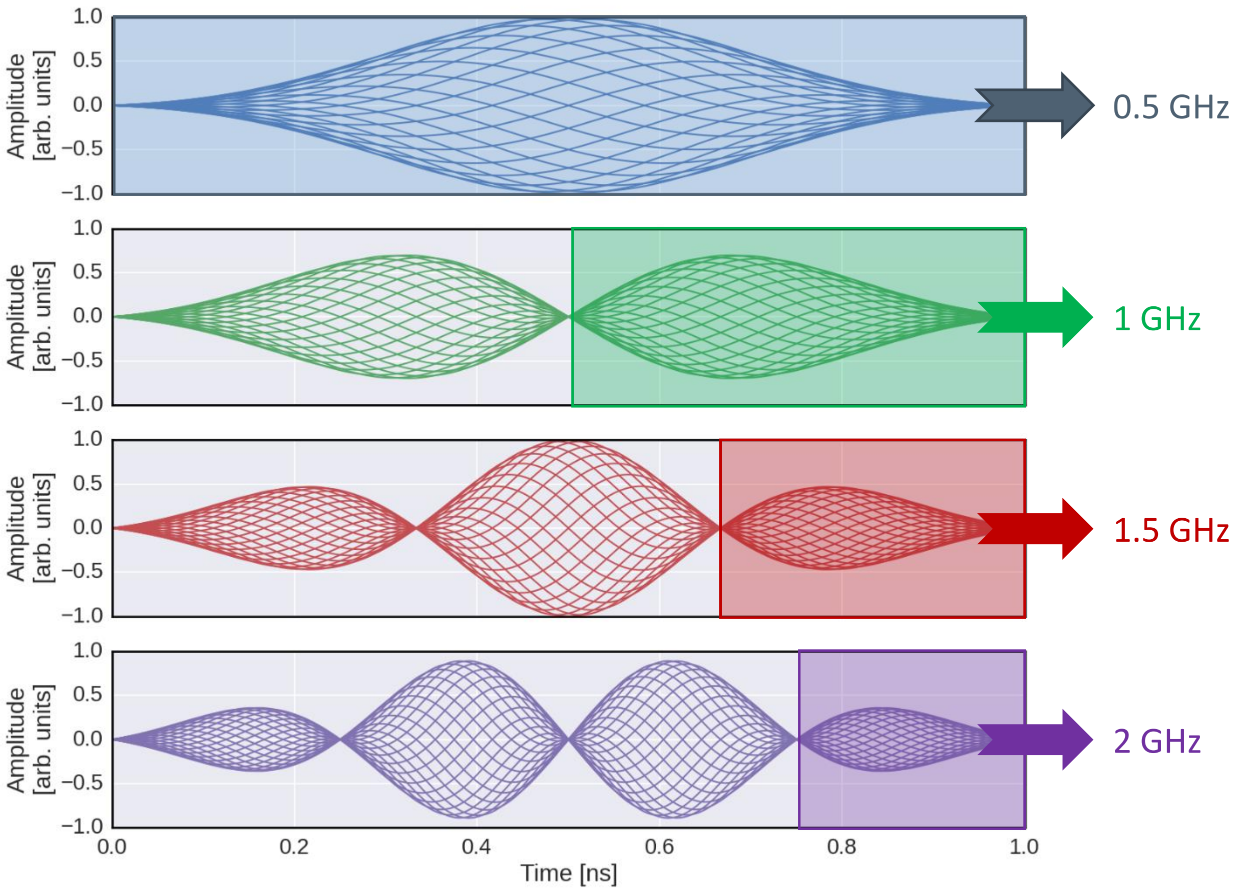



**Instabilities observed in the LHC, typically below 2GHz.**

# Context & Outline

## Context:

We answer the question whether a **wideband feedback system will be needed for HL-LHC** and check **how this compares to other mitigation measures** such as the **RF quadrupole**.

## Outline:

1. Introduction
2. Instabilities from impedance
3. Instabilities from electron cloud
4. Performance of demonstrator system
5. Specification together with need, capabilities and cost

# Do we need it? – HL-LHC predictions

- Impedances:
  - Simulations based on the present HL-LHC impedance model predict that the present means of stabilization (i.e. Landau octupoles and transverse damper) are sufficient to ensure beam stability
- E-cloud:
  - Simulation work is ongoing
  - E-cloud in dipoles: main source of instabilities (at least at flat top) – ‘scrubbable?’
  - E-cloud in quadrupoles: less crucial for instabilities
  - E-cloud in triplets: triplets are coated
- Incoherent effects:
  - Tune spread significant due to high chromaticities and octupoles
  - In addition enhanced by LR and HO collisions
  - Means of compensation are under investigation (i.e. wires)

# Do we need it? – HL-LHC predictions

Simulations using the impedance model suggest it may not be needed.

Simulations using e-cloud are still in progress.

Simulations rarely include all relevant effects:

- The real machine **tells a different story** – running at high chroma, instabilities are still observed throughout the cycle (2012, injection, squeeze, adjust, stable beams)
- The tasks is to **identify relevant effects** and to **include them into the simulations** (e-cloud, non-ideal transverse damper, **or linear coupling as a recent example**)
- Symbiosis between **observations and simulations** will eventually enable to draw a **complete picture**

- E-cloud in quadrupoles: less crucial for instabilities
- E-cloud in triplets: triplets are coated

Beam stability corresponding **to exclusively the pure impedance**, as such, was not yet demonstrated in the machine.

We do not know whether there are any **hard limits** (e.g. minimum SEY, correction limits).

Strategy

- We need to continue to **gather experience with the running machine**
- We need to in parallel **continue R&D on possible mitigation measures** to be **ready with a system** that can be deployed in case **nominal performance turns out to be limited or even excluded**.

# Comparison of mitigation techniques

| | Active feedback | Passive elements<br>(e.g. RF Quad) | Comments |
|---|---|---|---|
| Control method | Active – resistive feedback | Passive – tune spread | (*) AF: active feedback |
| Additional functionality | High | Low | AF: Individual bunch excitation, diagnostics etc. |

# Comparison of mitigation techniques

| | Active feedback | Passive elements (e.g. RF Quad) | Comments |
|---|---|---|---|
| Co | | Pass | |
| Ac | | Low | |
| Co | | Low | |
| Fl | | Low | |
| Co | | By d | |
| Sl | ns | Dem | |
| Fa | | Not | |
| E- | ns | Not | |
| St | | Prot deve | |
| Co | | ??? | |


- Highly **configurable and powerful** – can forge the 'ultimate' cure
- Complex, **needs setup, understanding, continuous expert support**


- General purpose, **all-round, generic cure** for 'light' instabilities – but has **inherent limits**
- Over-the-counter, **easy to operate**

# Path of choice

- Continue **R&D on kickers** – target for ~2 GHz
- Exploit the **SPS system** for studies and to gain experience
- Amplifiers can still be investigated, to ultimately favour:
  - Full-blown **wideband feedback** for maximum flexibility and gain – expensive and main cost driver
  - **Band-by-band** approach – less flexible but likely the cheaper solution

# Summary

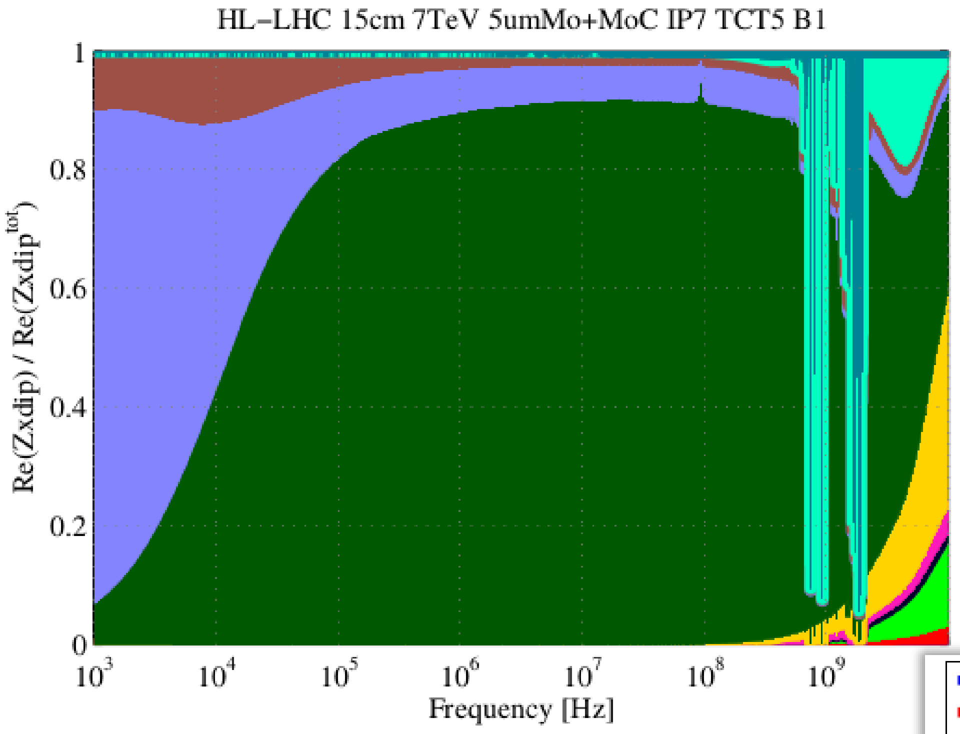
- We investigated beam instabilities in the HL-LHC **from pure impedances** and **demonstrated numerically** that a wideband feedback system can mitigate these instabilities.
- We sketched a path for investigating instabilities in the HL-LHC **from electron cloud** and how **we want to check** whether a wideband feedback system can mitigate these instabilities.
- We showed recent examples for an **experimental proof-of-principle** using the wideband feedback demonstrator system installed in the SPS.
- We sketched **possible scenarios of real systems** in the machine.
- We presented a strategy on **how to proceed** with this type of systems and **how they compare** to an RF quadrupole.

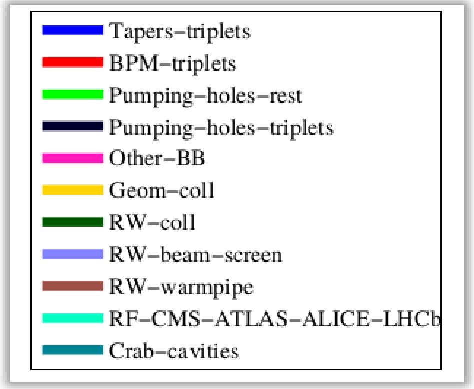
# Open questions and future studies

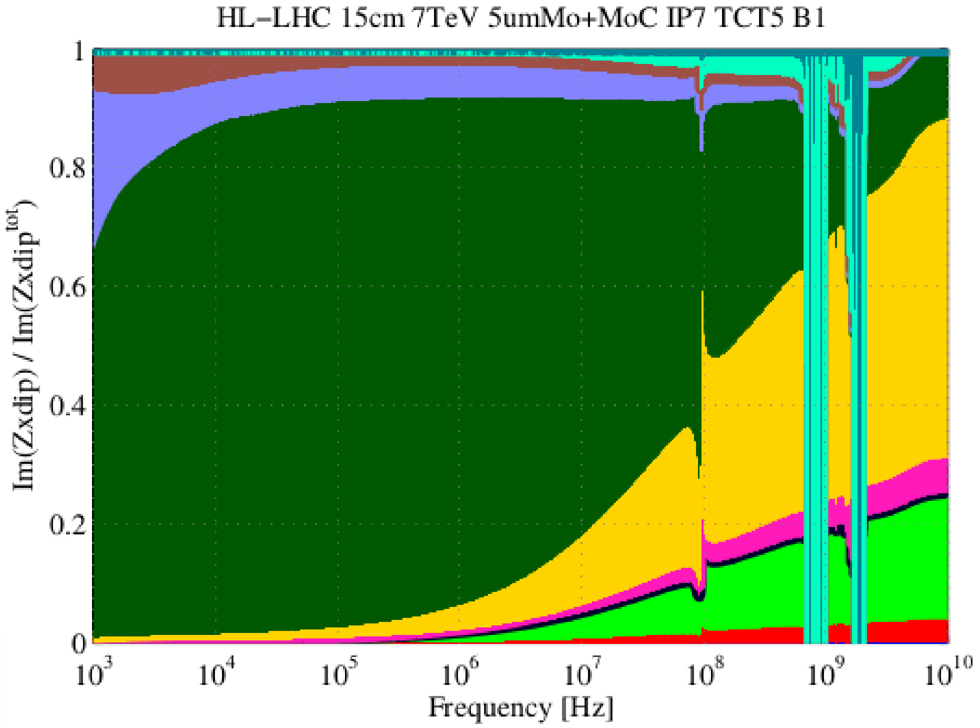
- Include the system in e-cloud simulations.
- Refine the system to add delays, real DSP, noise etc.
- Investigate the impact of noise on the emittance.
- Check saturation effects.
- Any other items linked to this that urgently need to be checked?

# BACKUP

# HL-LHC impedance horizontal plane – 7 TeV

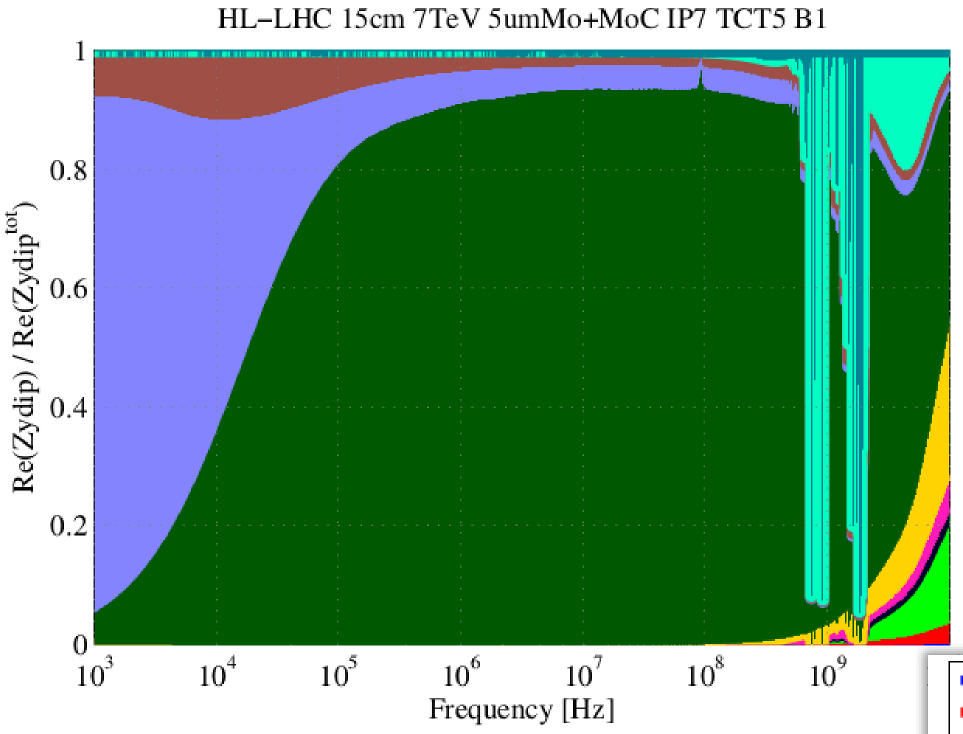


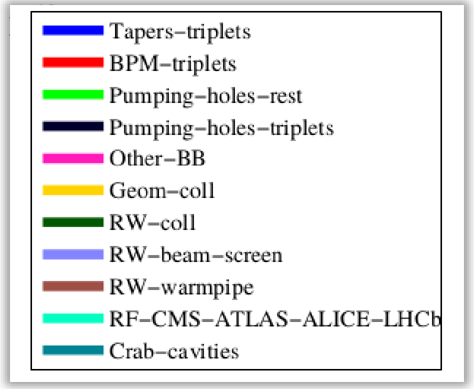



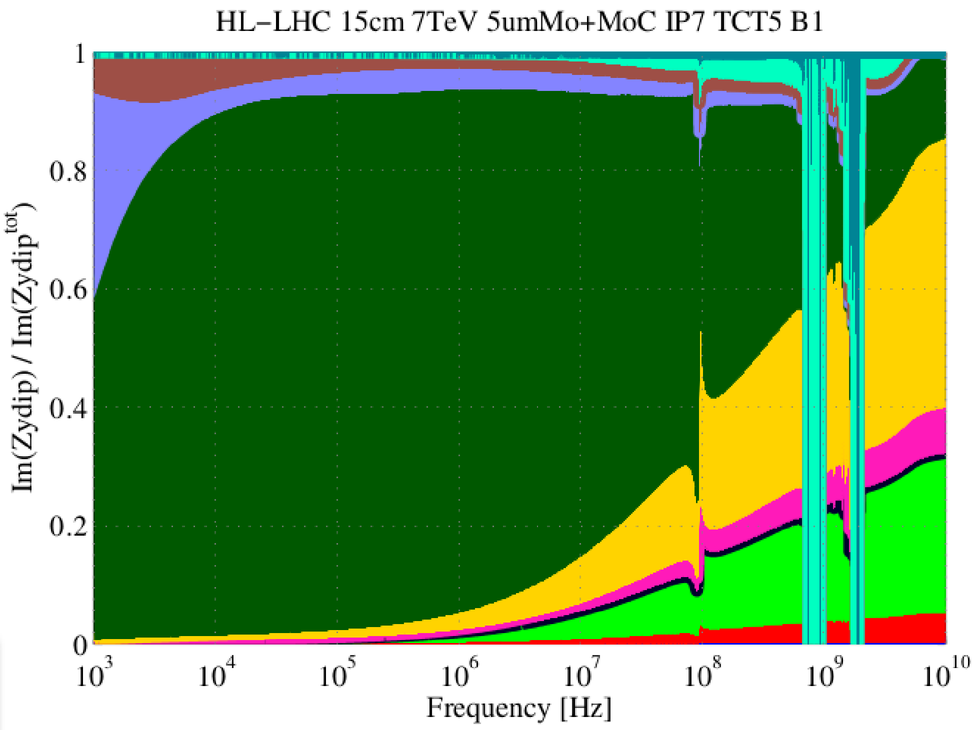




**N. Biancacci**

# HL-LHC impedance vertical plane – 7 TeV

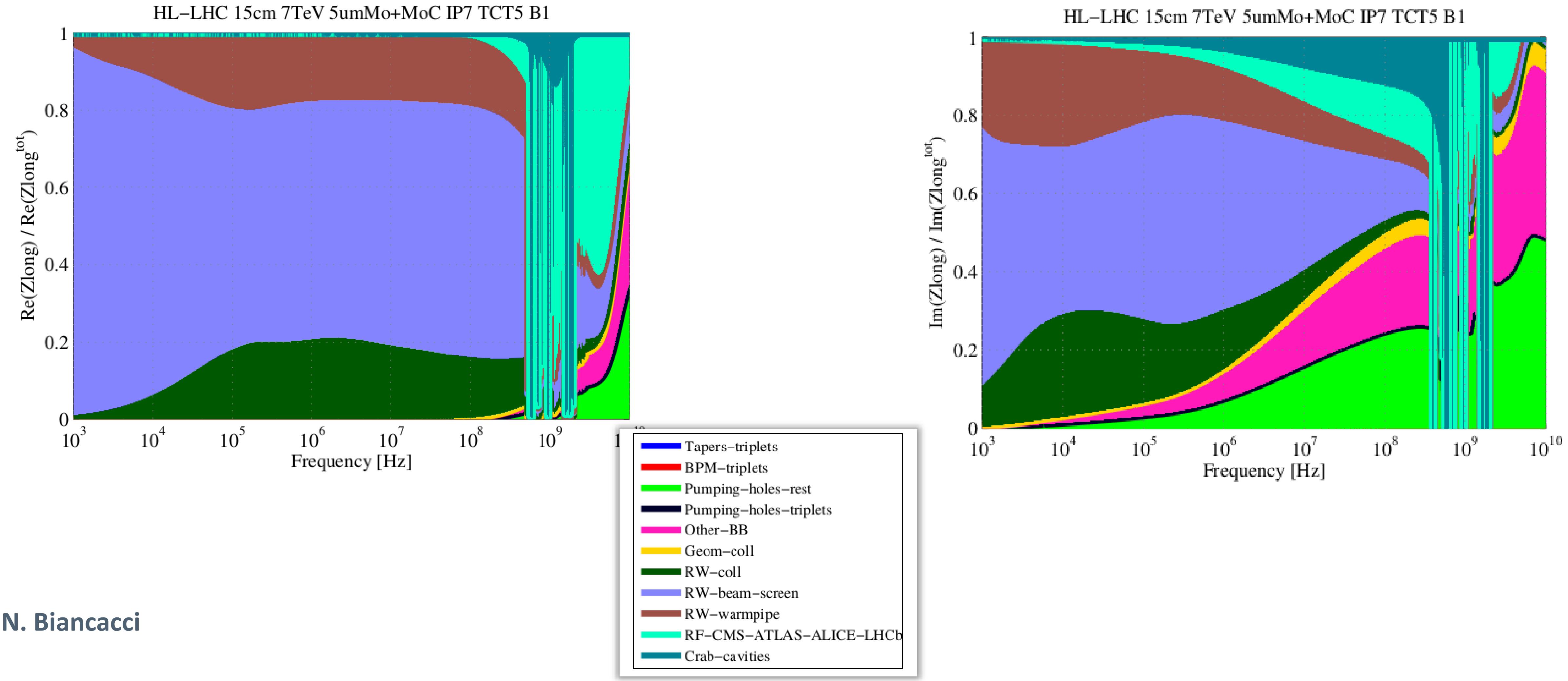



**N. Biancacci**

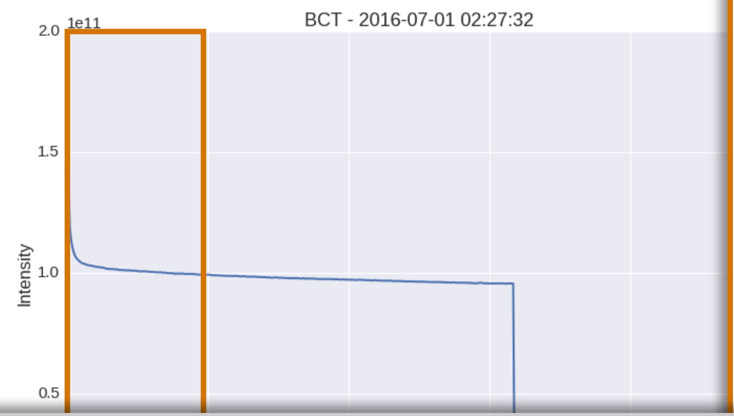
# HL-LHC impedance longitudinal plane – 7 TeV

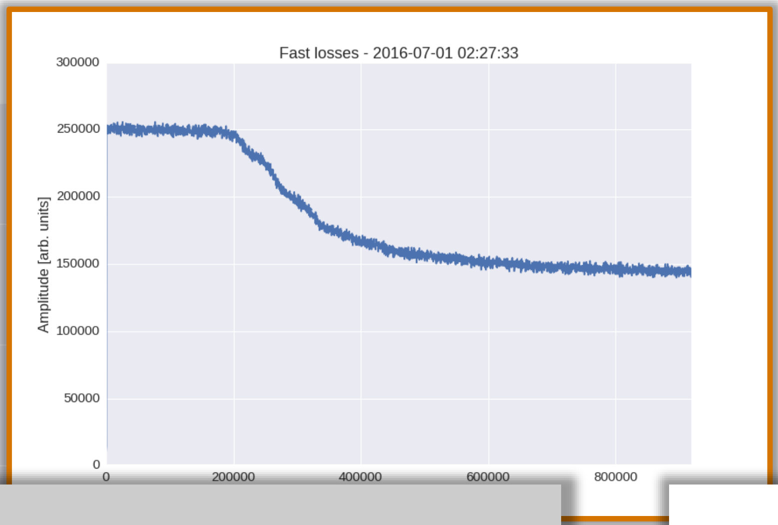


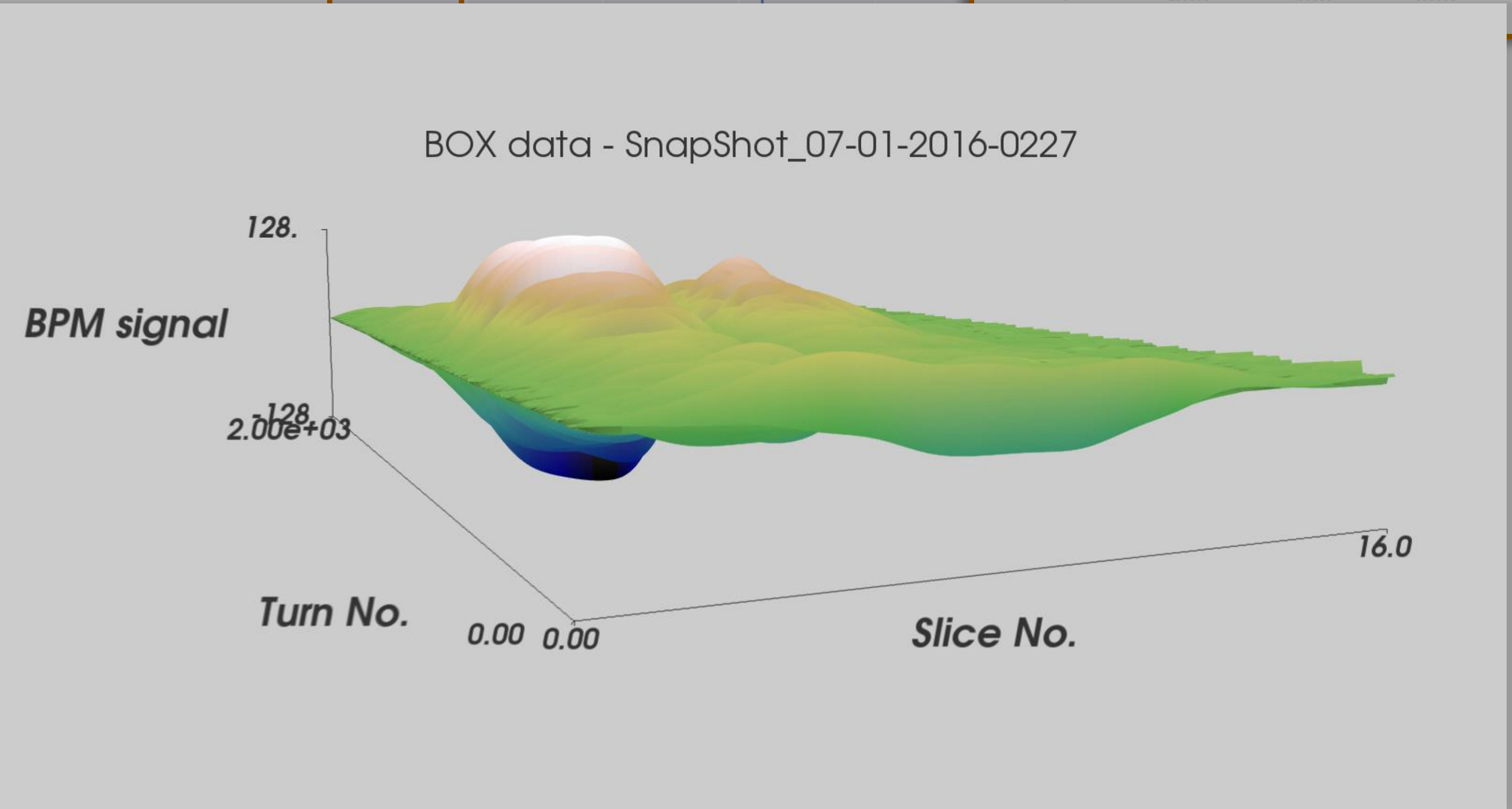

**N. Biancacci**

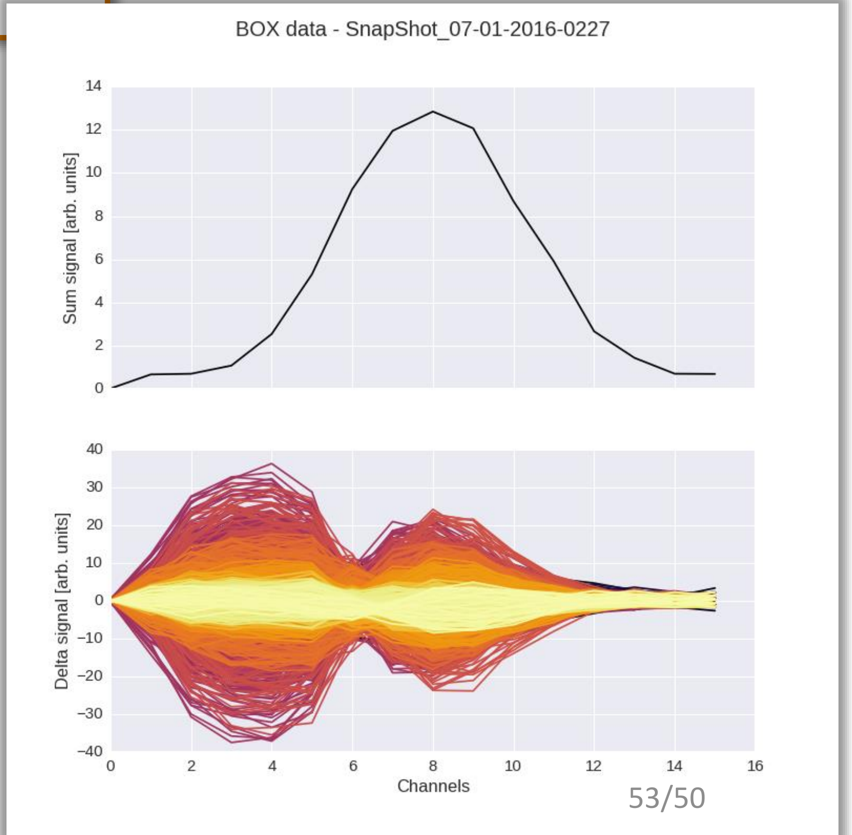
# Data from the ADC of the Box

**Open loop**



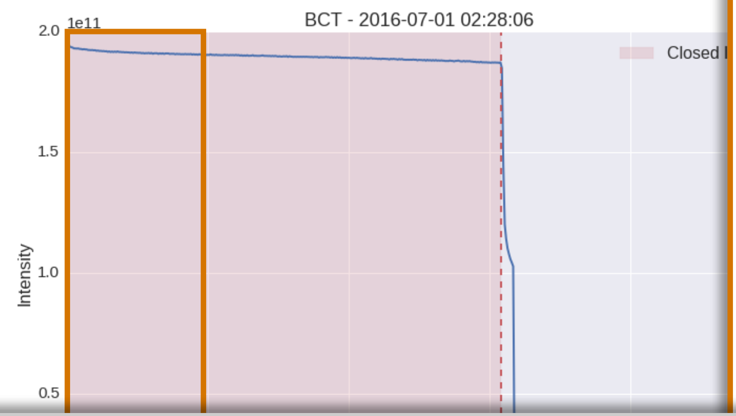



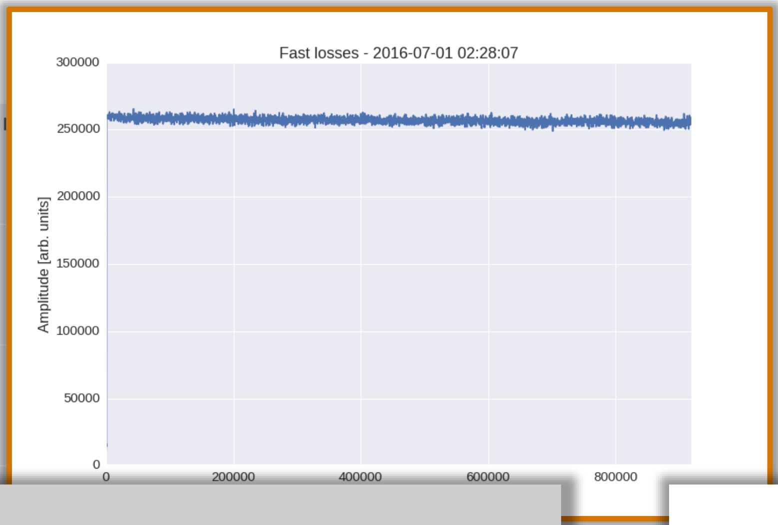



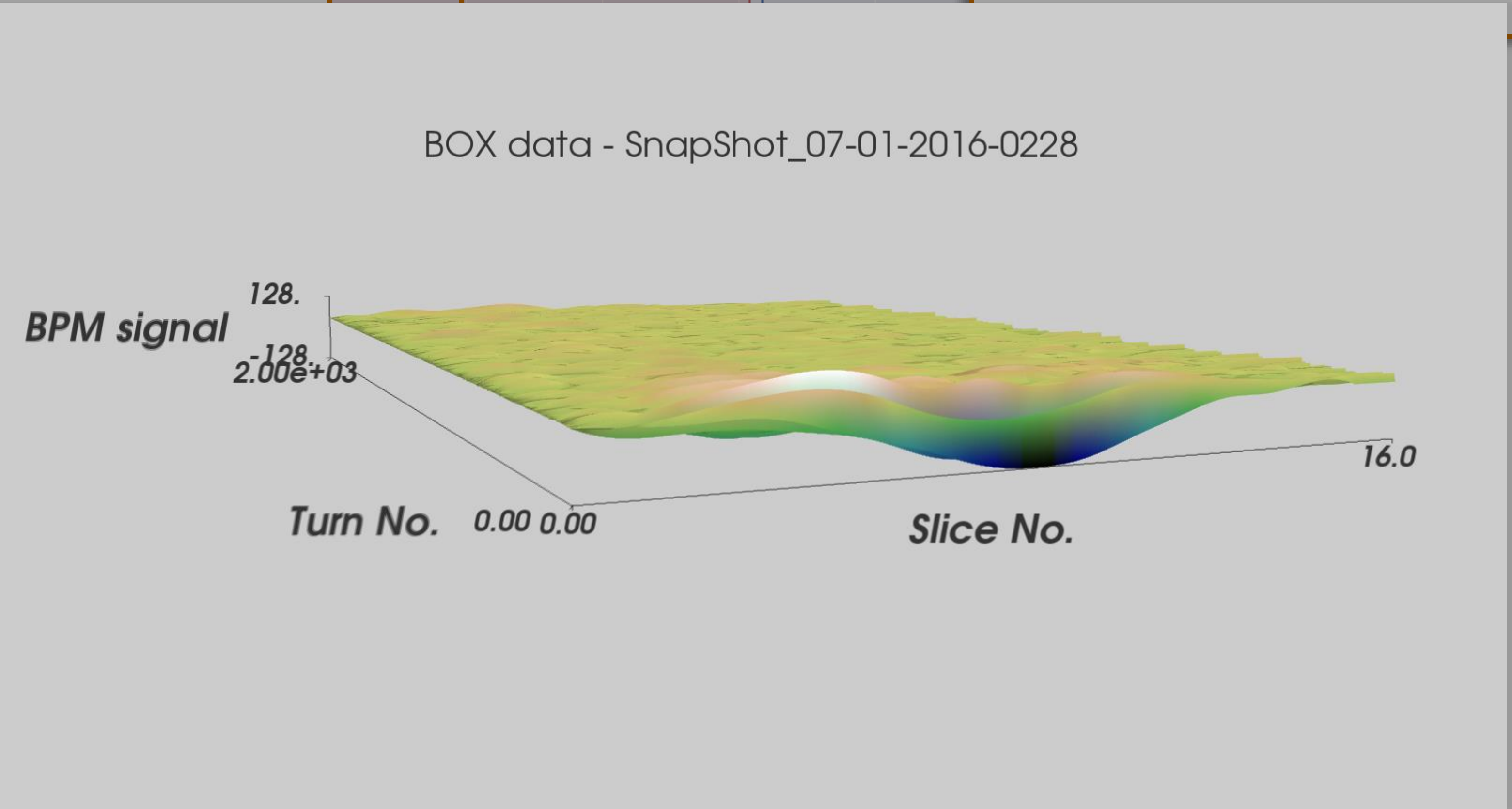



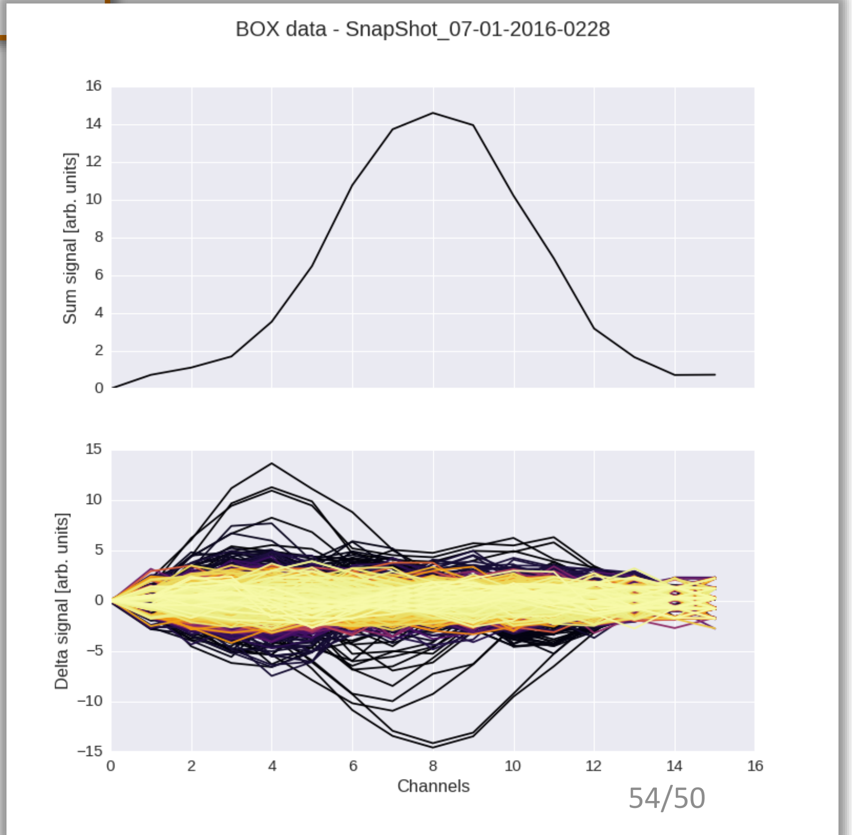
# Data from the ADC of the Box

**Closed loop**



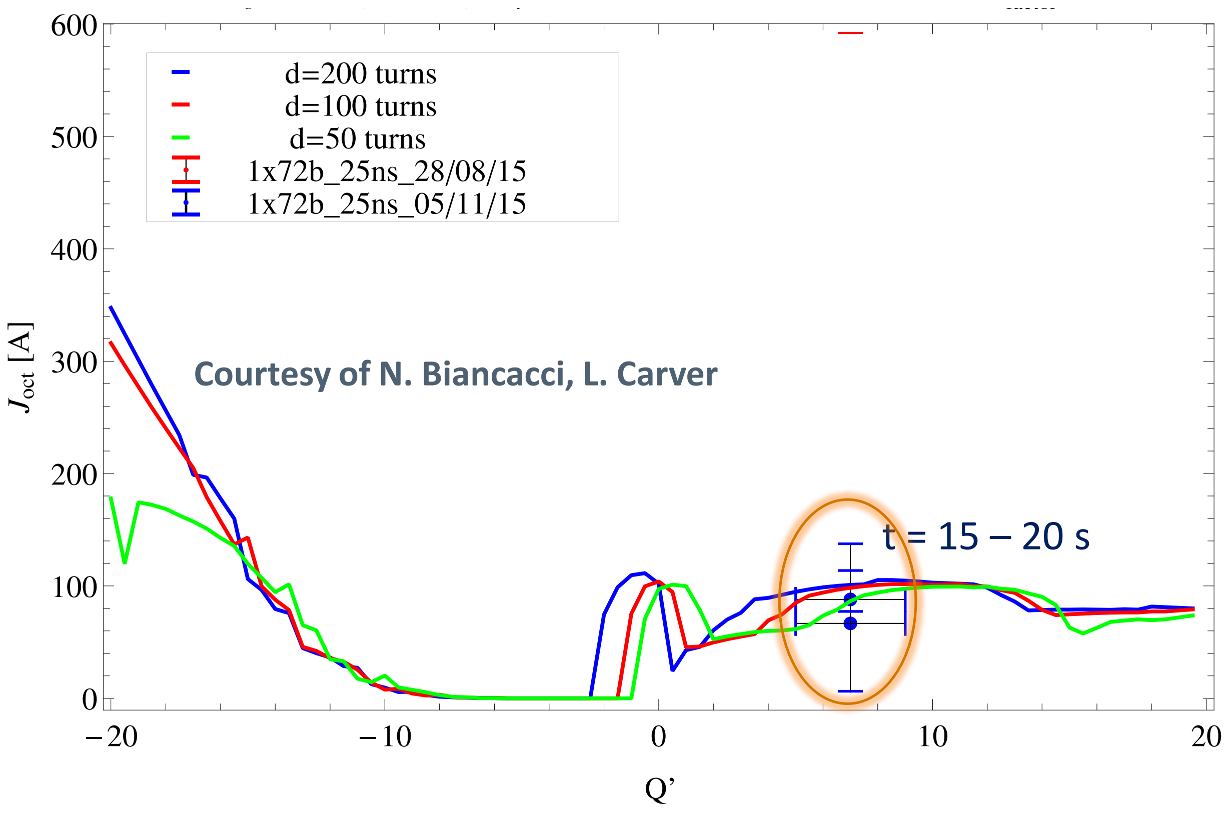
# Do we need it?

- Scalings based on available system in the SPS
- Assuming 1 GHz frequency range based on simulations
- Using slotline kicker with higher power amplifiers
- Other scenarios can be thought of, i.e. slotlines in combination with short striplines
- Kicker design and manufacturing expected to be feasible
- Power amplifiers with specified power over the full frequency range is more challenging

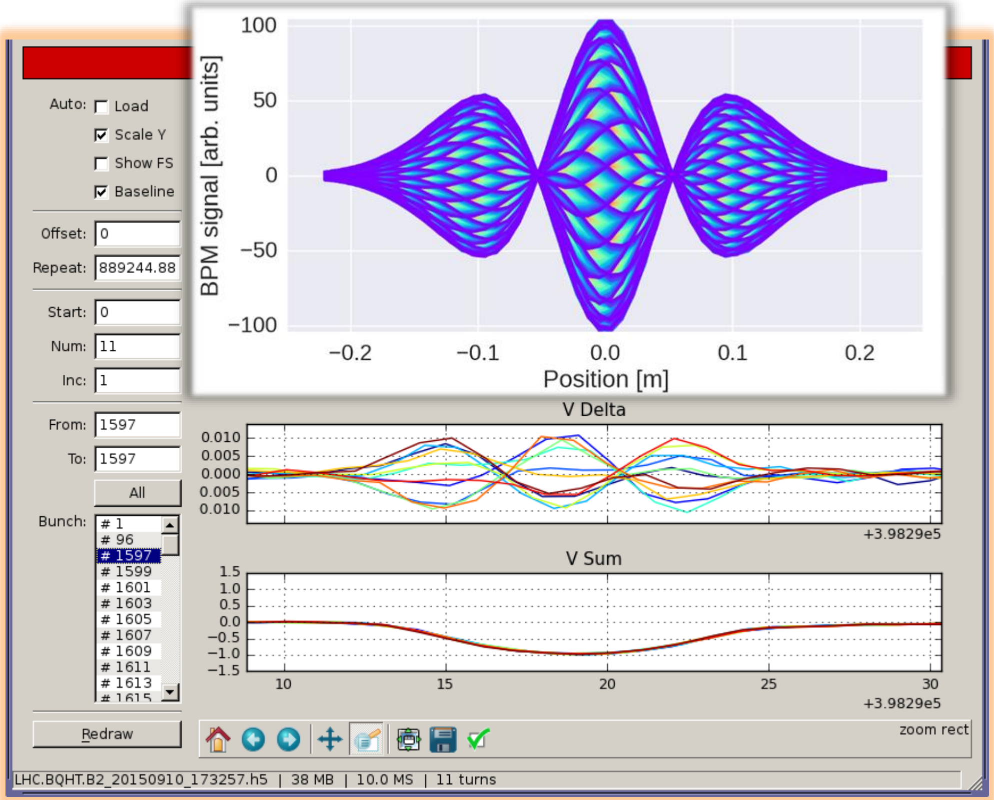
# Do we need it? – HL-LHC predictions

- Simulations using the impedance model suggest it may not be needed.
- Simulations using e-cloud are still in progress.
- Simulations rarely include all relevant effects:
  - The real machine tells a different story – running at high chroma, instabilities are still observed throughout the cycle (2012, injection, adjust, squeeze, stable beams)
  - The tasks is to identify relevant effects and to include them into the simulations (e-cloud, linear coupling, non-ideal transverse damper)
  - Symbiosis between observations and simulations will eventually enable to draw a complete picture
- Beam stability corresponding to pure impedance was never demonstrated in the machine.
- We do not know whether there are any hard limits (e.g. minimum SEY, correction limits).
- Strategy
  - We need to continue to gather experience with the running machine
  - We need to in parallel continue R&D on possible mitigation measures to be ready with a system that can be deployed in case nominal performance turns out to be limited or even excluded.

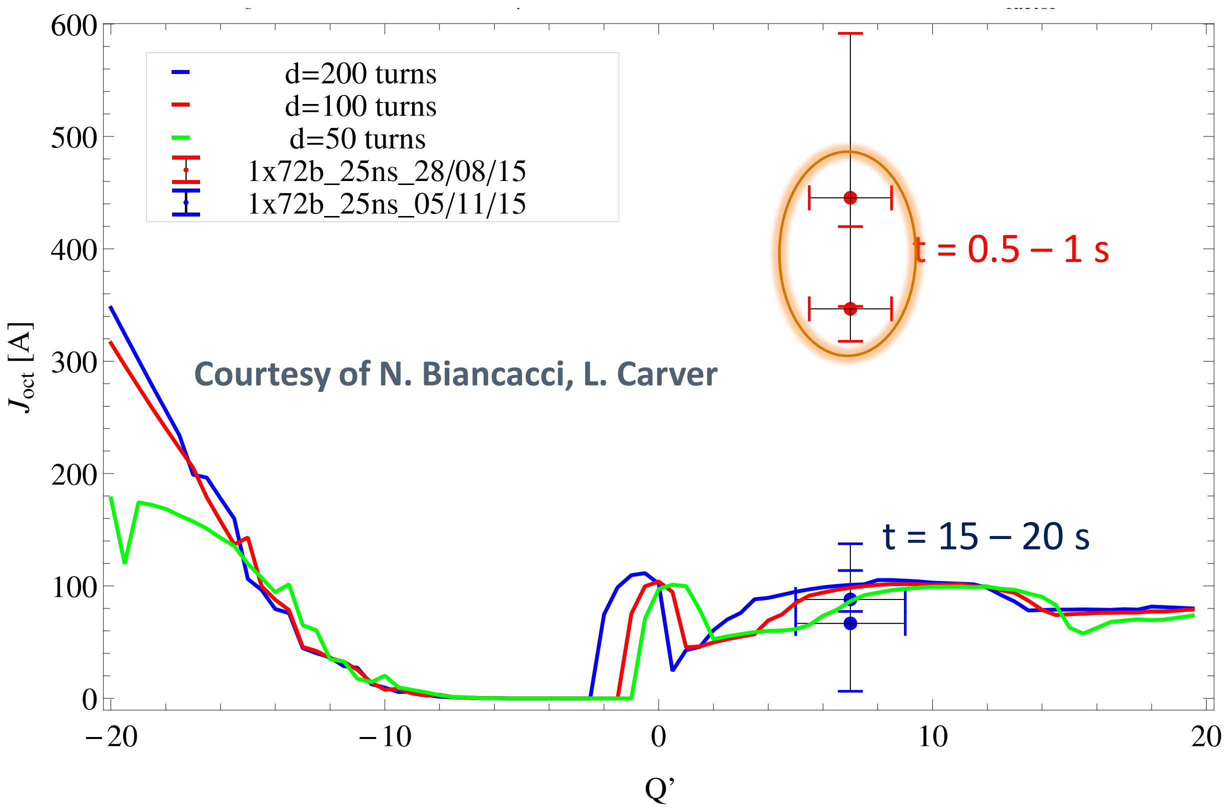
# Instability in the machine - LHC




- Stability predictions using the LHC impedance model show good agreement. However…

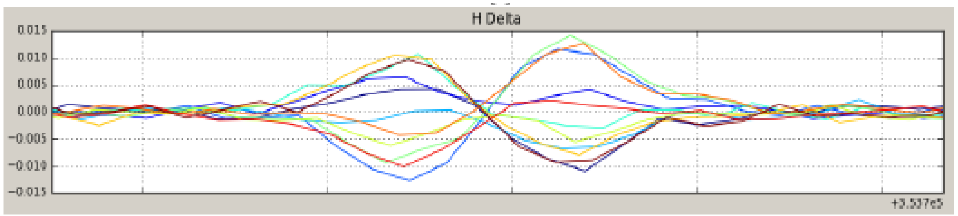


# Instability in the machine - LHC



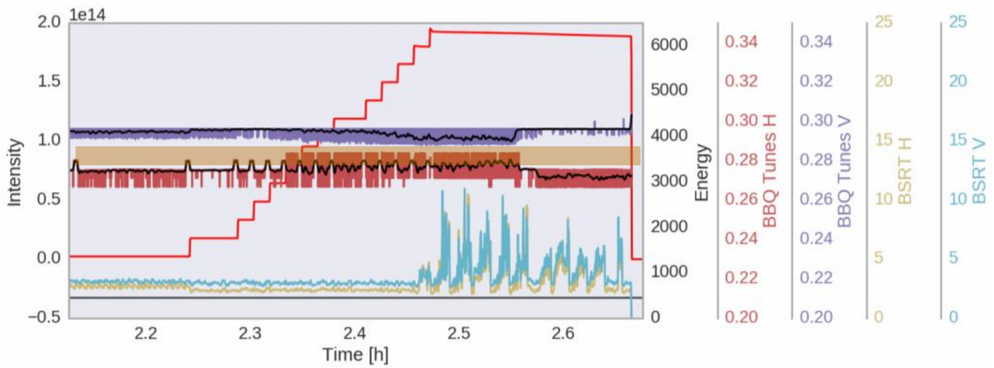

- Stability predictions using the LHC impedance model show good agreement. However…
- Additional effects (e.g. e-cloud) can considerably alter the predicted behaviour

Horizontal instability

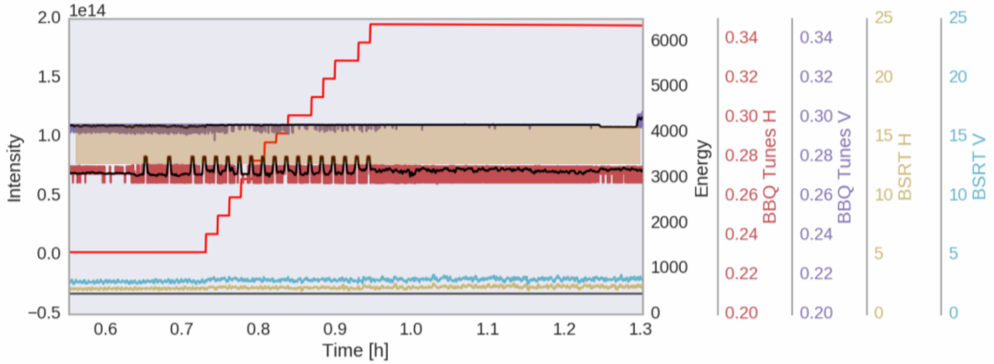


# Instability in the machine - LHC

- Fill 4642 with uncorrected tune drift
  → blow-up during injection




- Fill 4643 with tune correction
  → no blow-up




- Coupling C- for these fills was below 0.004

- **Tune separation and coupling correction**
  - At injection, when tunes approach each other and coupling is not well corrected, instabilities and **emittance blow-up**.
  - The instability mechanism was **studied in simulations** and identified as a **loss of Landau damping**.
  - This observation was **confirmed in MDs.**

# Comparison of mitigation techniques

| | Active feedback | Passive elements (e.g. RF Quad) | Comments |
|---|---|---|---|
| Control method | Active – resistive feedback | Passive – tune spread | |
| Additional functionality | High | Low | AF: Individual bunch excitation, diagnostics etc. |
| Complexity | High | Low | AF: requires expert support |
| Flexibility | High | Low | AF: constitutes a programmable impedance |
| Concomitant incoh. effects | Noise | By design (tune spread) | |
| Slow headtail | Demonstrated in simulations | Demonstrated in simulations | |
| Fast headtail | Demonstrated in experiments | Not demonstrated so far | |
| E-cloud instability | Demonstrated in simulations | Not demonstrated so far | |
| Status | Demonstrator system installed in the SPS | Prototype under study / development | |
| Cost | **???** | **???** | |