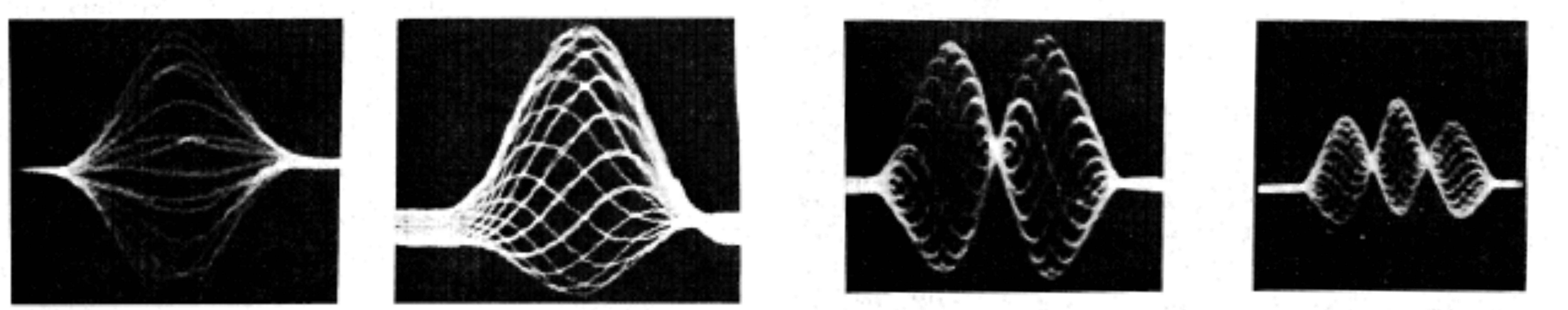


a) mode m = 0, χ = 0    b) m = 0, χ = 2.3 radians    b) m = 1, χ = 6.9 radians    d) m = 2, χ = 6.9 radians

# Recent Developments for Instability Monitoring at the LHC

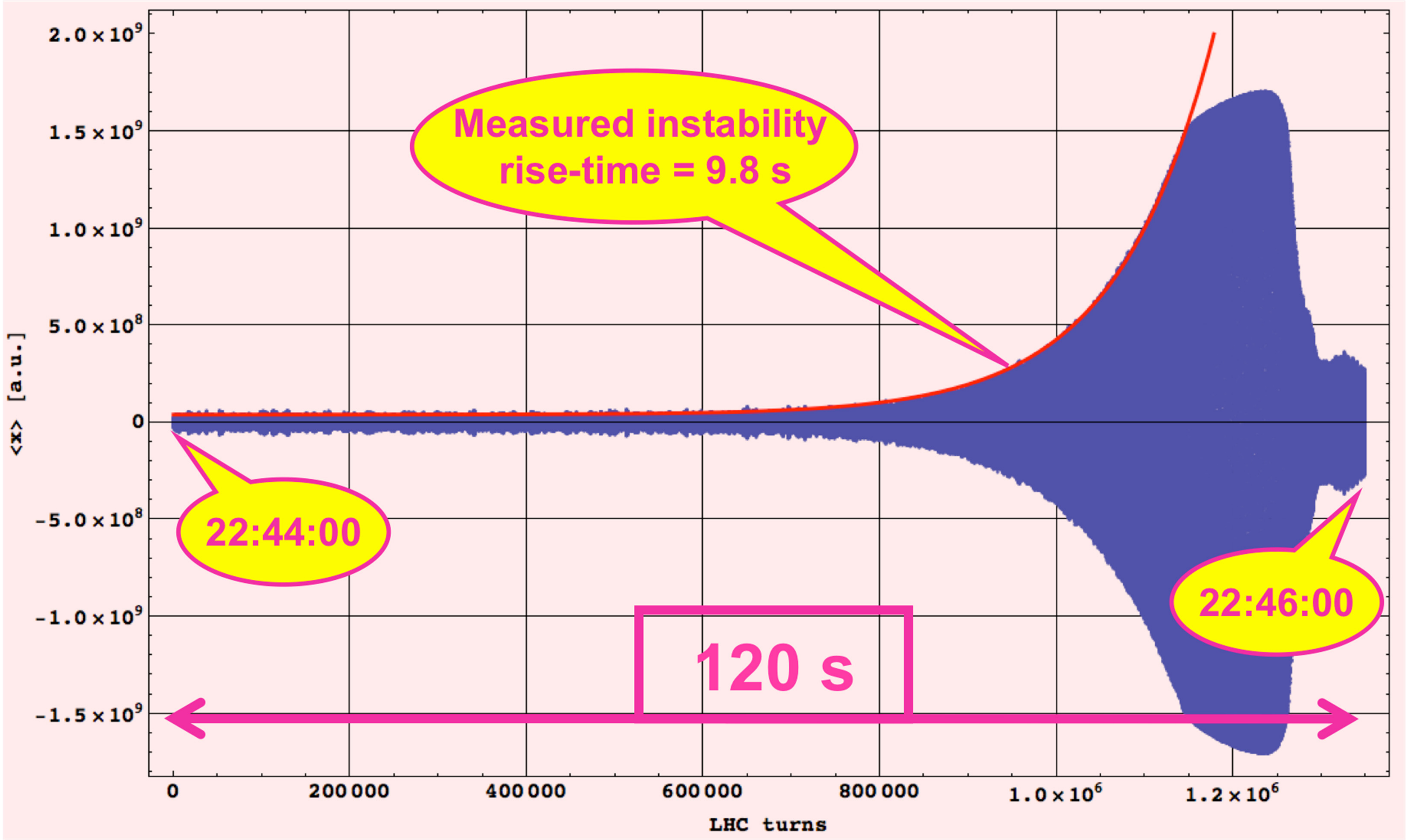
T. Levens, K. Łasocha, T. Lefevre
*Beam Instrumentation Group, CERN*

*Contributions and material:*
*L. Carver, J. Ellis, M. Gasior, R. Jones, E. Metral,*
*R. Steinhagen, D. Valuch, T. Włostowski*

International Beam Instrumentation Conference IBIC
11-15 September 2016 Barcelona

# Introduction

In general terms, a beam is unstable when a moment of its distribution exhibits exponential growth…




Instabilities are limiting factor of number of bunches that can be injected and stored in LHC – especially for run 2 machine parameters.

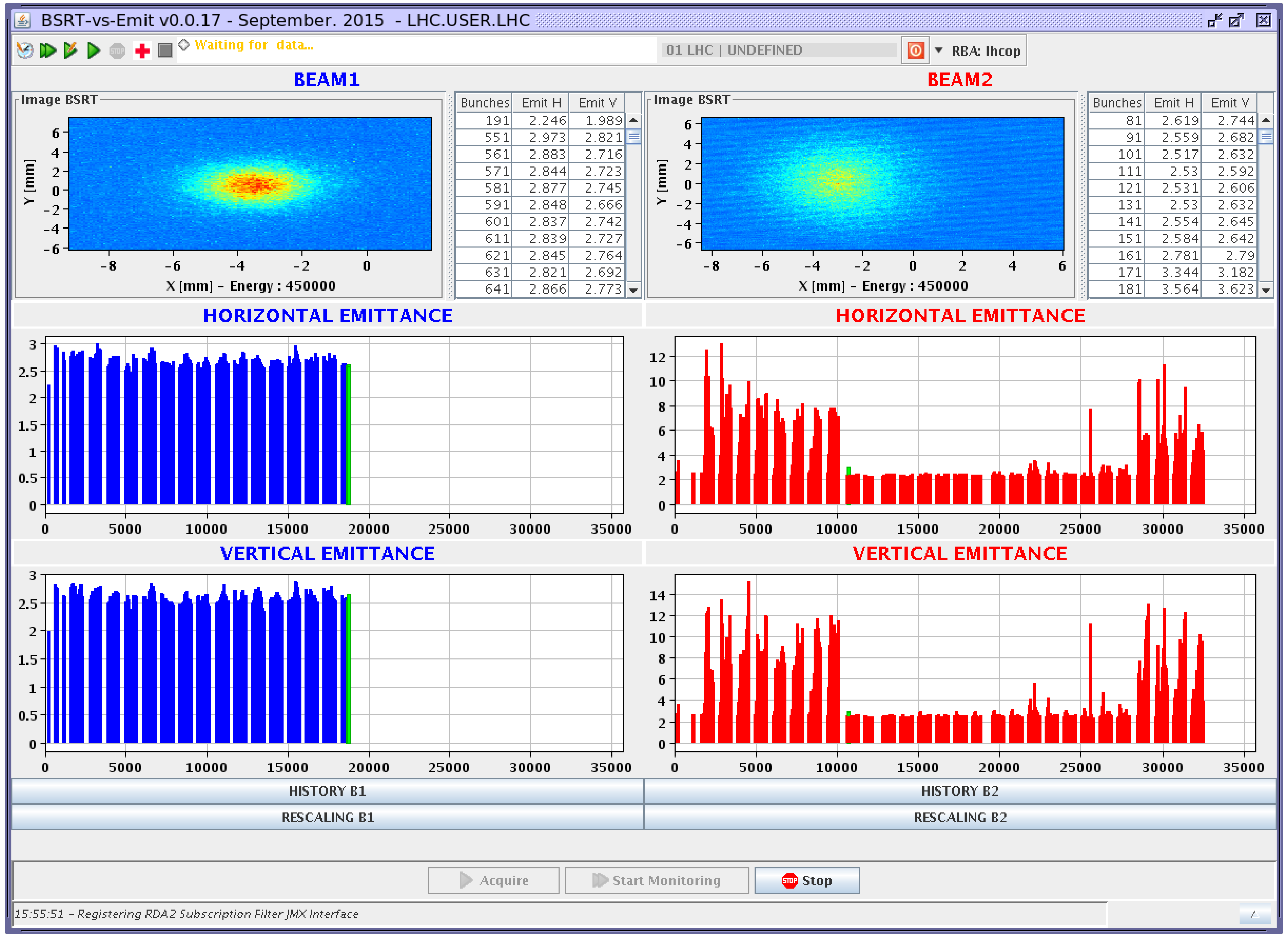
Important to be able to measure properties of the beam before, during and after an instability to understand the source and make corrections.

# Operational usage of instability diagnostics

From an operators point of view, usually the most obvious symptom is emittance growth and losses on some bunches.

Can happen at various, and not always predictable, times during regular operation.

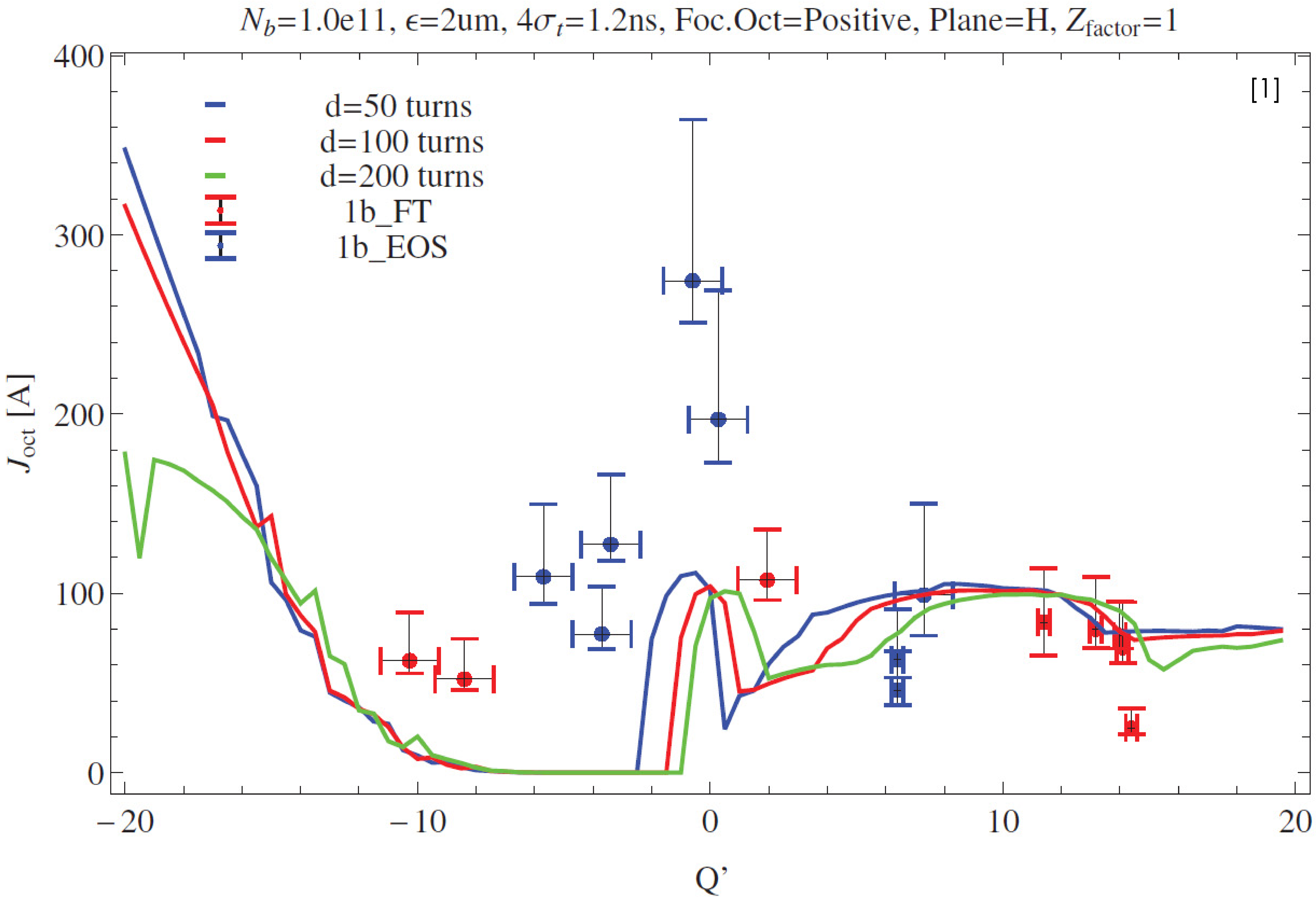
By the time the emittance growth is seen with BSRT it is often too late measure properties of instability.




Need to detect instabilities as they occur to measure relevant beam parameters to be able to make suitable corrections to machine settings.

# Machine development usage of instability diagnostics

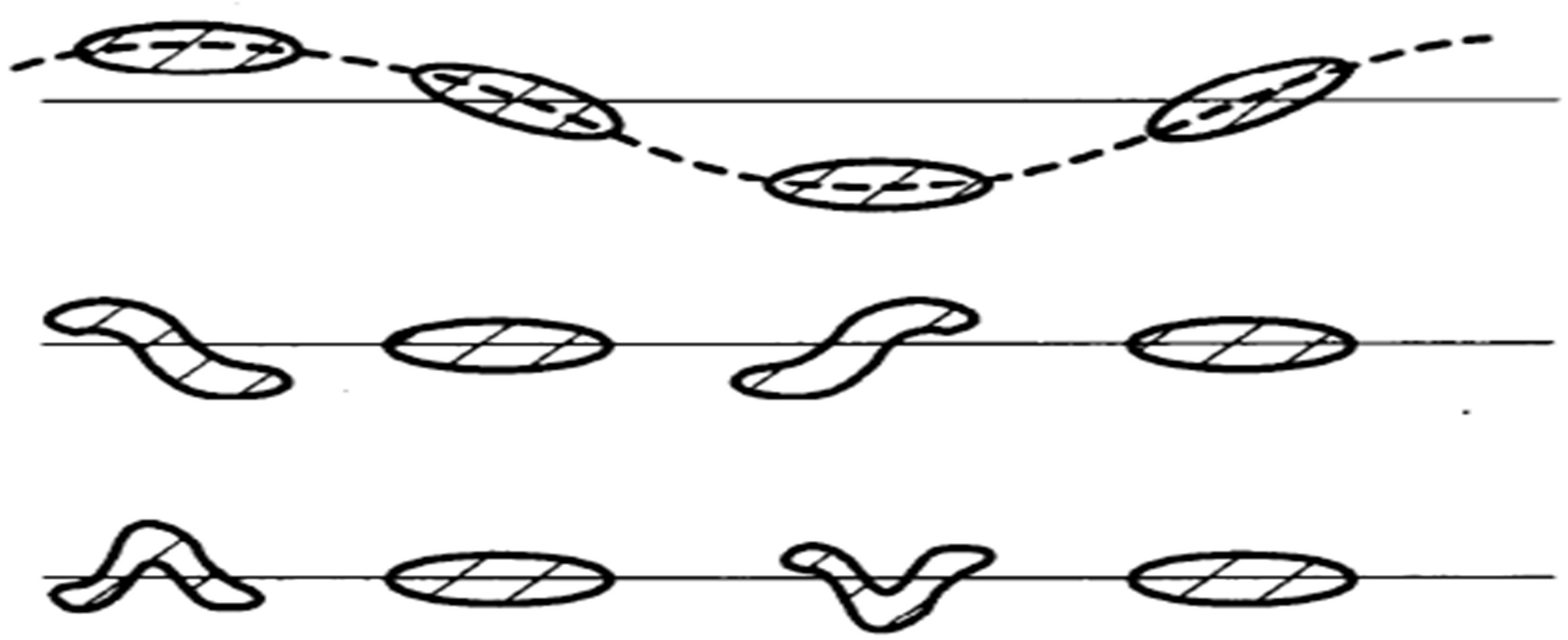
Also important for validating the LHC impedance model…




[1] L.R. Carver *et al*, "Current Status of Instability Threshold Measurements in the LHC at 6.5 TeV", IPAC 2016, Busan, Korea, TUPMW011, 2016

# Head-Tail modes

The Head-Tail (radial) mode numbers describe how the bunch is oscillating:

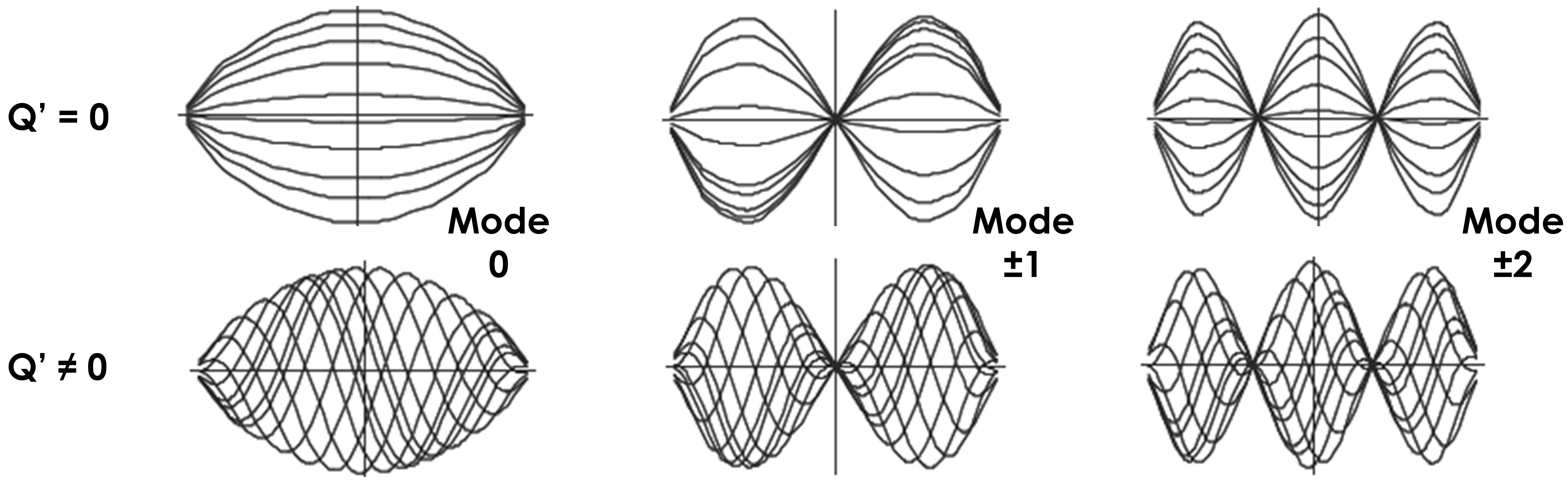


**Mode 0:** rigid bunch motion

**Mode ±1:** head and tail out of phase

**Mode ±2:** head and tail in phase, center in opposition

For mode ±N, there are N stationary points. Seen by a transverse BPM:

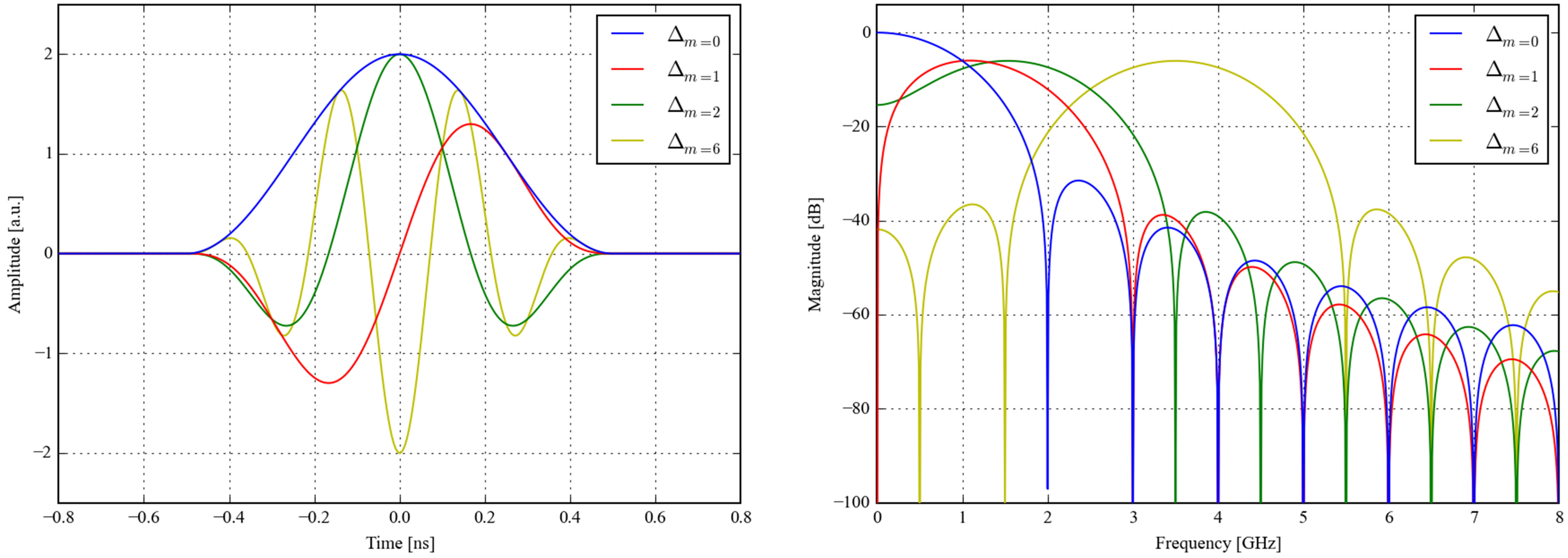


# LHC bunch spectrum

The bunch spectrum depends strongly on bunch shape and length.

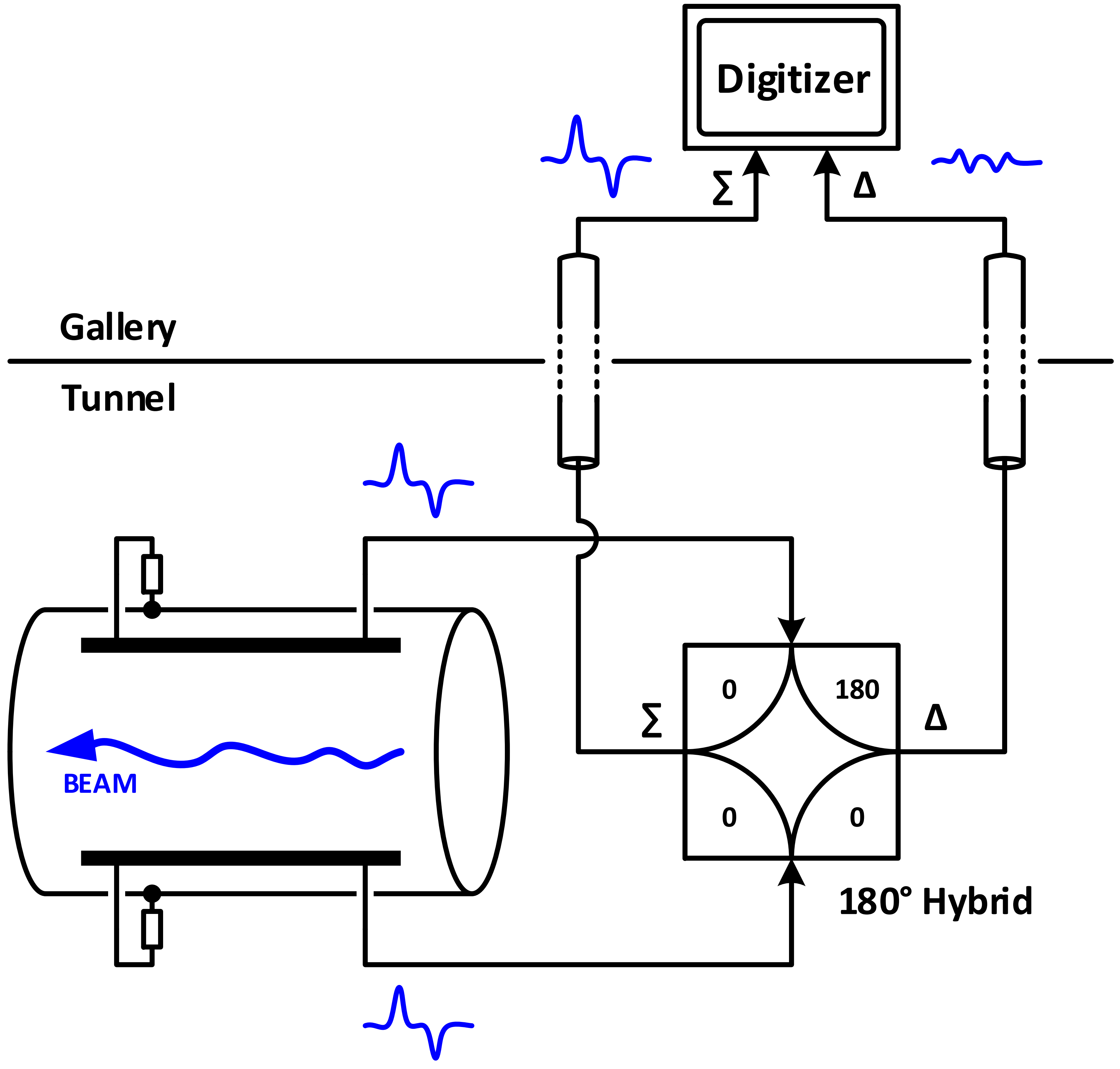
For a typical LHC bunches ($4\sigma \approx 1$ns) spectrum extends to several GHz.

In the presence of intra-bunch motion, there is a shift of the bunch spectrum to higher frequencies as the mode number increases:




So, we need a wideband BPM and acquisition chain to resolve intra-bunch motion…

# LHC Head-Tail Monitor

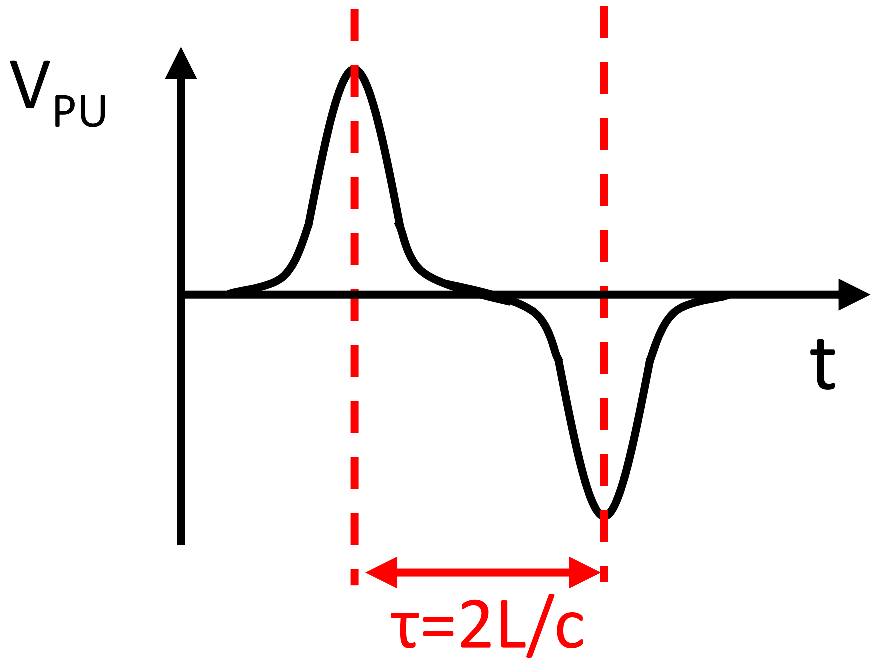


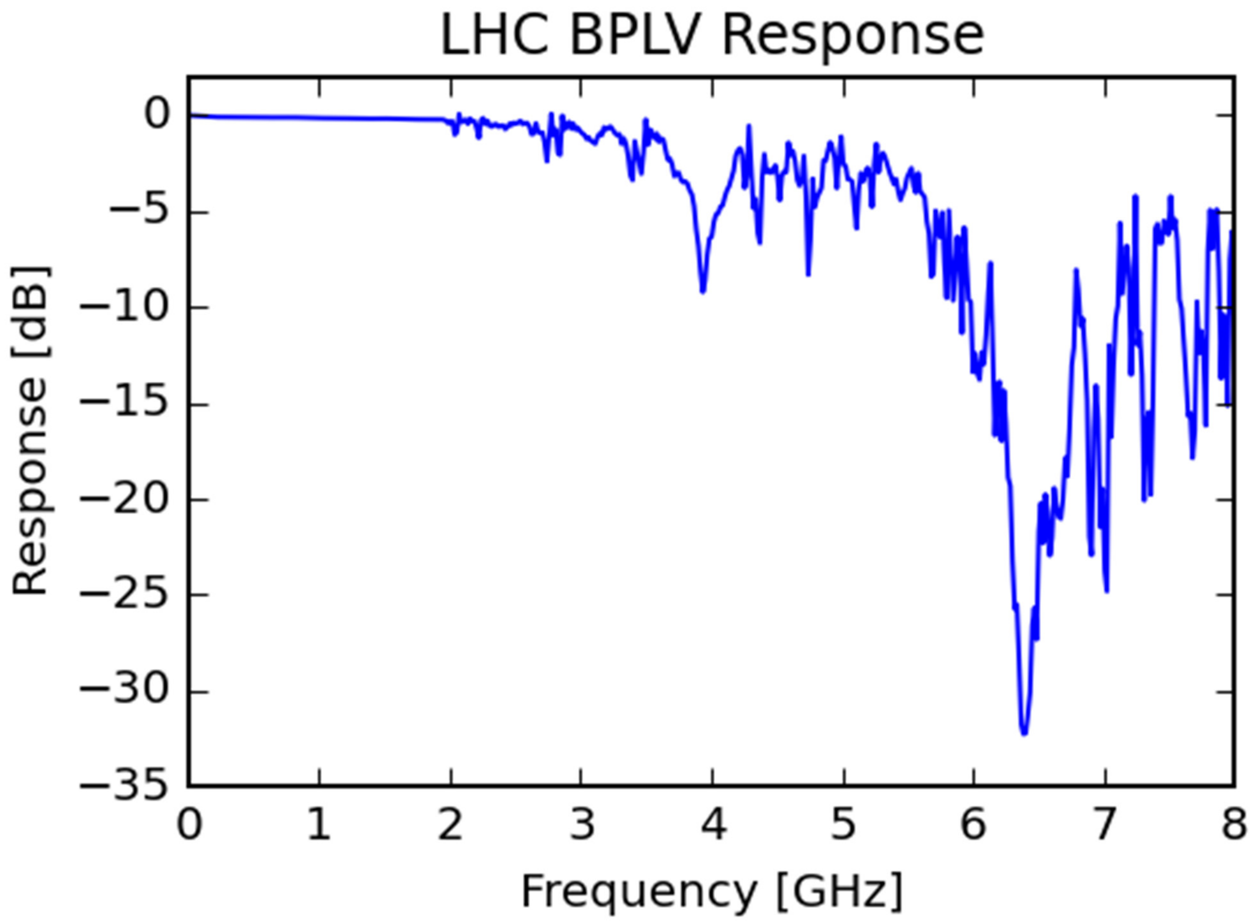

Acquisition of transverse BPM sum/difference signals with a fast oscilloscope.

Originally installed in SPS (and later LHC) for chromaticity measurements through observation of head-tail phase shift [2].

Stripline length dimensioned to separate pulses in time. Can gate on first pulse and remove the notches the spectrum.

- LHC bunch length ~ 1 ns
- LHC bunch spacing ~ 25 ns
- L = 40 cm (τ = 2.7 ns)

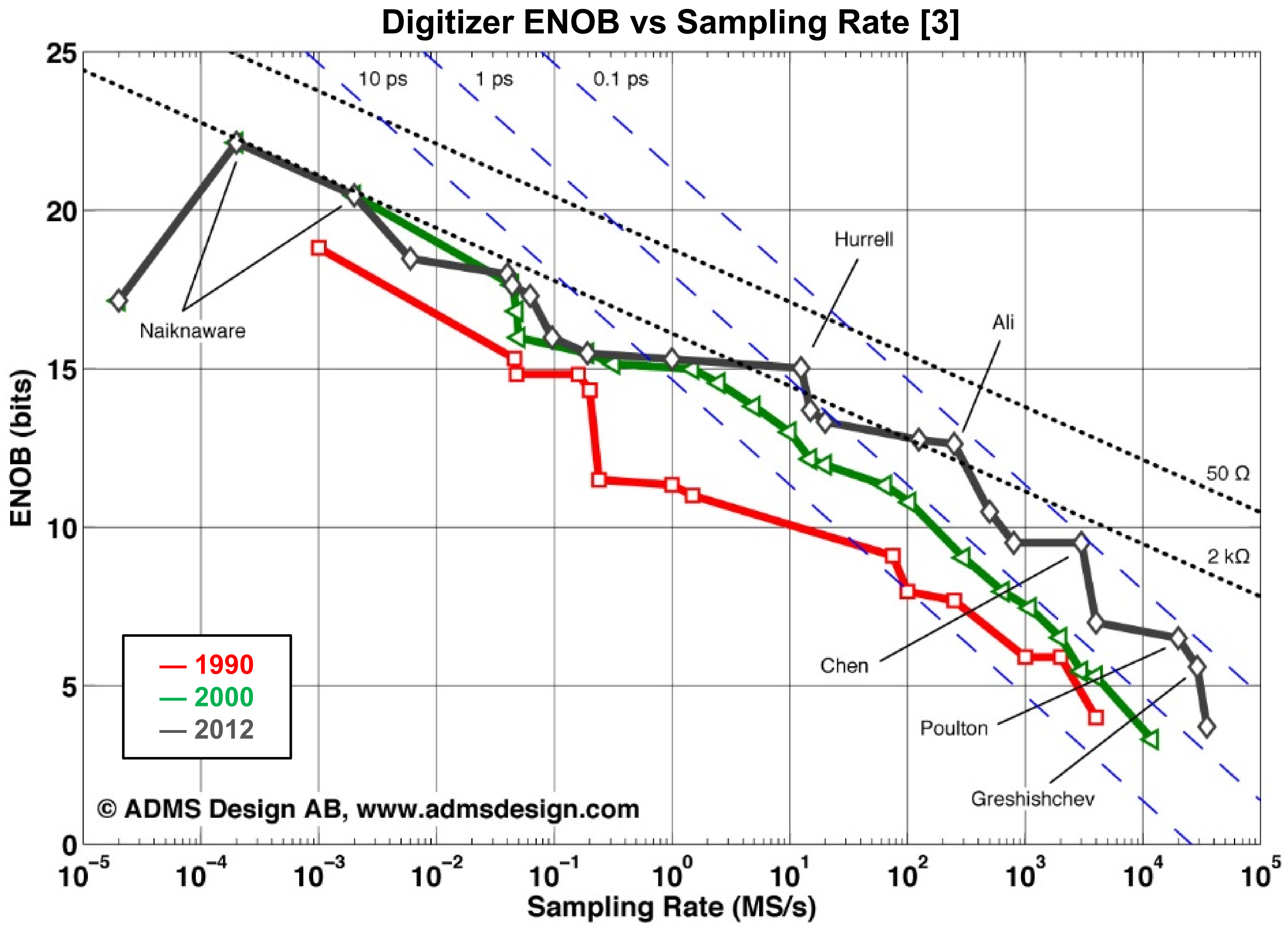



[2] S. Fartoukh & R. Jones, "Determination of Chromaticity by the Measurement of Head-Tail Phase Shifts …", CERN-LHC-Project-Report-602, Jul. 2002

# Practical problems with fast digitizers

1. Limited dynamic range (ENOB)
   - Can only see larger instabilities
   - ADCs approaching fundamental limits, cannot expect drastic improvements
2. Slow readout
   - 10-15 seconds for LHC
   - Limits time between triggers
3. Short acquisition length
   - Makes it difficult to catch an instability
   - 11 turns for all bunches in LHC
   - New digitizers with very large acquisition memories being tested (64GB = 1.6s = 18k turns)
4. Large data files
   - Challenging to store, analyse




[3] B.E. Jonsson, "ADC performance evolution: Sampling rate and resolution", Converter Passion, August, 2012

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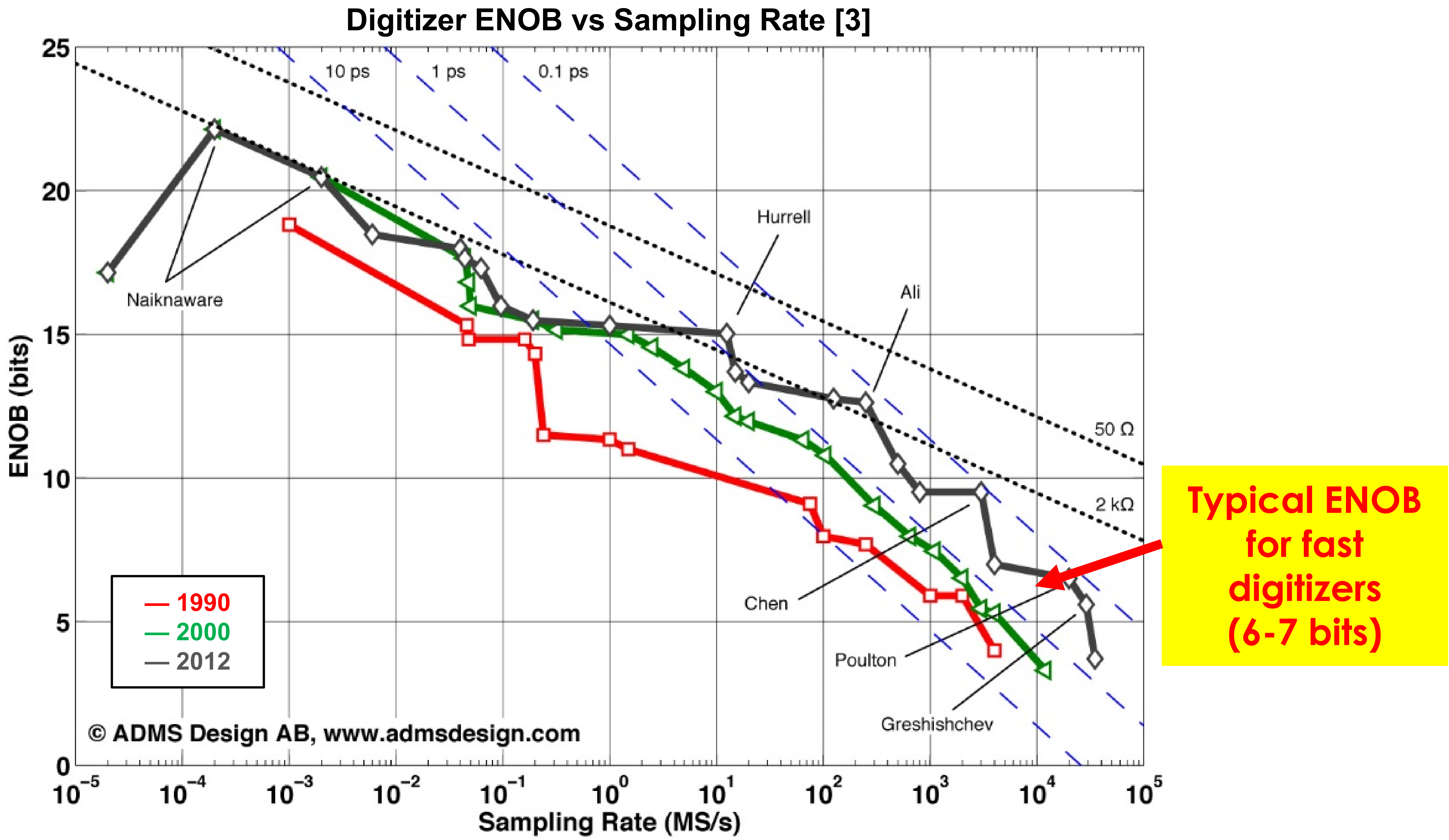


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# LHC Head-Tail – data processing

Processing required for each acquisition:

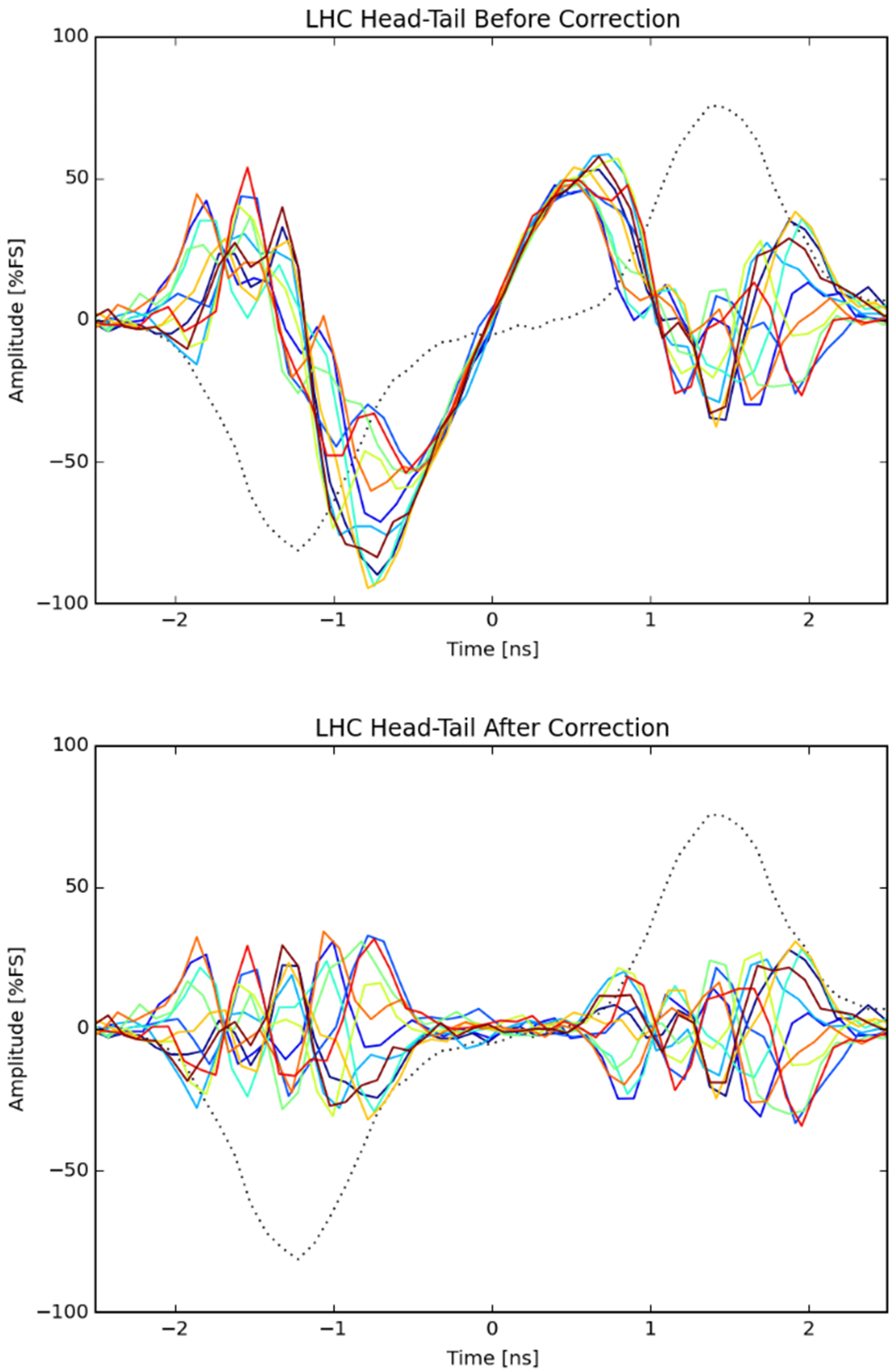
- Bunch detection
- Turn-to-turn alignment of traces
- Baseline removal

Previously performed manually… bearable for small numbers of "MD" measurements.

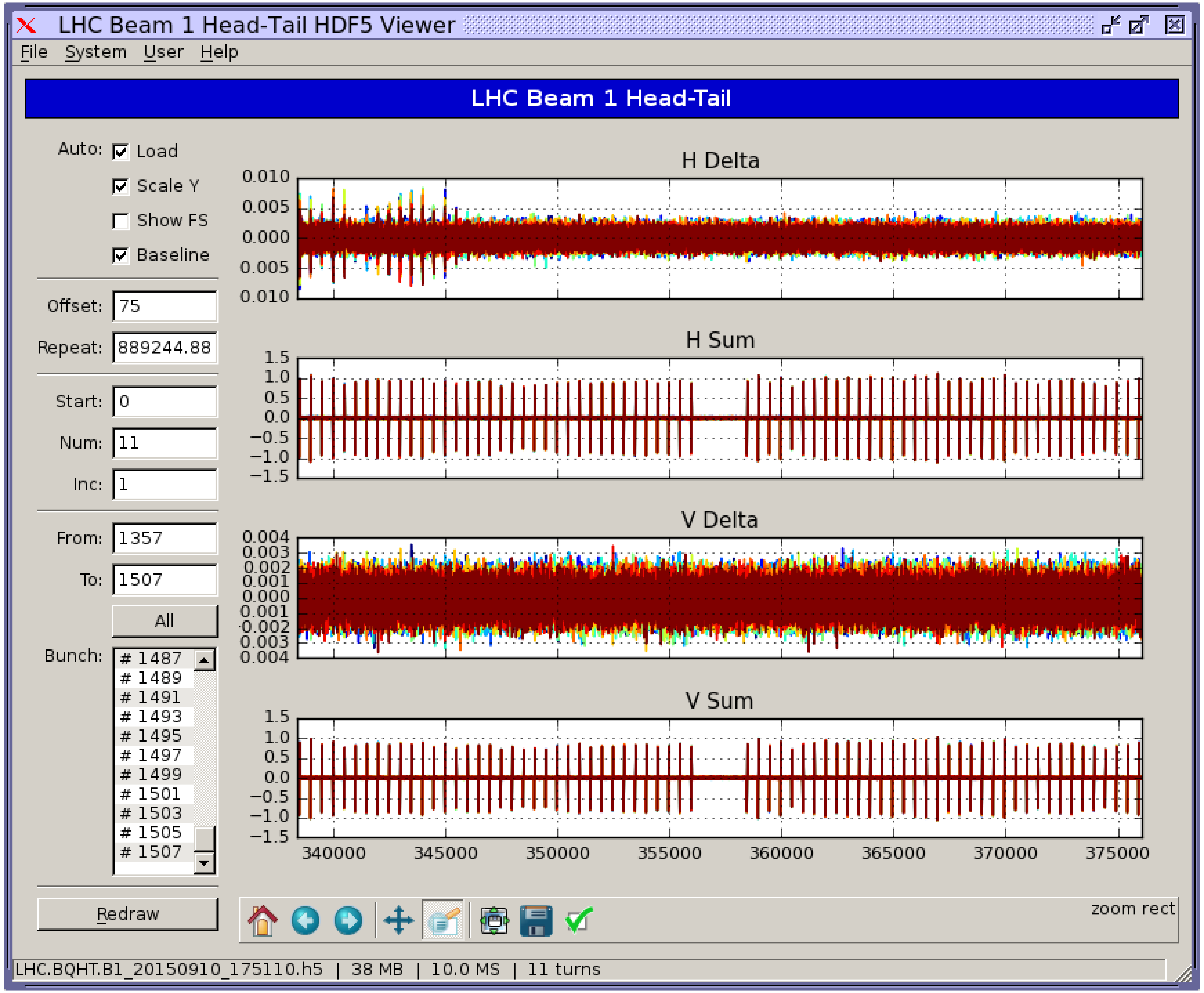
Not practical for large amounts of data saved during day-to-day operation.

Fully automated tools built to analyse and detect acquisitions with unstable bunches.

"Uninteresting" acquisitions can be removed automatically to reduce data set size.

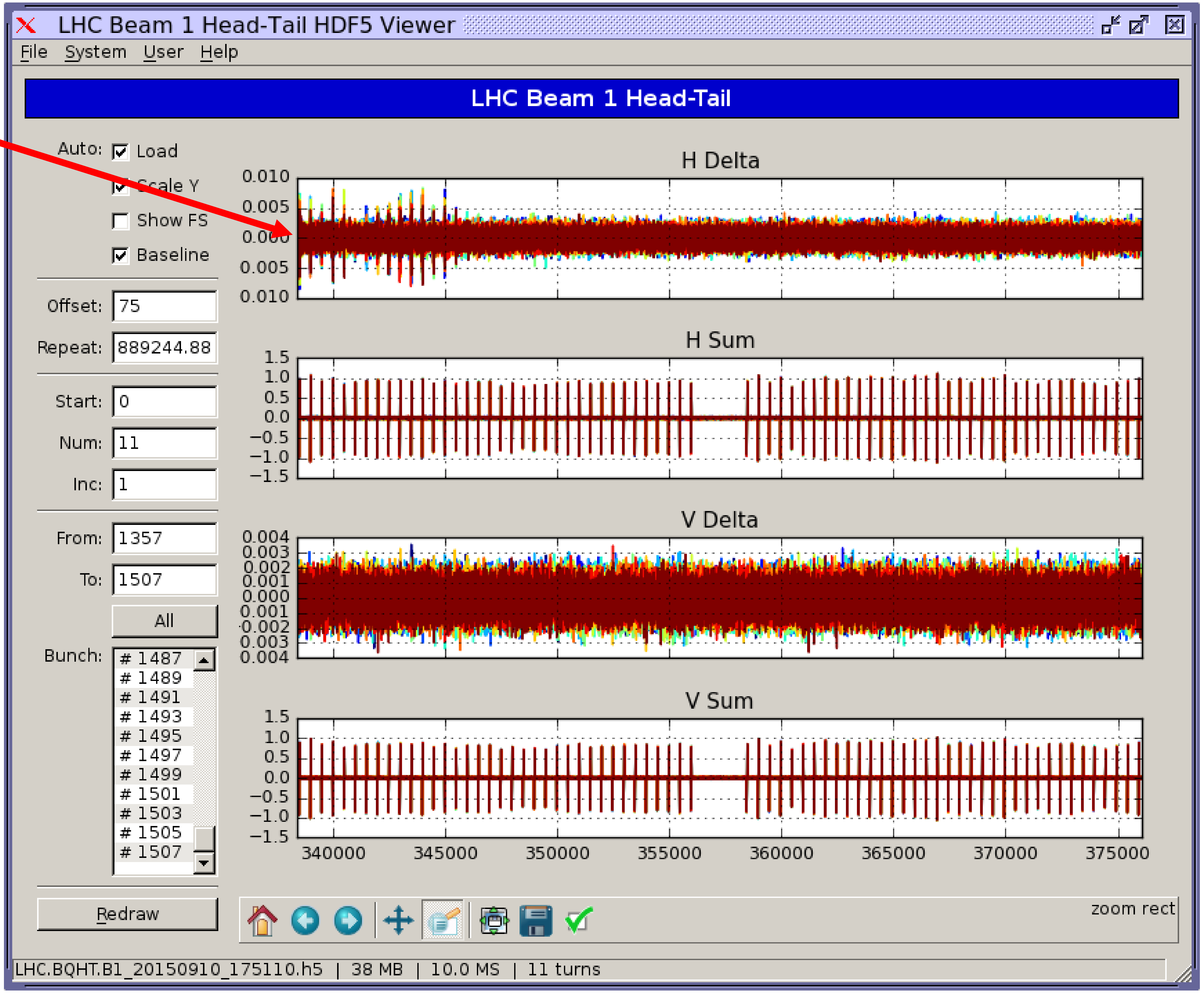


# LHC Head-Tail – as seen by operation



# LHC Head-Tail – as seen by operation

**Start of batch unstable in horizontal plane**



# LHC Head-Tail – as seen by operation

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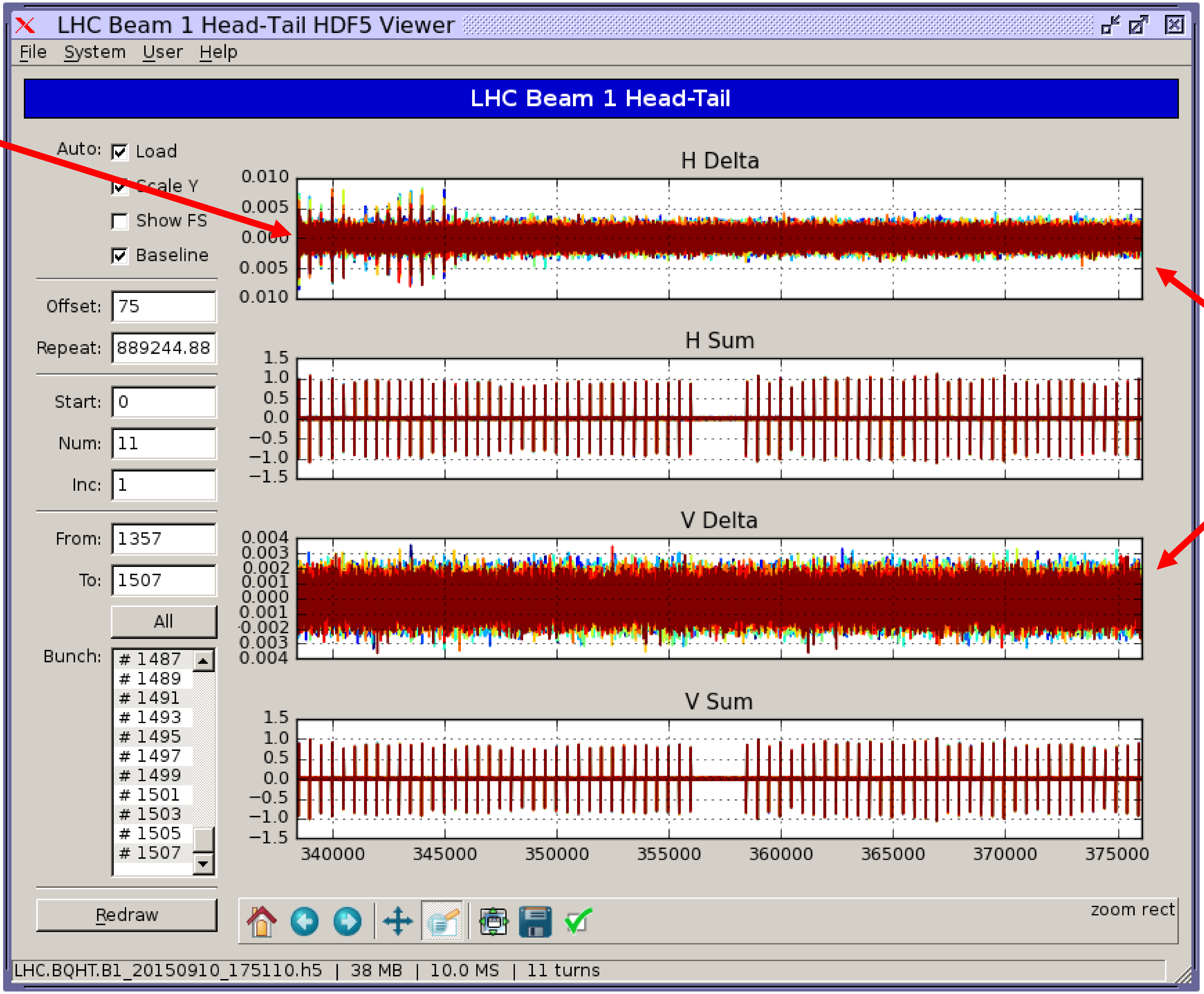
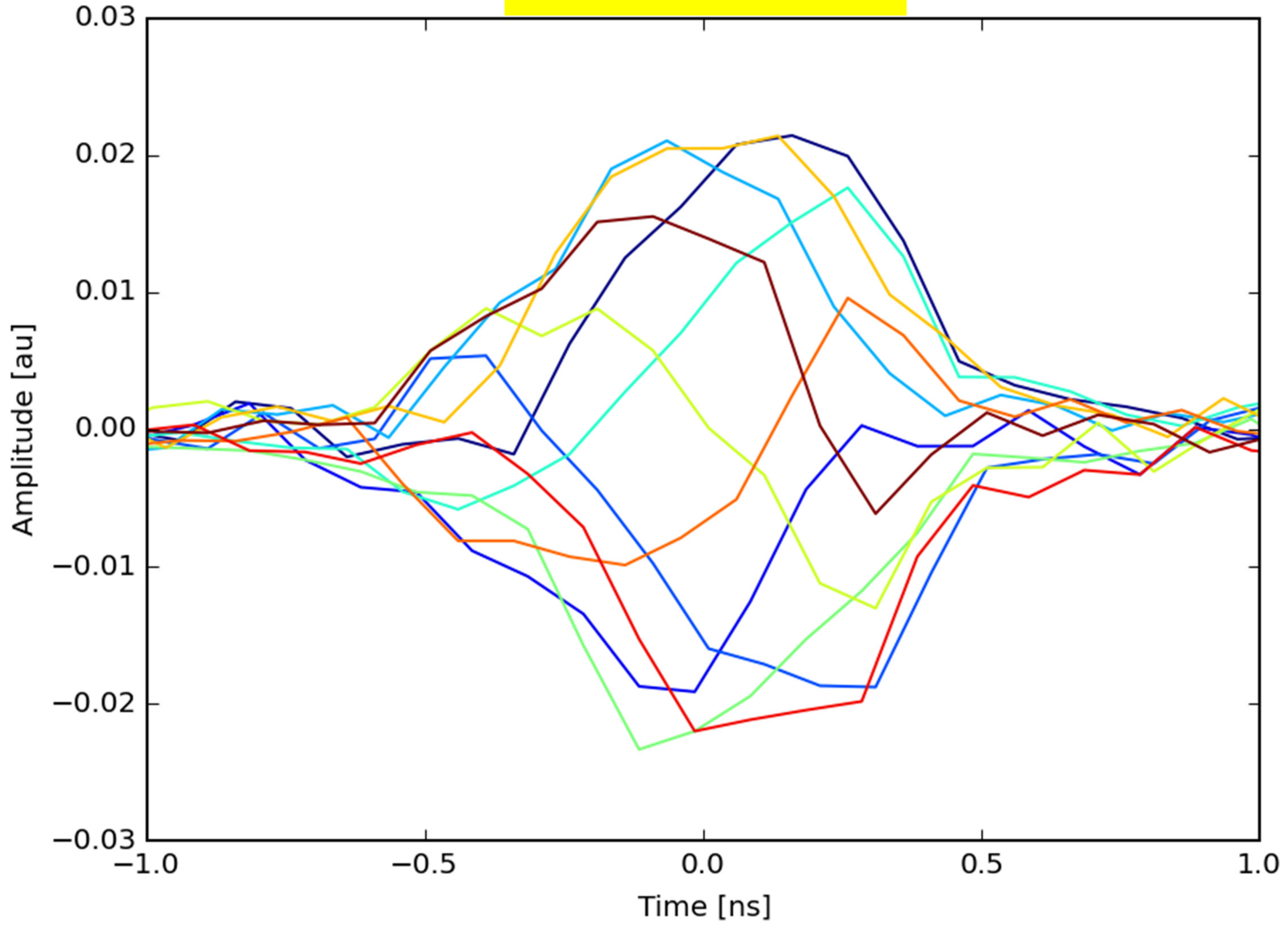


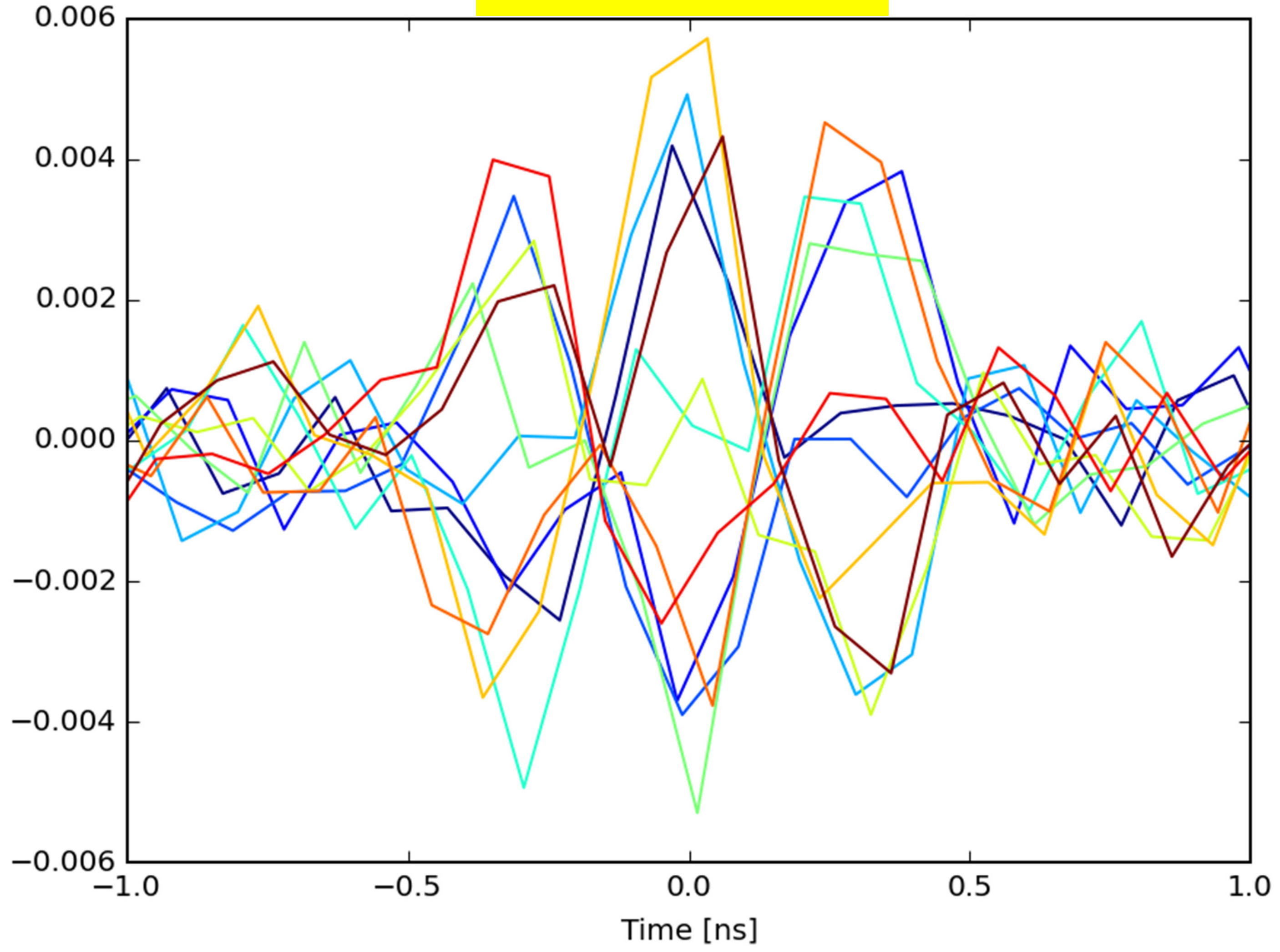

No activity at end of batch or in vertical plane (n.b. different scales in H/V)

# LHC Head-Tail – some results

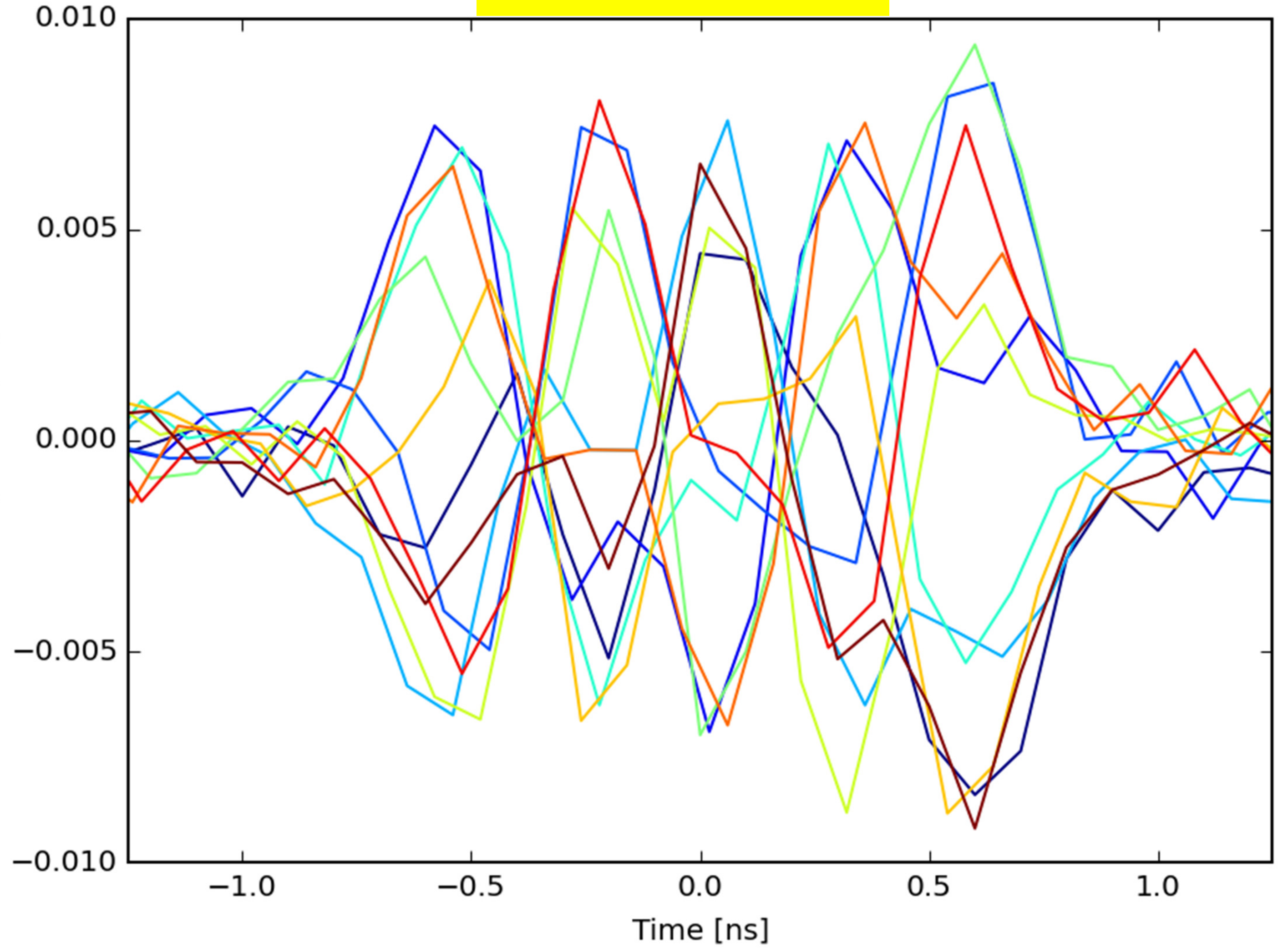
MODE 0



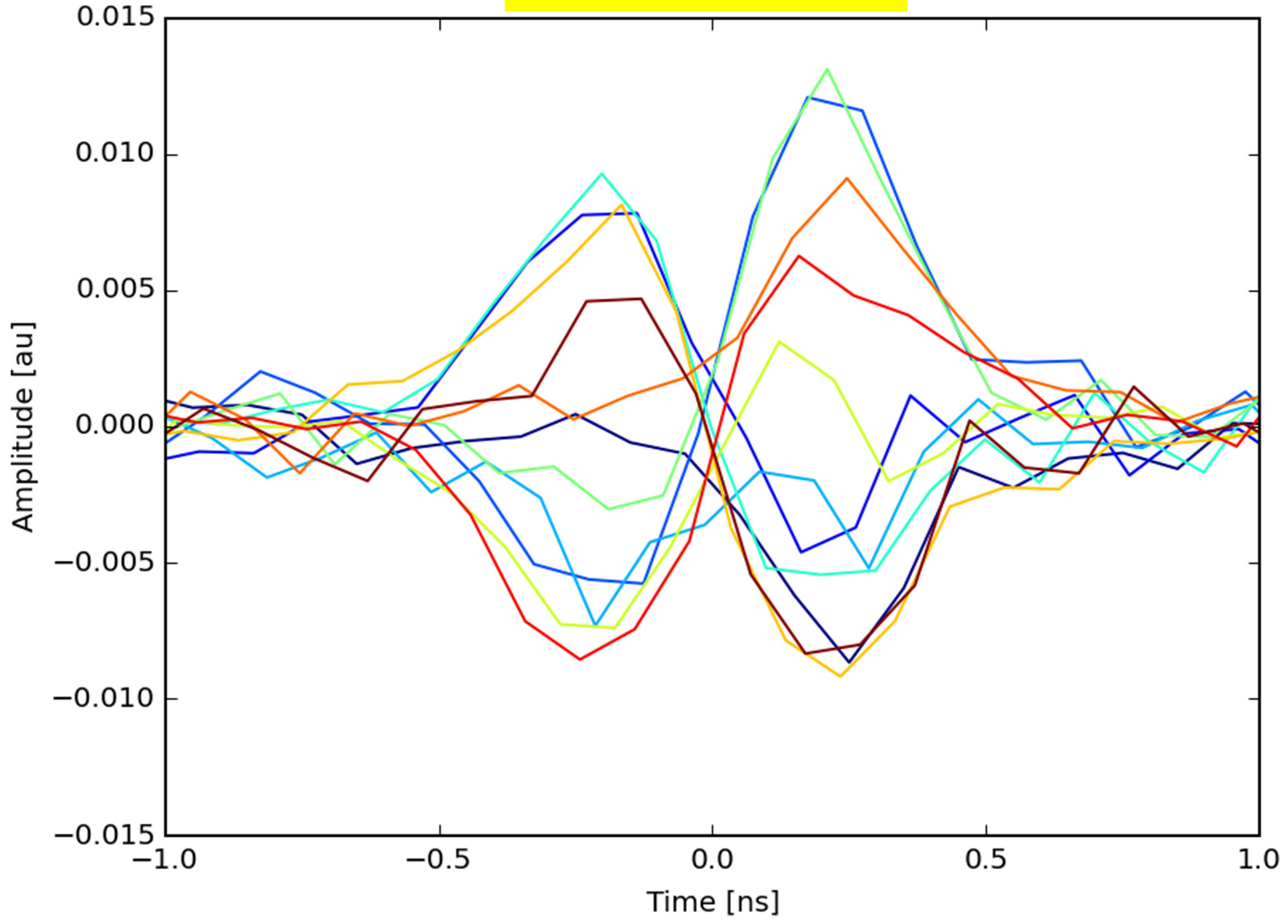

MODE 2



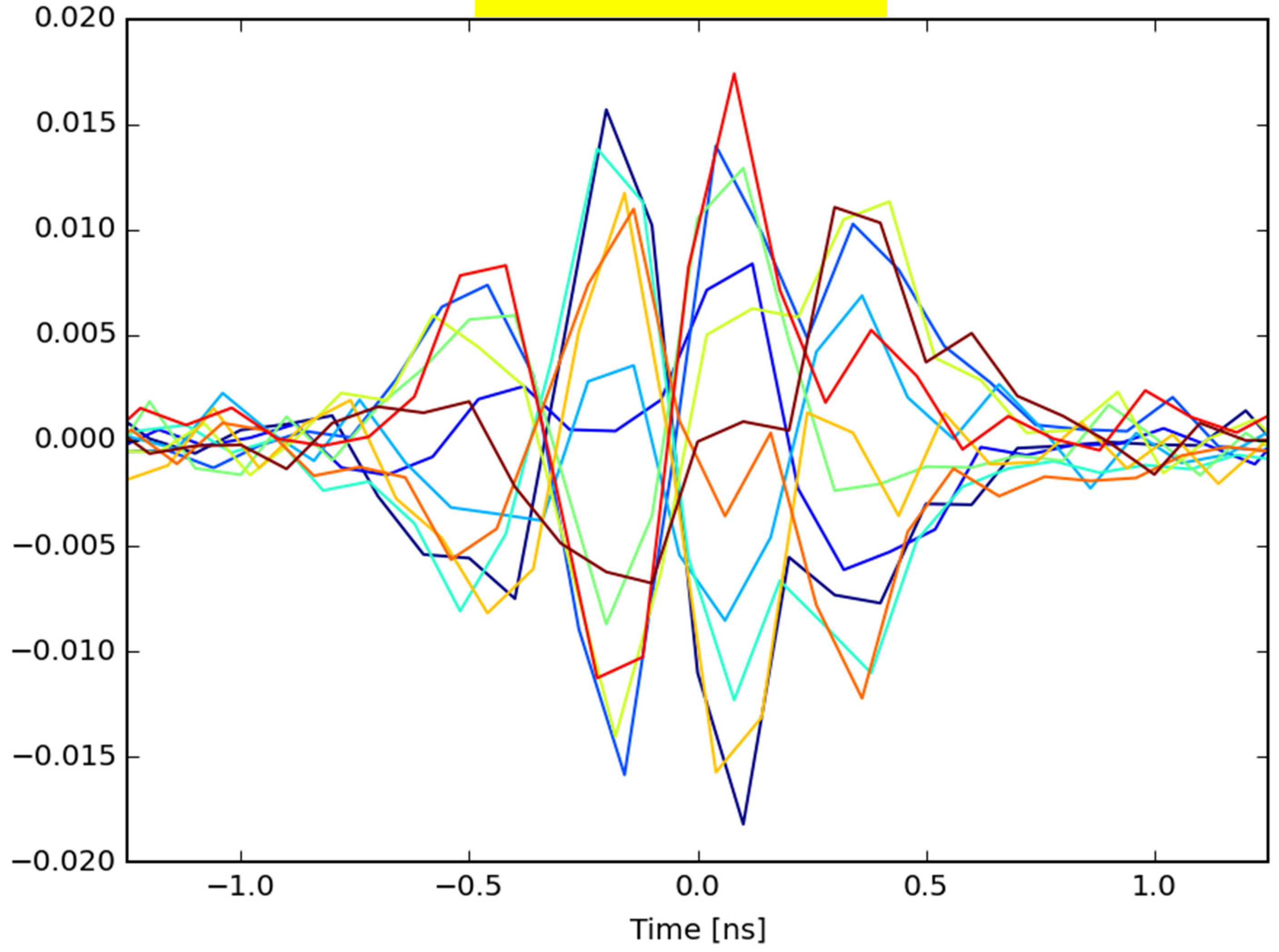

MODE 4




MODE 1




MODE 3




…

# Synchronous triggering

- Head-Tail monitor requires precise triggering to catch instabilities with optimum amplitude.
- Many other instruments can potentially generate useful information – beneficial to have concurrent measurements.
- Need a synchronous trigger system for multiple instruments, distributed around the LHC ring.

Basic operational principal:

1. High resolution detector sees growth of an instability.
2. Sends a trigger across the network.
3. Triggers other instruments after suitable delays.

# LHC Instability Trigger Network

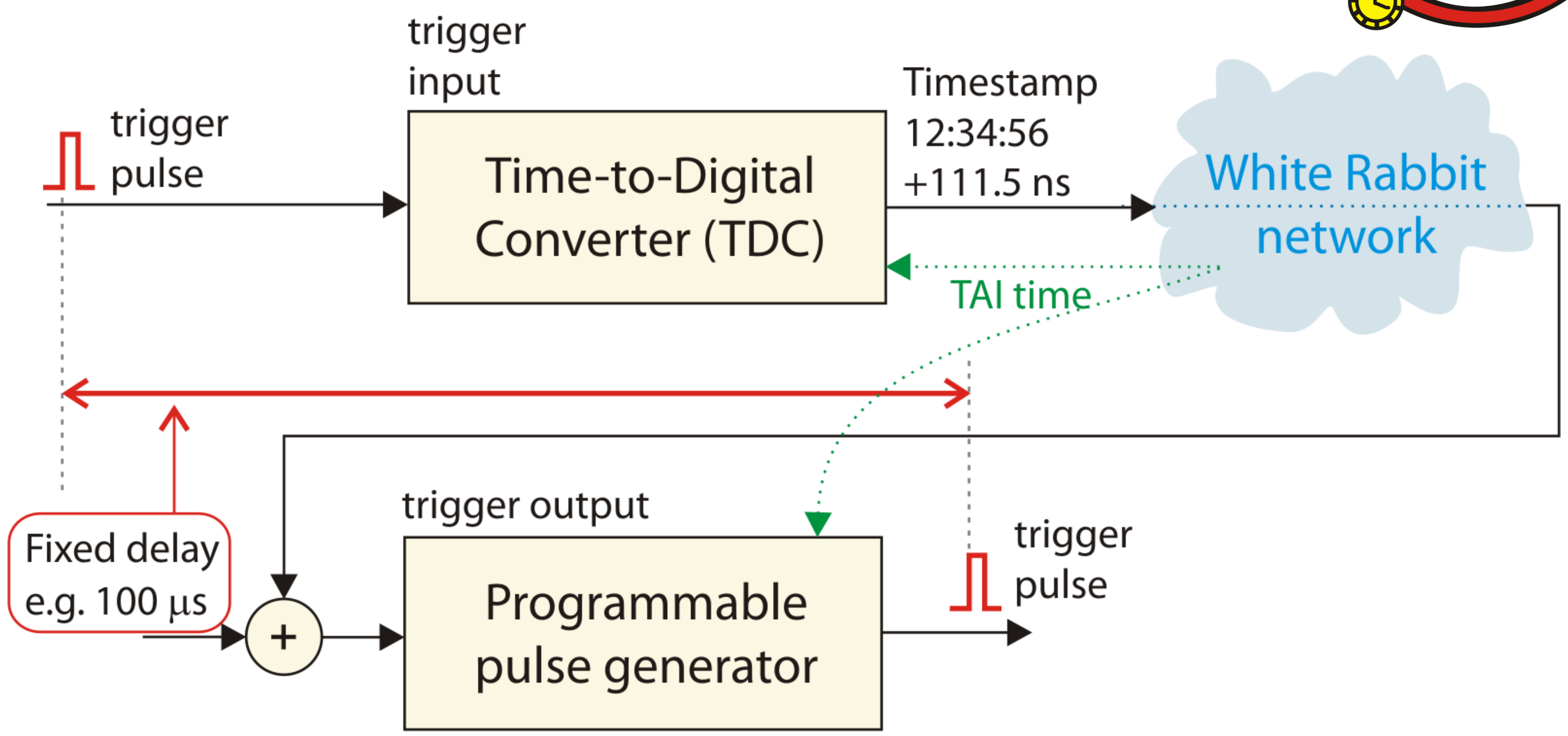
Synchronous Ethernet network based on White Rabbit technology. [4]

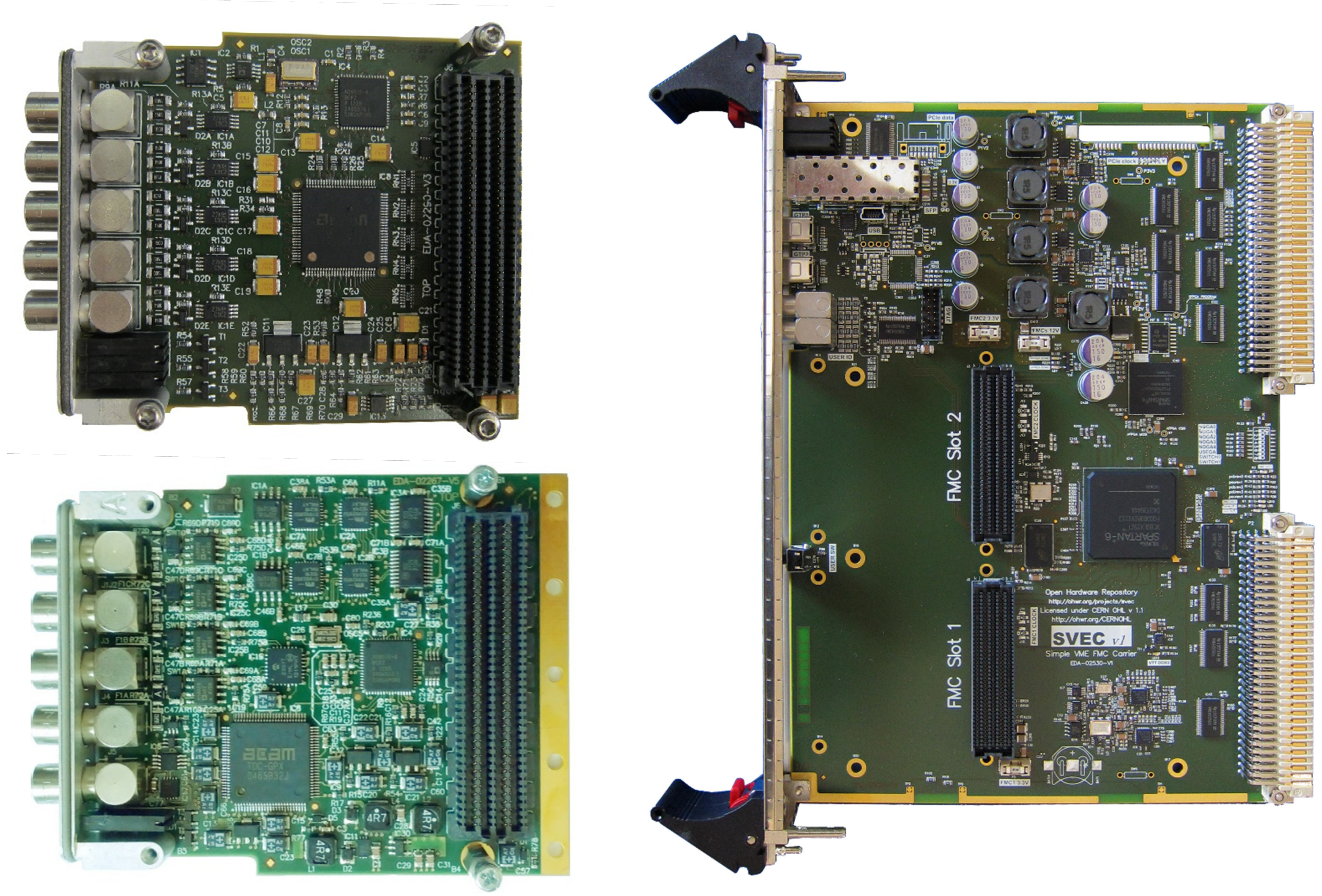
Input trigger pulses timestamped and distributed over network.

Pulse can be recreated at any one or more outputs after a fixed delay.

Synchronisation of all node's clocks assures fixed delay between any input and any output with sub-nanosecond accuracy and picosecond precision.

*Based on CERN Open Hardware designs (SVEC, TDC & Fine Delay).* [5]

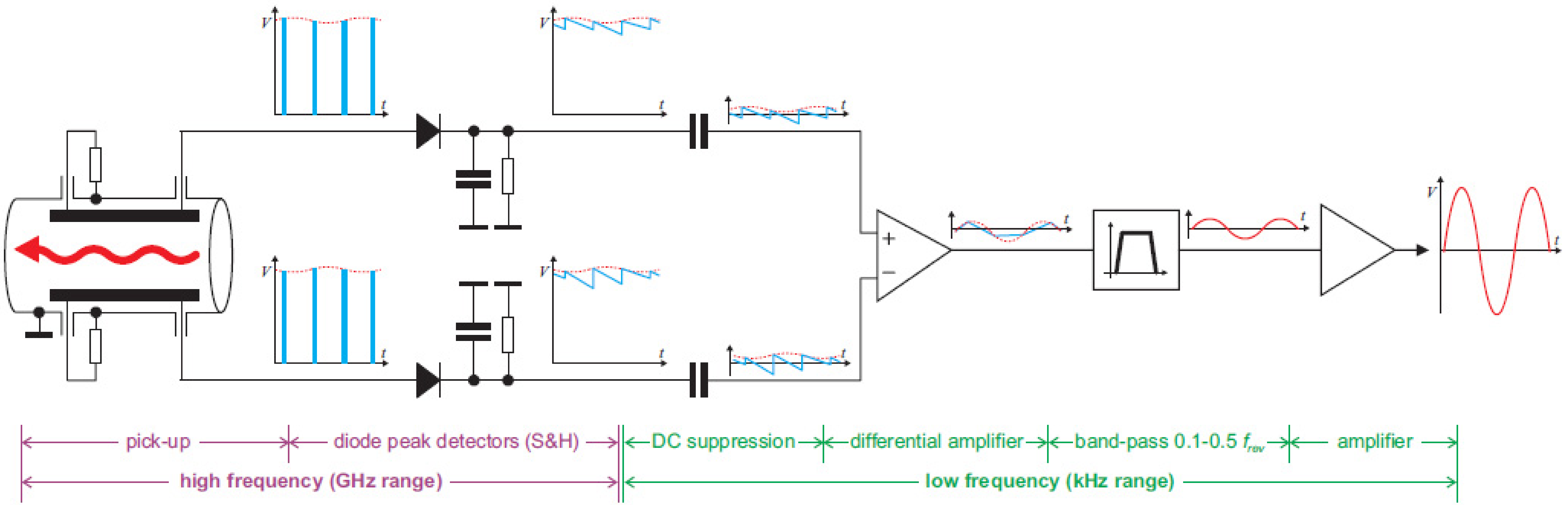


[4] T. Włostowski *et al*, "Trigger and RF distribution Using White Rabbit", ICALEPCS 2015, Melbourne, Australia, WEC3O01, 2015.
[5] http://www.ohwr.org/projects/wr-node-core/wiki/LHC_Instability_Trigger

# LHC base-band tune system

LHC is equipped with a base-band tune (BBQ) measurement system with high sensitivity detectors sampled by high resolution audio ADCs. [6]

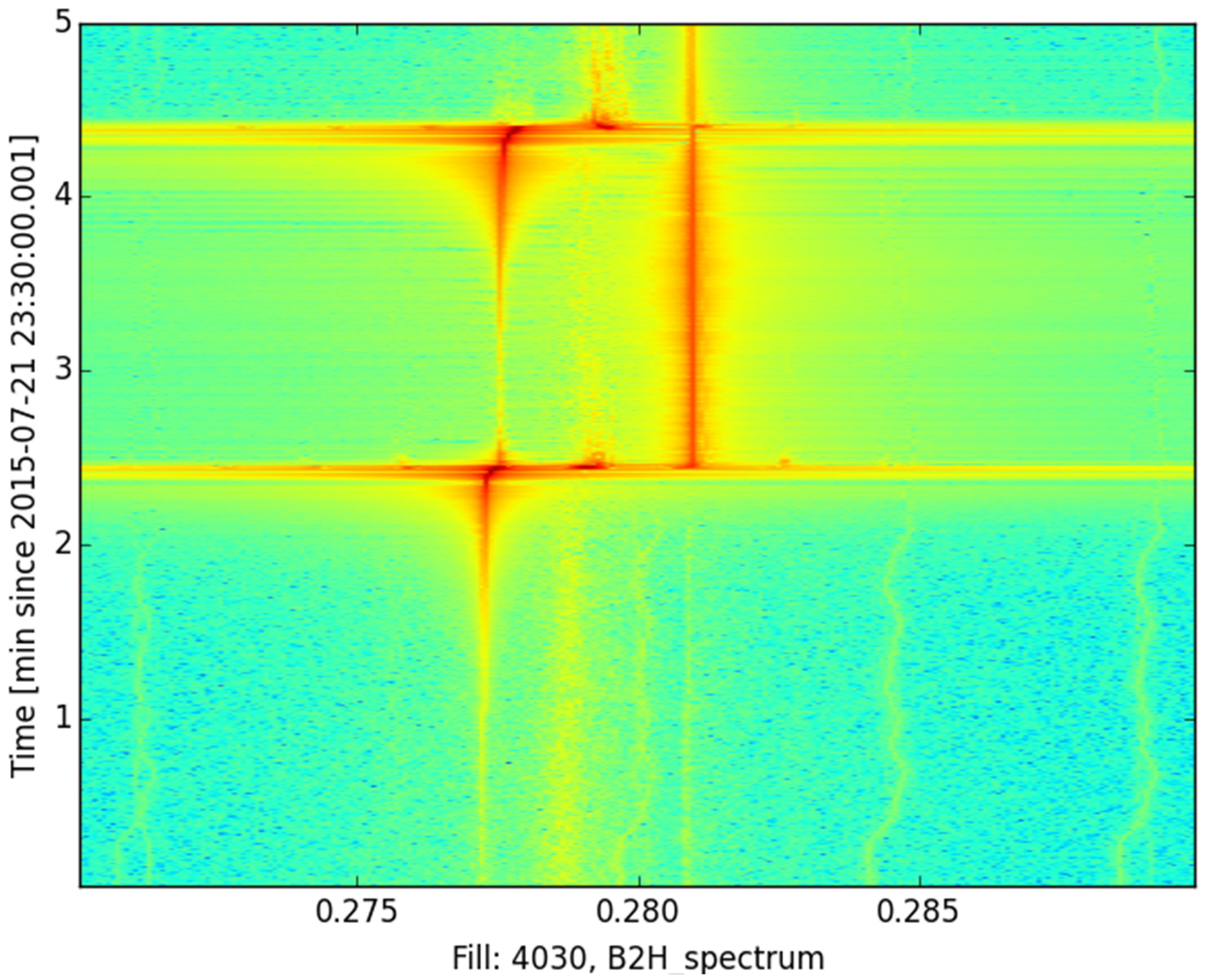



Note, diode detectors operate as peak detectors and are sensitive to largest amplitude bunches, smaller amplitude bunches can be “hidden”.

[6] M. Gasior, “Faraday Cup Award: High Sensitivity Tune Measurement using Direct Diode Detection”, BIW 2012, Newport News, VA USA,2012.

# Trigger generation from BBQ

Instabilities seen as a growth in the spectrum at tune frequency Q ($\pm n\times Q_S$)




Can use growth of peak amplitude to detect instabilities. As instability peak often dominates spectrum, looking at time-domain information gives similar information and is simpler for real-time, low-latency, analysis.

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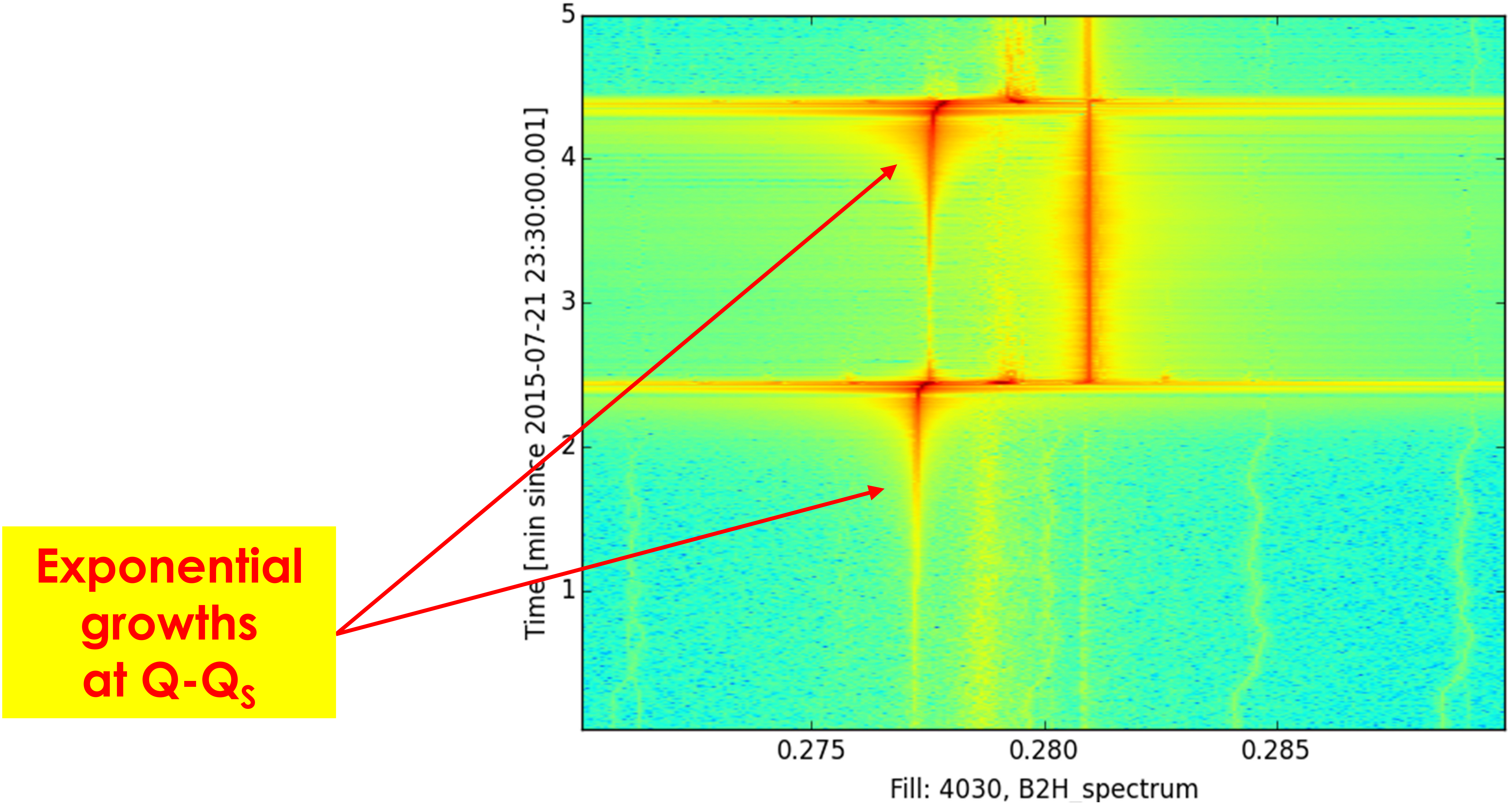
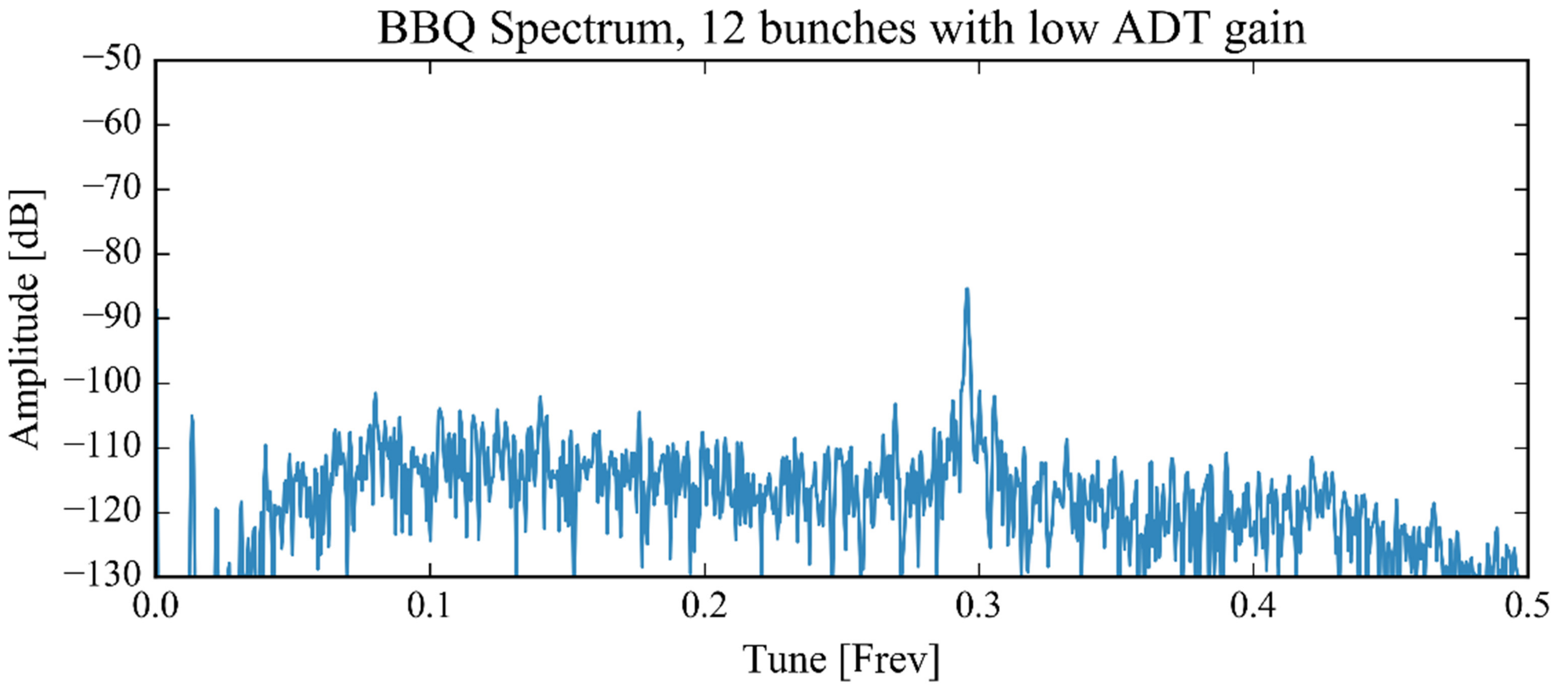


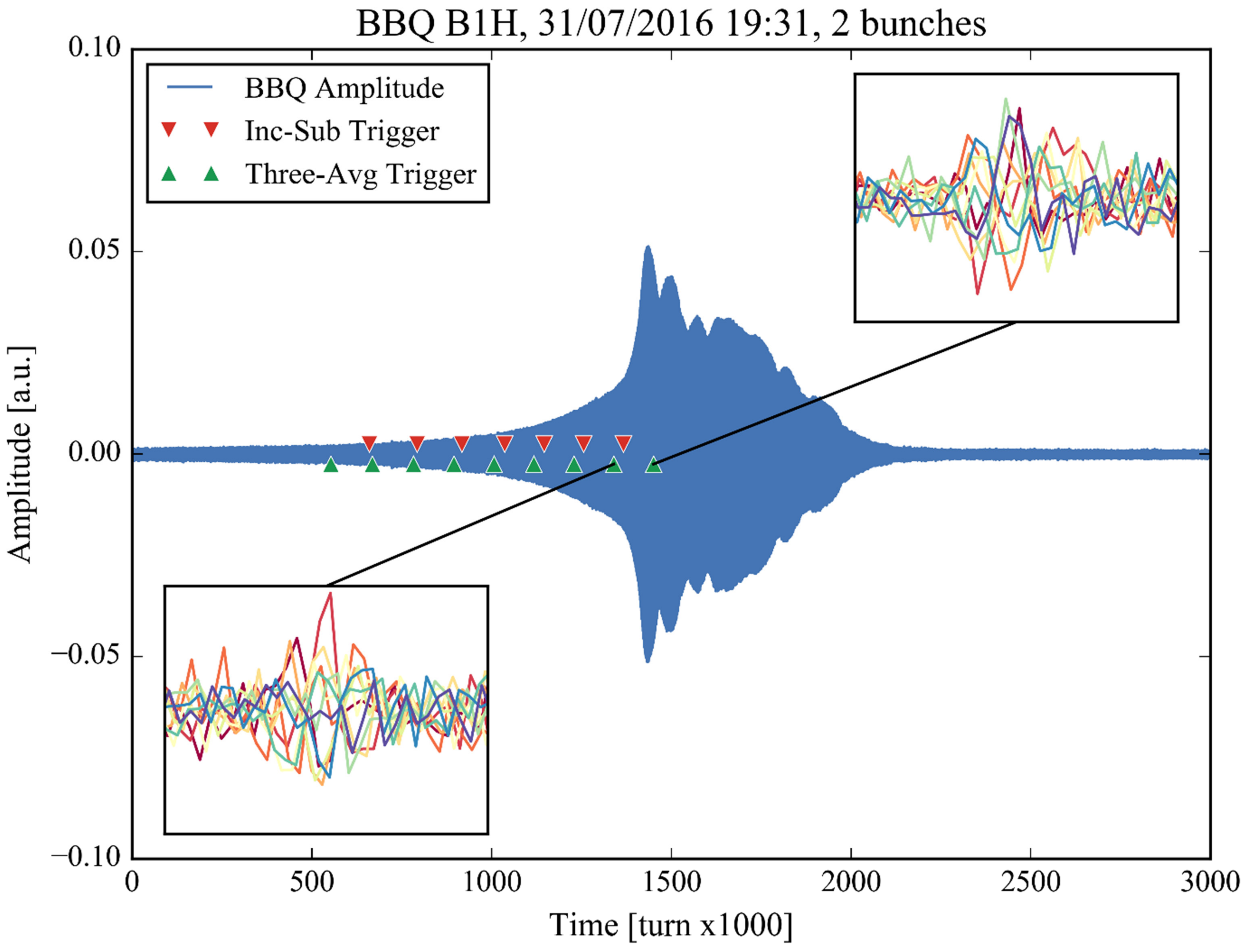

Can use growth of peak amplitude to detect instabilities. As instability peak often dominates spectrum, looking at time-domain information gives similar information and is simpler for real-time, low-latency, analysis.

# Trigger generation from BBQ

Two algorithms developed and tested running in real-time on FPGA soft-core:

1. Compares the amplitude difference of three averages of time domain signal with different lengths
   - Found to be sensitive to noise, glitches
   - Has many parameters to tune
   - Cannot detect slow amplitude growths
2. Uses a more statistical analysis of behaviour of time domain data
   - Less susceptible to noise and glitches
   - Similar or better performance with "obvious" amplitude growths
   - Can detect slow amplitude growths



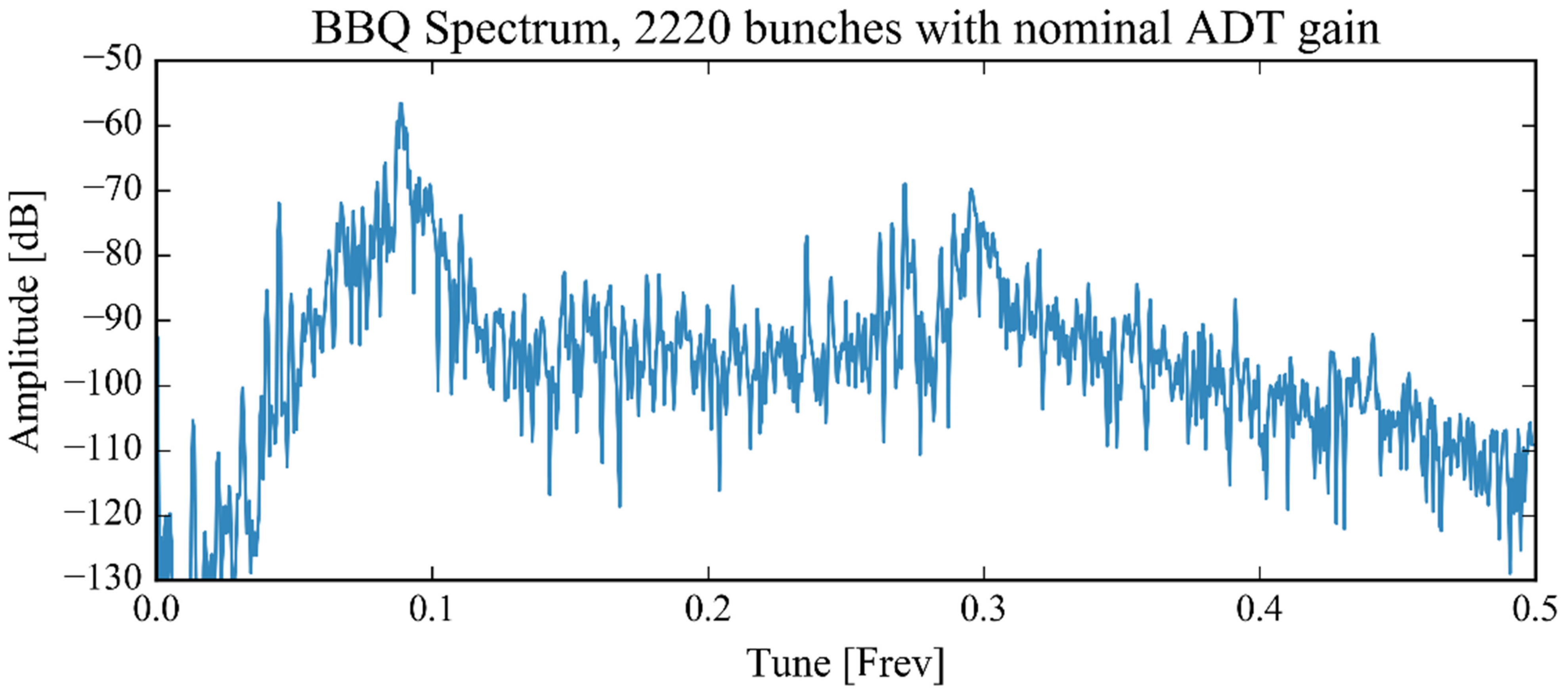
# Trigger generation from BBQ

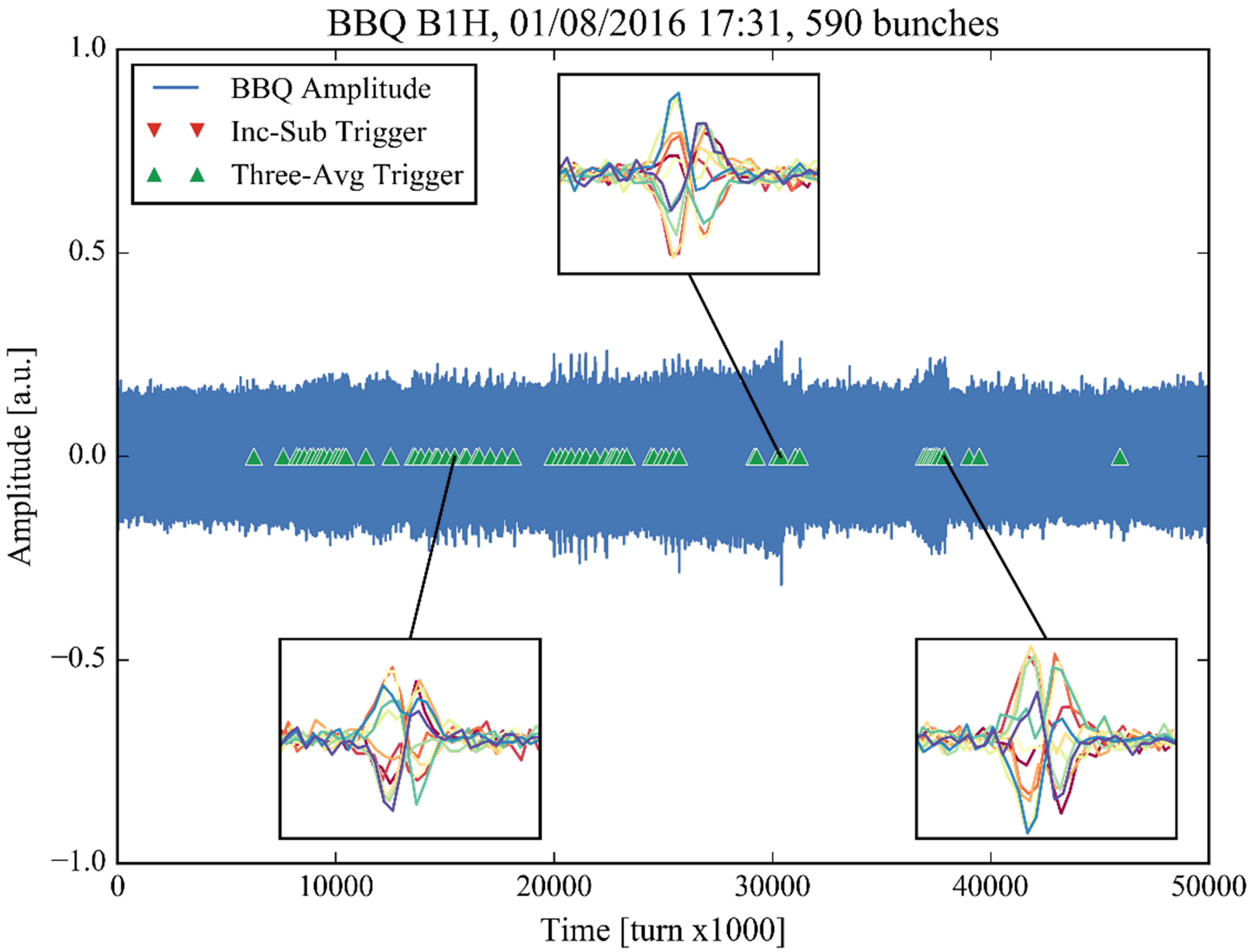
With higher number of bunches and high transverse damper (ADT) gain, situation is less clear:

- Raw BBQ spectrum can be dominated by other noise sources
- Higher intensity bunches can mask instability of lower intensity bunches

More sensitive algorithm can still detect instabilities of a small number of bunches and trigger the Head-Tail – but generates many spurious triggers.

Work is ongoing to improve the robustness of these algorithms.



# Ongoing developments

Remember, increasing head-modes have shift of beam spectrum to higher frequency.

Multi-band Instability Monitor (MIM) [8] uses a RF filter bank to select different frequency bands of beam spectrum.

- For LHC: 0.4, 0.8, … 2.8, 3.2 GHz

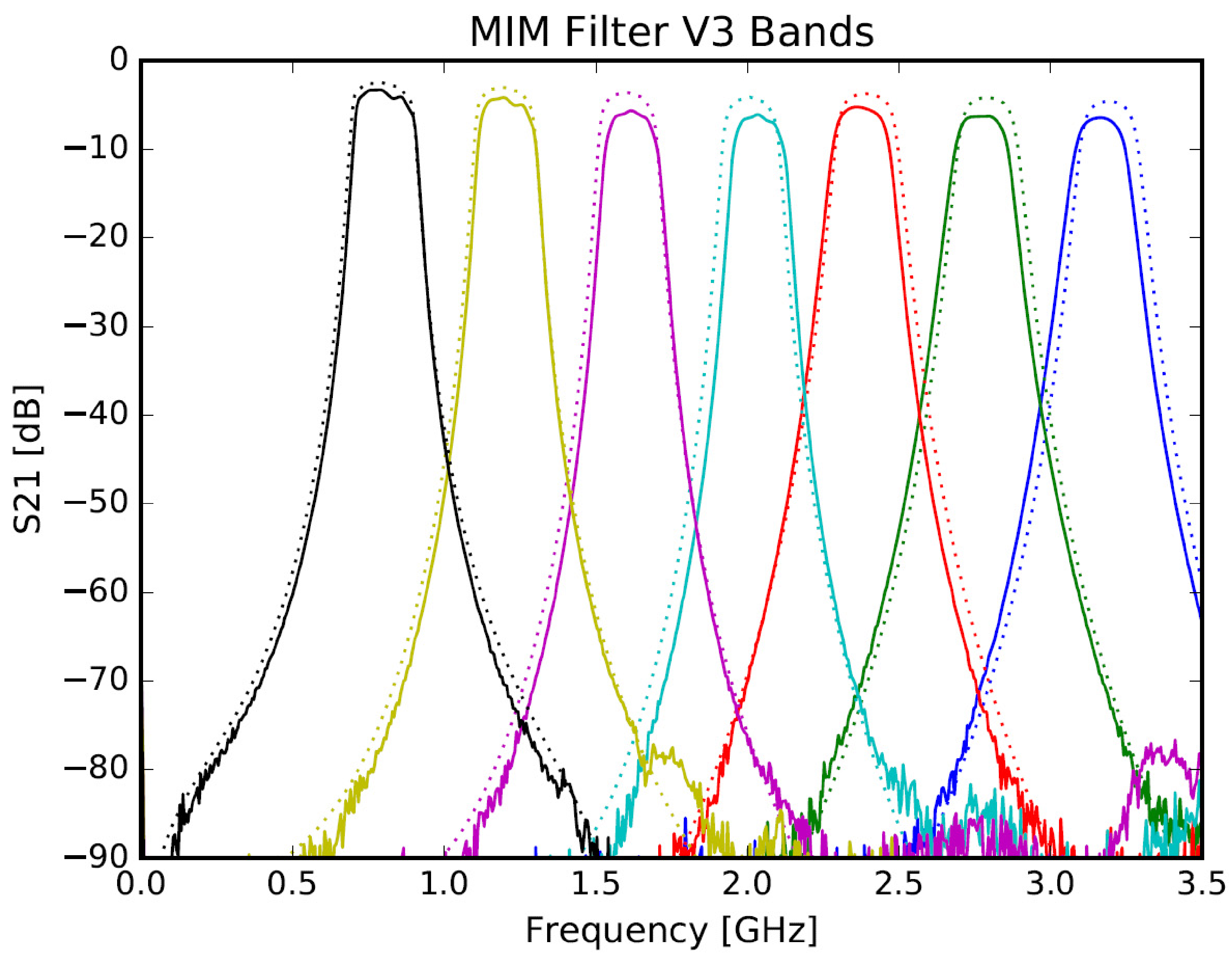
BBQ like diode detection and acquisition.

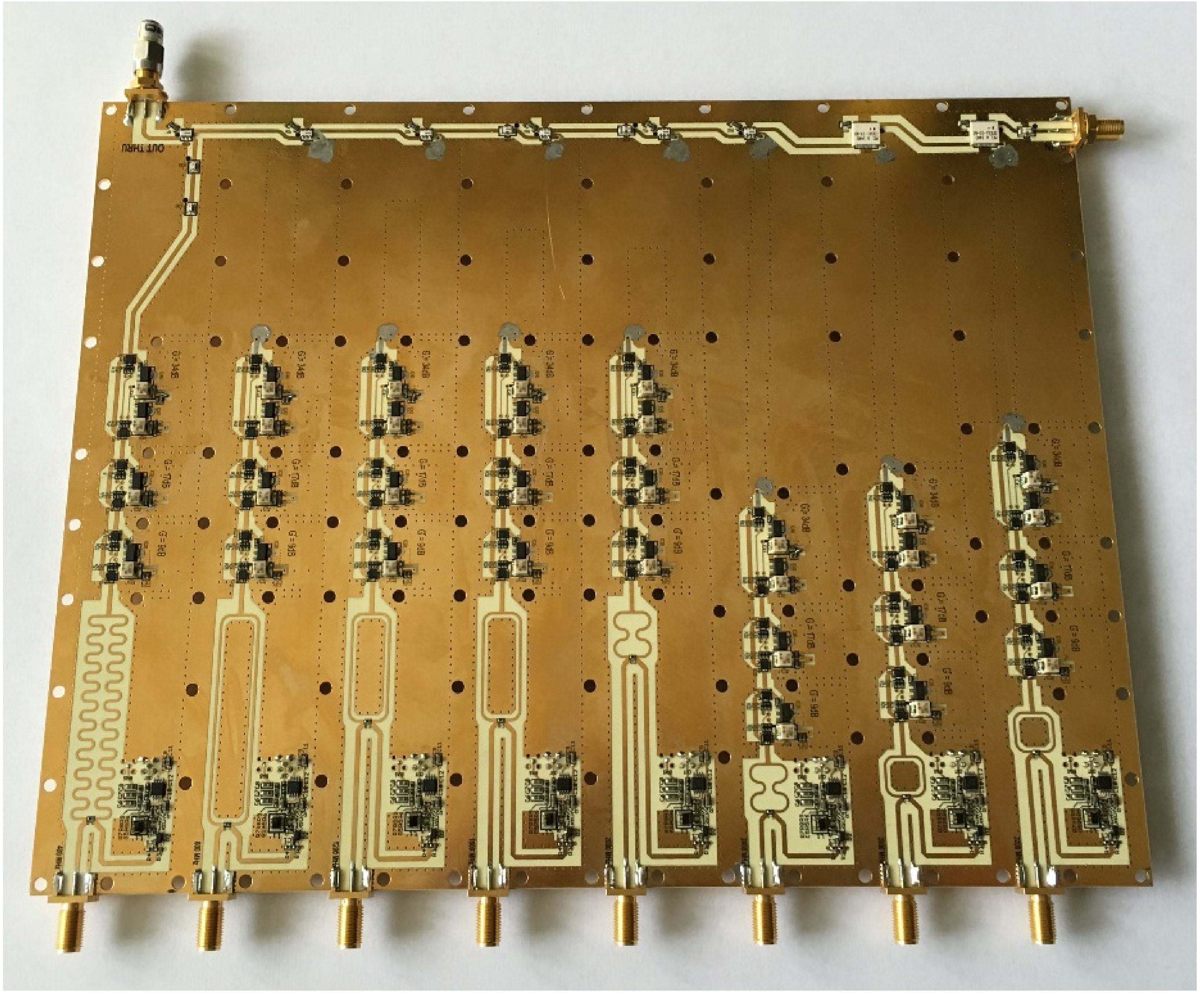
- Options for later bunch by bunch upgrade

Comparison of relative power in bands gives indication of mode number.

First version now installed for testing in LHC.

Concept has also been tested at higher frequency at Australian Synchrotron [8] with three bands up to 12 GHz.



[7] R. Steinhagen, *et al*, "A Multiband-Instability-Monitor for High-Frequency Intra-Bunch Beam Diagnostics", IBIC, Oxford, 2013
[8] T. Lucas, *et al*, "An Optical Intra-Bunch Instability Monitor for Short Electron Bunches", IBIC, Melbourne, 2015

# Conclusions

Instability diagnostics are important for understanding sources of transverse instabilities seen during normal operation in the LHC.

LHC Head-Tail monitor allows direct time domain analysis of intra-bunch motion but has limited dynamic range and acquisition length, so must be accurately triggered to catch fast instabilities. Automatic tools for data analysis have been developed to remove automatically “uninteresting” acquisitions.

LHC now has an Instability Trigger Network to synchronously distributed triggers between various diagnostics with sub-nanosecond precision.

Sensitive BBQ acquisition system has been used to generate a trigger for the Head-Tail monitor with good results. Two different algorithms have been tested but suffer from BBQ signal quality with many bunches and high ADT gain.

Ongoing developments in frequency domain analysis with MIM.

# Thank you for your attention!

www.cern.ch