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International Beam Instrumentation Conference

A Multiband-Instability-Monitor for High-Frequency Intra-Bunch Beam Diagnostics

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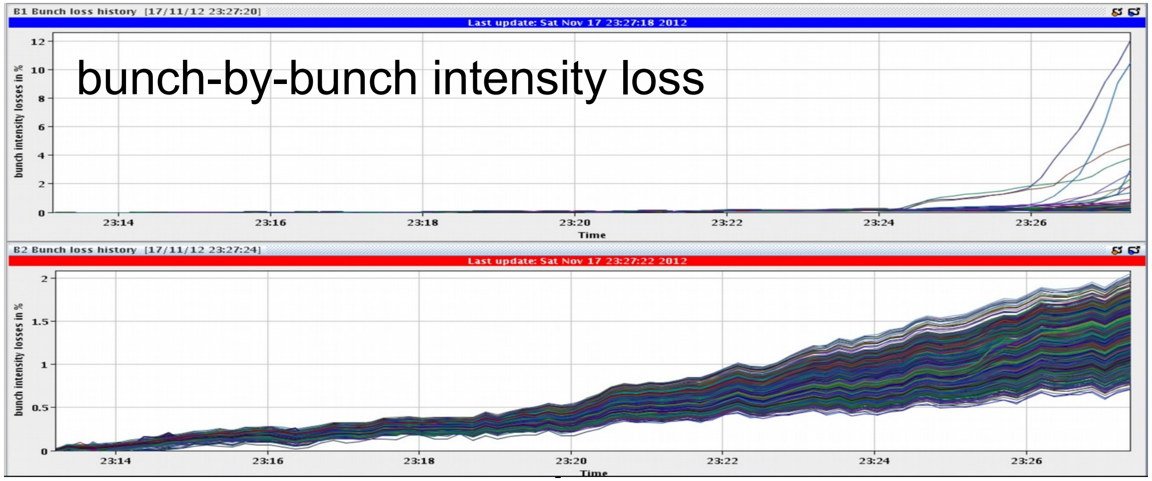
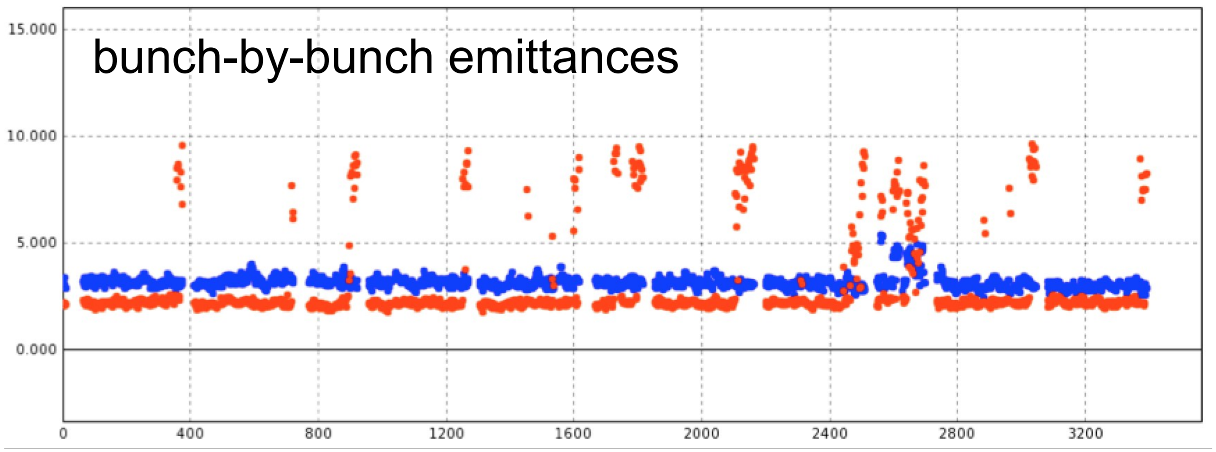
LHC Performance Limitations

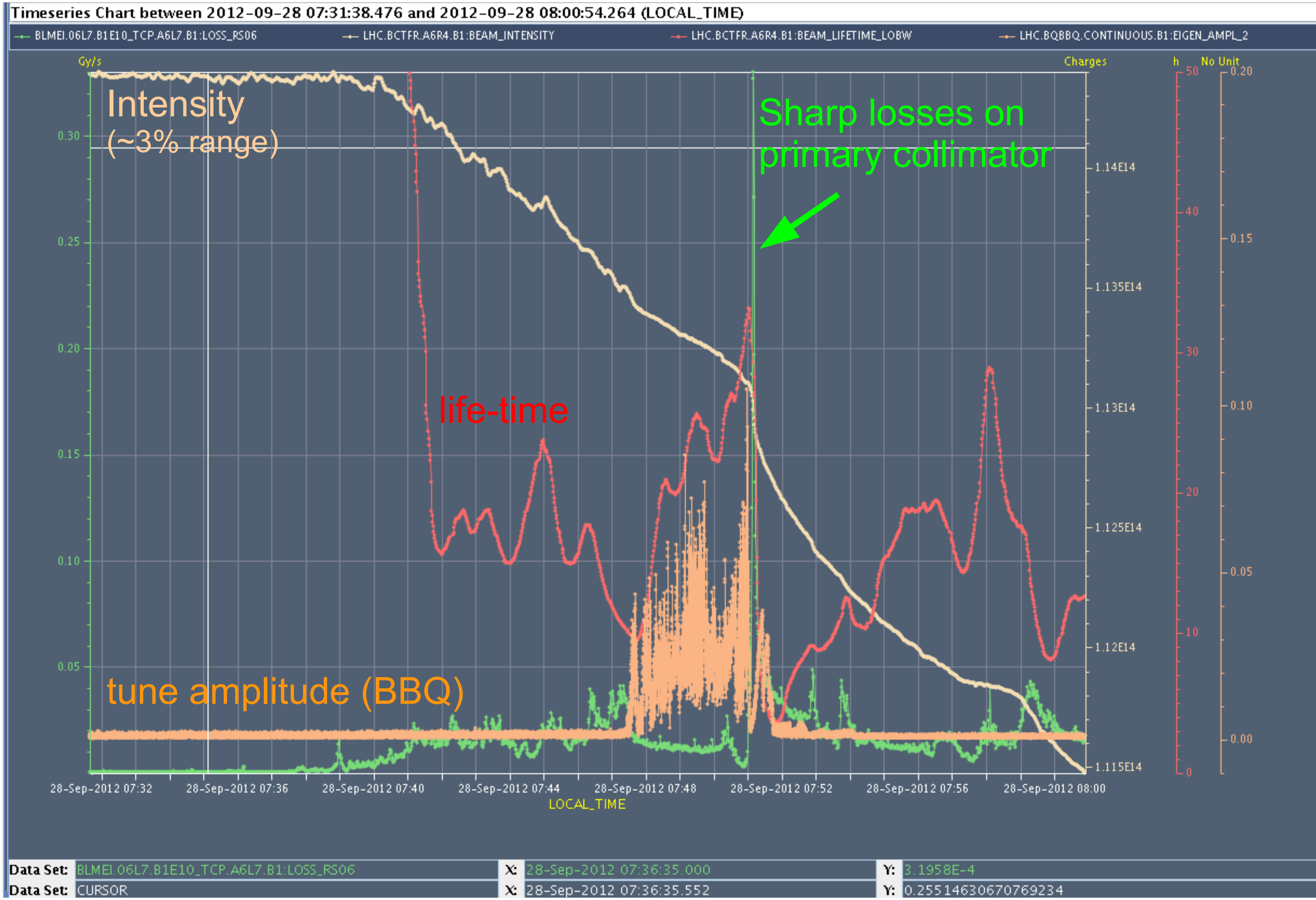
- Instabilities occurring during last steps of the final-focus β^*-squeeze



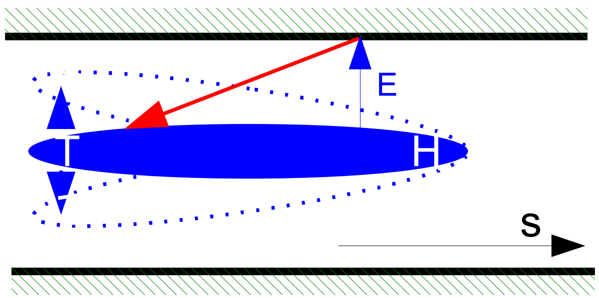


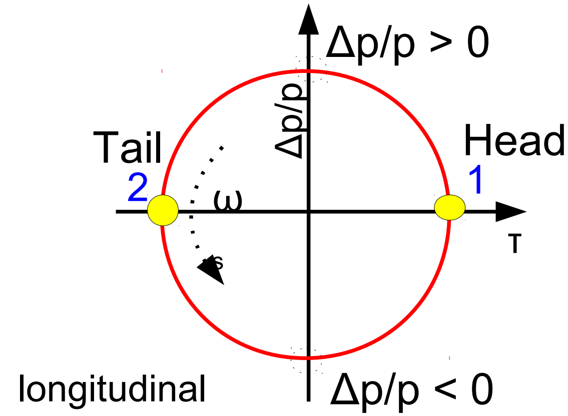
- Need better diagnostics to understand and mitigate these effects after LS-1

- Preceding oscillations typically only detected by sensitive RF detectors

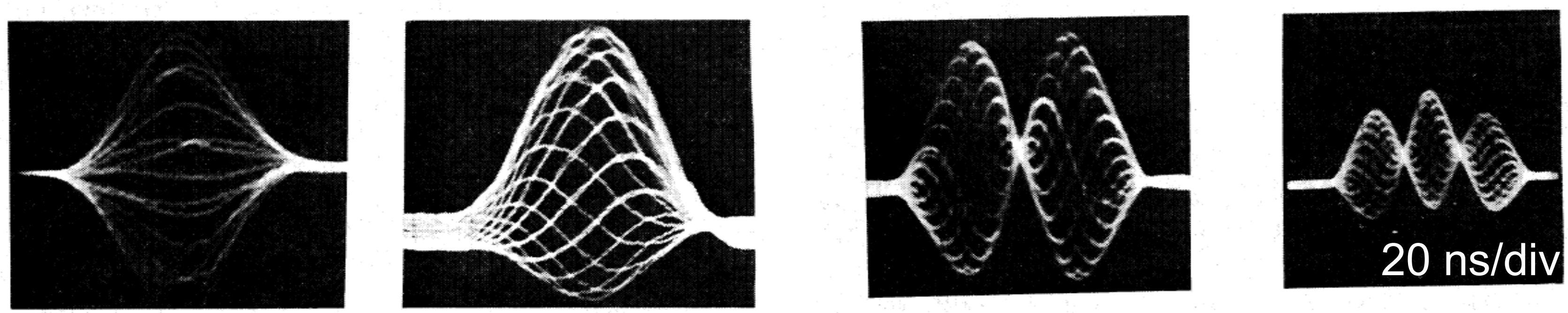


Classic Head-Tail Oscillations I/II





- First direct observation at the CERN-Booster[2]:

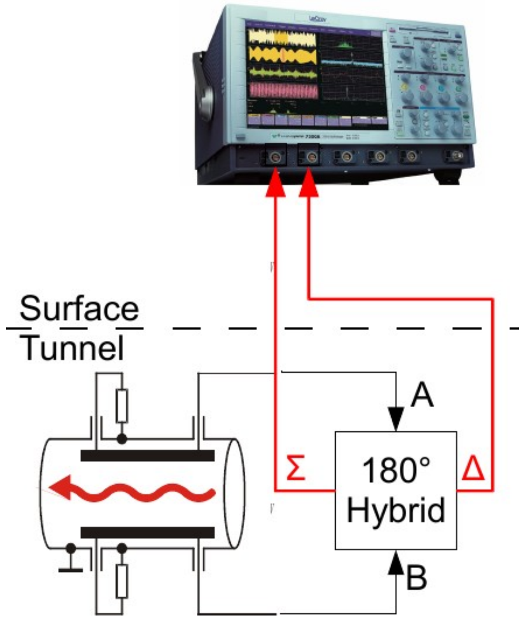


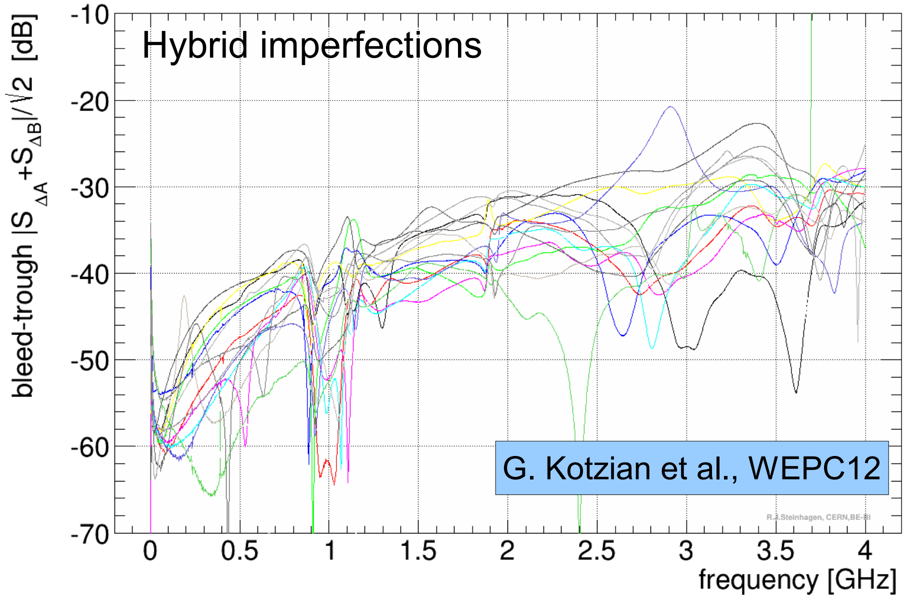
a) mode m = 0, χ = 0   b) m = 0, χ = 2.3 radians   b) m = 1, χ = 6.9 radians   d) m = 2, χ = 6.9 radians

- PS: 120 ns bunch length ↔ less demanding in terms of bandwidth
- SPS/LHC: bunch base length below 1 ns → requires multi-GHz bandwidths

1 M. Sands, *"The Head-Tail Effect: An Instability Mechanism in Storage Rings"*, SLAC-TN-69-008, 1969
2 J. Gareyte, "Head-Tail Type Instabilities in the PS and Booster", CERN, 1974

Classic Head-Tail Diagnostics
Direct Wide-Band Time-Domain Acquisition



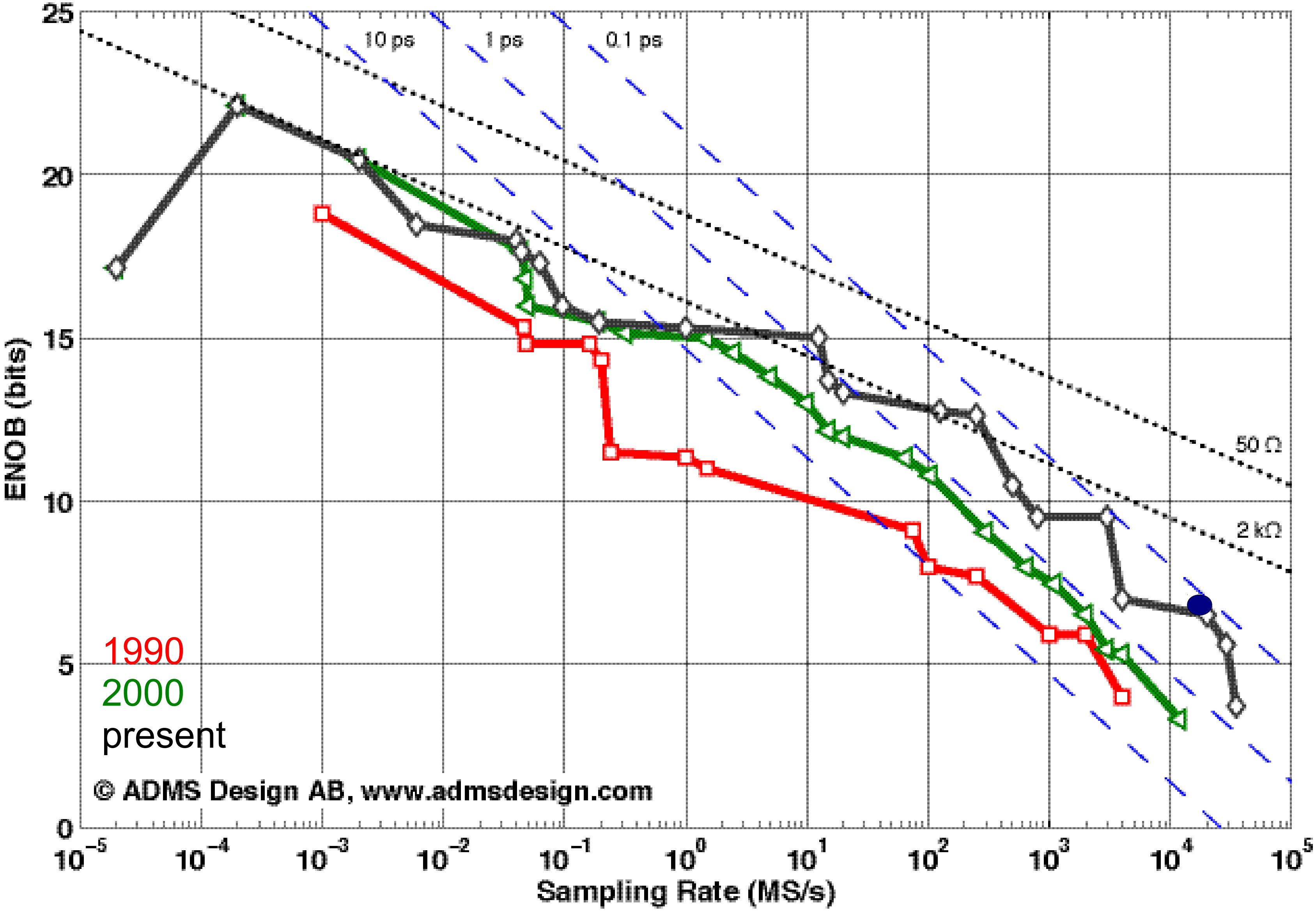


- Shorter bunches, higher modes → need to increase system bandwidth MOPC20
  → Electro-Optical- and Synchrotron-Light BPMs with >12 GHz bandwidth
- 180°-Hybrid imperfections ~1%@1GHz + limited oscilloscope resolution
  - Effective resolution ~100 um → beam typically lost
- Instabilities occurring …
  - … on <u>any</u> & a priori <u>unknown</u> bunch,
  - … at a not precisely/unknown time during the fill

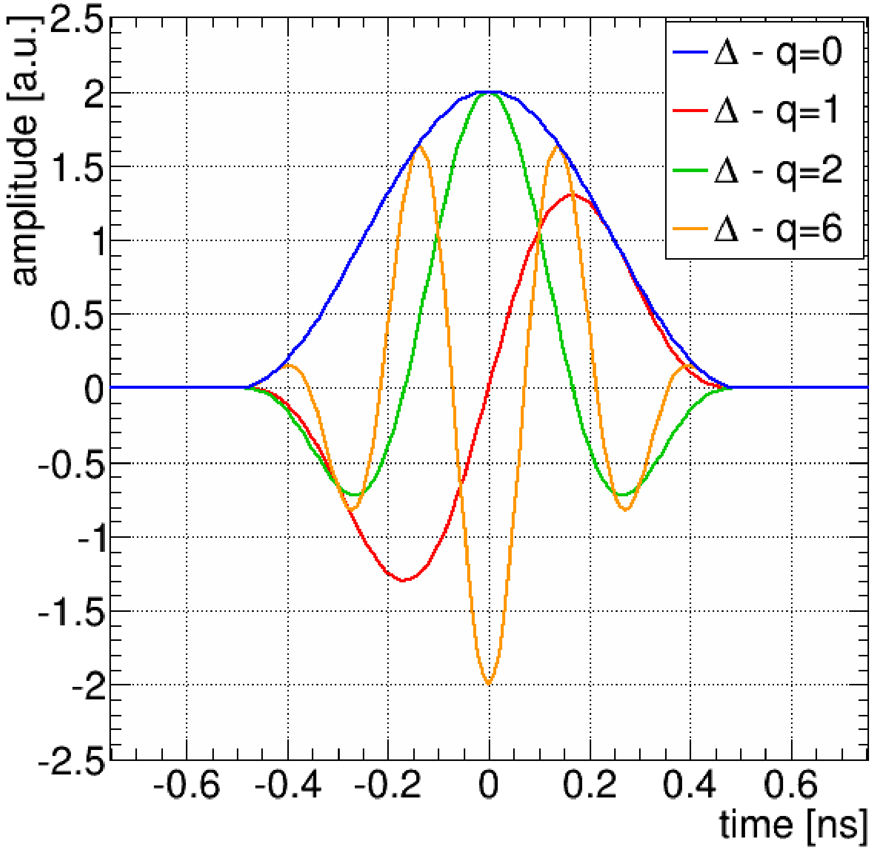
→ need something similar to a 'flight recorder'

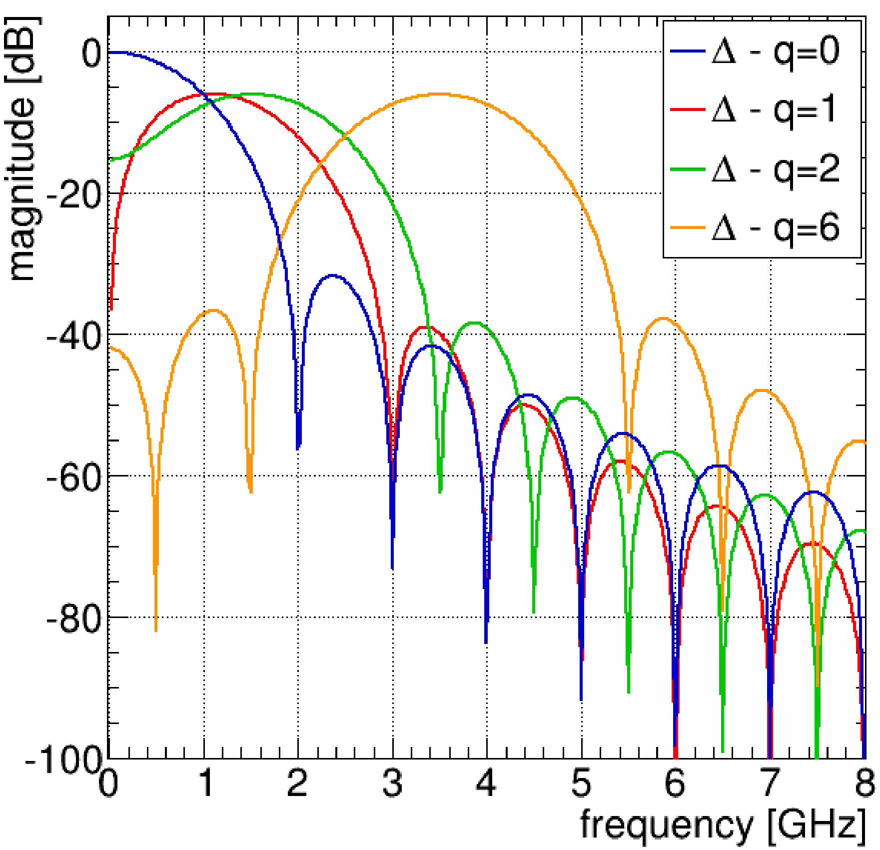
Limits of direct time-domain digitization

- ADCs performance levels out and approaching fundamental physical limits



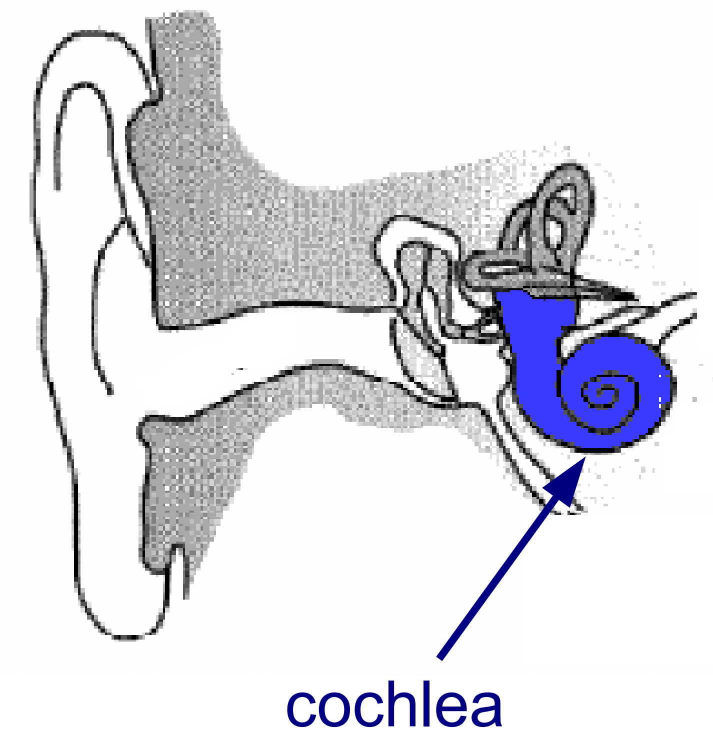
Equivalence of Time- and Frequency-Domain Observables

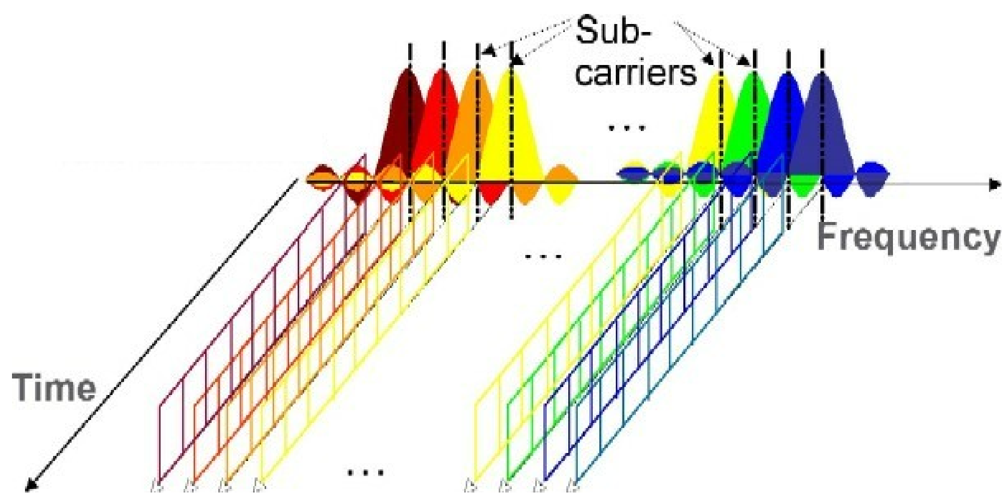




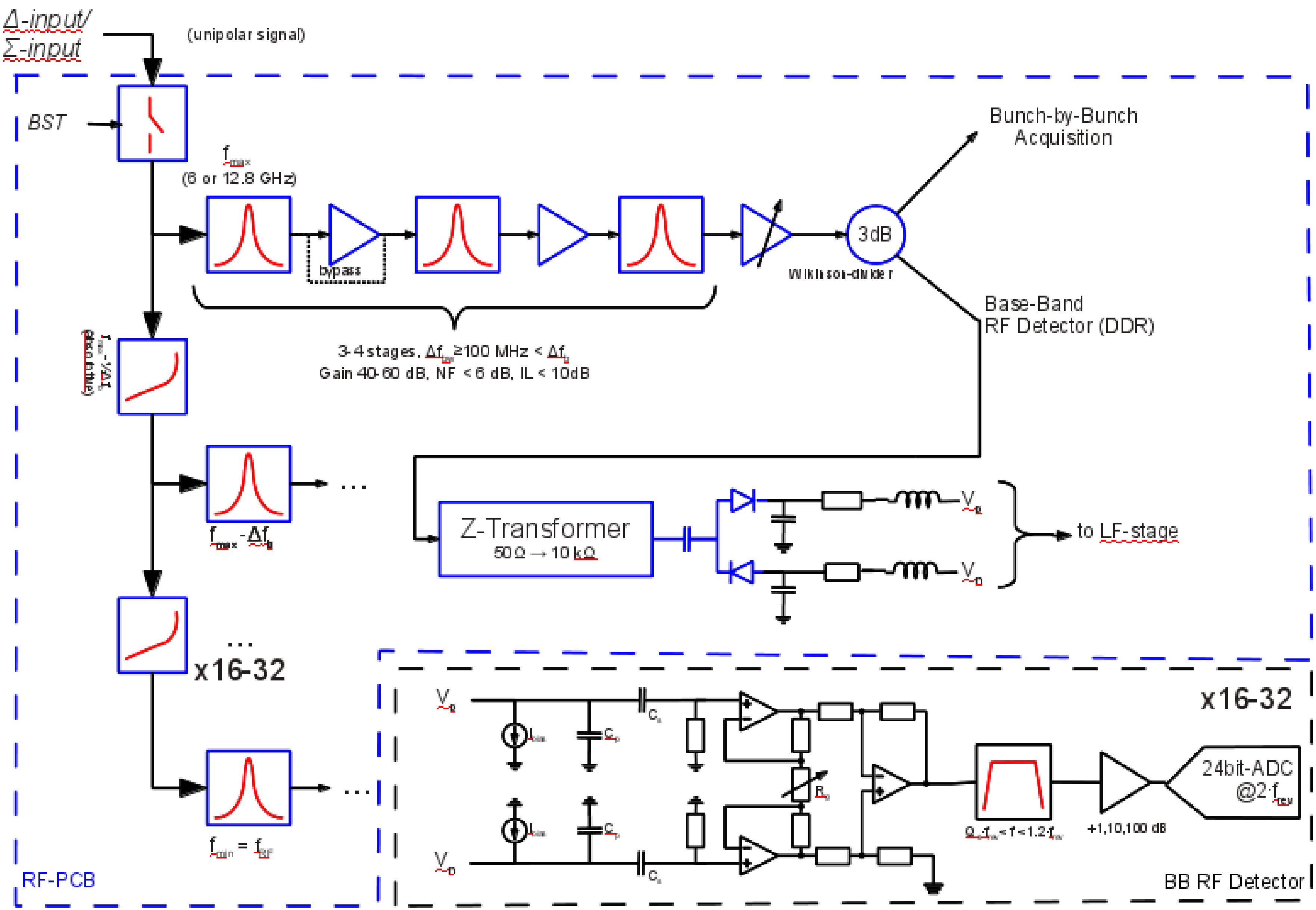
How to beat the ADC ENOB Limit?
Divide-and-Conquer Strategy – Interleaving of multiple ADCs

A) Time-domain interleaving → limited by thermal noise and jitter
B) orthogonal-frequency multiplexing or *cochlear radio*



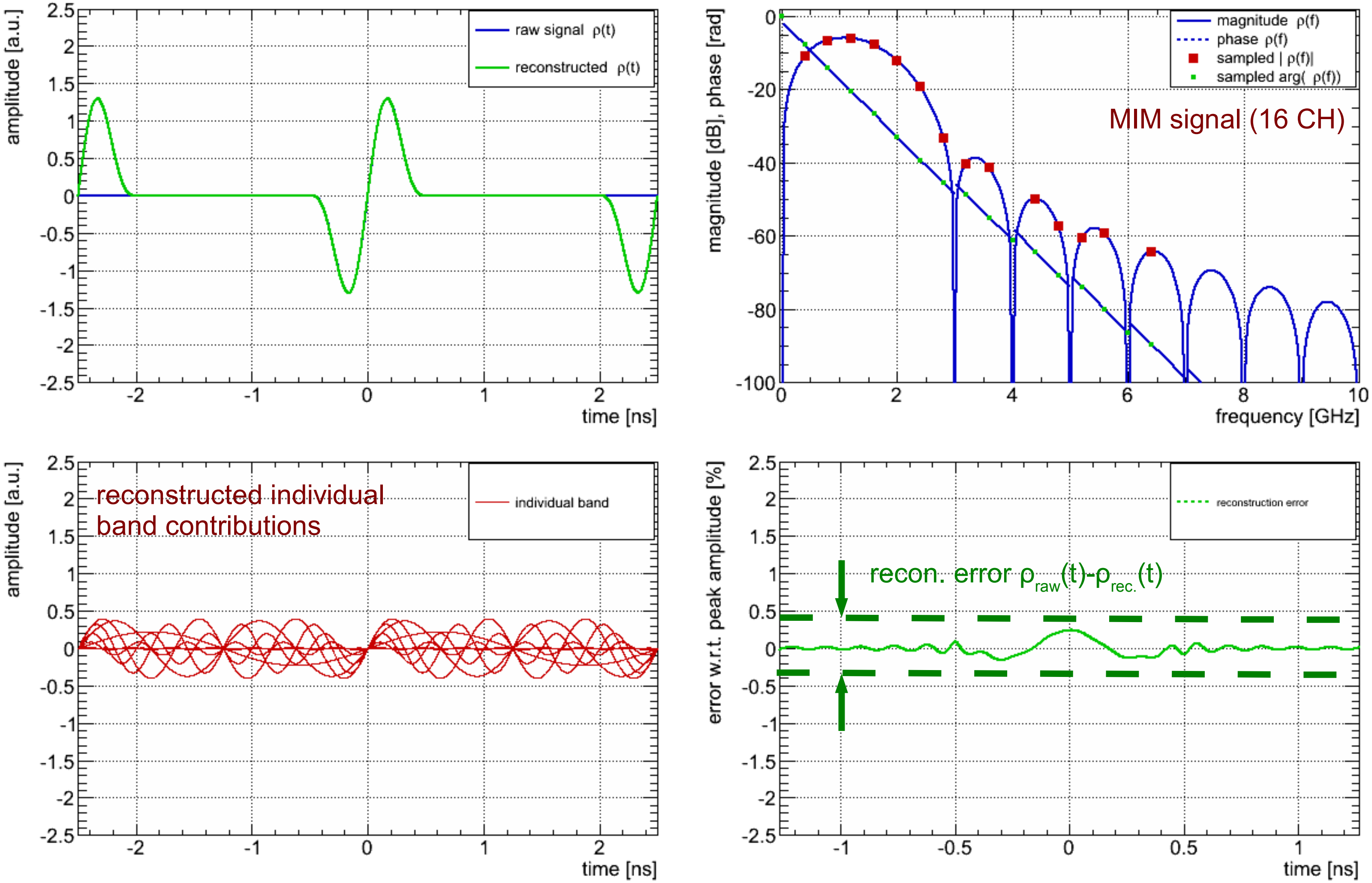


Multiband-Instability-Monitor (MIM) – Schematic



Example: Time-Domain Reconstruction

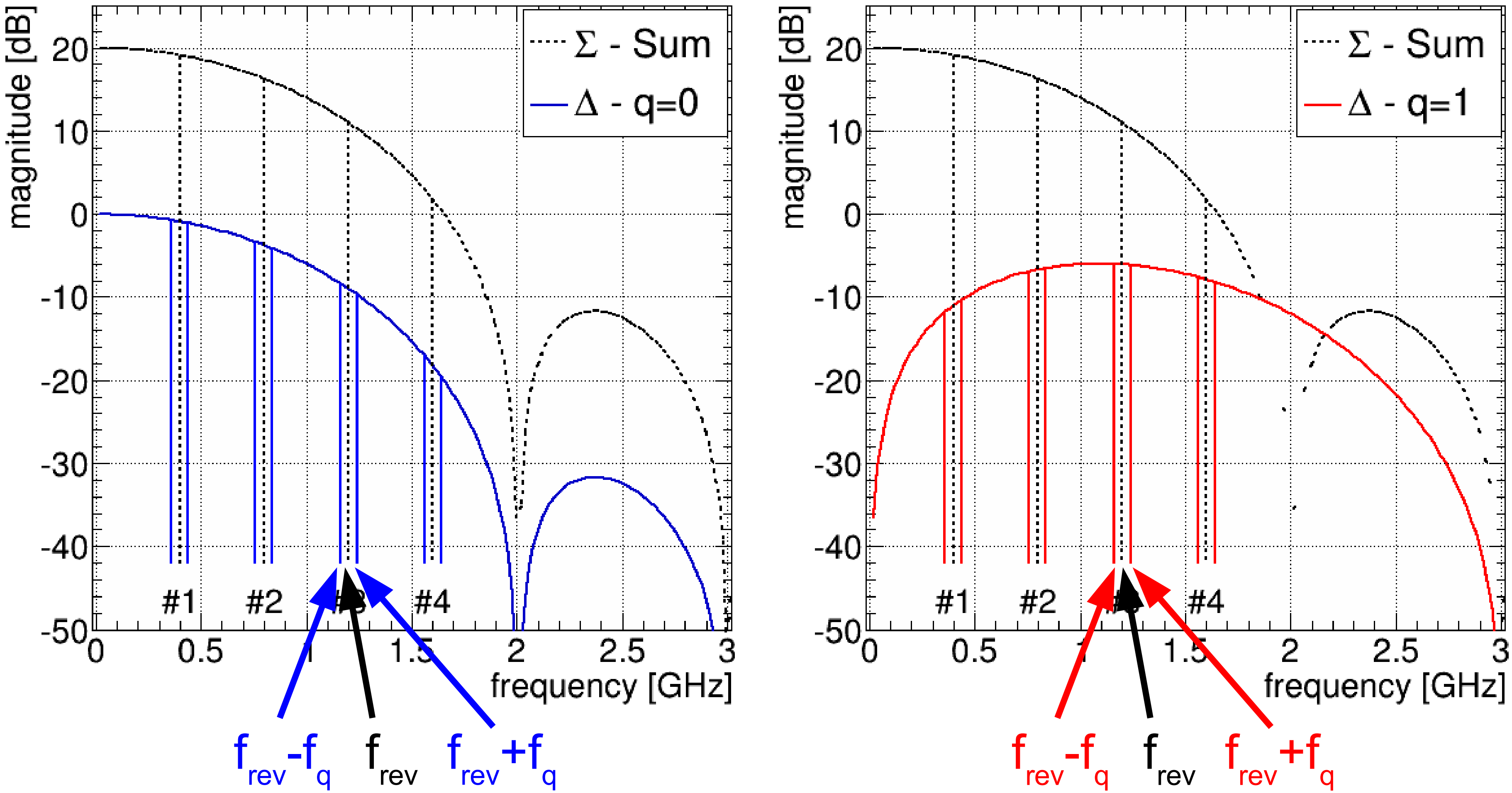
- Single bunch/turn – q=1, 16 bands @ Δf_b=0.4 GHz



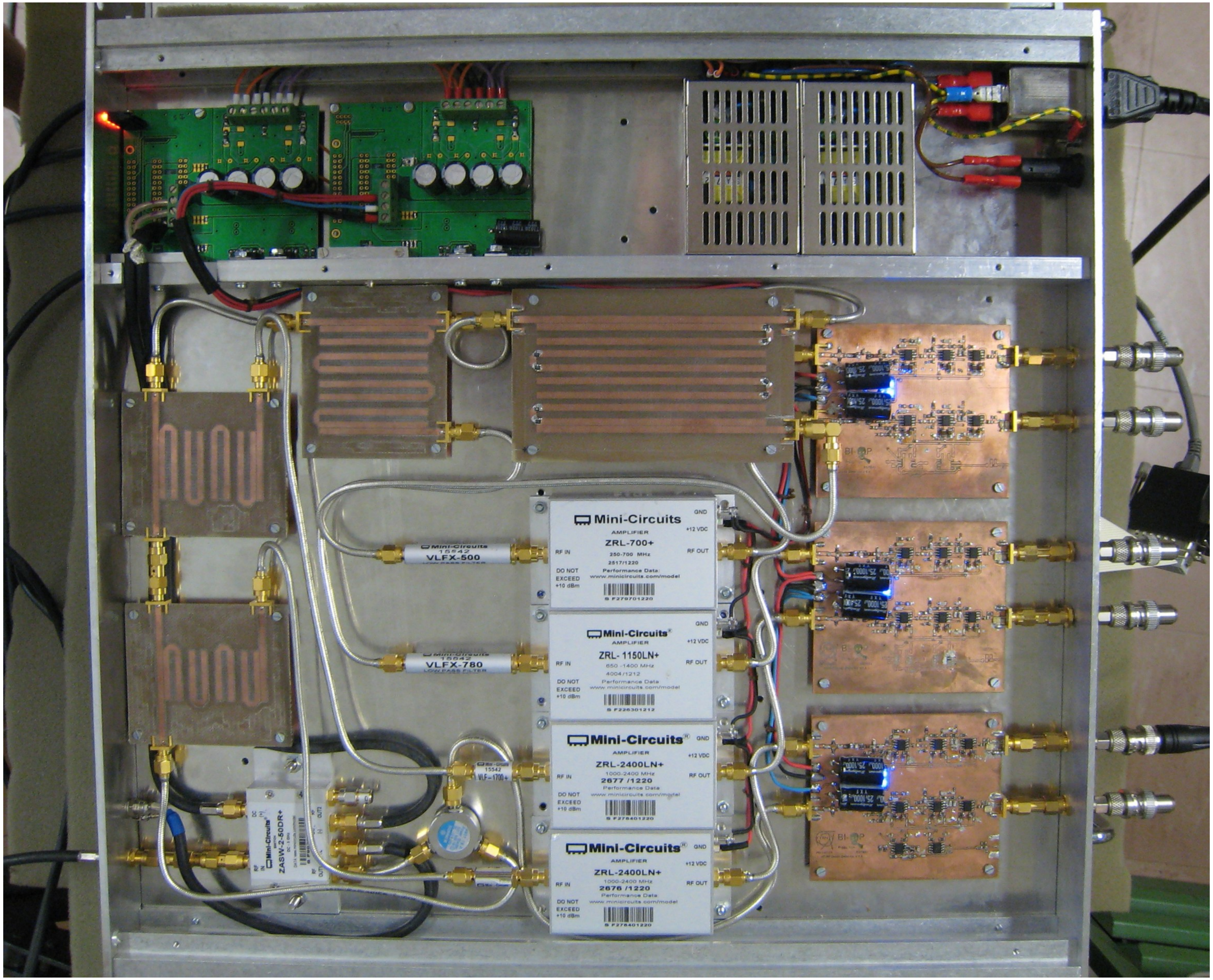
- percent-level reconstruction for 16 bands

Multiband-Instability-Monitor (MIM)
Example: Frequency-Domain Reconstruction

- Many of the instability information is accessible without knowledge on phase:



Multiband-Instability-Monitor (MIM)
Proof-of-Concept Prototype



Δ-Signal

full-range

0.4 GHz

0.8 GHz

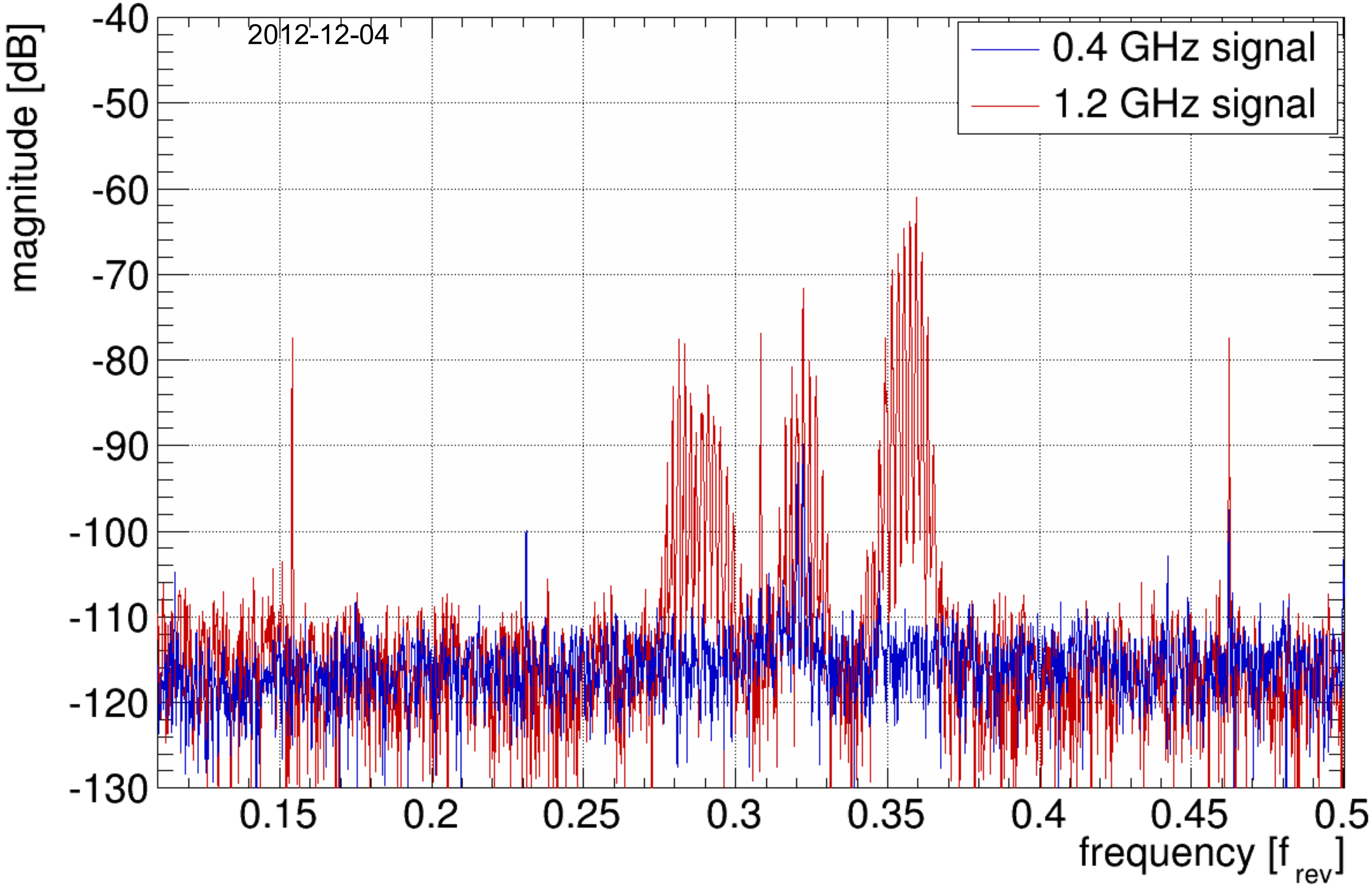
1.2 GHz

1.6 GHz

full-range

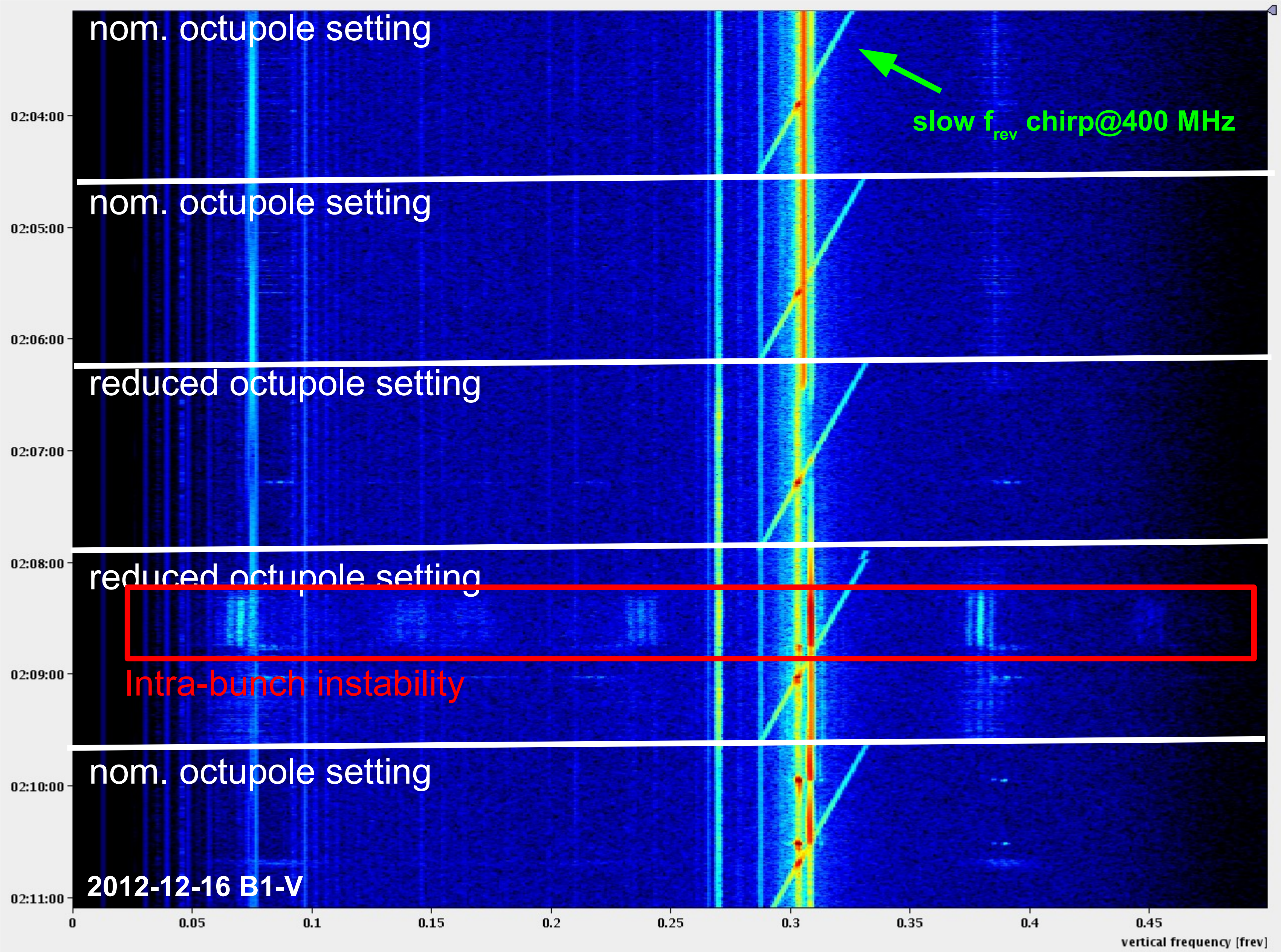
Multiband-Instability-Monitor (MIM)
LHC Instability Example

- B1-V instability during ADJUST as measured by the MIM prototype:



- Indicative that instability is due to an intra-bunch motion (N.B. vivid Q_s sidebands)
  - more sensitive than any other direct time-domain detection

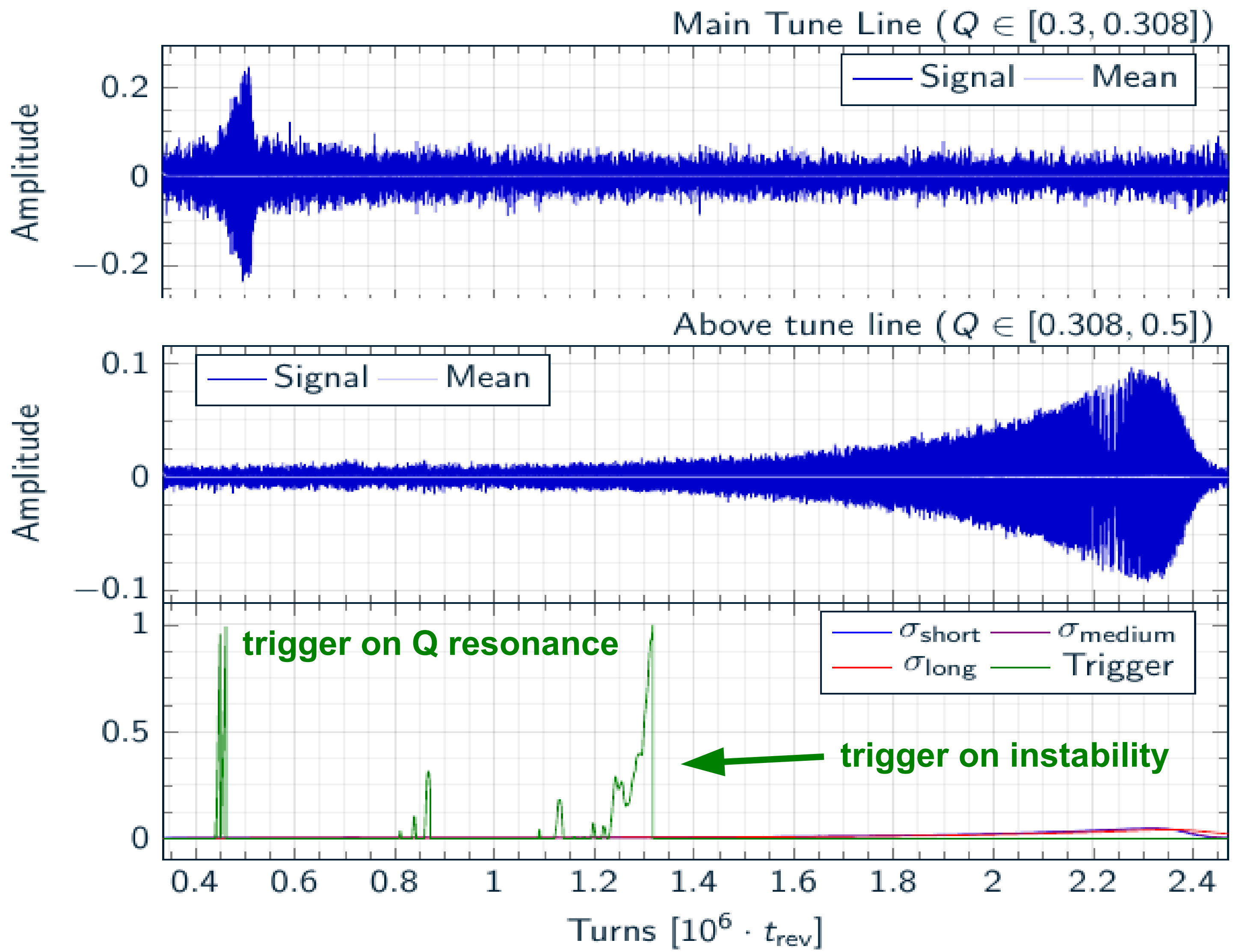
Multiband-Instability-Monitor (MIM)
Testing Stability Margin with HF Exciter (0.3-2.5 GHz)



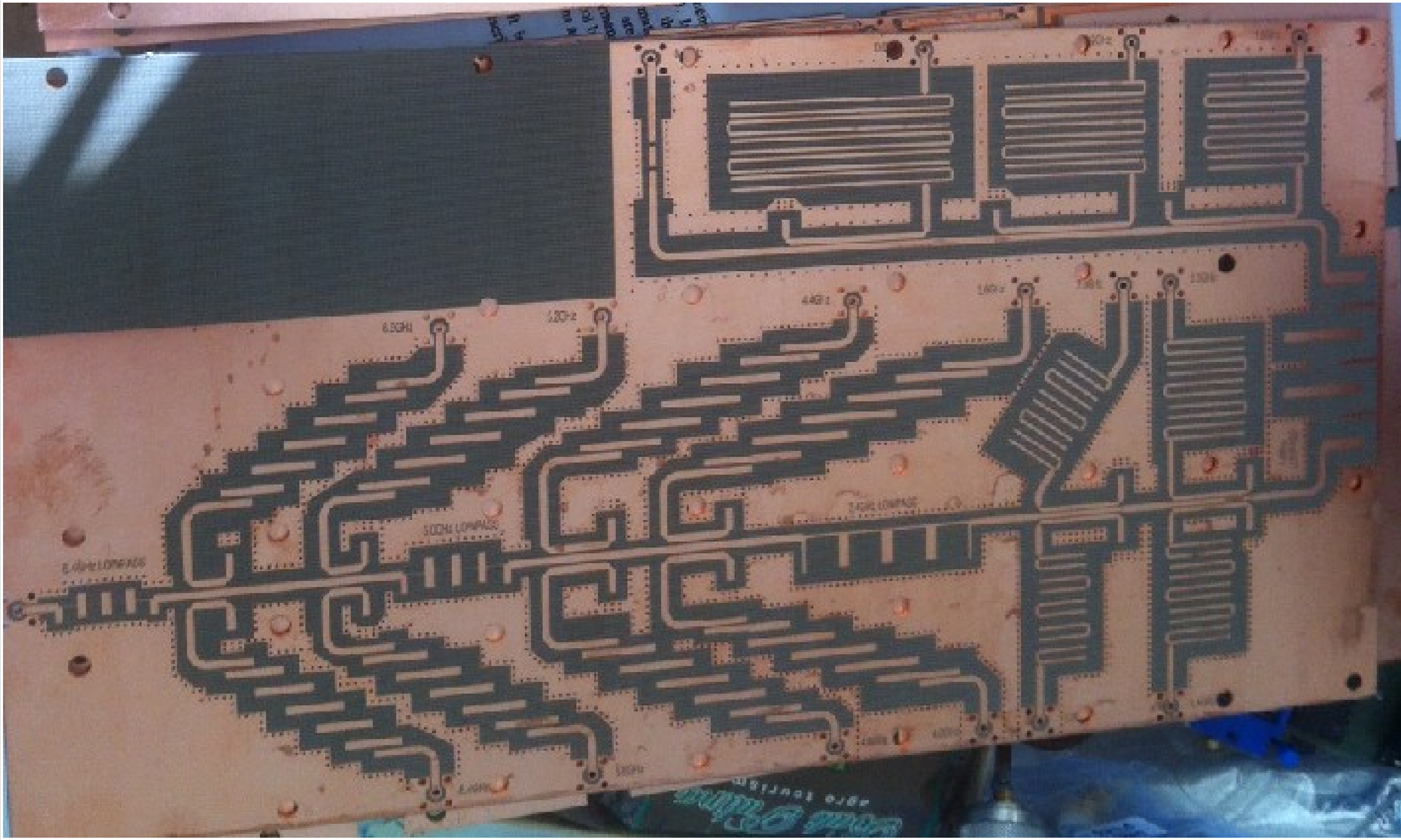
ADT BBQ Q comparison, Ralph.Steinhagen@CERN.ch, 2012-08-25

MIM Instability Trigger for post-LS-1

- First iteration on fast instability trigger (Joshua Ellis et al., ACAS):
  - nice feature: provides indication of rise-time



Multiband-Instability-Monitor (MIM)
Next Steps: Full Filter-Bank (16 Bands) Prototype



Summary

- 2012/13 LHC operation indicated potential performance instabilities
  - need better diagnostics to precisely assess these intra-bunch motion
  - time-domain digitization fundamentally limited and destined to level-out

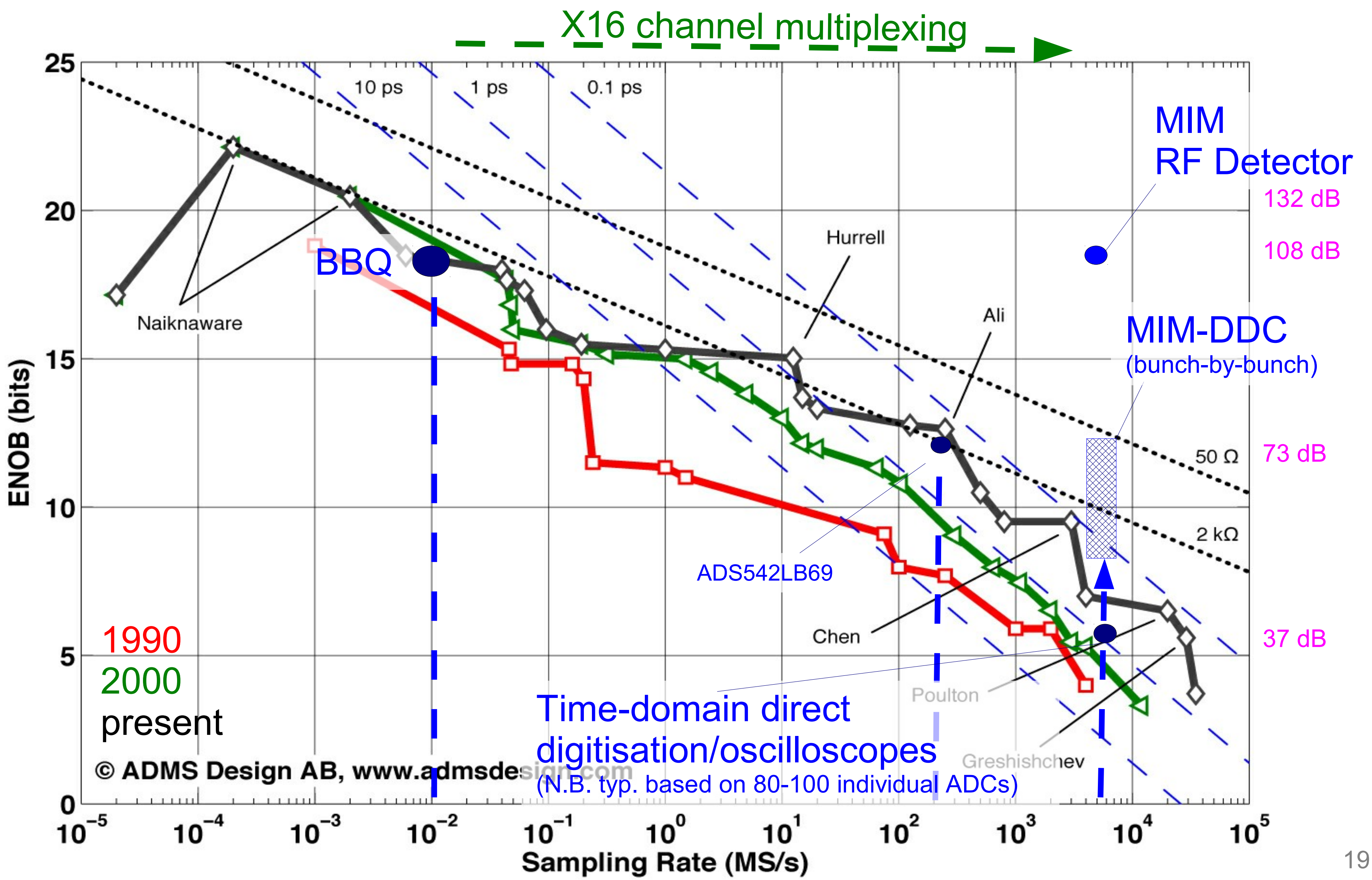
- Multiband-Instability-Monitor (MIM) provides an alternative nm-level and wide-bandwidth (> 6(12 GHz) transverse and longitudinal instability diagnostic
  - SPS/LHC beam oscillations being related to intra-bunch motion
  - driven intra-bunch BTF evaluate machine settings w.r.t. beam stability.

- Three areas of active R&D and possible upgrades during LS1
  - Pickups: Electro-Optical and Sychrotron-Light BPMs → MOPC20
    - further tests at the Australian Synchrotron
  - Analog-FE: wide-band hybrid & gain-control → WEDPC12
  - Deploy Multiband-Instability-Monitor operationally
    I. Balanced Schottky Diode Detector
       - highest possible, nm-level resolution, most robust → instability trigger

    II. Bunch-by-Bunch 'RF Schottky Diode Detector' vs. Direct-Down-Conversion' additional supporting slides

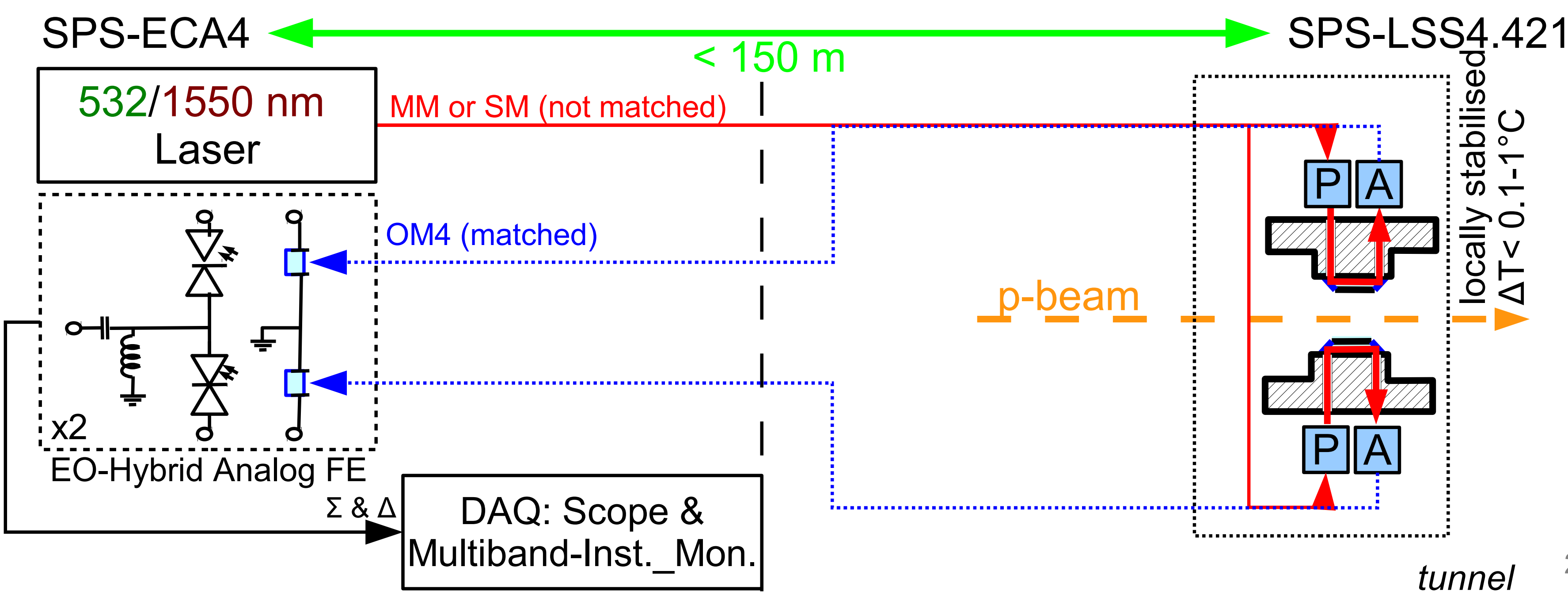
Time- & Frequency-Domain Resolution

- Pushes the envelope of what can be done with modern ADCs



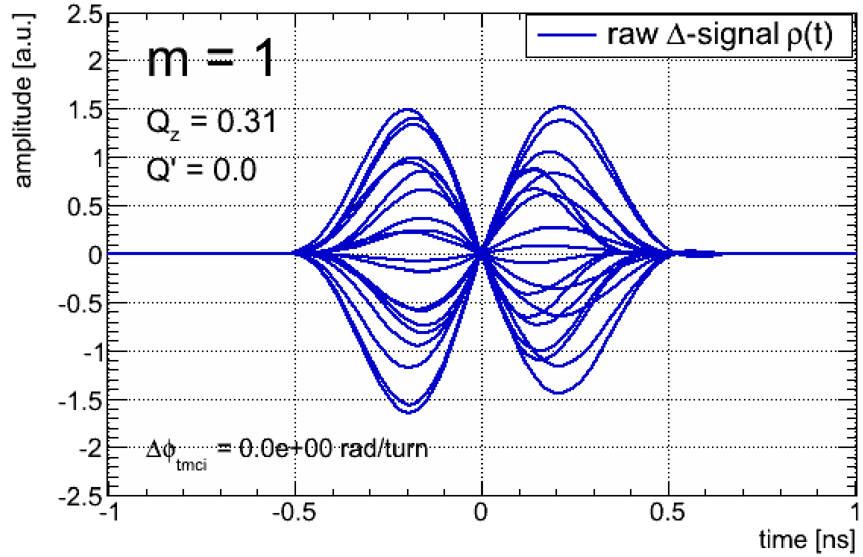
Synchrotron Light- & Electro-Optical Beam Position Pickup

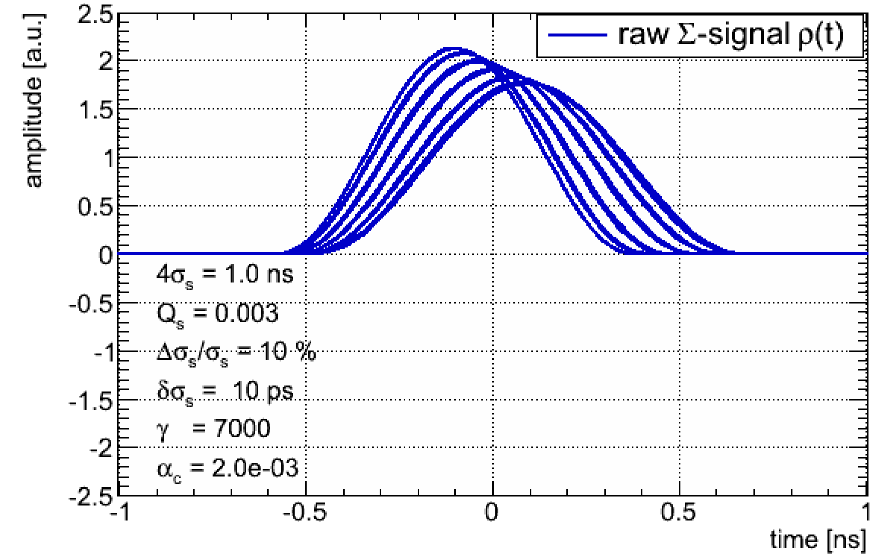
- SynchLightBPM – collaboration with ACAS (Australian Universities & Labs)
  - pro: very wide-band signal (tested up to 12 GHz), large dynamic range, DC response
  - con: not enough free view-ports available → envisage this for LS2?
- Electro-Optical Pick-Up
  - working principle similar to LCD/TFT screen: particle beam modulates crystal birefringence → intensity of two laser beams A & B, position ~ (A-B)/(A+B)
  - pro: very wide-band signal, no beam power issues, true DC response (alt. AGM?)
  - SPS Prototype to be installed during LS-1 → also in LHC (LS-2?)

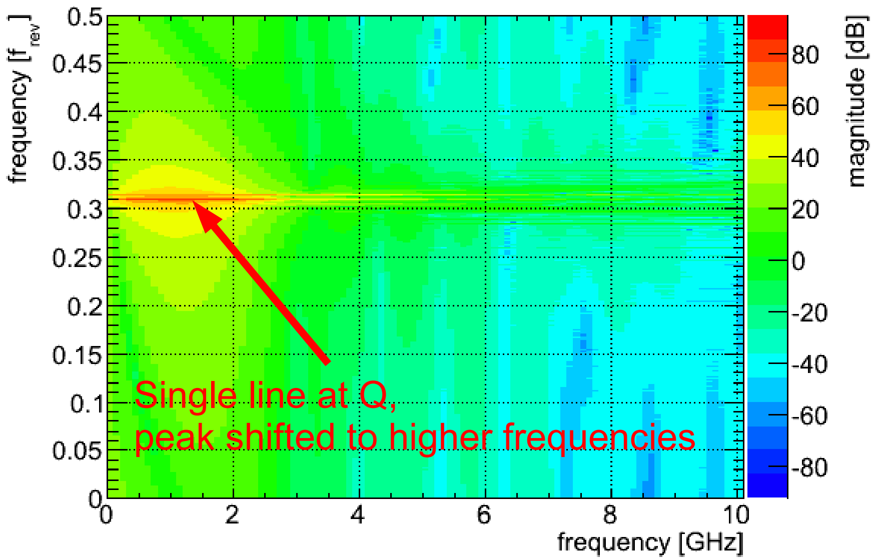


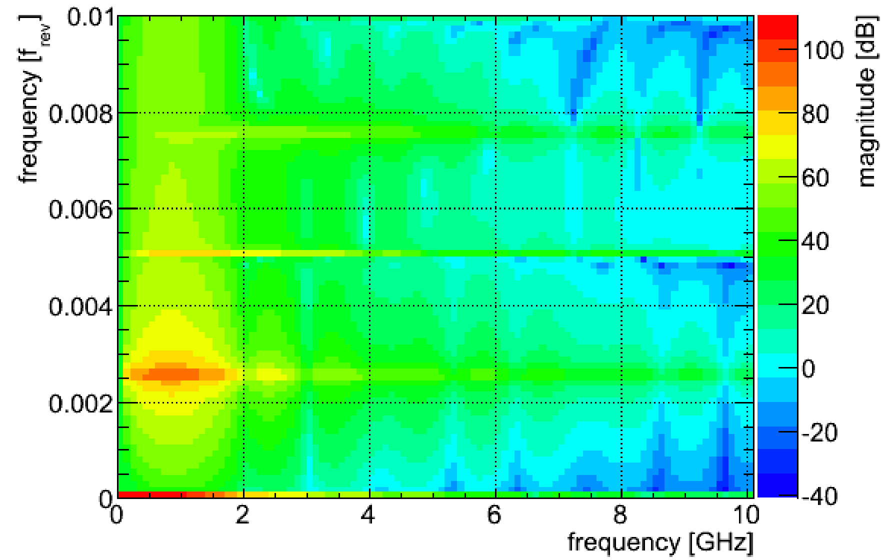
Multiband-Instability-Monitor (MIM)
Examples illustrating Difference between TMCI and HTI in F-D

Head-Tail mode only



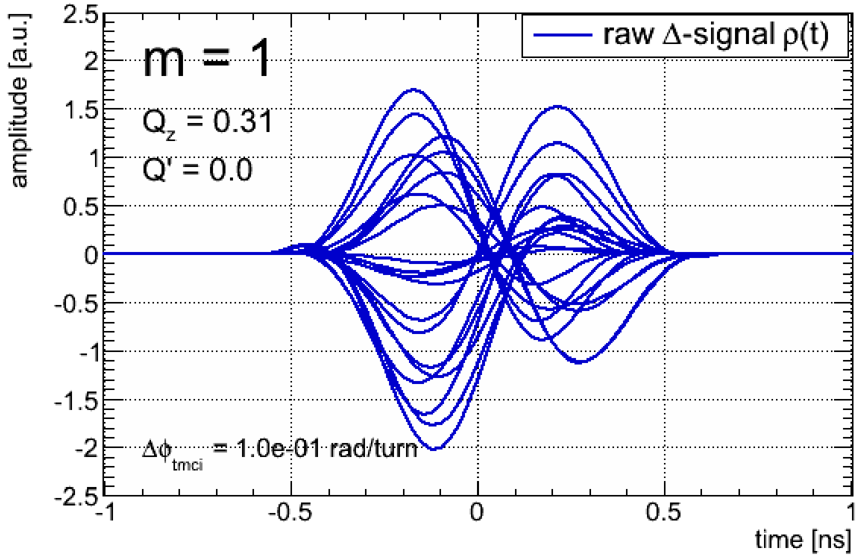


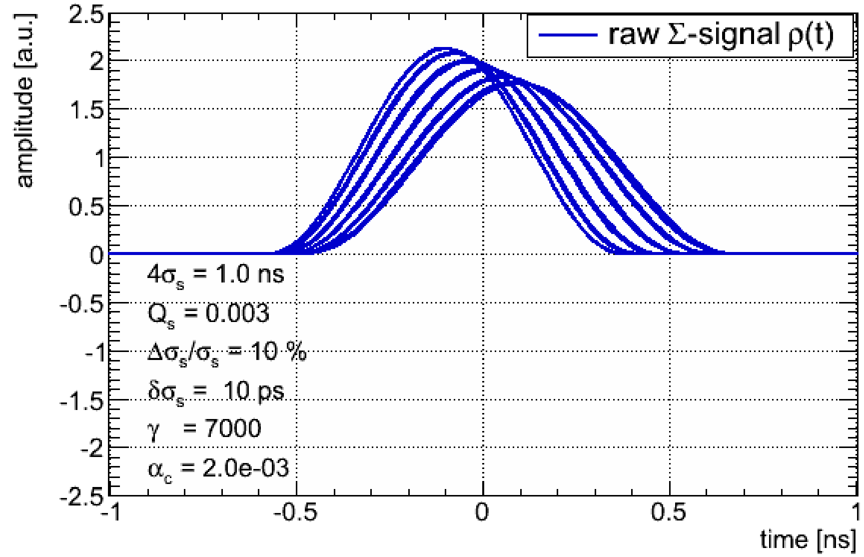


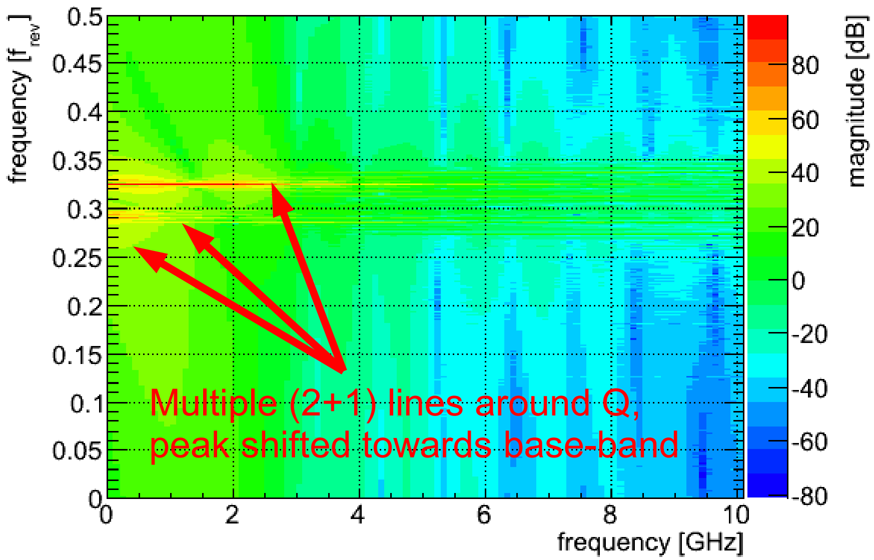


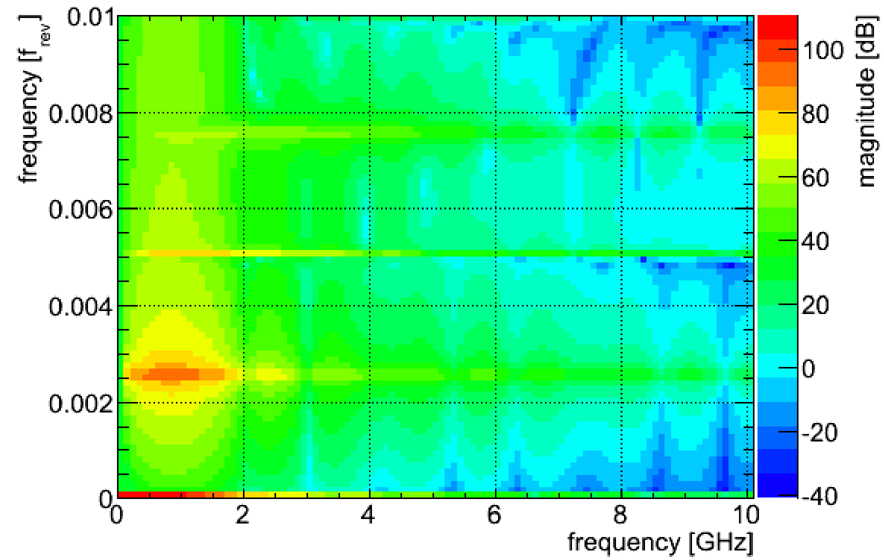
Multiband-Instability-Monitor (MIM)
Examples illustrating Difference between TMCI and HTI in F-D

Head-Tail mode + TMCI



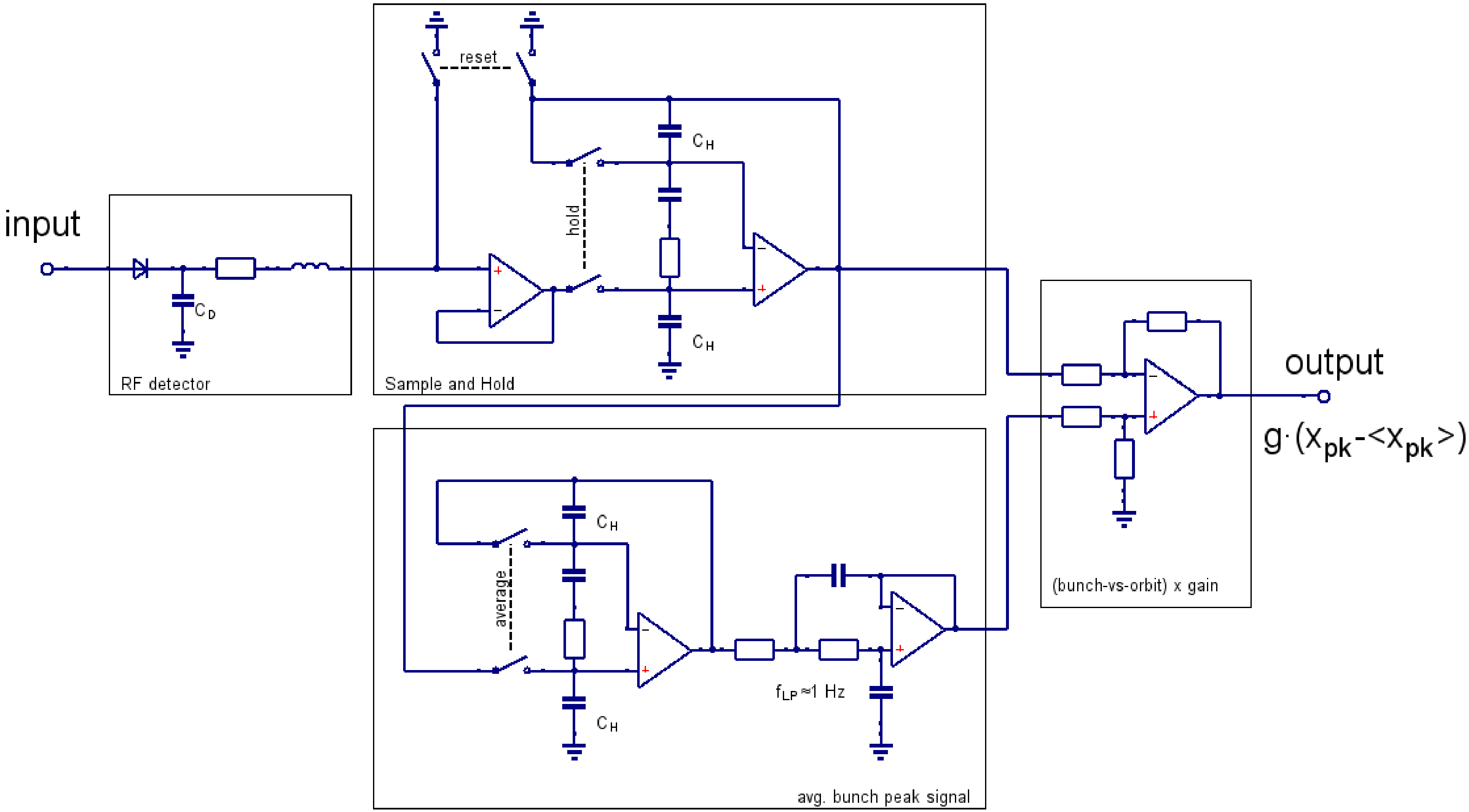






Multiband-Instability-Monitor (MIM) Bunch-by-Bunch RF Schottky Diode Detector

- Differential measurement between the bunch-by-bunch signal and avg orbit
  - PRO: reduces common-mode → higher dynamic range than BPM electronic.
  - CON: less sensitive than simple RF det., no phase information for f>400 MHz

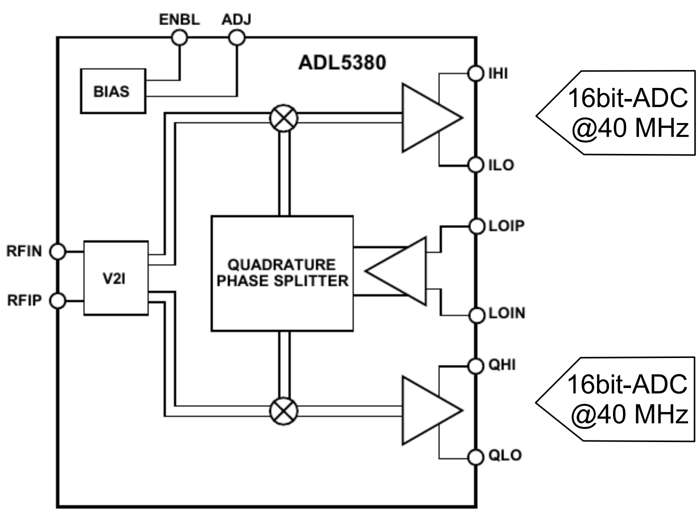


Idea based on fast track-and-hold Analog Device's reference circuit

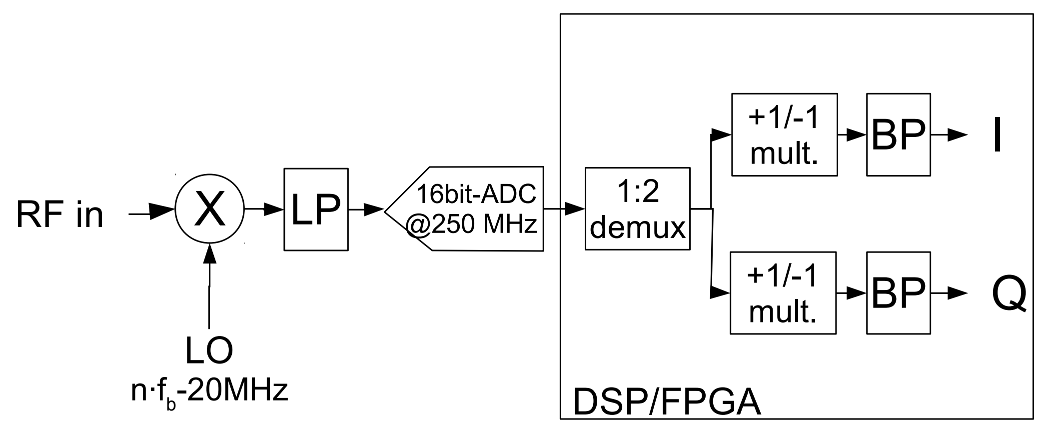
Multiband-Instability-Monitor (MIM)
Bunch-by-Bunch Amplitude and Phase Detection

- Direct-Down-Conversion Scheme (DDC) aka. 'Software-Defined-Radio' (SDR)
- Exists in two flavours: Analog and direct (digital) I/Q-demodulator
  - analog: has wide bandwidth but affected by systematic drifts of RF mixers
  - digital: less drifts, easier to implement (SDR) but more syst. for large bw.
  - both: exists as system-on-chip, poorer signal-to-noise (N.F. ~12dB due to mixers/VGA) compared to RF Detector, no CERN integration (yet)

Analog IQ Demodulator:



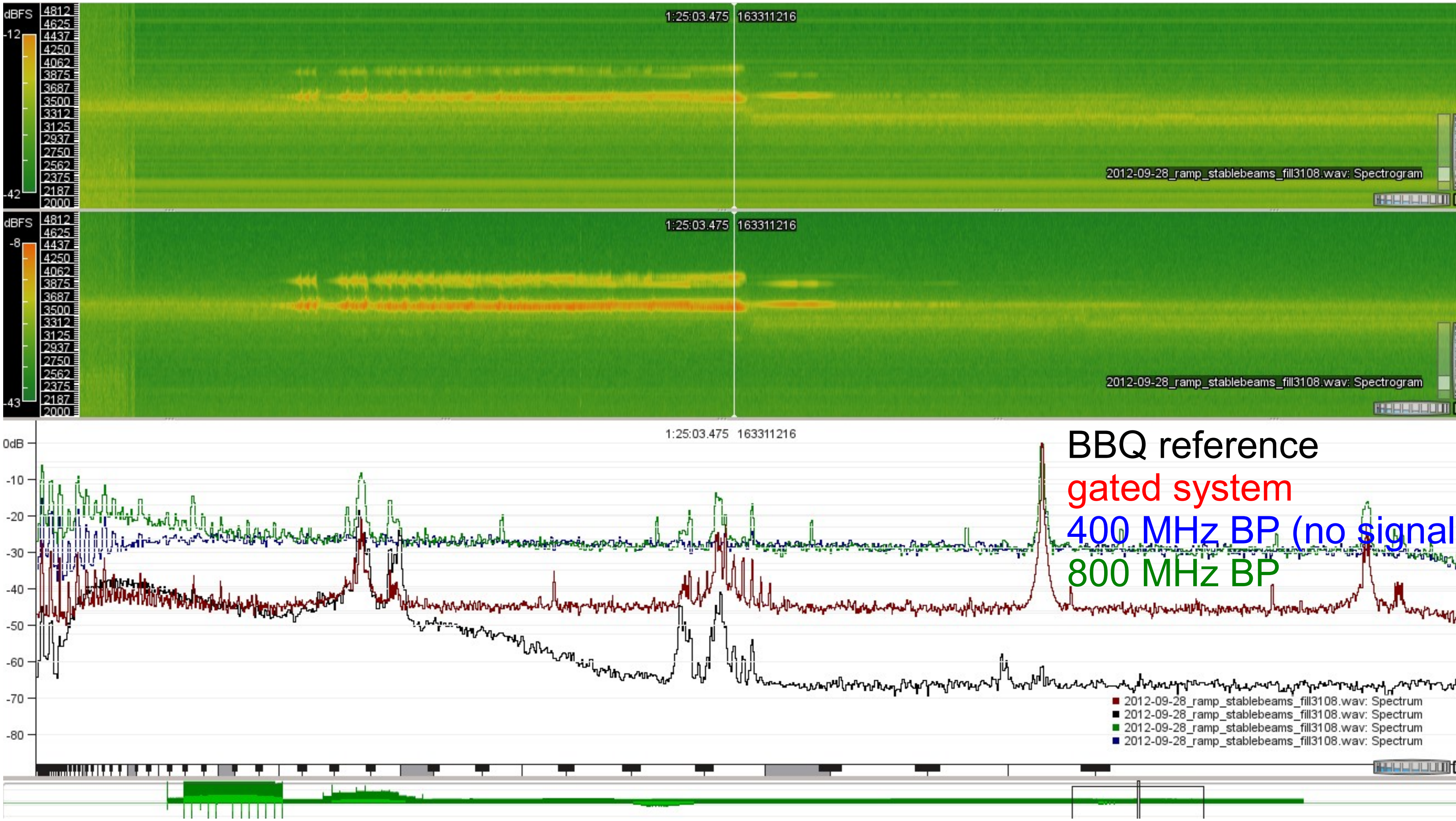
Direct IQ Demodulator:



N.B Any RF Schottky Diode Detector is de-facto an unbalanced RF mixer with RF &LO tight together

Instabilities detected by BBQ at β*=60 cm II/II

- Signal not seen on first six bunches



- Q-amplitute-to-f_{rev} ratio larger at 800 MHz than <400 MHz → intra-bunch motion

Multiband-Instability-Monitor (MIM) – Acquisition Options

I. Balanced RF Schottky Diode Detector
   - highest possible sensitivity (close to thermal noise limit)
   - most robust → proposal to use this as an early instability trigger/detector
   - only either all bunches or gating on single-bunch
   - more suited for frequency-domain analysis

II. Bunch-by-Bunch RF Schottky Diode Detector
   - similar to above + instantaneous measurements for all bunches possible
   - only magnitude information (i.e. no phase/time-domain reconstruction)
   - reduced sensitivity, more elaborate DAQ needed (n x 80 MB/s)

III. Direct-Down-Conversion Receiver
   - full amplitude & phase information
     → bunch-by-bunch time-domain reconstruction possible
   - Complex (multiple mixing frequencies, noise, clock jitter)
   - >12 dB less sensitive then the above but still a bit more than scopes

- Present baseline being designed to be compatible with having 'option I' + either 'option II' or 'option III' which could be upgraded at a later stage.

Multiband-Instability-Monitor (MIM)

- Nyquist-Shannon Sampling and Fourier Theorem: processing in time- or frequency-domain are equivalent, provided the given bandwidth and sampling criteria are met. **!**
- For the LHC (SPS) this corresponds to:
  - Min. (design) bunch length 0.2 ns r.m.s. $\rightarrow f_{max} \approx 15$ GHz
  - Finite RF bucket size of 2.5 (5) ns $\rightarrow \Delta f_b|_{min} = 0.4$ (0.2) GHz
  - 25 ns bunch repetition frequency $\rightarrow \Delta f_{bw} > 2\text{-}3 \cdot 40$ MHz

- However, bandwidth of existing strip-line pick-ups supports only $f_{max} \approx 6$ GHz
  - Initially using BPL[H/V]): $f_{max} \approx 6$ GHz & $\Delta f_b|_{min} = 0.4$ GHz $\rightarrow$ 16 bands
  - with EO- & SL-BPM ($f_{max} > 12$ GHz) upgrade to 32 channels