WCM-based Satellite Measurements during the July 2012 vdM scans

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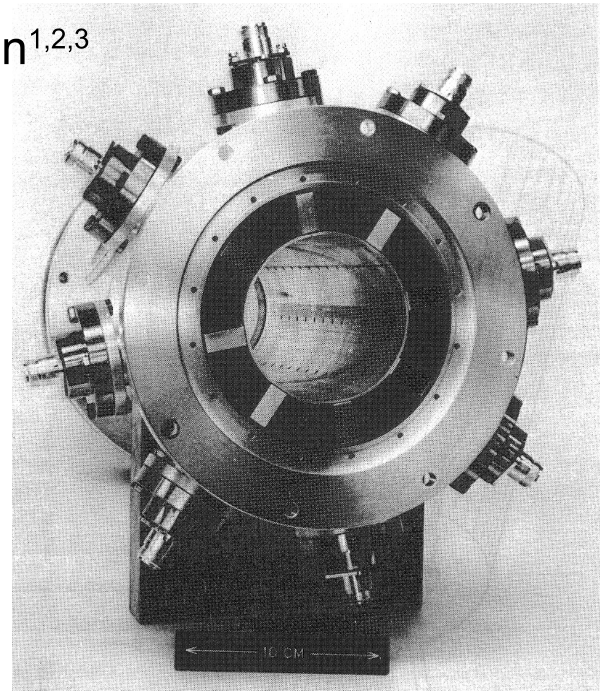
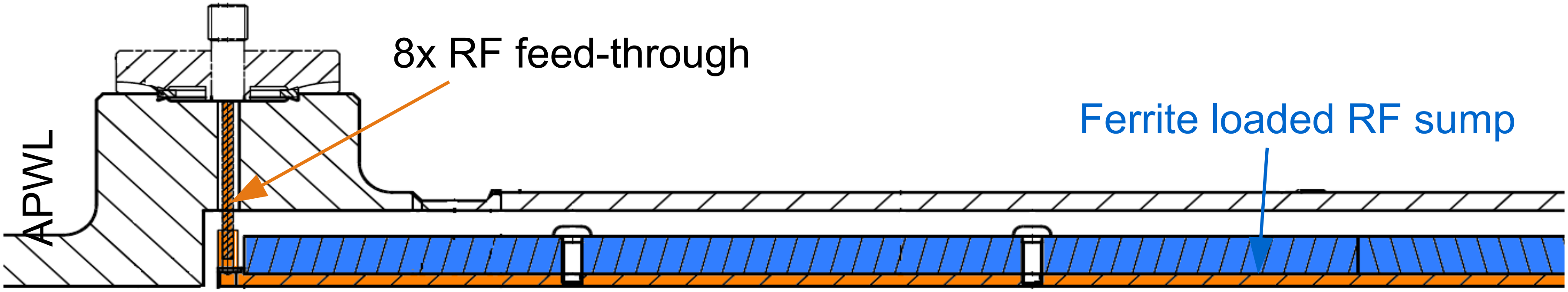
SPS/LHC Wall Current Monitor Design

- WCM pickup designs based on established 78' design[1,2,3]
- Proof-of-principle: *"What can be achieved/are the limits re-using the existing infrastructure"*
- Simplicity is key necessity to control systematics and reflections below the <10^{-3} level at few-GHz:
  WCM + "star combiner" → 3/8" pig-tail
  → 30 (100) m 7/8" cable
  → 40 dB attenuator → 3+ GHz fast sampling scope
- Intensity etc. measurement relies on beam-based off-/online calibration and signal post-processing

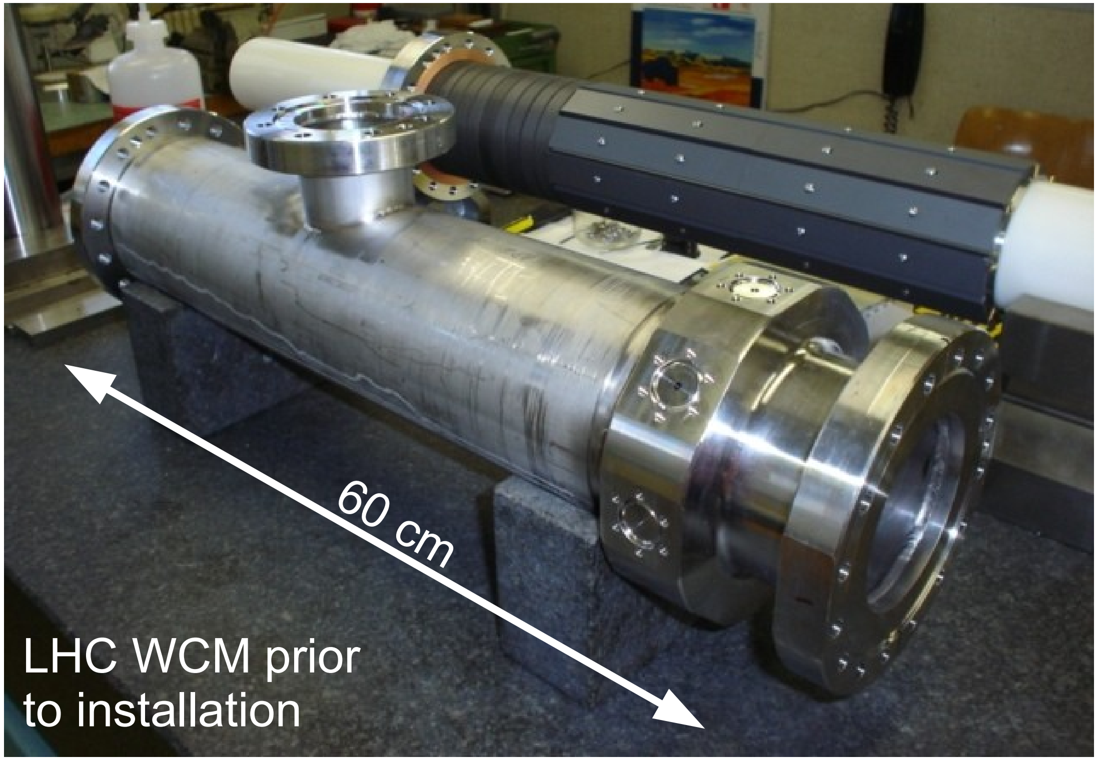


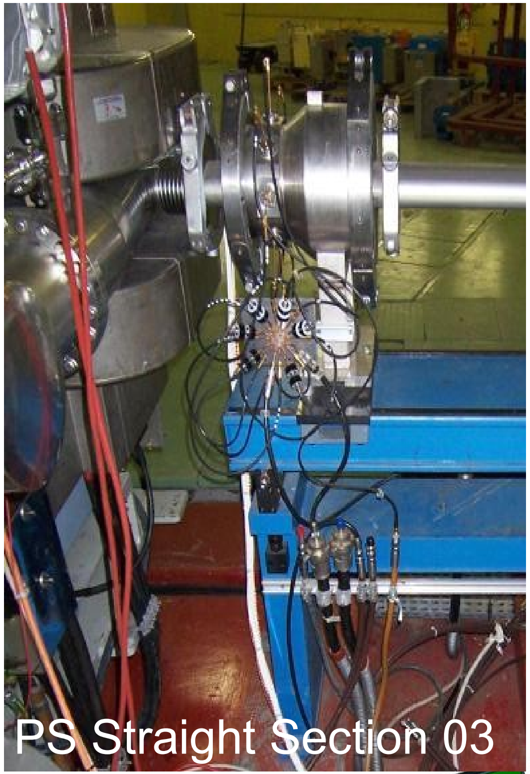


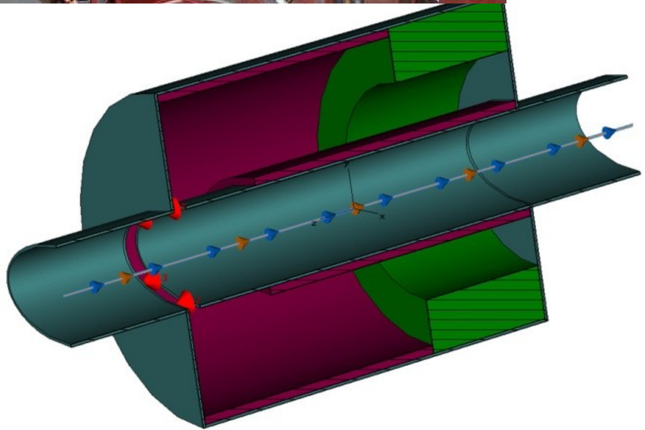
[1]T. Linnecar, "The high frequency longitudinal and transverse pick-ups used in the SPS", CERN-SPS/ARF/78-17, 1978
[2]Th. Bohl, "The APWL Wideband Wall Current Monitor", CERN-BE-2009-006, 2009
[3]R. Cappi et al., "Single-Shot Longitudinal Shape Measurements [..]", CERN-PS-87-31-PSR, PAC 1987, 1987

SPS/LHC Wall Current Monitor Design

- Prior to installation



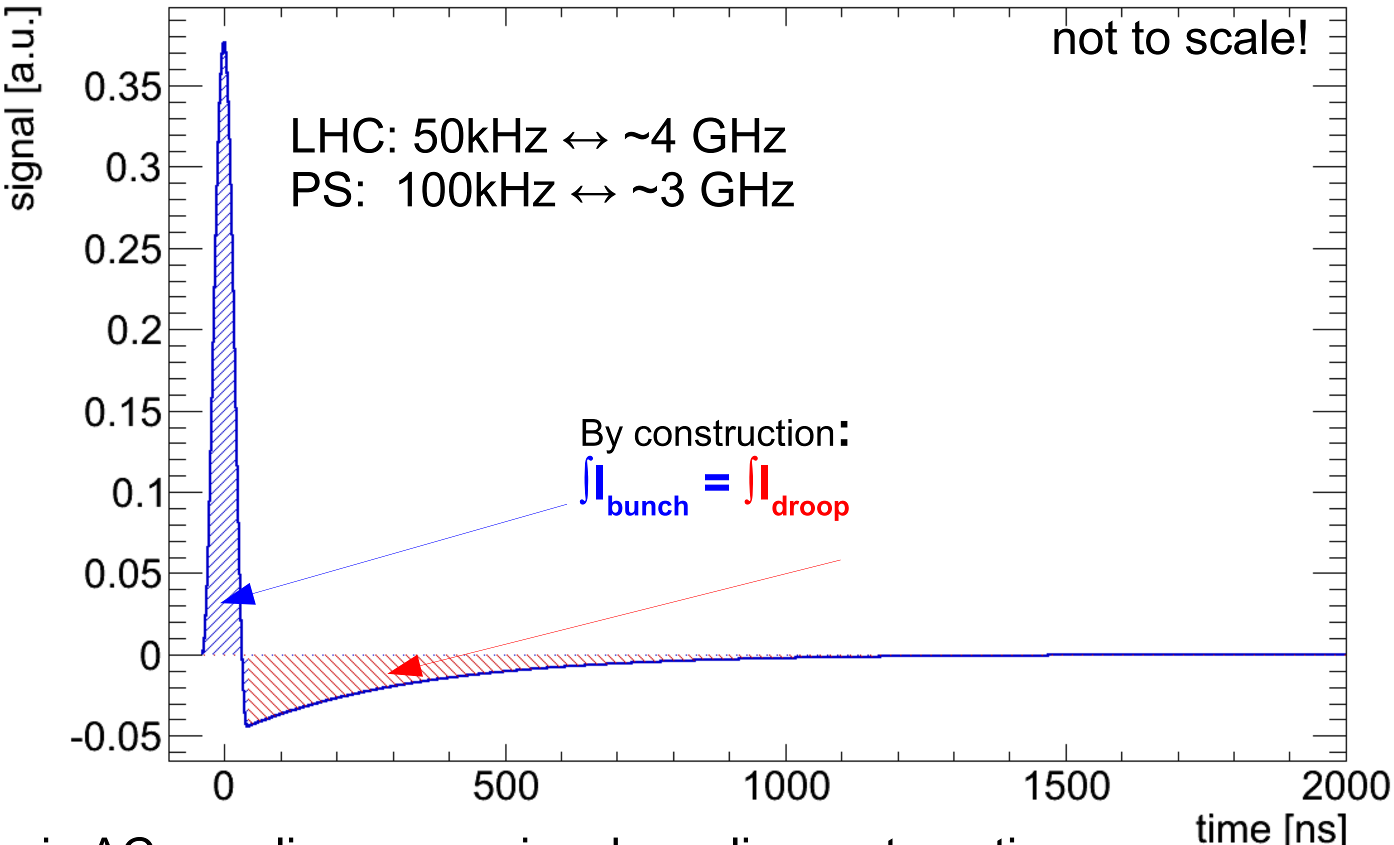




- Combiner: star-topology 8(+8) x 50Ω-matched inputs (outputs)
- Aged/experienced PS-WCM is targeted to be upgraded for reliability and maintainability reasons

Typical WCM response – Low-Frequency Base-Line

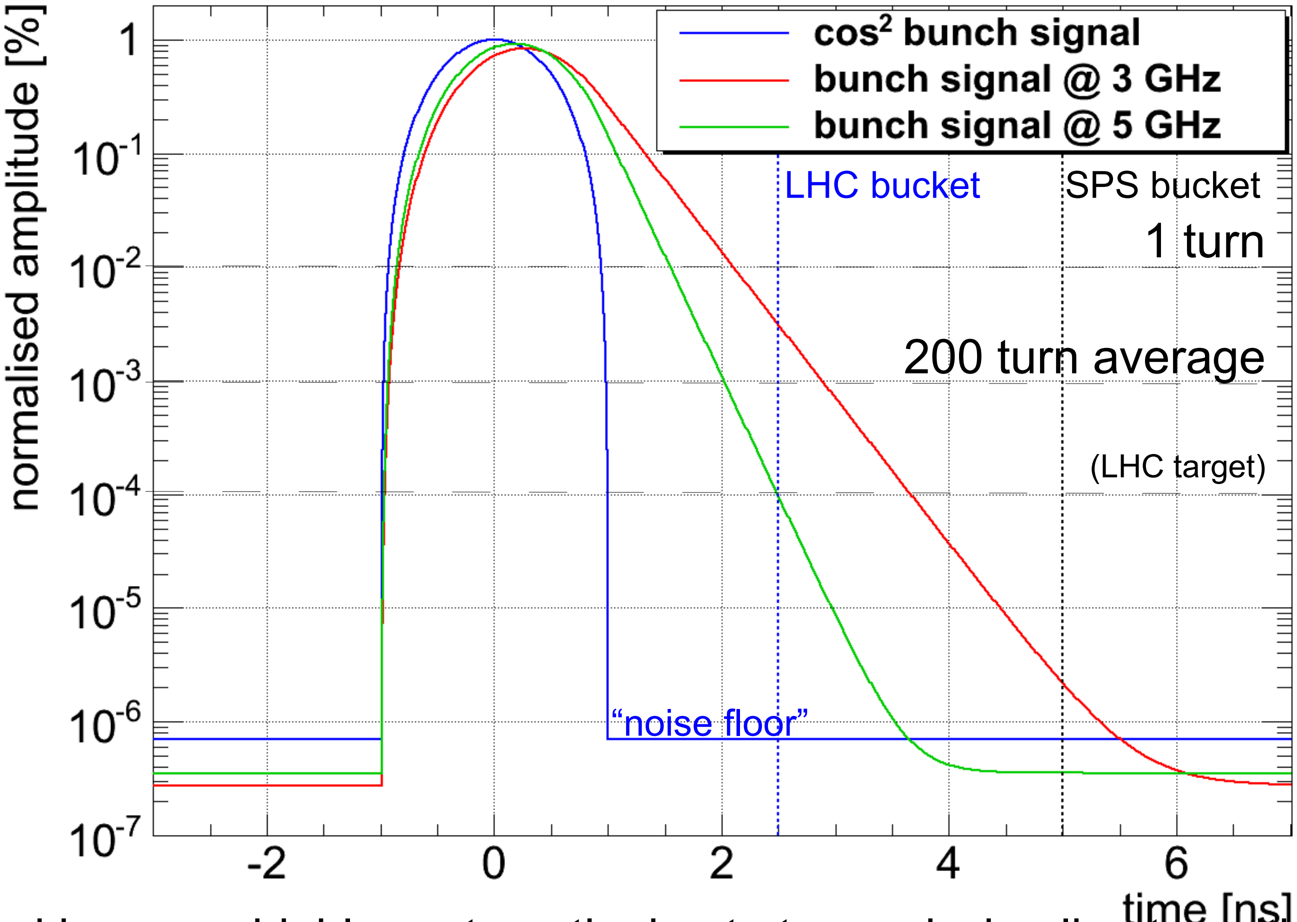
- Naive approach: Fourier Integral definition for 'ω:=0': $F(\omega)=\int_{-\infty}^{+\infty} f(t)\, e^{-i\omega t}\, dt$
- However: DC information is in-accessible:



- Intrinsic AC-coupling → requires base-line restauration
  - typ. 1rd-order zero-pole IIR filter works fine on %-level
    - Particularly important for filling patterns with many bunches (LHC: <2808)
  - observed sub-%-level drifts related bunch-filling pattern, bunch charge,...

Reconstruction Requirements II/II
Typical WCM response – High-Frequency Bandwidth

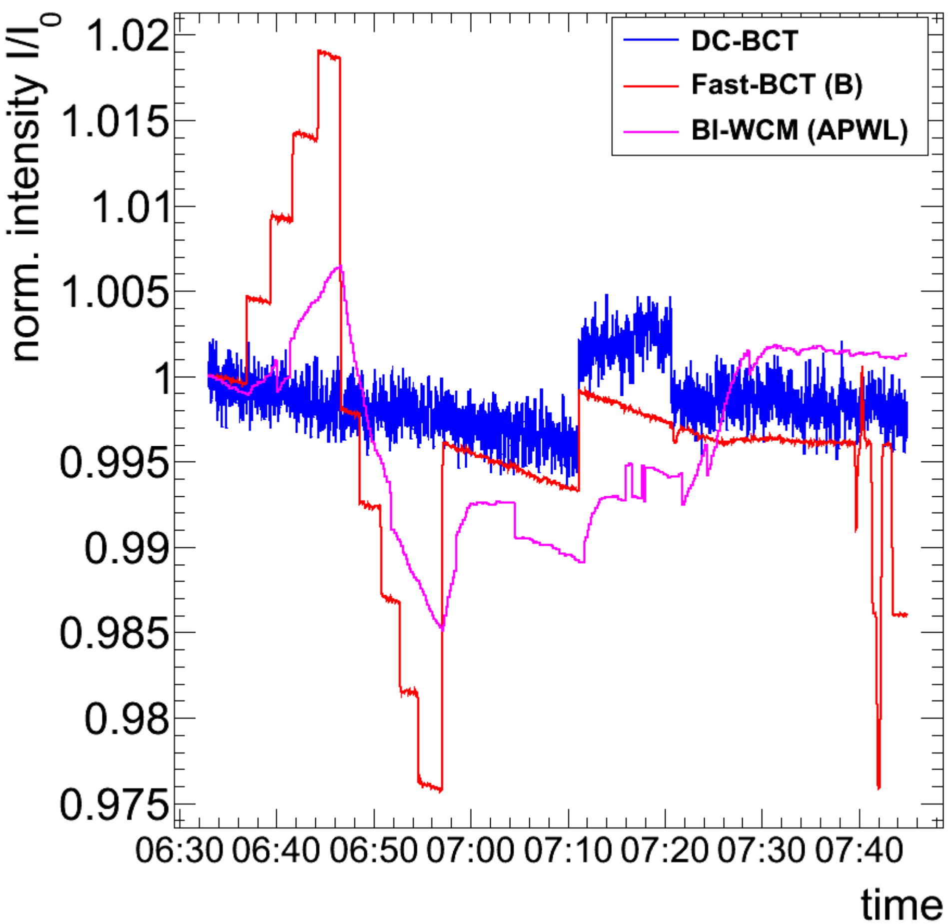
- Need high pick-up and cable bandwidth to distinguish between large bunches and tiny satellites/ghosts in the vicinity:

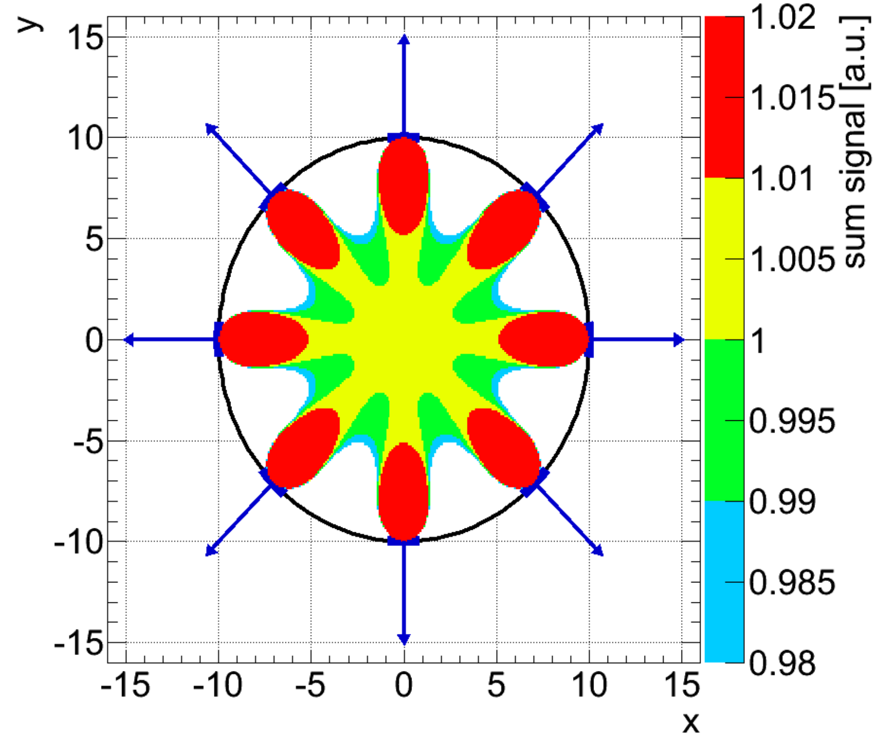


- … limited by unavoidable systematic due to transmission line transitions, reflections, etc. (N.B. difficult to control better than 10^{-3} on > 2 m distances)

Position and Time-of-Flight Dependencies

- "Re-discovered" expected position dependence while doing a ±5 mm orbit bump around LHC-Pt4 (RF, BI insertion):

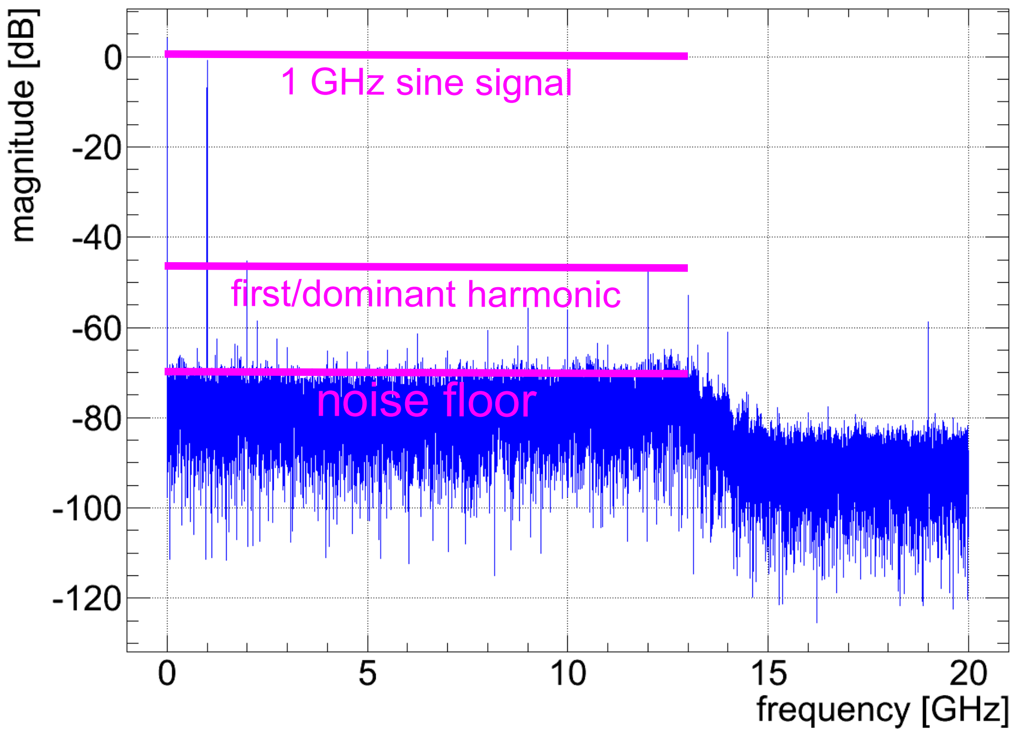


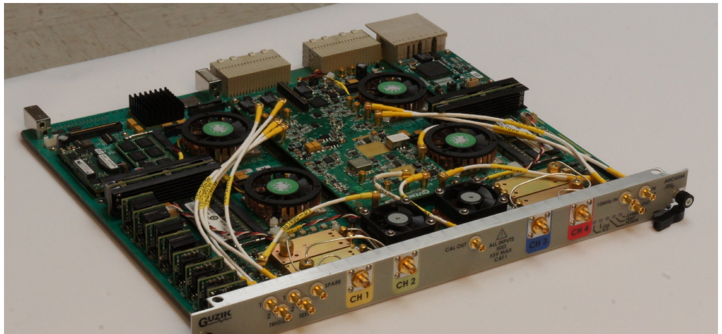


- Usually suppressed by ±200 um orbit stability during regular operation

Tested/Deployed Oscilloscopes

- Our garden variety: Agilent 54853A (DSO 90000), LeCroy WavePro 7300 A (7Zi), Tektronik & under evaluation: GUZIK's GSA digitizers





GUZIK ADC6044

- Analog performance very similar between systems/brands:
  - Signal-to-Noise-And-Distortion (SINAD) ratios of typically ~44 dB
    → ~1% accuracy on absolute intensity measurements
  - Noise-floor sufficiently flat/white up to the specified bandwidth
    → can gain in resolution resolution for repetitive signals

Oscilloscope Acquisition Mode Options and Achievable Measurement Resolution

Turn-by-turn acquisition using

A) Instantaneous 'raw' data: intensity resolution Δn_b limited by 8-bit quantisation, ADC noise (ENOB) and number of samples per bunch n_s

$$\sigma(n_b) \sim \frac{1}{\sqrt{n_s} \cdot 2^{ENOB}}$$

– LHC ($4\sigma_t$~1 ns, 10 GS): ~ 10^{-3} PS ($4\sigma_t$~5-10 ns, 10 GS): ~ 10^{-4}

B) Average over n_{turn}: $\sigma(\bar{n}_b) \sim \frac{1}{\sqrt{n_s} \cdot 2^{ENOB}} \cdot \frac{1}{\sqrt{n_{turn}}}$

– LHC: <10^{-4} (10^{-6})@0.1Hz & PS: <$2\cdot10^{-4}$ ($2\cdot10^{-5}$)@0.1Hz achieved (theo.)

– n_{turn} essentially only limited by

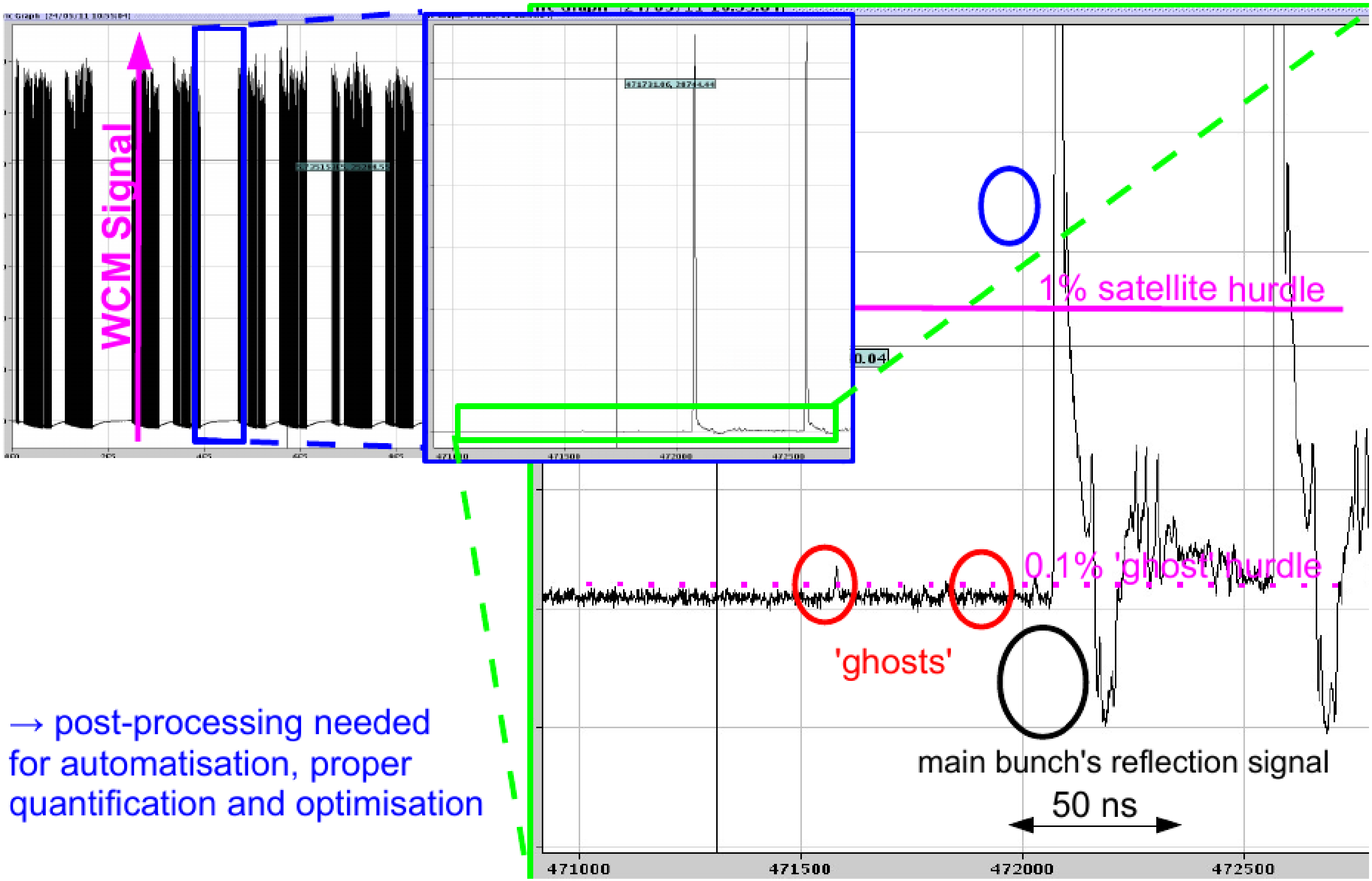
- required measurement bandwidth/time-scale the parameter changes
- acquisition HW limitations, e.g. LHC: tested oscilloscopes average in SW: 0.1 Hz bandwidth ↔ 112k turns max needed to be limit the to 500 turns/10s (data transfer limit) → upgrade in place/being evaluated

C) Dynamic range splitting: resolution is basically the same as raw turn-by-turn acquisitions but shifting range for satellite/ghosts into favourable ADC range

– First results are quite promising... see later slides

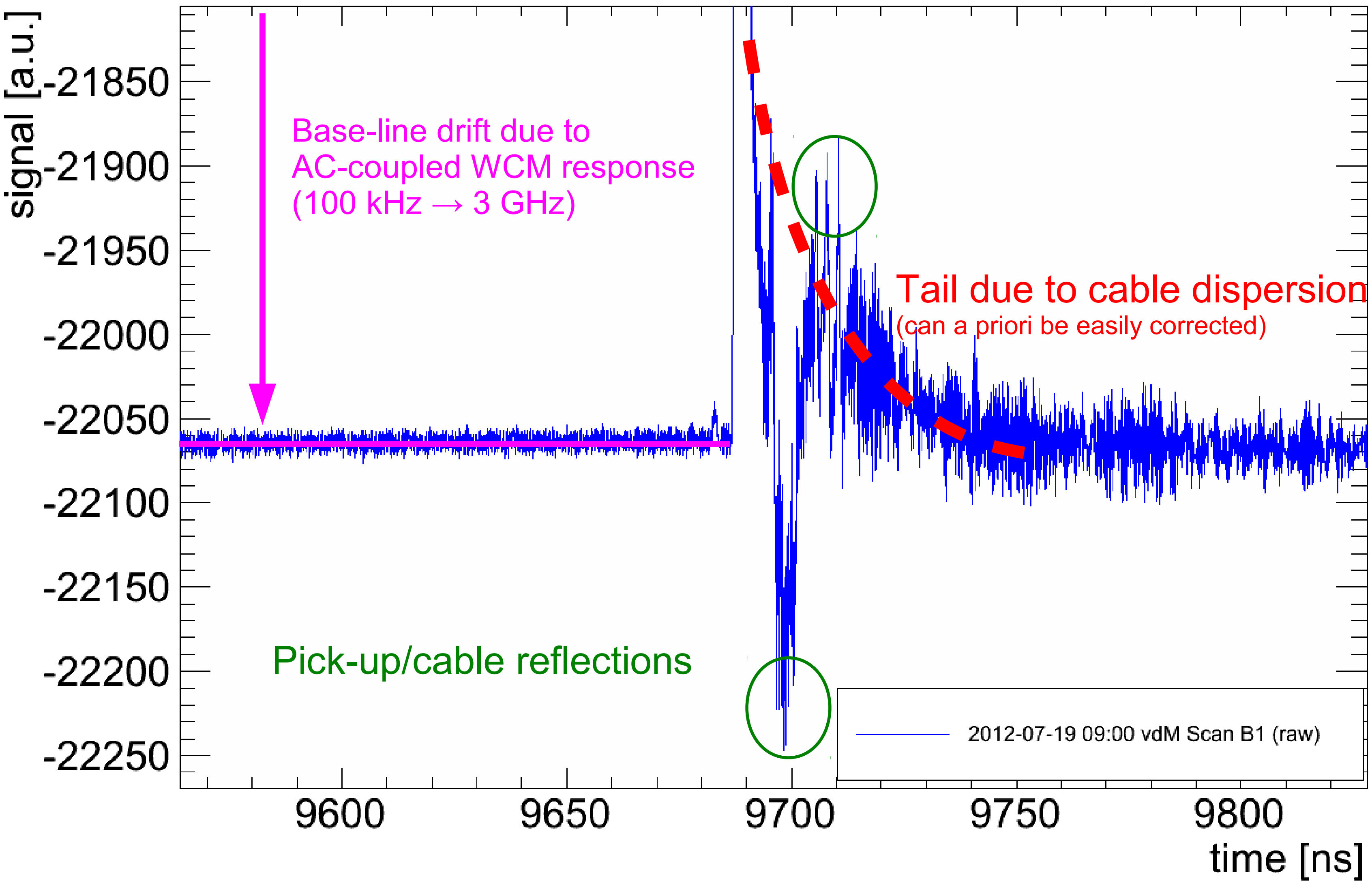
LHC Wall-Current-Monitor Raw Measurement Example

- From a pure resolution point of view: “Can detect Ghosts by Eye”



→ post-processing needed for automatisation, proper quantification and optimisation

Instrumental Reflections and Cable dispersion



Ghost/Satellite Post-Processing

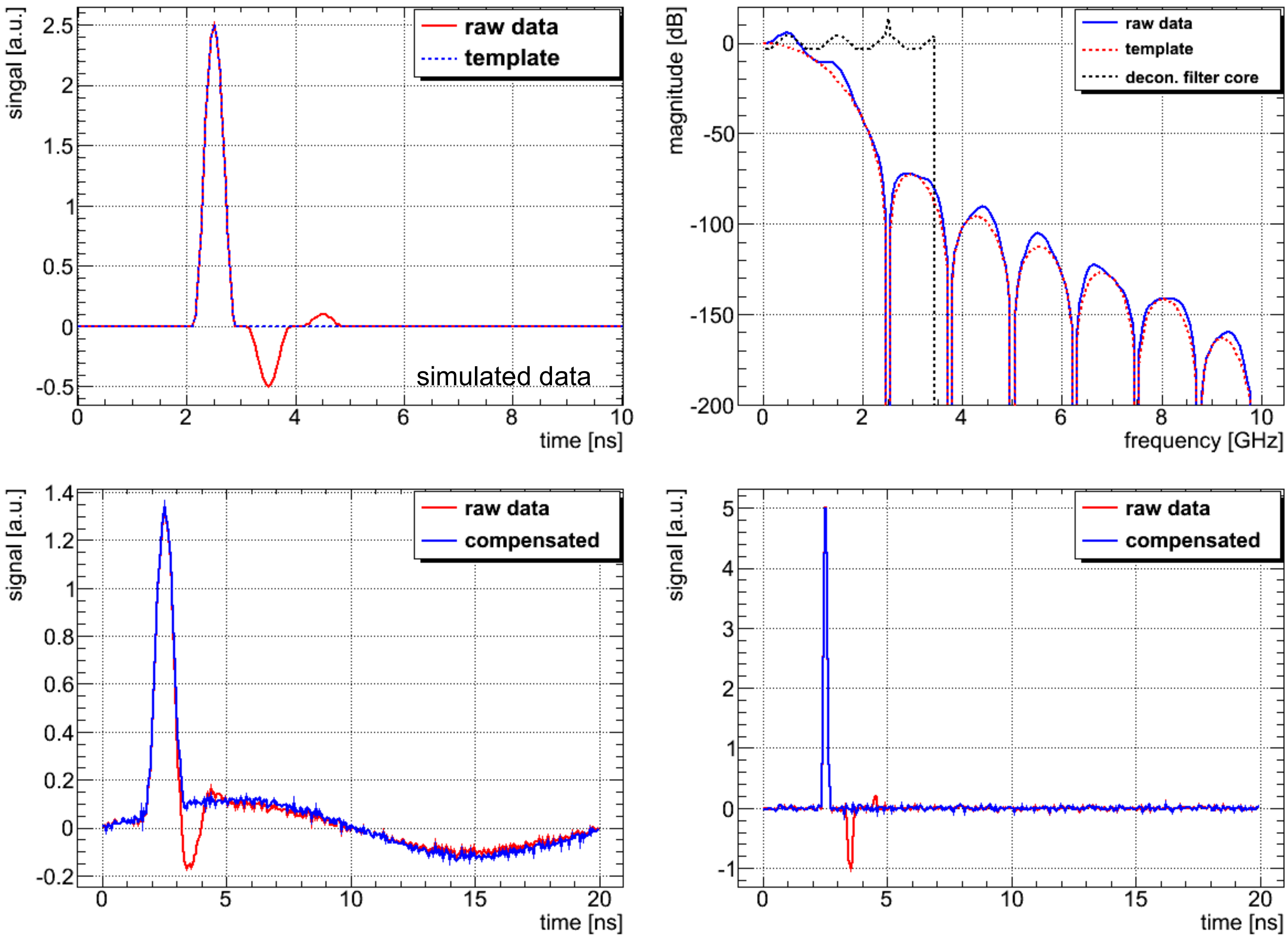
- Detection needs to be done in the presence of
  - Sub-% level reflection caused be unavoidable geometric imperfections
  - variable systematic background caused by temperature effects of dielectrics and ferrites in cable/pick-up

- Going below 10^{-3}-level requires additional measures.
  The most promising combination found:
  I. Sub-percent level compensation of the pick-up response
     - Classical Fourier-/Wiener-filter based Deconvolution
  II. High-frequency Noise Rejection
     - Savitzky-Golay χ^2-fitting[1]
  III. Base-line restoration
     - SNIP background estimate[2,3]

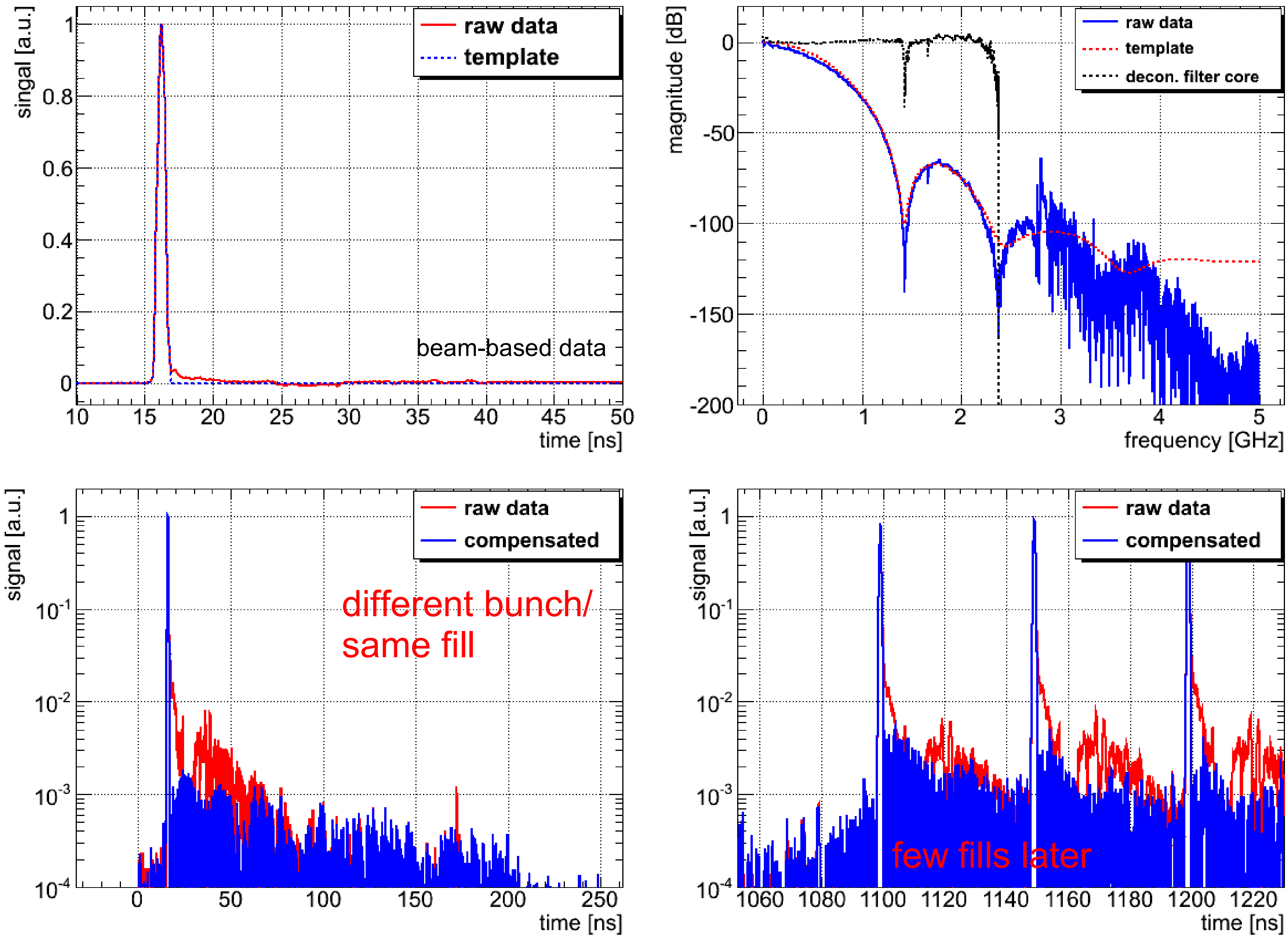
[1] A. Savitzky and M. Golay, "Smoothing and Differentiation of Data by Simplified Least Squeares Procedures", Analytical Chemistry, Vol. 36, No. 8, July 1964, pp. 1627–1639
[2] C.G. RYAN et al., "SNIP, A Statistics-Sensitive Background Treatment for the quantitative Analysis of PIXE Spectra in Geoscience Applications, NIM B34 (1988), 396-402
[3] M. Morháč, J. Kliman, V. Matoušek, M. Veselský, I. Turzo: "Background elimination methods for multidimensional gamma-ray spectra". NIM, A401 (1997) 113-132.

I. Linear Response Compensation I/II

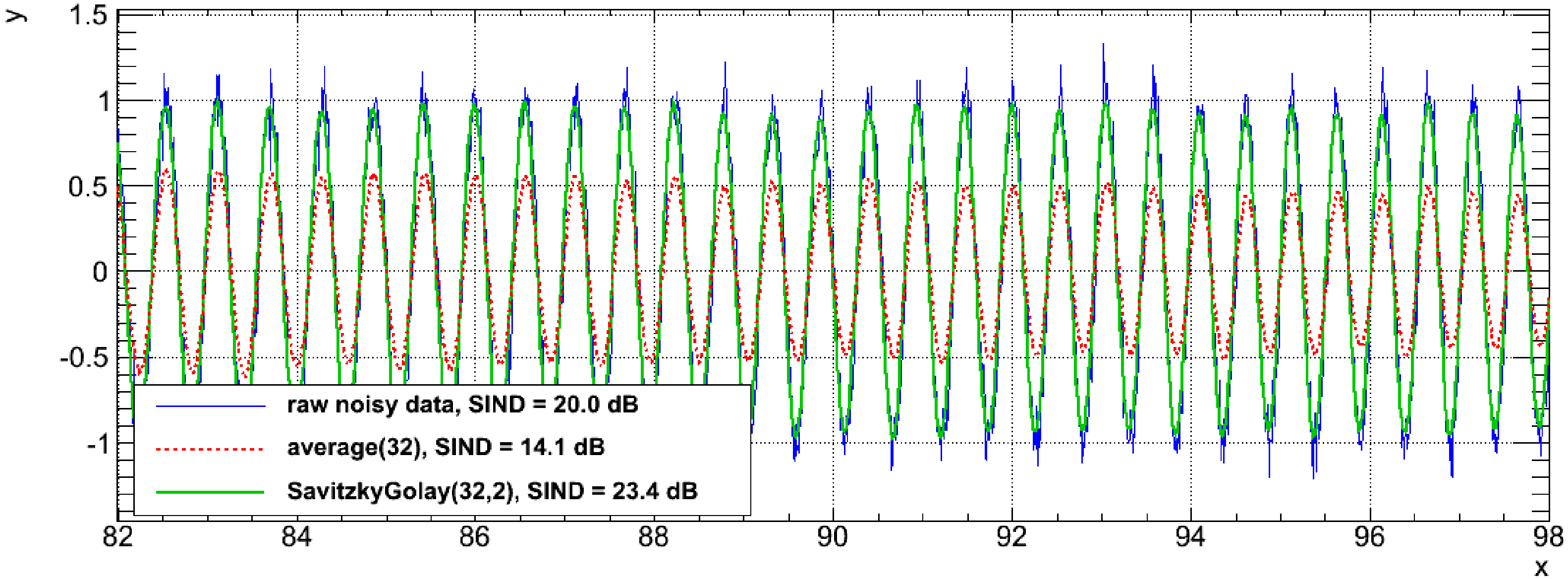
- Real-life installation will deviate from what has been measured in the lab before installation → requires re-calibration with beam, principle:

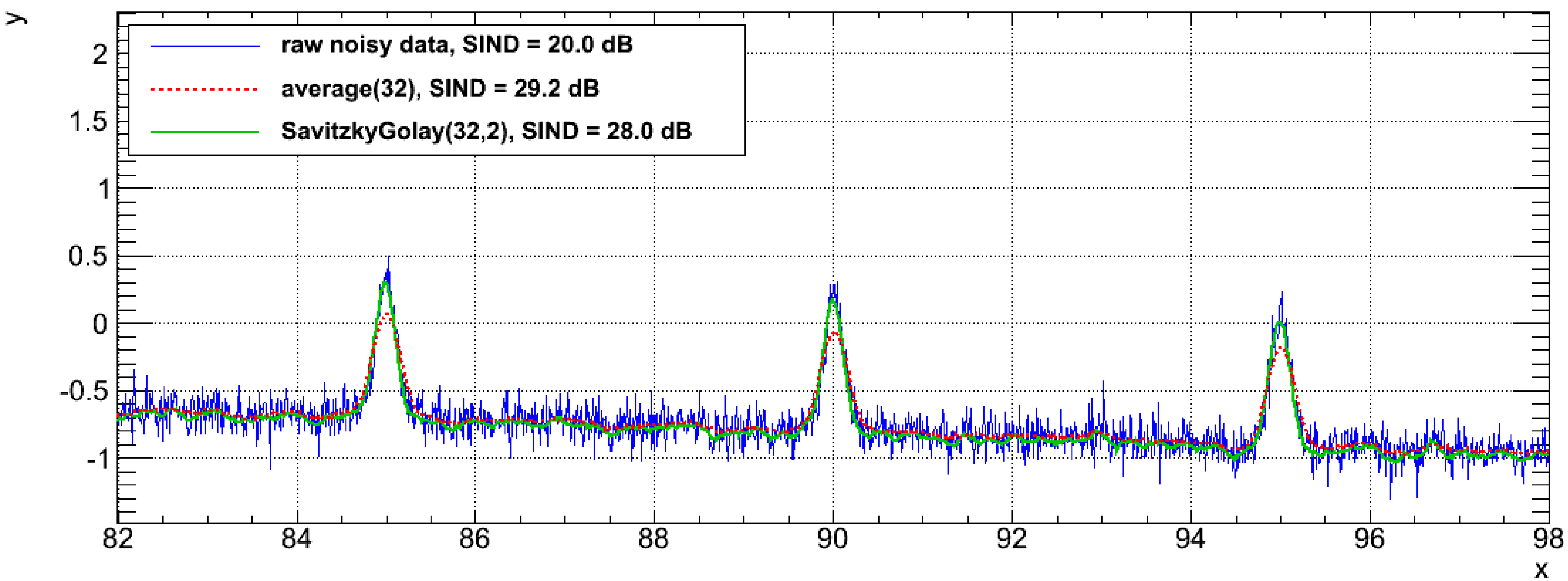


I. Linear Response Compensation II/II – Life-Beam Data



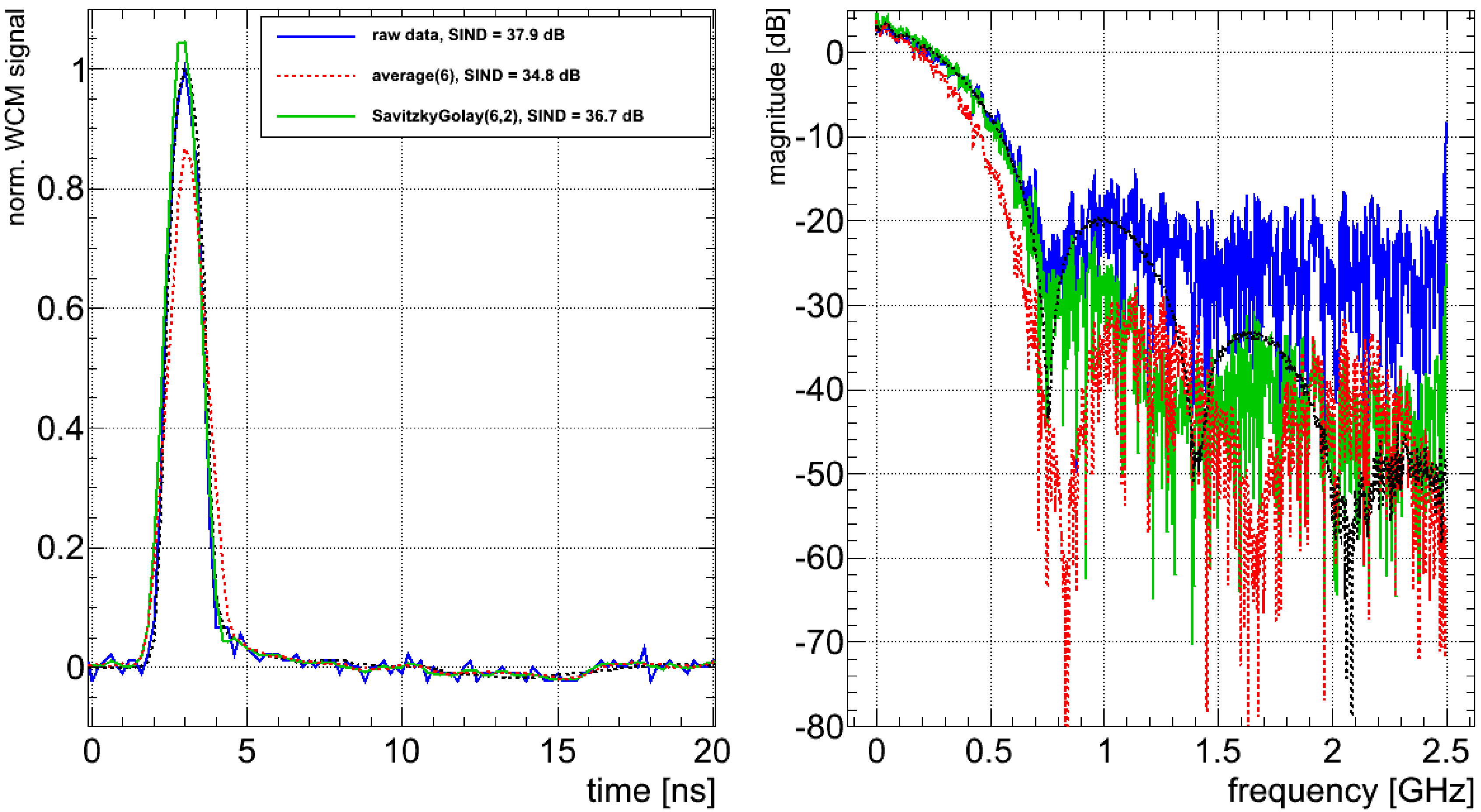
II. High-Frequency Noise Rejection – Average vs. X^2-Fit based Method (Simulation, Zoom)





II. High-Frequency Noise Rejection – Example SPS

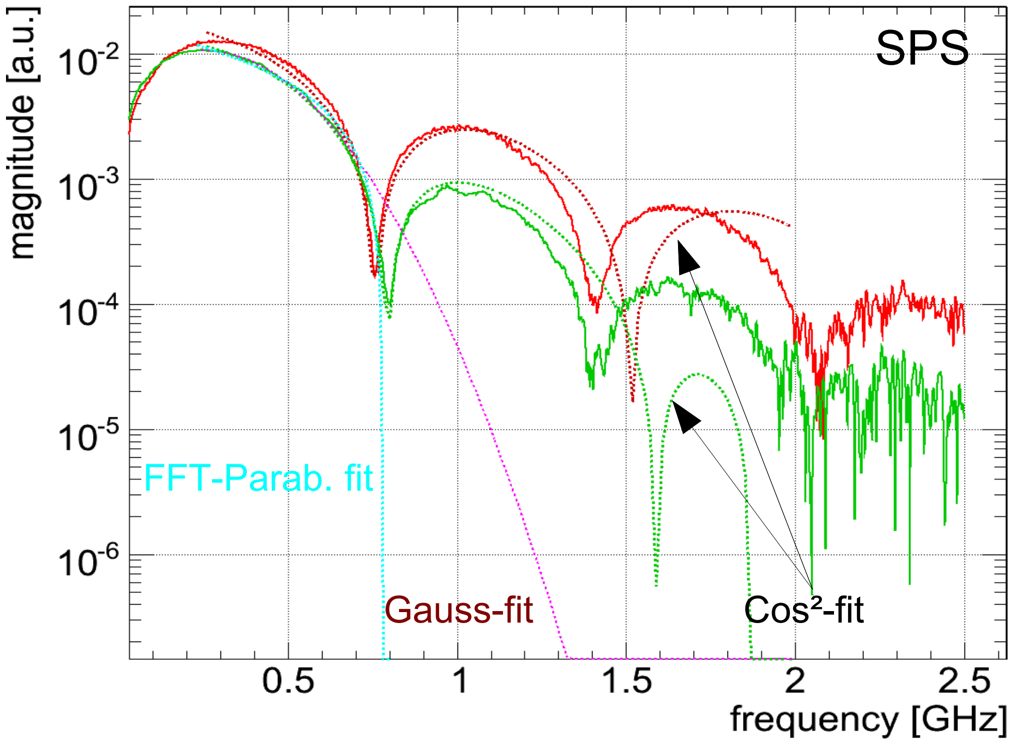
- Example: single bunch in the SPS at flat-top before extraction (black trace: reference based on 100 turn average)



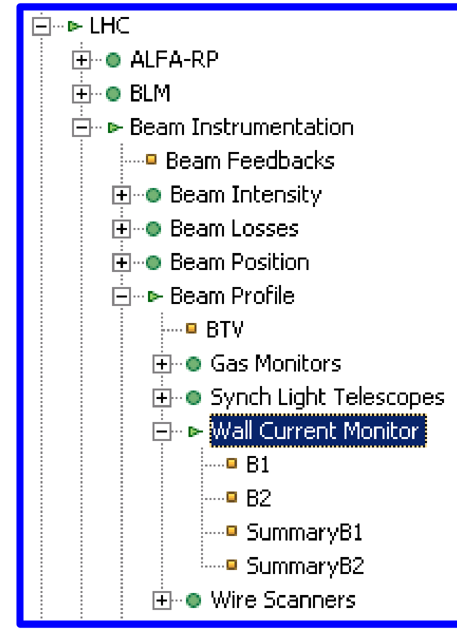
- Savitsky-Golay algorithm is de-facto a dynamic low-pass filter (within limits)

Beam-Parameter Measurement and Integration

- Real bunches do not necessarily obey 'Gaussian' shapes

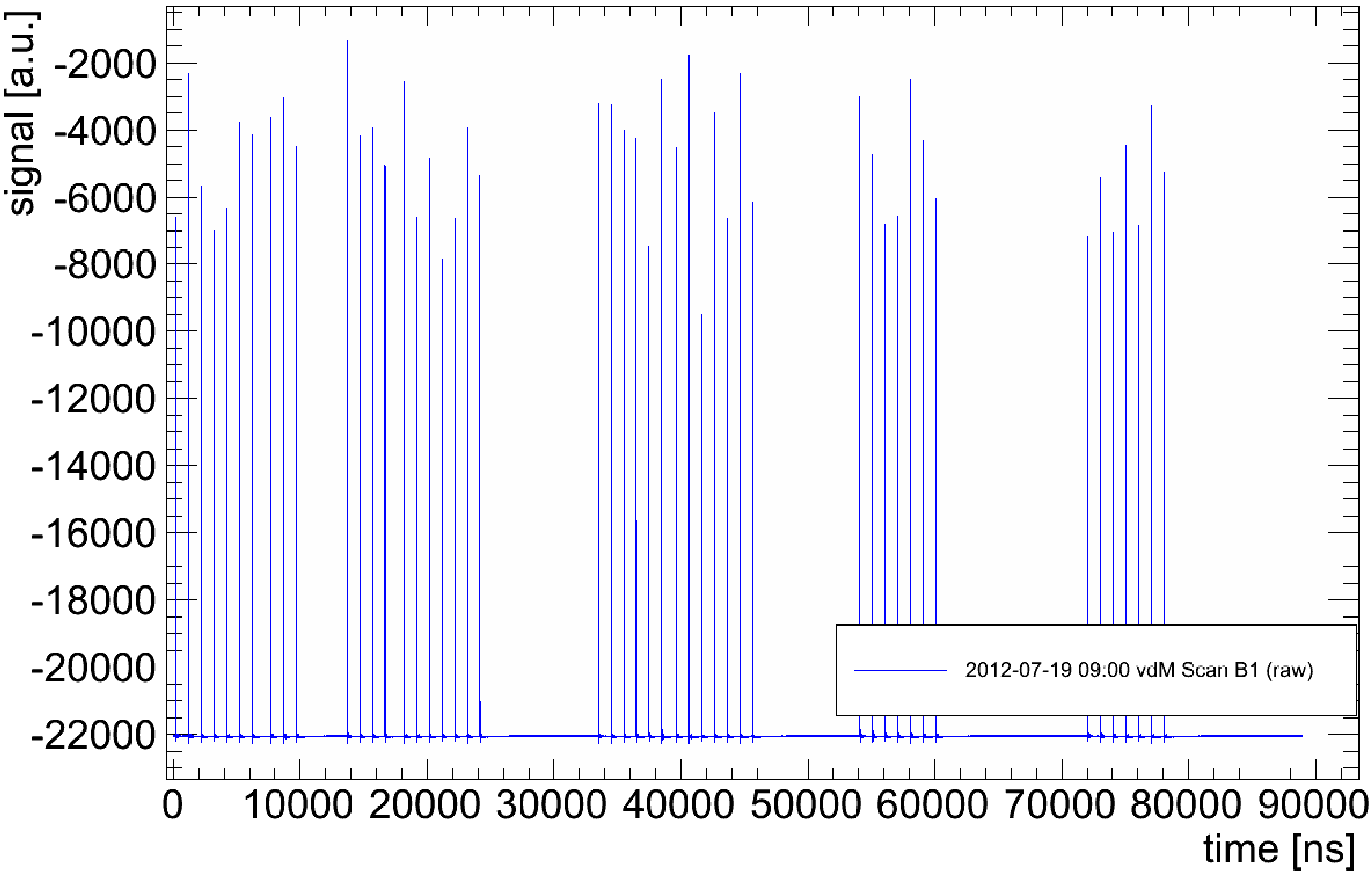


LHC Logging:

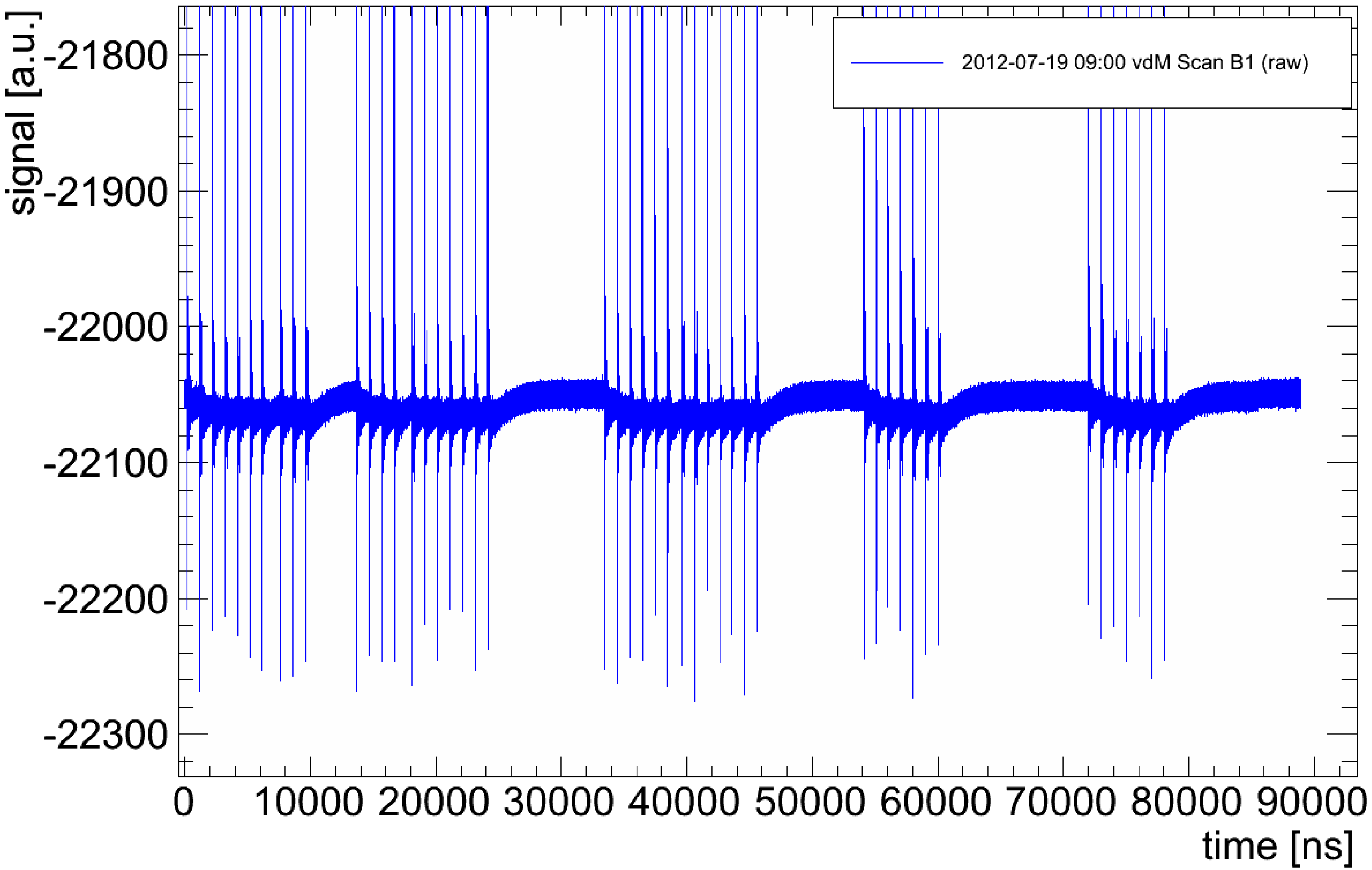


- What's derived from the WCM data up to now:
  - number & intensities of bunches & satellites (per 400 MHz bucket)
  - true Cos²- , Parabolic- & Gaussian bunch length χ^2-fits
  - Frequency containing 50/95/99% of bunch power/intensities, peak voltages
  - Bunch profiles, power spectra (→ machine impedances), …
- Main aim of WCM is to provide an independent tool with different systematic to cross-checks with other more precise instruments (e.g. DC- and Fast-BCTs, Schottky)

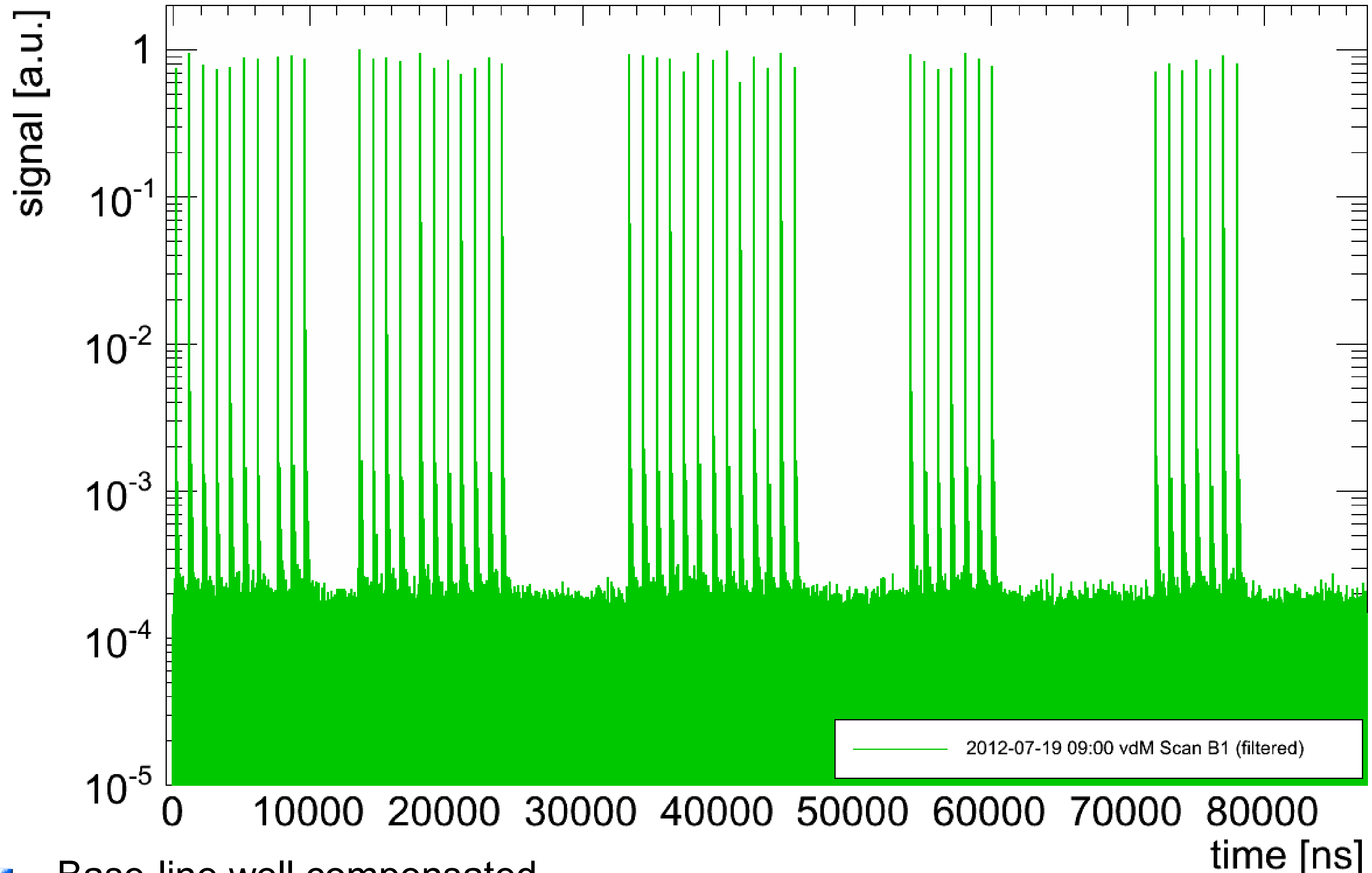
2012-07-19 09:00 VdM Scan – Raw WCM Data B1 I/III



2012-07-19 09:00 VdM Scan – Raw WCM Data B1 II/III
Zoom around raw base-line

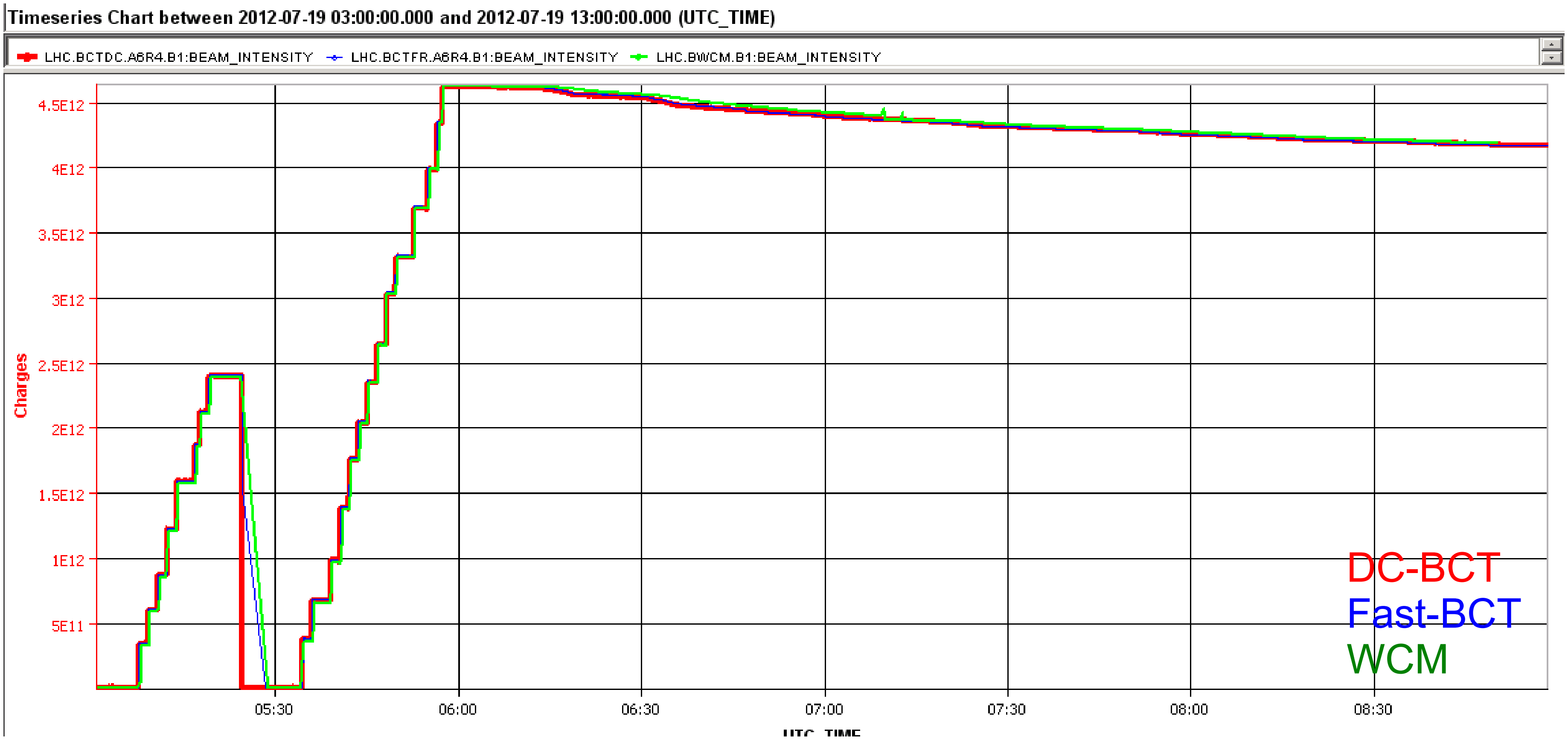


2012-07-19 09:00 VdM Scan – Compensated WCM Data B1 I/III



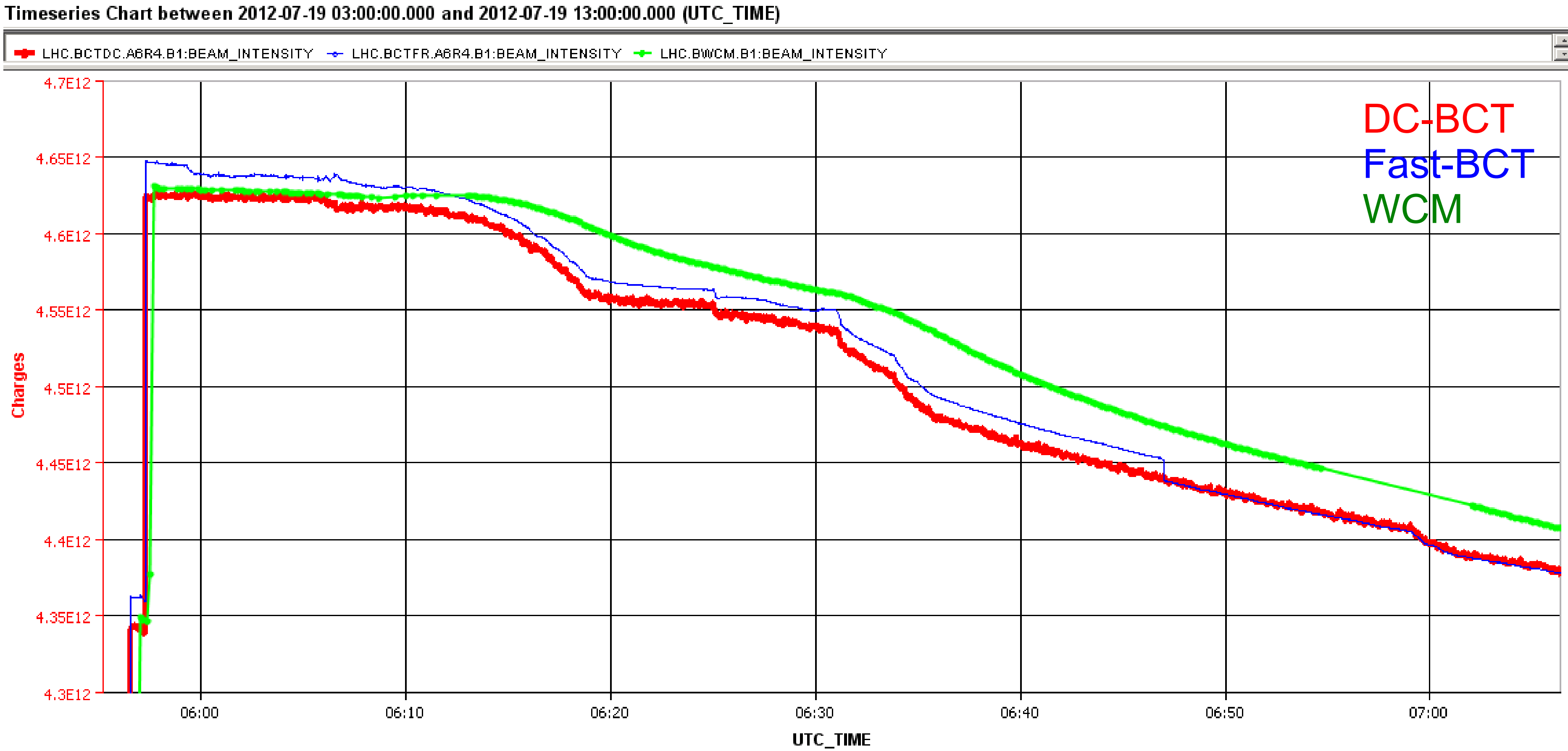
- Base-line well compensated
- Relative amplitude (intensity) resolution of ~10^{-4} (10^{-5}) visible

2012-07-19 09:00 VdM Scan



- WCM calibrated using regular physics fill against DC-BCT
  - Calibration factor consistent over several weeks
  - Re-tuned mostly only when changing cabling compensation, etc.

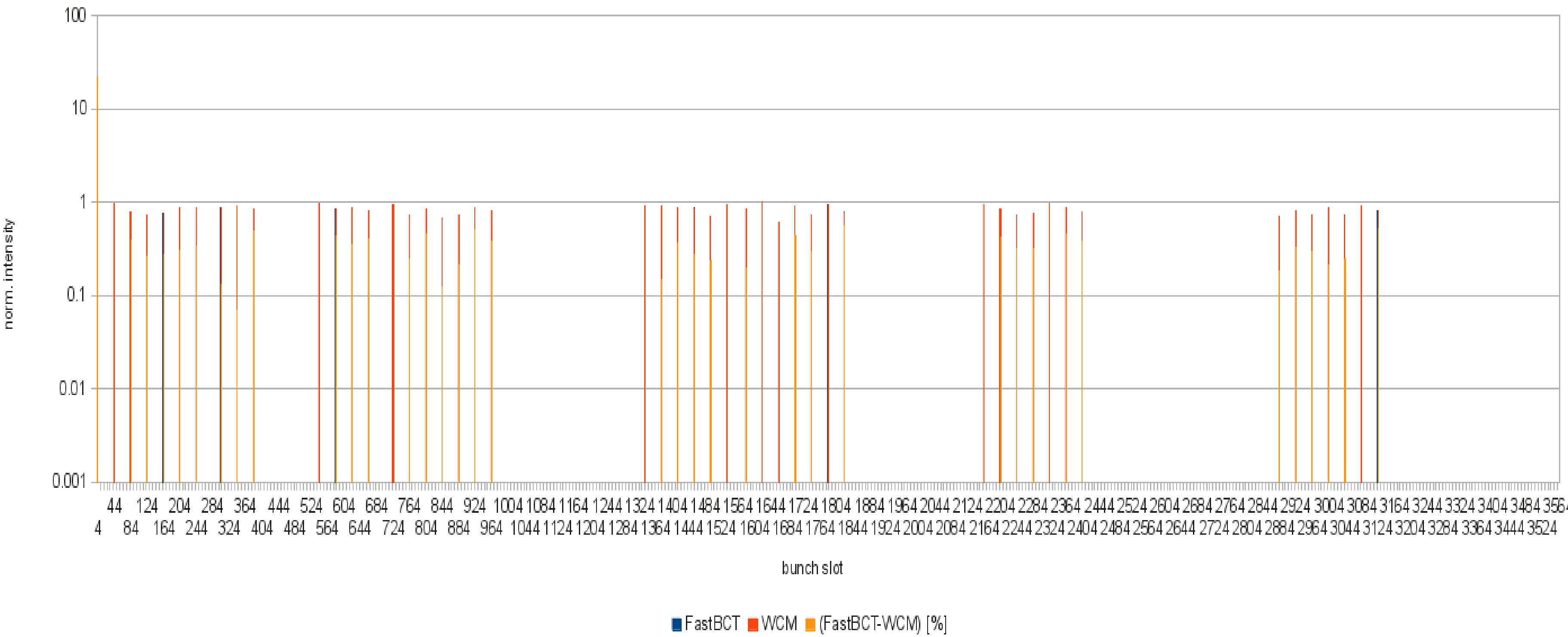
2012-07-19 09:00 VdM Scan – ZOOM



- WCM calibration consistent during injection & ramp
- Some deviation (overestimate?) once going into collisions.
- 'Beam Intensity' depends only on first bucket out of 10 buckets per 25 ns slot (→ lower bias)

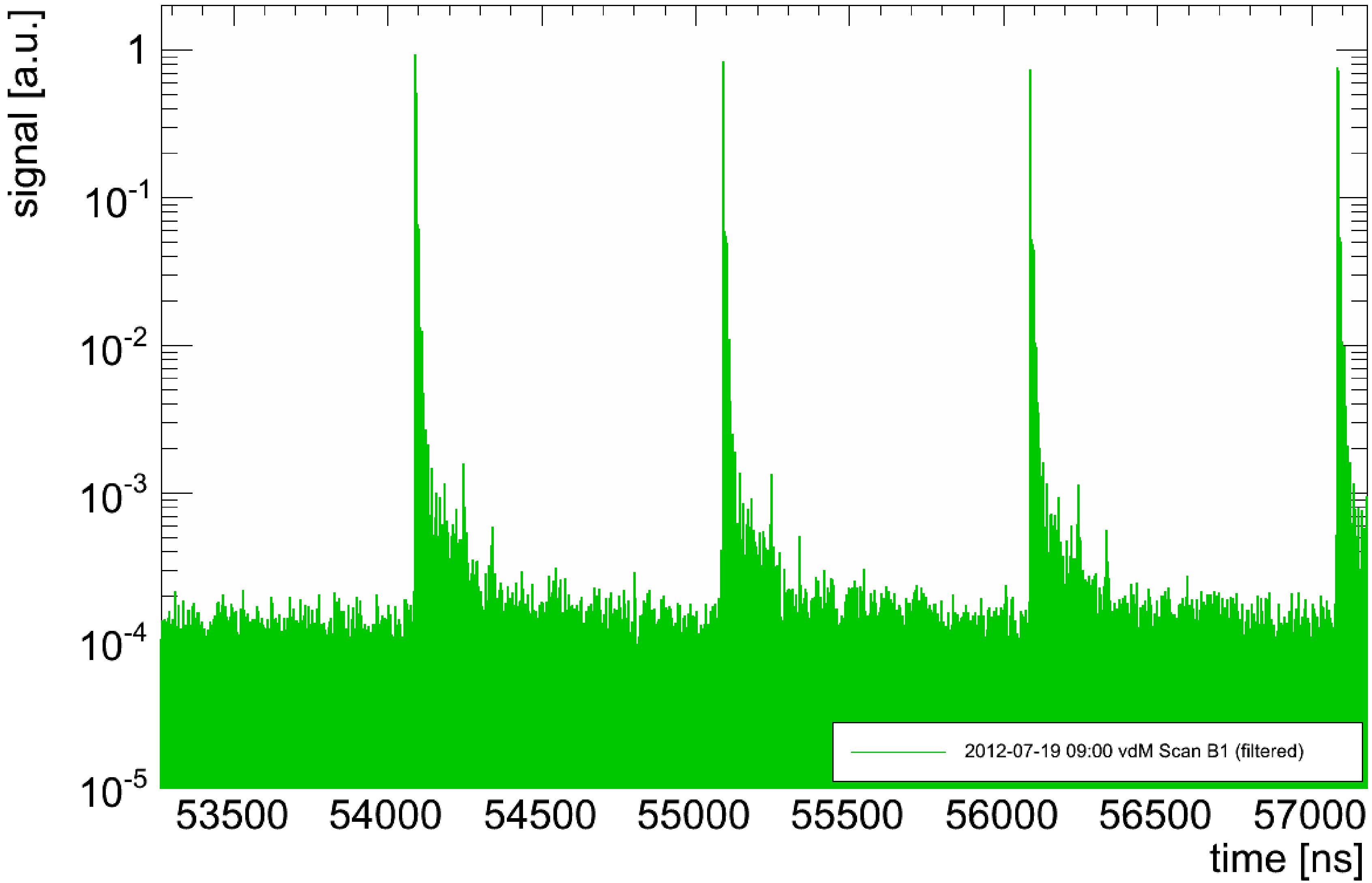
Fast-BCT vs. WCM Bunch-by-Bunch Comparison

- Detect the same bunches... good.
- Individual bunch intensities agree within ~ 0.25 ± 0.25%
  - WCM exception: first slot is being 'split in two' → SW bug to be fixed

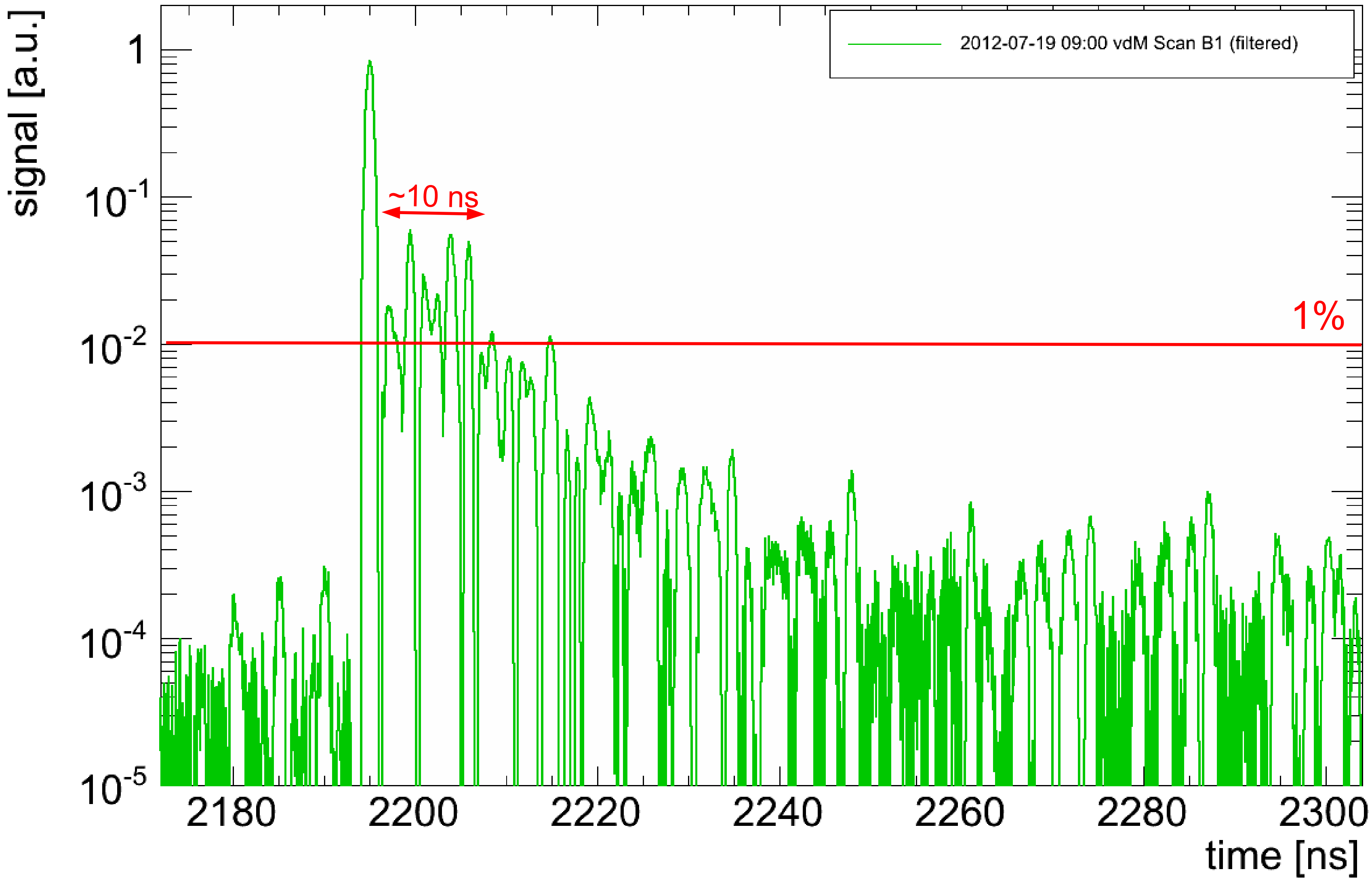


- WCM operates at 400 MHz → would a priori expect smaller/no bunch-by-bunch dependence for 50 (25 ns) bunch spacing compared to Fast-BCT (how to test this?)

2012-07-19 09:00 VdM – Compensated WCM Data B1 II/III

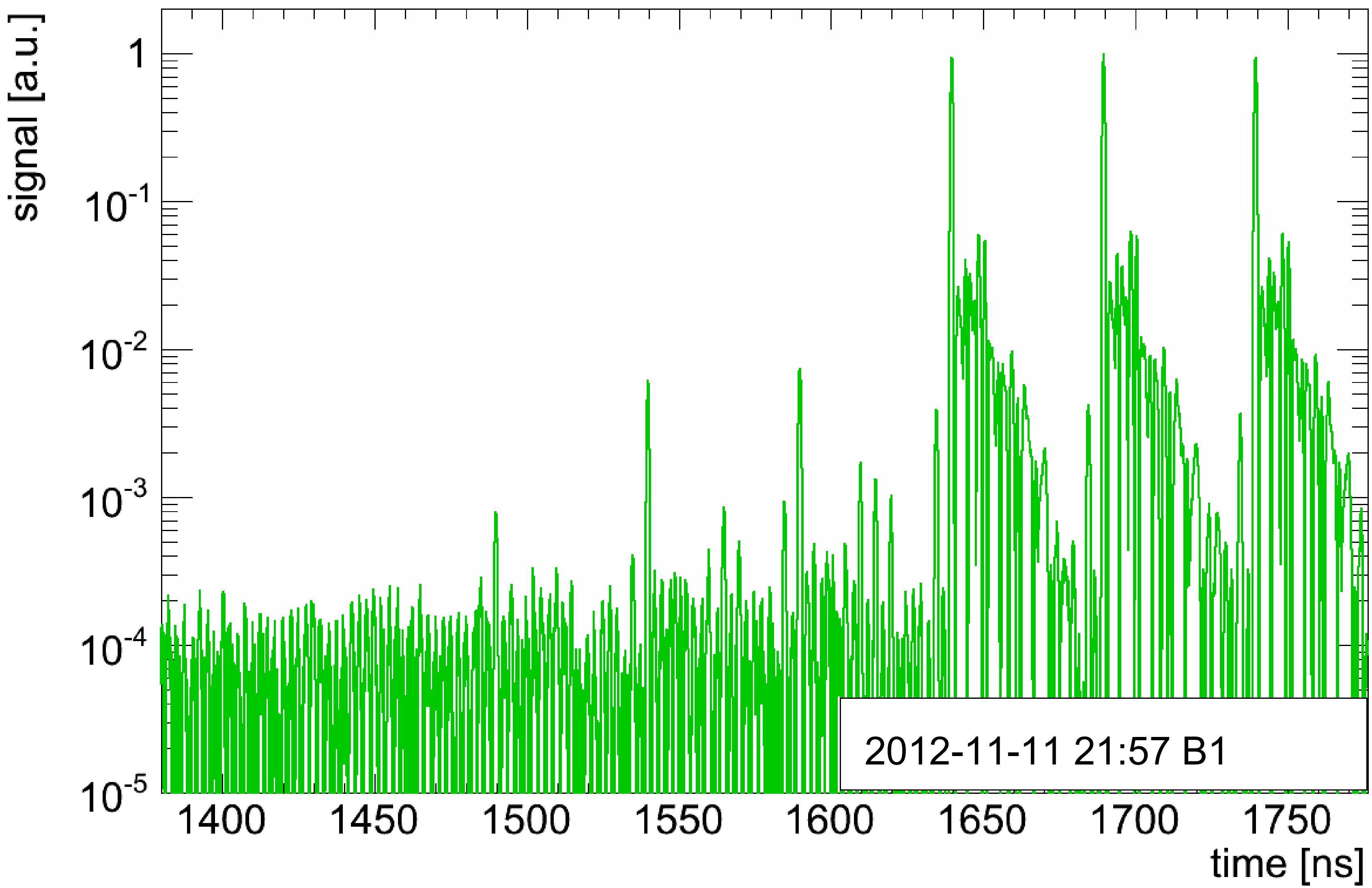


2012-07-19 09:00 VdM – Compensated WCM Data B1 III/III

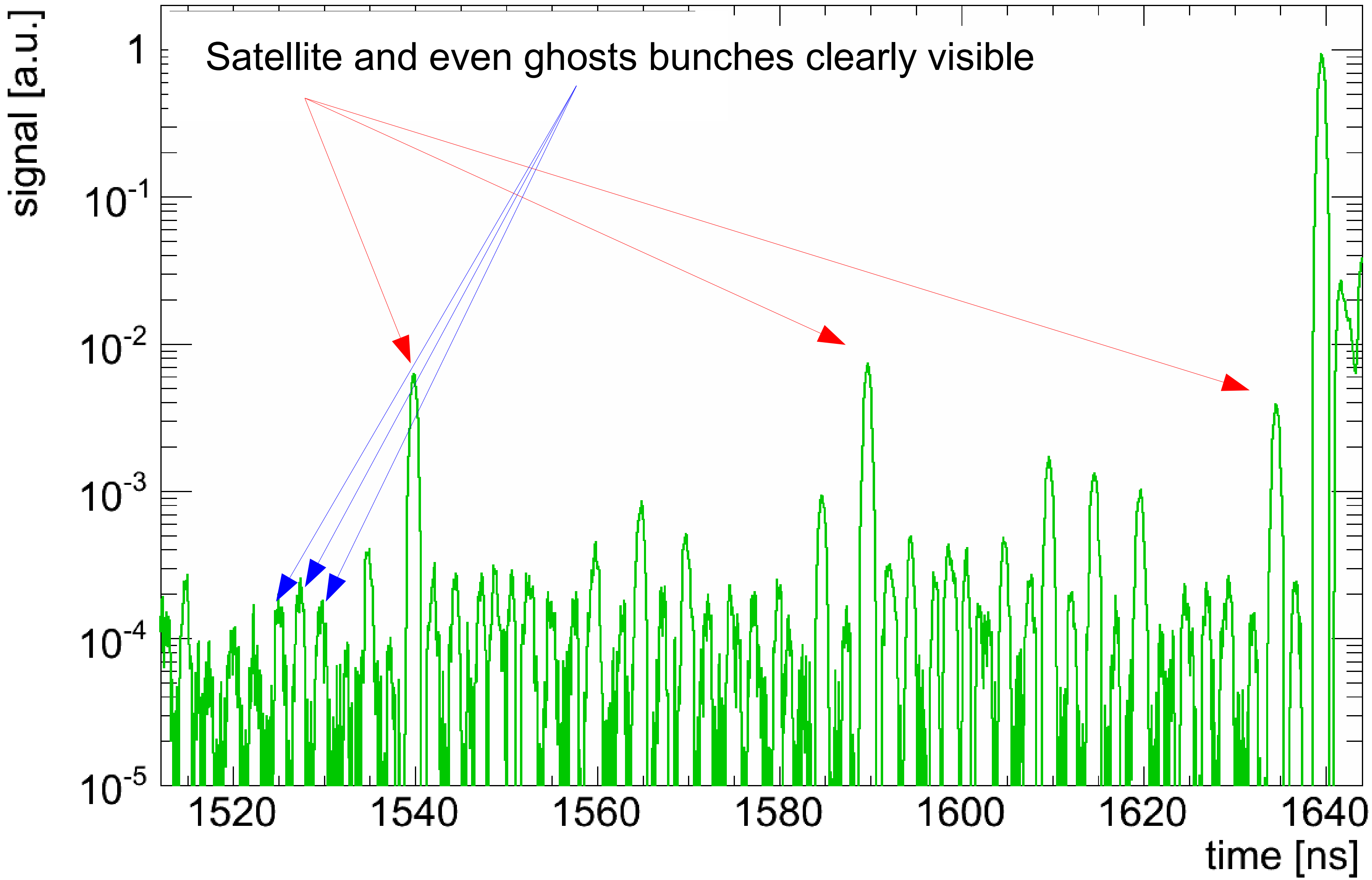


- Reflections after main bunch could be a priori be masked but few-% level reflections more indicative of a HW problem → access last Friday

For comparison
2012-11-11 21:57 – Regular Physics Fill I/II



For comparison
2012-11-11 21:57 – Regular Physics Fill II/II



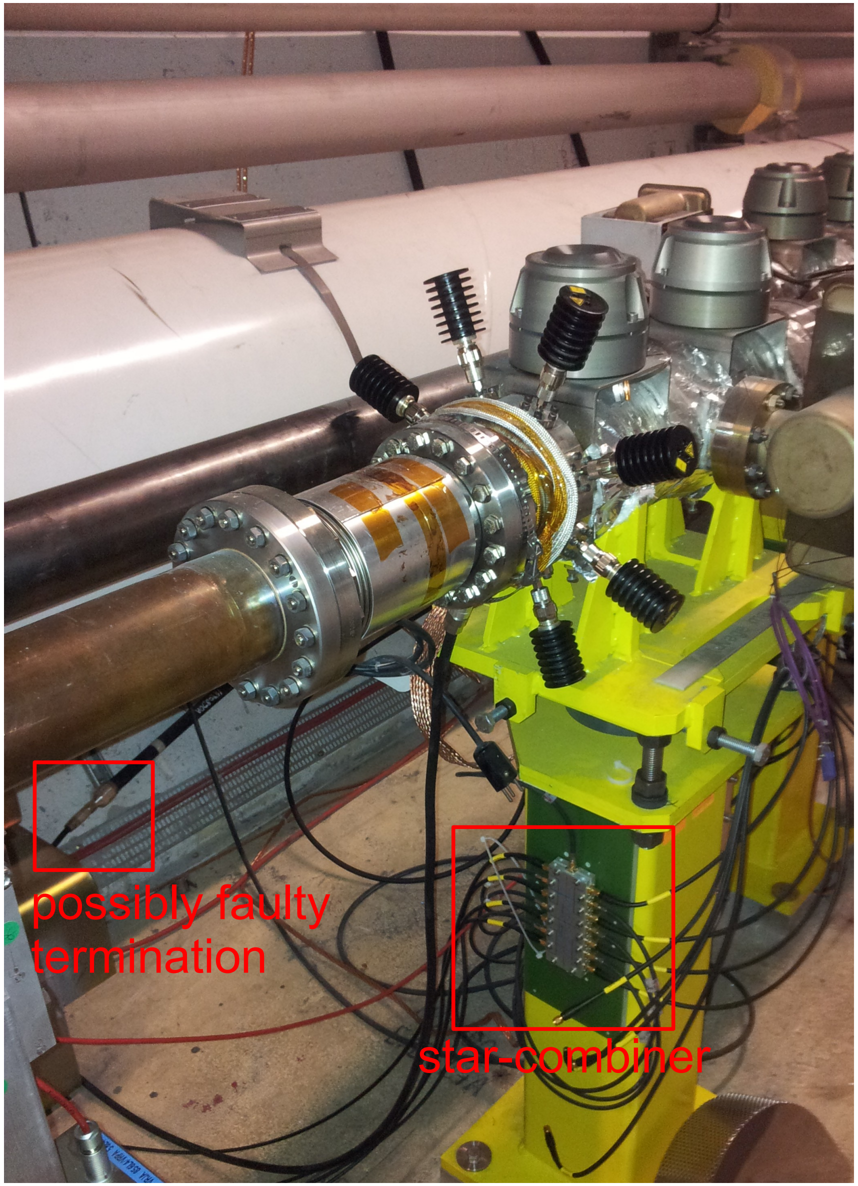
2012-11-09 modifications of WCM (APWL) B1

- Removed star-combiner
  (since not a matched 50Ω system)
  → will increase the sensitivity to position but should be acceptable (N.B. Orbit-FB)

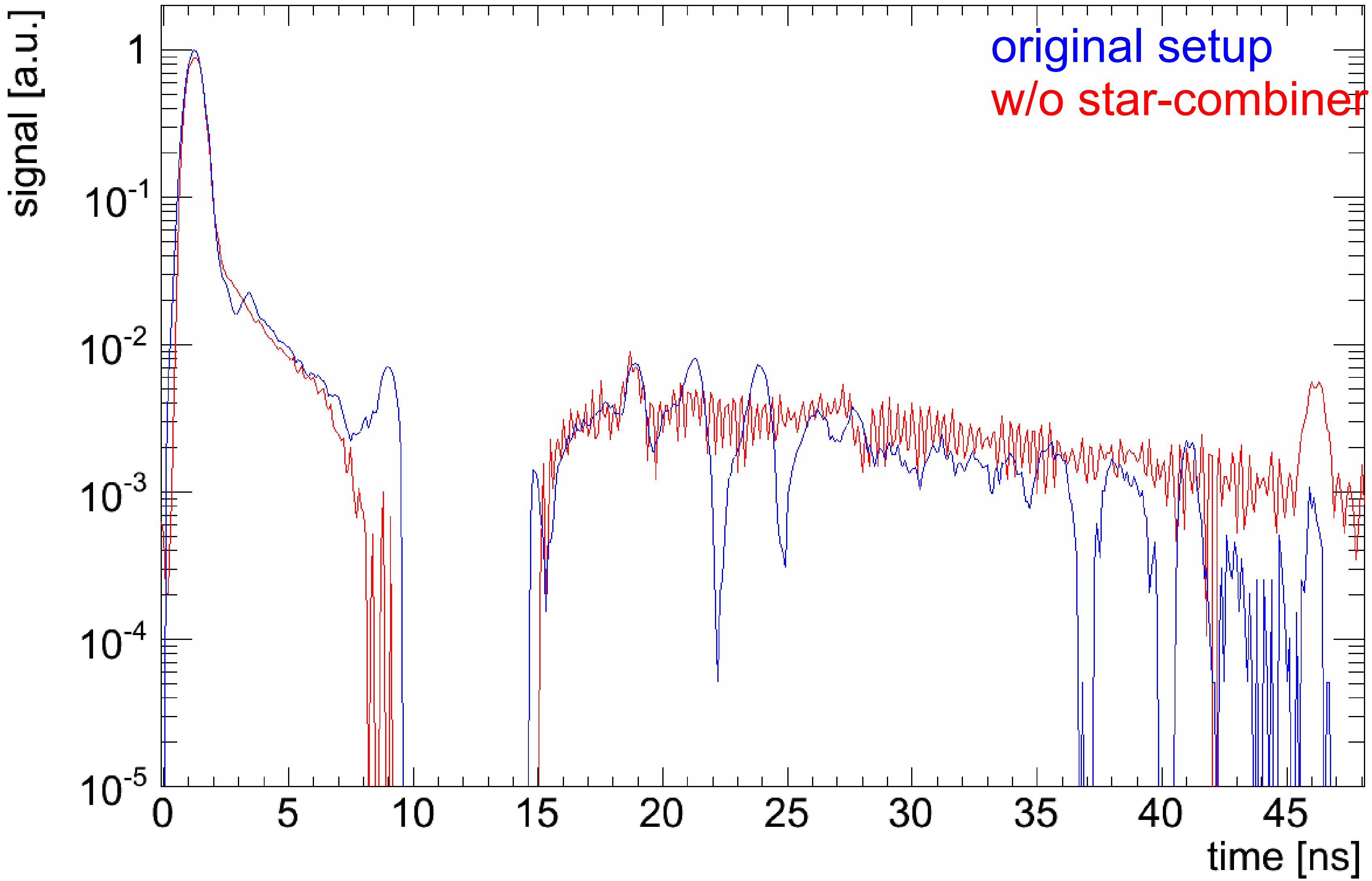
- loaded 7 out of 8 ports at source, matched to ~ -30 dB
  → needs to be redone during next TS/LS1

- Noticed a 7/8 cable termination that was a bit loose
  → need to check redo this during the next TS

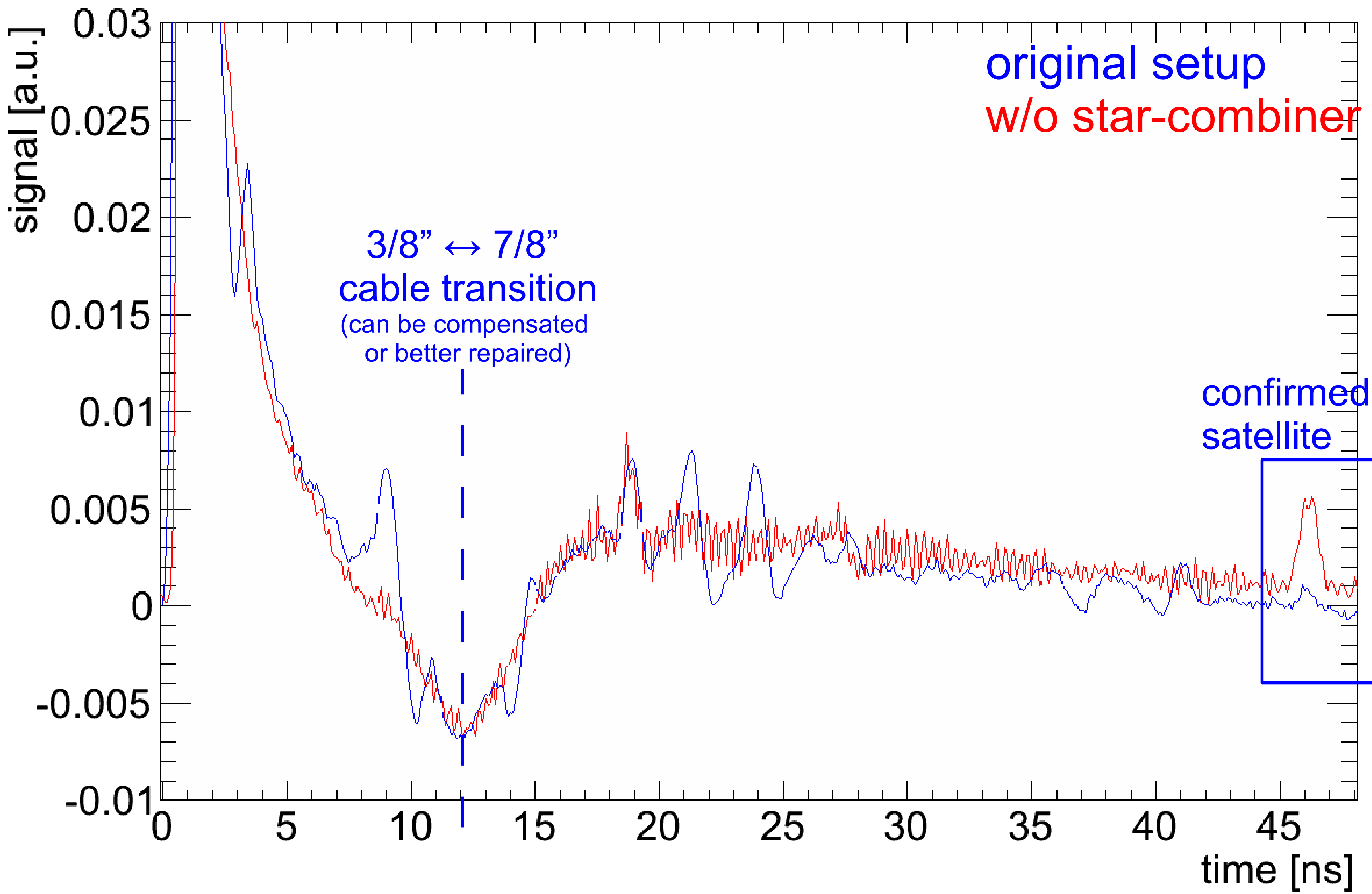
- Further plans: shift/split 40 dB attenuation to WCM (will add some back-matching to the otherwise reflective pick-up)



First Beam Data after Modifications



First Beam Data after Modifications – ZOOM

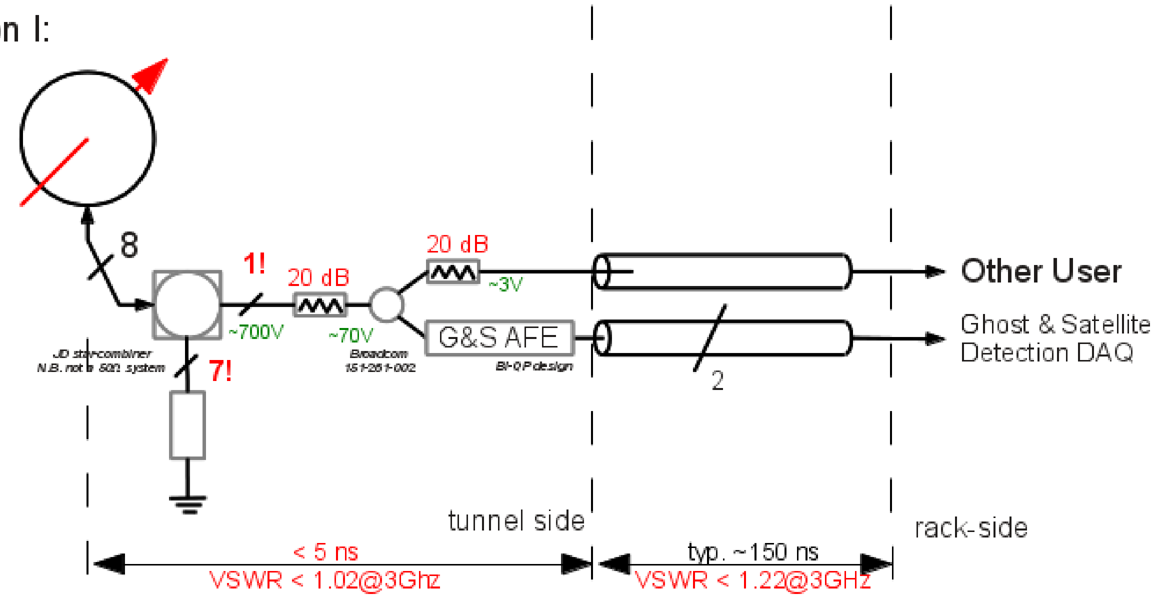


- Gain by post-compensating the reflections but limited overall to factor ~10 → should be fixed in HW

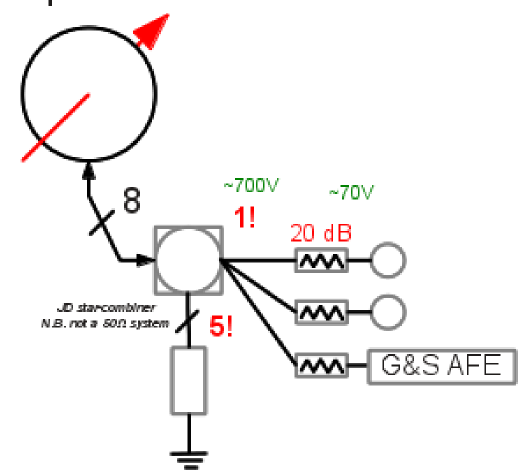
Alternative: Ghost and Satellite Detection in the PS
Should we follow this up also for the LHC?

New PS WCM – Proposed System Layout (>LS1)

Option I:

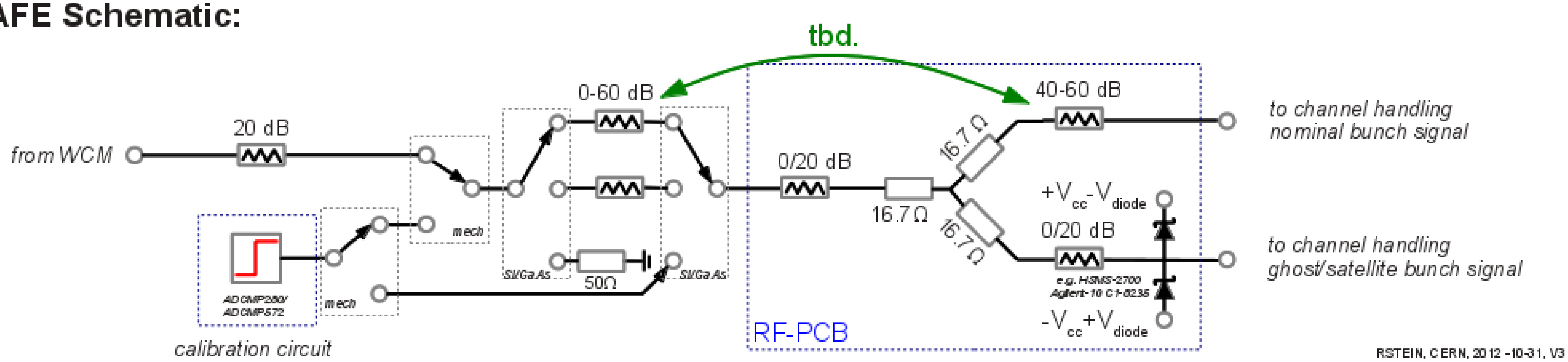


Option II:



Pro: more signal (i.e. ions)
Con: much tighter VSWR requirements
less transient protection

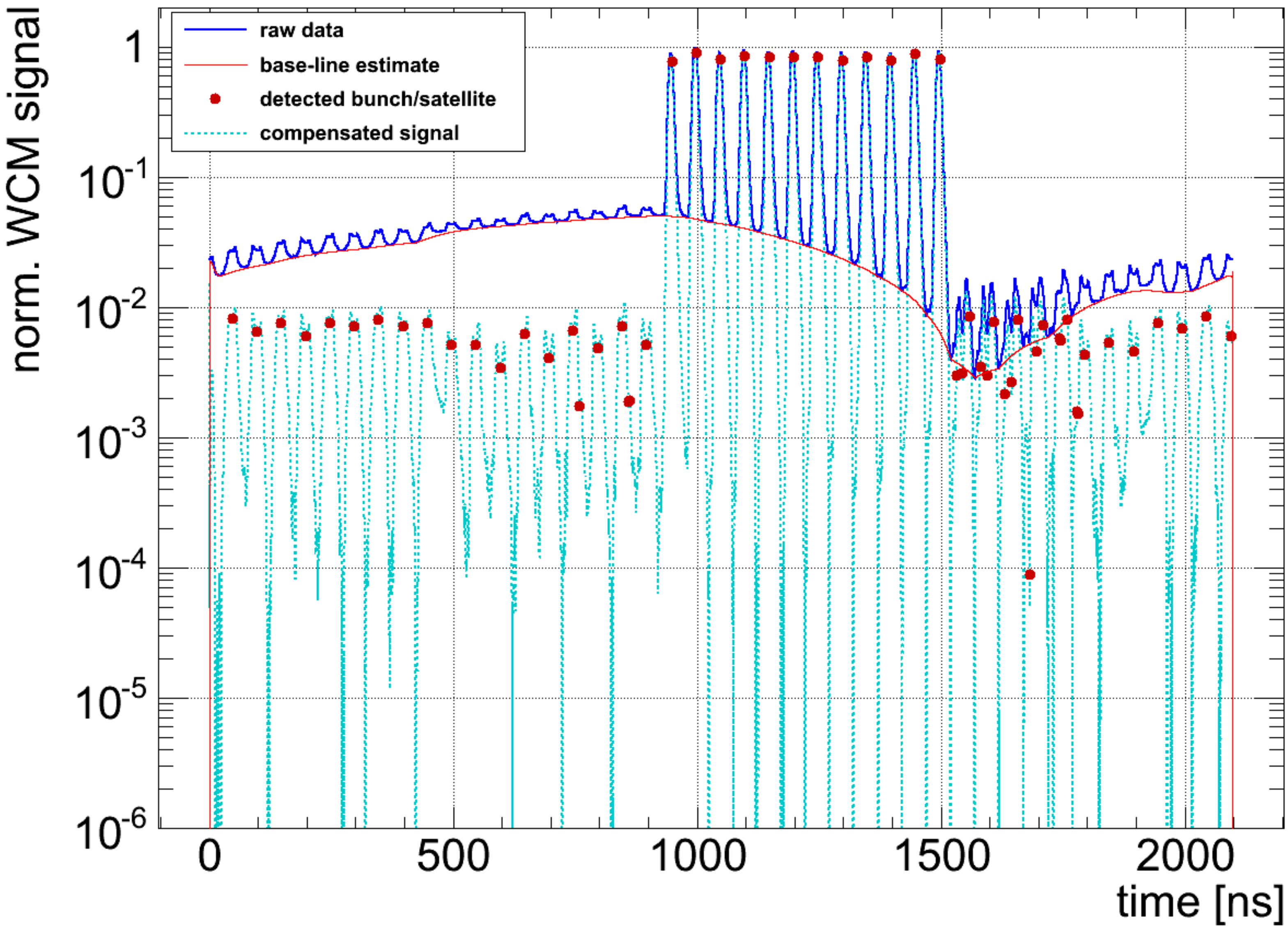
G&S AFE Schematic:



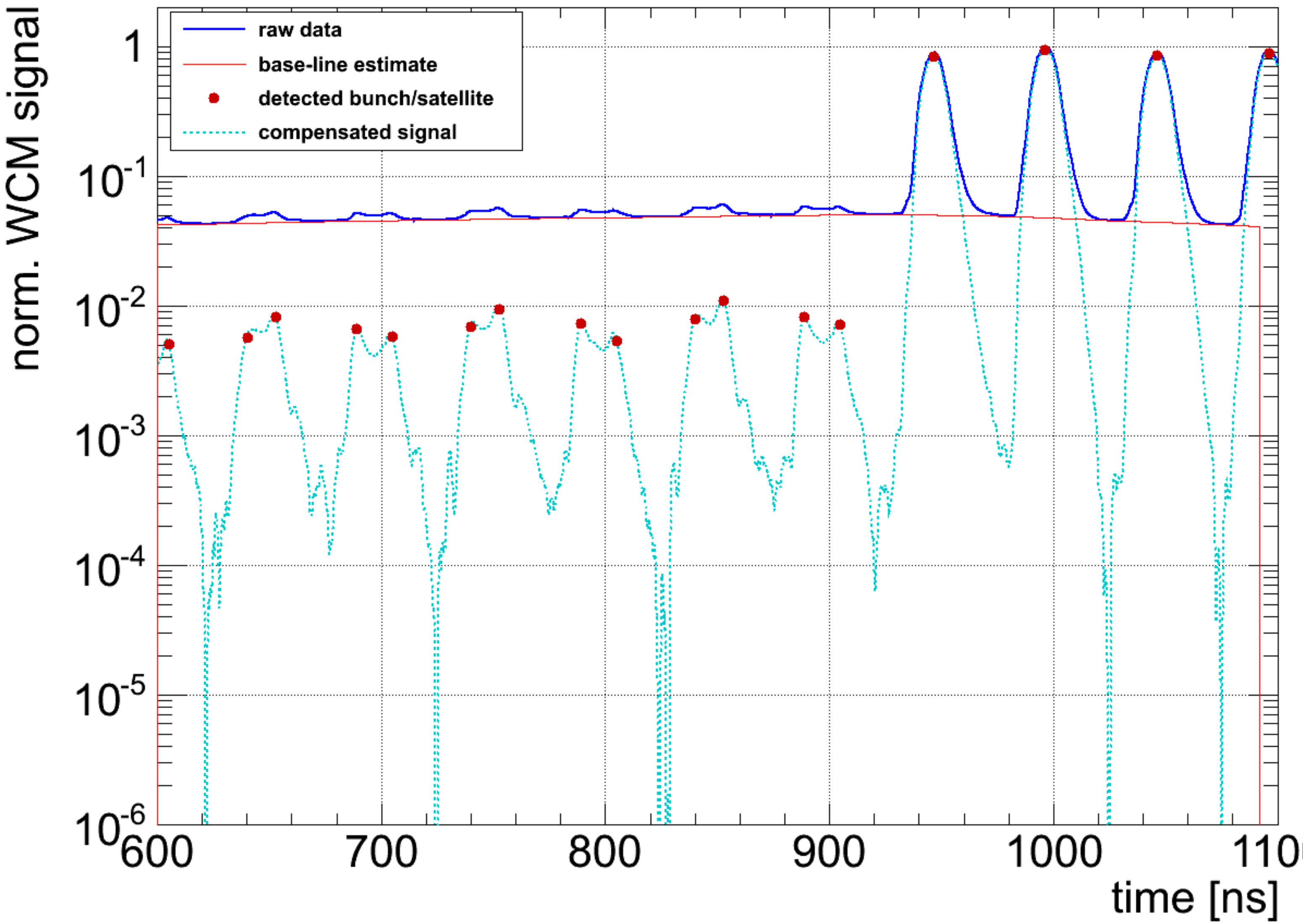
RSTEIN, CERN, 2012-10-31, V3

Example PS WCM Signal

- Satellites have been deliberately produced for better proof-of-principle:

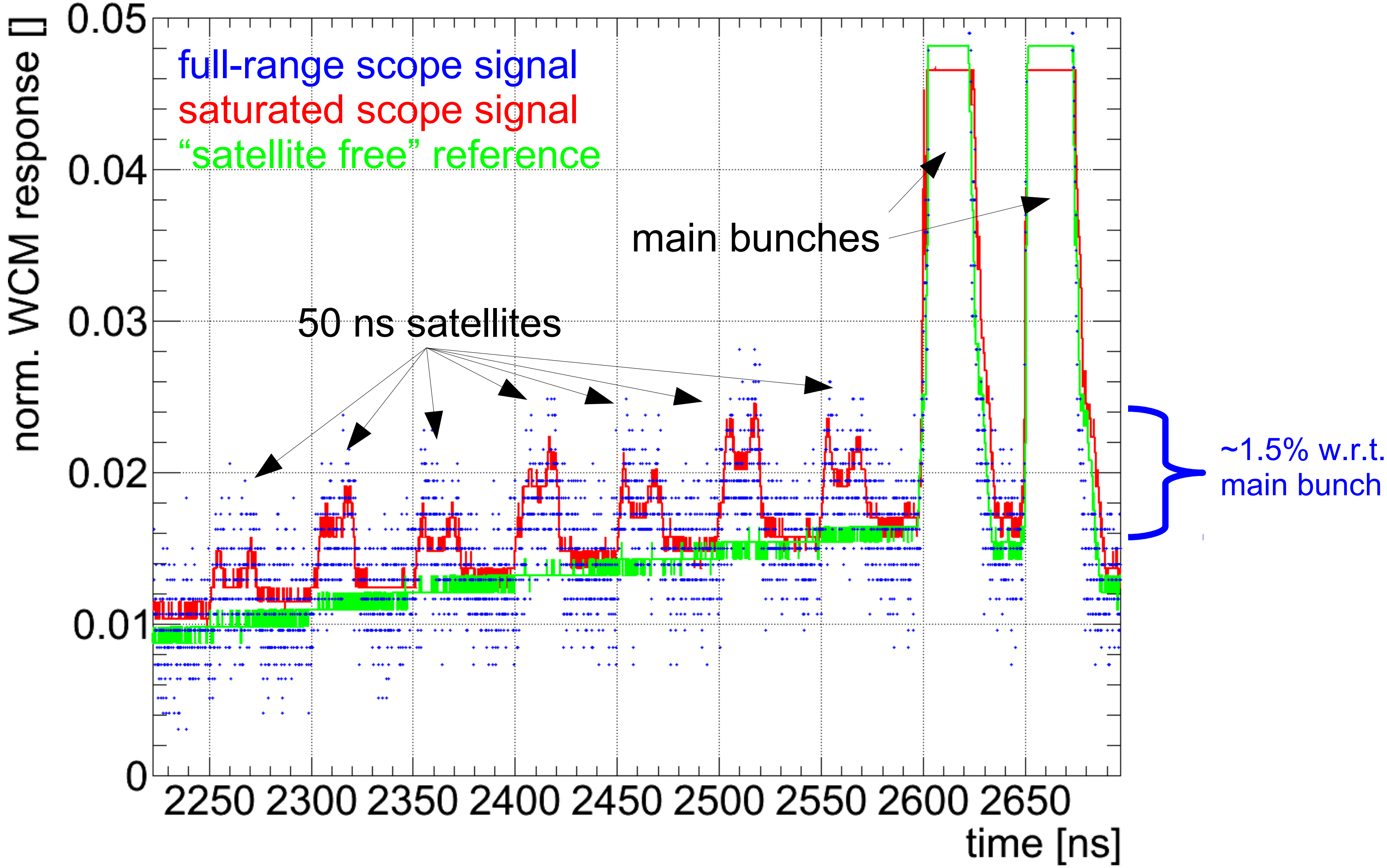


III. Base-Line Restoration – SNIP Algorithm
Example PS WCM Signal - ZOOM



- Especially satellites/ghosts may have very special distributions (e.g. hollow for recaptures particles → double peak structure)

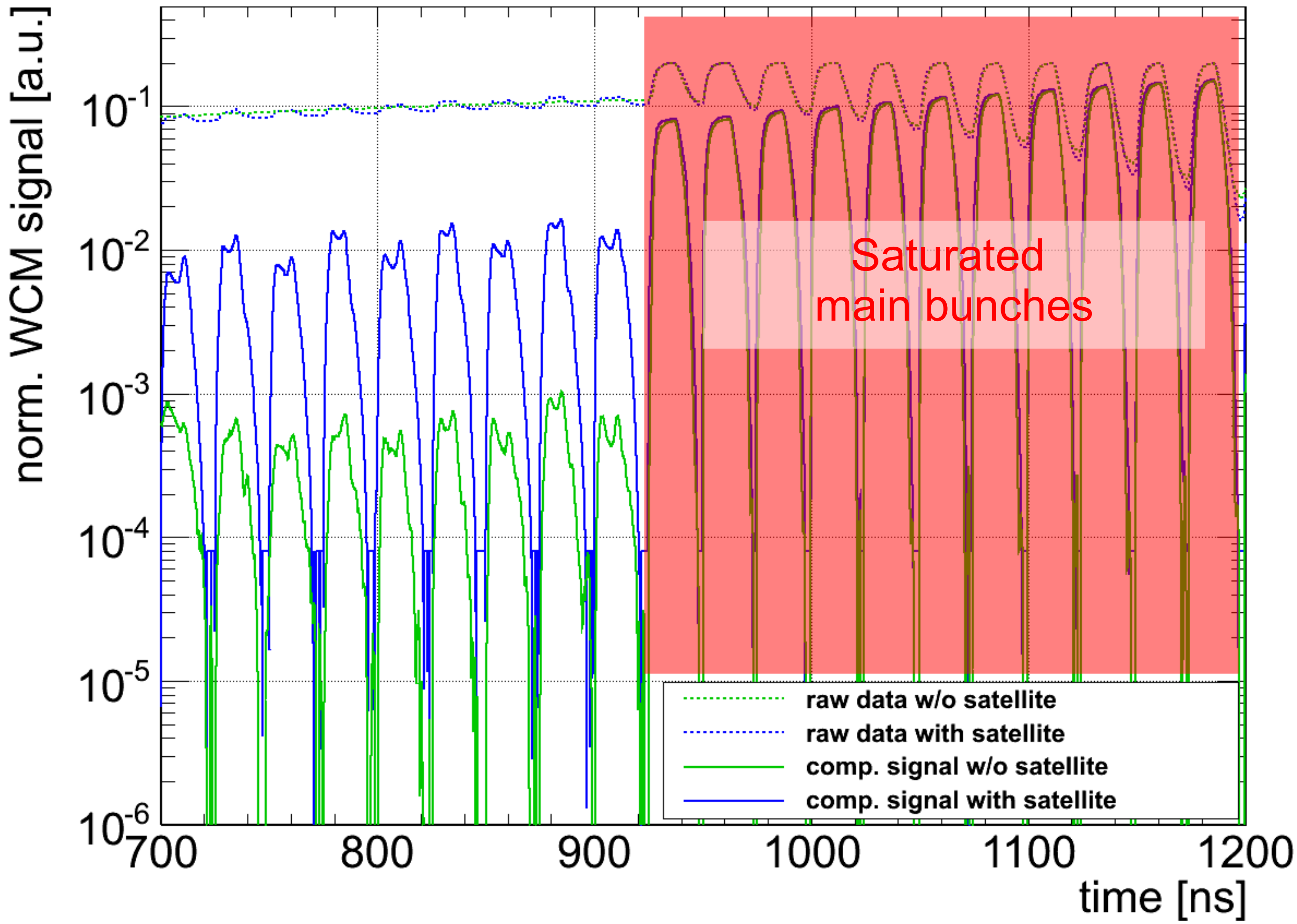
- Forcing satellites and saturating the scope input (fast recovery time)



- Satellites 'visible' and results look promising but requires post treatment to compensate for reflections, pick-ups response, droop etc.

What could be achieved – PS II/III

- After full post-processing chain of smoothing and removing background:



- Satellites visible in “clean” condition, prel. noise-floor estimate ~10^{-5} w.r.t max

Summary

- Nom. empty LHC RF buckets may be filled with minute amounts of particles → aka. 'Satellites' and 'Ghosts' up to 10^{-6} smaller than nominal bunches

- Proof-of-principle: "Can these be detected already in the injectors before the arrive in the LHC using standard wall-current-monitors?"
  Test confirmed that the existing system...
  - can achieve 10^{-5} resolutions @3 GHz over a few turns or single-shot via:
    a) turn-by-turn averaging over a couple of hundred turns
    b) splitting signal and saturating its copy to specifically detect satellites
  - Requires beam-based baseline compensation since the system drifts on the up to 10^{-3}-level due to temperature, saturation and other effects

- Present performance limited by:
  - Reduced duty cycle of 10k vs. 100k@0.1Hz
  - Cable/pick-up reflections during first 10 ns after main bunch
    → However, can estimate satellites via WCM to DC-BCT differences

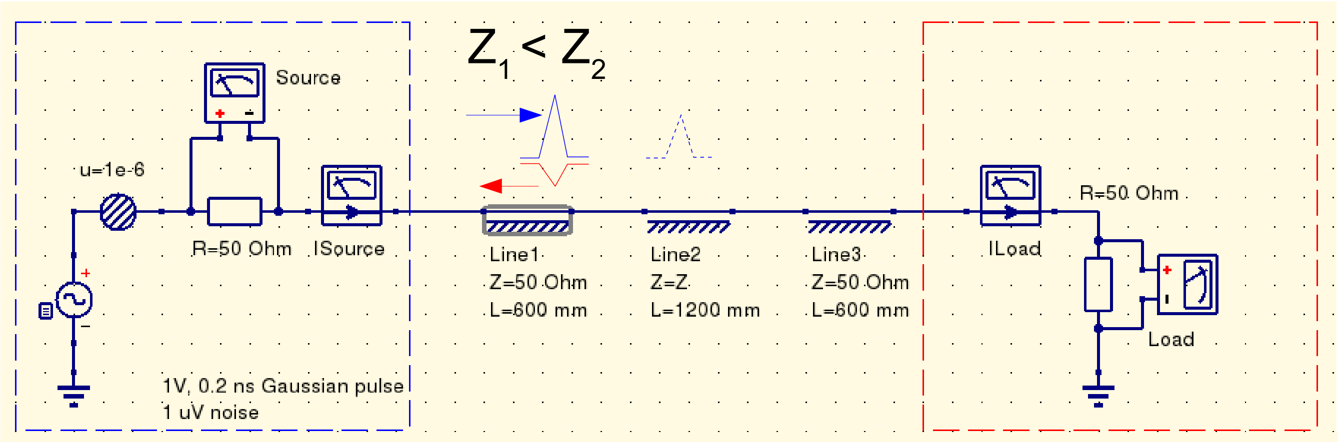
- Acquisition HW upgrade being in progress (LS-1):
  - Improve to 100% duty cycle for the averaging, quality of cabling
  - compensation algorithm being done in FPGA
  - Dual-range 'full vs. 1% saturated' setup (electronics in preparation)

Thank you for your Attention!

Supporting Slides

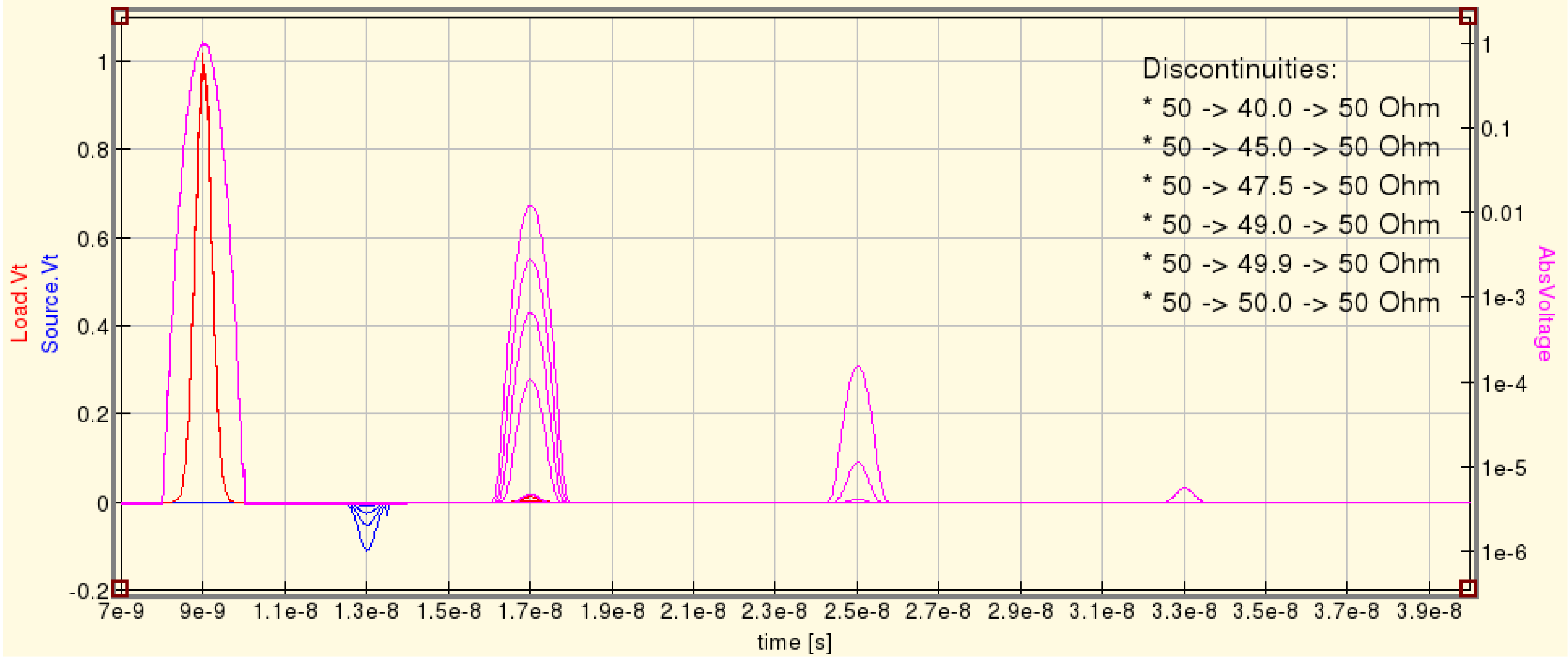
RF Reflections – Definitions

- ...are unavoidable impedance mismatches



$$\rho := \frac{Z_1 - Z_2}{Z_1 + Z_2}$$

$$VSWR := \frac{1-\rho}{1+\rho}$$



Reflections: RF Connector and Cable Geometry I/II

- Selection of common connectors and adapters (H&S):
  - Naively, one would expect these to be inert
  - static and frequency dependent component
- For comparison, a VSWR of
  - 1.02 ↔ r = 1% ↔ 40 dB
  - 1.03 ↔ r = 1.4% ↔ 36.6 dB
  - 1.05 ↔ r = 2.4% ↔ 32.3 dB
- RF transitions are unavoidable in real life
- %-level reflections are common/normal

VSWR ≤ 1.03 + 0.01·f [GHz]

≤ 1.19 + 0.06·f [GHz]

VSWR ≤ 1.03 + 0.004·f [GHz]

VSWR ≤ 1.025 + 0.007·f [GHz]

≤ 1.05 + 0.015·f [GHz]

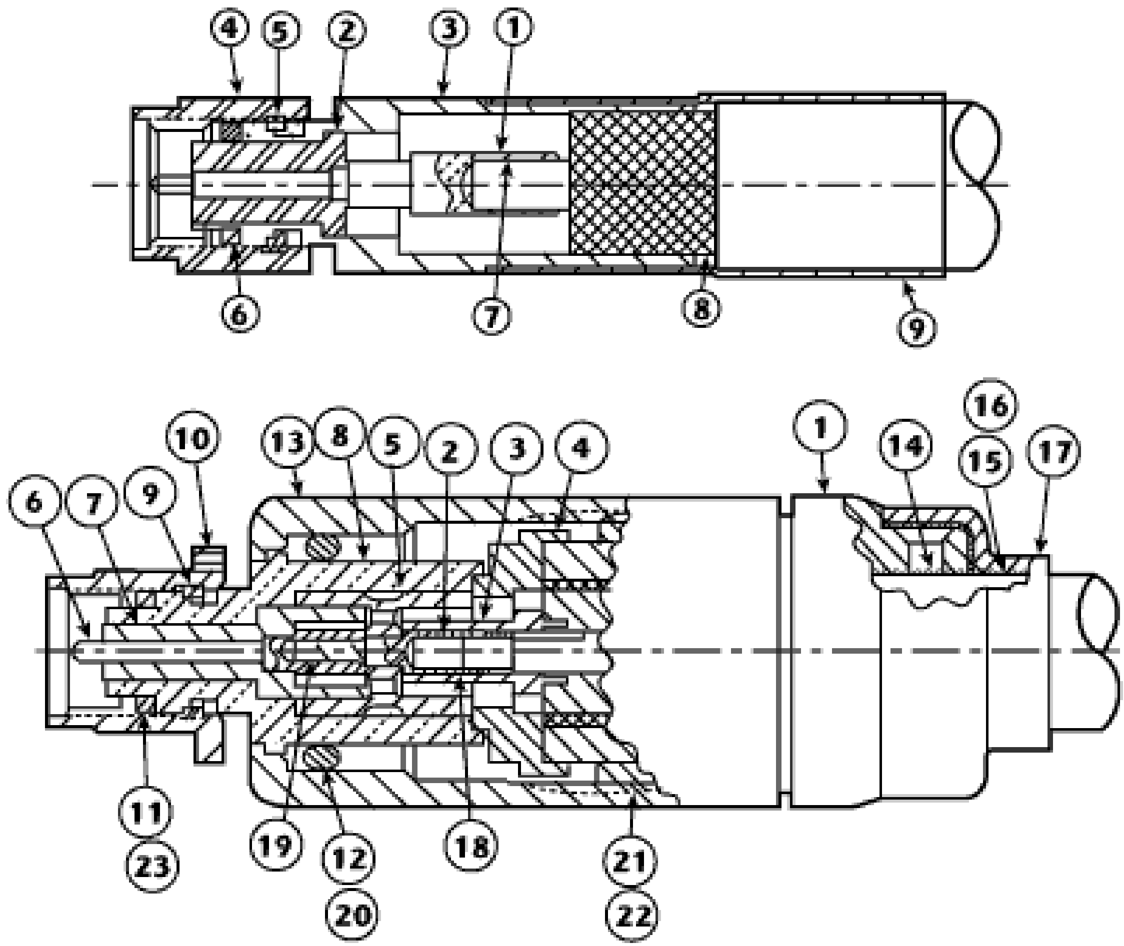
VSWR ≤ 1.06 + ~0.01·f [GHz]

VSWR ≤ 1.02 + 0.03·f [GHz]

≤ 1.05 @ 6GHz

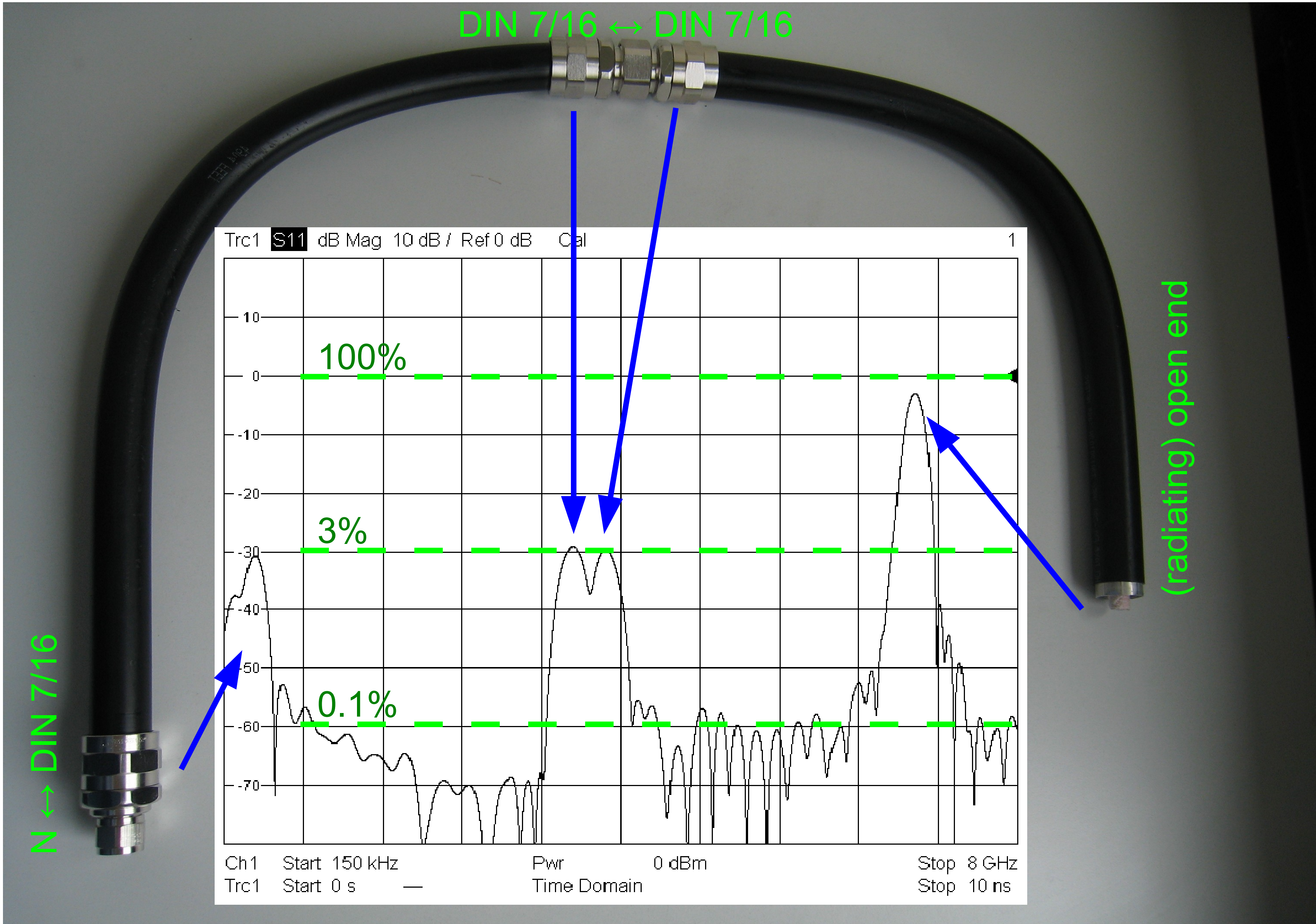
Reflections: RF Connector and Cable Geometry II/II

- Anatomy of a SMA connector:



- … however: imperfections can be compensated using the measured cable transmission transfer function for the specific installation (relaxes a bit if λ >>l)

Reflections: RF Connector and Cable Geometry
Real-Life Example



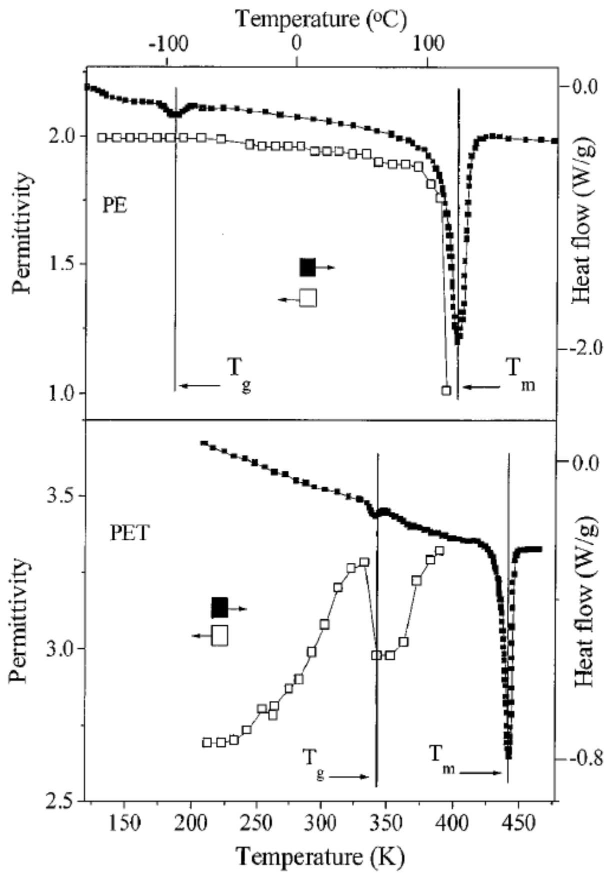
Permittivity and Dependence on Temperature

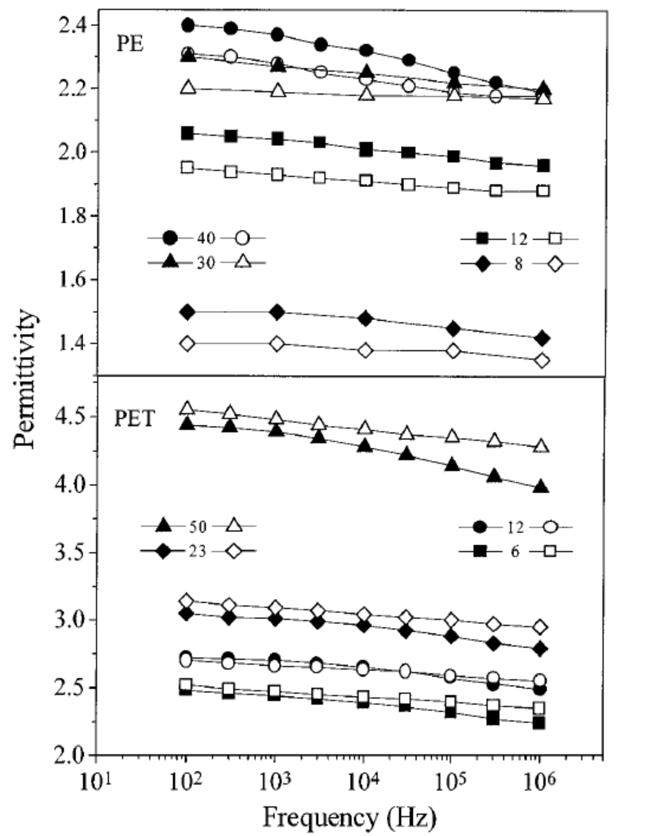
- Permittivity depends on frequency and temperature

N.B. $Z_0 \sim \sqrt{\frac{\mu_r}{\epsilon_r}}$

$$\frac{\partial}{\partial T}\left(\frac{\Delta\epsilon}{\epsilon}\right) \sim \pm 30\ ppm/{}^\circ C \quad (e.g.\ ceramics)$$

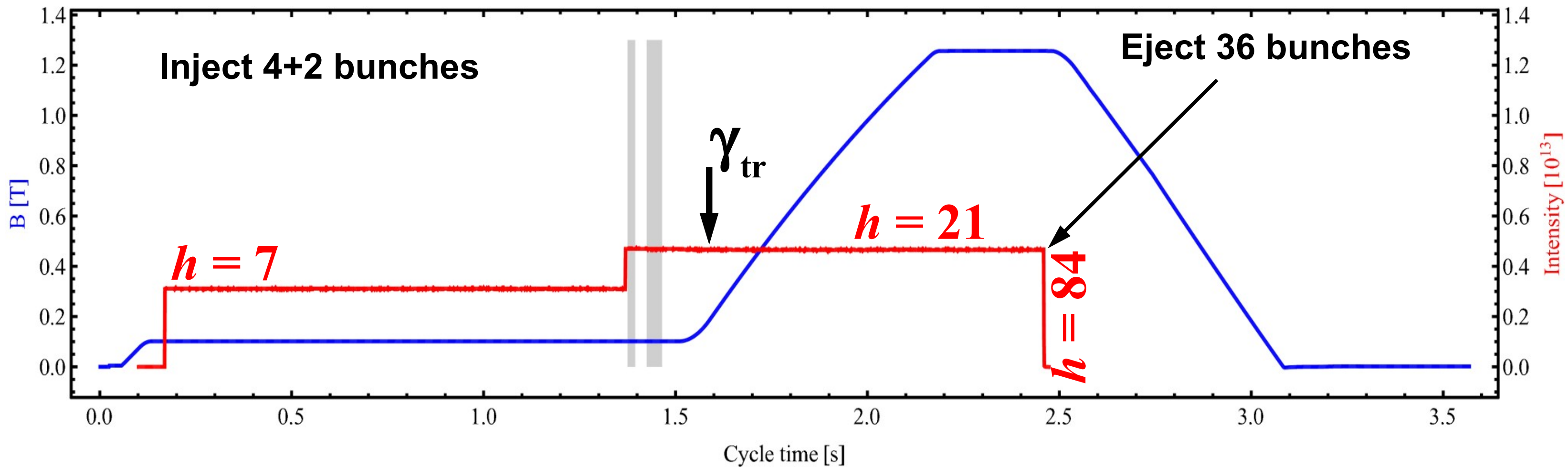
$$\frac{\partial}{\partial T}\left(\frac{\Delta\mu}{\mu}\right) \sim 0.1 \ldots 1 \cdot 10^{-2}/{}^\circ C \quad (typ.\ ferrites)$$

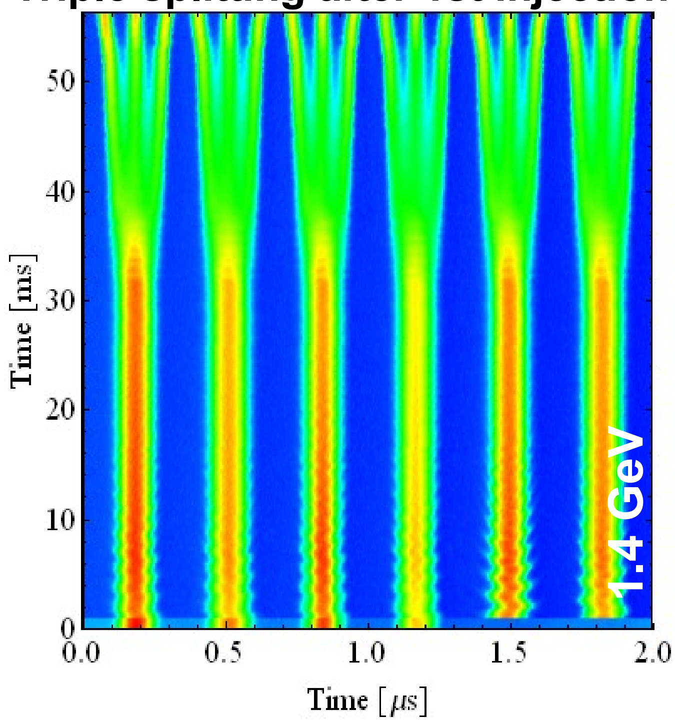


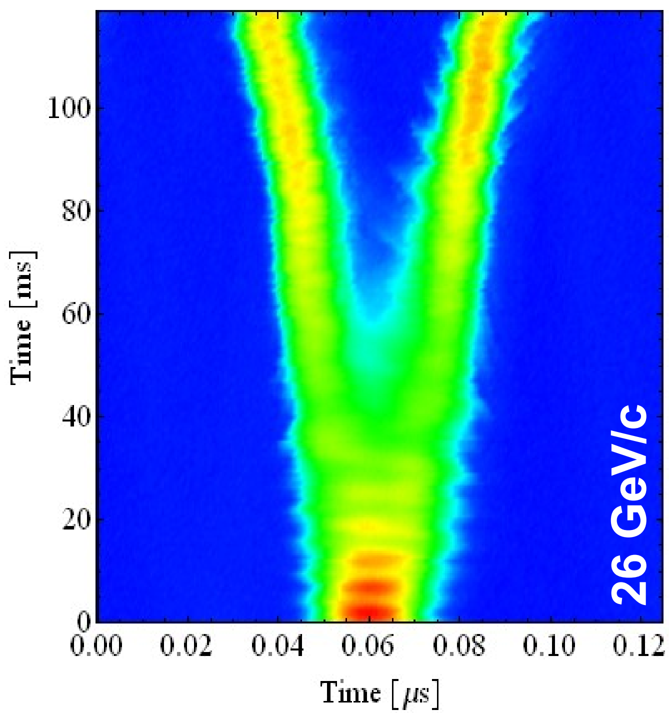


- Highly non-trivial and active research topic
- N.B. PE melts at a very low temperature around 100 °C ↔ ~20 W/m power loss in cables (thanks to S. Smith for pointing this out!)

LHC-type Beam Production in the CERN-PS here: 50 ns beam



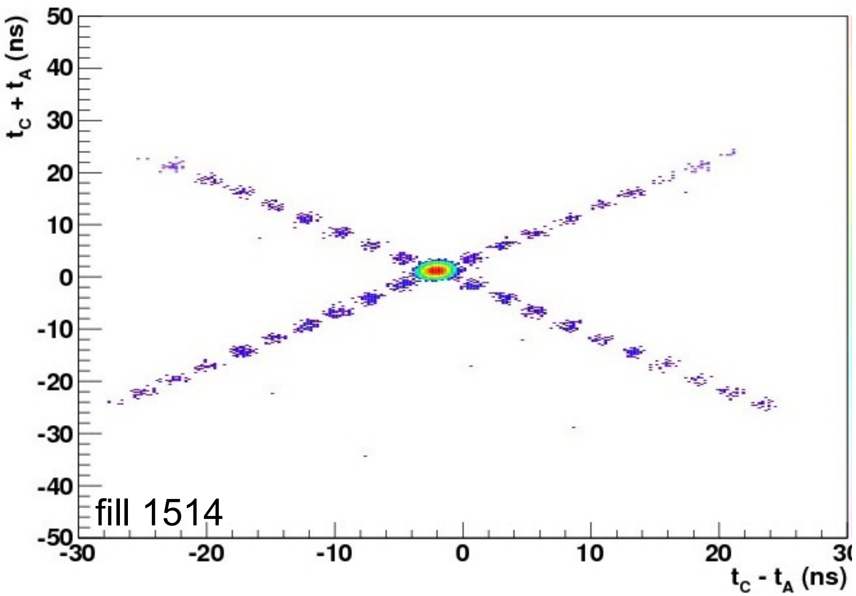




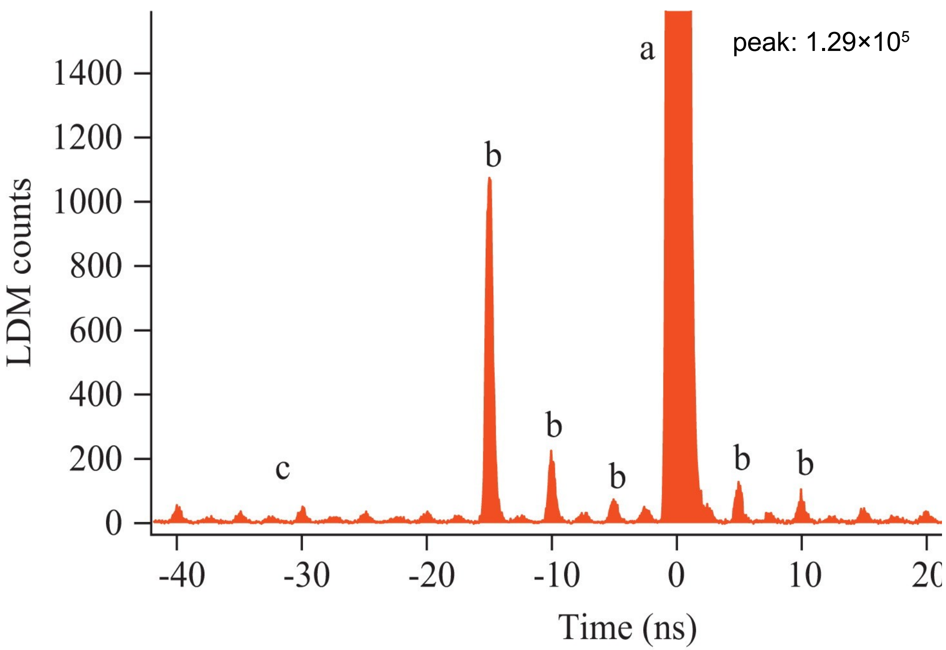
Terminology and Impact on LHC Physics

- Depending on the particle population per bucket:
  - Nominal bunch: $n_b \sim 10^9$ -$1.6 \cdot 10^{11}$ p/bucket
  - 'Satellite': %-level filled buckets typ. in vicinity of nominal bunches
    - *mostly PS beam production, particle transfer*
  - 'Ghost': $<10^{-4}$ w.r.t. nom. bunch filled bucket
    - *capture losses/recapture beam at LHC injection*

ALICE Interaction Point reconstruction:



Synch-Light Single Photon Counting (APD)[1]:



[1]A. Jeff et al., “First results of the LHC longitudinal density monitor”, NIMA, Vol. 659, Issue 1, 2011, pp. 549–556