Wall-Current-Monitor based
Ghost and Satellite Bunch Detection
in the CERN PS and LHC accelerators

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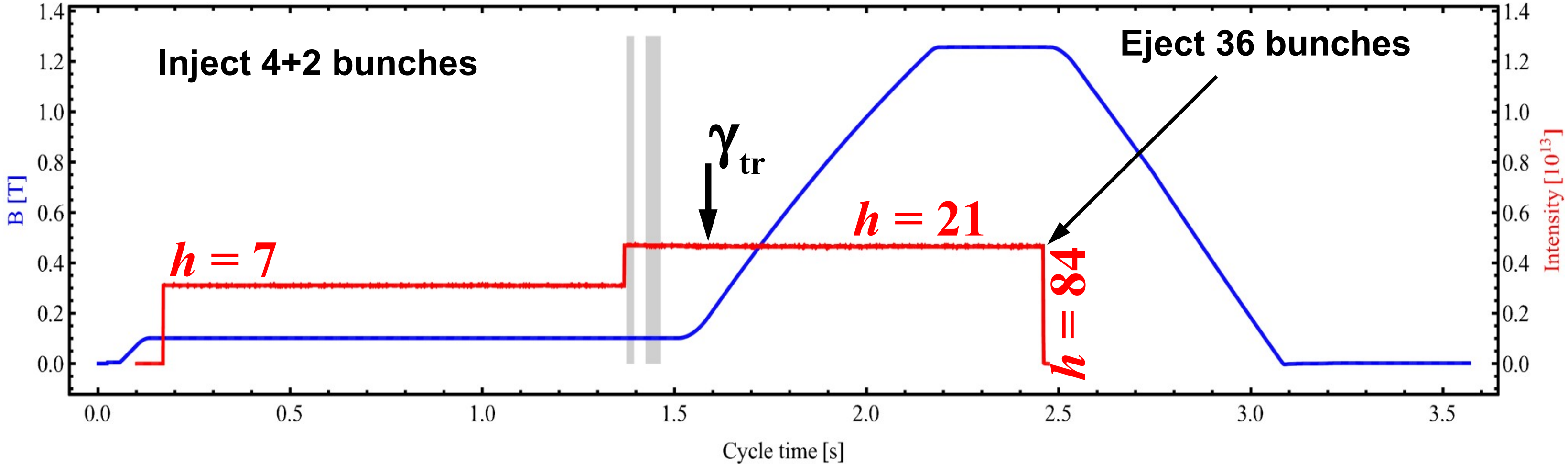
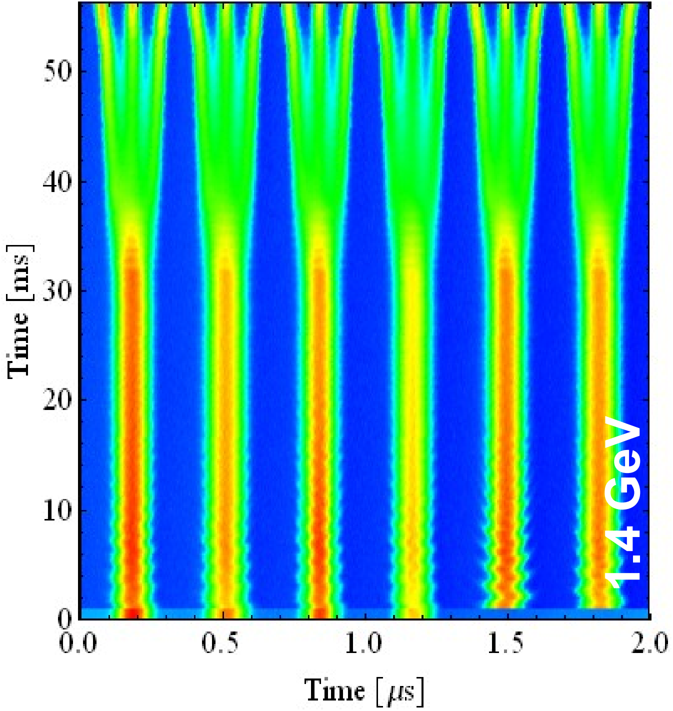
CERN Beam Instrumentation and RF Group

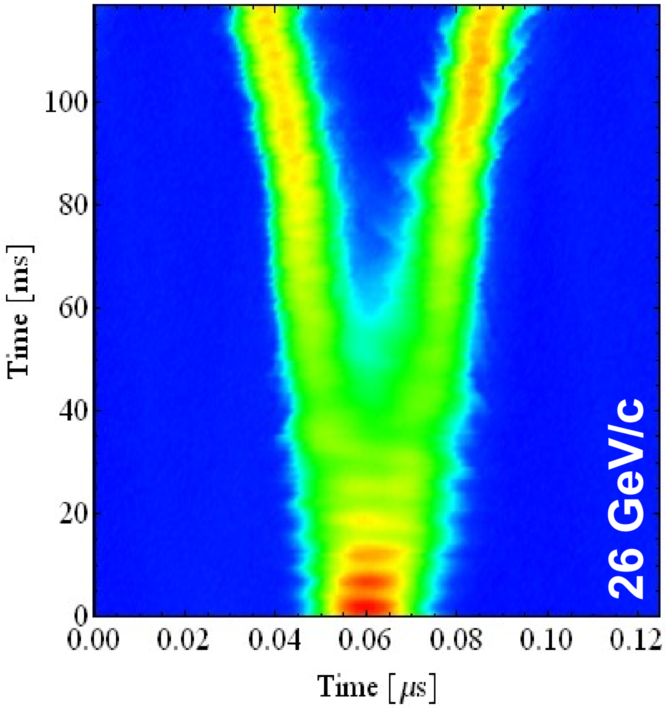
LHC-type Beam Production in the CERN-PS
here: 50 ns beam



Triple splitting after 1st injection



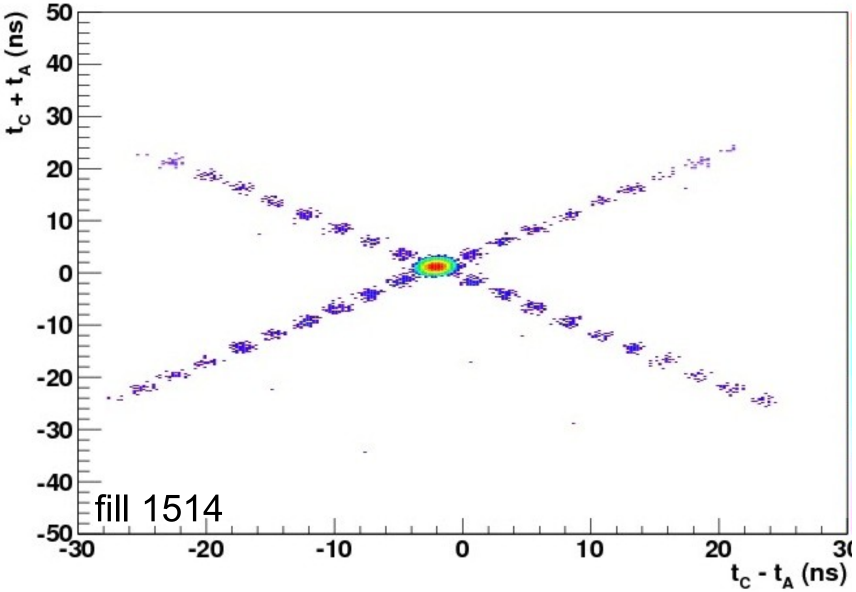
Split in two at flat top energy



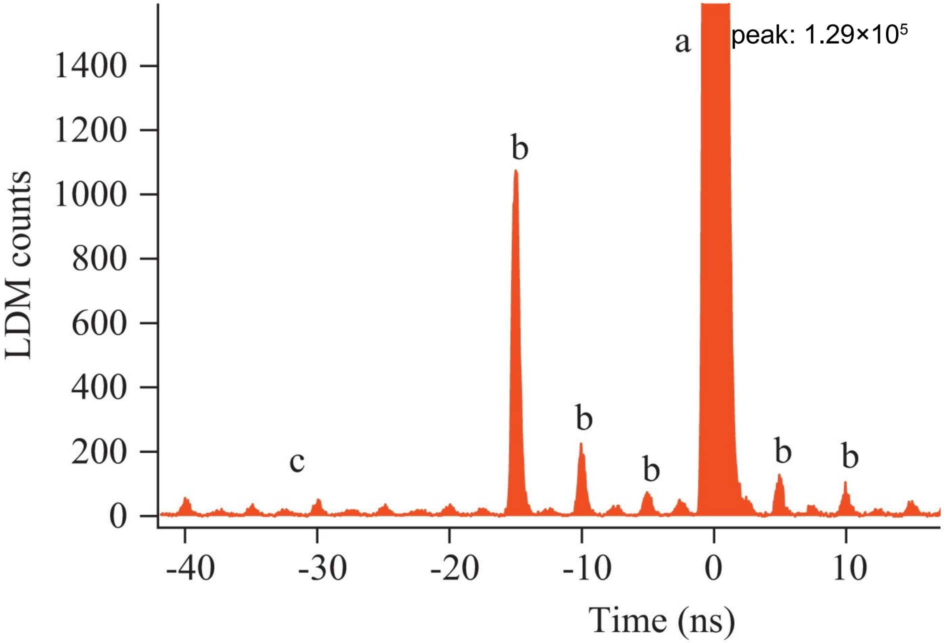
Terminology and Impact on LHC Physics

- 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]:



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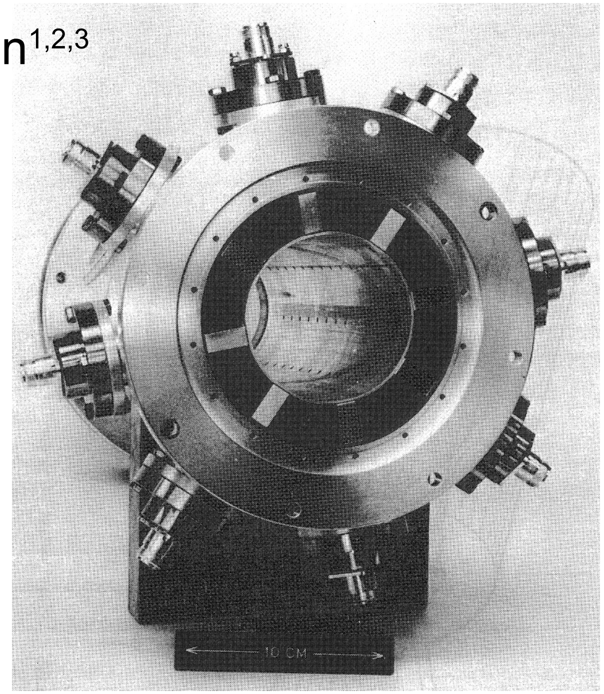
[1] A. Jeff et al., "First results of the LHC longitudinal density monitor", NIMA, Vol. 659, Issue 1, 2011, pp. 549–556

Outline

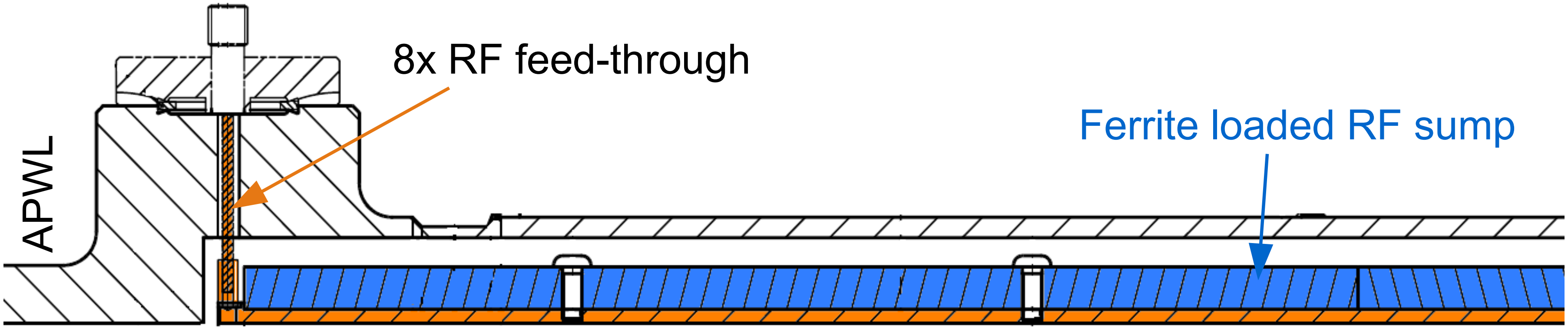
- Terminology: Ghosts and Satellites
- Wall-Current Monitor Infrastructure
  - Pick-up response, cabling, star-combiner & limitations
- Intensity Measurement Resolution and Acquisition Mode
- Post-processing
  - Calibration based signal compensation with and without beam
  - Base-line restoration and noise reduction
- Some results and future plans

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



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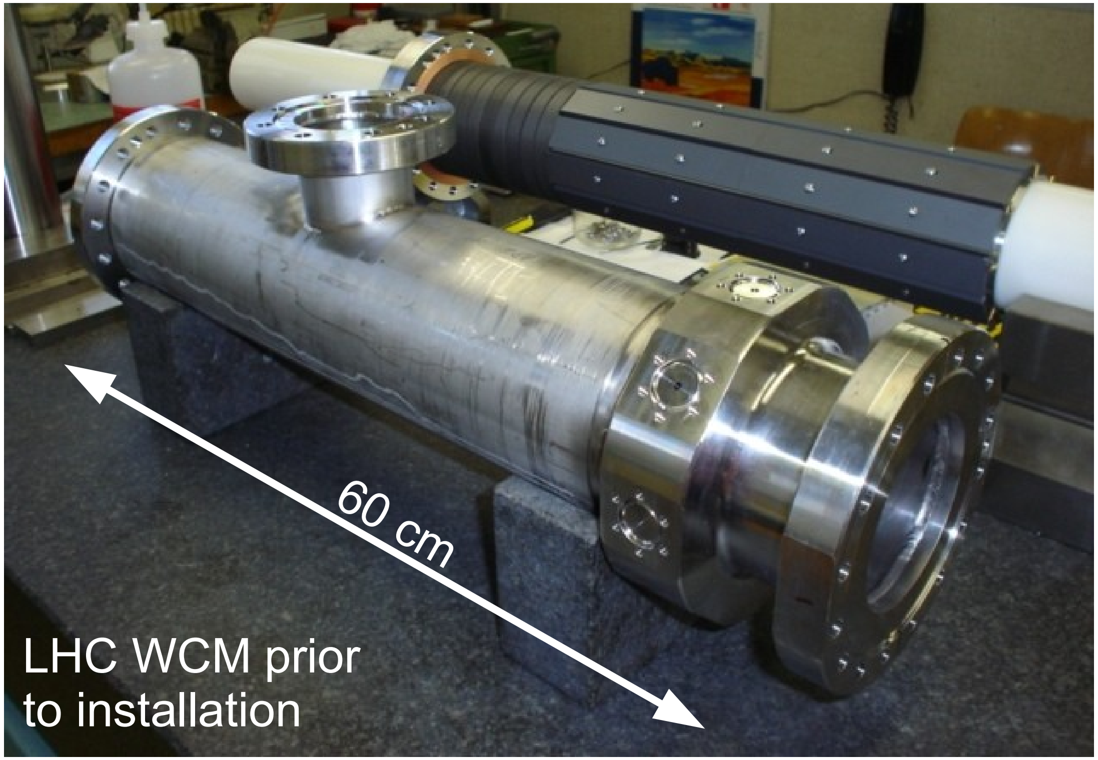
[1] T. Linnecar, “The high frequency longitudinal and transverse pick-ups used in the SPS”, CERN-SPS/ARF/78-17, 1978

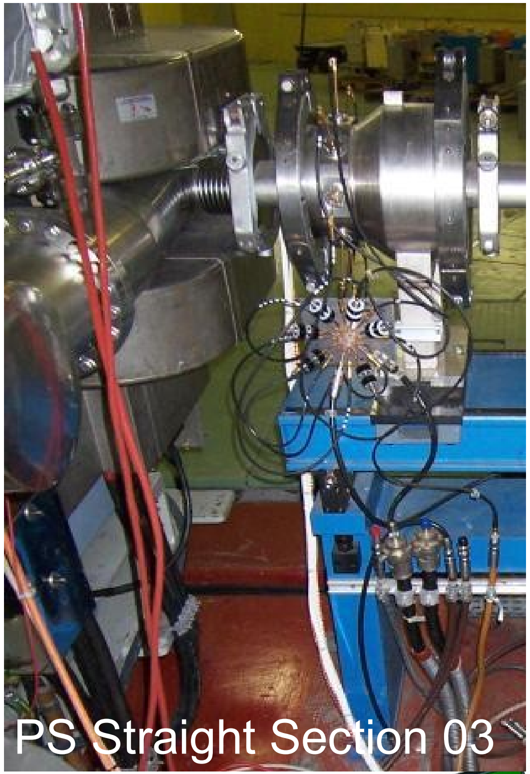
[2] Th. Bohl, “The APWL Wideband Wall Current Monitor”, CERN-BE-2009-006, 2009

[3] R. Cappi et al., “Single-Shot Longitudinal Shape Measurements [..]”, CERN-PS-87-31-PSR, PAC 1987, 1987

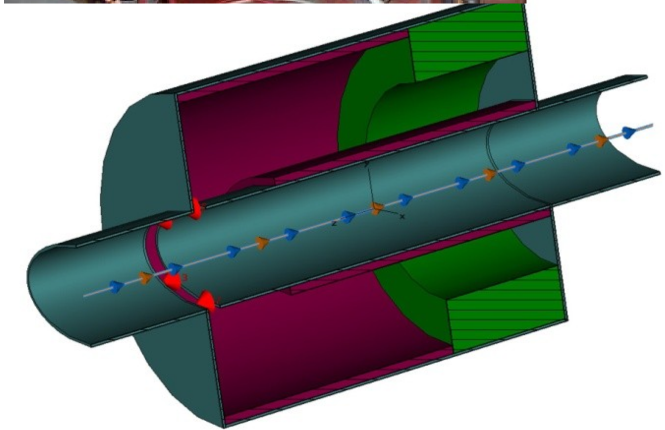
SPS/LHC Wall Current Monitor Design

- Prior to installation



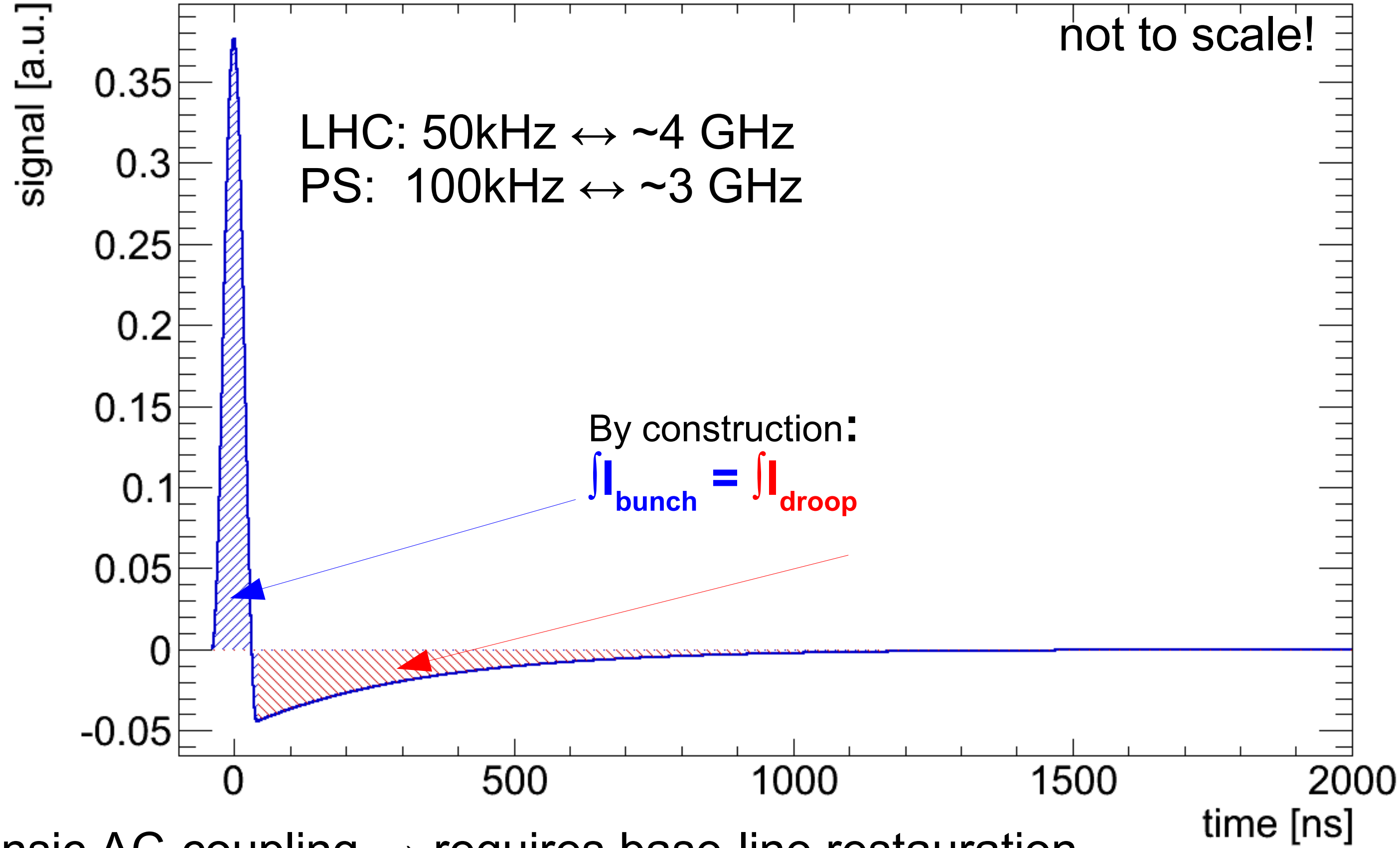


- Combiner: star-topology 8(+8) x 50Ω-matched inputs (outputs)
- Aged/experienced PS-WCM is targeted to be upgraded for reliability and maintainability reasons



Reconstruction Requirements I/II
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:



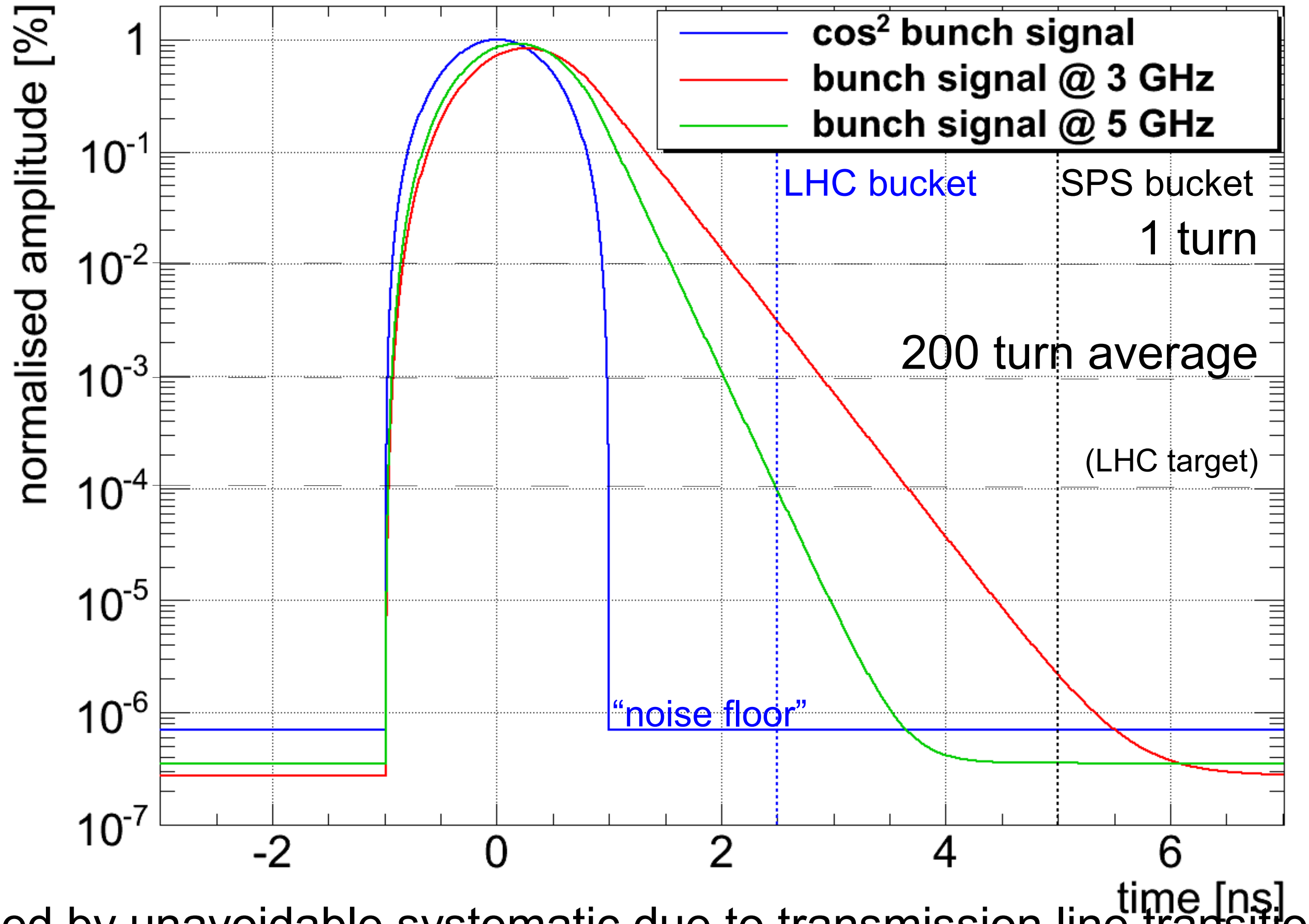
LHC: 50kHz ↔ ~4 GHz
PS: 100kHz ↔ ~3 GHz

By construction: $\int I_{bunch} = \int I_{droop}$

- 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

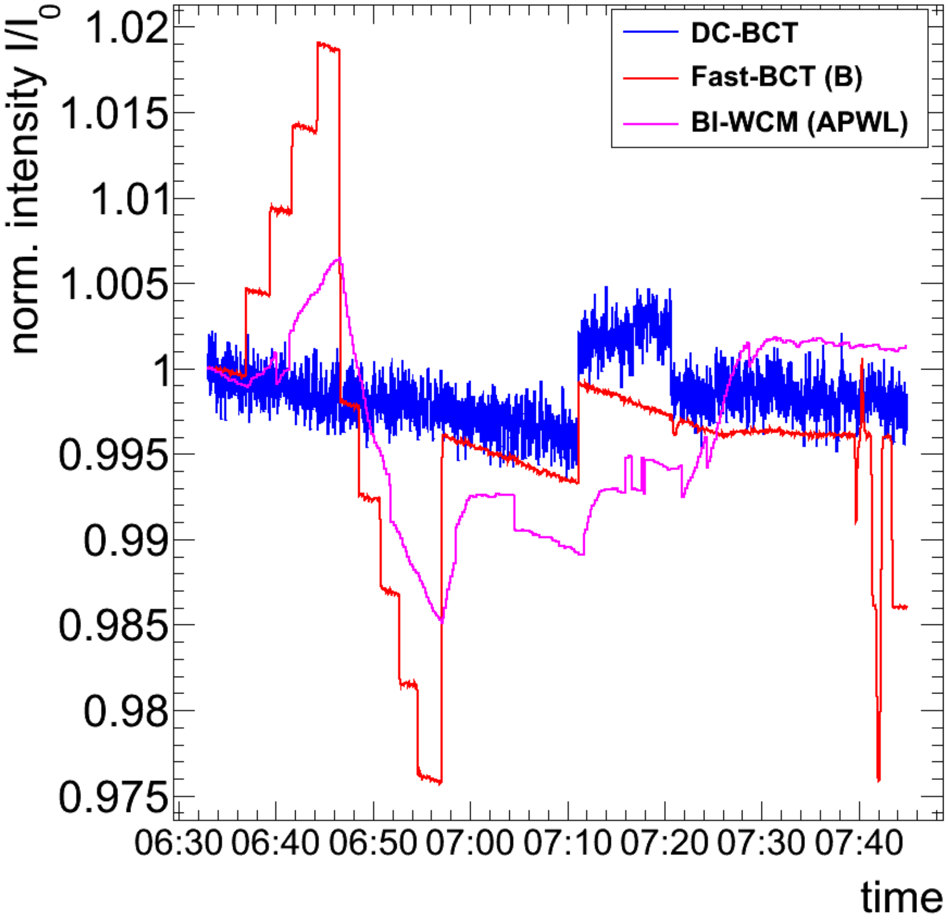
- Need high pick-up and cable bandwidth to distinguish between large bunches and tiny satellites/ghosts in the vicinity:

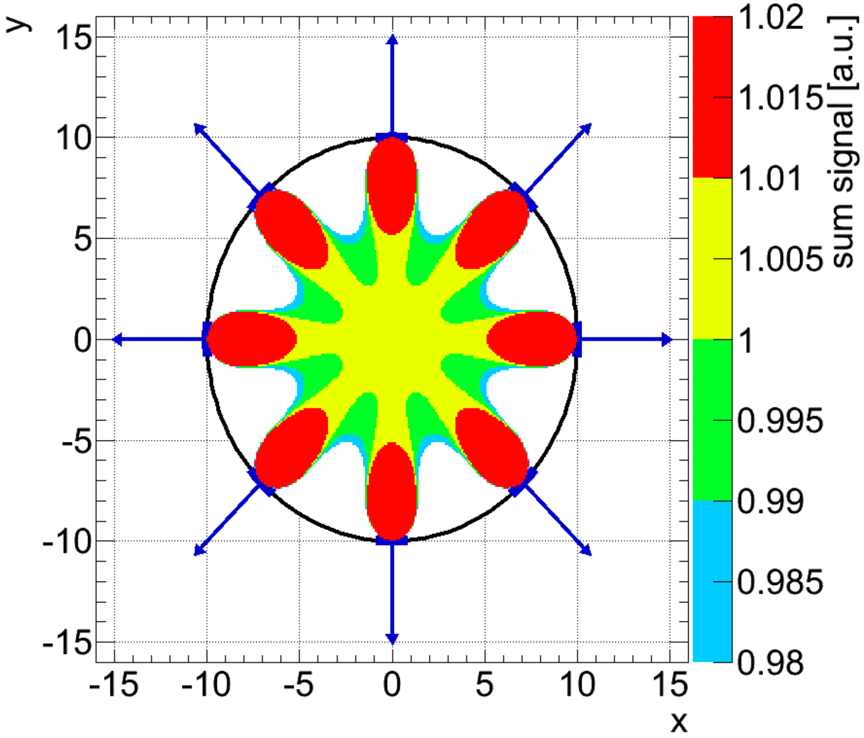


- … limited by unavoidable systematic due to transmission line transitions, reflections, etc. (N.B. difficult to control better than 10^{-3} on > 2 m distances)

Position and Time-of-Flight Dependencies

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

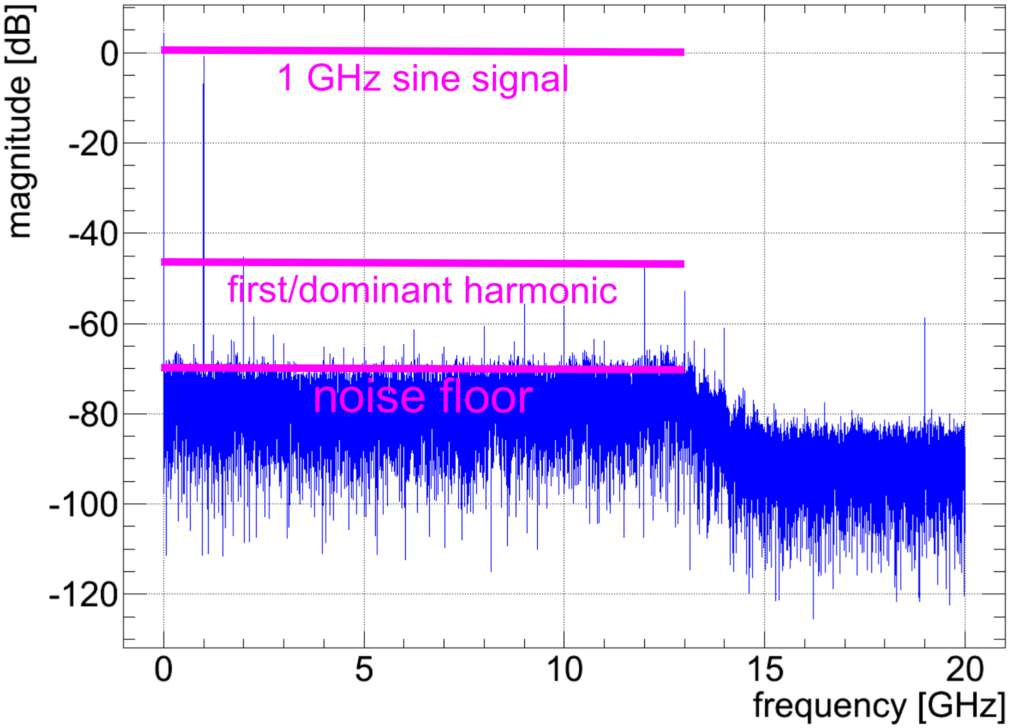


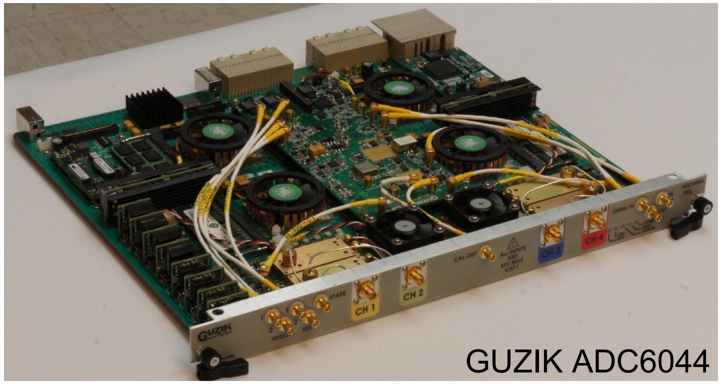


- Usually suppressed by ±200 um orbit stability during regular operation

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

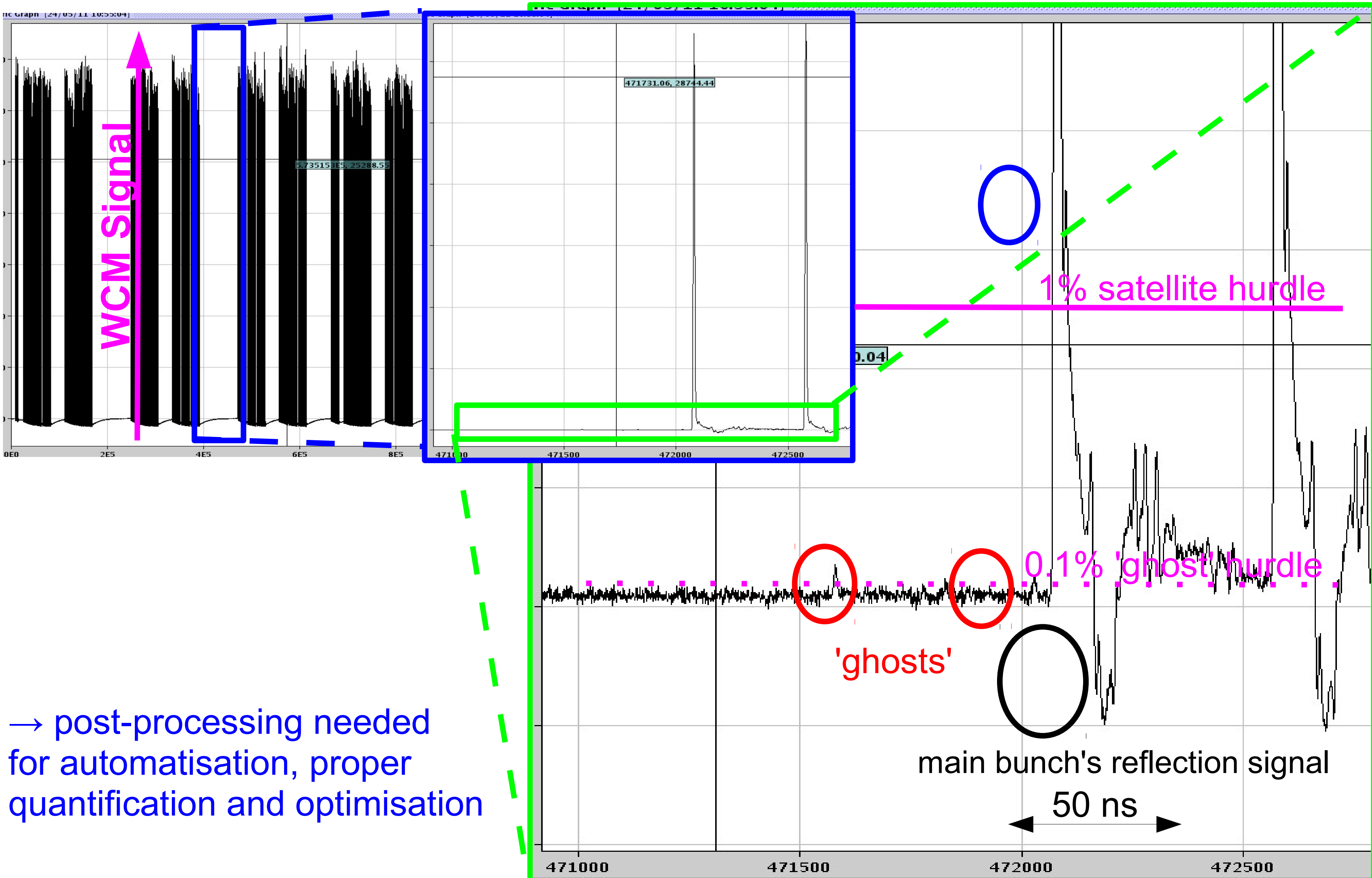
- LHC: <10^{-4} (10^{-6})@0.1Hz & PS: <$2 \cdot 10^{-4}$ ($2 \cdot 10^{-5}$)@0.1Hz achieved (theo.)
- n_{turn} essentially only limited by
  - required measurement bandwidth/time-scale the parameter changes
  - acquisition HW limitations, e.g. LHC: tested oscilloscopes average in SW: 0.1 Hz bandwidth ↔ 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

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:
  1. Sub-percent level compensation of the pick-up response
     - Classical Fourier-/Wiener-filter based Deconvolution
  2. High-frequency Noise Rejection
     - Savitzky-Golay χ^2-fitting[1]
  3. Base-line restoration
     - SNIP background estimate[2,3]

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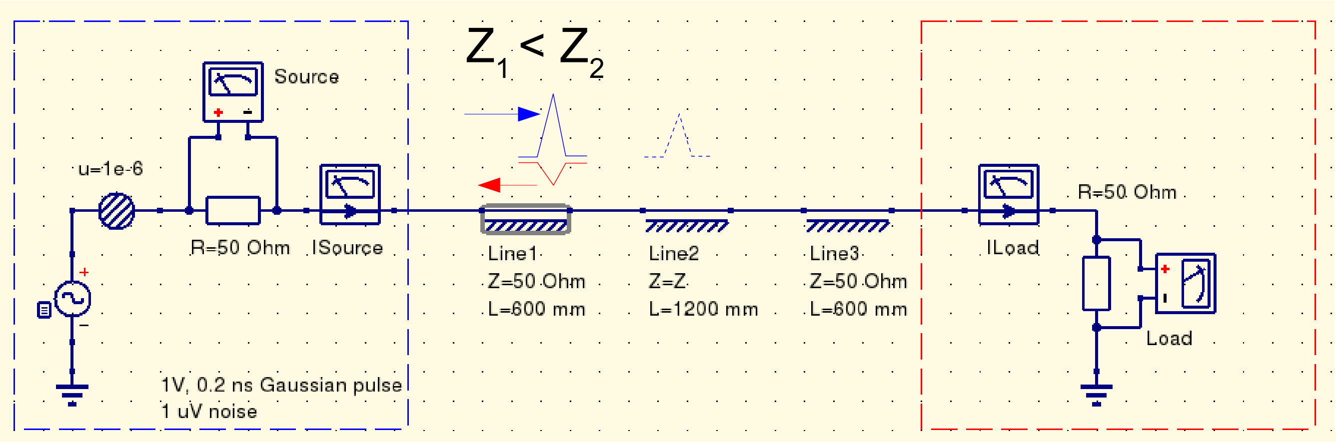
[1] A. Savitzky and M. Golay, "Smoothing and Differentiation of Data by Simplified Least Squeares Procedures", Analytical Chemistry, Vol. 36, No. 8, July 1964, pp. 1627–1639

[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.

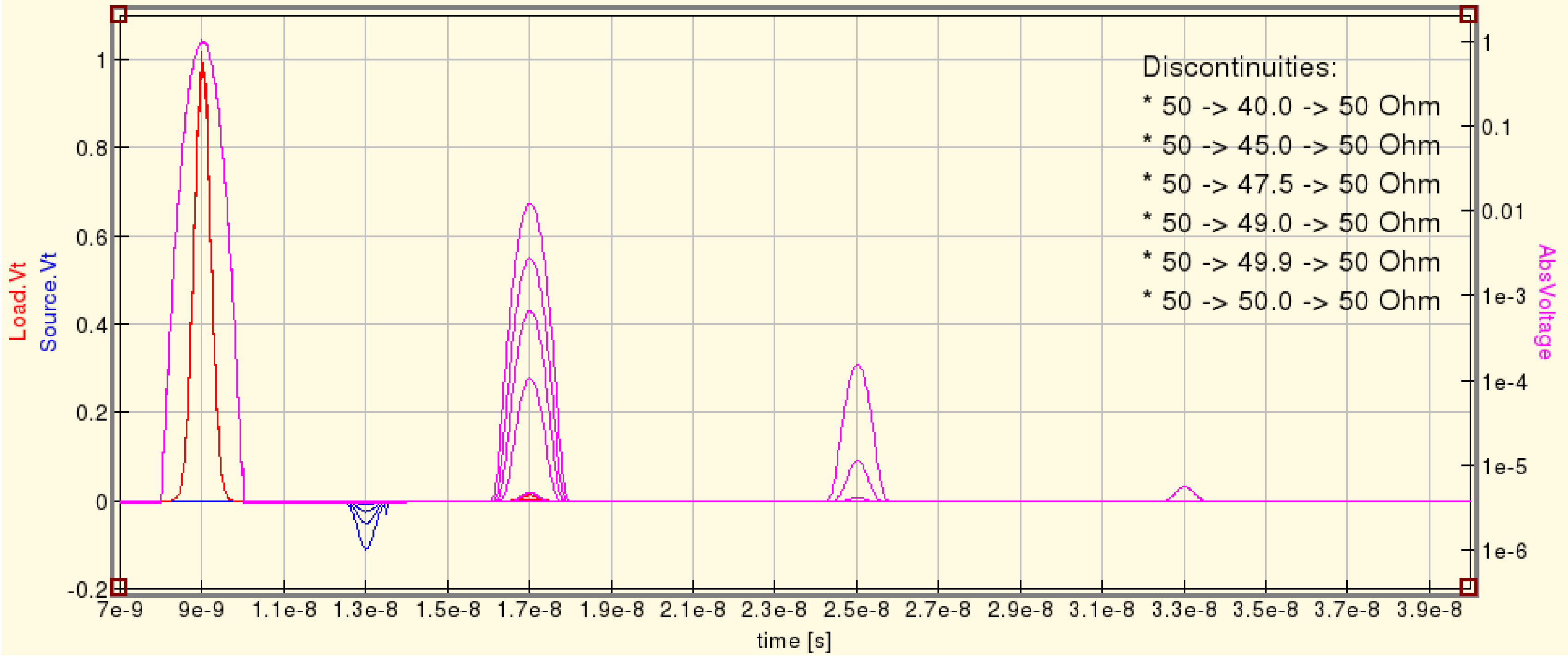
RF Reflections – Definitions

- ...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]

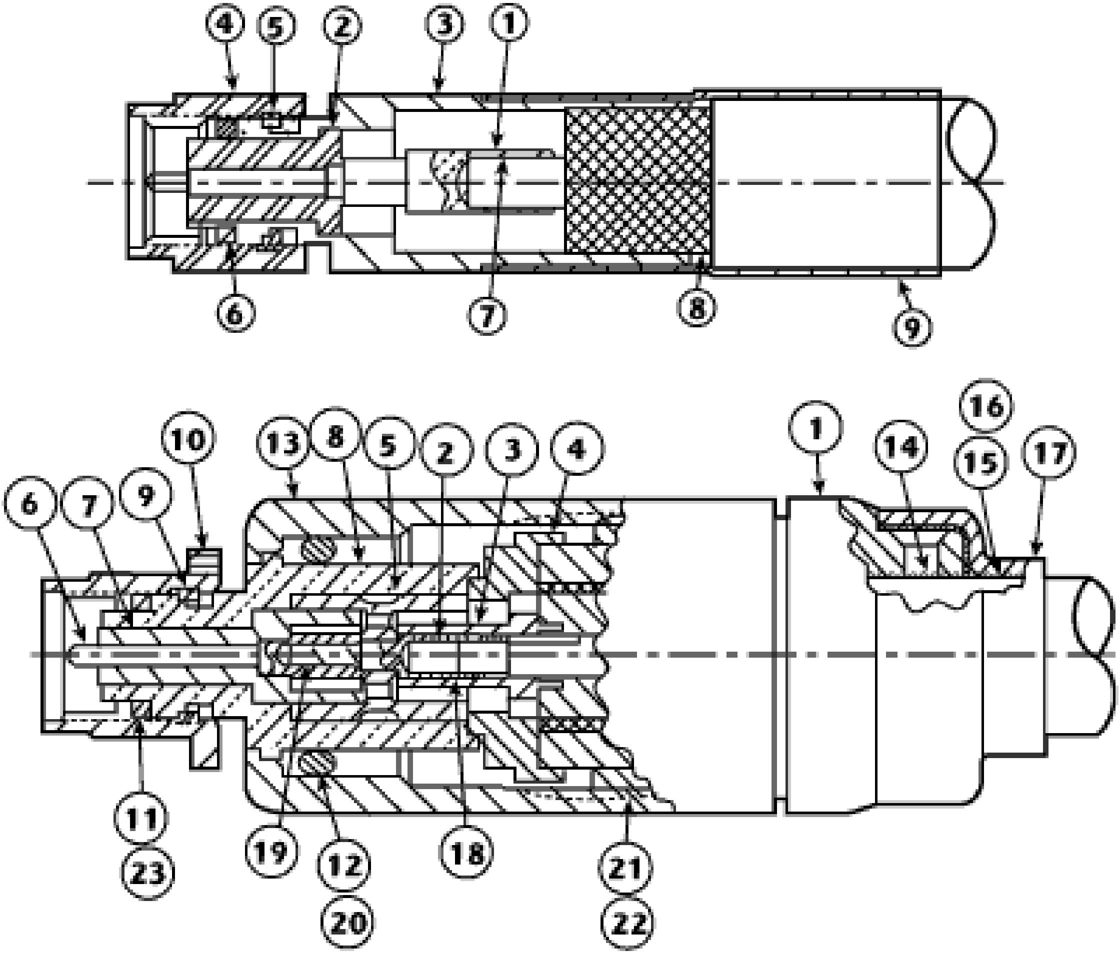
VSWR ≤ 1.06 + ~0.01·f [GHz]

VSWR ≤ 1.02 + 0.03·f [GHz]

≤ 1.05 @ 6GHz

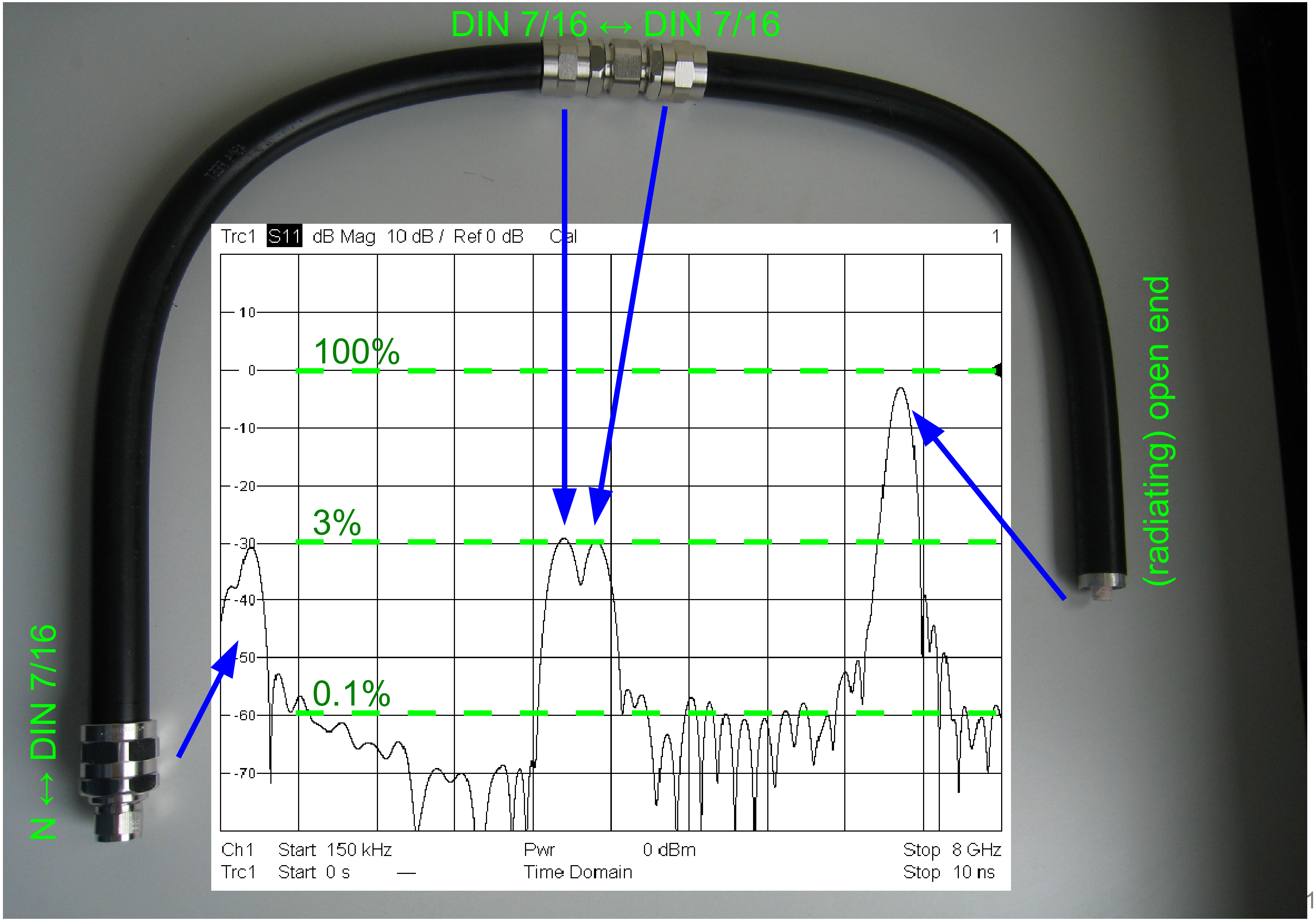
Reflections: RF Connector and Cable Geometry II/II

- 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



Trc1 S11 dB Mag 10 dB / Ref 0 dB Cal 1

Ch1 Start 150 kHz Pwr 0 dBm Stop 8 GHz

Trc1 Start 0 s — Time Domain Stop 10 ns

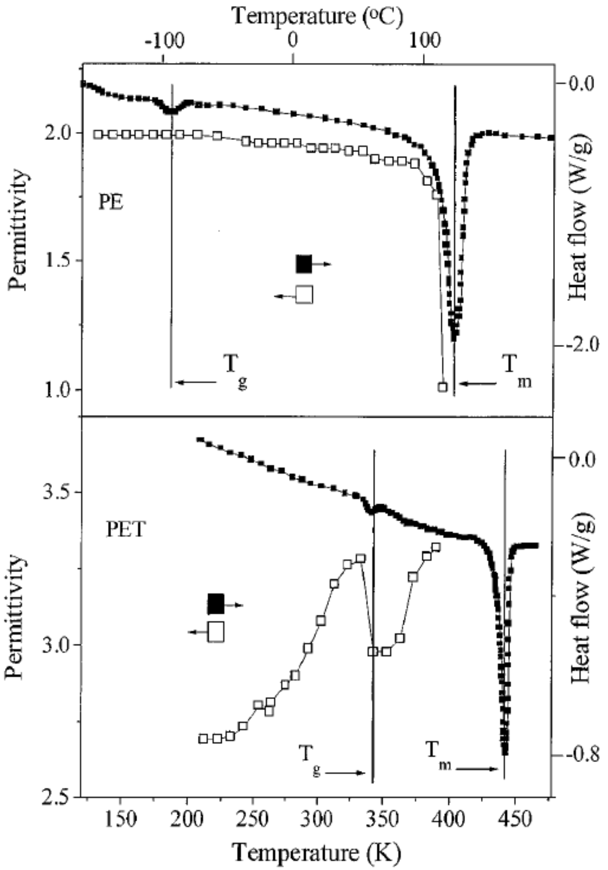
Permittivity and Dependence on Temperature

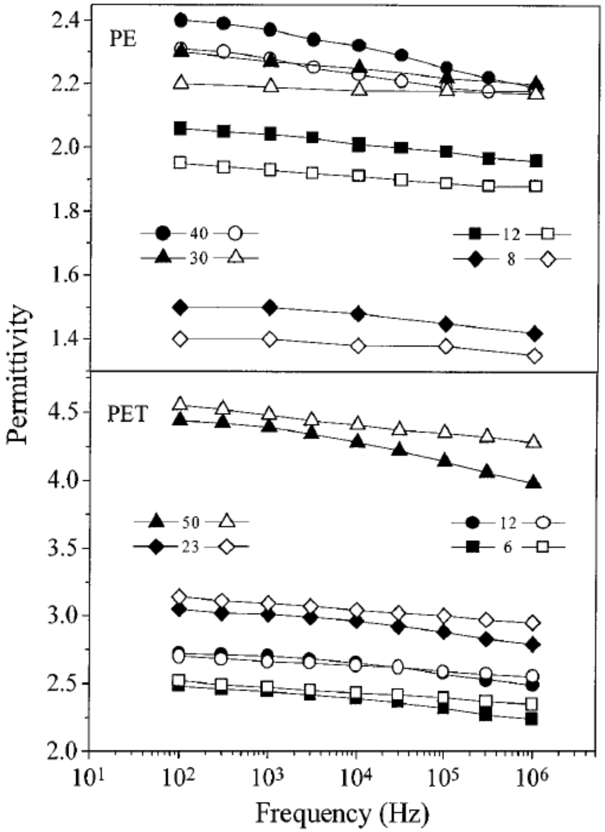
- Permittivity depends on frequency and temperature

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

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

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

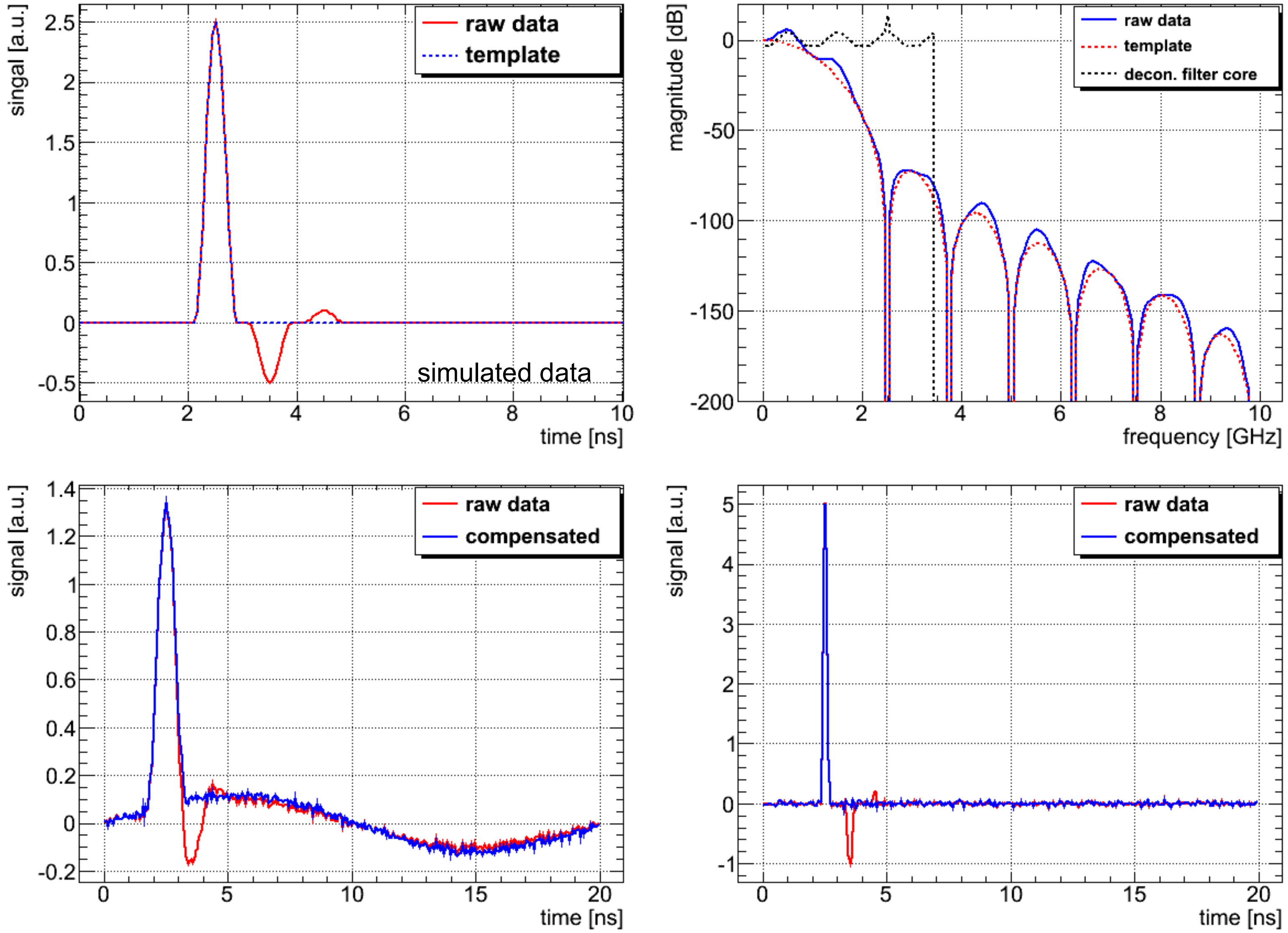




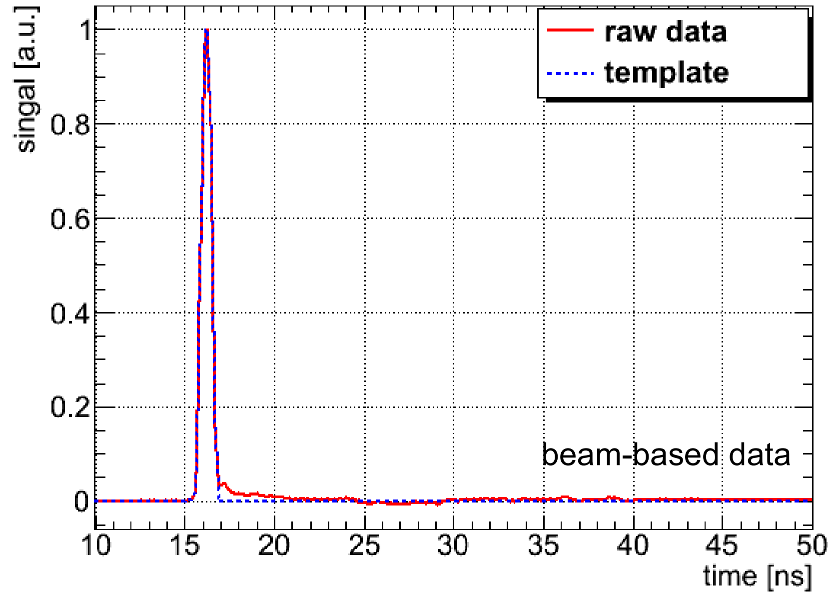
- Highly non-trivial and active research topic
- N.B. PE melts at a very low temperature around 100 °C ↔ ~20 W/m power loss in cables (thanks to S. Smith for pointing this out!)

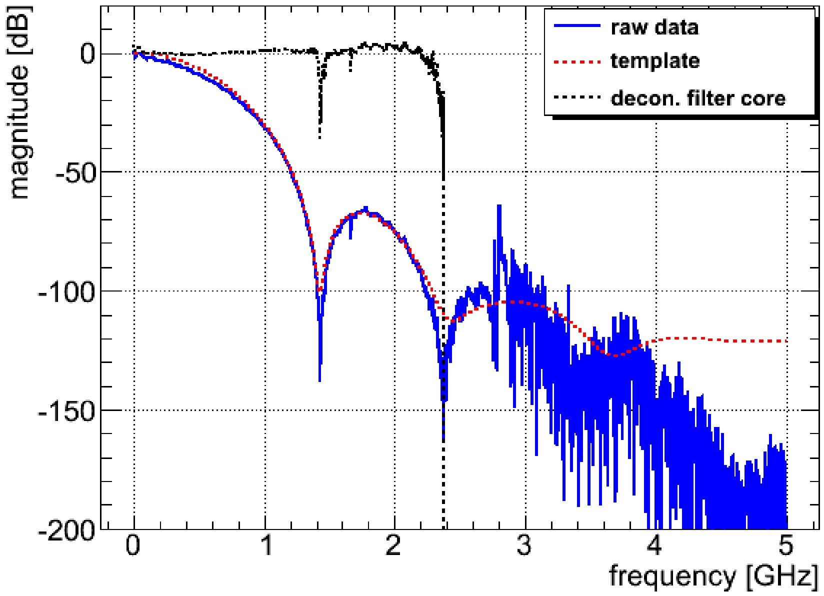
I. Linear Response Compensation I/II

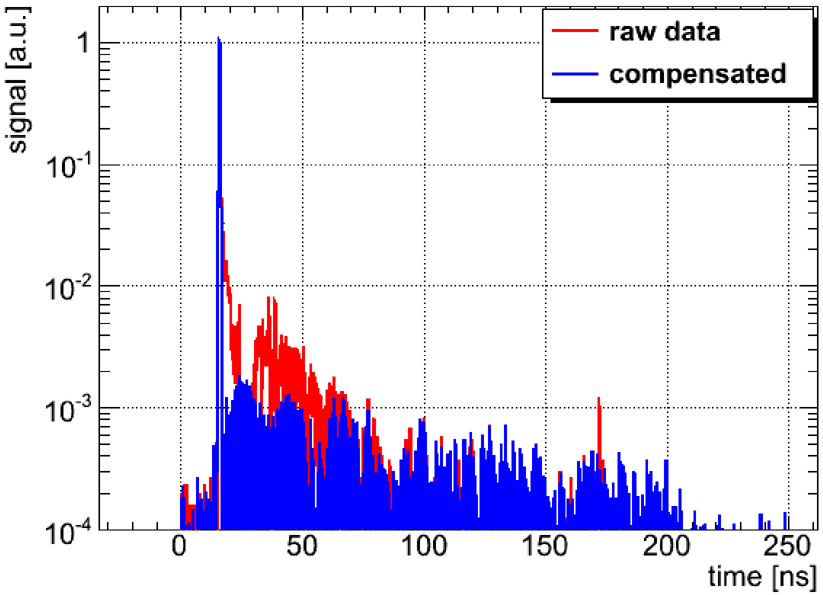
- Real-life installation will deviate from what has been measured in the lab before installation → requires re-calibration with beam, principle:

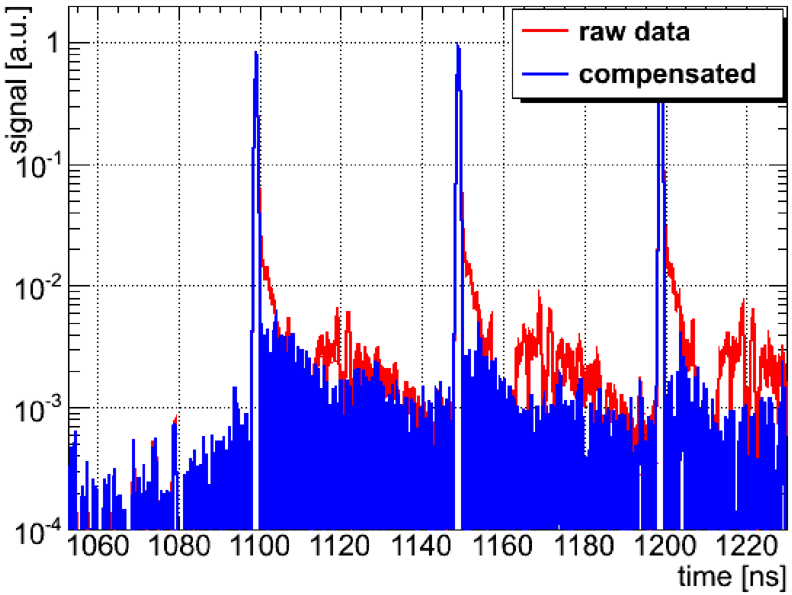


I. Linear Response Compensation II/II – Life-Beam Data



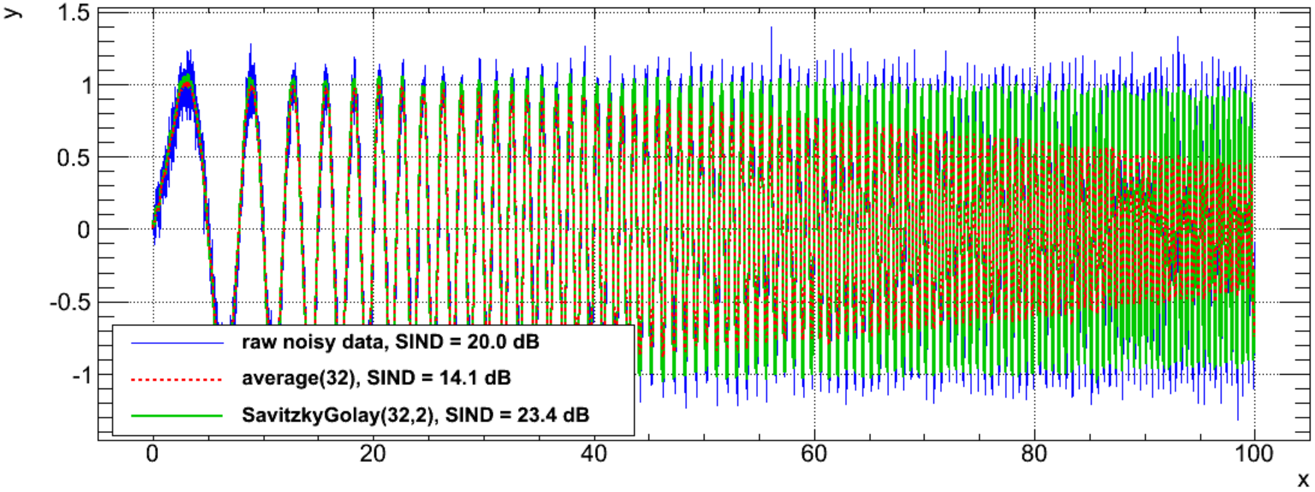


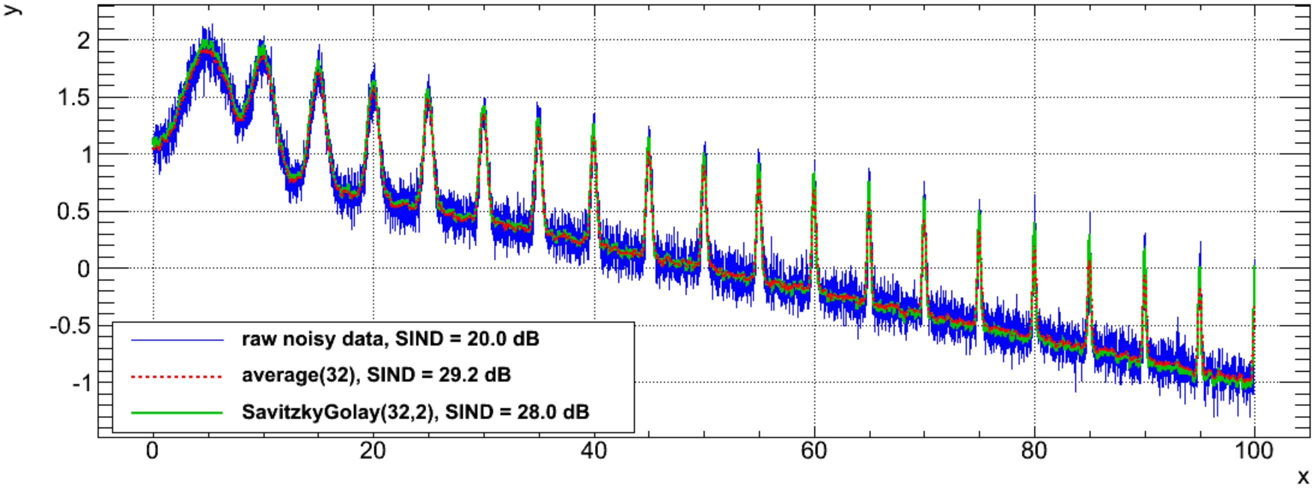




II. High-Frequency Noise Rejection
– Average vs. X²-Fit based Method (Simulation)

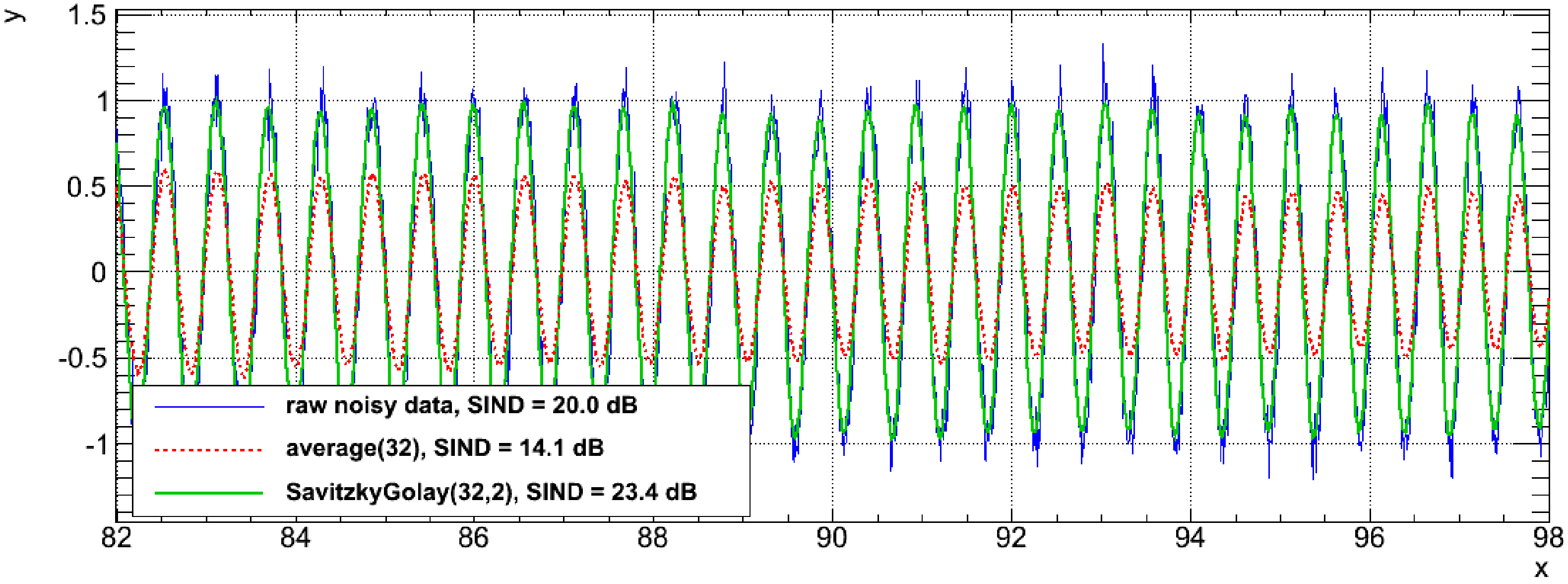
- Sliding-Average or low-pass filter may distort signal amplitude and shape

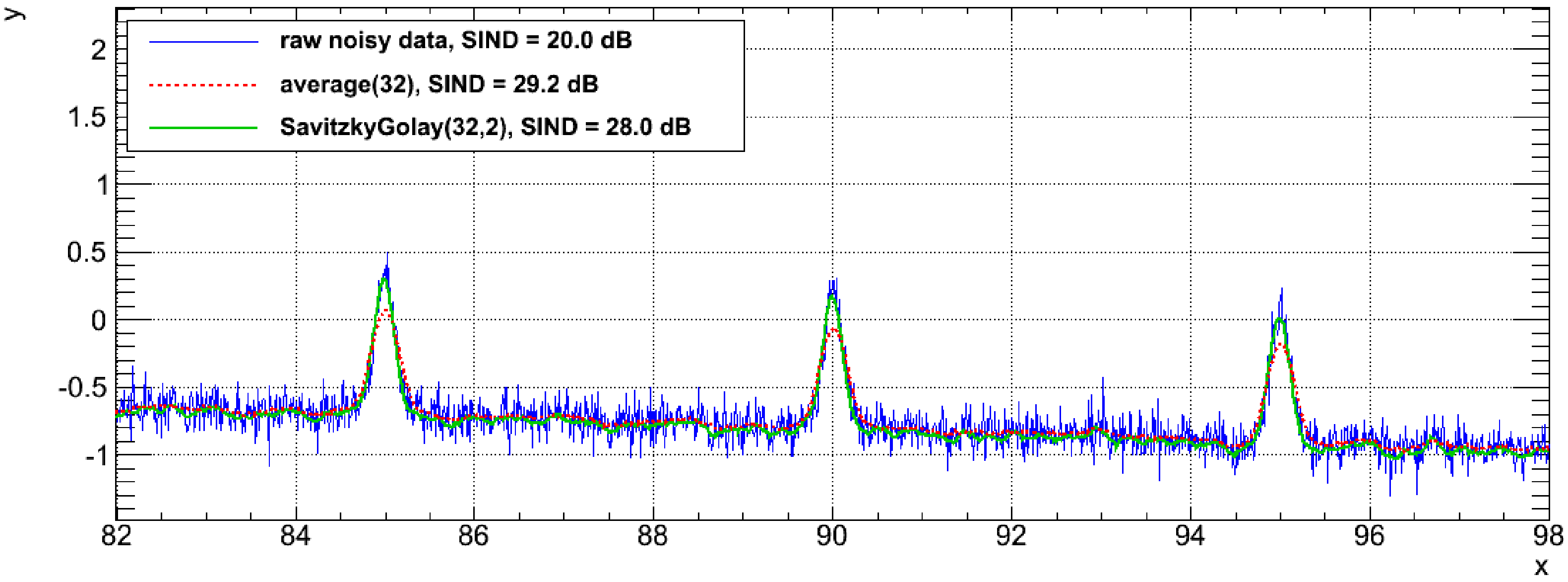




- Depending on bunch-shape/width, x^2 based-method has ~20dB higher SIND

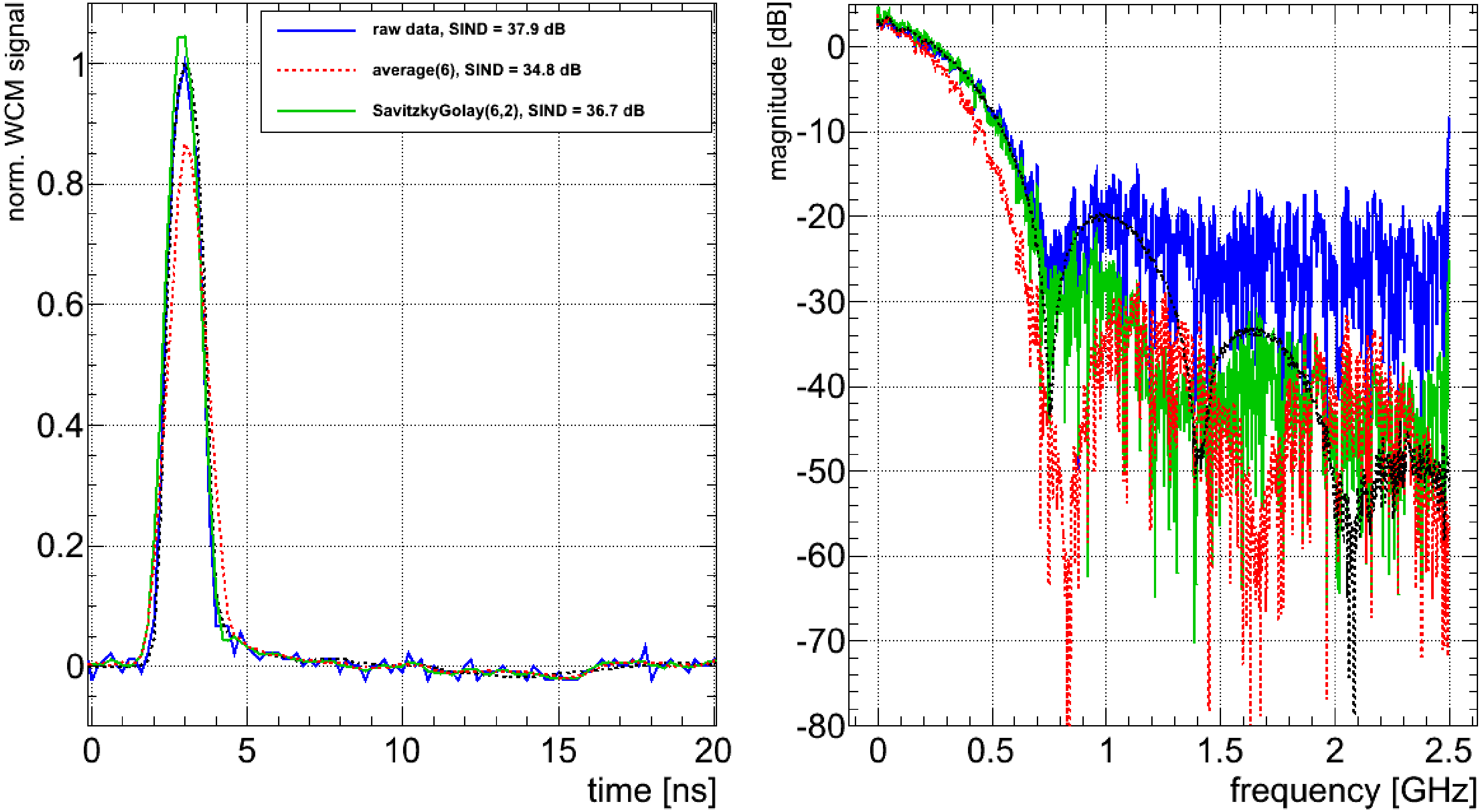
II. High-Frequency Noise Rejection – Average vs. X²-Fit based Method (Simulation, Zoom)





II. High-Frequency Noise Rejection – Example SPS

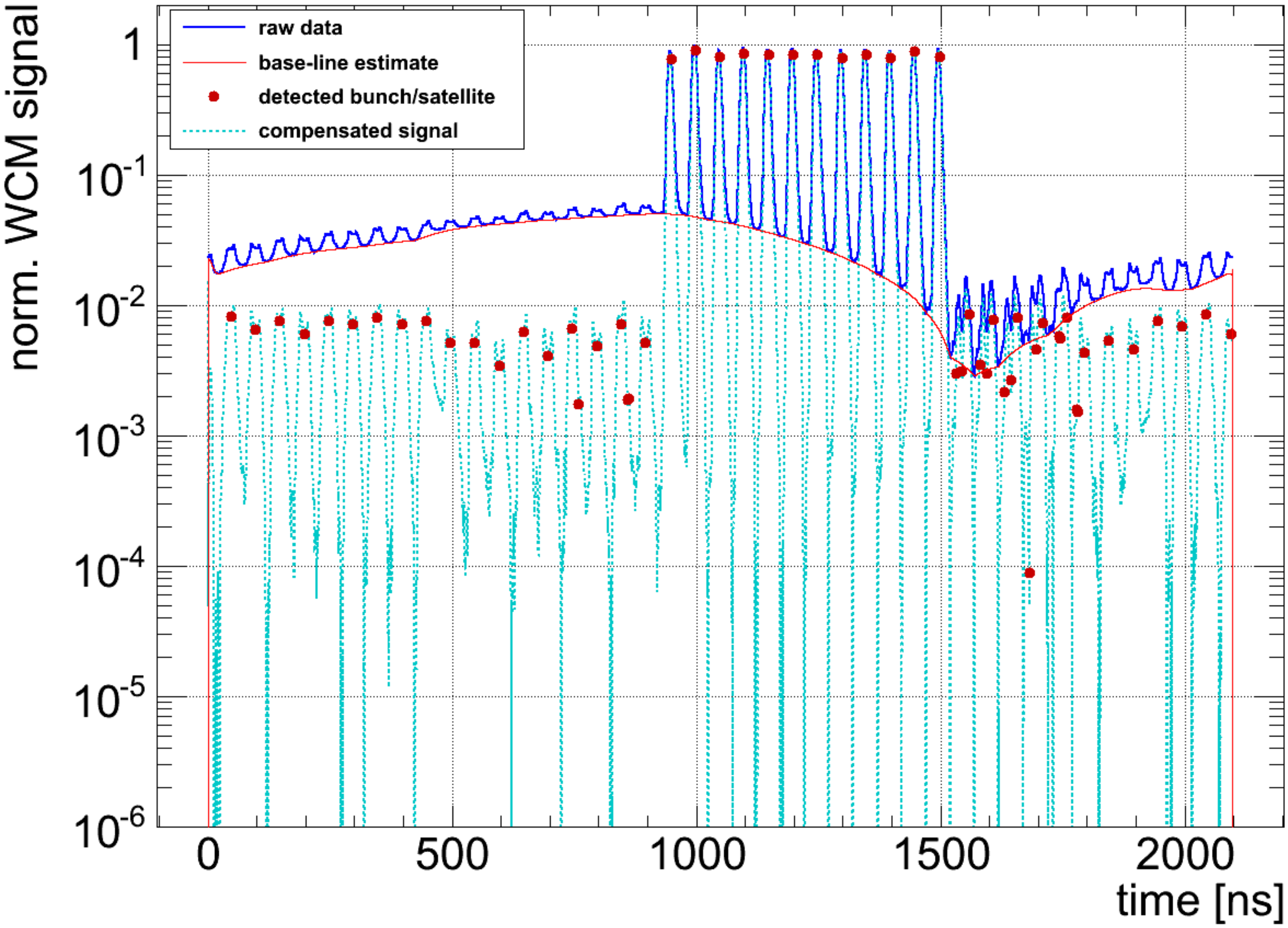
- Example: single bunch in the SPS at flat-top before extraction (black trace: reference based on 100 turn average)



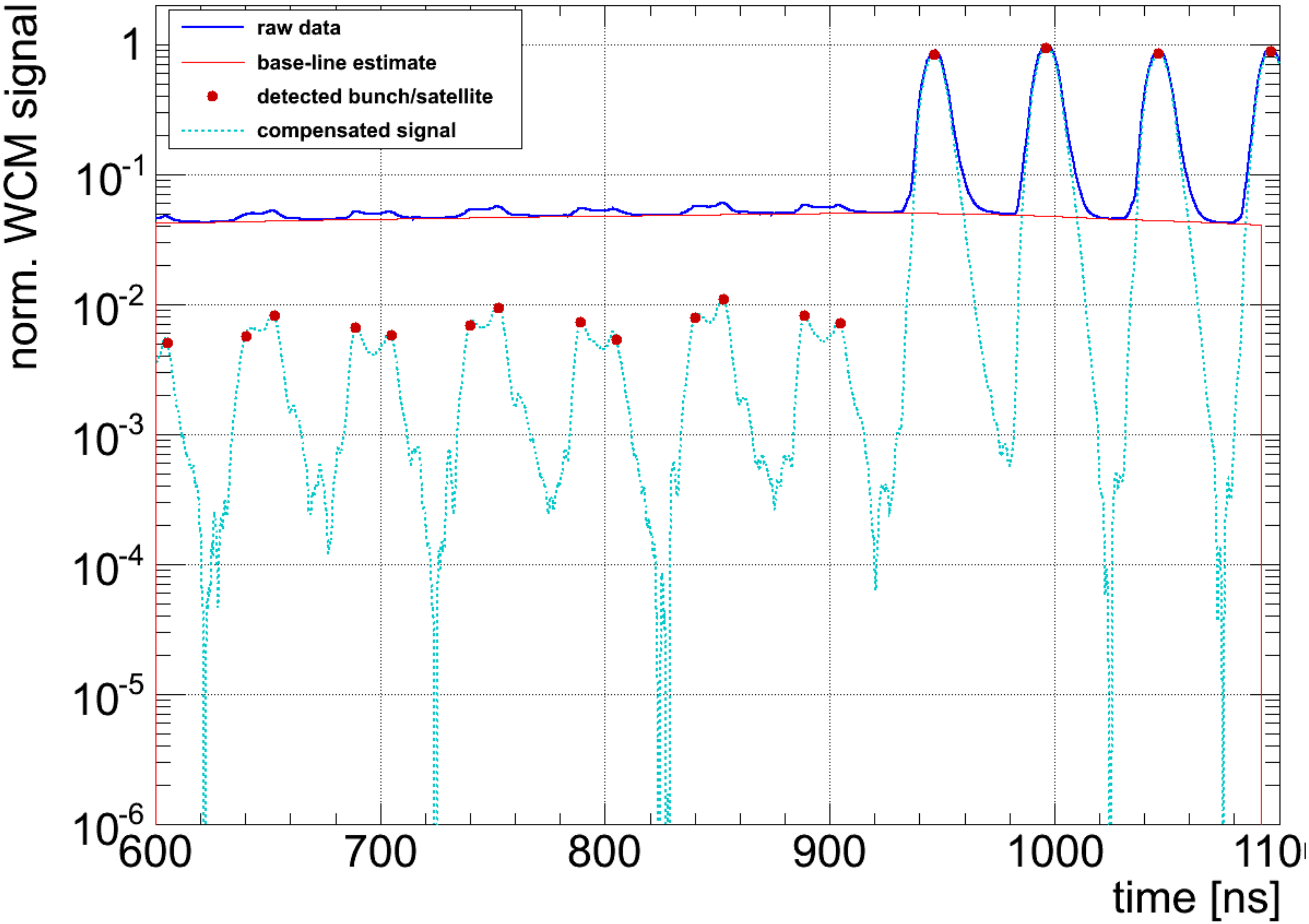
- Savitsky-Golay algorithm is de-facto a dynamic low-pass filter (within limits)

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

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



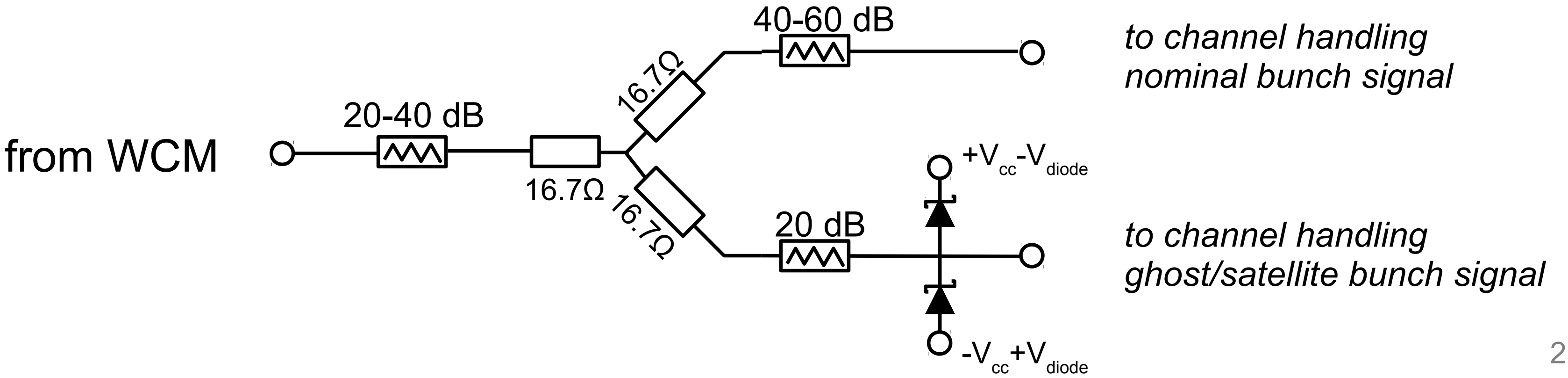
III. Base-Line Restoration – SNIP Algorithm
Example PS WCM Signal - ZOOM



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

Dual Range Operation Option

- Idea: split signals and saturate one copy to zoom-in on satellites
  - possible due fast-recovery time of oscilloscope's input pre-amplifier and/or dedicated diode clamping cirucit
  - saturated channel can be normalised w.r.t. full range copy
  - limit: droop that has to be accomodated by the ADC range
  - advantage: get reasonable results sub-% estimates within few turns!!
  - Some caveats/design constraints:
    - Some digitizers inputs are not protected → ded. clamping circuit is mandatory!
    - Clamping creates reflection that may return to the WCM/other channel
    - Matching at high frequencies (C parallel to scope input)
    - Schottky diodes need to handle the clamped power (<5 V)
    - Signal path-lengths need to be kept to a minimum

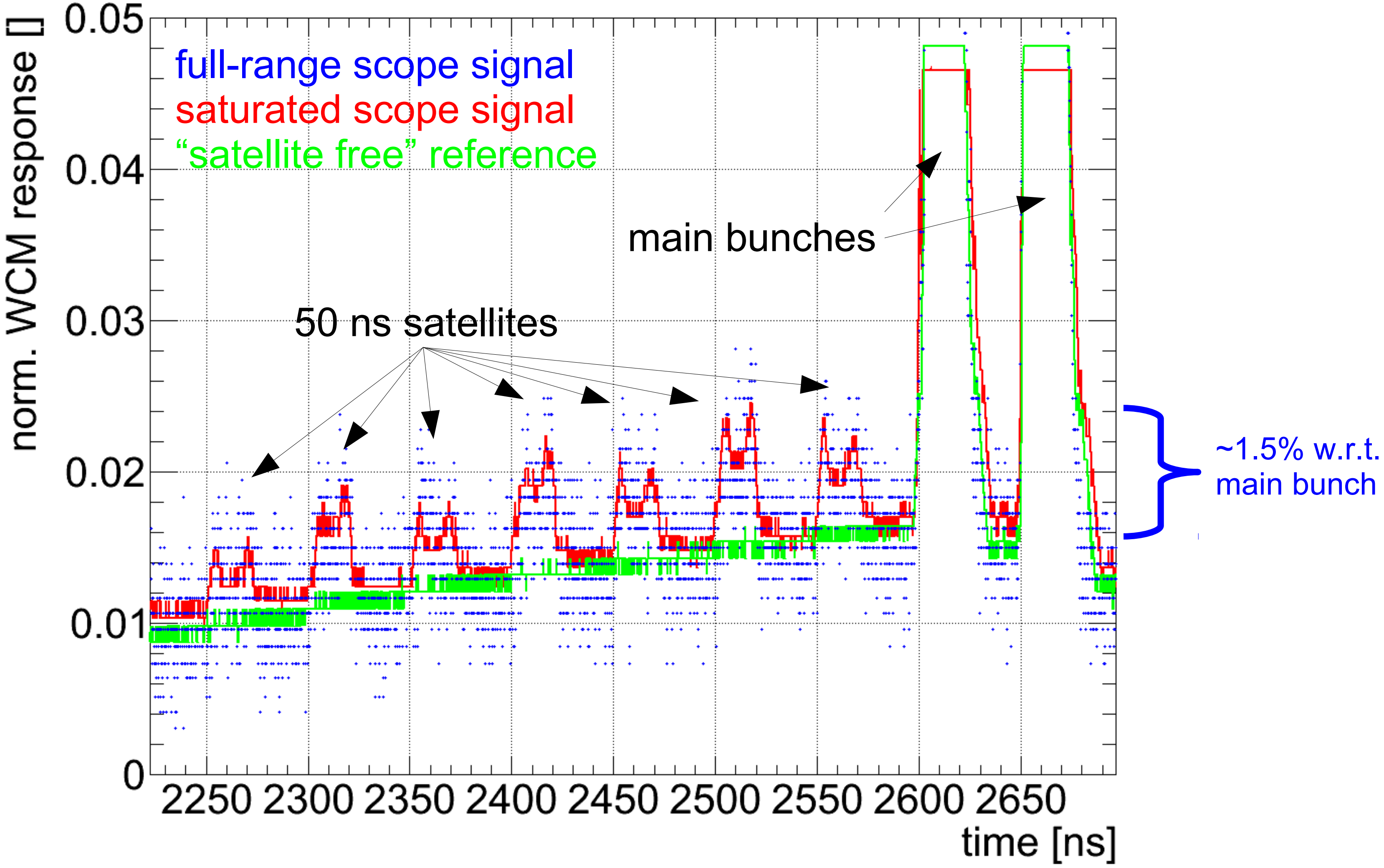


to channel handling nominal bunch signal

to channel handling ghost/satellite bunch signal

What could be achieved – PS II/III

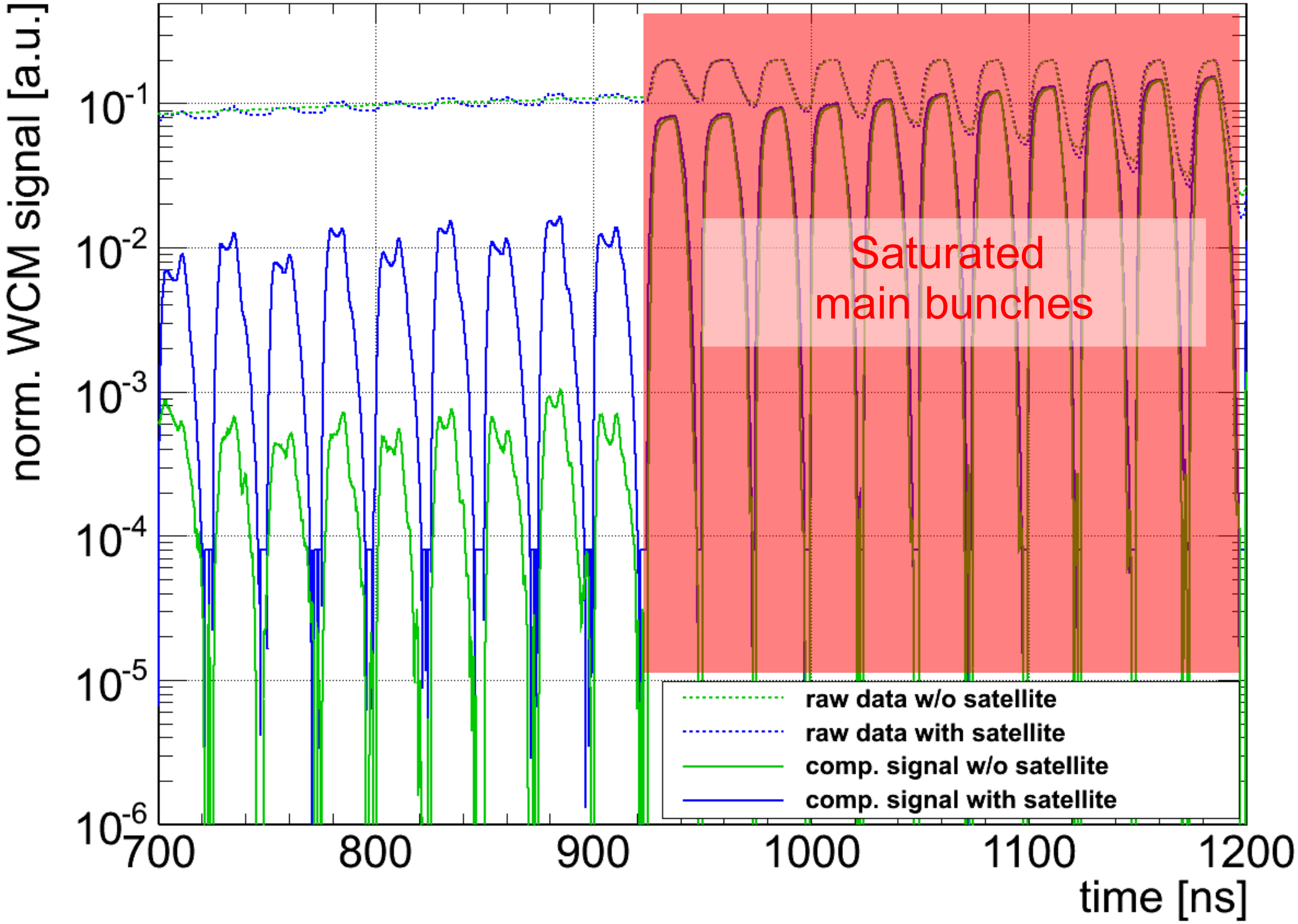
- Forcing satellites and saturating the scope input (fast recovery time)



- 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

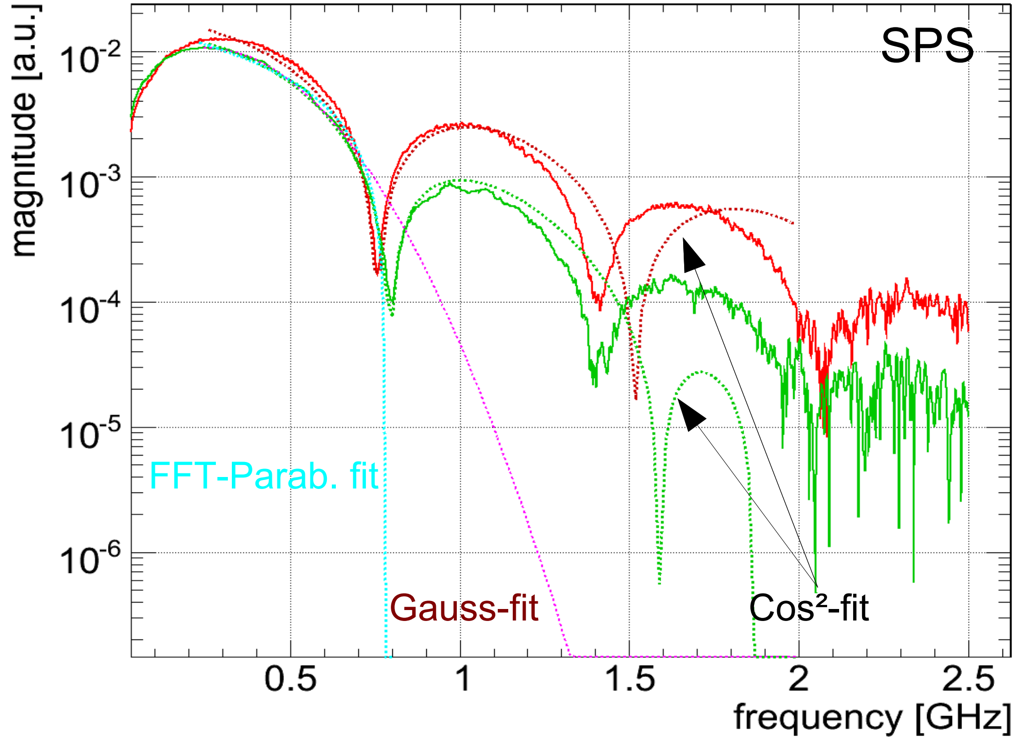
- After full post-processing chain of smoothing and removing background:



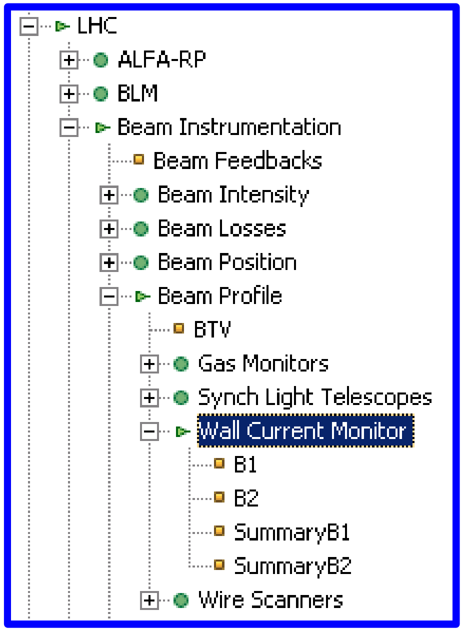
- Satellites visible in “clean” condition, prel. noise-floor estimate ~10^{-5} w.r.t max

Beam-Parameter Measurement and Integration

- Real bunches do not necessarily obey 'Gaussian' shapes

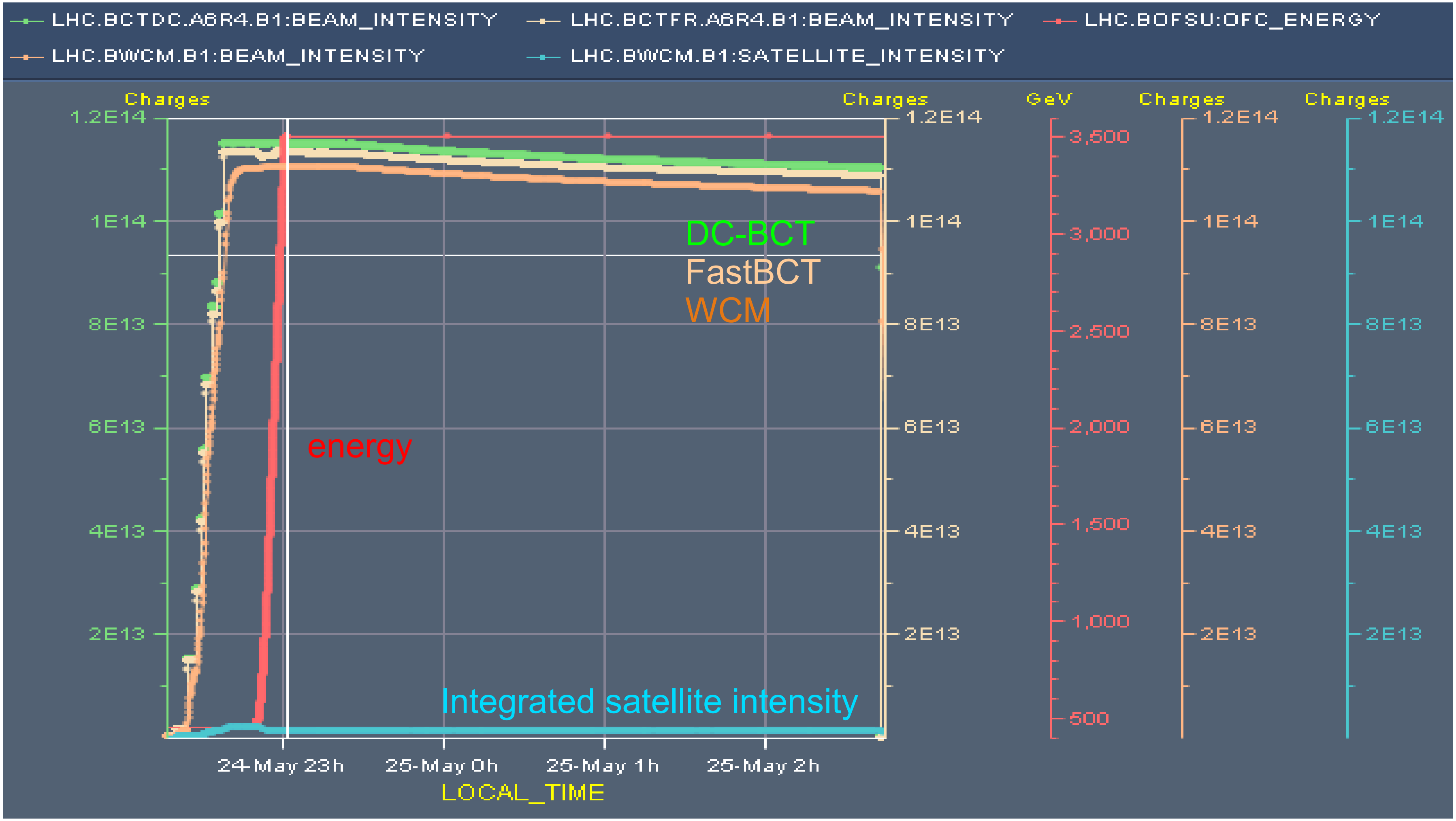


LHC Logging:



- 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 χ²-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)

Comparison of Bunch Intensity Estimates



- WCM cross-calibrated to DC-BCT using a single nominal bunch (satellite free)
  - Typically percent-level beam outside nominal bucket

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?”

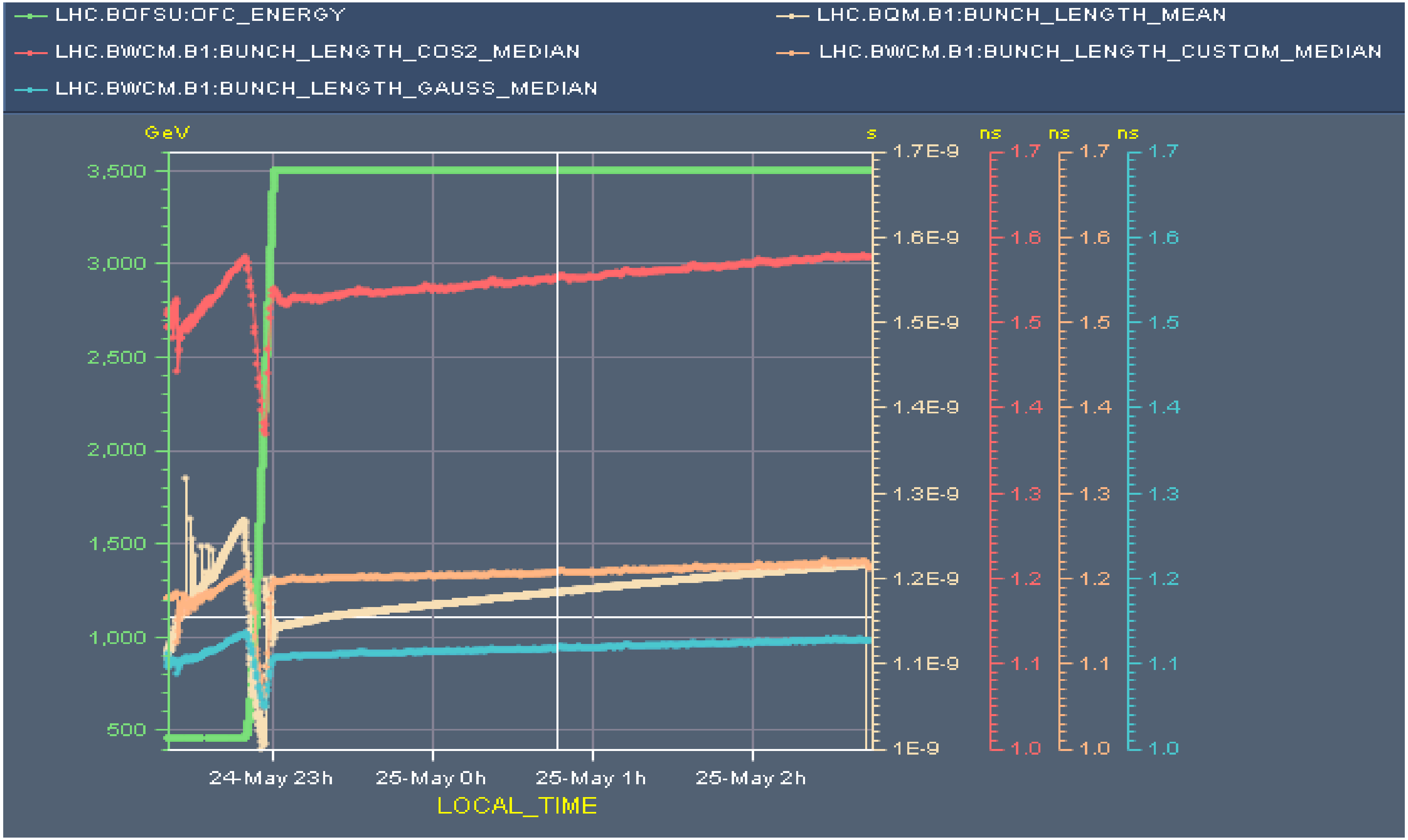
- Test confirmed that the existing system...
  - can achieve 10^{-5} resolutions @3 GHz over a few turns or single-shot via:
    a) turn-by-turn averaging over a couple of hundred turns
    b) splitting signal and saturating its copy to specifically detect satellites
  - Requires beam-based baseline compensation since the system drifts on the up to 10^{-3}-level due to temperature, saturation and other effects

- Acquisition HW upgrade being in progress:
  - Improve to 100% duty cycle for the averaging
  - compensation algorithm and parameter done being done in FPGA

Thank you for your Attention!

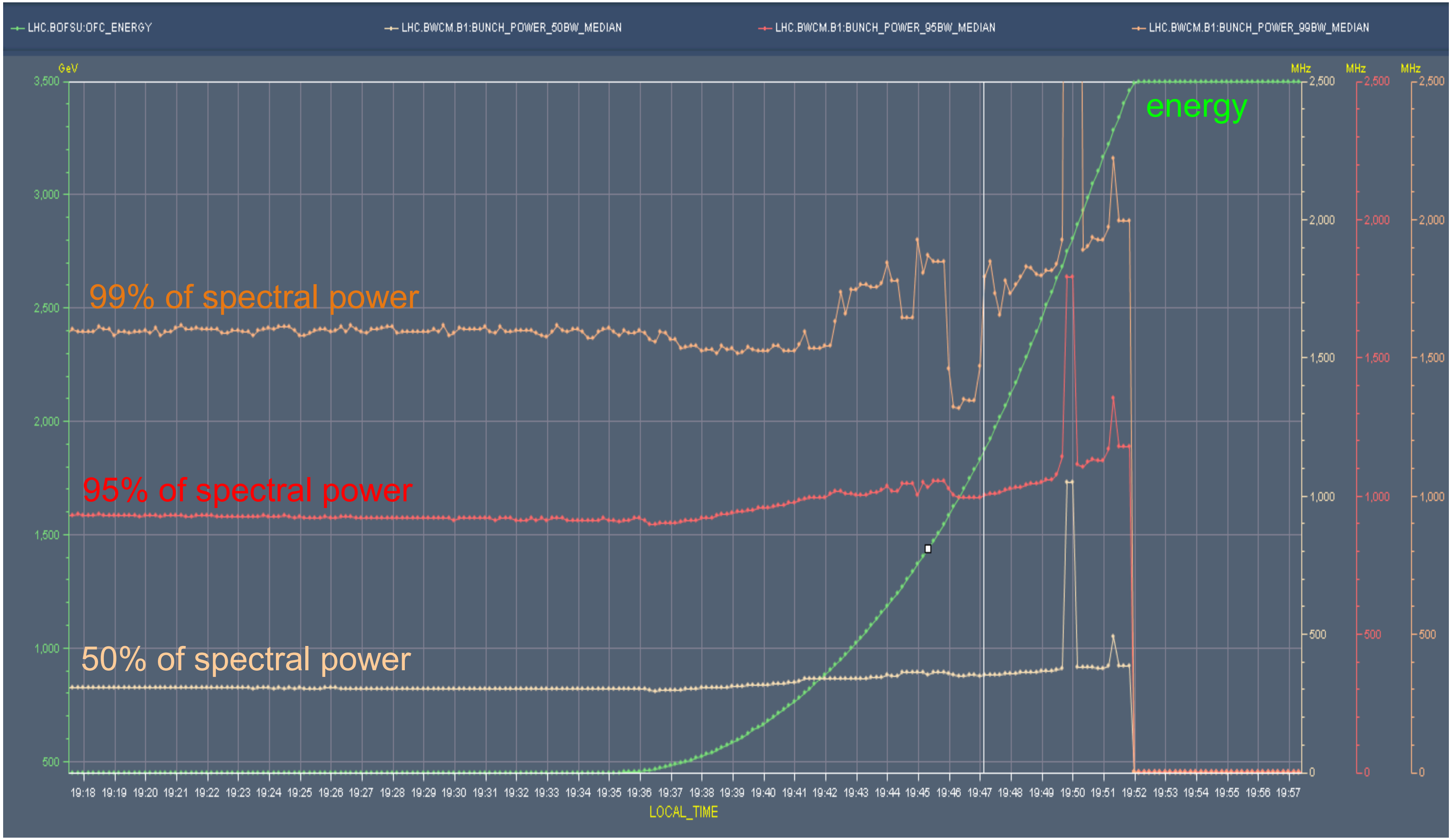
Supporting Slides

Comparison of Bunch Length Estimates



- … there is no obvious bunch length → shape changes are important
  - difference between FWHM (BQM) and x^2-fit Gaussian length estimate

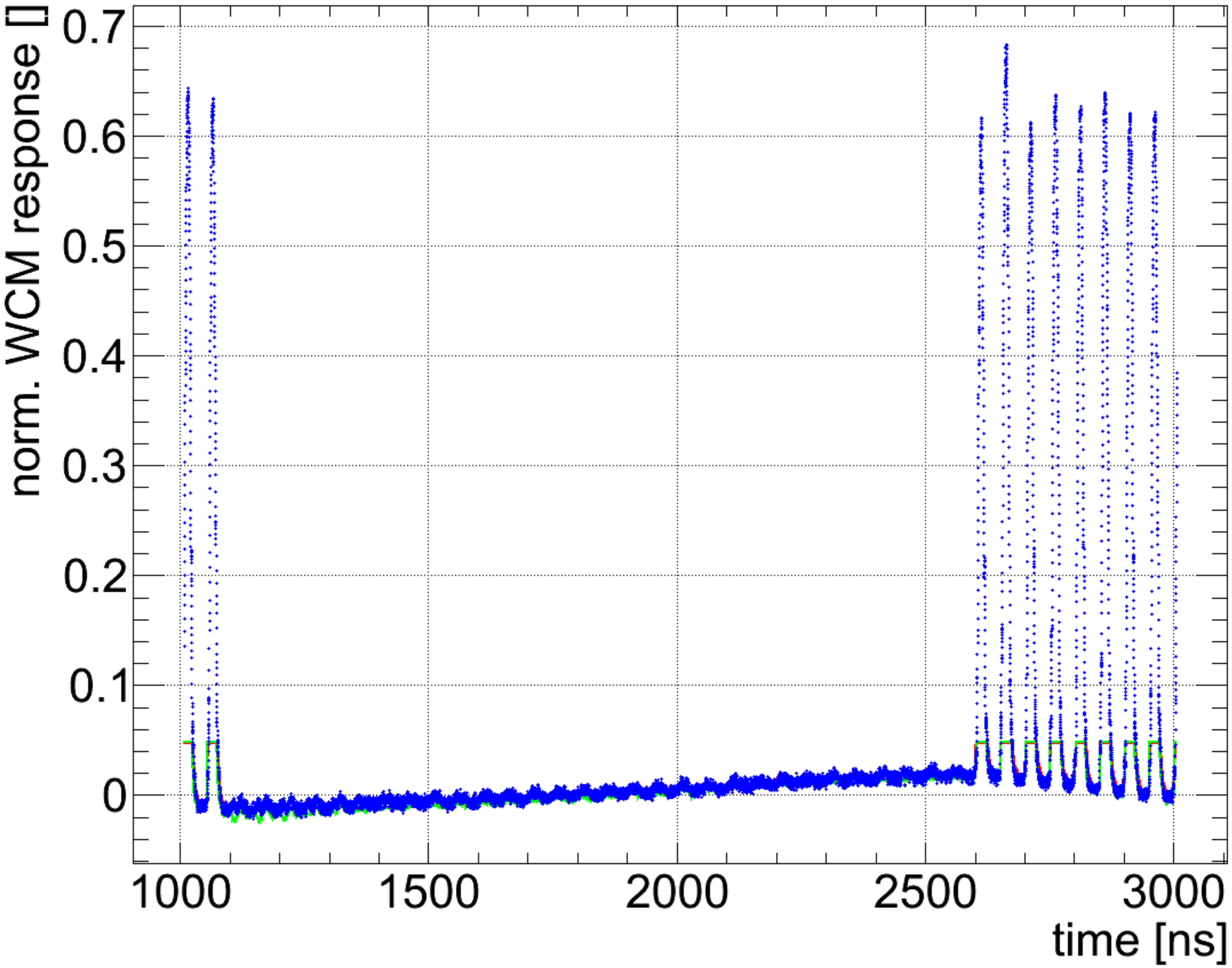
Comparison of Bunch Power Estimates



- Estimates give an indication of shape and required device bandwidths

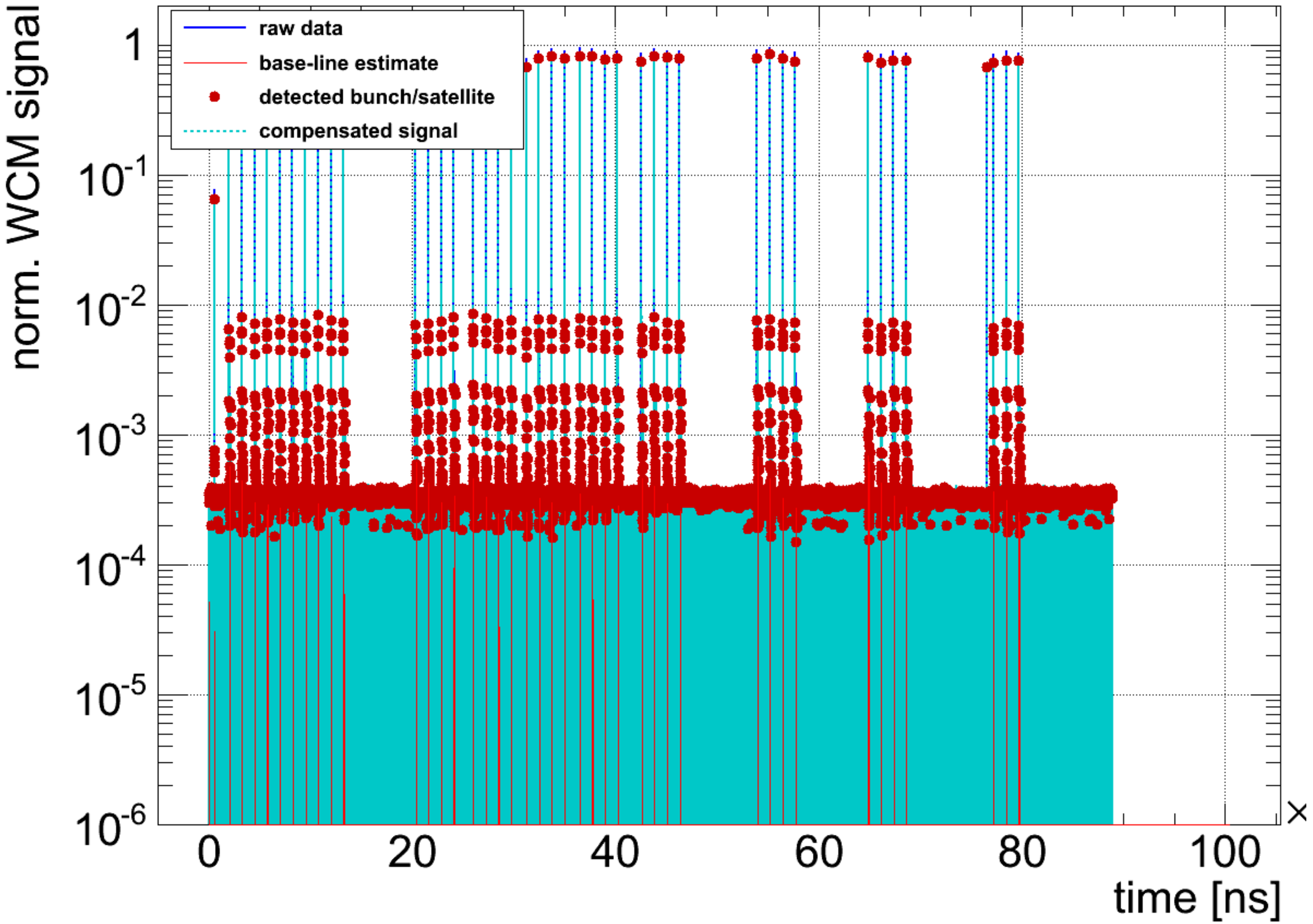
What could be achieved – PS I/III

- Initial test comparing single turn acquisition

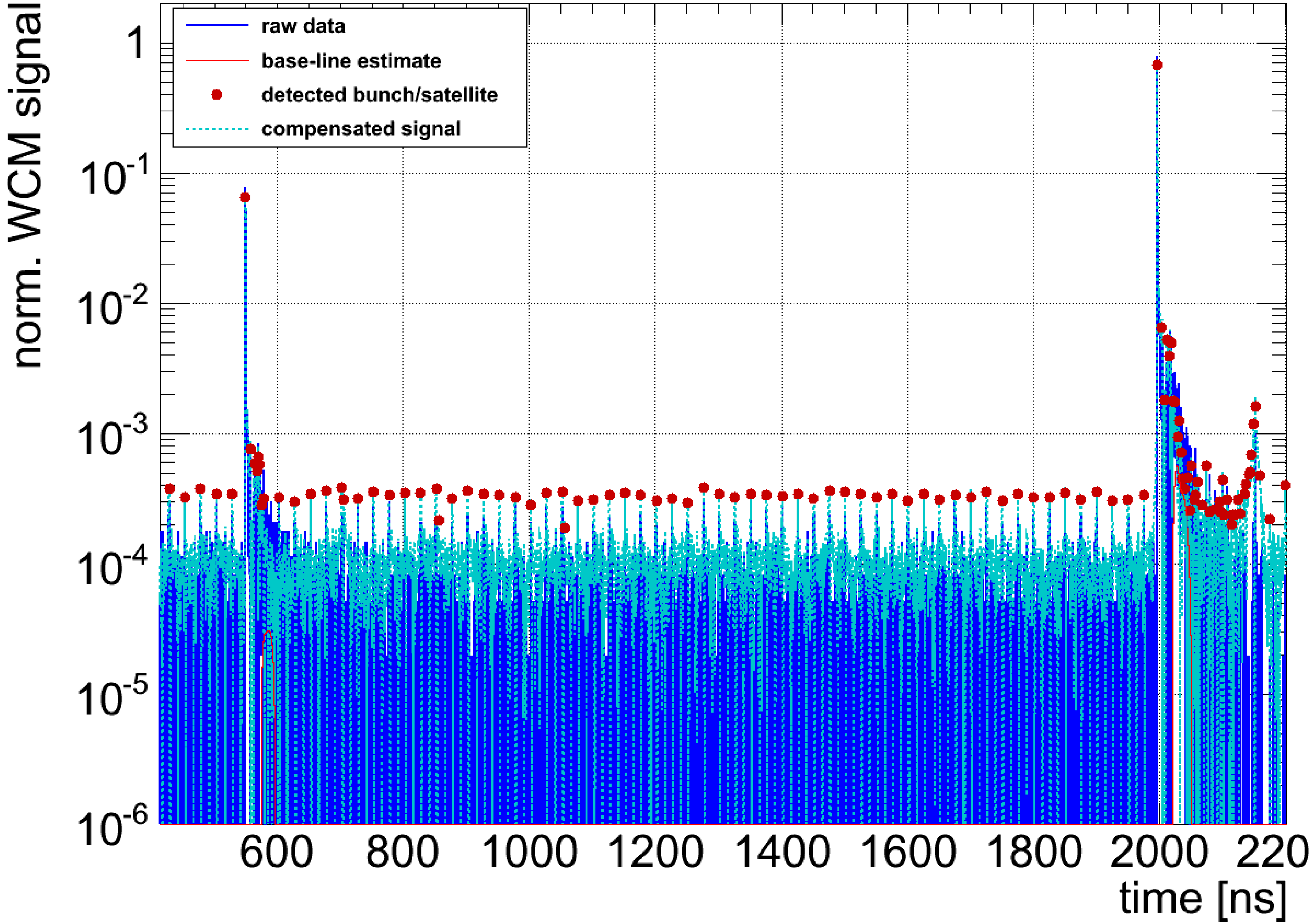


- Range limited by known systematic reflection after main bunches in 2011
  → improved for 2012

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

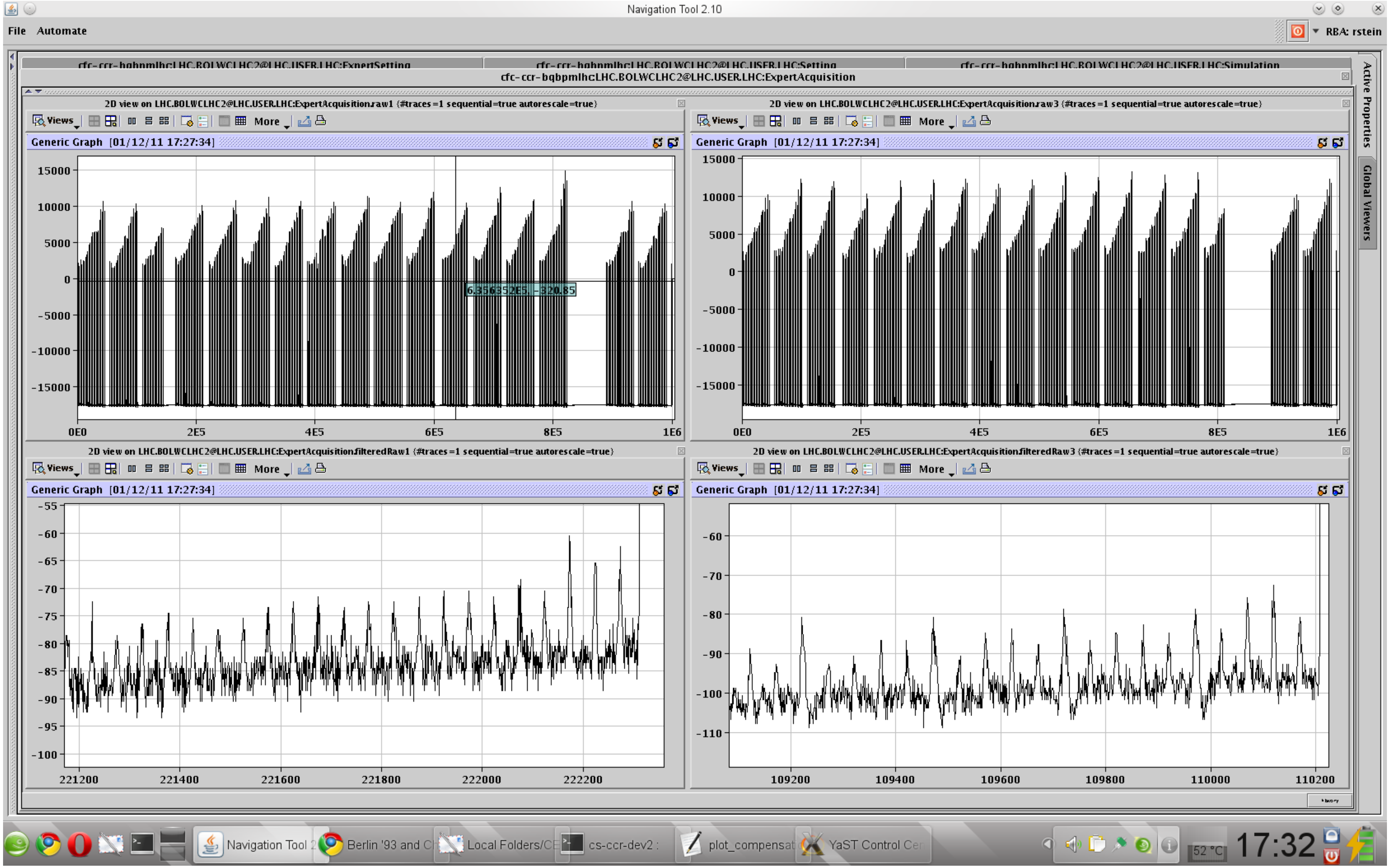


III. Base-Line Restoration – SNIP Algorithm
Example LHC WCM Signal - ZOOM



VdM Scan on 1st of December

- Similar Performance with Pb-Beam… S/N ratio of below the 10^{-3} level

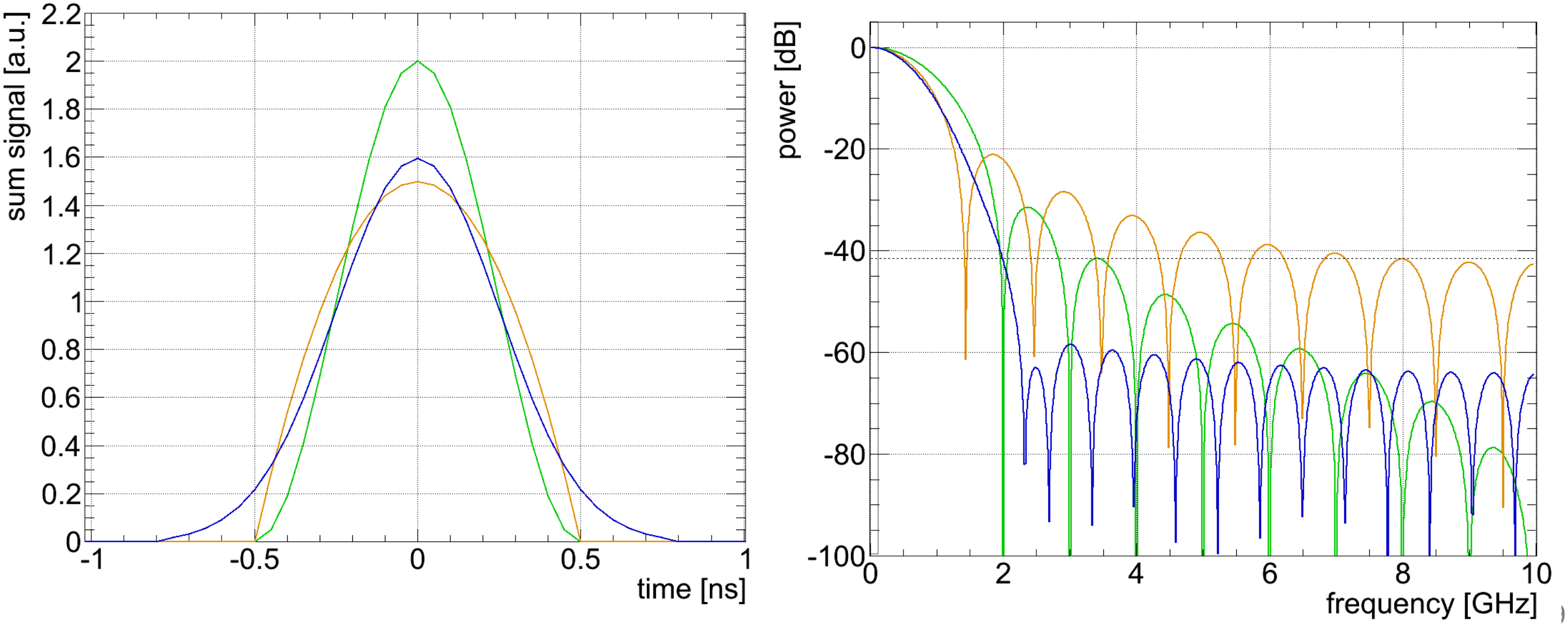


Why not using simply Fourier Spectra's DC-Component

- Fourier Integral definition for 'ω:=0':

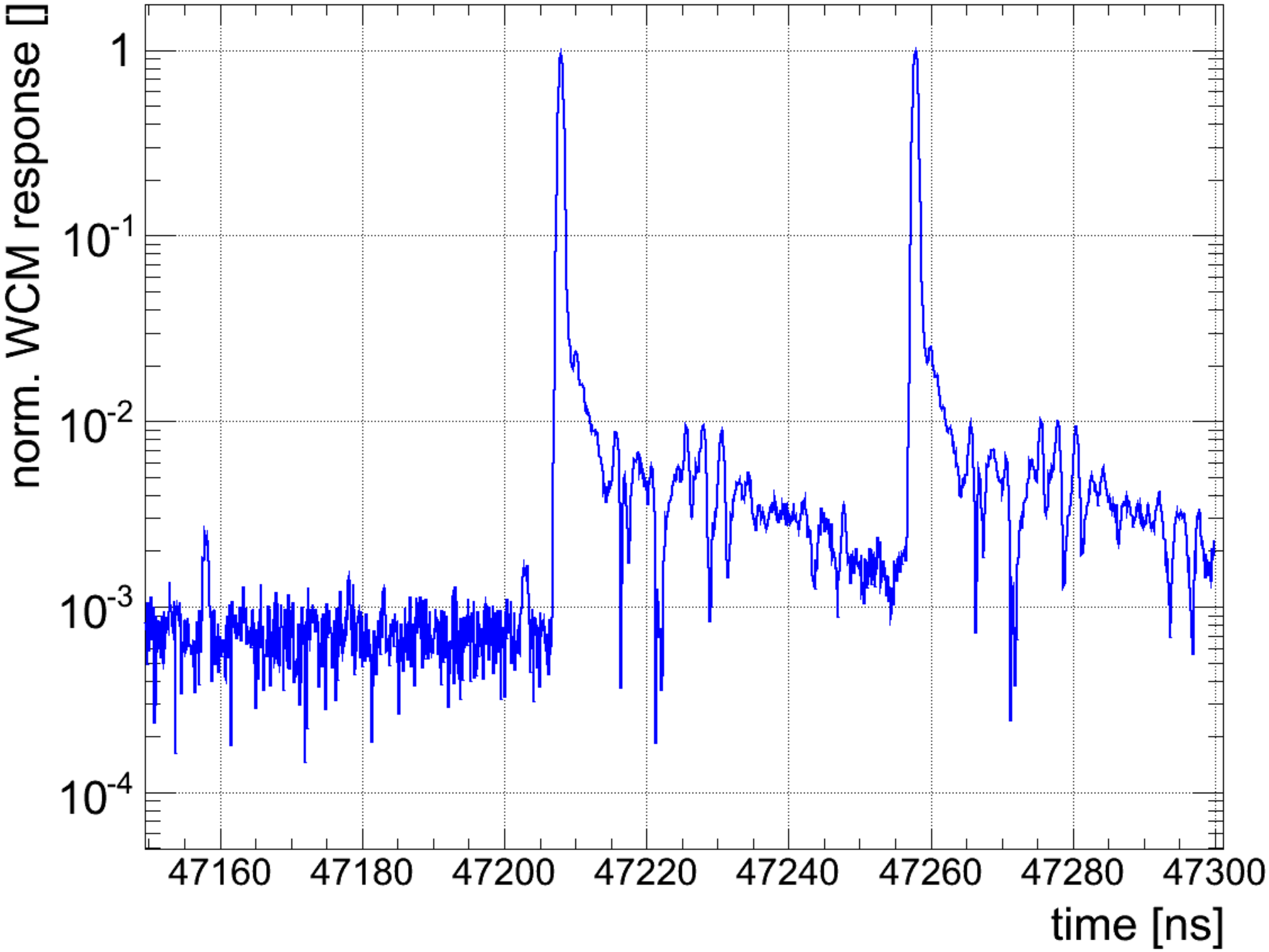
$$F(\omega)=\int_{-\infty}^{+\infty} f(t)\, e^{-i\omega t}\, dt$$

- DC information is in-accessible
  - AC-coupling of WCM (~50 kHz)
  - Short bunches (<1ns @25ns) ↔spectral leakage, difficult to resolve structures < 40 MHz
  - Bunch shape-dependence if 'interpolating' to DC or applying “magic” numbers



What can be achieved – LHC

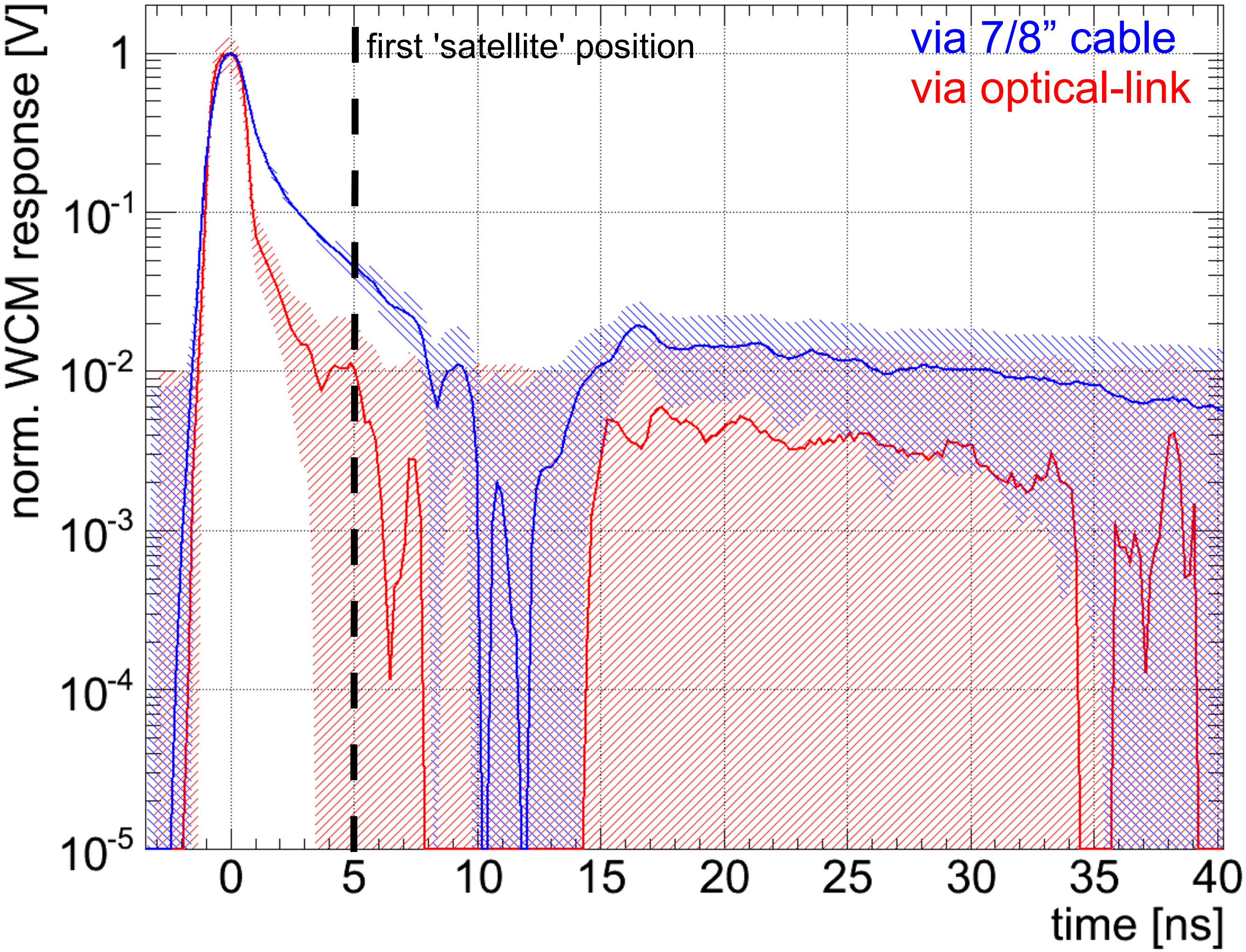
- Example: satellites 50 (PS?) and 2.5 ns (LHC) prior to bunch train



- 2.5 ns satellites after bunch visible but dominated by WCM tails/reflections...

What can be achieved – SPS

- “Mother” design for LHC APWL, would expect similar performance



- higher bandwidth with optical link but noise compared to 7/8” cable
→ shorter cables/acquisition system in the SPS tunnel needed

Reflections: RF Connector Geometry

- Selection of common connectors and adapters (H&S):
  - 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
- Simple N-Barrels
  - H&S: 37_N-50-0-1/133_N:
  - H&S: 31_N-50-0-51/199_NE:
- H&S: 33_N-716-50-51/-33_NE: VSWR ≤ 1.03 + 0.004·f [GHz]
- H&S: 31_N-SMA-50-1/1--_UE : VSWR ≤ 1.05 + 0.015·f [GHz]
- H&S: 31_N-SMA-50-51/1--_UE: VSWR ≤ 1.025 + 0.007·f [GHz]
- H&S: 53_N-50-0-4/133_UE: VSWR ≤ 1.06 + ~0.01·f [GHz]
- H&S: 53_SMA-50-0-51/199_NE: VSWR ≤ 1.02 + 0.03 f
- H&S: 53_SMA-50-0-2/111_N: VSWR < 1.05 @6 GHz
  - Copper Beryllium Alloy

VSWR ≤ 1.03 + 0.01·f [GHz]

≤ 1.19 + 0.06·f [GHz]

VSWR ≤ 1.03 + 0.004·f [GHz]

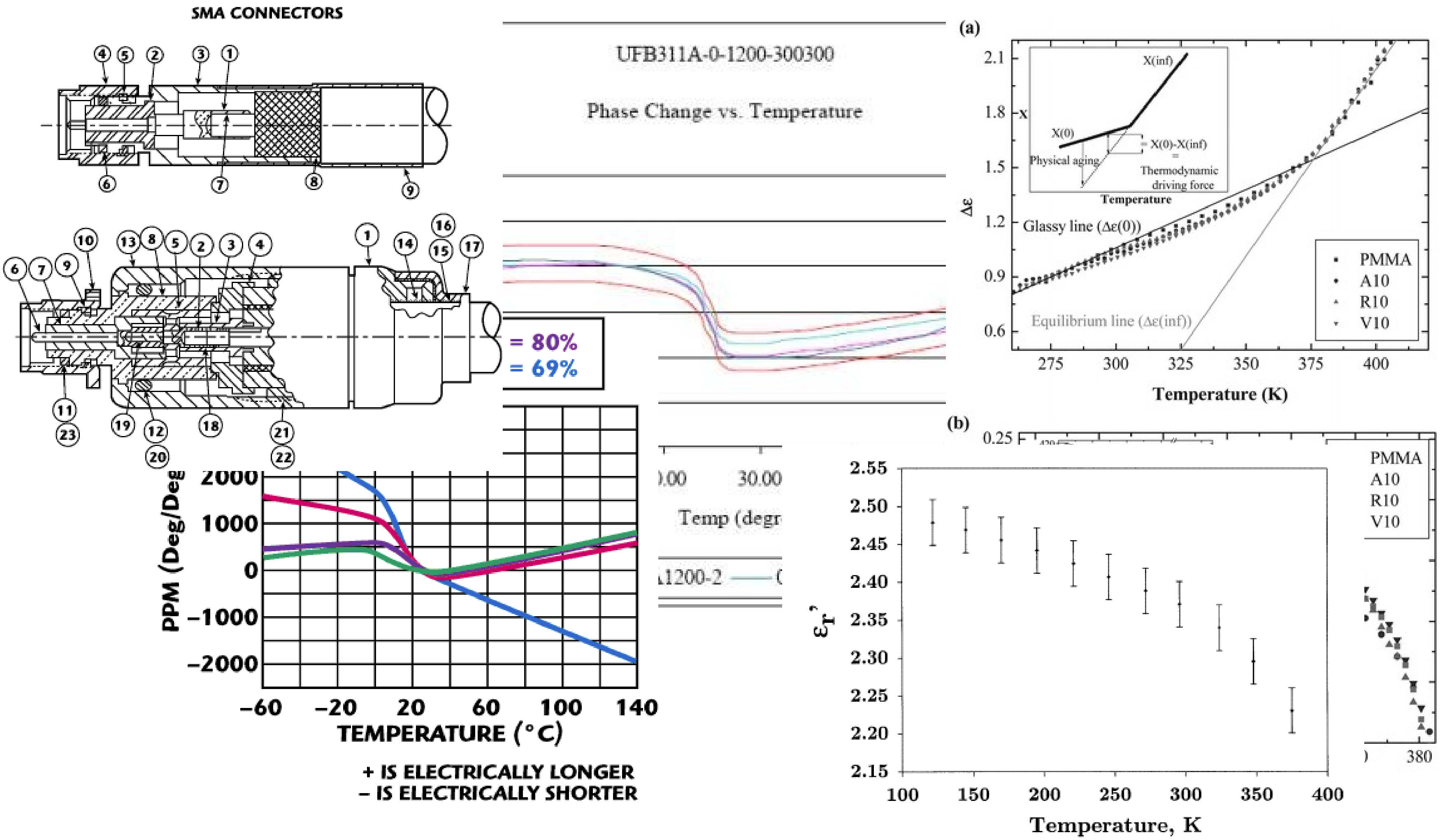
VSWR ≤ 1.025 + 0.007·f [GHz]

≤ 1.05 + 0.015·f [GHz]

VSWR ≤ 1.06 + ~0.01·f [GHz]

VSWR ≤ 1.02 + 0.03·f [GHz]

≤ 1.05 @ 6GHz


SMA CONNECTORS
+ IS ELECTRICALLY LONGER
– IS ELECTRICALLY SHORTER
PPM (Deg/Deg
2000
1000
0
−1000
−2000
−60
−20
20
60
100
140
TEMPERATURE (°C)
= 80%
= 69%
UFB311A-0-1200-300300
Phase Change vs. Temperature
).00
30.00
Temp (degr
.1200-2
(a)
Δε
2.1
1.8
1.5
1.2
0.9
0.6
X(inf)
X(0)
X(0)-X(inf)
Physical aging
Thermodynamic driving force
Temperature
Glassy line (Δε(0))
Equilibrium line (Δε(inf))
PMMA
A10
R10
V10
275
300
325
350
375
400
Temperature (K)
(b)
0.25
ε_r'
2.55
2.50
2.45
2.40
2.35
2.30
2.25
2.20
2.15
100
150
200
250
300
350
400
Temperature, K
380