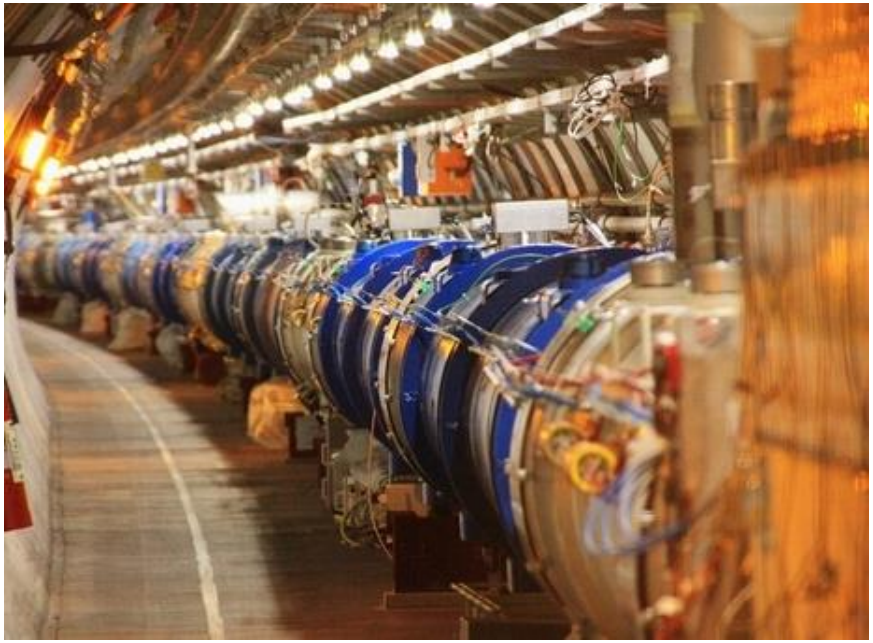
Phase advance measurements using DOROS

Jakub Olexa

Contents

Optics measurements in LHC

- To measure optics parameters, such as local coupling or phase advance, can be measured by exciting transverse beam oscillations and measuring the response of the beam along the ring using a Beam Position Monitoring (BPM) system.
- The beam response in the LHC can be measured in more than 500 locations.
- The beam excitation is important for achieving consistent and repeatable results when measuring the beam responses in the BPMs.
- Optics measurement requiring excitation of the beams in the LHC require dedicated safe beams and machine setup and are typically done during dedicated time
- So far, such measurements were not performed with the physics beams used for luminosity production (~2500 bunches and nominal beam intensity ~10^{14}).



Photograph of the LHC tunnel: Courtesy of CERN

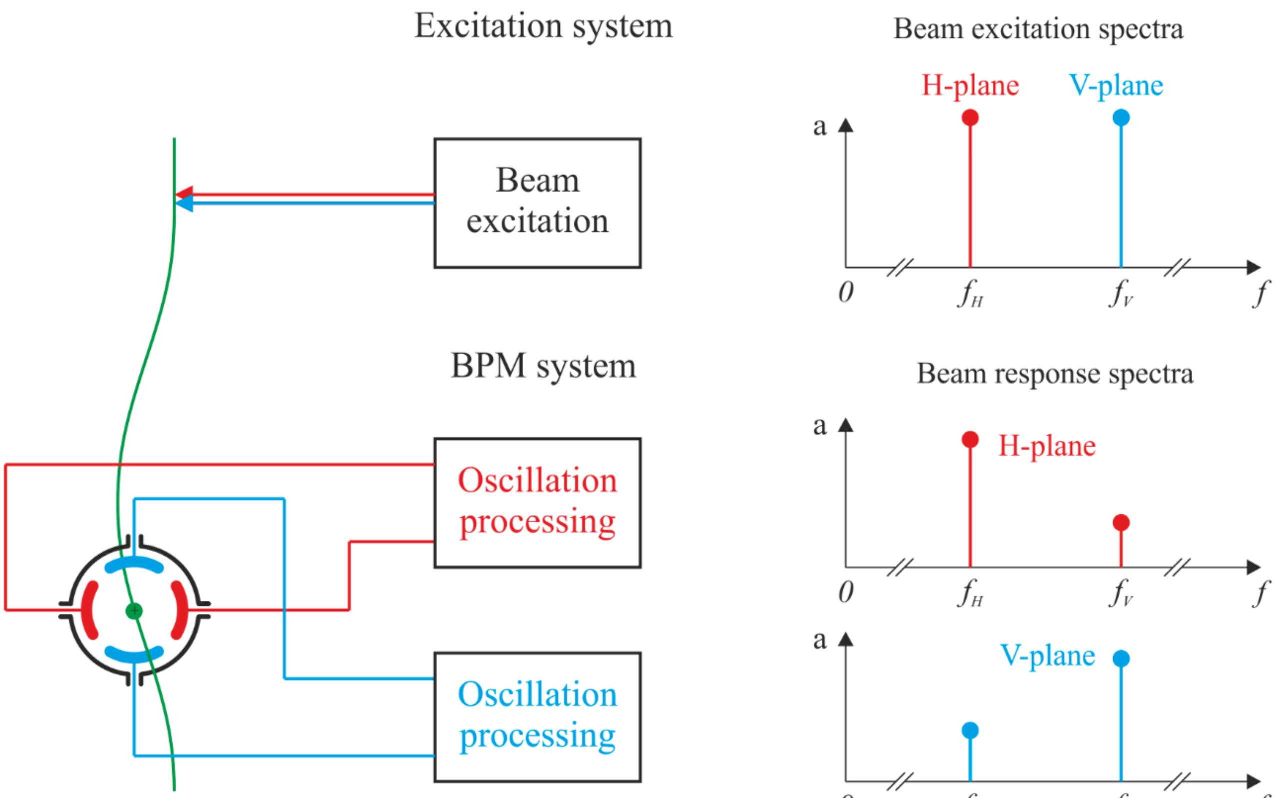
Optics measurements in LHC

- There are two LHC systems used for exciting the transverse beam oscillations for optics measurements:
  - AC dipole magnet
    - ✓ Drives large oscillation amplitudes (> 1mm)
    - ○ Difficult to excite with small amplitudes (<100 µm)
    - ○ Maximum excitation duration ~ 1 s (10^4 LHC beam revolutions)
    - ○ Asynchronous to beam revolution frequency f_{rev}
  - Transverse damper system (ADT)
    - ✓ Arbitrary excitation duration
    - ✓ Oscillations are related to LHC f_{rev}
    - ✓ (almost) arbitrary excitation amplitude
    - ○ Can't drive large oscillations (< ~ 0.1 mm)
- Sensitivity of a BPM system to the beam oscillations matters:
  - Beam quality (emittance blow-up).
  - Safety of the machine (particle losses).
  - Achievable quality of the measurement, representative conditions.
- Decrease the required excitation amplitudes to the minimum could also:
  - Possibly allow for measurements in more representative conditions (more beam types, dedicated or regular physics beams)
  - Possibly allow for continuous measurement and monitoring of the optics parameters. This was tested in the SPS using the LHC base band tune system with promising results [1].

[1] R.J. Steinhagen, et al, On the continuous measurement of the LHC beta-function – Prototype studies at the SPS, CERN-ATS-2009-031

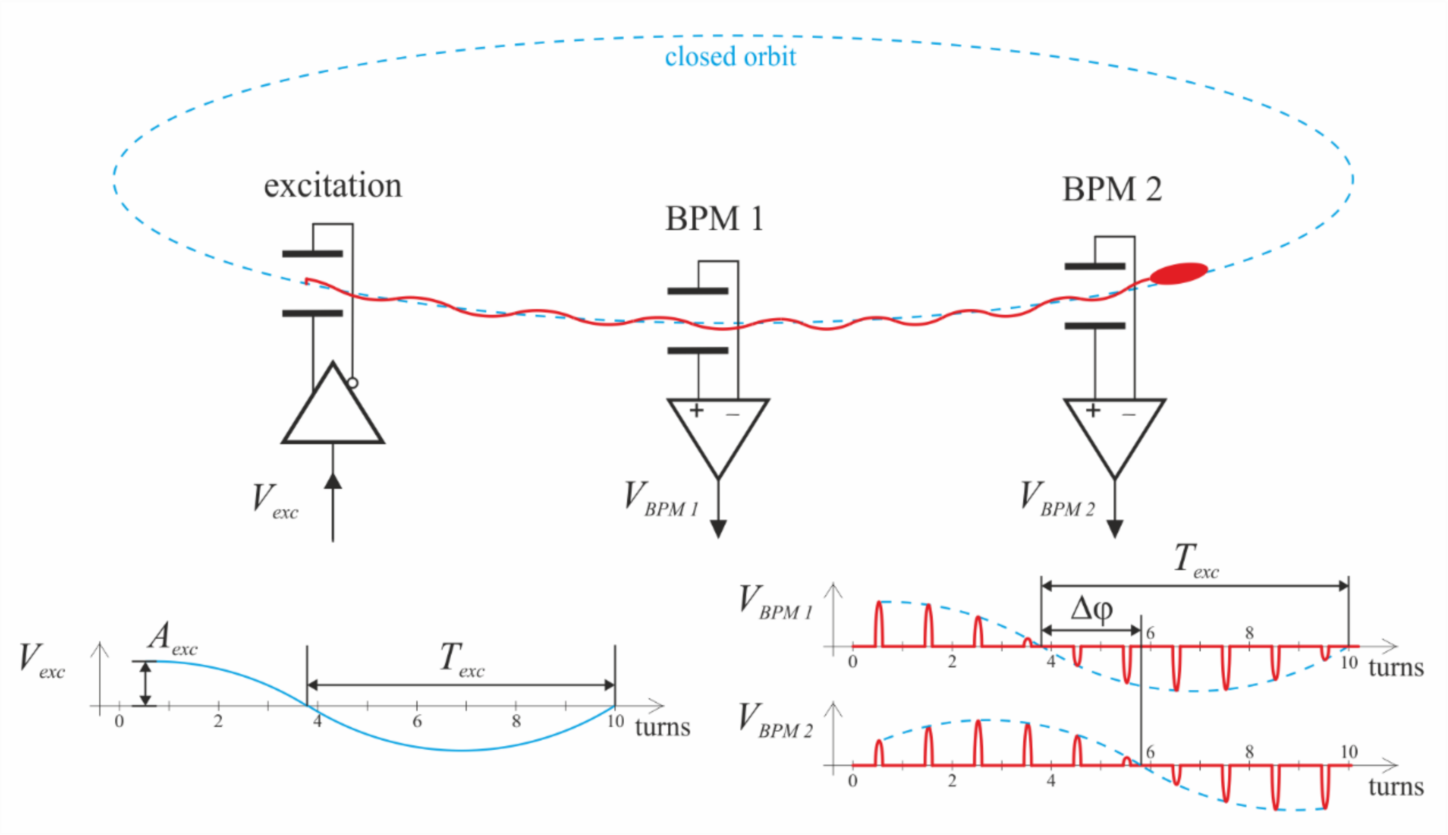
Local coupling measurement

- An example of an optics measurement in the LHC using transverse beam excitation is the local betatron coupling:
  - Each plane of the beam is harmonically excited at a different frequency.
  - The frequency of the excitation is chosen to be close to the tune (usually 10^{-2} – 10^{-3} f_{rev}).
  - Based on the standard LHC BPM system to measure the beam oscillations and compute the coupling corrections.
  - Required to measure the phase of the oscillations between the H and V planes in a BPM.



Phase advance measurement

- The harmonic beam excitation can be also used to measure and compute the phase advance between two BPMs.
  - Beam is harmonically excited at single chosen frequency.
  - The beam oscillations are detected by the BPM system sampling synchronously to the beam.
  - Quality of the measured oscillation (SNR) can be controlled with amplitude and duration of the excitation.
  - Sophisticated data analysis methods can combine measurement results from several BPMs to further improve the measurement resolution [2].



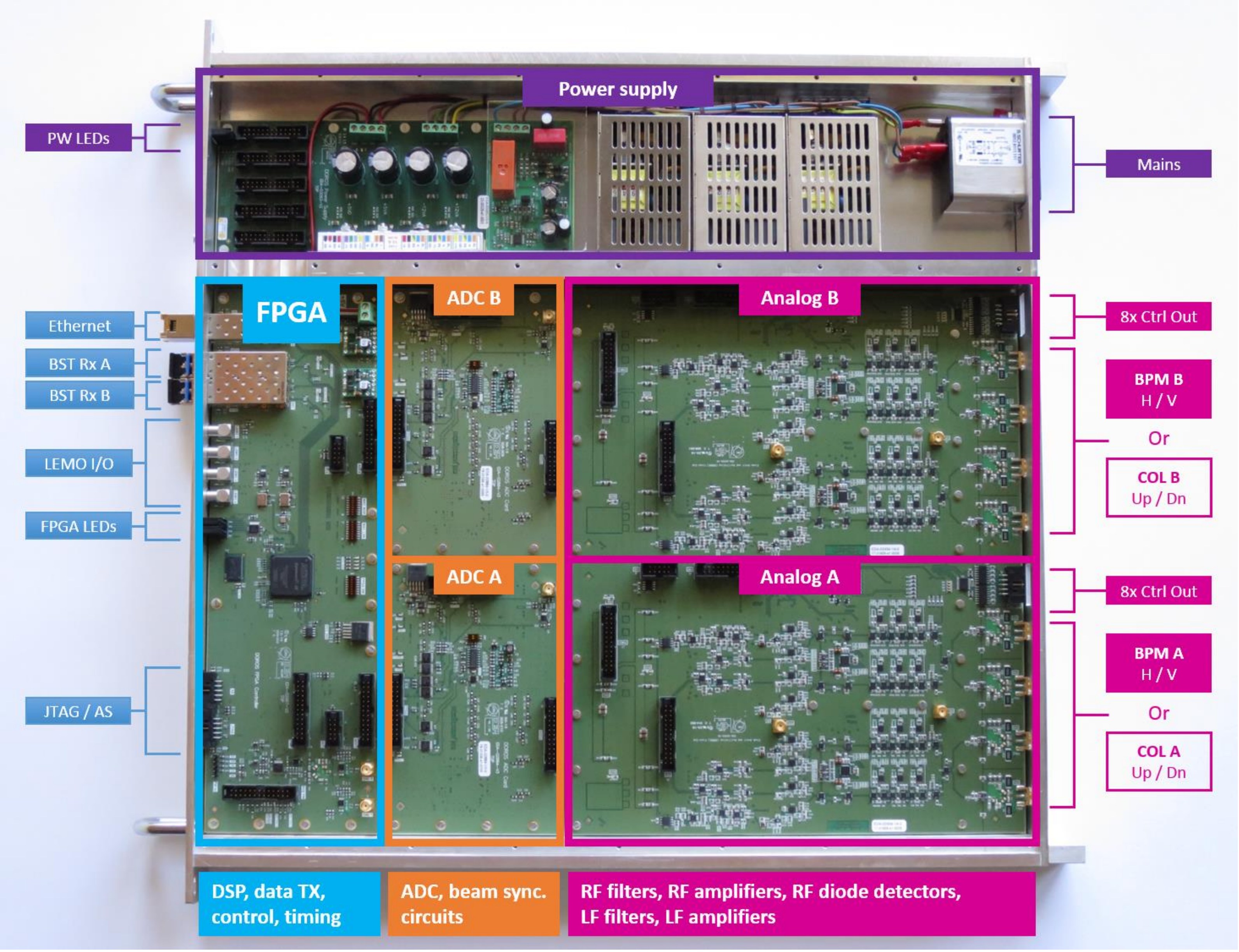
[2] A. Franchi, Error analysis of linear optics measurements via turn-by-turn beam position data in circular accelerators, arXiv:1603.00281

Diode ORbit and OScillation system (DOROS)

- DOROS (Diode ORbit and Oscillation) is a BPM electronics system based on diode detectors.
- The system consists of DOROS front-ends built as 1U 19” units for processing 8 BPM electrode signals and send the results over Ethernet.
- The front-ends can receive beam synchronous timing (BST) of the two LHC beams distributed over optical fibres.
- DOROS was primarily designed and optimised for the LHC collimator BPMs to allow the fast jaw alignment.
- There the DOROS system shares the signals with the standard LHC BPM system at some strategic BPMs in the LHC, mostly the so called Q1 BPMs around the interaction regions of the experiments.
- The front-end hardware of both the standard and collimator DOROS systems is identical.
- Some 40 DOROS front-ends equip about 20 collimators and more than 40 BPMs in the LHC.

Photograph of the DOROS front-end front panel (top) and the accompanying ventilation unit (bottom)

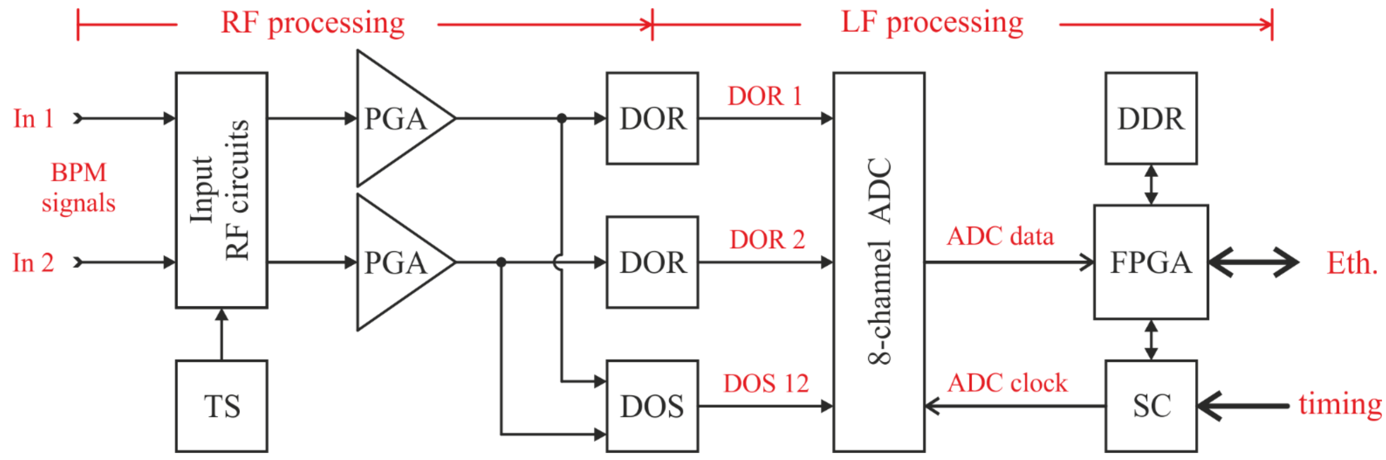
DOROS



Photograph of the DOROS front-end without the top cover and internal cables.

DOROS

- Basic block diagram of a DOROS front-end for one BPM plain:

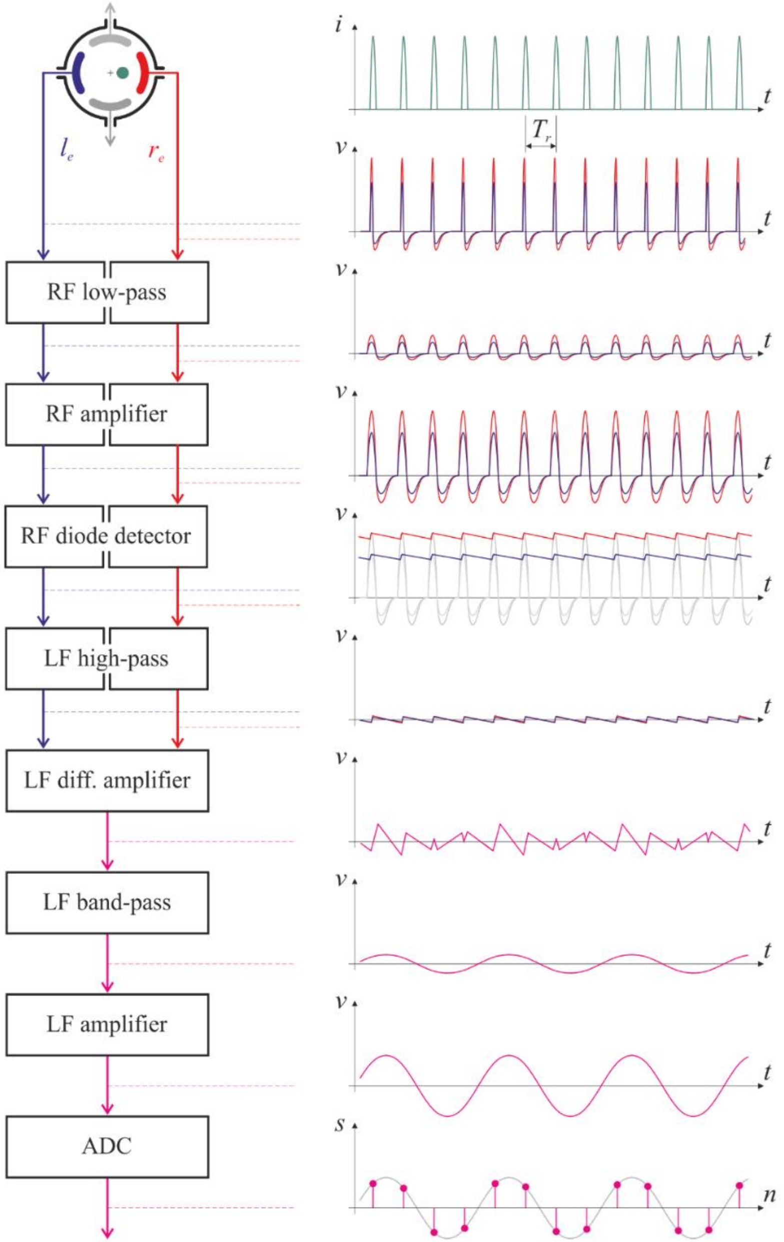


PGA – Programmable Gain Amplifier, TS – Test Signal generator, DOR – Diode Orbit processing channels,
DOS – Diode Oscillation processing channels, SC – Synchronization Cirscuits

- Each DOROS front-end contains two subsystems that share the input RF circuits:
  - **DOR**: based on compensated diode detectors and optimized for sub-micrometre resolution of the beam orbit measurements. The bandwidth is limited to some 100 Hz.
  - **DOS**: based on RF diode detectors optimized for measuring small beam oscillations in the bandwidth 0.05 – 0.5 f_{rev} that is some 500 Hz – 5 kHz.
- The signal processing in the DOS subsystem was inspired by the LHC tune system (BBQ) based on the same principles.
- The DOS also accommodates the synchronization and timing circuits to allow ADC sampling with the beam revolution frequency f_{rev}.

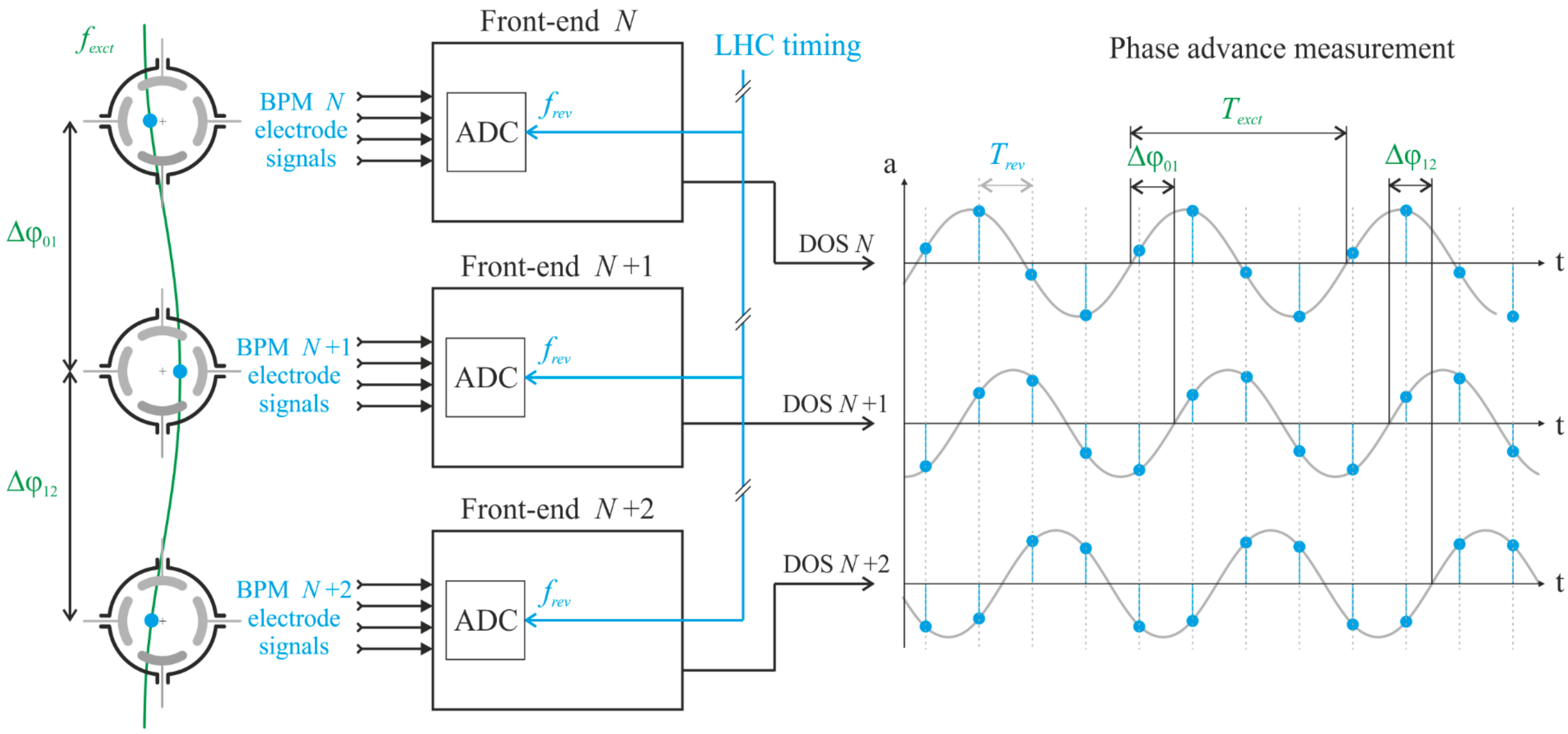
Oscillation signal processing

- Input RF low-pass absorptive filters limit the bandwidth to some 80 MHz and reduce BPM signal amplitudes before active electronics.
- Programmable RF amplifiers allow an 80 dB dynamic range and 1 dB gain control.
- The diode detectors convert nanosecond pulses from the BPM electrodes into low frequency signals.
- The LF high-pass removes most of the beam intensity signal.
- The LF differential amplifier subtracts signals from opposing BPM electrodes.
- The further band-pass filtering removes most of the revolution frequency content.
- Samples are converted by a 24-bit sigma-delta ADC, sampling at LHC f_{rev} (~11.2 kHz).
- The resulting data is then further processed in the front-end FPGA.



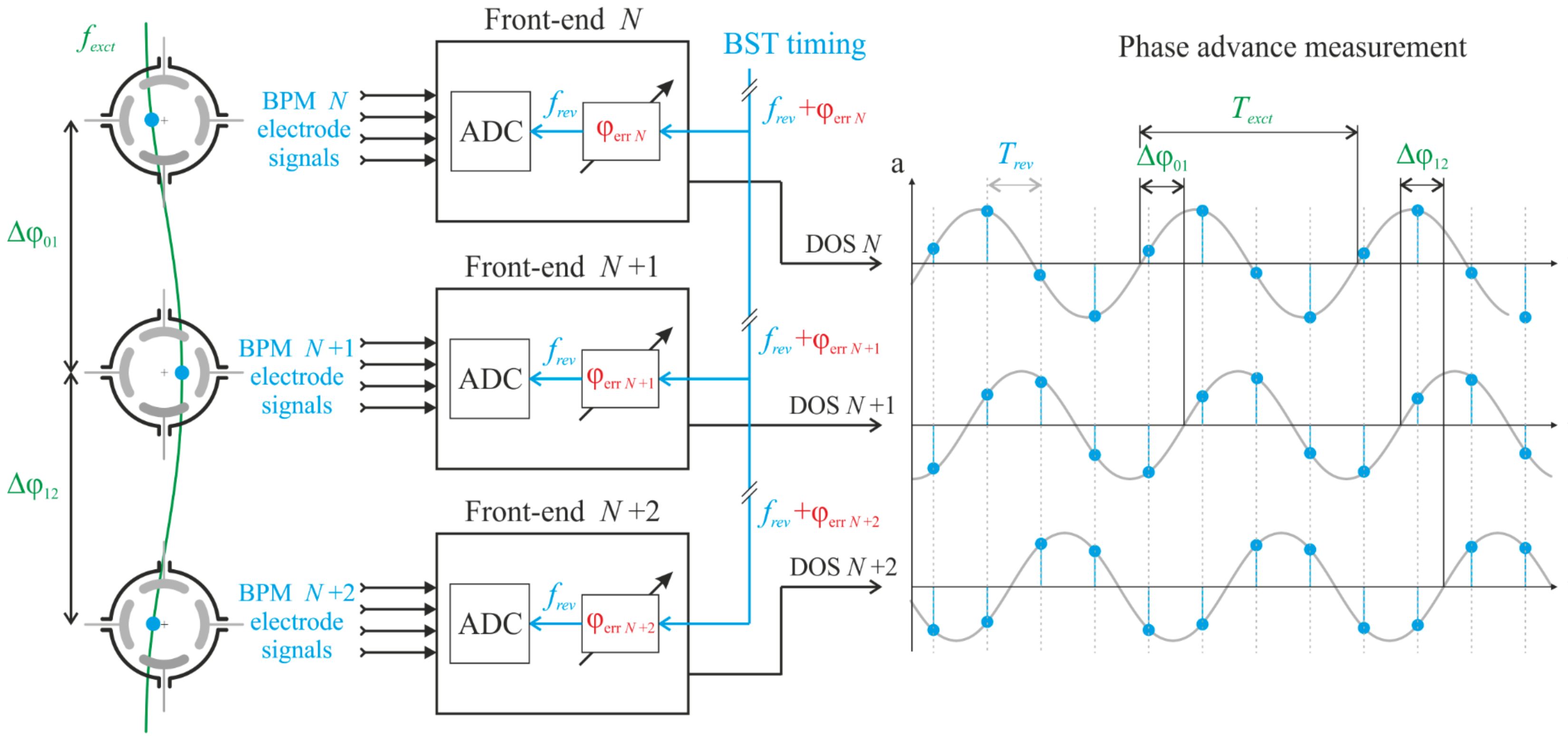
Phase advance measurement with DOS

- The phase advance measurement with DOS requires a common frequency phase reference.
- Beam Synchronous Timing network is a source of stable LHC revolution clock suitable for the ADCs.
- The scheme drawn on the picture requires guaranteed phase relationship between the front-ends.
- Any skew on the reference phase between the front-ends is translated as a systematic measurement error.
- Time of beam propagation is not compensated in this example.
- Requirement to adjust the phase of the ADC sampling to the beam to minimize such errors.



Phase advance measurement with DOS

- Under certain beam conditions the front-end can generate a local reference clock derived from the input BPM signals.
- The synchronization circuits allow to align the distributed f_{rev} clock to the beam reference by means of programmable phase shifters.
- The phase errors in the timing distribution as well as the beam propagation time are minimized.
- The resolution of the phase alignment system is 100 ps, equivalent to some 0.0004 deg phase shift of the f_{rev} clock.

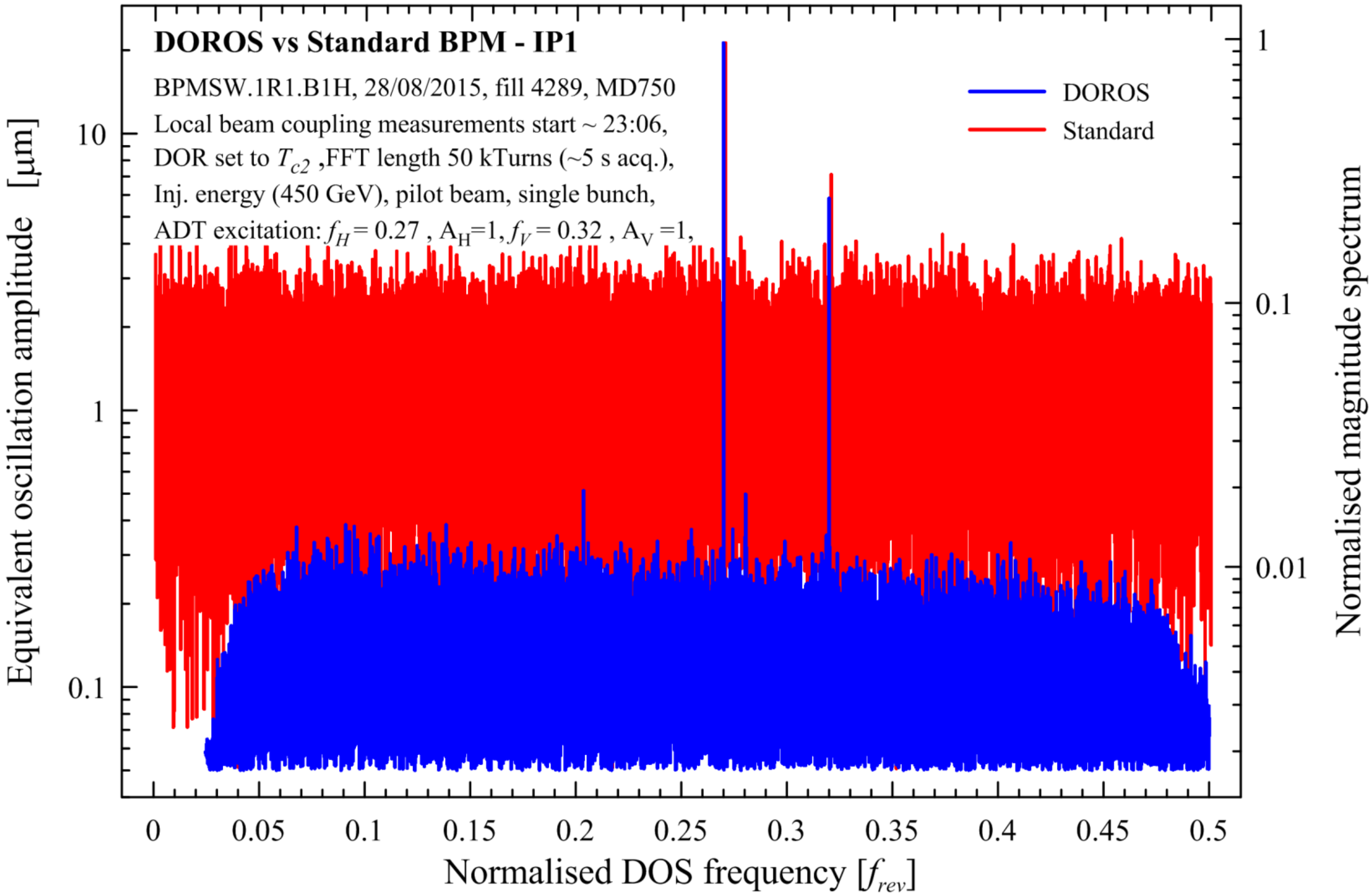


DOS in a nutshell

- The DOS measures beam oscillations in bandwidth of 0.05 – 0.5 f_{rev} (some 500 Hz – 5 kHz)
- The resulting DOS signal is proportional to the beam position change. However, in the current DOS implementation it is not normalised by the intensity.
- Sampling of the ADCs in each DOROS front-end can be synchronised to the LHC revolution frequency acquired from the BST or beam signals from the BPM.
- Option to synchronize phase of the ADC sampling clocks between the front-ends.
- The ADC data (both the orbits and oscillations) are continuously stored in the local DDR memory in the front-end.
- The data is then available in the FESA class through on-demand “Capture/Freeze” functionality:
    - Rolling turn-by-turn buffer depth of more than 1.8 million turns (up to 3.5 minutes @ f_{rev})
    - Capture triggered with dedicated Beam Synchronous Timing (BST) events.
    - Optional capture/freeze triggers from FESA commands.
- The DOS data is foreseen to undergo real-time synchronous detection performed in the system FPGA to obtain directly the oscillation amplitudes and phases. This way the oscillation processing can be based on very long data sets to increase the system sensitivity without the need of storing raw data. The synchronous detection can be done at two separate frequencies to measure also local betatron coupling. The resulting amplitudes and phases (just a few numbers) can be sent continuously along with the orbit data.

DOROS vs. standard BPMs for beam oscillations (one pilot)

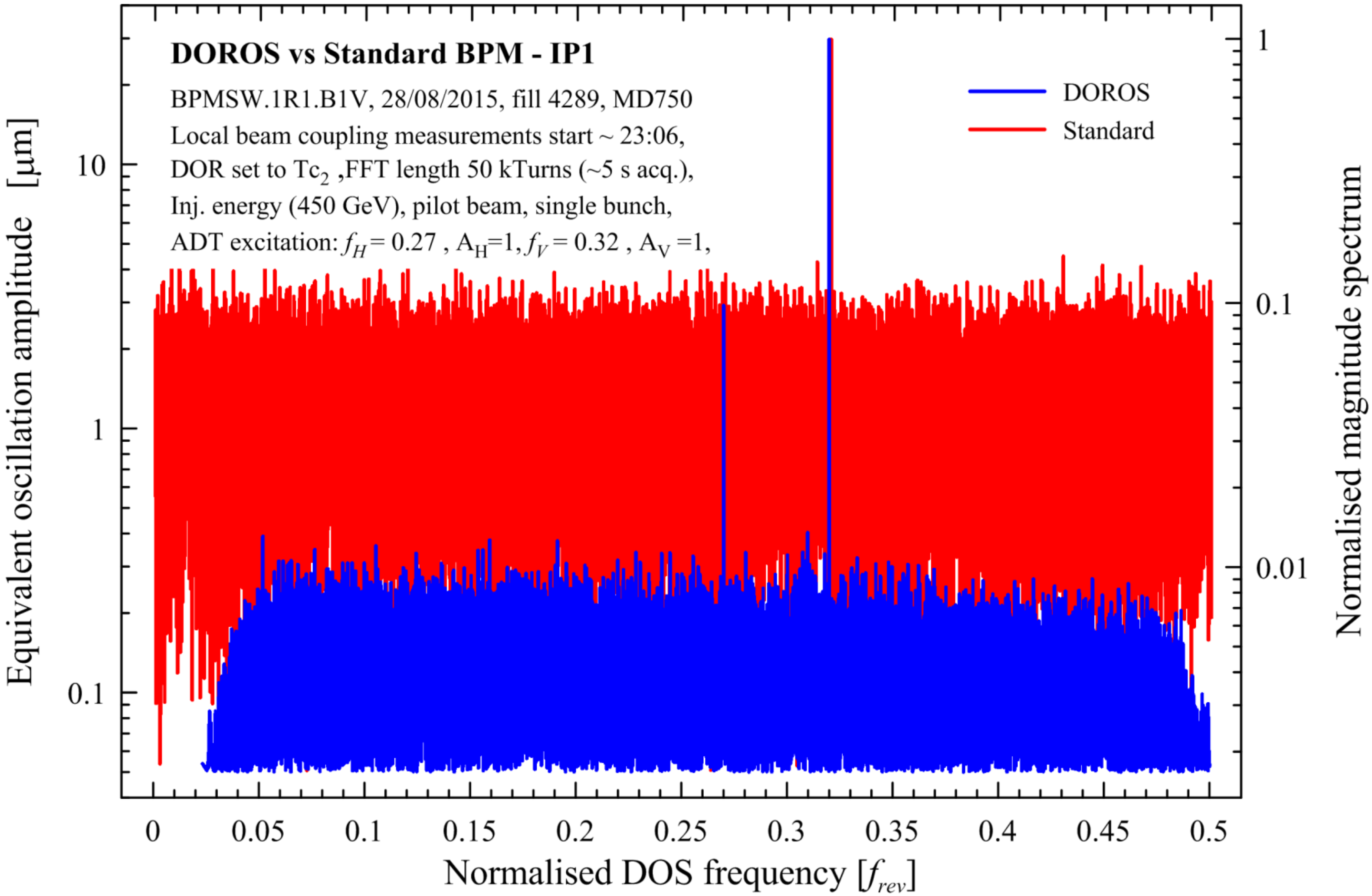
- Local betatron beam coupling measured close to ATLAS interaction region (H plane):



Notes: The vertical axis is scaled in the equivalent time domain amplitudes assuming harmonic components.
For better visibility the upper frequency axis for the standard BPM data is slightly shifted with respect to the bottom axis of the DOROS data.

DOROS vs. standard BPMs for beam oscillations (one pilot)

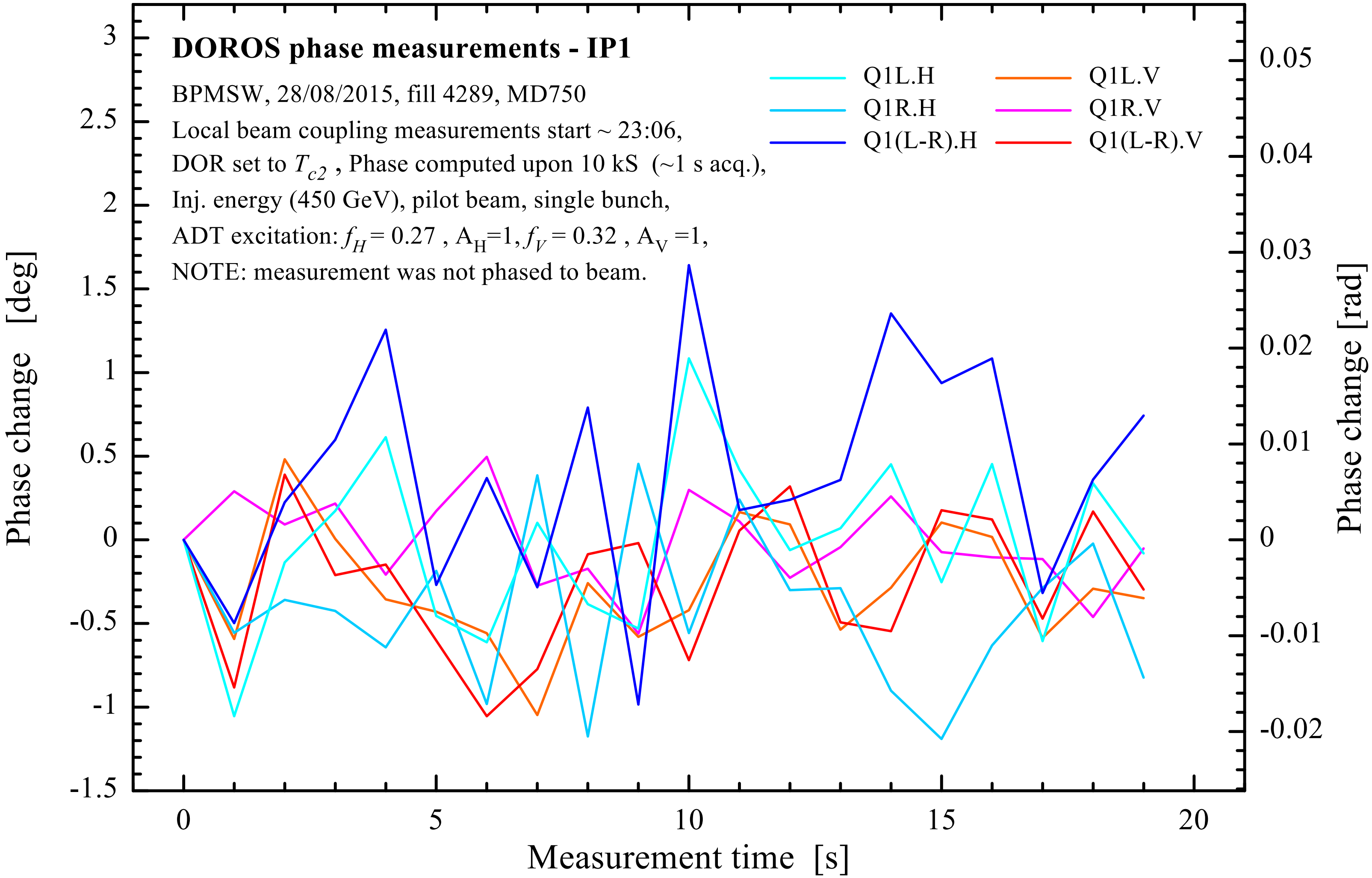
- Local betatron beam coupling measured close to ATLAS interaction region (V plane):



Notes: The vertical axis is scaled in the equivalent time domain amplitudes assuming harmonic components.
For better visibility the upper frequency axis for the standard BPM data is slightly shifted with respect to the bottom axis of the DOROS data.

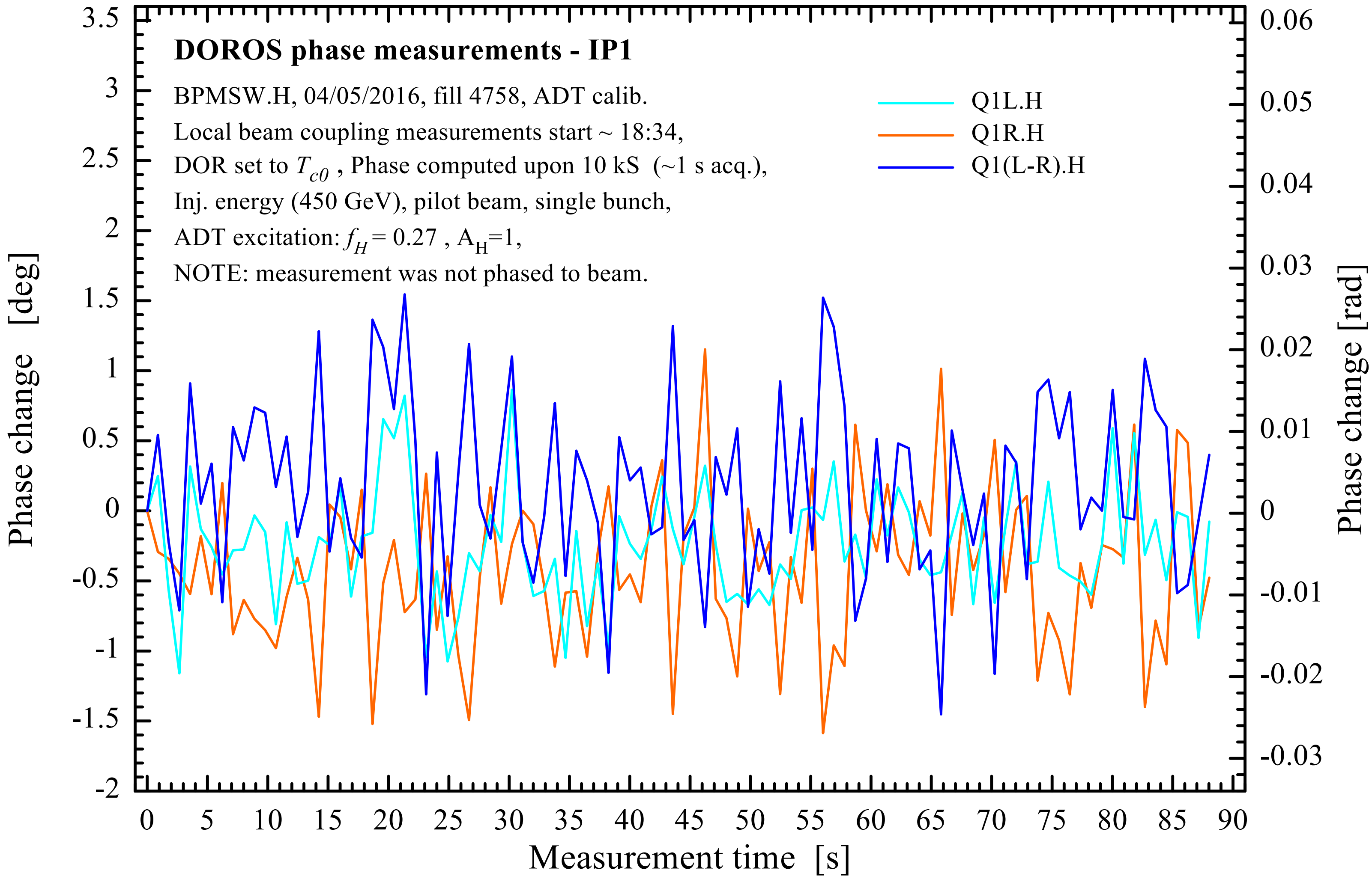
Measurement of the beam phase advance change (1)

- Alignment of the ADC sampling with beam was not available during this measurement. Absolute phase values were arbitrary.
- Phases we computed using 10 kS FFTs (equivalent to ~1 s measurement duration).
- Computed standard deviations: STD H = 0.67 deg (0.01 rad) STD V = 0.42 deg (0.007 rad)



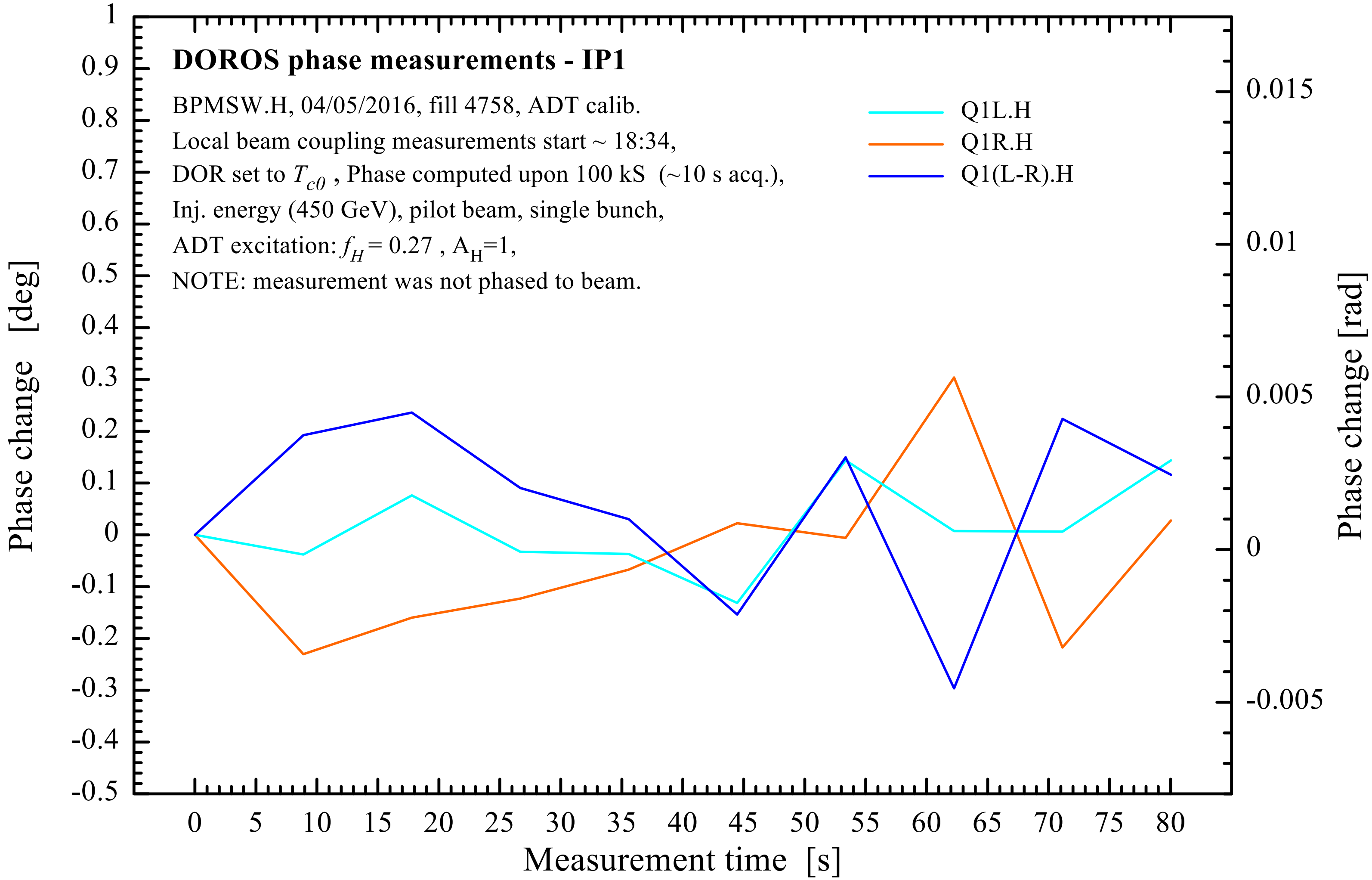
Measurement of the beam phase advance change (2)

- Alignment of the ADC sampling with beam was not available during this measurement. Absolute phase values were arbitrary.
- Phases we computed using 10 kS FFTs (equivalent to ~1 s measurement duration).
- Computed standard deviation: STD H = 0.63 deg (0.01 rad)

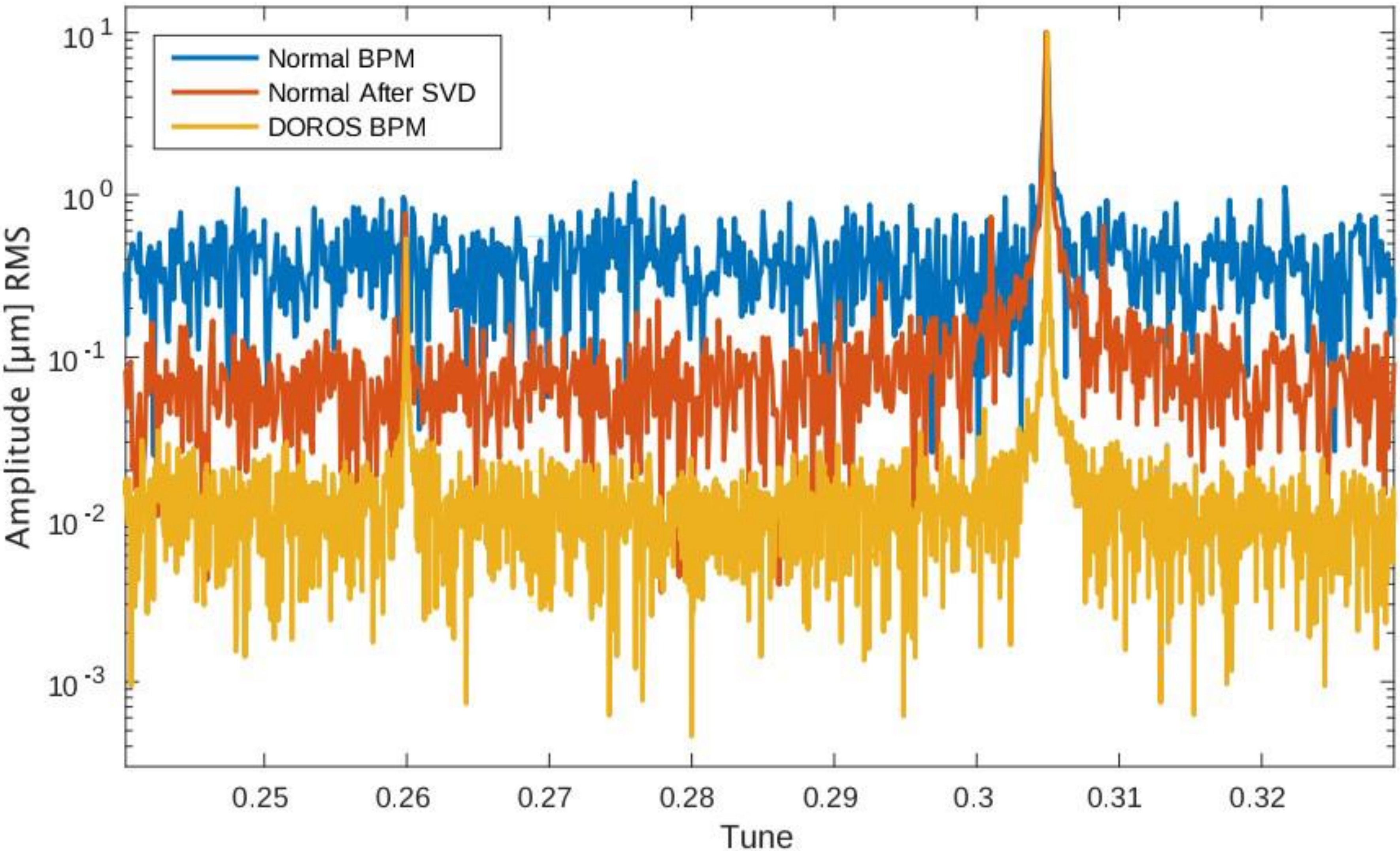


Measurement of the beam phase advance change (3)

- Alignment of the ADC sampling with beam was not available during this measurement. Absolute phase values were arbitrary.
- Phases we computed using 100 kS FFTs (equivalent to ~10 s measurement duration).
- Computed standard deviation: STD H = 0.16 deg (0.003 rad)



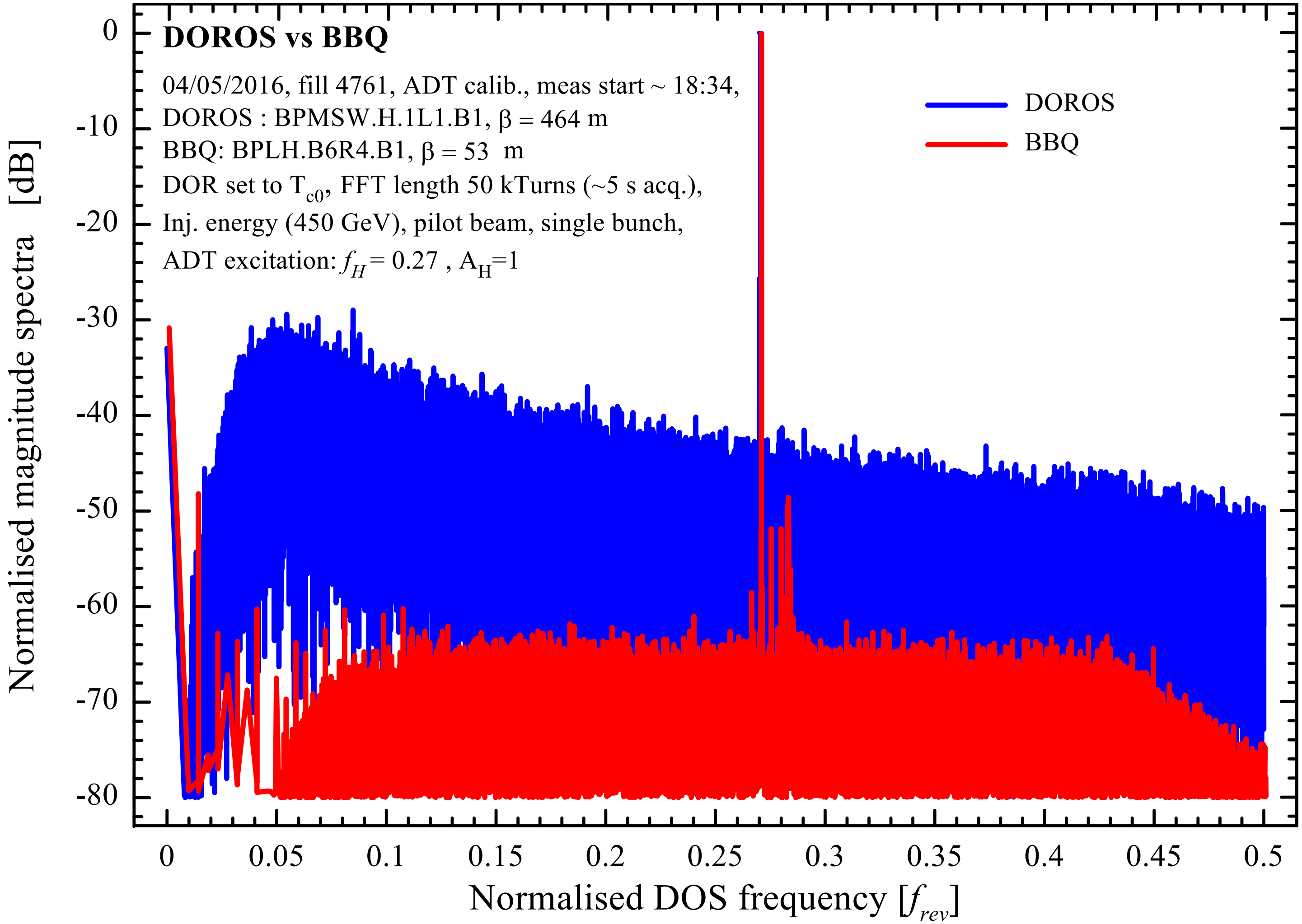
DOROS vs. standard BPMs for beam oscillations (one nominal)



T. Persson, “Online coupling measurement: Method and Experience”, LBOC 7/03/17

DOROS vs. BBQ (one pilot)

- Measurement of the beam oscillations with DOS subsystem in PT1 and the BBQ in PT4 during amplitude calibration of various LHC systems.
- NOTE: amplitudes not scaled with respective beta functions.



Conclusions and Outlook

- The DOS subsystem in the DOROS has a number of advantages:
    - Improved sensitivity to small beam oscillations when comparing to the measurement from the standard LHC BPM system (>30 dB).
    - Ability to synchronize the acquisition with the beam revolution with minimal phase error (100 ps or ~ 0.0004 deg).
    - With synchronous detection the phase of the oscillations can be measured continuously.
- The system currently installed “as is” in the LHC has also some disadvantages.
    - Not as sensitive as the BBQ system (>30 dB). Observing LHC tunes without excitation is difficult.
    - The oscillation amplitudes are not directly measured in millimeters. It is therefore required to cross-calibrate the measurement with other systems.
    - bunch-by-bunch not possible “by design”.

Conclusions and Outlook

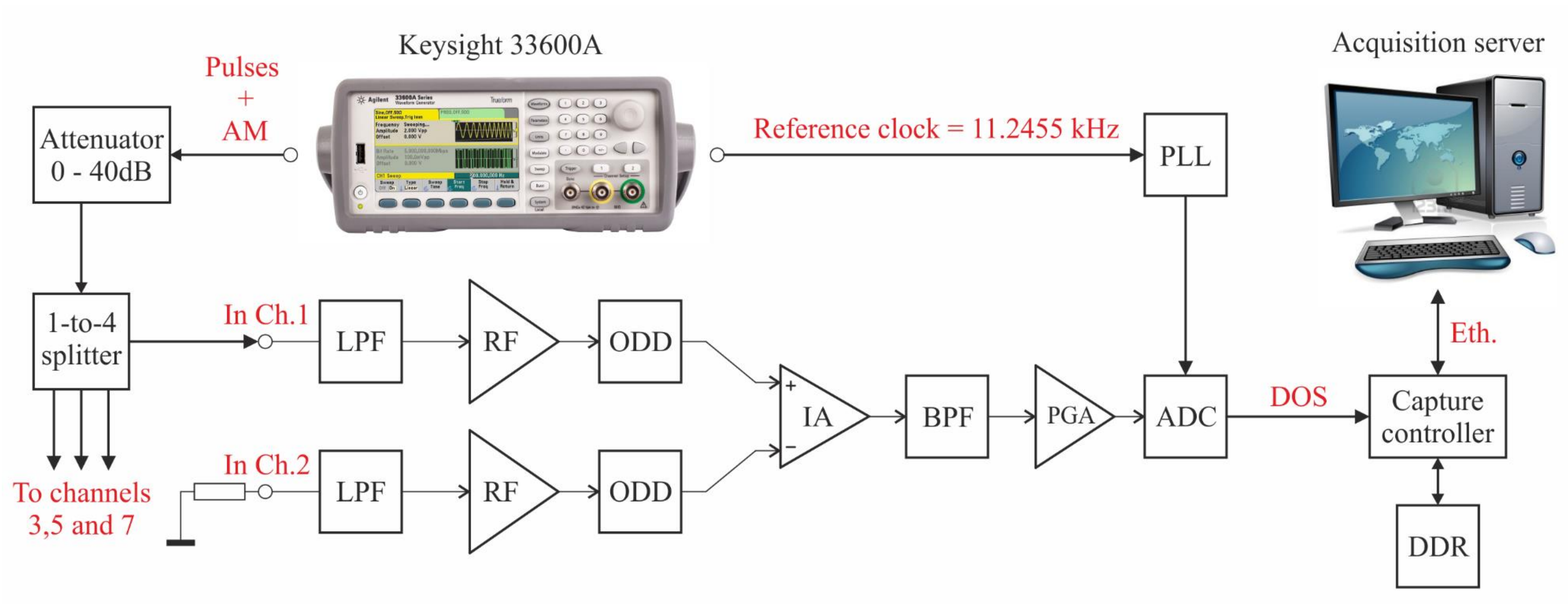
- There is still a lot of work foreseen for 2018:
  - Require more systematic beam measurements and studies.
  - Develop automated scripts for phase alignment of the front-ends to the beam phase reference. For the moment this procedure is manual and requires a lot of time (~15 minutes per front-end).
  - Apply the phase alignment before optics measurements in the LHC so that the absolute phase advance could be measured at the same time.
  - The FESA class will perform periodic buffer readouts on selected DOROS front-ends, ~100 kTurns every minute (~10s), to measure low frequency beam oscillations with DOR channels. DOS data can be available at the same time for beam diagnostics and analysis.
  - One of the current developments looks into possibilities of using the DOR subsystem to calibrate the DOS readings in each channel.
  - In order to measure oscillations of selected bunches, further development looks into implementing the signal gating on the DOROS inputs. Similar mechanism is already employed in the gated version of BBQ.

Thank you for your attention!

Spares

Laboratory measurement setup

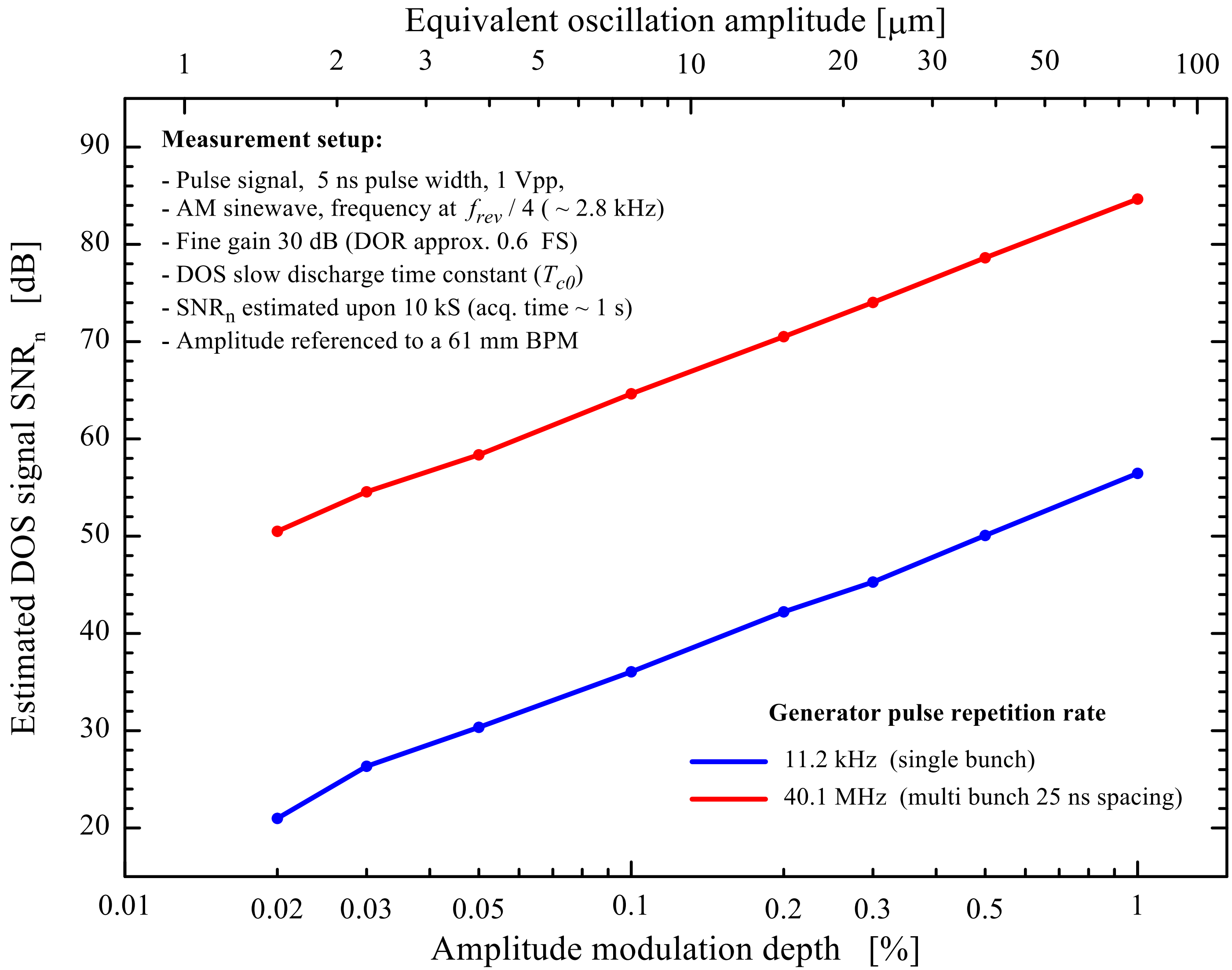
- Measurement setup used to characterize the DOS subsystem in the laboratory.
- The arbitrary waveform generator was used to simulate the BPM signals with 5 ns pulses and 1 Vpp amplitude.
- The beam oscillation was simulated with pulse amplitude modulation from the generator



AM – Amplitude Modulation, LPF – Low-Pass Filter, RF – Radio Frequency amplifier stage, ODD – Oscillation Diode Detector, IA – Instrumentation Amplifier, BPF – Band-Pass Filter, PGA – Programmable Gain Amplifier, DOS – Diode Oscillation signal, ETH – Ethernet network

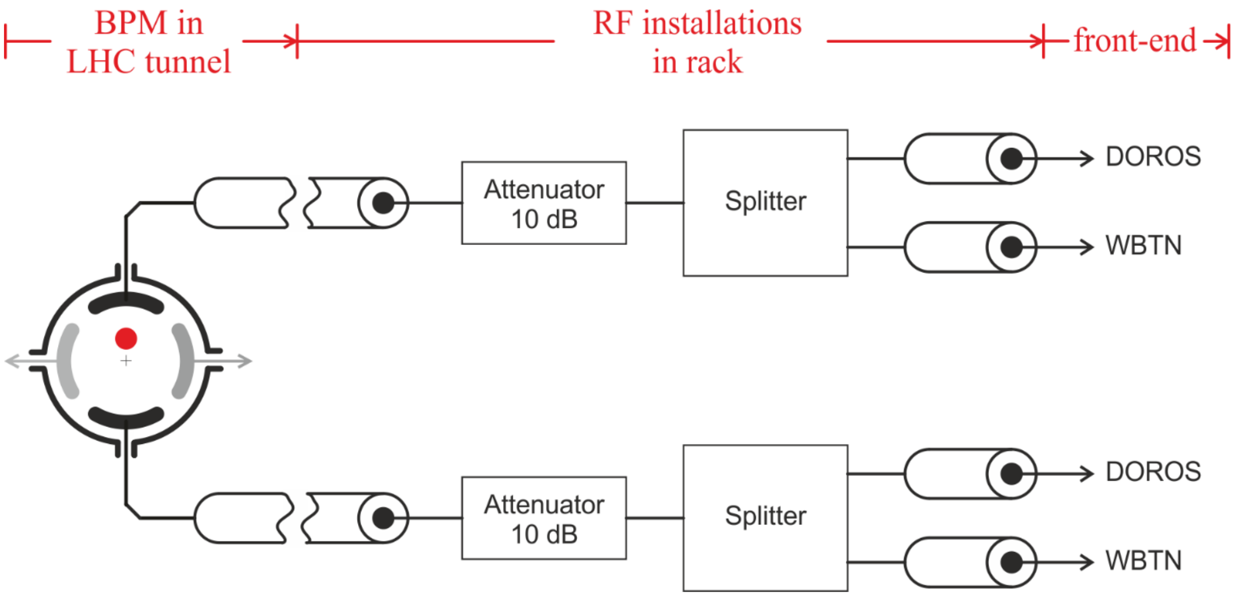
Laboratory measurements

- Sensitivity of the DOS subsystem to amplitude oscillation simulating beam excited oscillations.
- Measured with waveform generator simulating BPM signals on the DOROS inputs.



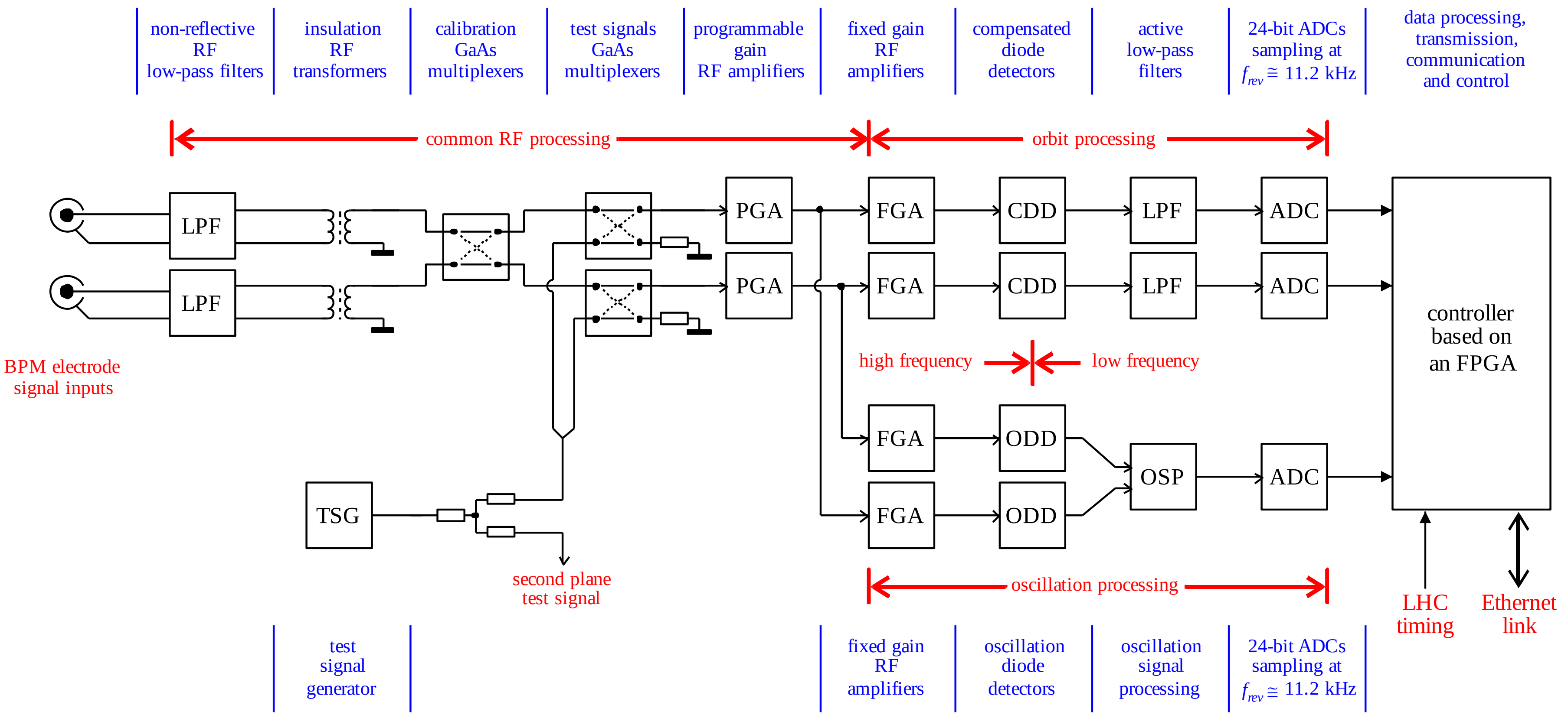
LHC measurement setup

- Measurement setup in LHC point 1 (ATLAS)
- The setup was used to compare the DOROS based on diode detectors and the standard LHC BPM system based on the Wide-Band Time Normalization (WBTN)



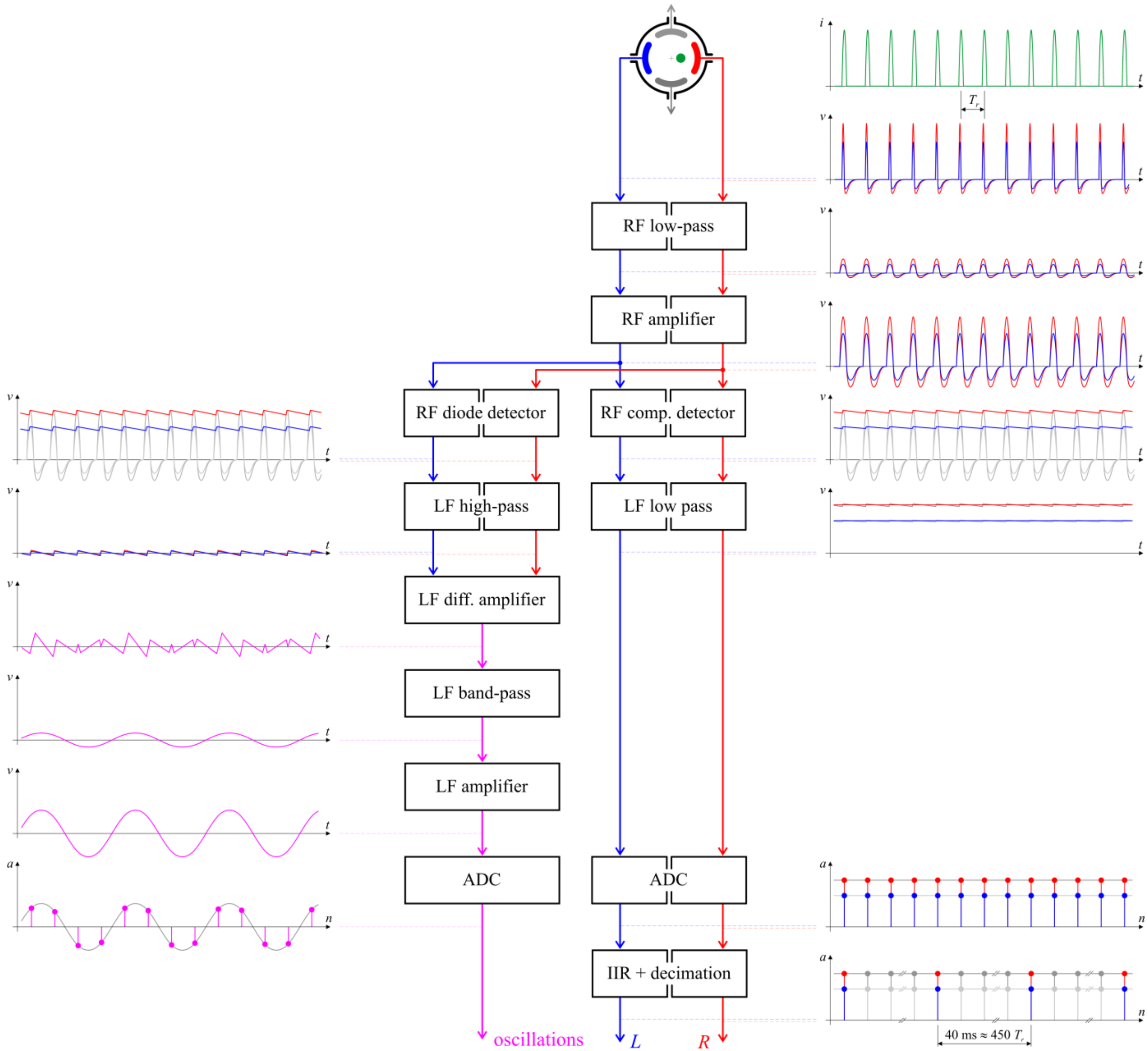
DOROS – Diode Orbit and Oscillation system, WBTN - Wide-Band Time Normalizer

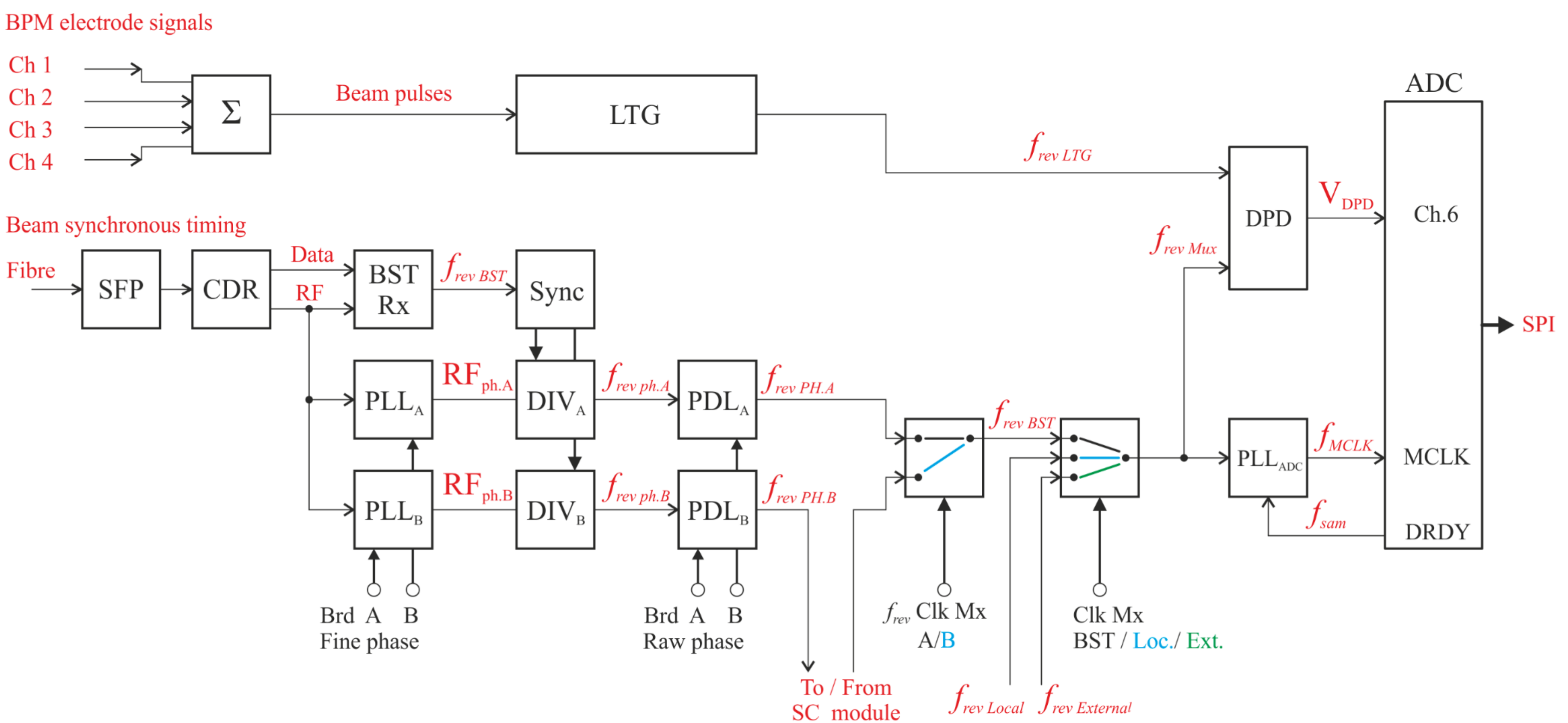
DOROS signal processing (1)

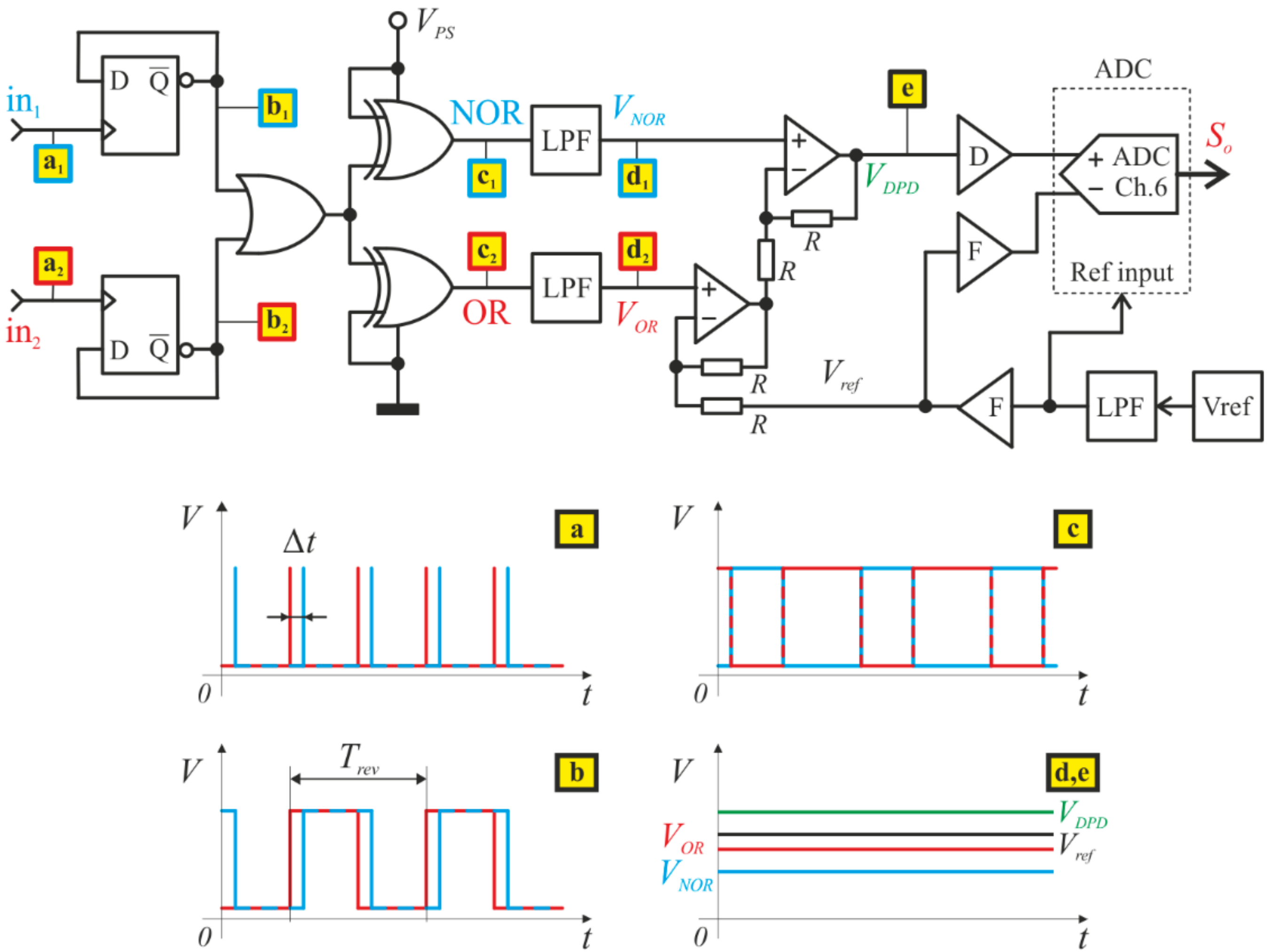


LPF – low-pass filter, TSG – test signal generator, PGA – programmable gain amplifier, FGA – fixed gain amplifier,
CDD – compensated diode detector, ODD – oscillation diode detector, OSP – oscillation signal processing.

DOROS signal processing (2)

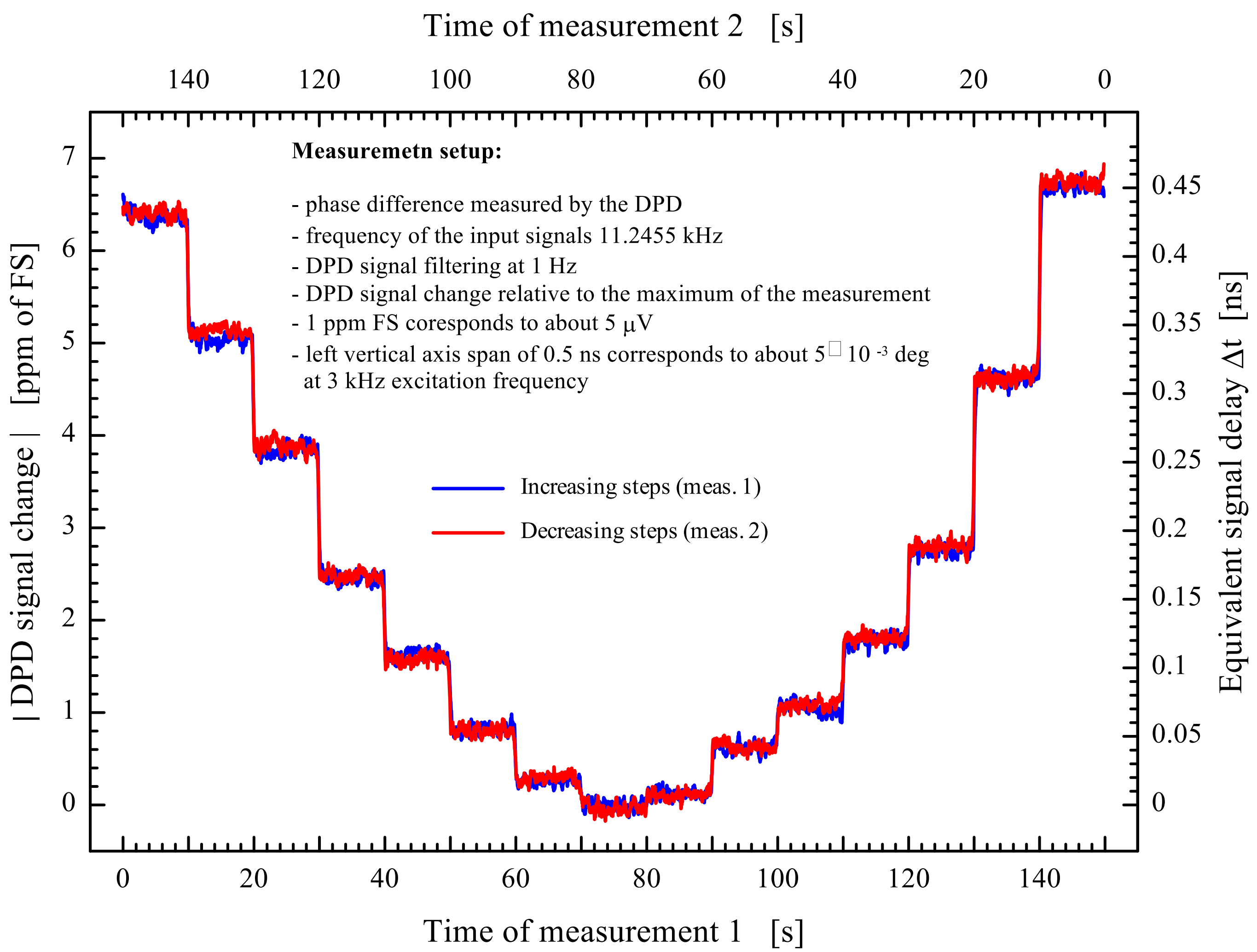



BPM electrode signals
Ch 1
Ch 2
Ch 3
Ch 4
Σ
Beam pulses
LTG
ADC
$f_{rev\ LTG}$
DPD
V_{DPD}
Ch.6
$f_{rev\ Mux}$
Beam synchronous timing
Fibre
SFP
CDR
Data
RF
BST Rx
$f_{rev\ BST}$
Sync
SPI
PLL_A
$RF_{ph.A}$
DIV_A
$f_{rev\ ph.A}$
PDL_A
$f_{rev\ PH.A}$
$f_{rev\ BST}$
PLL_{ADC}
f_{MCLK}
MCLK
PLL_B
$RF_{ph.B}$
DIV_B
$f_{rev\ ph.B}$
PDL_B
$f_{rev\ PH.B}$
f_{sam}
DRDY
Brd A B
Fine phase
Brd A B
Raw phase
f_{rev} Clk Mx
A/B
Clk Mx
BST / Loc./ Ext.
To / From
SC module
$f_{rev\ Local}$
$f_{rev\ External}$



V_{PS}
in₁
in₂
D
Q̄
a_1
a_2
b_1
b_2
NOR
OR
c_1
c_2
LPF
V_{NOR}
V_{OR}
d_1
d_2
e
V_{DPD}
R
D
F
ADC
+ ADC
− Ch.6
Ref input
S_o
V_{ref}
LPF
Vref
a
Δt
b
T_{rev}
c
d,e
V_{DPD}
V_{ref}
V_{OR}
V_{NOR}
V
t
0

DOROS synchronisation (3)



DOROS synchronisation (4)