Diode orbit electronics

Marek Gasior

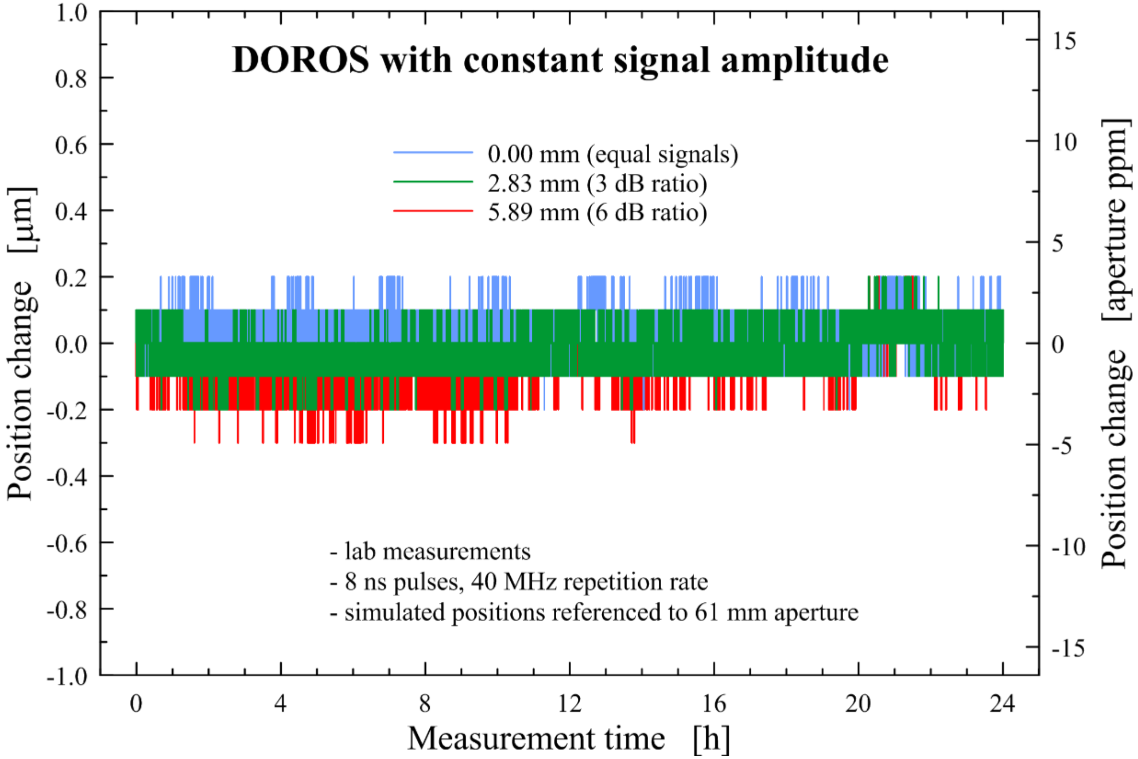
CERN Beam Instrumentation Group

Next Generation Beam Position Acquisition and Feedback Systems

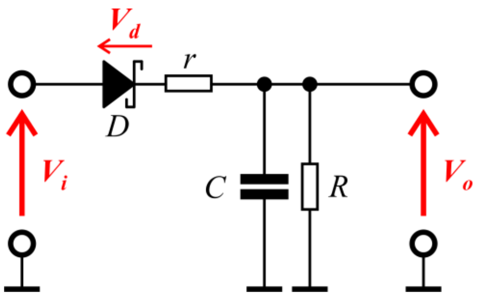
Joint ARIES Workshop on Electron and Hadron Synchrotrons
ALBA Synchrotron, 12 – 14 November 2018

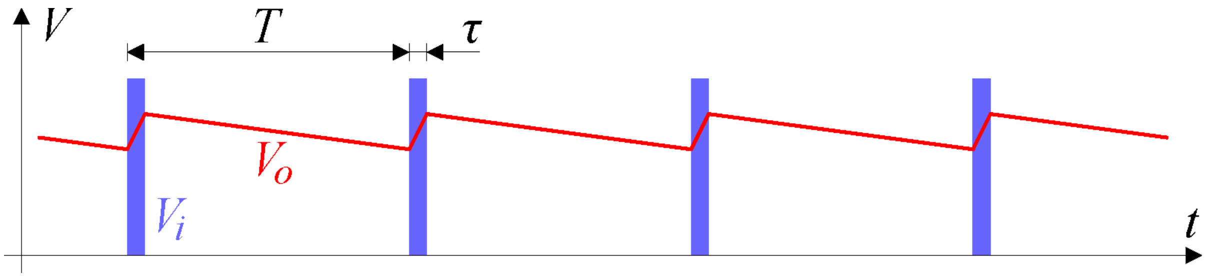
Why diodes for orbit measurements ?

- With diode detectors short beam pulses are converted to slowly varying DC voltages
- DC voltages can be measured with high resolution ADCs, resulting in large resolution of orbit measurements
- Very good long term stability
- With large detector time constants the output signal changes little with the number of circulating bunches (LHC: 1 .. 2600)
- Simplicity and robustness
- The most important limitation: slow



Diode detectors for short pulses





- Charge balance equation for the following assumptions:
  - a simple diode model with a **constant** forward voltage V_d and a **constant** series resistance r
  - constant charging and discharging current, i.e. output voltage changes are small w.r.t. the input voltage
- For large T to τ rations (small signal duty cycle) peak detectors require large R values and a high input impedance amplifier, typically a JFET-input op-amp
- For LHC with one bunch the duty cycle is very small: $\tau \approx 1$ ns and $T \approx 89$ µs, so $\tau / T \approx 10$ ppm. In practice 10 MΩ resistors in use.
- The slowest capacitor discharge is limited by the reverse leakage current of the diode (in the order of 10 nA for RF Schottky diodes)

$$\frac{V_o}{R} T = \frac{V_i - V_o - V_d}{r} \tau$$

⇓

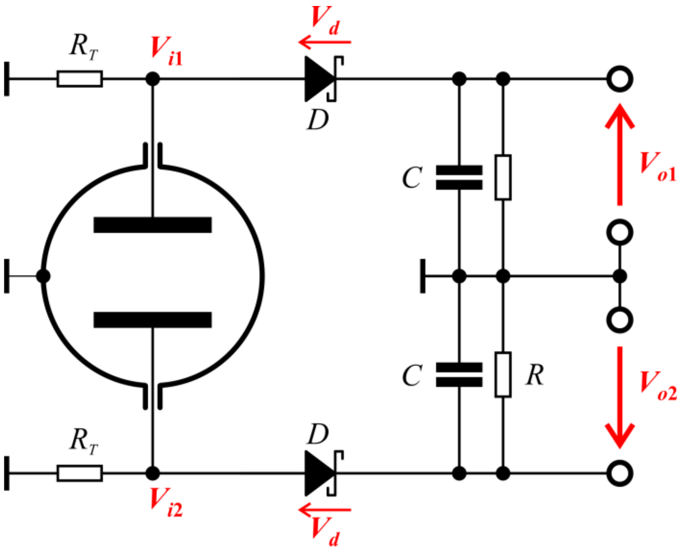
$$\frac{V_o}{V_i - V_d} = \frac{1}{1 + \frac{r}{R} \cdot \frac{T}{\tau}}$$

⇓

- $V_i >> V_d$
- n bunches

$$\frac{V_o}{V_i} = \frac{1}{1 + \frac{r}{R} \cdot \frac{T}{n\tau}}$$

Simple diode detectors for BPM signals

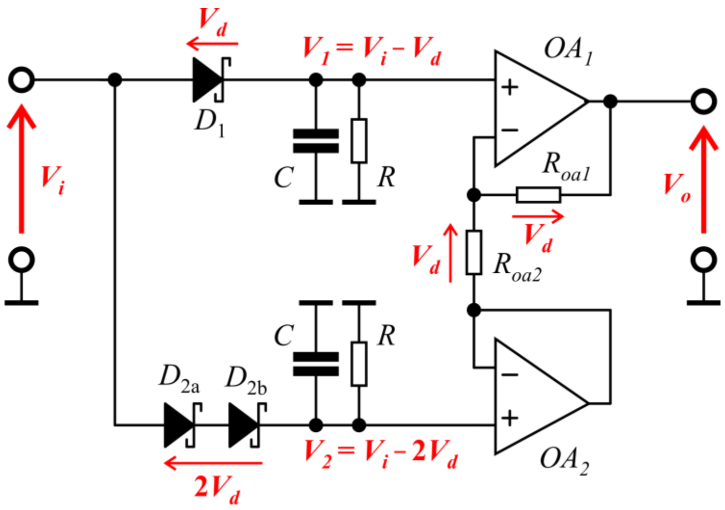


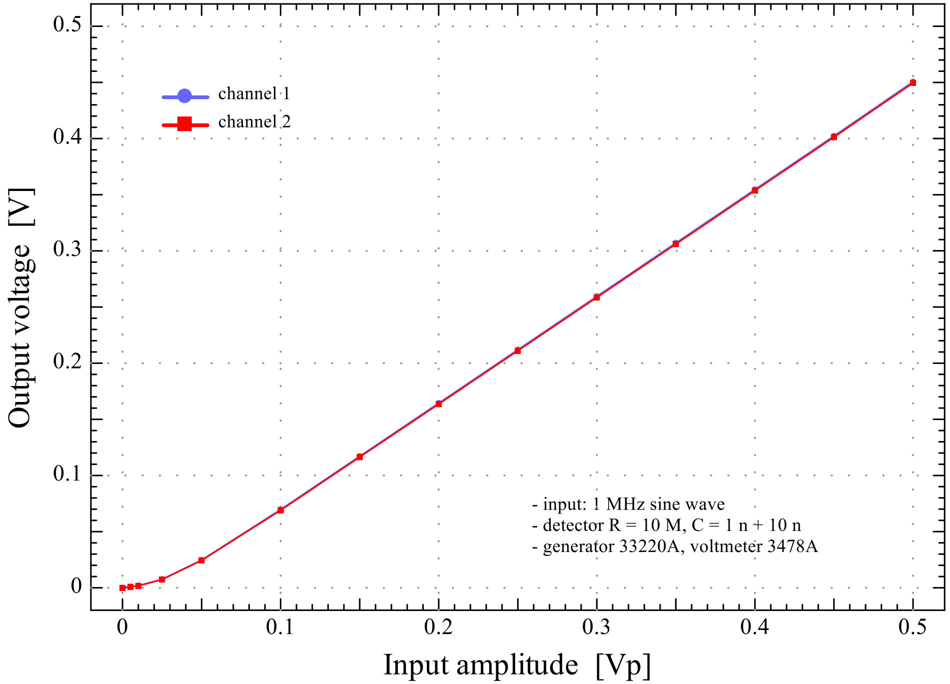
$$\text{ideal:} \quad p = c_g \frac{V_{i1} - V_{i2}}{V_{i1} + V_{i2}}$$

$$\text{real:} \quad p = c_g \frac{V_{o1} - V_{o2}}{V_{o1} + V_{o2}} = c_g \frac{V_{i1} - V_{i2}}{V_{i1} + V_{i2} - 2\,V_d}$$

- One diode detector for each BPM electrode
- Subtracting signals before the detectors (e.g. by a 180° hybrid) does not help, as the resulting signal would be:
  - smaller, resulting in larger position errors
  - changing the sign when crossing the BPM centre
- The diode forward voltage V_d introduces a significant position error
- V_d depends on the diode current (and by consequence on V_i) and temperature
- Simple diode detectors can be used for applications when beam position errors are not important, e.g.
  - tune measurement systems
  - “intensity” beam presence detection systems (LHC Beam Presence Flag System)

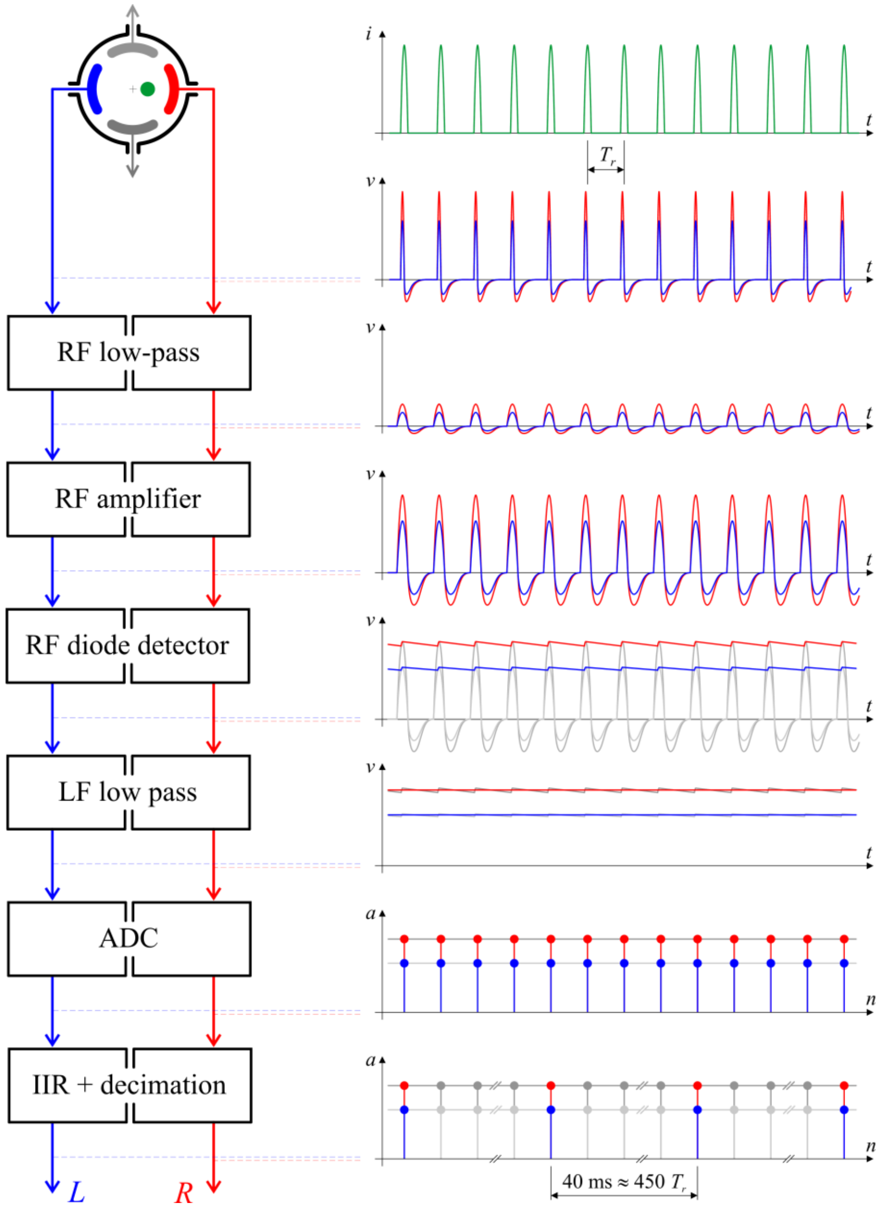
Compensated diode detector





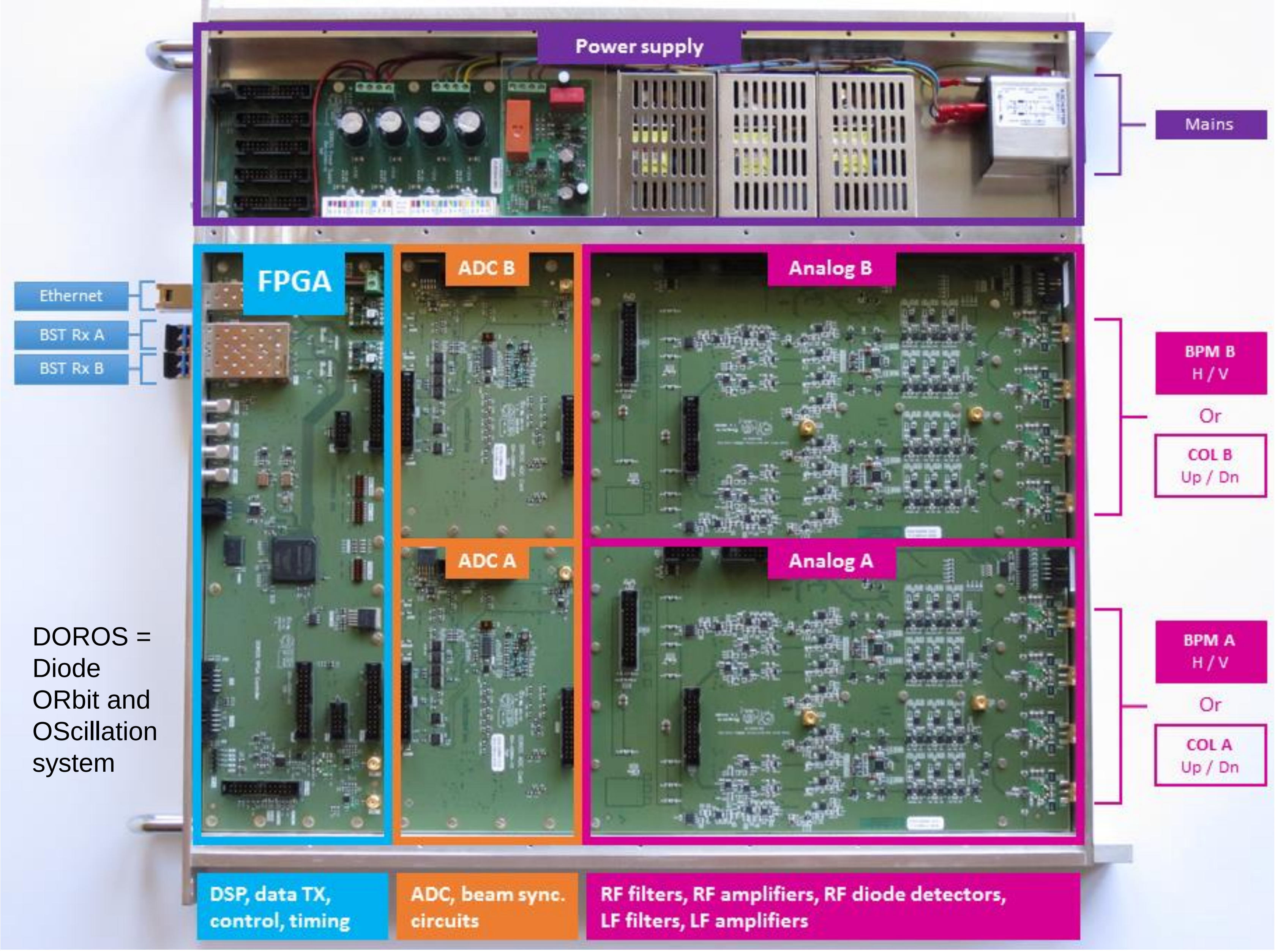
- Compensated diode detector consists of two diode peak detectors, one with single, second – with two diodes. All three diodes are in one package, for good thermal coupling and symmetry of the forward voltages V_d.
- Two operational amplifiers are used to derive 2 V_d voltage and to add it to the output of the two-diode detector. This way the resulting output voltage is equal to the input peak voltage.
- To get an “ultimate peak mode operation”, the discharge resistors are in practice omitted. In this case the discharge is done by the reverse leakage current of the diodes.
- The asymmetry in the charging conditions for each individual detector becomes less important for larger input voltages. Therefore, the compensation improves with increasing signal levels
- In practice the largest signal level is limited by the linear operation levels of the driving amplifier

Diode orbit processing overview



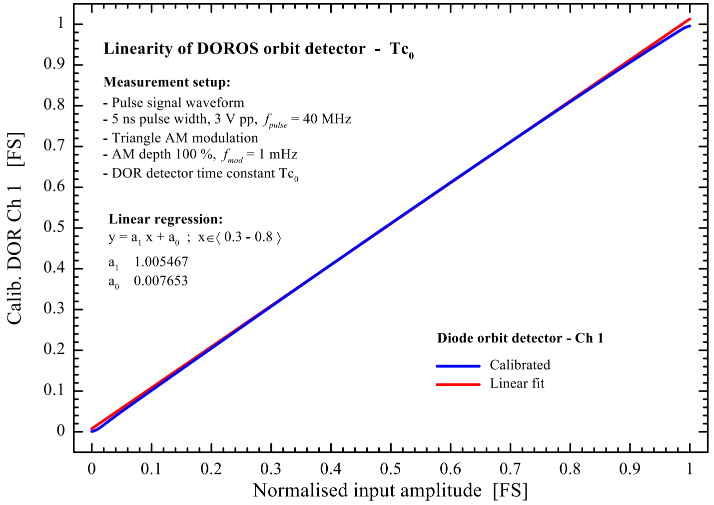
- Short pick-up pulses go through input low-pass filters to limit their slew rate and reduce peak amplitudes
- RF amplifiers provide optimal amplitude of the pulses on the compensated diode detectors
- Diode detectors convert pulses into slowly varying signals
- Low frequency low-pass filters remove bunch pattern ripple and act as anti-aliasing filters
- 24-bit ADC digitises detector signals at the f_{rev} rate (for LHC 11.2 kHz)
- IIR acts as an averaging filter to decrease signal noise and as an mailbox between two clock domains (f_{rev} of the machine and ms of the control system)
- The filtered signals are decimated to 25 Hz for compatibility with the LHC orbit feed-back system

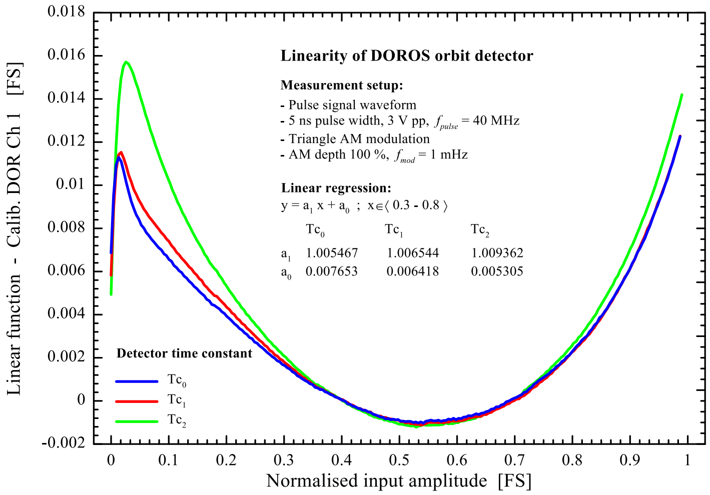
Is it really so simple ?



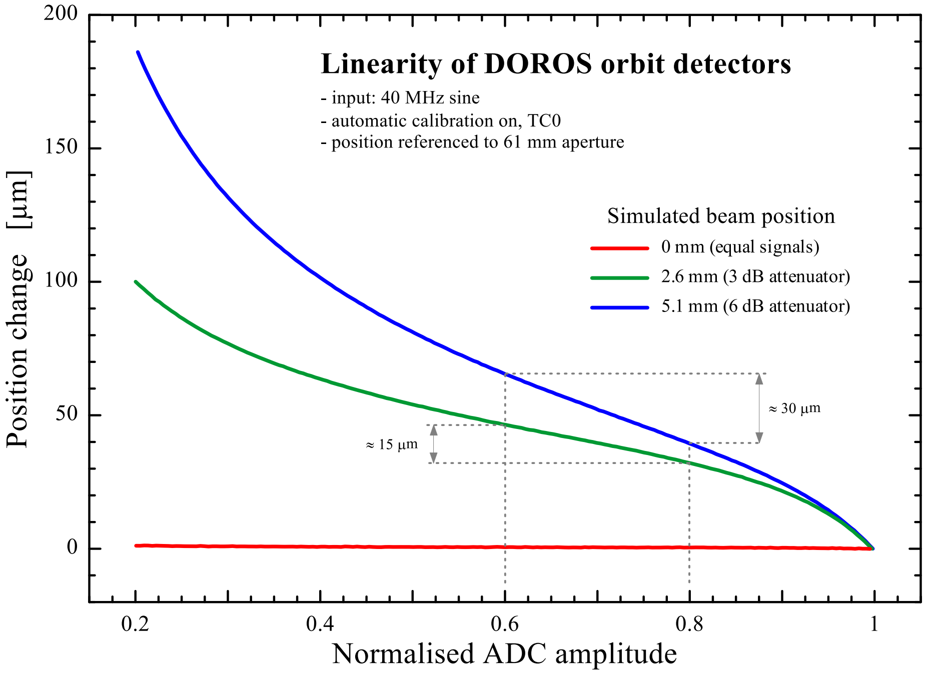
DOROS = Diode ORbit and OScillation system

Linearity of orbit diode detectors

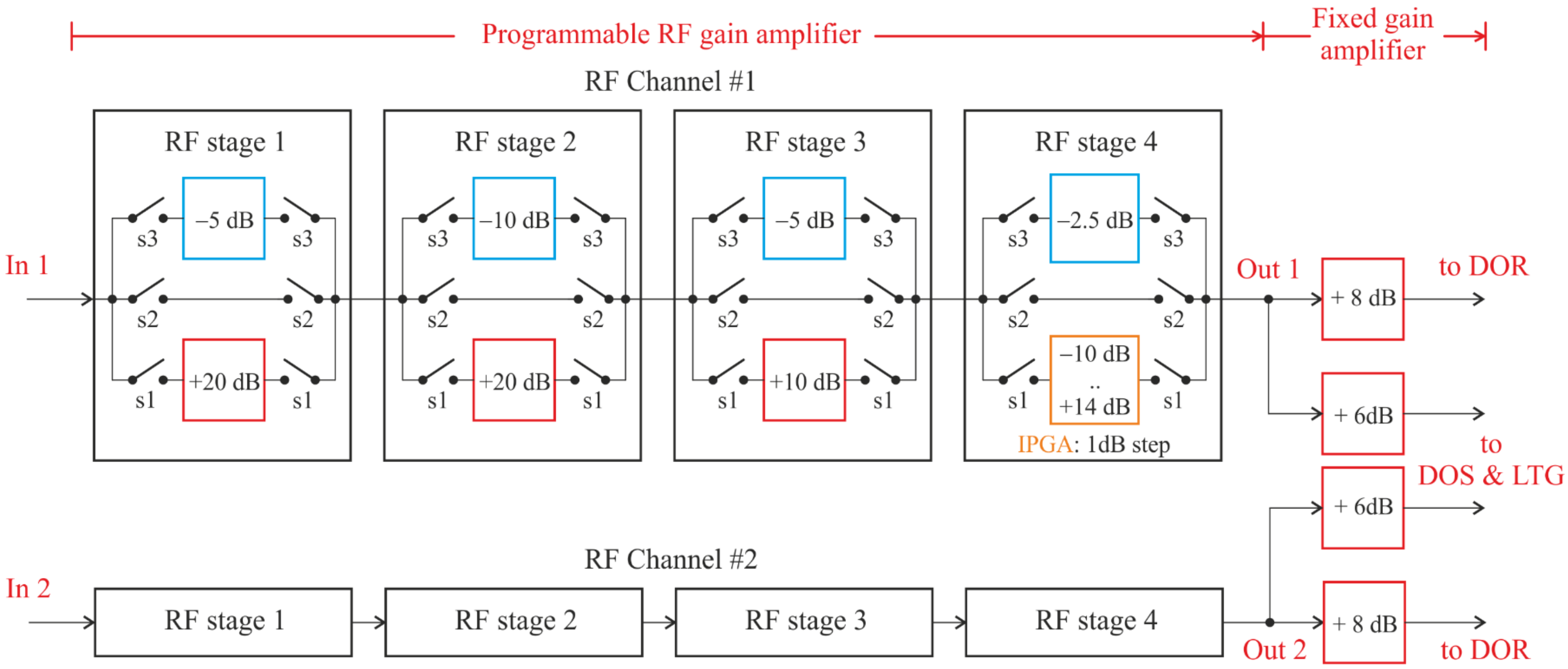




- The left upper plot shows a laboratory measurement of the detector linearity together with its linear fit.
- The right upper plot shows the deviation of the detector characteristic from the linear fit for three detector time constants. Which time constant is used depends on the number of circulating bunches.
- Systematic position errors show up when there is at the same time a larger position offset and important signal amplitude change

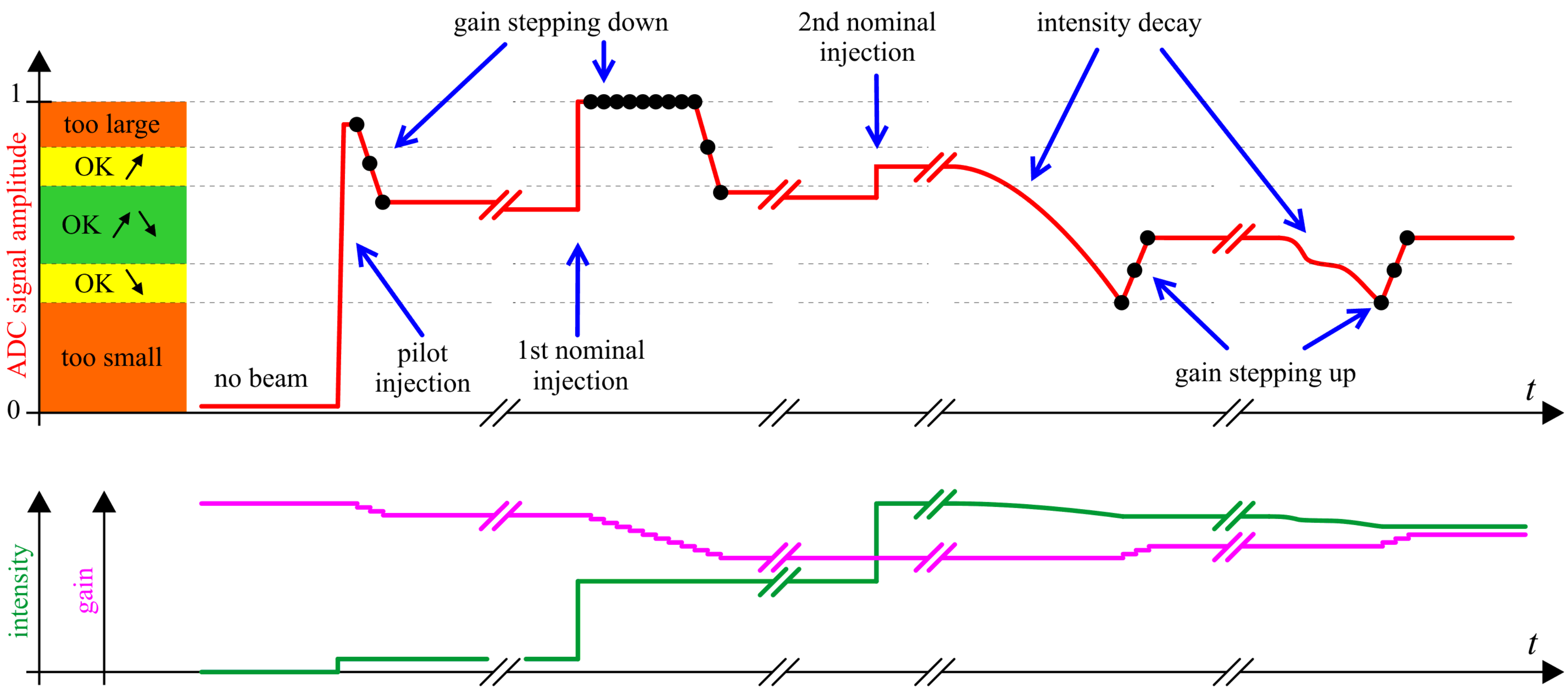


RF amplifier



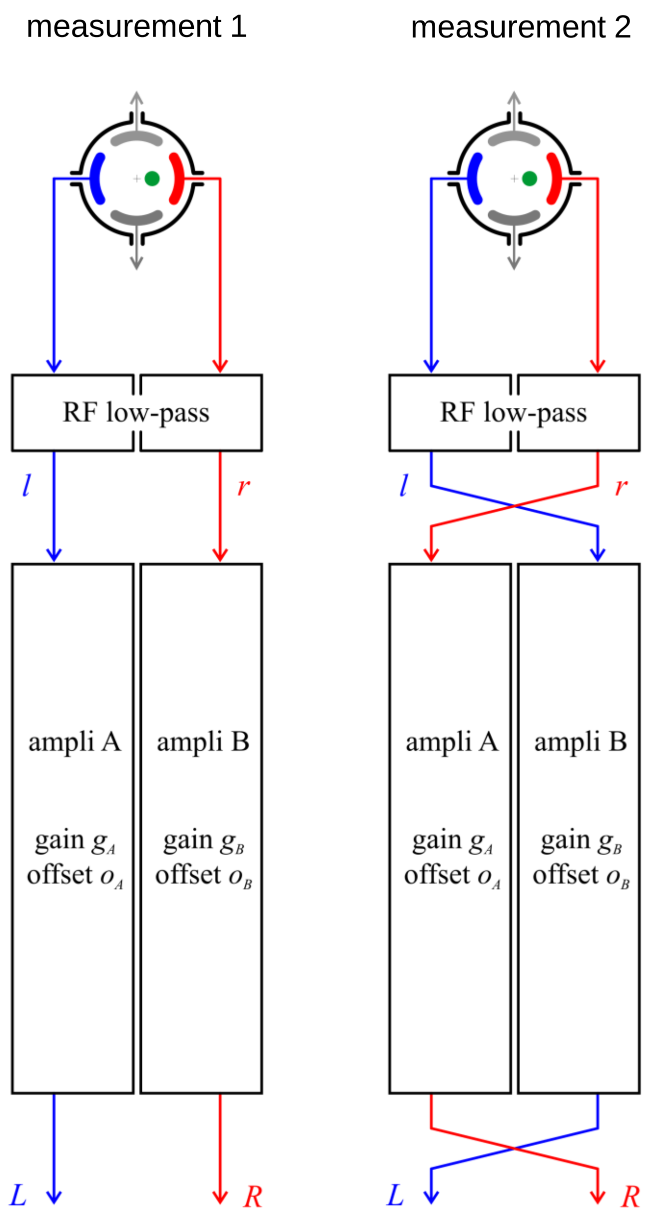
- Shown one RF amplifier pair for one BPM plane (out of 4 of one DOROS front-end)
- Each RF amplifier is identical
- The RF amplifier block is the most complex analogue part of the DOROS front-end and required the longest development
- Each channel consists of 4 attenuators, 5 fixed gain amplifiers and one programmable gain amplifier with 1 dB gain step
- Each RF amplifier has at least 200 MHz bandwidth
- The gain of the RF amplifier can be changed from -14 dB to 72 dB in 1 dB steps, covering an 86 dB dynamic range

Automatic gain control of the RF amplifier



- Four channels of one pick-up have the same gain
- Gain control is based on the largest signal of all four electrodes
- The gain is adjusted to cause the largest signal to have the amplitude in the green zone
- The gain control levels are programmable and can be changed according to actual beam conditions
- One gain step is 1 dB i.e. about 12 %

Channel asymmetry compensation (“auto-calibration”)



$$L_1 = g_A\, l + o_A$$

$$R_1 = g_B\, r + o_B \qquad L_c = \frac{L_1 + L_2}{2}$$

$$L_2 = g_B\, l + o_B \qquad R_c = \frac{R_1 + R_2}{2}$$

$$R_2 = g_A\, r + o_A$$

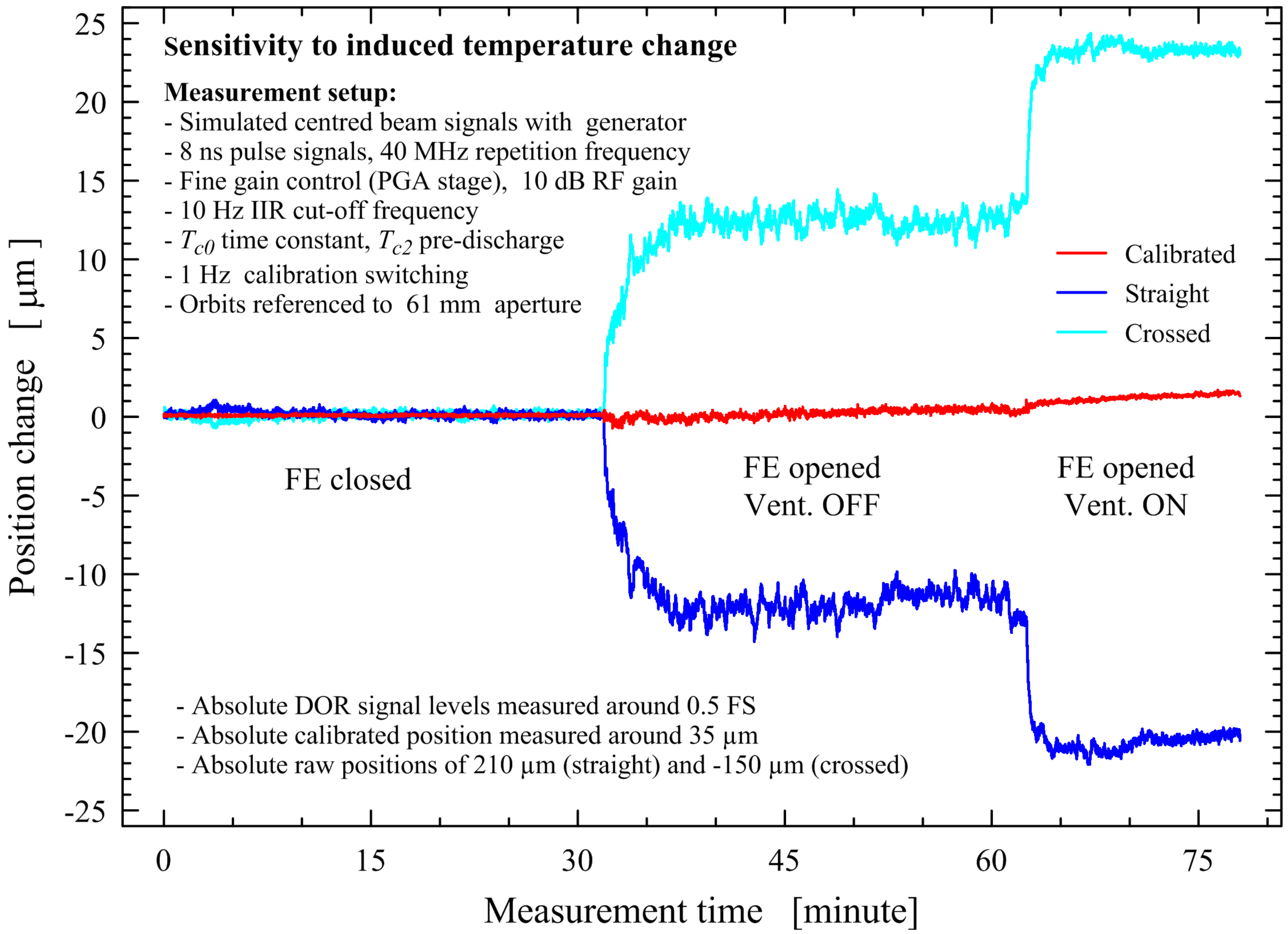
$$p_{Hc} = \frac{R_c - L_c}{R_c + L_c} = \frac{(g_A + g_B)(r - l)}{(g_A + g_B)(r + l) + 2(o_A + o_B)} \cong \frac{r - l}{r + l}$$

- Channel switching is done typically every 1 s.
  The fastest can be 12.5 Hz.
- One calibrated measurement comes from two simple ones using moving average = one calibrated measurement every 1 s with 1 s delay
- Typically g_A, $g_B \in [0.95, 1.05]$, o_A, $o_B \in [-0.001, 0.001]$

A numerical example (assuming simple linear characteristic of the pick-up):

- Perfect amplifiers ($g_A = g_B = 1$ and $o_A = o_B = 0$):
  for $l = 0.5$, $r = 1$, $p_H = 0.3333$ and $P_H = 5.083$ mm for Q1 BPM with $d = 61$ mm.
- Assume amplifiers with $g_A = g_B = 1.05$ and $o_A = o_B = 0.001$:
  $p_H = 0.3329$ and $P_H = 4.927$ mm, resulting in an error of 6 µm

Orbit auto-calibration dealing with drifts



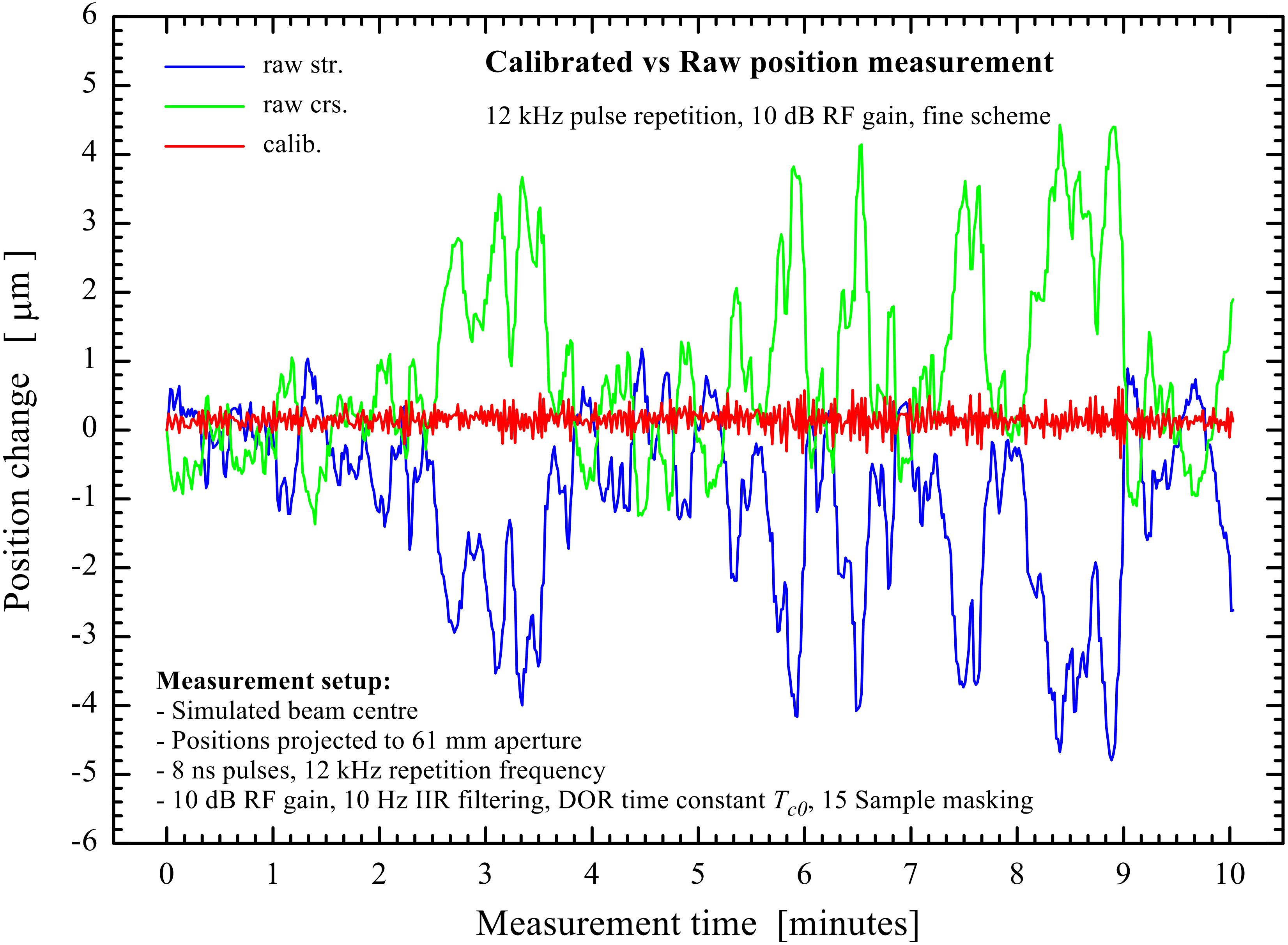
Sensitivity to induced temperature change

Measurement setup:

- Simulated centred beam signals with generator
- 8 ns pulse signals, 40 MHz repetition frequency
- Fine gain control (PGA stage), 10 dB RF gain
- 10 Hz IIR cut-off frequency
- T_{c0} time constant, T_{c2} pre-discharge
- 1 Hz calibration switching
- Orbits referenced to 61 mm aperture

- Absolute DOR signal levels measured around 0.5 FS
- Absolute calibrated position measured around 35 µm
- Absolute raw positions of 210 µm (straight) and -150 µm (crossed)

Orbit auto-calibration dealing with noise



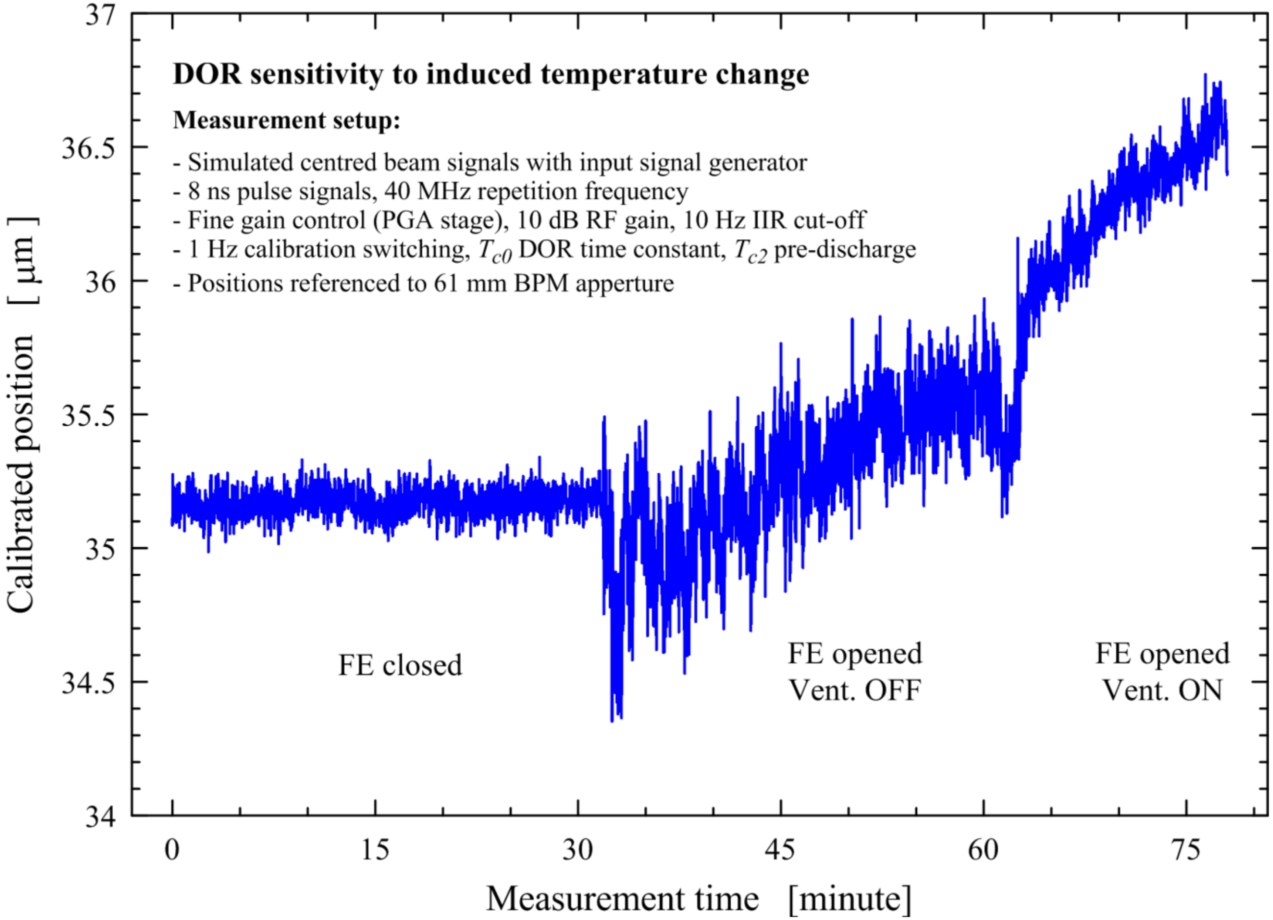
Calibrated vs Raw position measurement

12 kHz pulse repetition, 10 dB RF gain, fine scheme

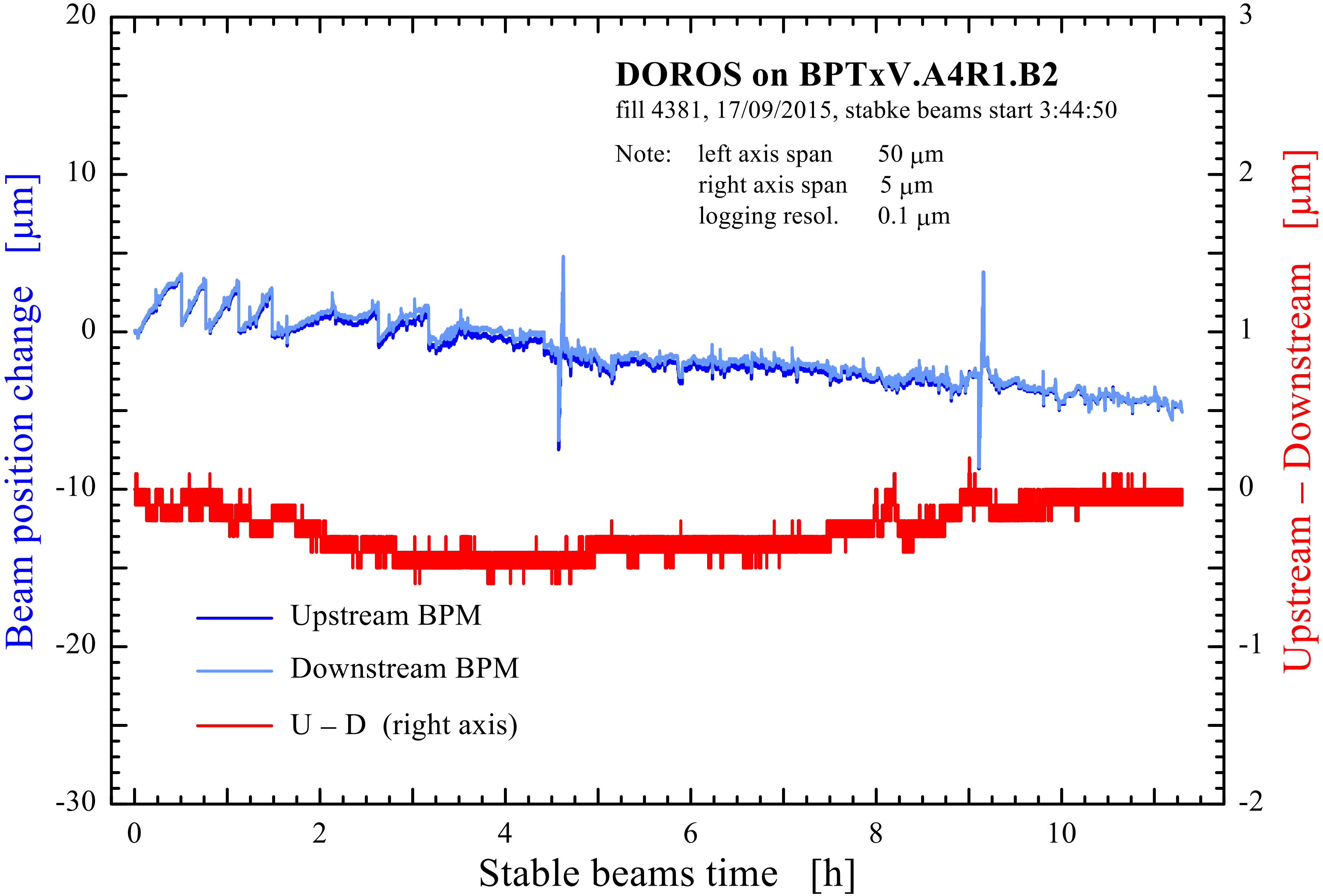
Measurement setup:

- Simulated beam centre
- Positions projected to 61 mm aperture
- 8 ns pulses, 12 kHz repetition frequency
- 10 dB RF gain, 10 Hz IIR filtering, DOR time constant T_{c0}, 15 Sample masking

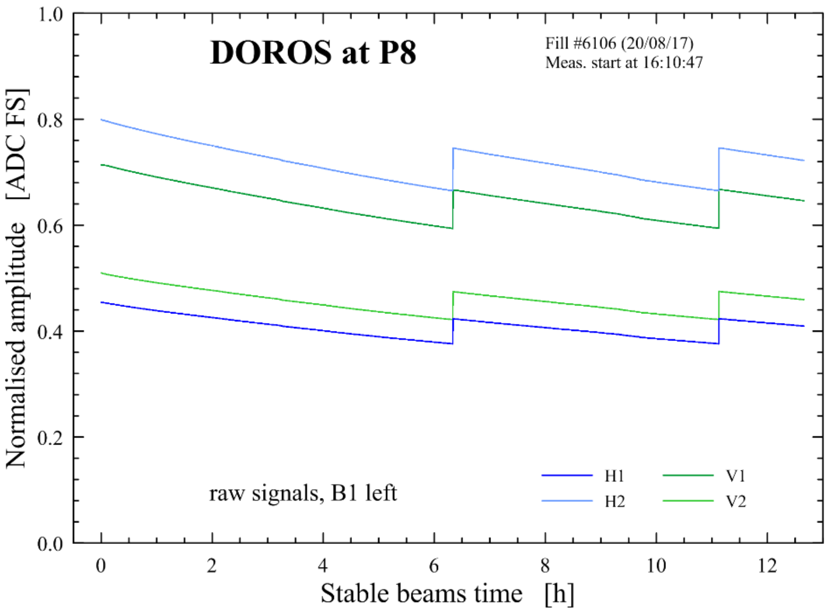
Thermal sensitivity

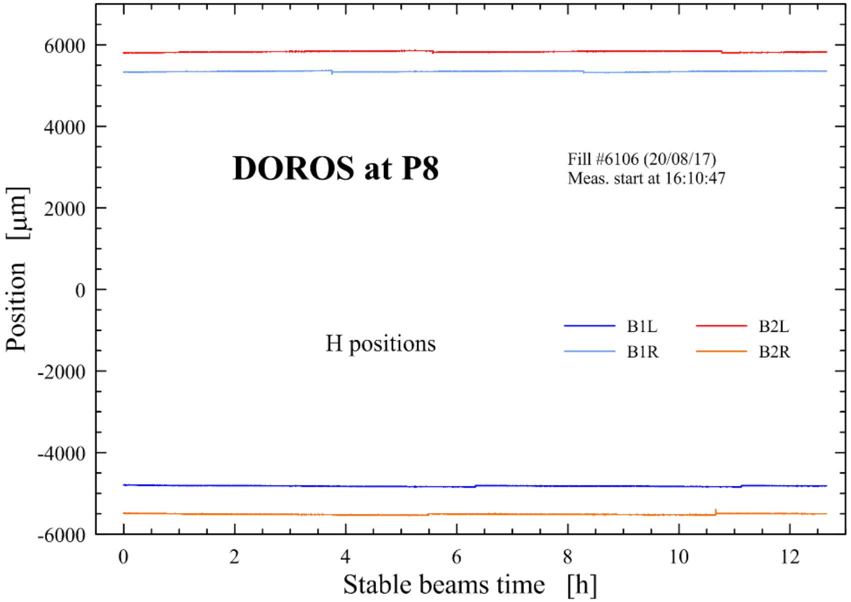


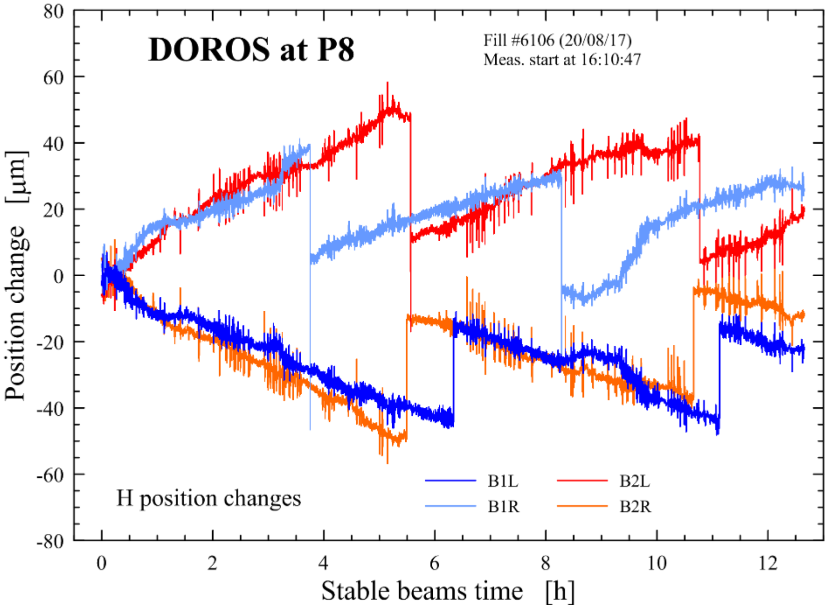
Stability with LHC beam and collimator BPMs

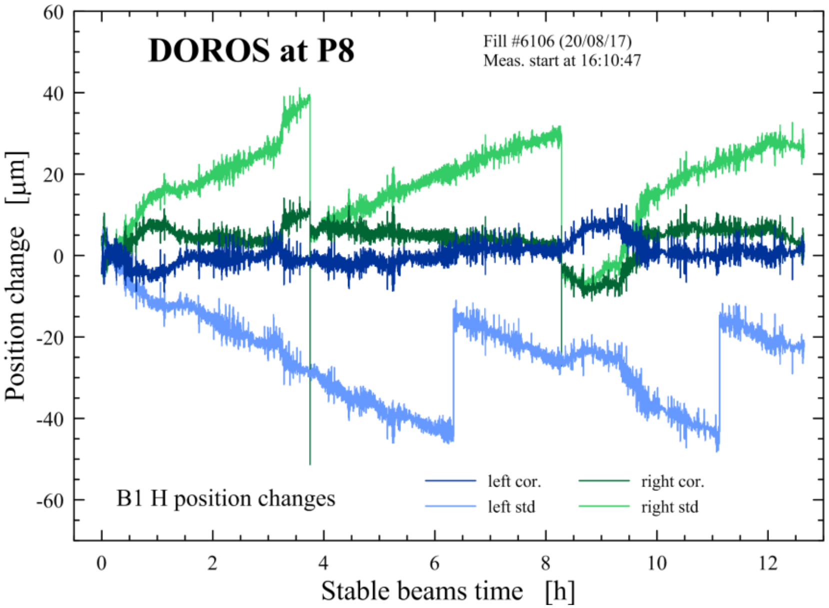


Stability at LHC P8 and the detector linearity correction

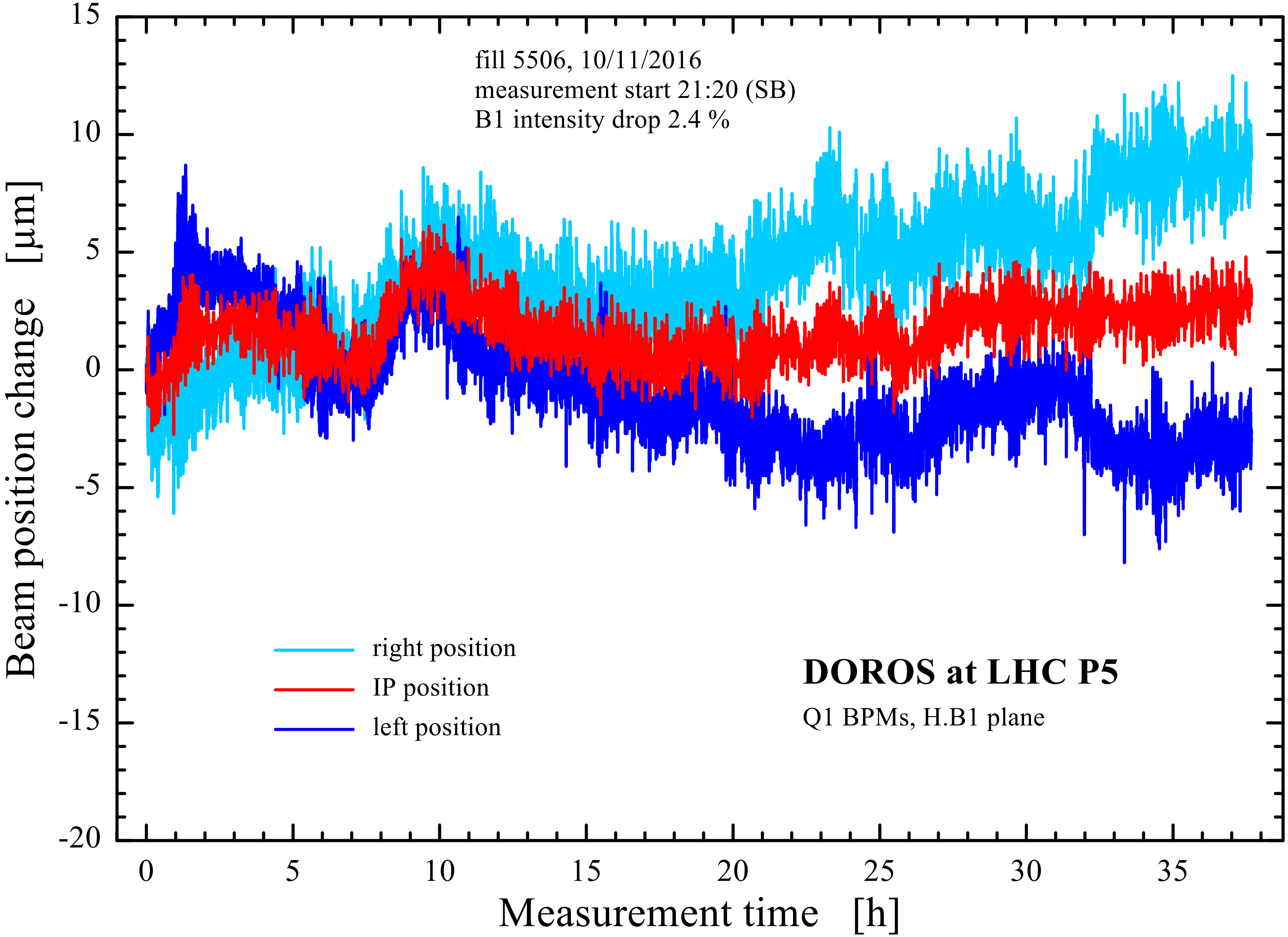




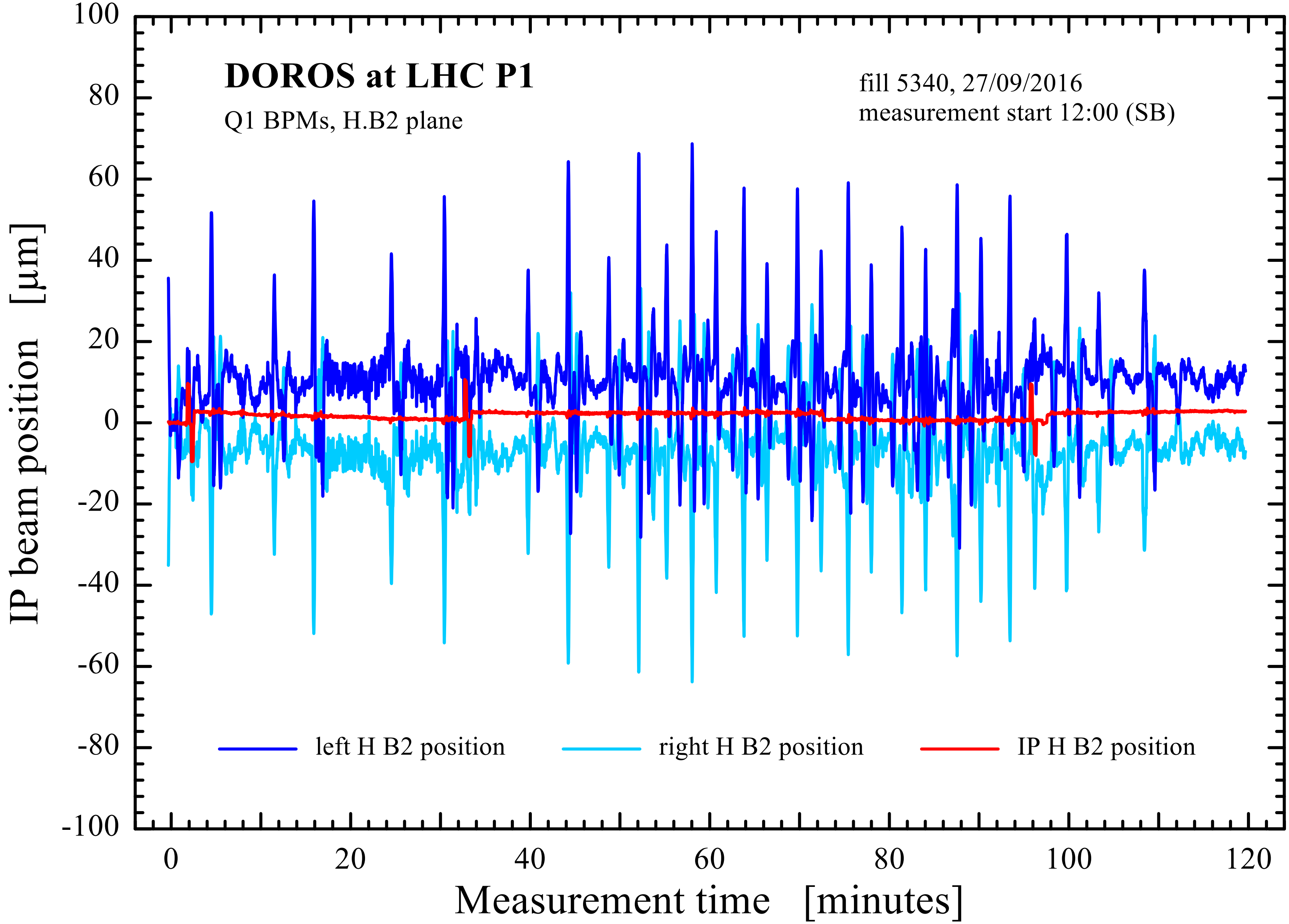




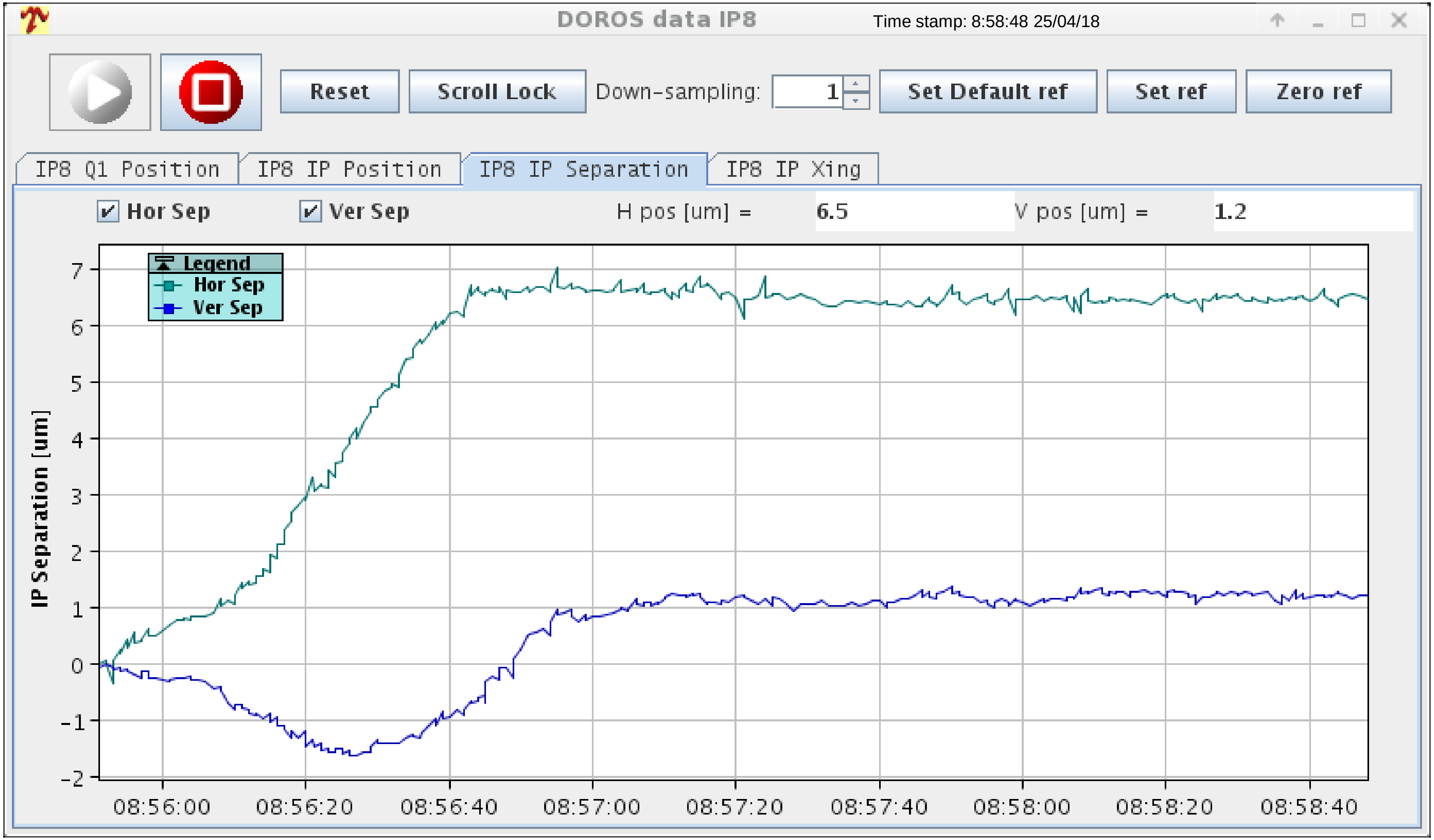
Stability with (almost) constant intensity



Beam orbit stability and noise

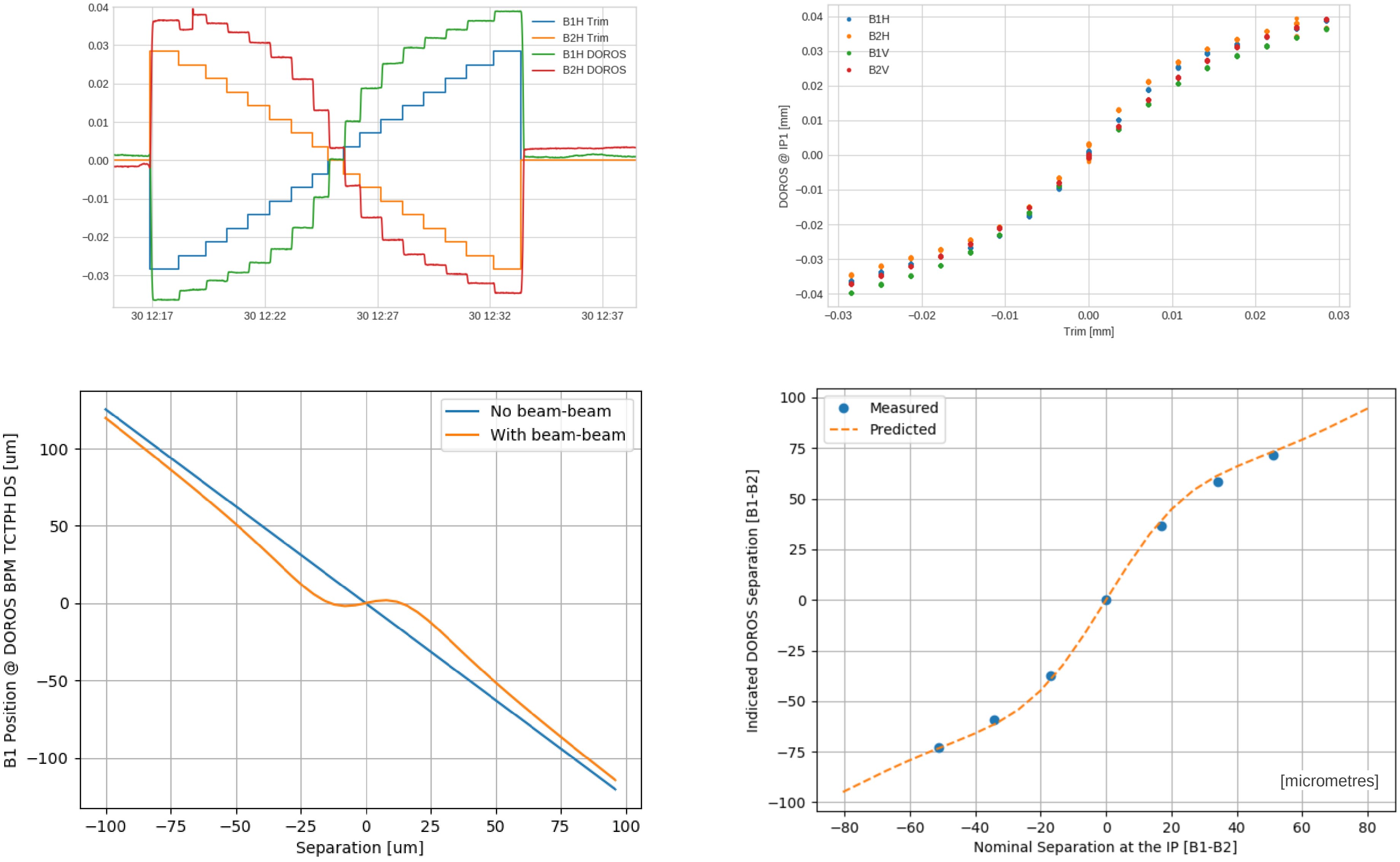


An example from the LHC logbook: beams separation in IP8



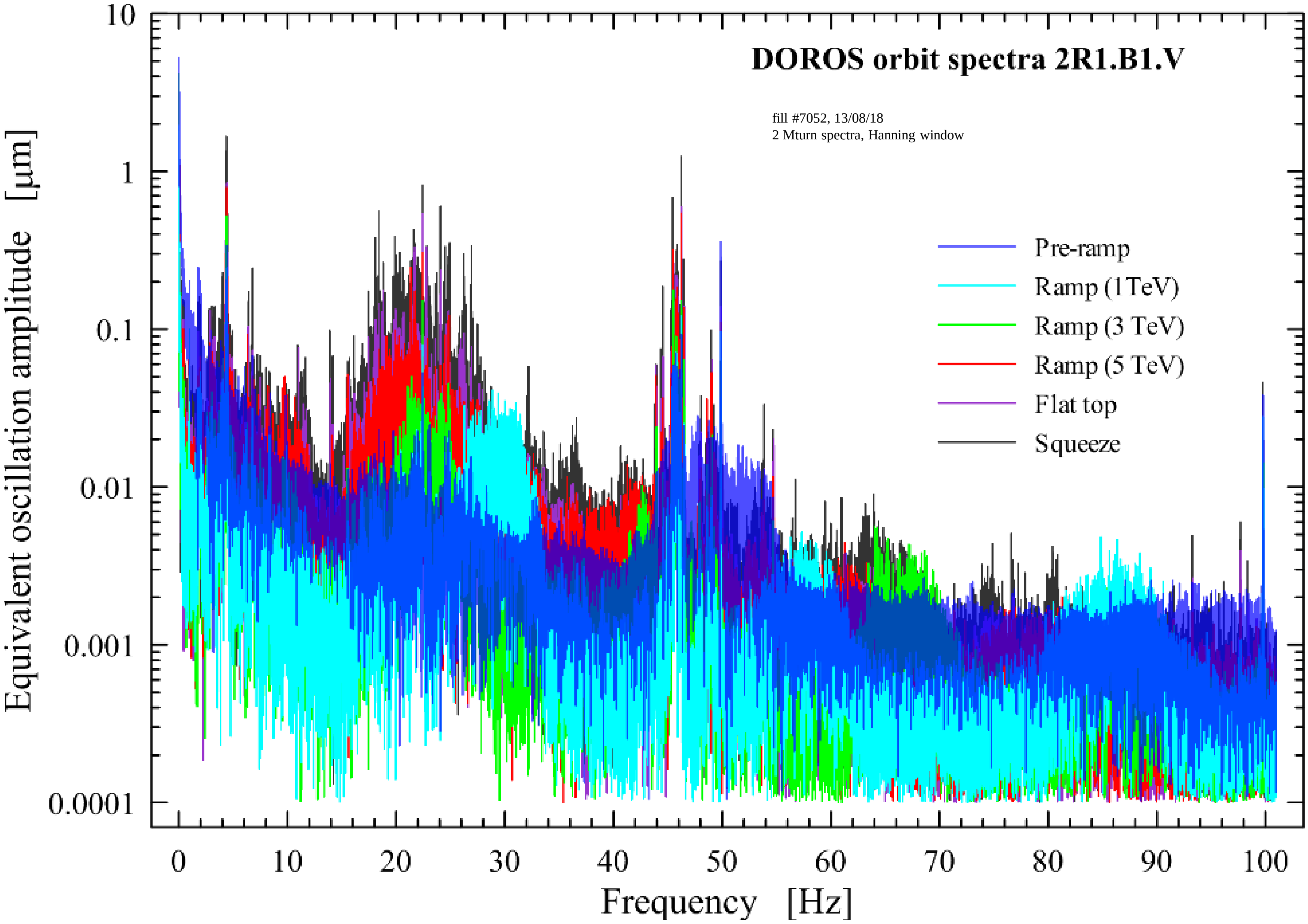
- Beam 1 to beam 2 separation in the interaction point (IP) is calculated using beam positions from the left and right BPMs closest to the experiment, interpolated to the IP
- Please note that each separation on the plot is calculated upon readings from 4 BPMs.

Beam-beam orbit effects observed with DOROS



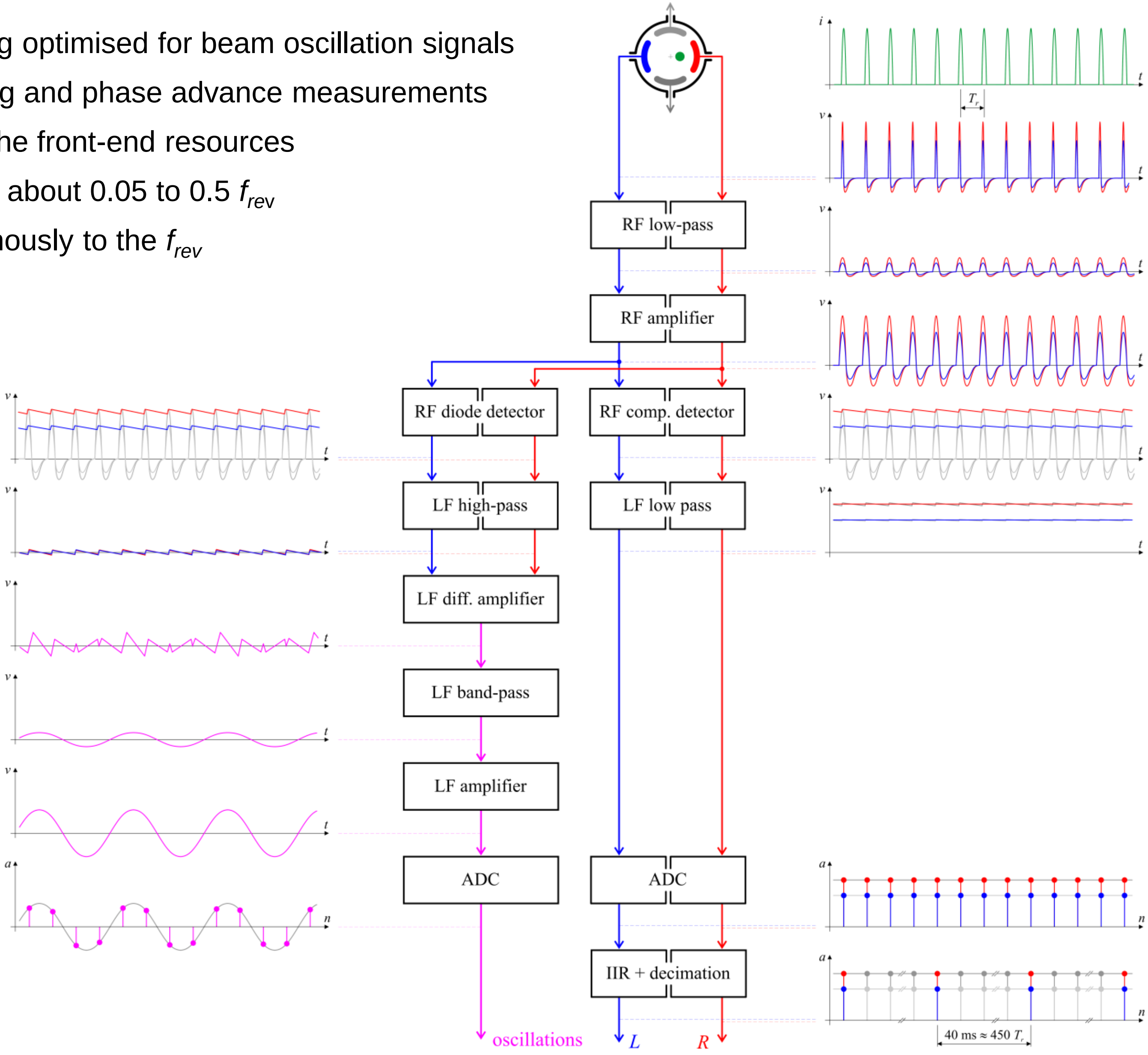
Measurements first reported as a DOROS non-linearity, later explained by beam-beam forces. Plots curtesy of M. Hostettler et al.

2 Mturn LHC orbit spectra at P1



DOROS – oscillation part

- Separate analogue processing optimised for beam oscillation signals
- Designed for betatron coupling and phase advance measurements
- Shares with the orbit a lot of the front-end resources
- Processing bandwidth is from about 0.05 to 0.5 f_{rev}
- Signals are digitised synchronously to the f_{rev}



Summary

Diode orbit strengths:

- Excellent resolution
- Very good long term stability
- Limited dependence of the output voltages on the number of circulating bunches
- Simple and robust
- Very low rates of the digital data
- “Perfect beam sampling” even for very short bunches without any precise timing
- Slowly varying signals at the detector output, easy for precise signal processing and high resolution digitization
- “Natural noise gating” due to very low “diode detector gain” for noise between beam pulses
- No limit for beam offsets, as signals from each electrode are processed separately

Diode orbit weaknesses:

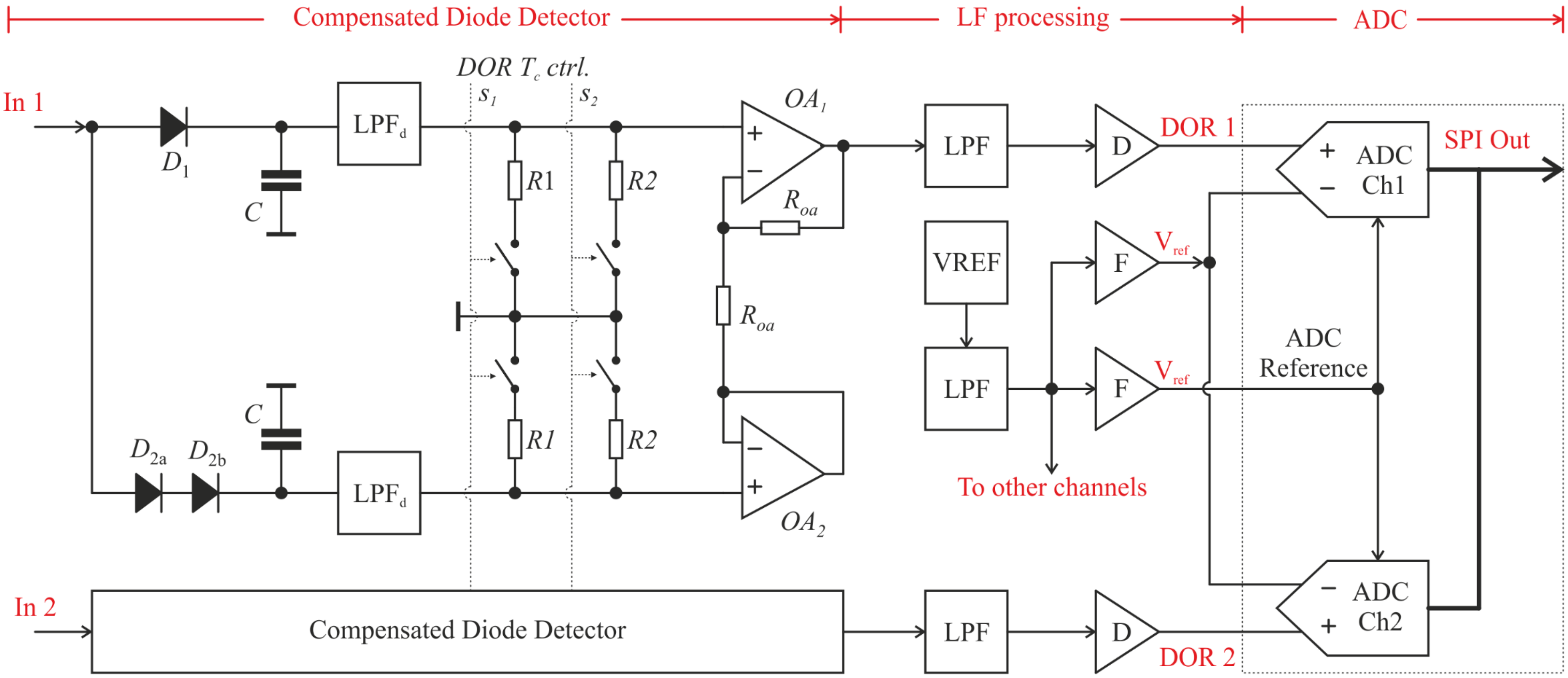
- Limited dynamic range of the detector linear operation, variable gain amplifiers required to compensate important bunch intensity variations
- Only turn by turn, bunch by bunch not easy (some ”reset techniques” required)
- Large bunches favoured (good for masking undesirable reflections)
- Important dependence of the measured position on the signal amplitude change for large beam offsets. Related errors some two orders of magnitude larger than the system resolution…

LHC DOROS system:

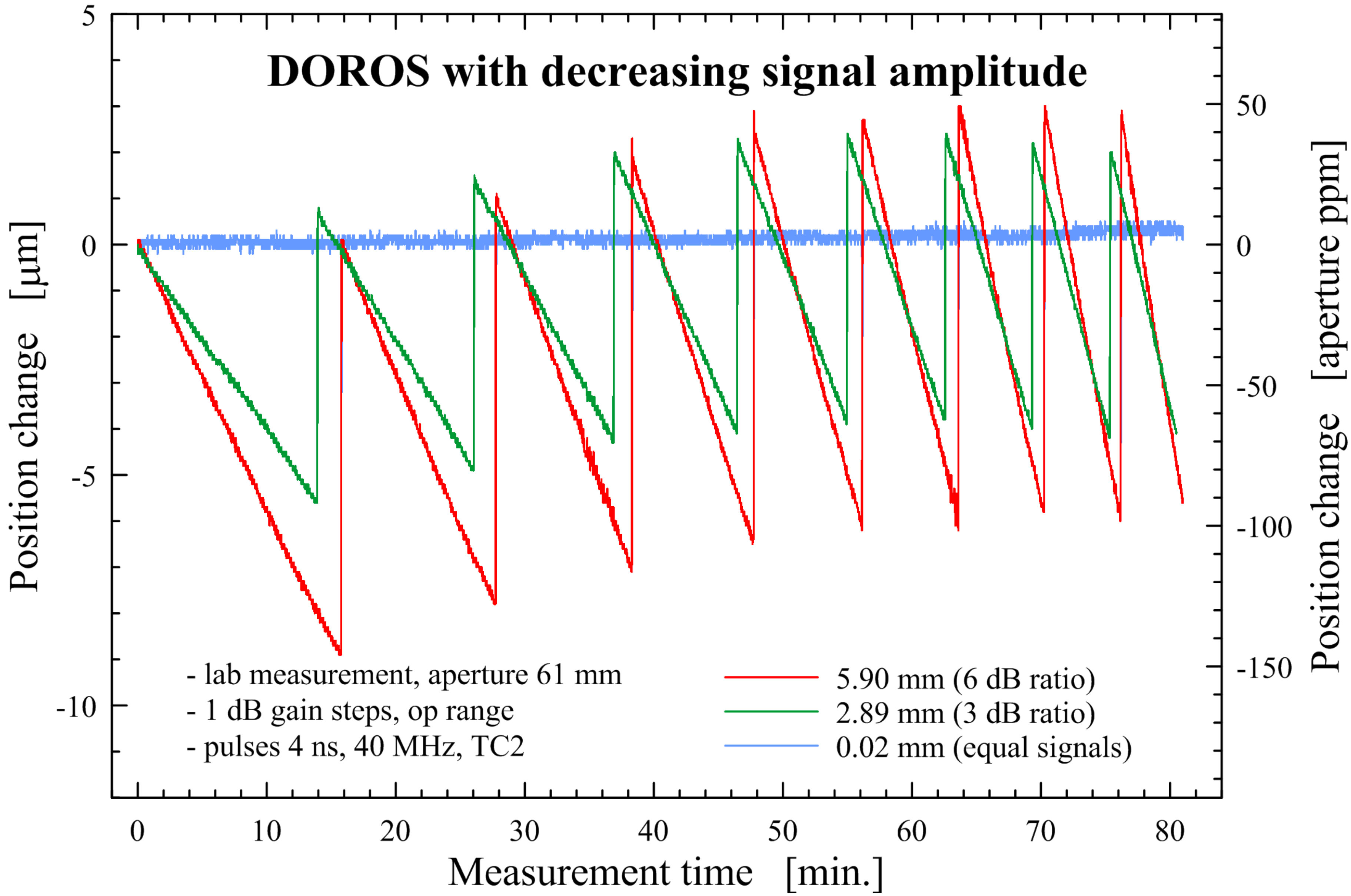
- Currently some 50 FEs in use on some 100 BPMs; about 50/50 on collimator and standard BPMs
- Very good performance on BPMs with small beam offsets
- Ongoing development to improve systematics with large beam offsets and changing intensity. The most promising strategy: smaller gain step. Currently studied PIN diode attenuators.

Spare slides

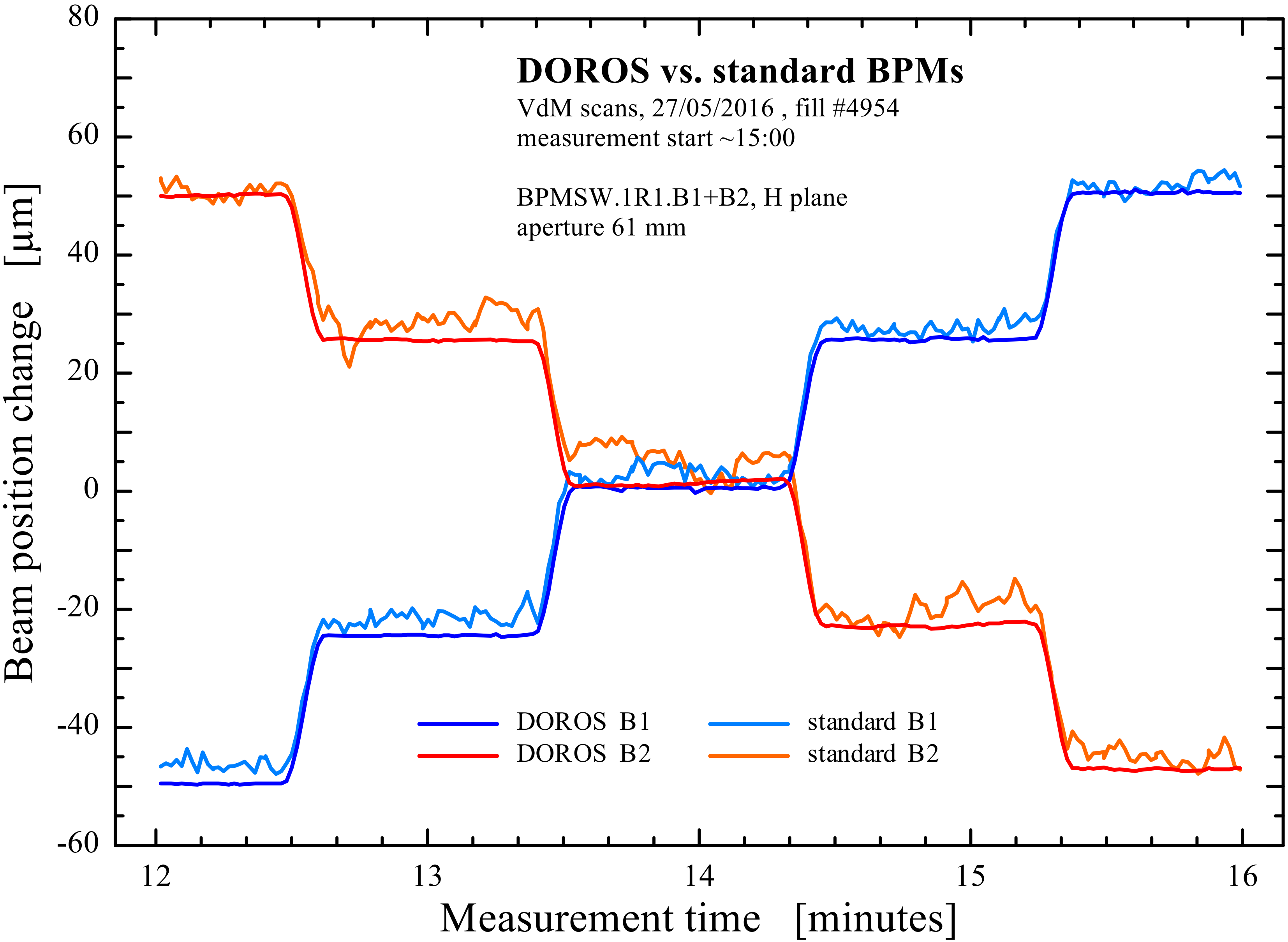
Analogue orbit processing



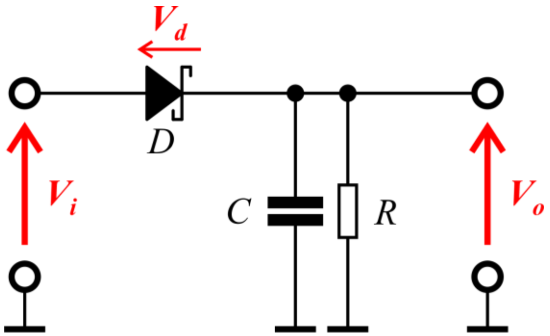
Systematic errors due to signal amplitude changes



DOROS vs. standard BPMs for orbits

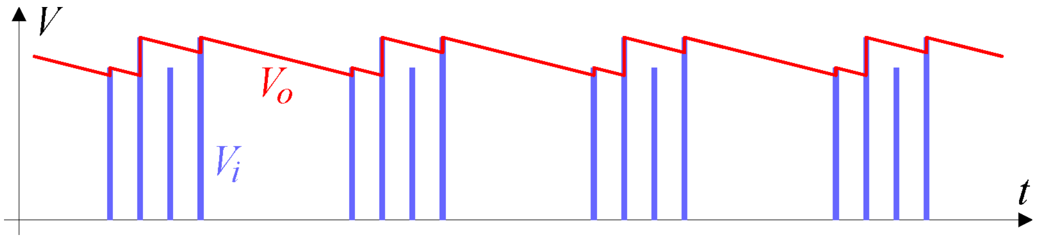


A simple detector and short pulse signals

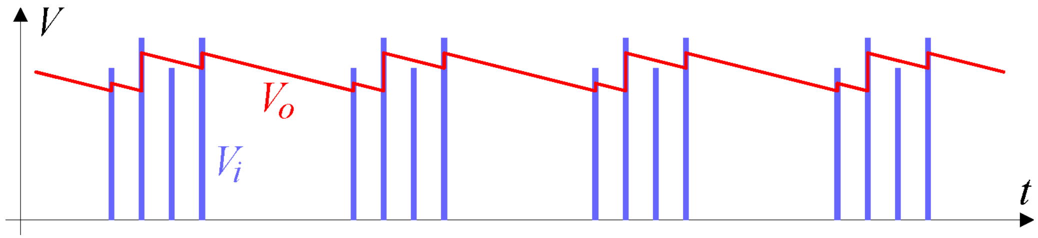


Input (V_i) and output (V_o) voltages

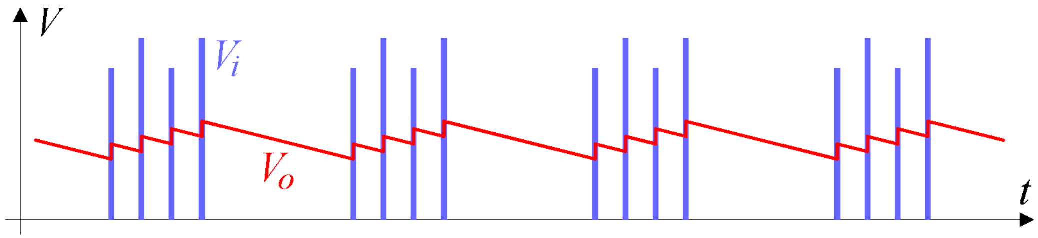
peak detector, ideal diode



peak detector, real diode



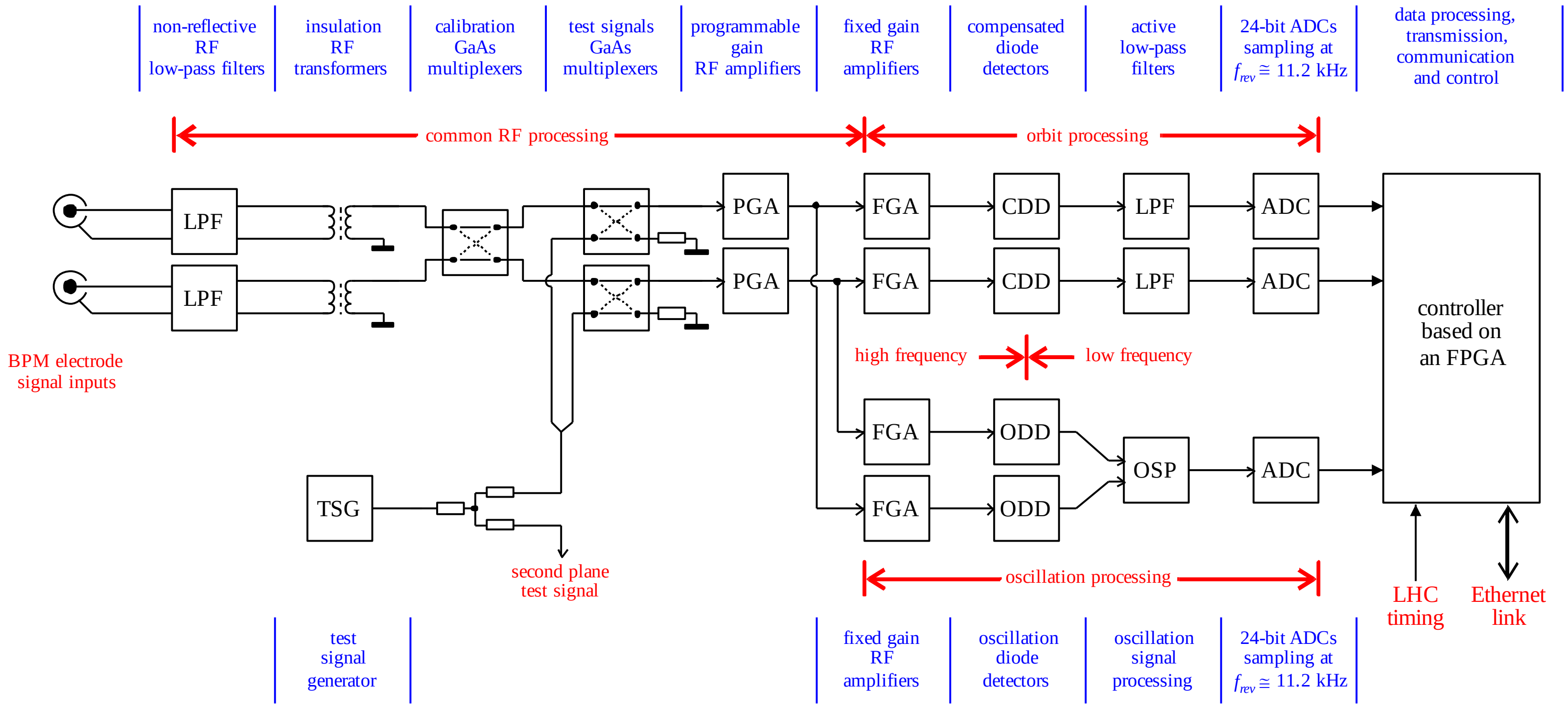
“average” detector, real diode



Diode ORbit and OScillation system (DOROS)

- DOROS is a beam position measurement system based on diode detectors
- The system has been developed to be used with the LHC collimators equipped with embedded BPMs. It is also installed on selected LHC standard BPMs.
- DOROS front-ends contain two parallel subsystems which share the same RF processing:
  - **DOR** – diode orbit processing
    - optimised for sub-micrometre resolution and micrometre precision
    - does not require beam synchronous timing
    - cost 1: bandwidth limited to some 100 Hz
    - cost 2: not bunch-by-bunch, it measures an “average” of all bunches
  - **DOS** – diode oscillation processing
    - optimised for processing of small beam oscillations in the bandwidth 0.05 – 0.5 frev
    - cost 1: orbit information removed from the processing
    - cost 2: signals not in mm and changing with the beam intensity

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.



Features of the DOROS orbit part

- Measuring orbits in the frequency range 0 – 100 Hz limited by analogue low-pass filters
- Each BPM electrode signal processed by a dedicated diode detector
- Cancellation of the residual asymmetry in the analogue processing of the signals from opposing BPM electrodes with periodic signal multiplexing (1 Hz rate)
- Processed electrode signals sampled simultaneously with 24-bit ADCs at the LHC f_{rev} (11.2 kHz)
- Real-time UDP streaming of the processed ADC data from the diode orbit channels
  - Raw electrode data IIR filtered, decimated and sent to a system server at a 25 Hz rate
  - Cut-off of the IIR filter can be programmed in the range 0.01 Hz – 2 kHz.
  - System server computes orbit data and absolute beam orbits in mm;
they are published at 1 Hz rate with 1 s latency.
  - Beam data and front-end parameters are logged
  - 12.5 Hz asymmetry calibration switching available to reach data rates and latency compatible with the current orbit feedback operation
- On-demand “Capture/Freeze” mode:
  - Electrode ADC samples stored at f_{rev} rate in the front-end memory.
  - Rolling turn-by-turn buffer depth of about 1.8 million turns (up to 3.5 minutes @ f_{rev})
  - If enabled in the front-end the capture can be triggered with dedicated Beam Synchronous Timing (BST) event
  - Optional capture/freeze triggers upon server commands
  - Optional data decimation during front-end readout
  - Acquired data can be used to compute orbit spectra in the bandwidth 0 – 100 Hz.
(limited by the available signal bandwidth form the analogue processing)
- Post-mortem rolling buffers:
  - UDP datagrams stored in the front-end memory
  - The UDPs contain information on the electrode signals + statuses, temperatures, flags, settings…
  - Rolling UDP buffer depth of about 4600 UDPs (up to 3 minutes @ 25 Hz rate)
  - Buffer start/stop control and readout from the system server