# LHC beam orbit and position measurement

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for Beam Instrumentation Group

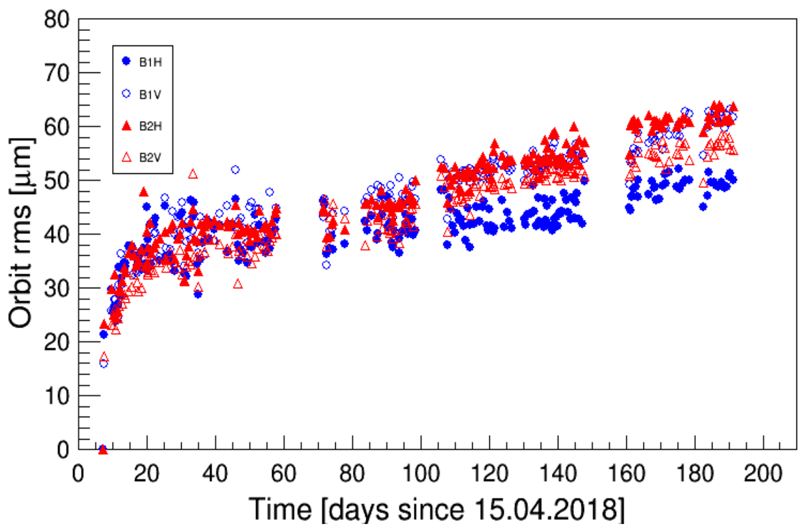
- BPM standard “normaliser” electronics
- DOROS electronics
  - performance and limitations
  - planned improvements during LS2

# BPM standard “normaliser” electronics

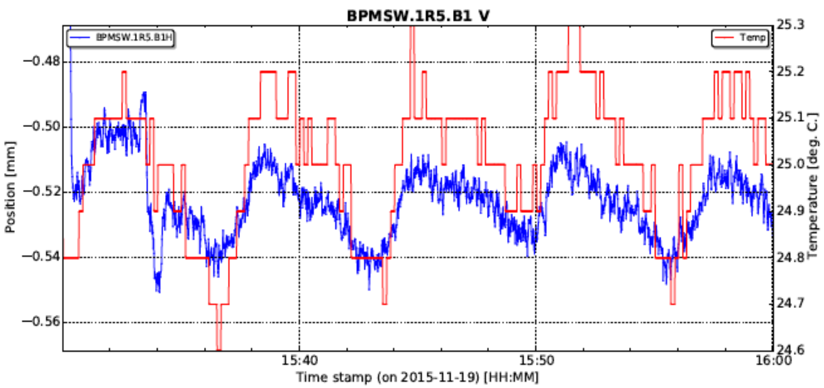
- Some 1100 BPMs in the orbit feedback system
  - orbit measurement resolution in the micrometre range
  - long term reproducibility around 50 µm
- Limitations of the analogue electronics
  - bunch pattern calibration errors smaller than 50 µm
  - dependence on temperature, mitigated to below 50 µm by installing electronics in thermo-stabilised racks
- Improvements during Run 2
  - Multiple system firmware upgrades to fix bugs and to provide more stability and maintainability
  - Introduced “synchronous orbit” for p/Pb run
  - Reduced noise with an automatic adjustment of the orbit filter bandwidth to the current bunch pattern
  - Introduced dry runs on testbeds before commissioning
- No major interventions during LS2
  - system firmware upgrades
- Consolidation planned for LS3

From Evian presentation by Michał Krupa

**LHC orbit stability**

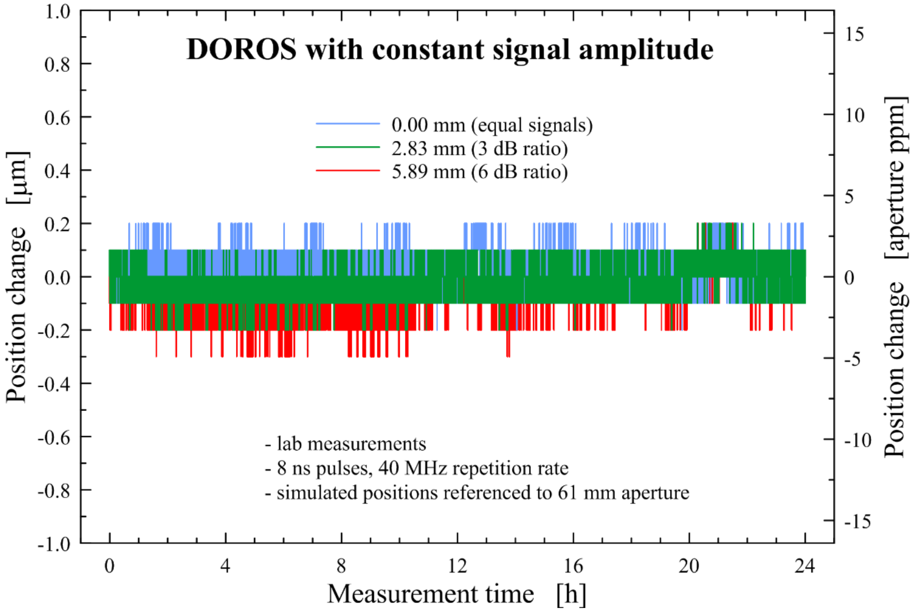


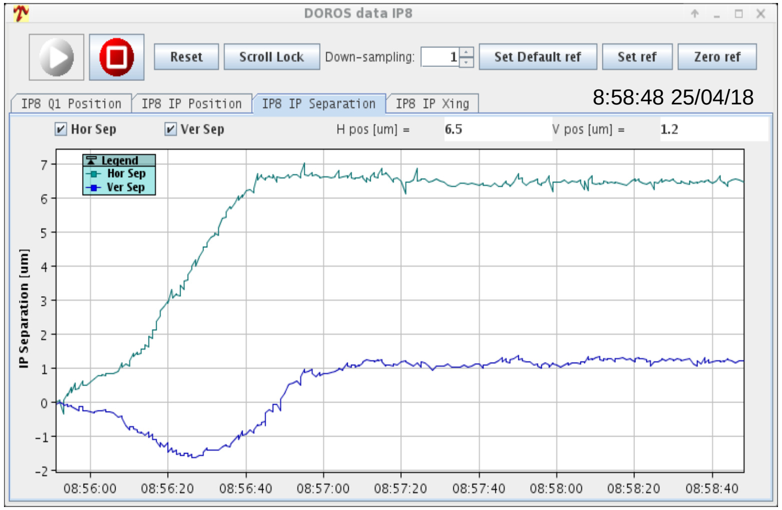

**Rack temperature vs beam position**



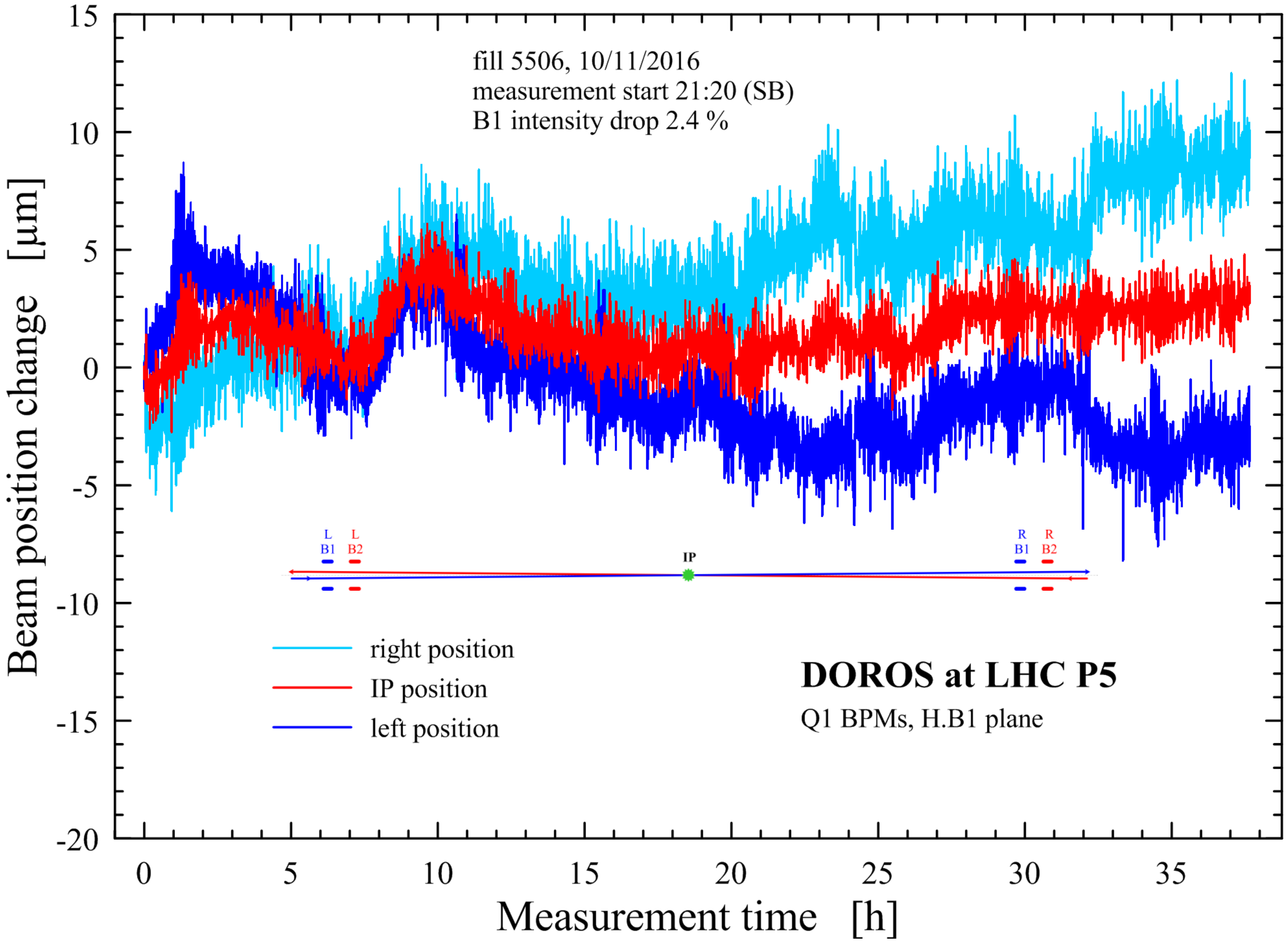
# DOROS electronics

- DOROS shares BPMs with the standard electronics (passive signal splitting)
- BPM electrode amplitudes measured individually at the revolution frequency and averaged to 1 s for orbit measurement
- At the end of 2018 run 21 DOROS front-ends were installed on 40 standard BPMs:
  - P1: Q1, Q2, Q7, AFP L+R
  - P2: Q1, Q6R
  - P4: Q6L, “on demand” BBQ
  - P5: Q1
  - P6: Q5
  - P8: Q1, Q6
- Sub-micrometre resolution
- Sub-micrometre reproducibility as long as the signal amplitude does not change significantly
- Largest limitation: orbit readings depend on the beam intensity changes, errors up to some 20 - 30 µm (i.e. some 1000 times the resolution)
- Very good reliability: only two hardware faults in the whole history of the system. They were induced by residual radiation in UJ56 and UJ16. A remedy found and will be implemented for run 3.

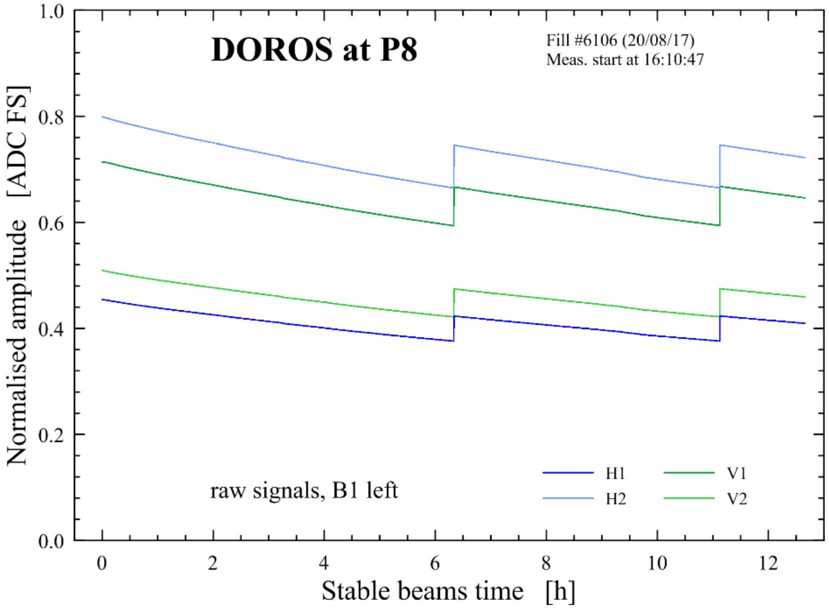


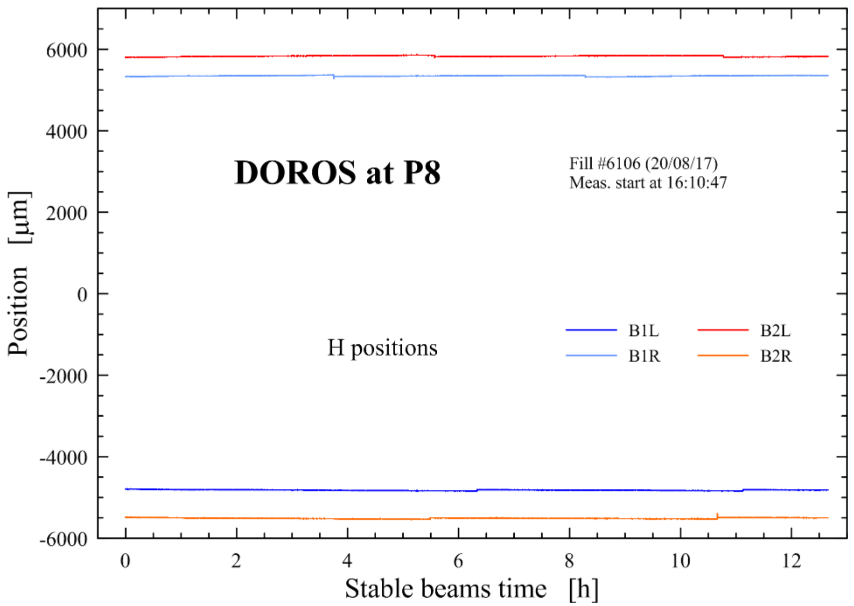



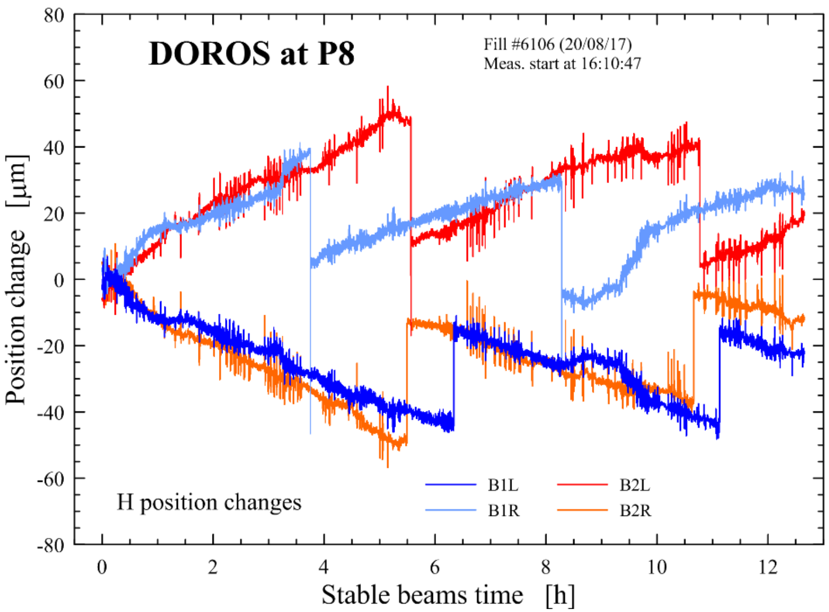
# DOROS stability with (almost) constant intensity

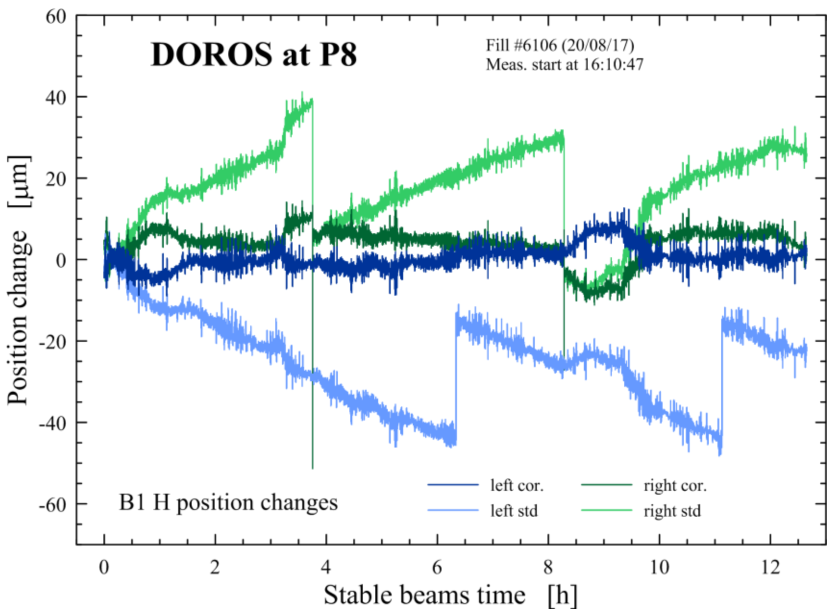


# Explanation of DOROS systematics

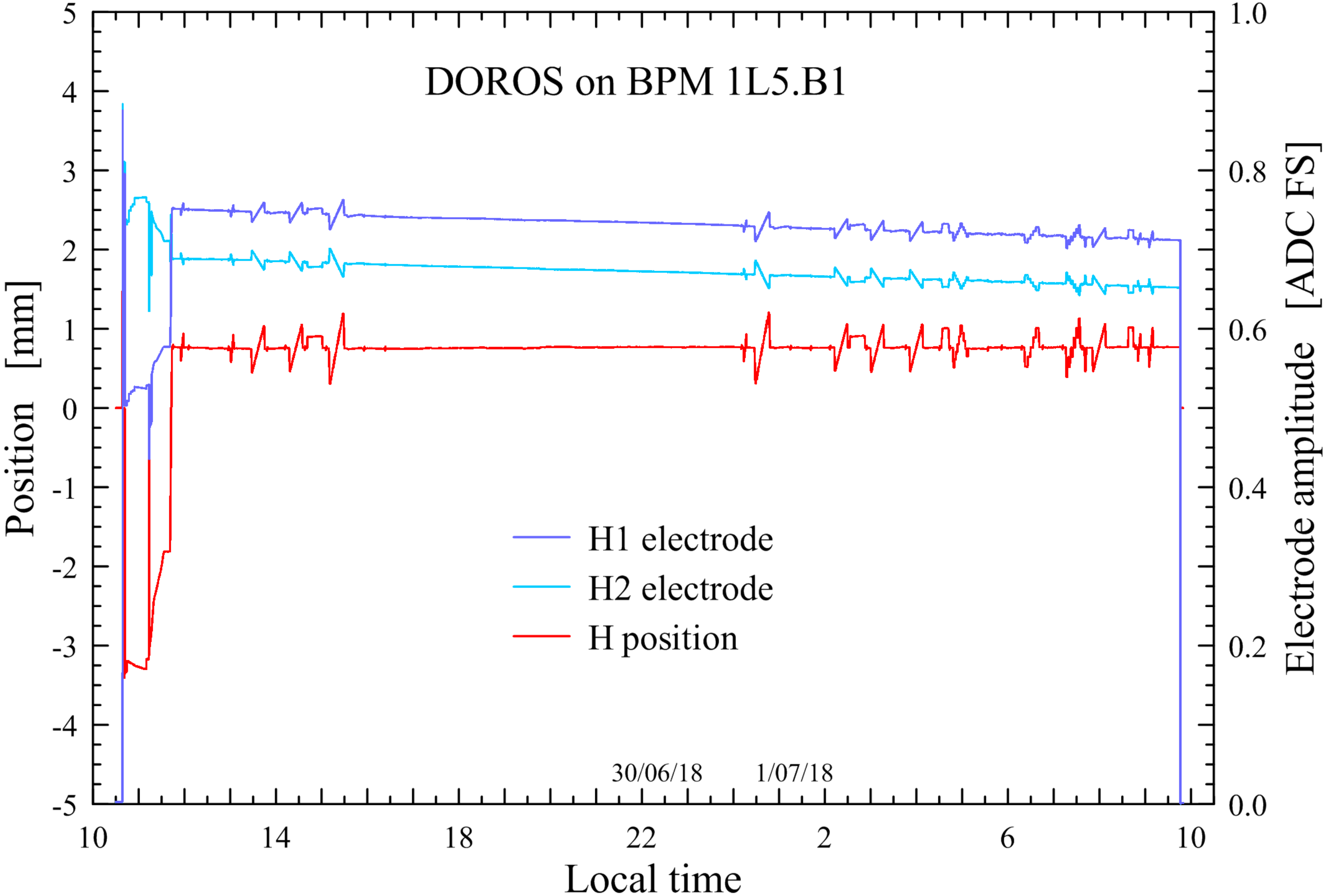


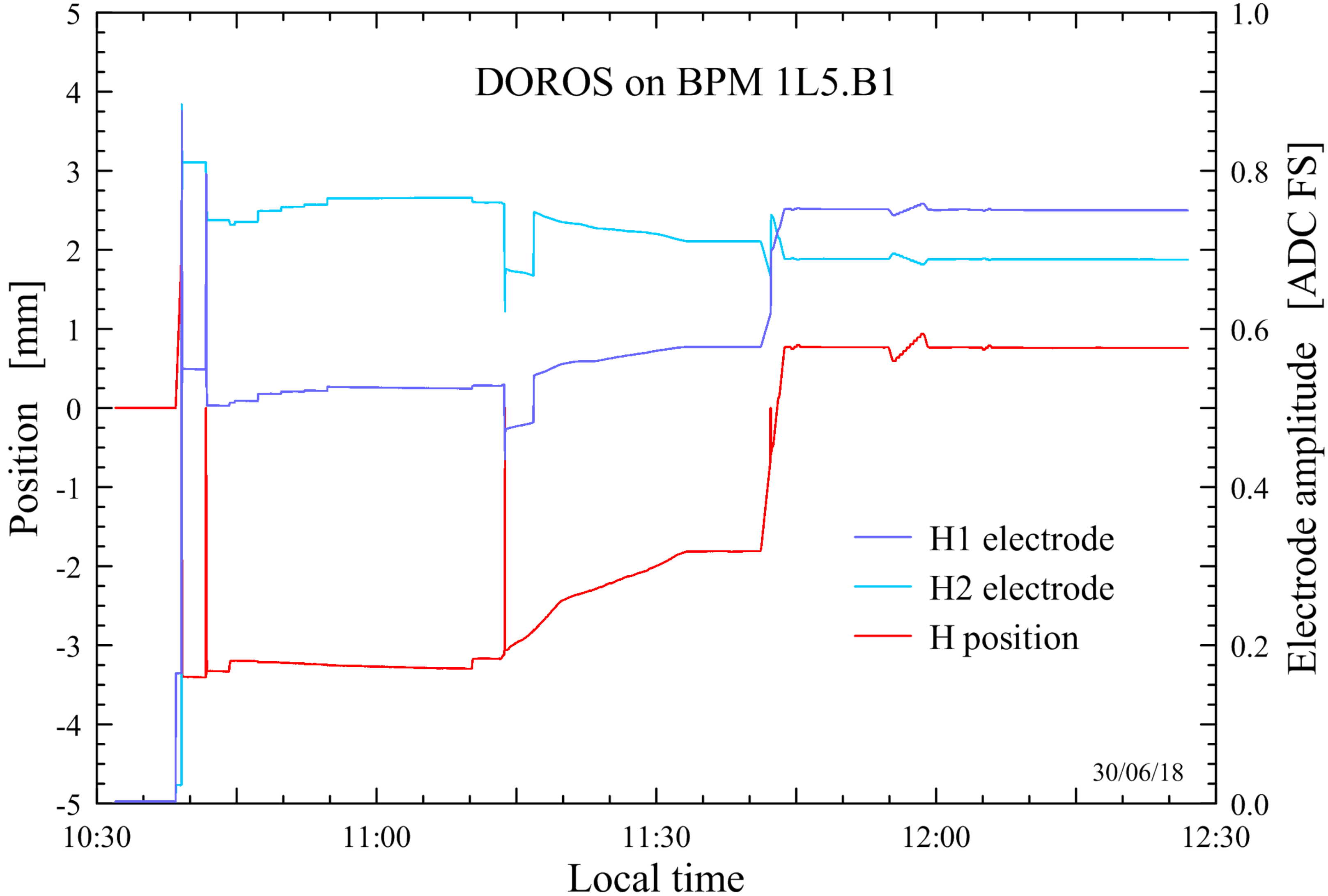



# DOROS during VdM scans



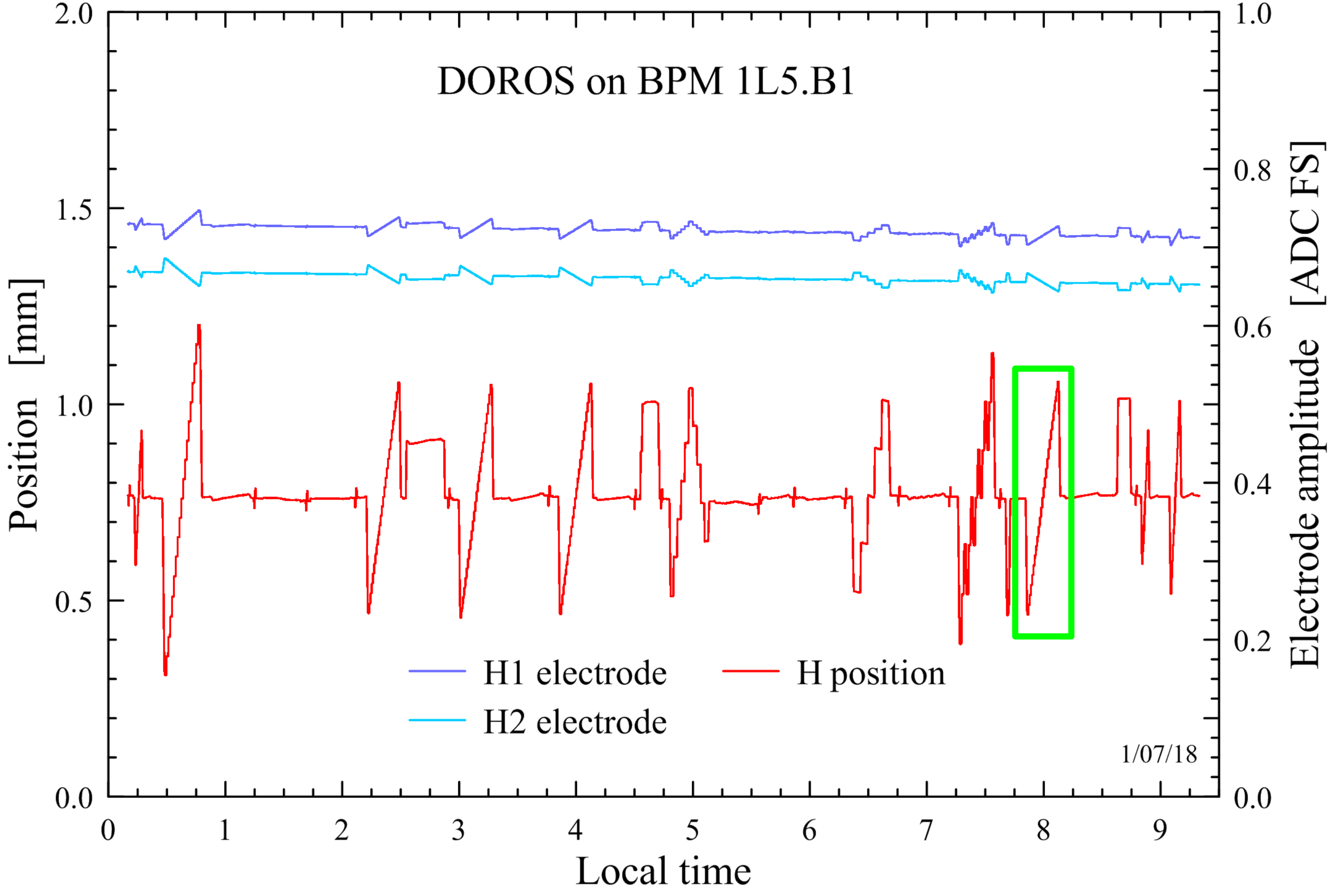

- Good news for the VdM scans: small beam intensity decay and reasonable beam offsets

# DOROS during VdM scans

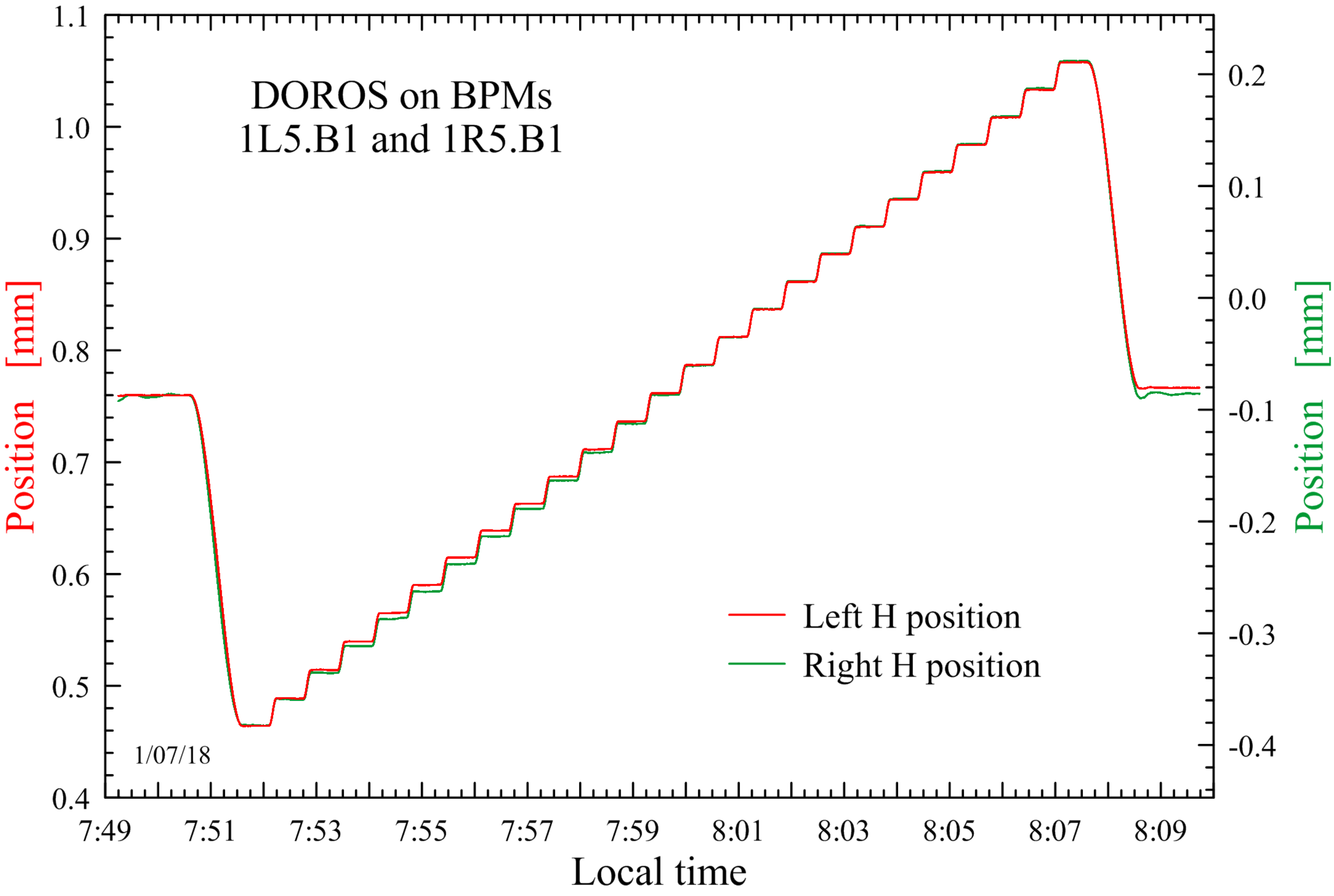



- FESA wisdom still limited, ongoing work, working prototypes in the lab (Python)

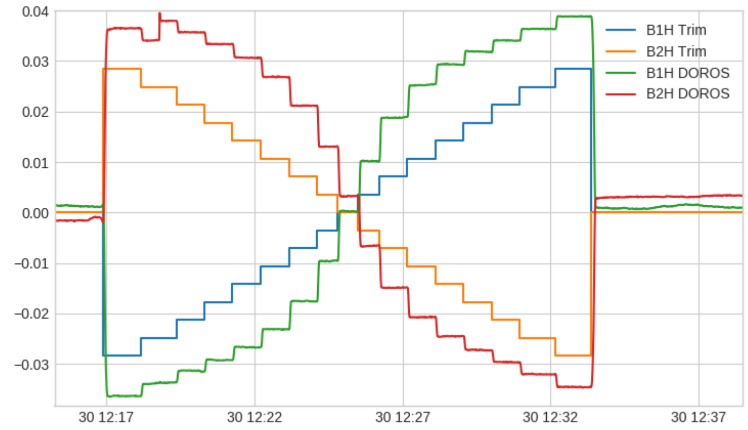
# DOROS during VdM scans

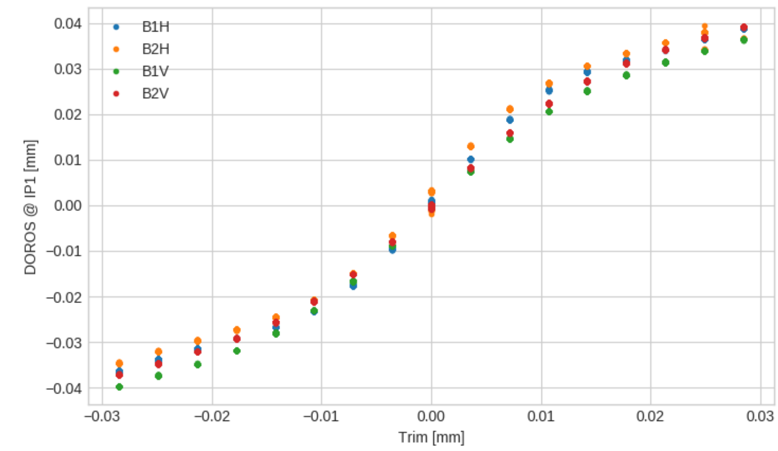


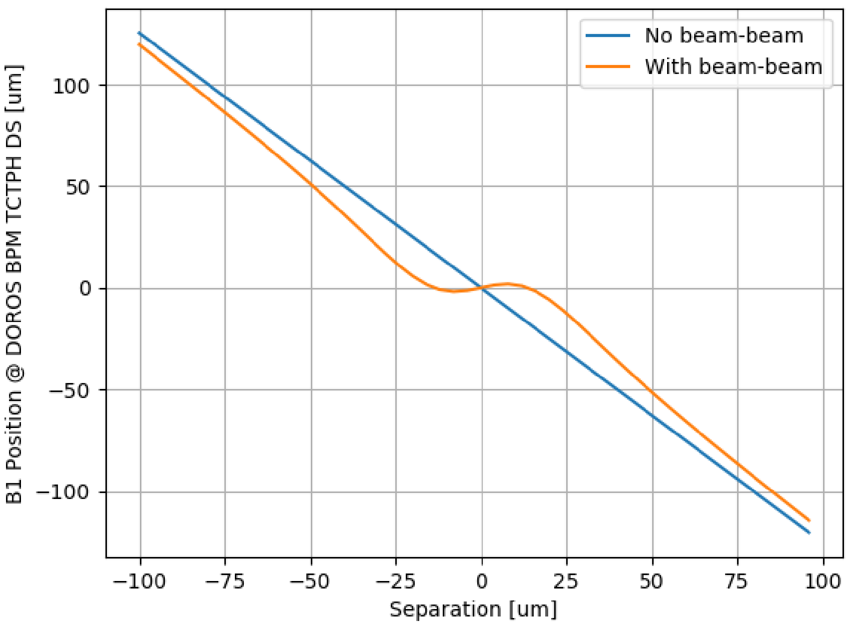
# DOROS during VdM scans

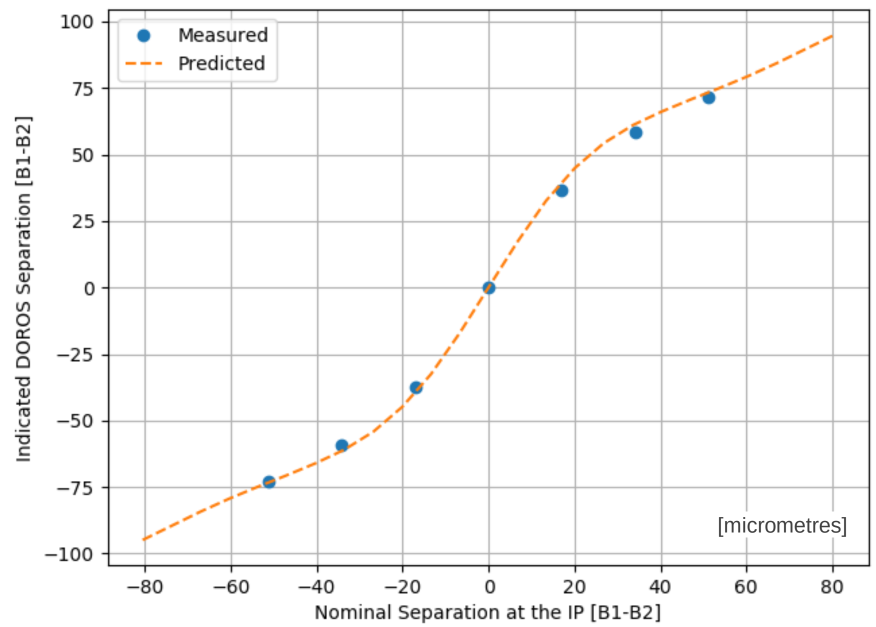


# Beam-beam orbit effects observed with DOROS



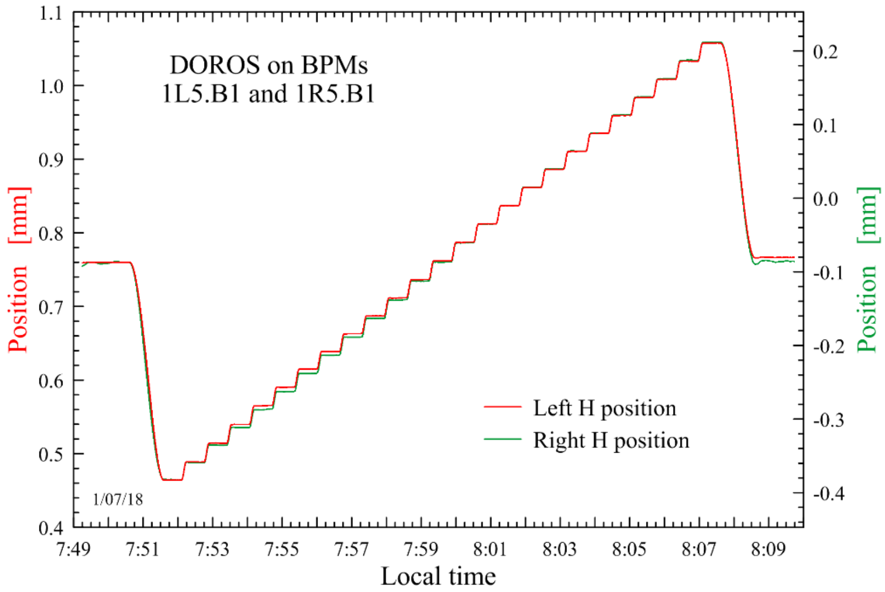



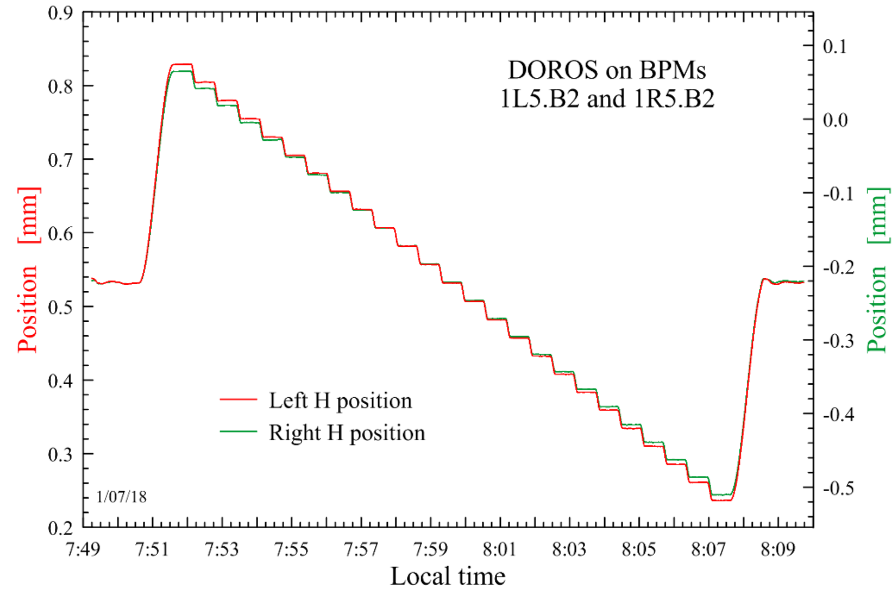



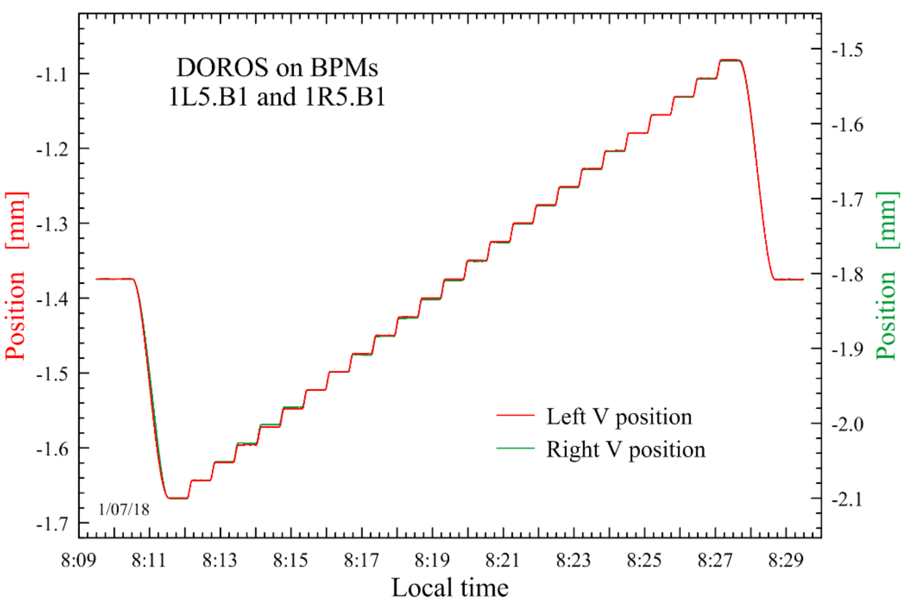



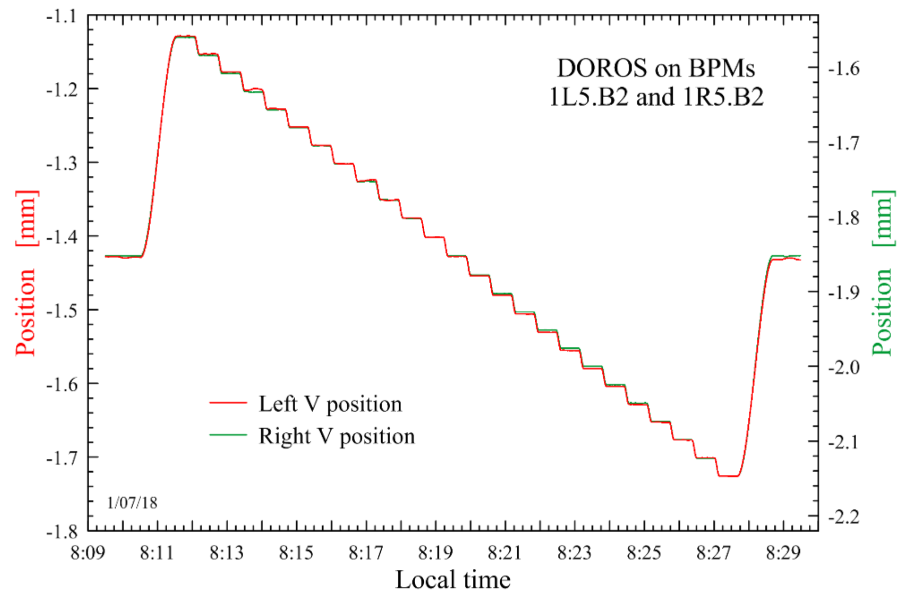

Measurements first reported as a DOROS non-linearity, later explained by beam-beam forces. Plots curtesy of M. Hostettler et al.

# DOROS during VdM scans (P5)

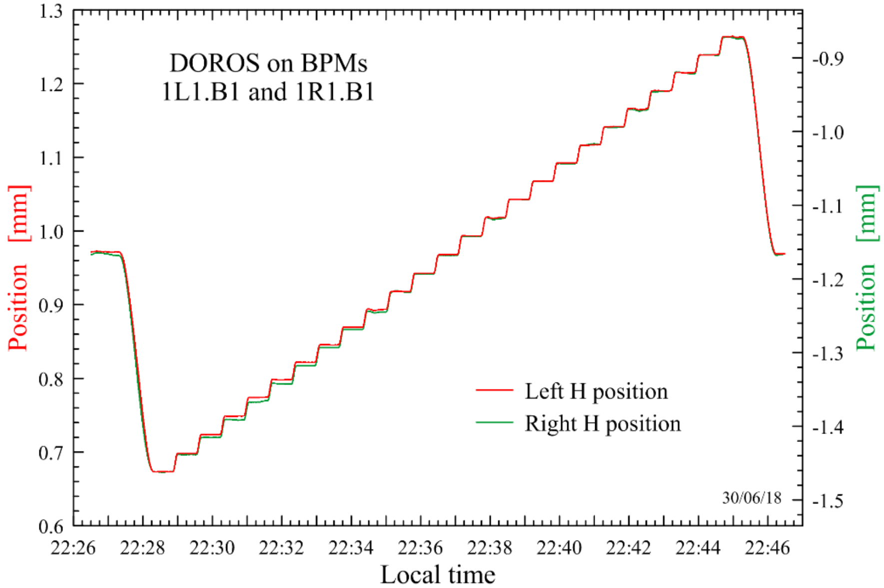


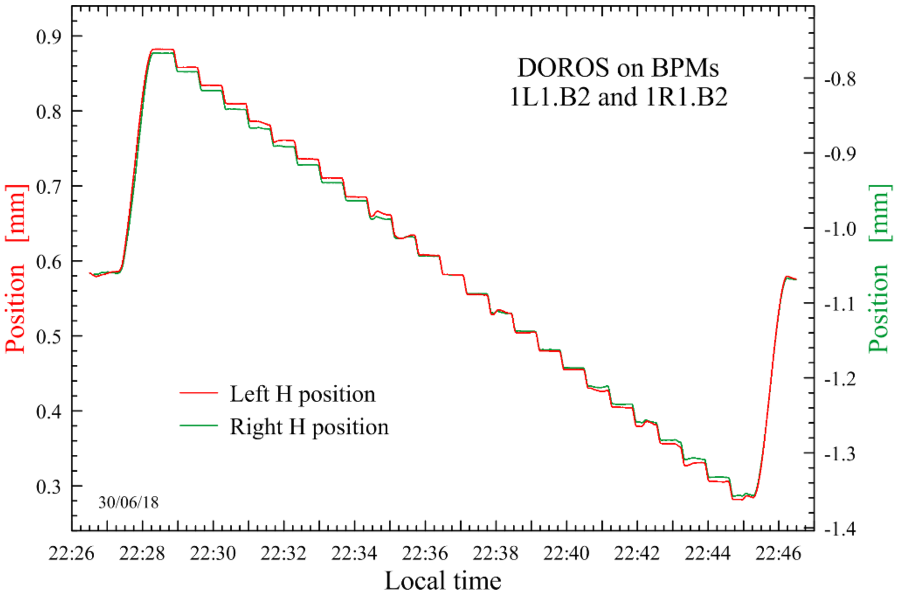



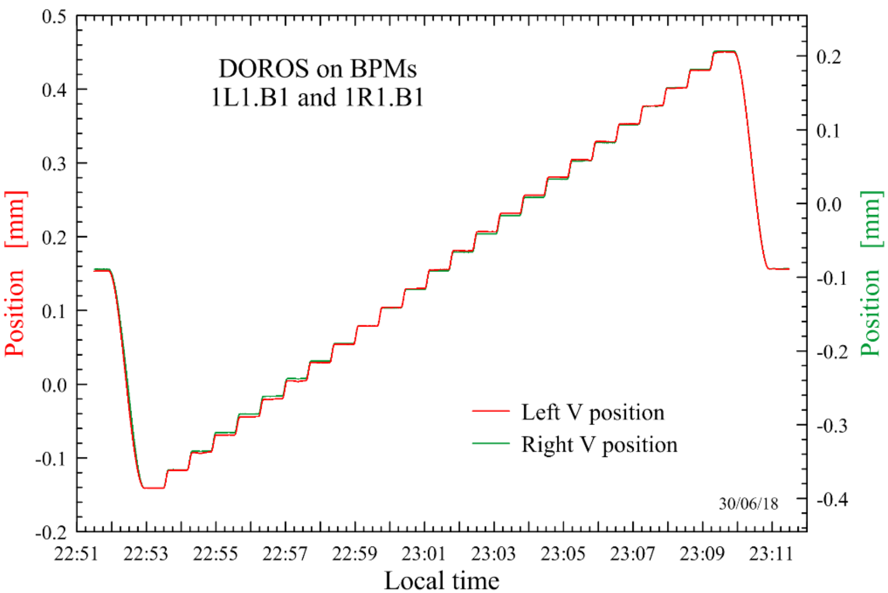



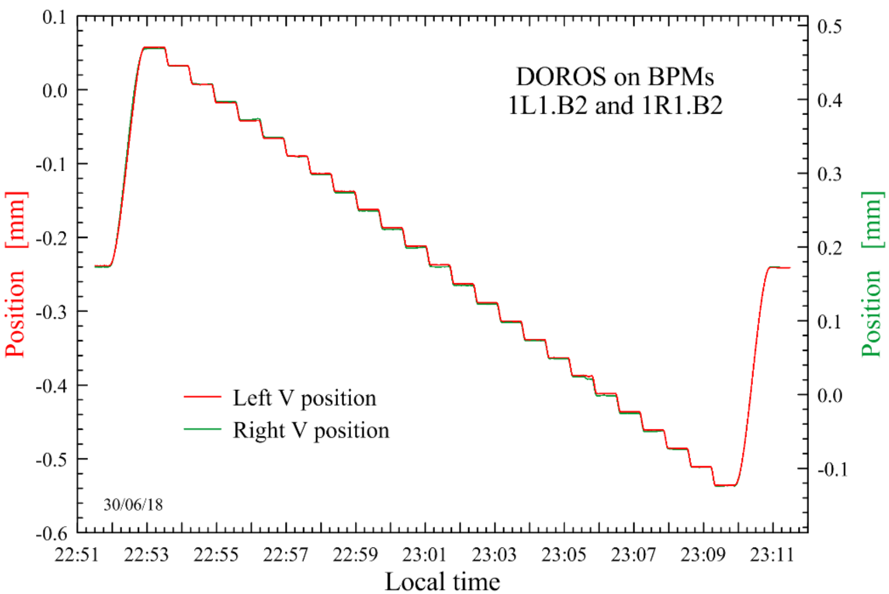



# DOROS during VdM scans (P1)



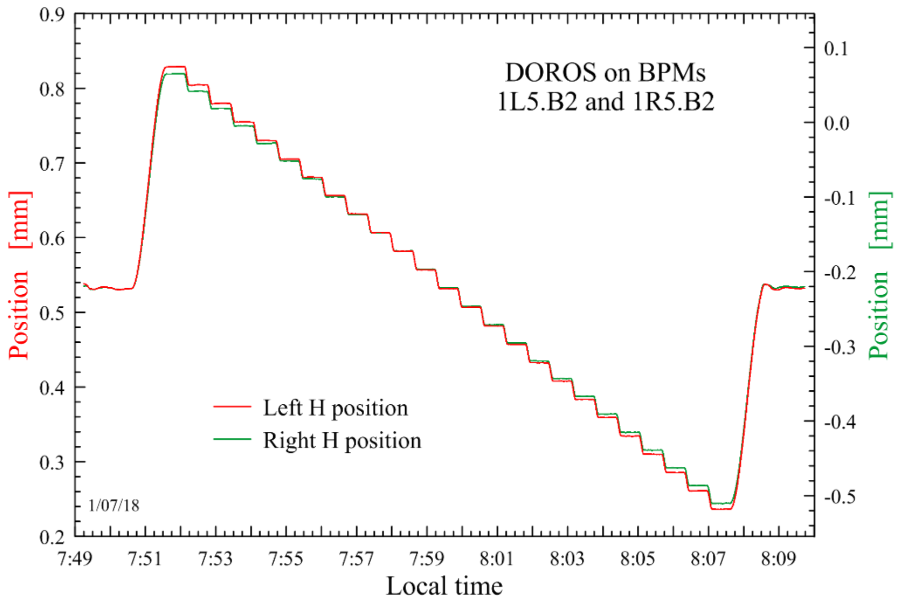



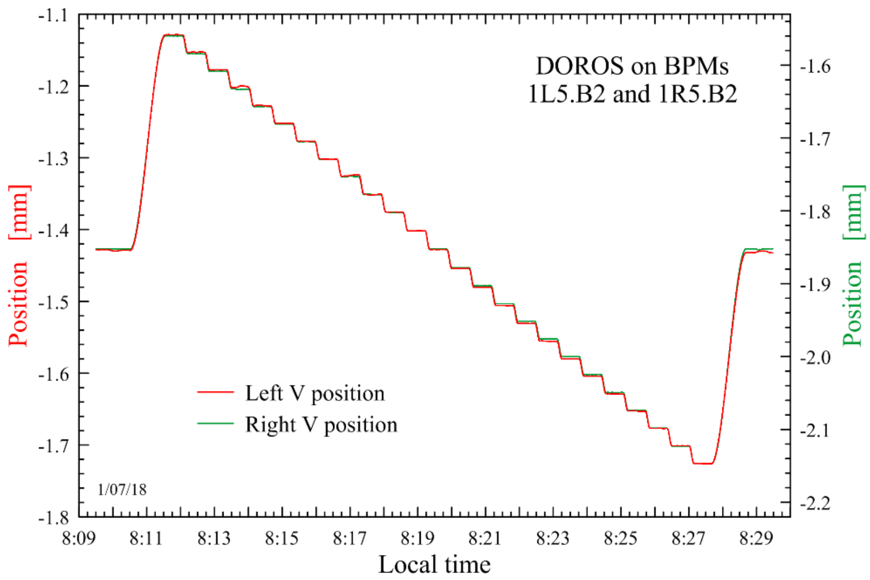



# Factors influencing the "DOROS scale"

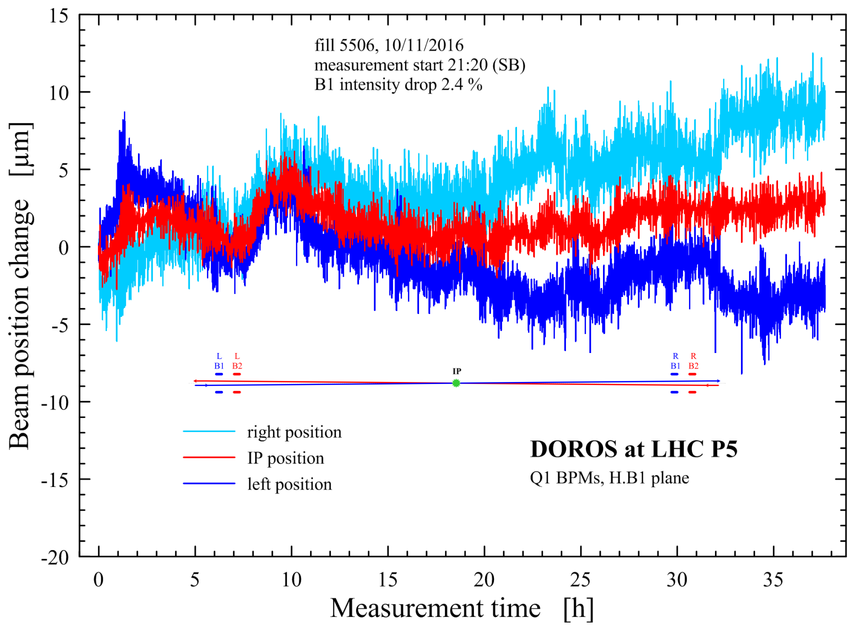
- Geometry of the BPMs themselves
- Software correction of the BPM nonlinear position characteristic based on simulations
- Cable attenuation asymmetry
- Attenuator asymmetry
- Signal splitter asymmetry
- Asymmetry of the load from the normaliser electronics
- DOROS input filter asymmetry (80 MHz non-reflective low-pass)
- Residual asymmetry of the electronics channels, as most of the asymmetry is canceled by periodic swapping of the processing channels
- No obvious way to identify the errors and correct them
- Ongoing studies how to improve the situation.
  Most promising option for the time being:
  mechanical switches as close to the BPM
  as possible to extent the "switching calibration"

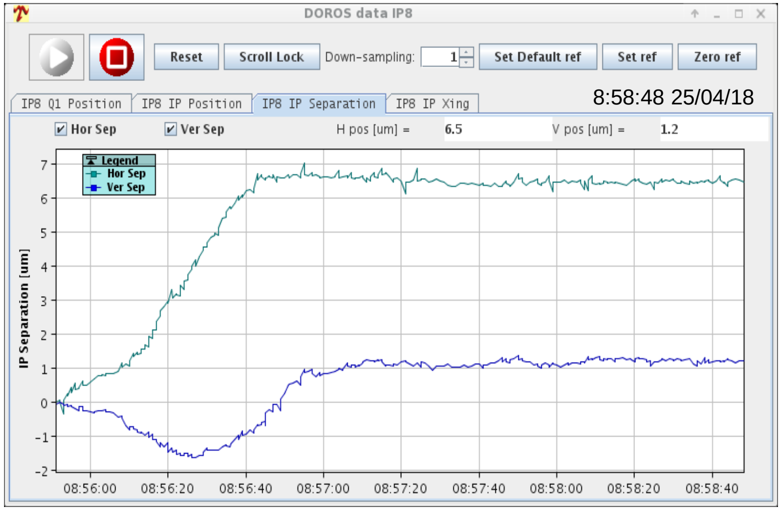


# Summary

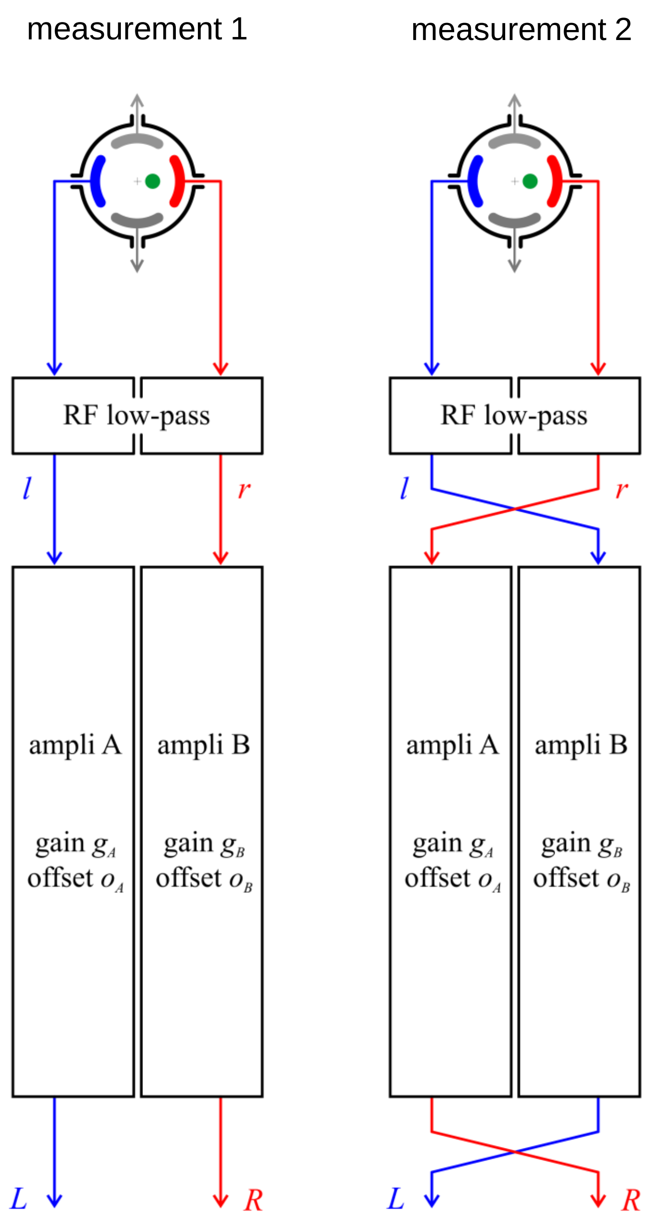
- Run 3 will be with the same BPM infrastructure
- Standard “normaliser” BPM system work on the firmware level
- DOROS system improvements:
  - FESA
  - mode allowing using DOROS readings in the orbit feedback (only FESA work needed)
  - reduction of intensity dependence with smaller step of the automatic gain regulation (ongoing hardware development)
  - no more problems with residual radiation (new radiation-tolerant power supplies)
- Ongoing studies on the DOROS system:
  - how to identify systematic errors
  - how to correct systematic errors
- **Feedback from the experiments most welcome**



# Spare slides

# Channel asymmetry compensation ("auto-calibration")




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

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

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

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

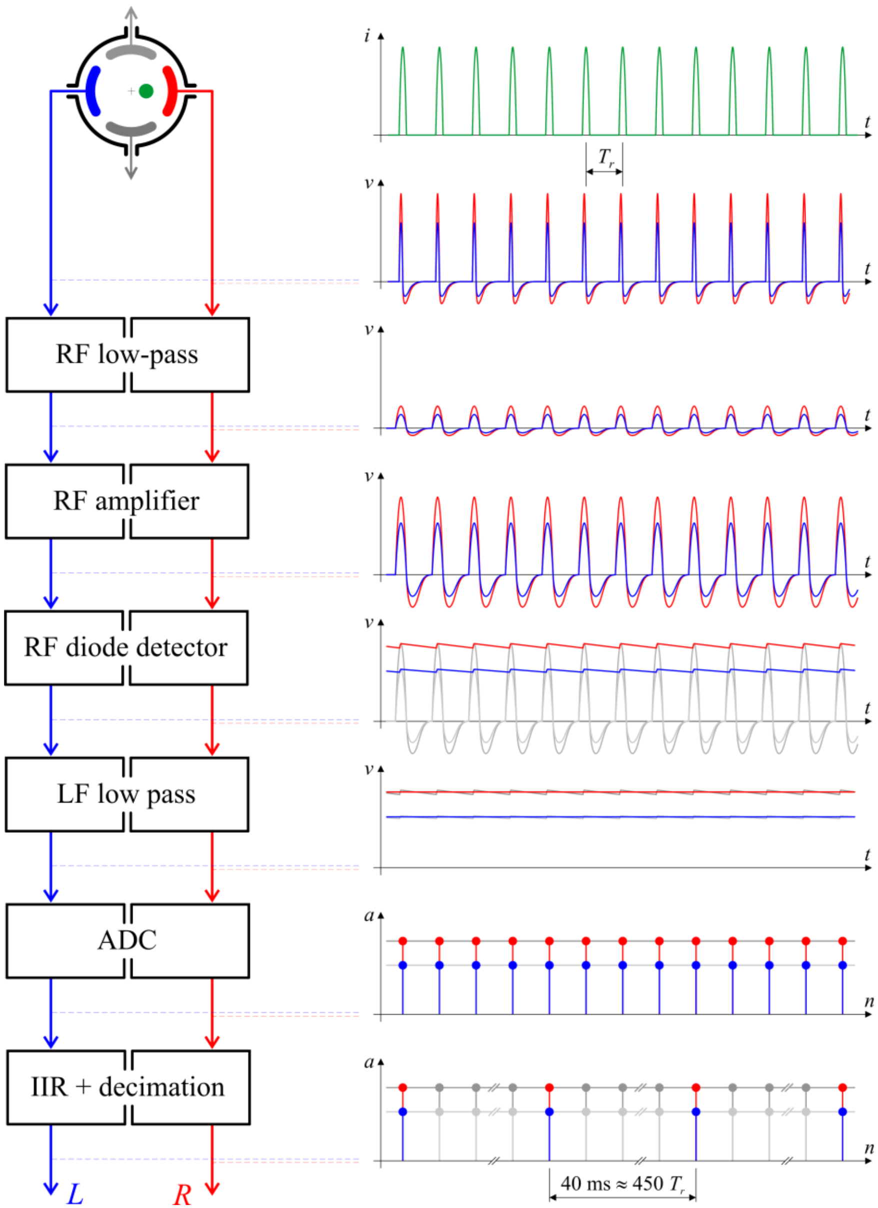
$$p_{Hc} = \frac{R_c - L_c}{R_c + L_c} = \frac{(g_A + g_B)(r - l)}{(g_A + g_B)(r + l) + 2(o_A + o_B)} \cong \frac{r - l}{r + l}$$

- 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):

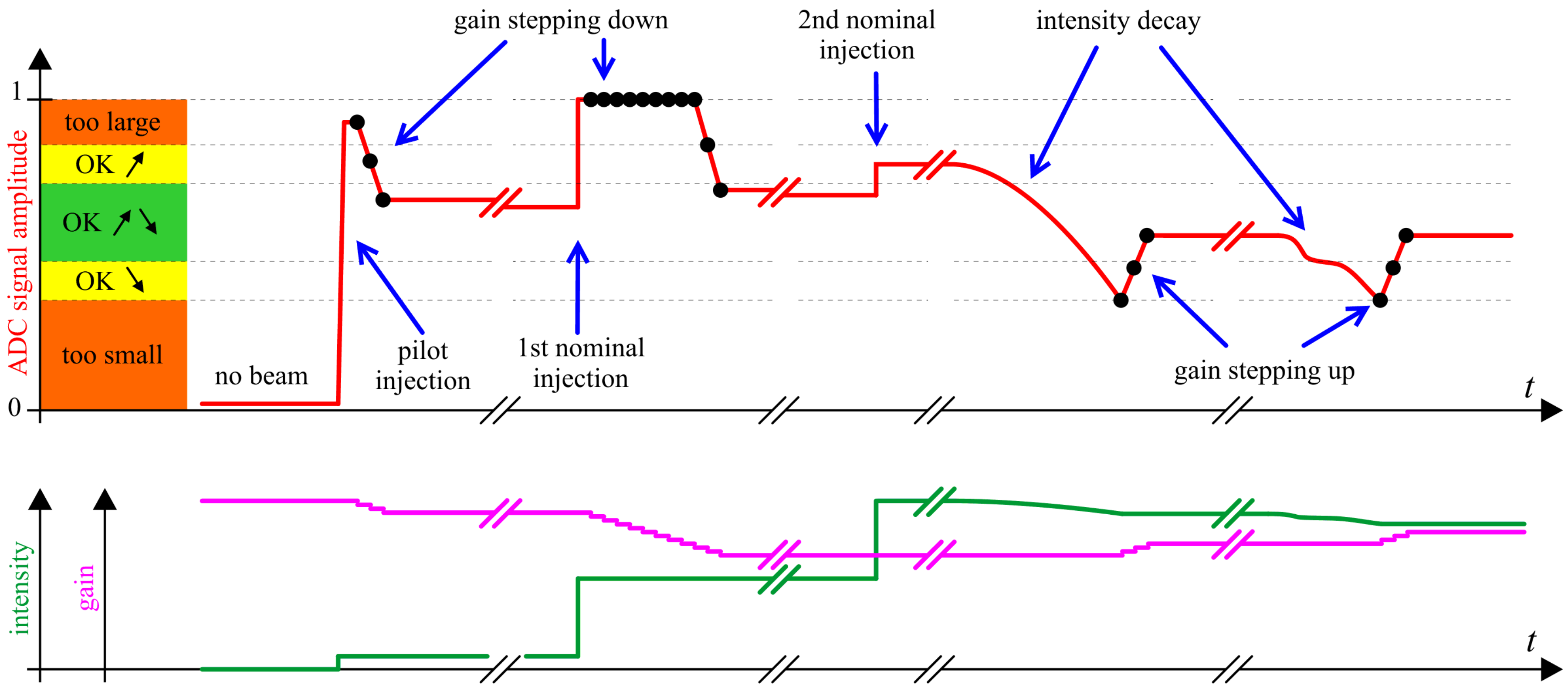
- Perfect amplifiers ($g_A = g_B = 1$ and $o_A = o_B = 0$):
  for $l = 0.5$, $r = 1$, $p_H = 0.3333$ and $P_H = 5.083$ mm for Q1 BPM with $d = 61$ mm.
- Assume amplifiers with $g_A = g_B = 1.05$ and $o_A = o_B = 0.001$:
  $p_H = 0.3329$ and $P_H = 4.927$ mm, resulting in an error of 6 μm

# Diode orbit processing overview



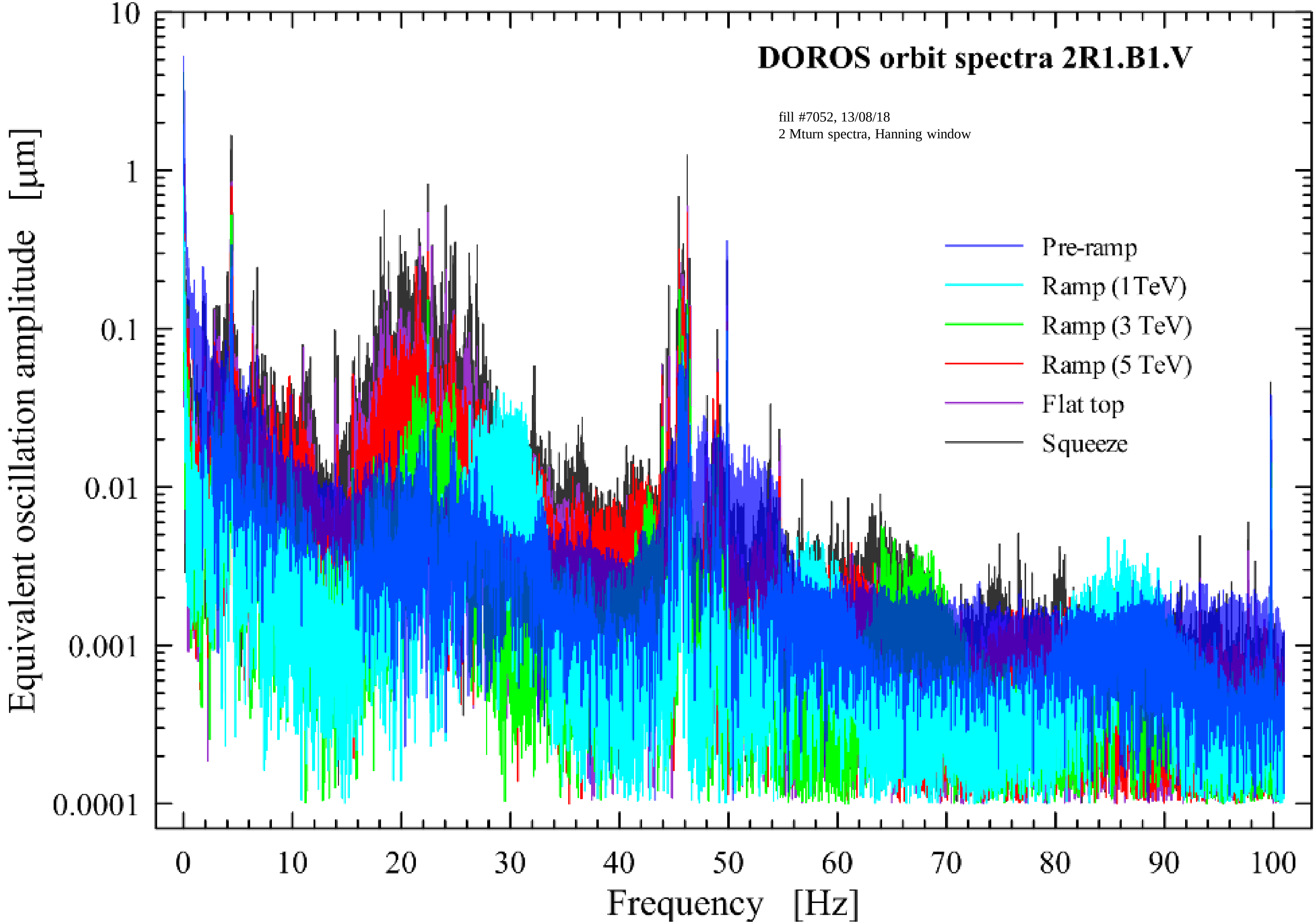

- Short pick-up pulses go through input low-pass filters to limit their slew rate and reduce peak amplitudes
- RF amplifiers provide optimal amplitude of the pulses on the compensated diode detectors
- Diode detectors convert pulses into slowly varying signals
- Low frequency low-pass filters remove 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

# Automatic gain control of the RF amplifier

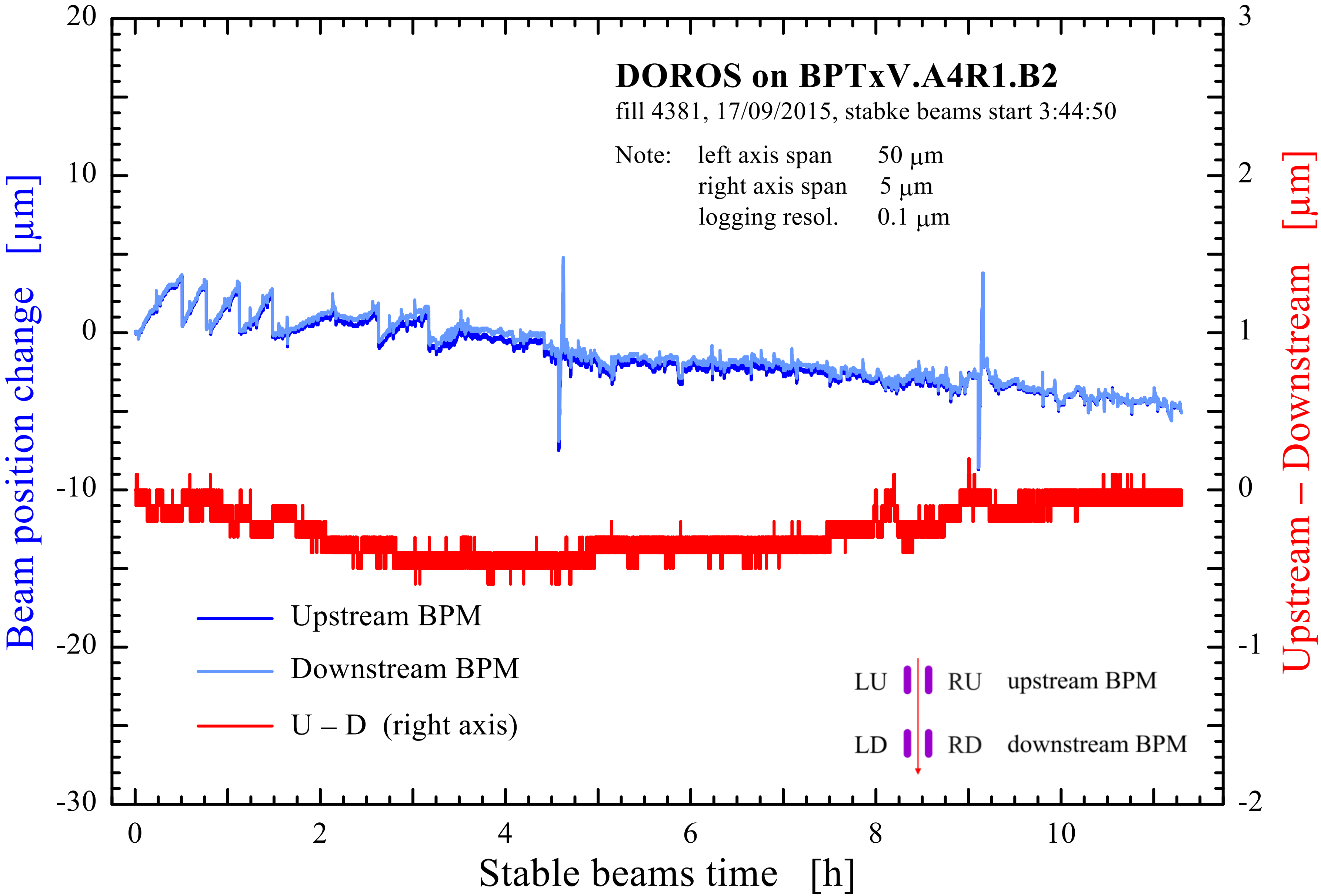



- Four channels of one pick-up have the same gain
- Gain control is based on the largest signal of all four electrodes
- The gain is adjusted to cause the largest signal to have the amplitude in the green zone
- The gain control levels are programmable and can be changed according to actual beam conditions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

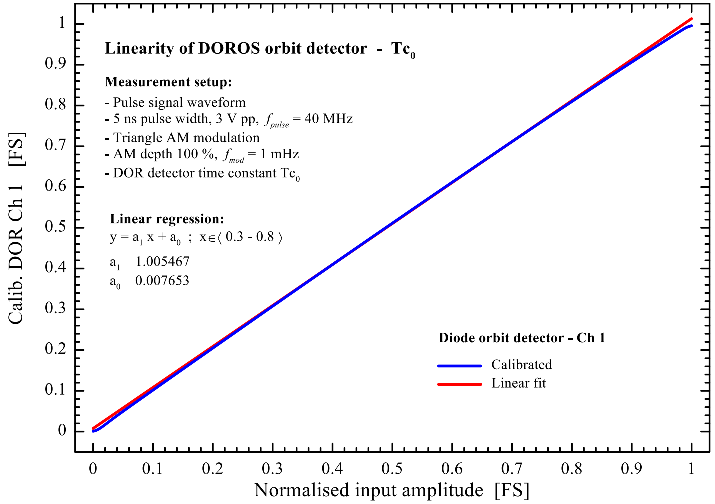
# 2 Mturn LHC orbit spectra at P1

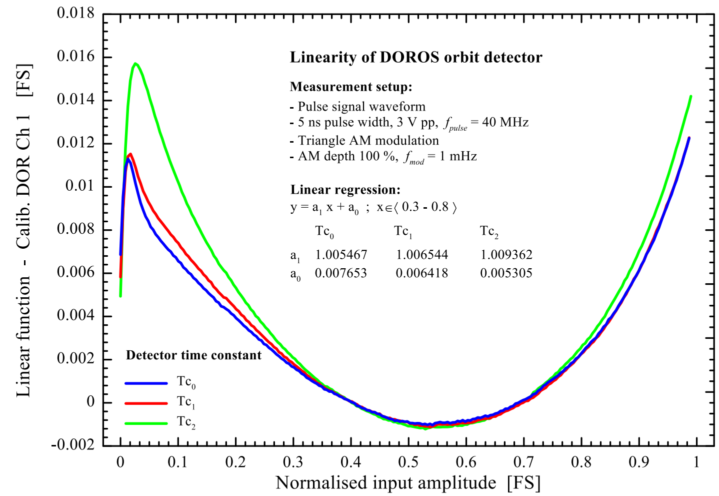


# Stability with LHC beam and collimator BPMs

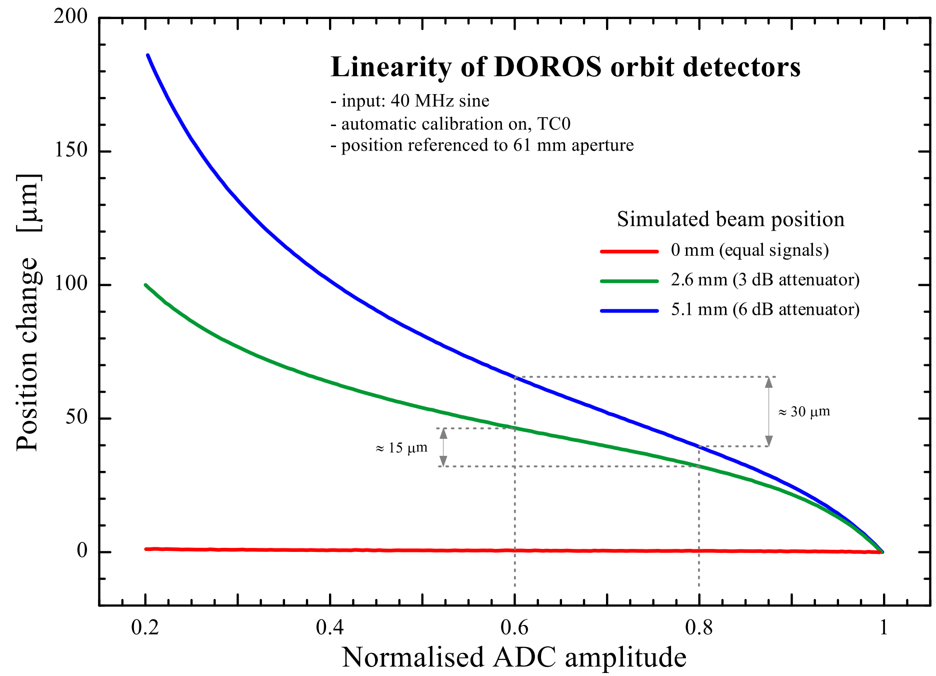


# Linearity of orbit diode detectors



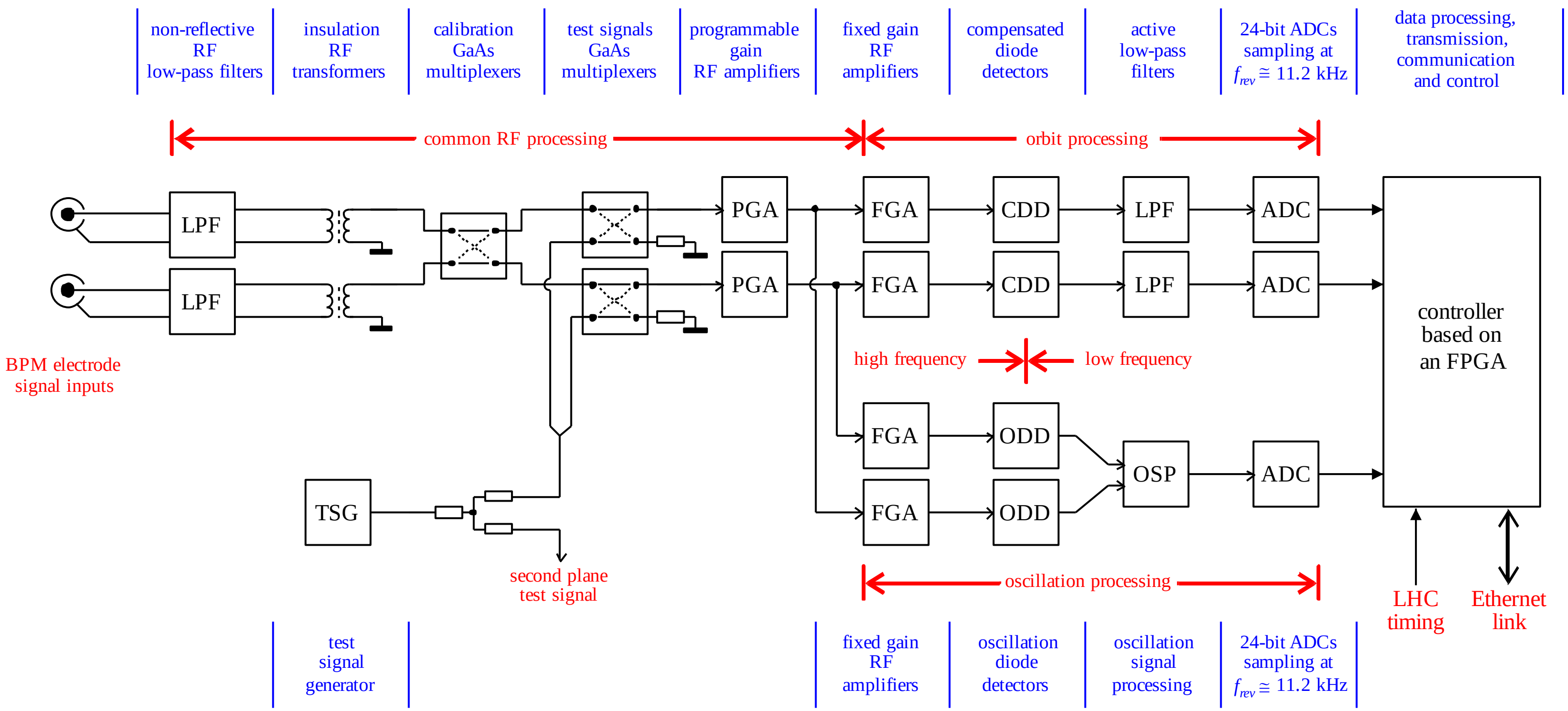

- The left upper plot shows a laboratory measurement of the detector linearity together with its linear fit.
- The right upper plot shows the deviation of the detector characteristic from the linear fit for three detector time constants. Which time constant is used depends on the number of circulating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



# 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.

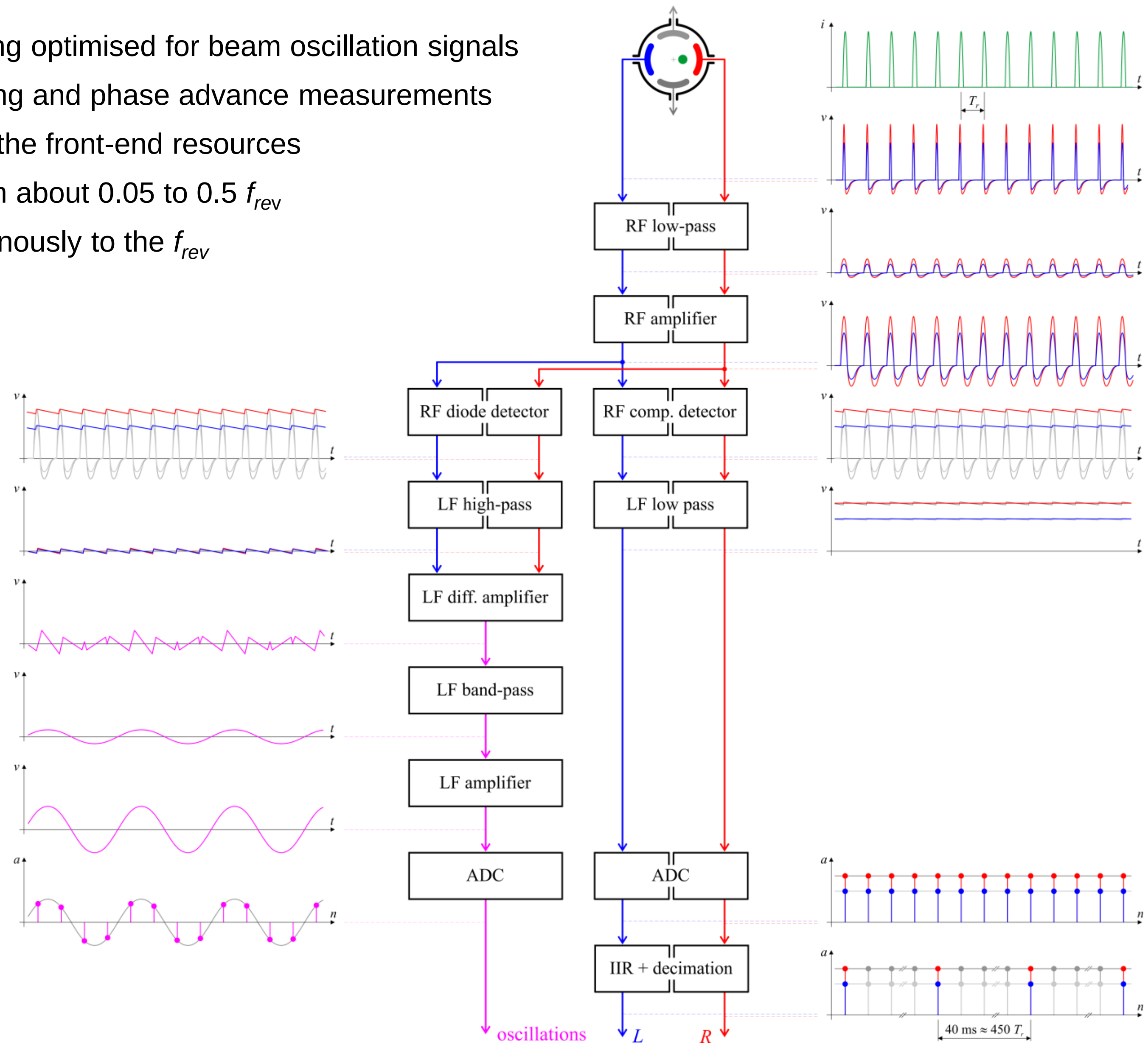


# Features of the DOROS orbit part

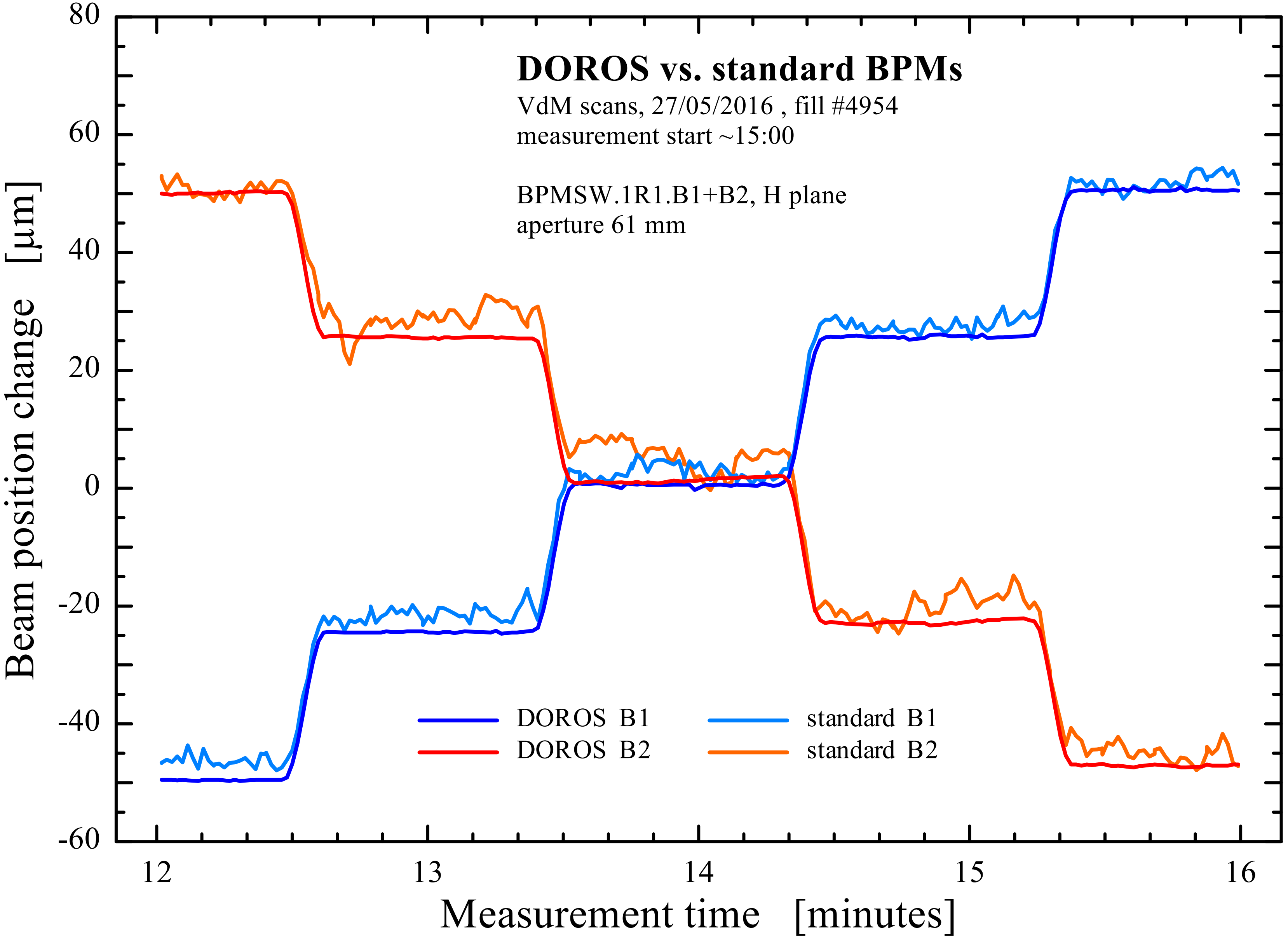
- Measuring orbits in the frequency range 0 – 100 Hz limited by analogue low-pass filters
- Each BPM electrode signal processed by a dedicated diode detector
- Cancellation of the residual asymmetry in the analogue processing of the signals from opposing BPM electrodes with periodic signal multiplexing (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

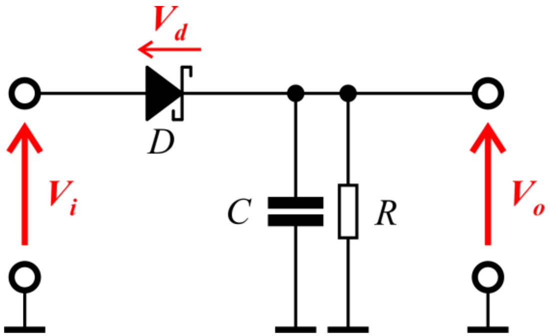
# DOR**OS – oscillation part**

- 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 $f_{rev}$



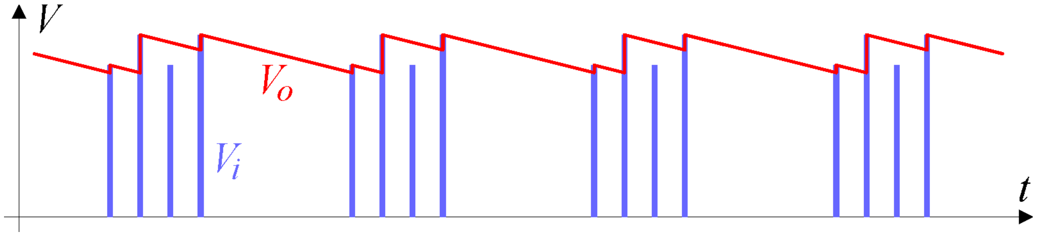
# DOROS vs normalisers



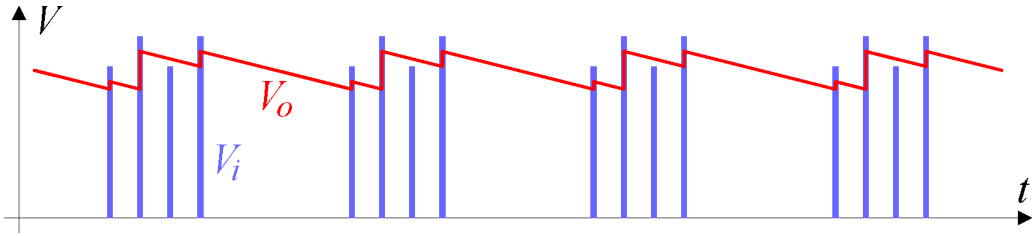



Input ($V_i$) and output ($V_o$) voltages

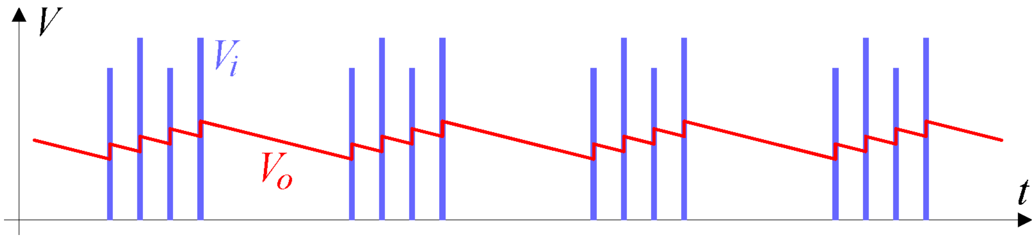
peak detector, ideal diode




peak detector, real diode




"average" detector, real diode



# Information on DOROS

← → ⟳ ⌂ ⓘ Not secure | mgasior.web.cern.ch/mgasior/pro/DOROS/index.html

Informations | Main | Misc | LHC+ | Projects

Home >> Professional >> DOROS

Documents on the DOROS system

- Introduction to the DOROS system
- DOROS front-ends declared in the CERN network database (login required):
  - list of all DOROS front-ends
  - front-ends on the standard BPMs, system DOROS-S
  - front-ends on the collimator BPMs, system DOROS-C
  - development front-ends, system DOROS-D
- Inventory of DOROS front-ends in PDF and XLSX
- Inventory of DOROS FESA devices in PDF and XLSX
- Details of the DOROS-S installations in PDF and XLSX
- Details of the DOROS-C installations in PDF and XLSX
- Photos of the DOROS-S installations
- Photos of the DOROS-C installations
- **DOROS front-end exchange:** the procedure in PDF and PPTX
- **Inventory of the interlocked collimator DOROS front-ends** in PDF and XLSX

Useful information

- DOROS experts: Marek 163104, Jakub 167883, Guillaume 167317.
- Localise the rack of a DOROS front-end on the GIS Portal.
  Just type the network front-end name in the search window.
- Software development: BIOROS JIRA ISSUES
- Vistar info LHC page 1
- LHC access conditions
- LHC logbook
- LHC morning meetings
- Software tools on the BI-SW section home



http://mgasior.web.cern.ch/mgasior/pro/DOROS/index.html