DOROS:
2017 news and 2018 plans

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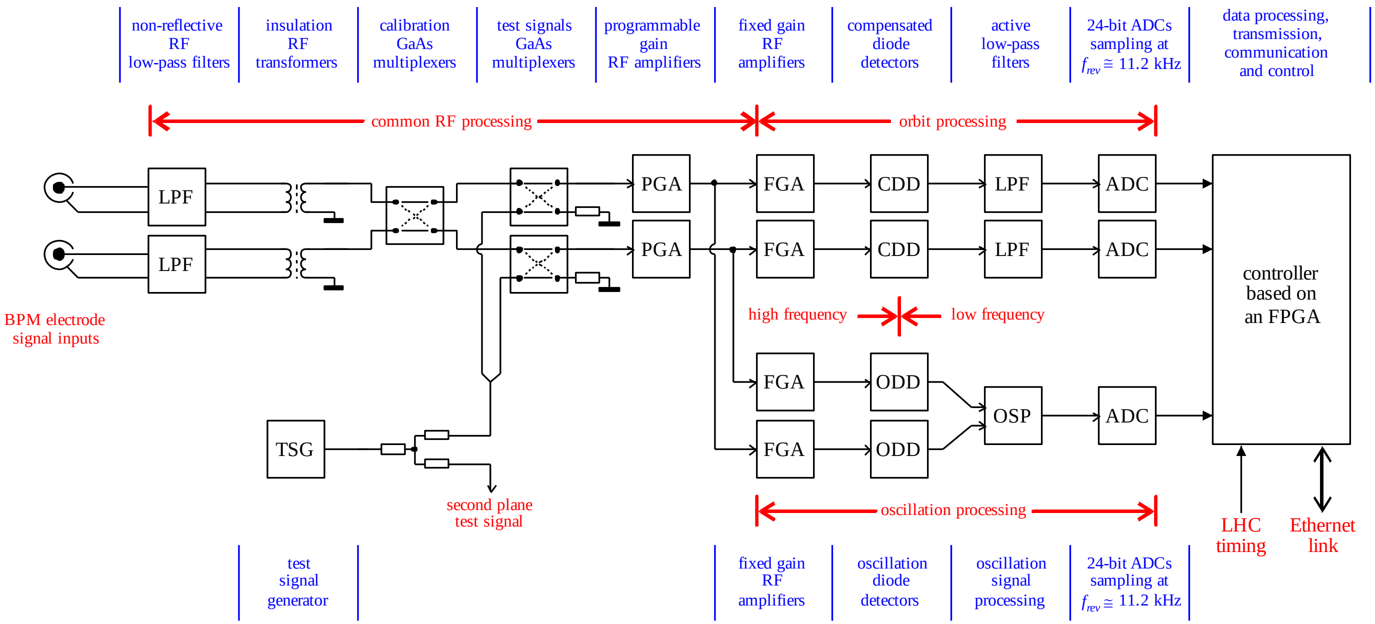
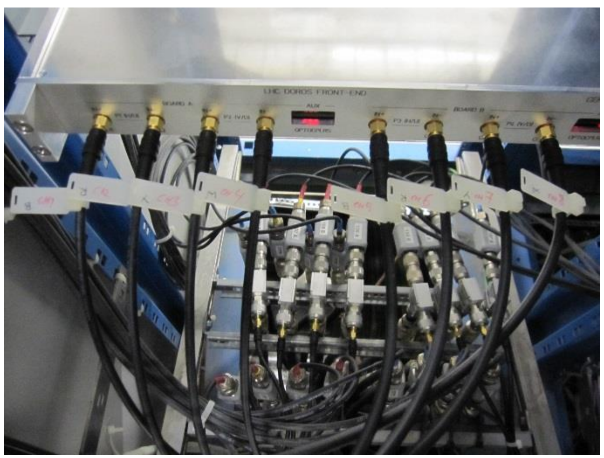
Diode ORbit and OScillation system (DOROS)

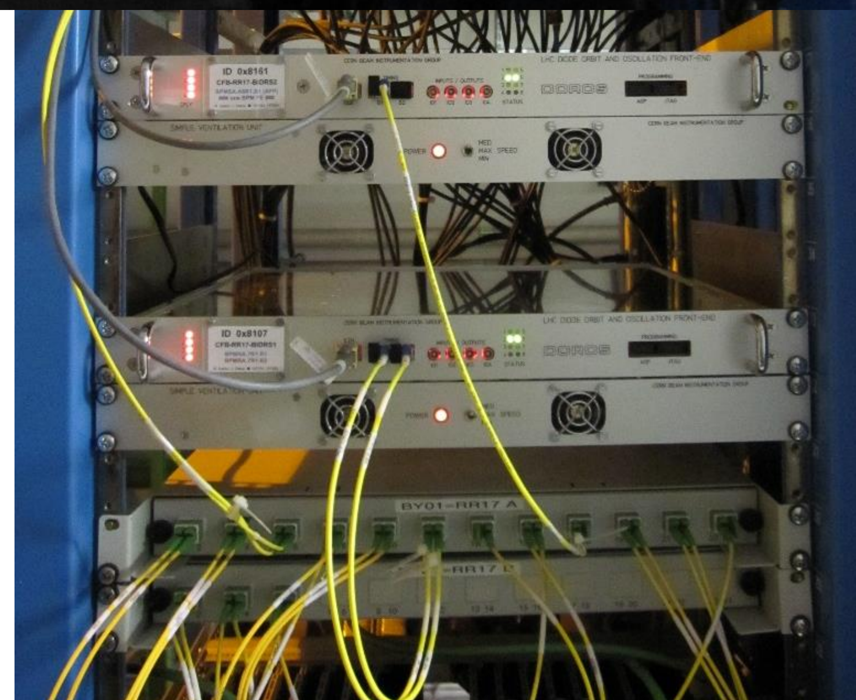
- DOROS is a beam position measurement system based on diode detectors
- The system has been developed to be used with the LHC collimators equipped with embedded BPMs. It is also installed on selected LHC standard BPMs.
- DOROS front-ends contain two parallel subsystems which share the same RF processing:
  - **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.

DOROS installations





- A DOROS front-end has:
  - 8 beam signal inputs (typically)
  - Ethernet
  - BST fibres (B1 and B2, or B1 only, or B2 only)

Current installations

- Collimator BPMs
  - In total 13 DOROS front-ends
  - 22 collimators, installed in P1, P2, P5, P6, P8
  - 10 collimators P1, P5 and P6, equipped with 6 front-ends provide data for software interlocks

- DOROS on standard LHC BPMs
  - In total 12 front-ends
  - 16 Q1 BPMs in P1, P2, P5 and P8, equipped with 8 front-ends
  - 2 AFP BPMs in P1, equipped with 2 front-ends
  - 4 Q7 BPMs in P1, equipped with 2 front-ends

- R&D installations
  - In total 3 front-ends
  - 1 SPS collimator prototype in BA5, equipped with 1 front-end (LHC collimator studies with SPS beams)
  - 2 SPS button BPMs in BA5, equipped with 1 front-end (it has modified bandwidths, used for ALPS studies)
  - LHC P4 in the tunnel: 1 front-end for radiation-tolerance studies, also the robustness of the FPGA code

2017 news: FESA progress

BIOROS-	type	created	updated	resolved	status	title
1	task	07/06/17	09/06/17	07/06/17	done	Create project
2	new feature	07/07/17	24/10/17		in progress	Add buttons to DOROS Expert GUI to load and send preset values to a set of DOROS servers over UDP
3	new feature	07/06/17	27/09/17		in progress	Create sequencer tasks to load different DOROS presets over UDP
4	new feature	07/06/17	09/06/17		to do	Add readout of post-mortem buffers from DOROS front-ends
5	task	07/06/17	09/08/17	09/08/17	done	Validate new FPGA code
6	task	07/06/17	09/06/17	09/06/17	done	Declare in FESA the new 2017 AFP BPM
7	task	07/06/17	24/10/17	24/10/17	done	Declare in FESA two DOROS SPS BPMs
8	bug	13/06/17	13/06/17	13/06/17	done	The expert GUI does not see many collimator front-ends
9	new feature	14/06/17	19/10/17	19/10/17	done	GUI: add a Summary Panel
10	task	20/06/17	09/08/17	09/08/17	done	Update CorrectionCoeffs settings for collimator DOROS BPMs
11	task	20/07/17	19/09/17	19/09/17	done	Raw signals should not be zero with no beam
12	task	24/07/17	21/09/17	20/09/17	done	Software reset of standard DOROS boxes before each fill
13	bug	24/07/17	05/09/17	05/09/17	done	Length limit for the GUI “Command Panel” script
14	improvement	25/07/17	05/09/17		in progress	Robust orbit calculation
15	new feature	25/07/17	28/09/17		to do	Periodic sending of an “RX check” command for a watchdog looking after the FPGA command reception task
16	improvement	06/09/17	19/09/17	19/09/17	done	Create sequencer task to check Collimator DOROS boxes are running
17	bug	21/09/17	23/10/17	03/10/17	done	BpmDorosMonitor: data are mixed up in OverviewPanel
18	task	26/09/17	03/10/17	02/10/17	done	Add to the standard system one front-end in P4
19	new feature	28/09/17	03/10/17	15/11/17	done	Position calculation linearity correction
20	task	28/09/17	26/10/17		in progress	CCC GUI to monitor and reset
21	task	28/09/17	28/09/17		to do	Set-up of a front-end after an emergency reset
22	bug	05/10/17	25/10/17	25/10/17	done	Commands do not work for "OTHERS" devices
23	improvement	09/10/17	09/10/17		to do	Re-write DOROS command parsing to be more robust
24	bug	10/10/17	23/10/17	23/10/17	done	Marek and Jakub cannot edit sequencer task files
25	bug	16/10/17	27/10/17		in review	LHC sequencer commands are sent also to the SPS DOROS BPMs
26	bug	23/10/17	24/10/17	24/10/17	done	In the DOROS Expert GUI impossible to monitor variable Acquisition#horRawValV1
27	bug	24/10/17	24/10/17		to do	Several rows can be selected in SummaryPanel
28	bug	24/10/17	31/10/17		in review	Orbit valid = 1 without beam on a BPM without data
29	bug	25/10/17	27/10/17		in review	Commands sent from the GUI opened with the “OTHERS” button go as well to the LHC STANDARD front-ends
30	bug	26/10/17	31/10/17		in progress	orbit_valid = -1 in the GUI but orbit_valid = 0 in the SIS and logging
31	new feature	31/10/17	16/11/17		in review	DIP data from Q7 and AFP DOROS BPMs of P1
32	bug	31/10/17	03/11/17	01/11/17	done	GUI: Summary panel shows zero raw amplitudes with beam for the collimator system
33	new feature	07/11/17			to do	Log commands sent to the DOROS front-ends
34	bug	10/11/17			to do	Orbits = 0 during gain change
35	improvement	14/11/17			to do	GUI: Limited size of the tables in the Summary and Overview Panels
36	bug	14/11/17	16/11/17		in review	Raw amplitudes sometimes (very) negative
37	bug	16/11/17	17/11/17	17/11/17	done	hhwErrCode has wrong logged values, but good in the GUI

- 37 issues declared so far
- 19 done, 5 in review, 5 in progress, 8 to do

2017 news: Reliability

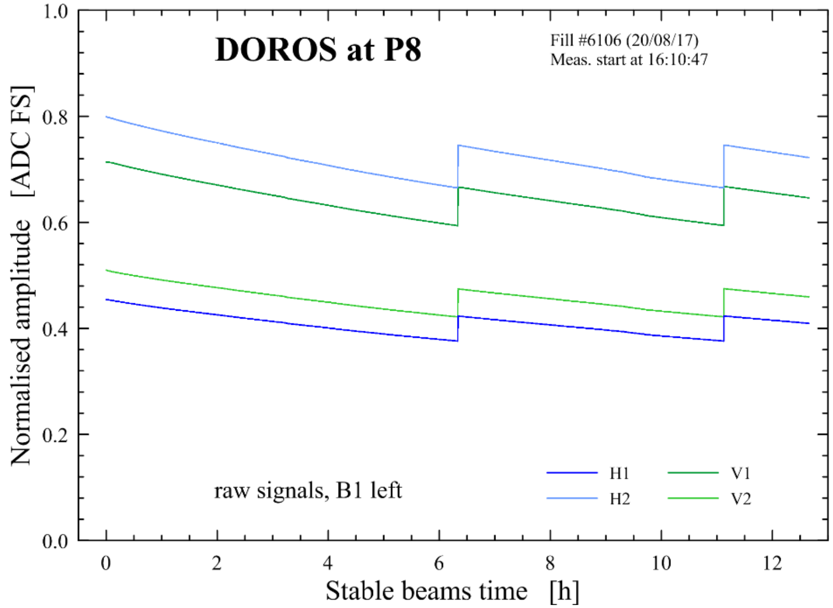
- Reliability is crucial for the collimator system:
  - The availability of all 13 collimator DOROS front-ends is checked by FESA every fill before the pilot injection
  - The LHC sequencer enables the beam injection only if all the front-ends are sending data
  - Beam is dumped if one of the 6 interlocked front-end stops sending data for more than 60 seconds
- No single failure = HW reliable + FPGA code reliable + FESA reliable

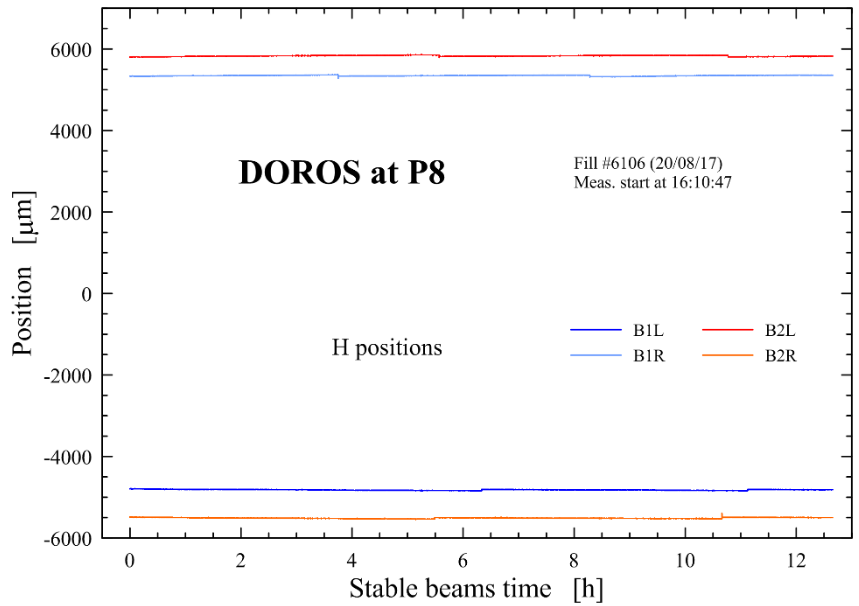
- Careful testing of the FPGA and FESA codes of the collimator DOROS system
  - lab testing
  - test stand testing of a few front-ends
  - tests in the LHC on the DOROS front-ends connected to the standard BPMs: 12 front-ends for a few weeks; this allows testing the FPGA code and FESA software in operational conditions

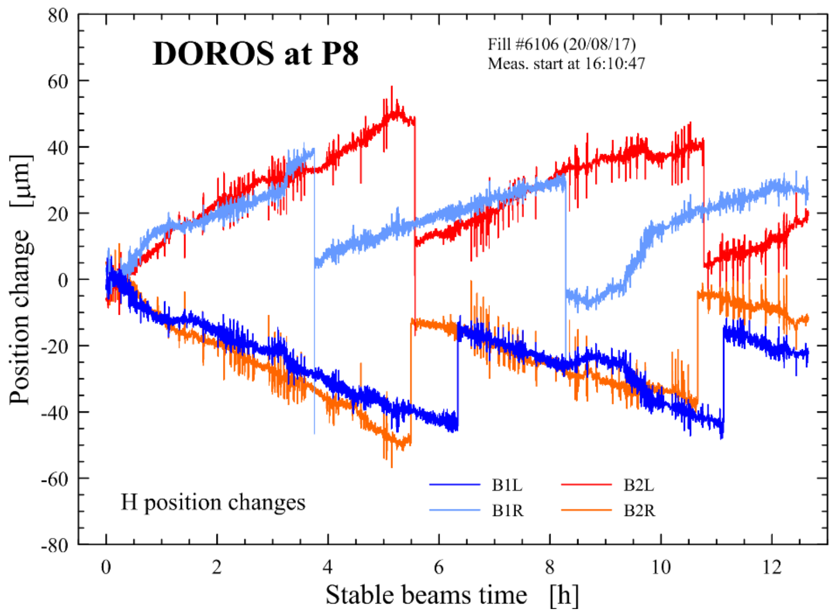
- The collimator system is kept as simple as possible:
  - The collimator front-ends operate always with the same “universal” settings, hardcoded in the FPGA
  - The front-ends are reset before each fill

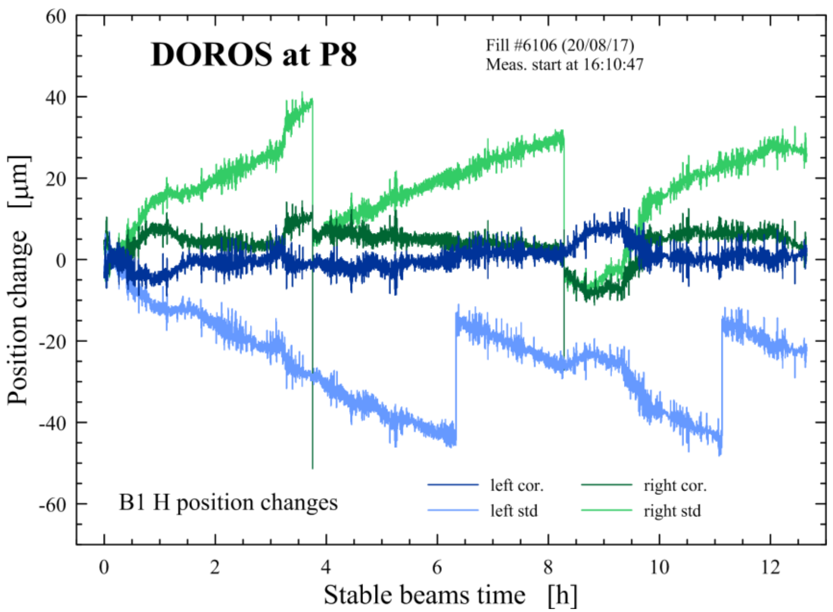
- The DOROS system on the standard BPMs is pushed much further and requires its settings to be changed according to the actual beam conditions (the most important is the number of bunches)
- It is used to test new FPGA and FESA codes before they are deployed on the collimator system
- Encountered issues:
  - A few cases of lost data transmission, all self-cured by the front-end auto-resetting
  - A few cases of lost communication to a front-end, all self-cured (unfortunately sometimes after a few days)
  - One hardware failure so far (-12 V power supply broken)
  - Badly configured 2 Ethernet switches, causing strange and rare problems;
    Jakub had to add a lot of diagnostics and error messaging to the FPGA code to understand the issue.

- By now more than 50 years of the integrated operation time of the installed DOROS front-ends

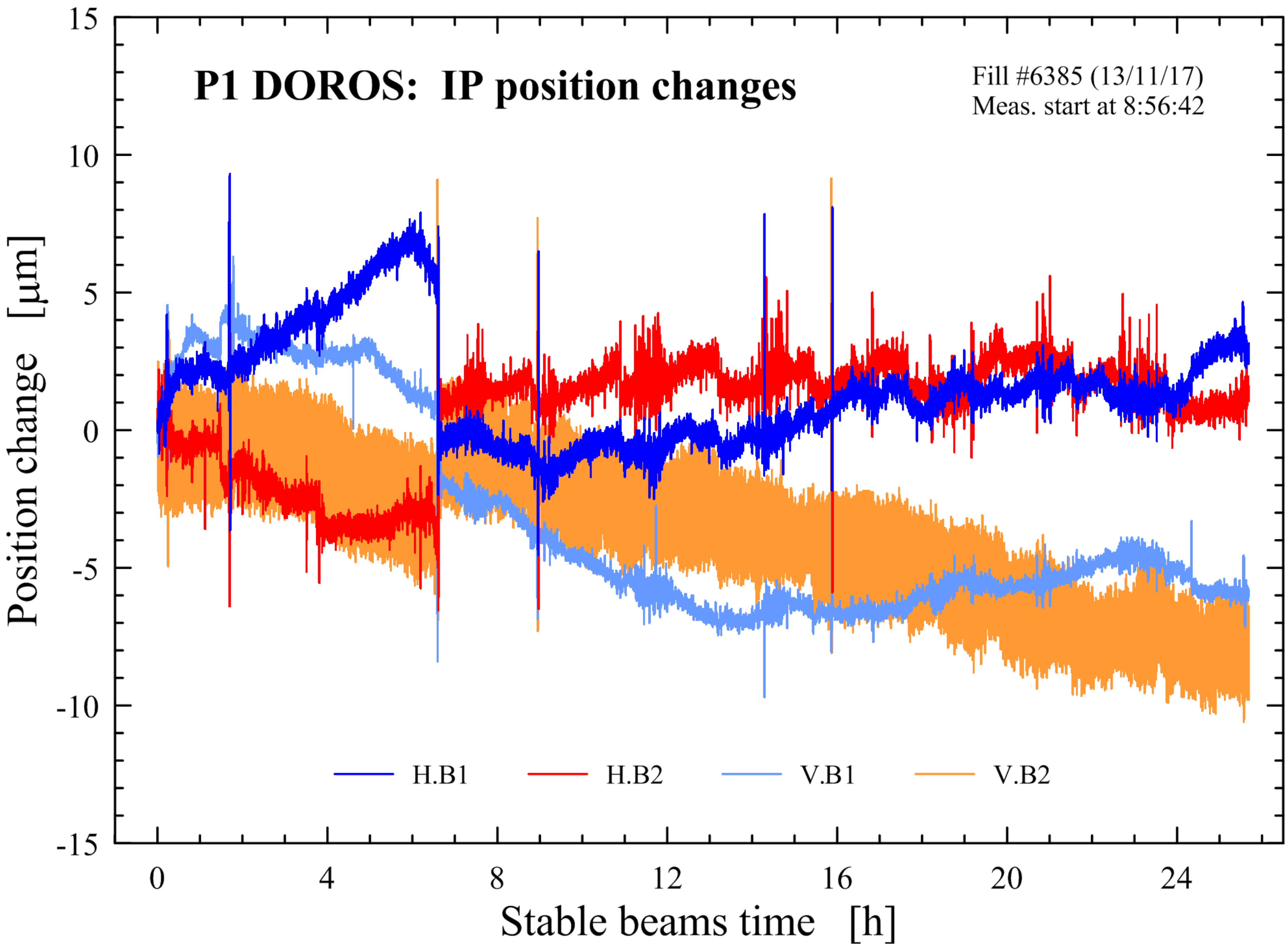

DOROS at P8
Fill #6106 (20/08/17)
Meas. start at 16:10:47
Normalised amplitude [ADC FS]
raw signals, B1 left
H1
H2
V1
V2
Stable beams time [h]


DOROS at P8
Fill #6106 (20/08/17)
Meas. start at 16:10:47
Position [µm]
H positions
B1L
B1R
B2L
B2R
Stable beams time [h]

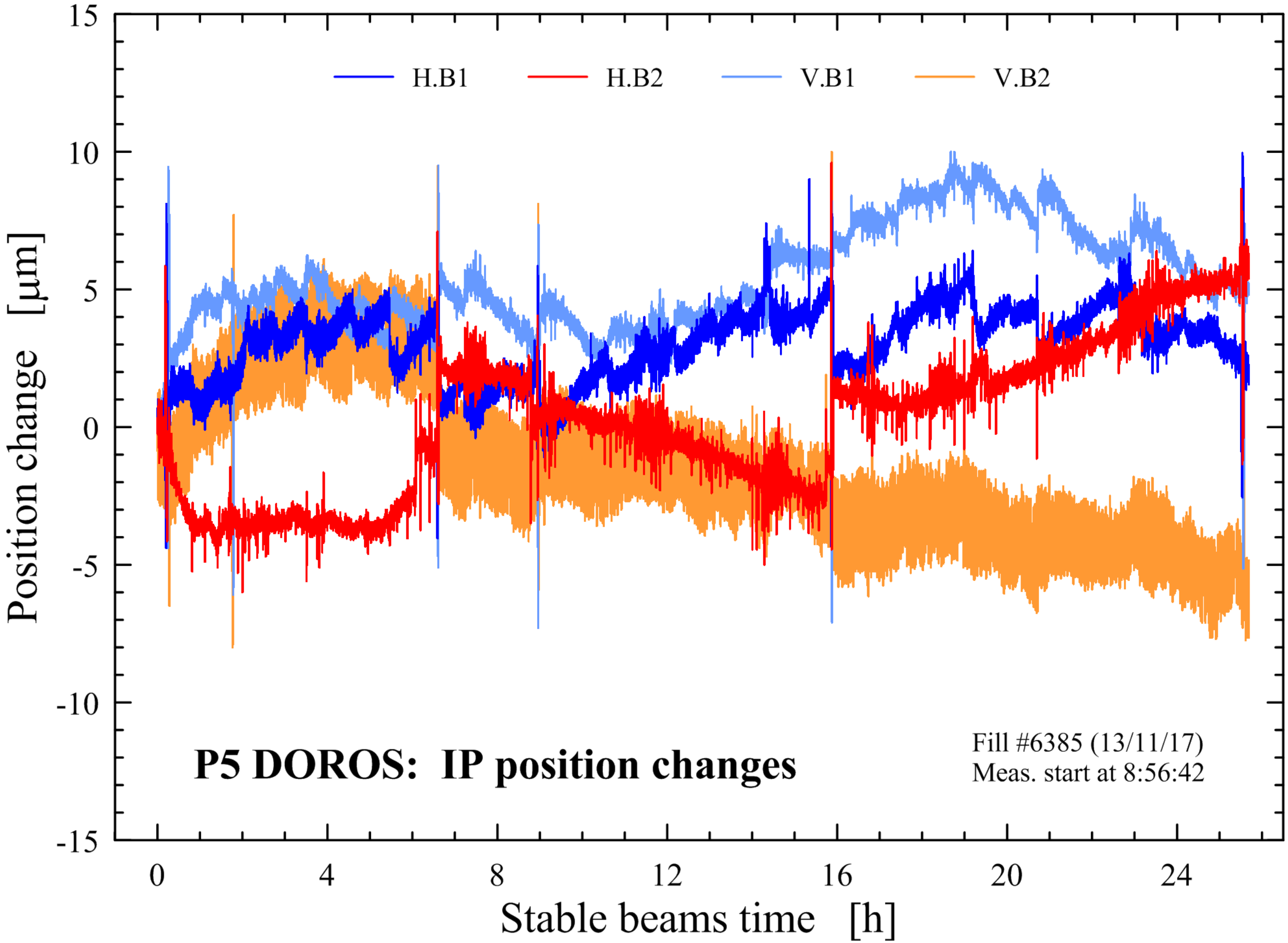

DOROS at P8
Fill #6106 (20/08/17)
Meas. start at 16:10:47
Position change [µm]
H position changes
B1L
B1R
B2L
B2R
Stable beams time [h]


DOROS at P8
Fill #6106 (20/08/17)
Meas. start at 16:10:47
Position change [µm]
B1 H position changes
left cor.
left std
right cor.
right std
Stable beams time [h]

2017 news: Real-time linearity correction



2017 news: Real-time linearity correction



2017 news: a list of smaller things

- Apostolos has very promising results of quadrupolar measurements using DOROS signals from collimator and standard BPMs.

- The 2 SPS BPMs equipped with DOROS electronics are used for MDs and beam studies
  - Beam stability monitoring for crystal collimation (coasting beams)
  - Studies of the beam low frequency spectral content (AWAKE MD)
  - Evaluation of the DOROS performance with SPS beams

- One DOROS front-end installed in the LHC tunnel in P4 (next to the BBQ pick-ups) for radiation robustness evaluation
  - Works fine, no problems at all

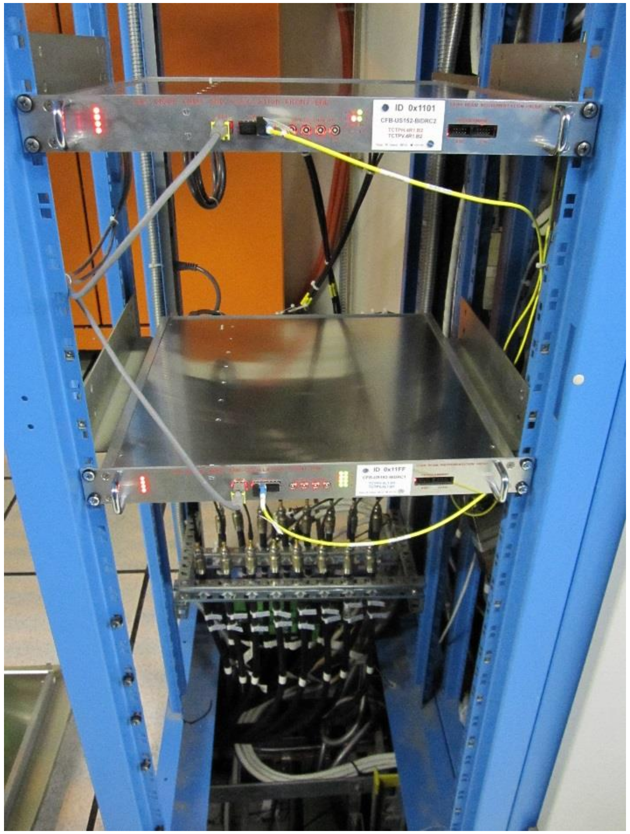
- Laboratory studies of the sensitivity of the oscillation measurements: oscillation detectors vs. orbit detectors.
  - Results: orbit detectors are some 3 times less sensitive than the oscillation detectors at the LHC tune frequencies.
  - Conclusion: we could have beam oscillations scaled in µm at the price of the 3 times reduced sensitivity.

- Fine gain control of the DOROS RF amplifiers with pin diode attenuators
  - Currently the gain is controlled in 1 dB steps. Smaller gain steps would reduce proportionally systematic errors caused by the beam intensity changes.
  - The pin attenuator would control the gain within 1 dB step practically continuously (a voltage control with a 16-bit DAC).
  - Design ready, the standard DOROS PCBs being modified for laboratory measurements.

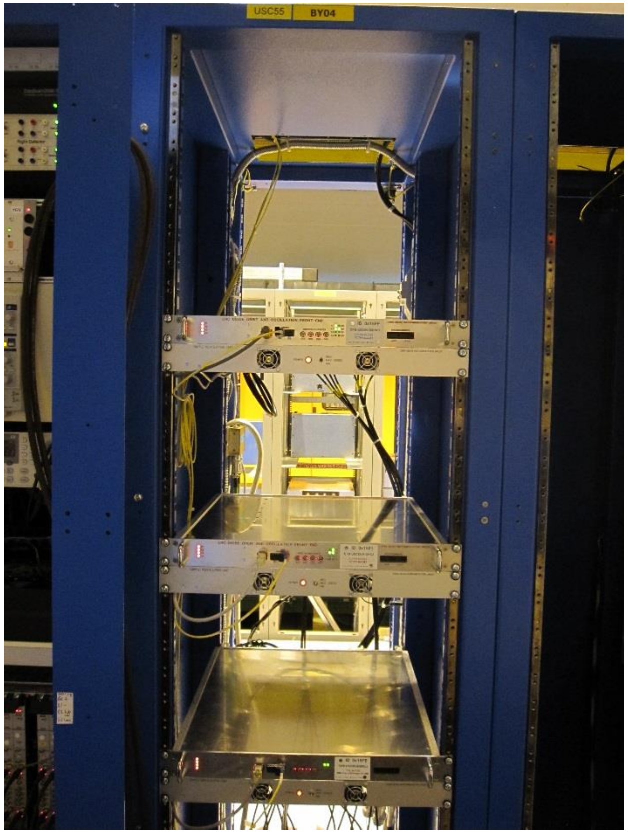
2018 plans: redundancy of the SIS collimator front-ends

6 Collimator DOROS front-ends used by the SIS:

- P1: 2 front-ends located in one rack and processing signals from 4 TCTP collimators: H+V.4L1.B1, H+V.4R1.B2
- P5: Like in P1, 2 front-ends located in one rack and processing signals from 4 TCTP collimators: H+V.4L5.B1, H+V.4R5.B2
- P6: 2 front-ends, one per rack located on each side, processing signals from 2 TCSP collimators 4L6.B2 + 4R6.B1



BY01.US152



BY04.USC55

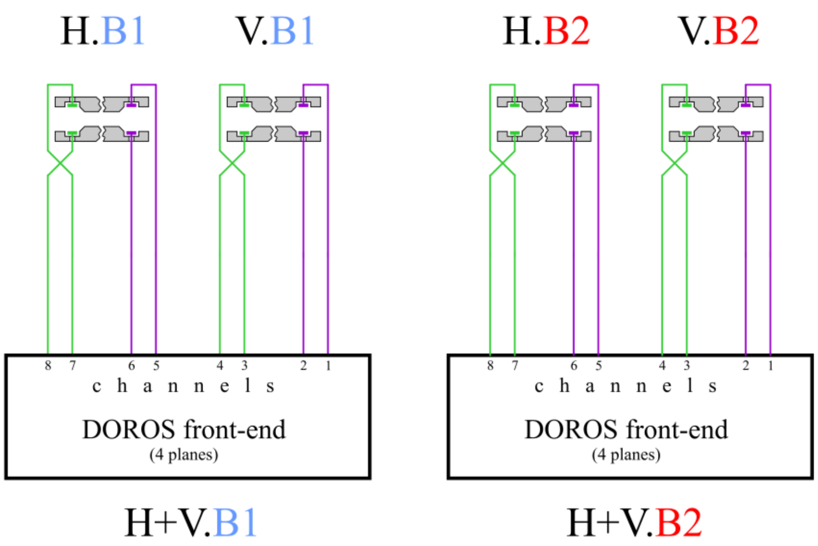
BY02.UA63

BY02.UA67

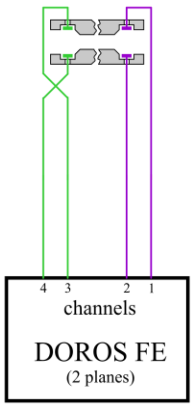
2018 plans: redundancy of the SIS collimator front-ends

- Signals from upstream and downstream BPMs of each collimator are processed with one DOROS front-end
- If one front-end does not work, then:
  - In P1 and P5 position data from 4 BPMs of 2 collimators is lost = beam dump or injections blocked
  - In P6 data from 2 BPMs of one collimator is lost = beam dump or injections blocked
- Hardware redundancy can be based on the implemented SIS logic “downstream OR upstream BPM”.
  Then to have redundancy it is enough to process the signals from the upstream and downstream BPMs with different DOROS front-ends. If one front-end does not work, the orbit data from only one BPM per collimator is lost and the second BPM still can drive the SIS.
- The broken front-end can be replaced at a convenient occasion. The intervention time should be about 1 hour.
  SIS DOROS front-ends are located in US152, USC55 (access possible even with circulating beam), UA63 and UA67.

Current BPM signal arrangement in P1 and P5 (2 front-ends per point)



Current BPM signal arrangement in P6L and P6R (1 front-end per side)

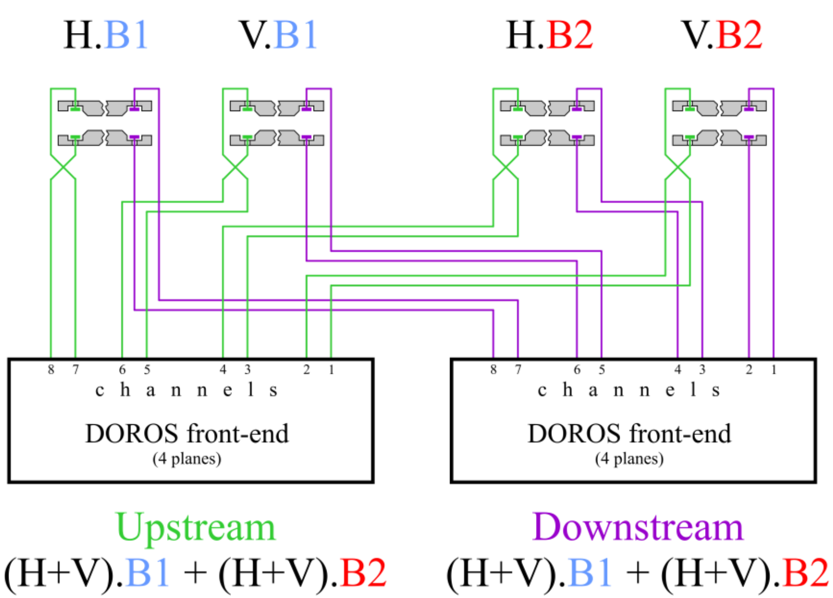


2018 plans: redundancy option 1 (“smart”)

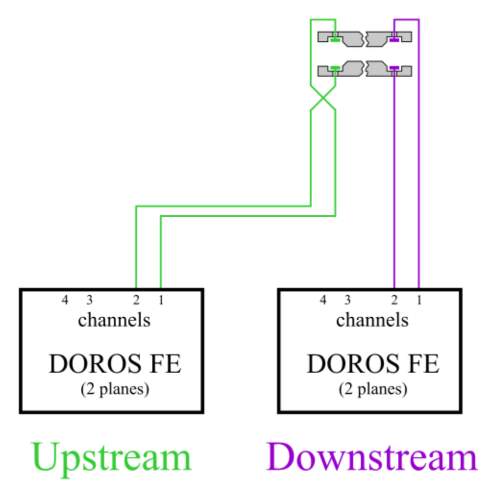
- In P1 and P5 there are already two front-ends in one rack, so it is enough to re-arrange the BPM signals in such a way that the upstream signals are processed by one front-end and the downstream signals by the second front-end.
- In P6 two additional front-ends should be installed for independent processing of the upstream and downstream signals.

- Cost:
  - 2 additional DOROS FEs (P6L, P6R)
  - Changes in the DOROS FPGA automatic gain control: “per collimator” -> “per port”
  - Exotic software configuration for the interlocked BPMs

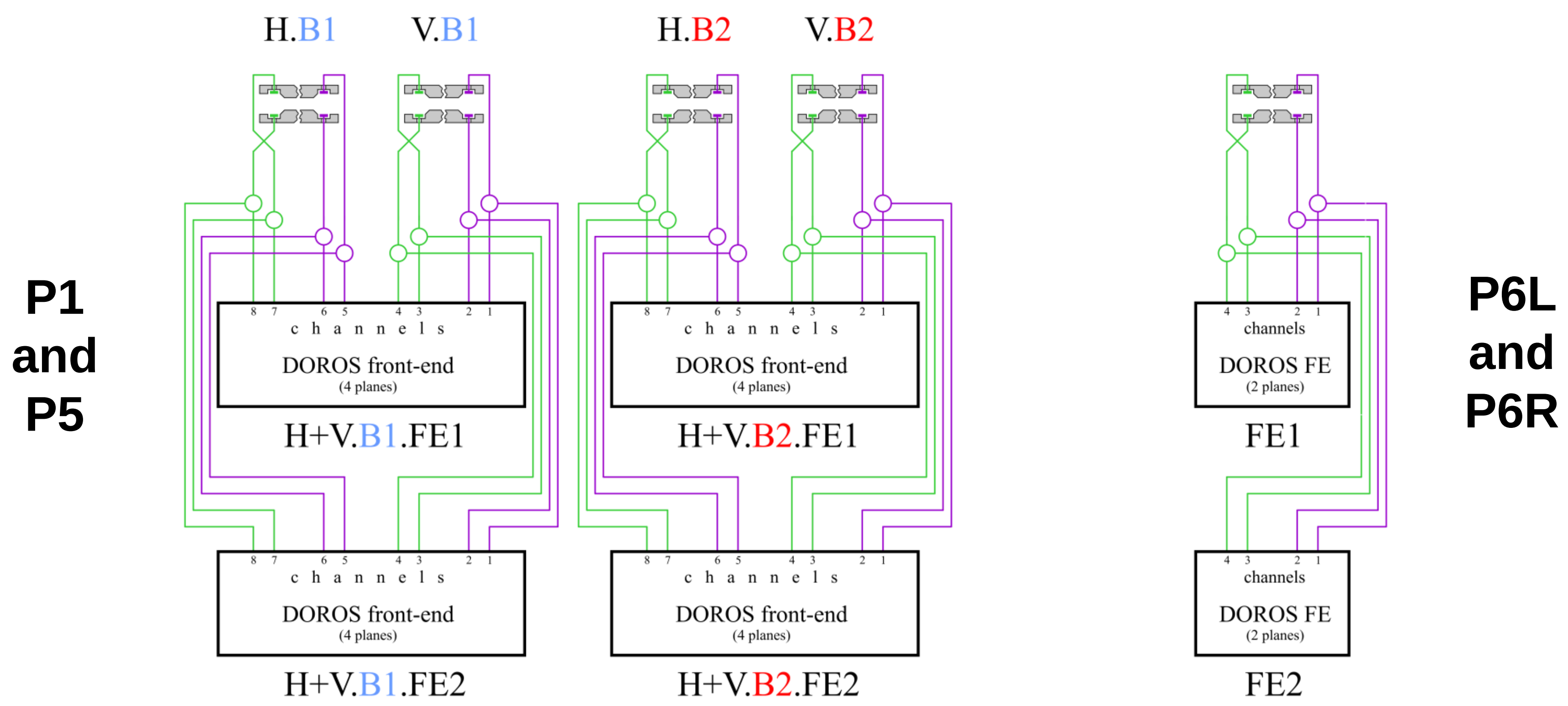
P1 and P5



P6L and P6R



- BPM signals are split and processed by separate DOROS FEs
- Cost:
  - 6 additional DOROS FEs (2 in P1, 2 in P5, 1 in P1L and 1 in P6R)
  - 40 % less signal: completely transparent for the nominal bunches, visible with the pilots and ions



2018 plans: a list of smaller things

- A dedicated DOROS front-end for the quadrupolar measurements of Apostolos
  - DOROS front-end has optimised symmetry for H and V plane measurements
  - Quadrupolar measurements require “corner symmetry”: H left + V up and H right + V down.
    Such a front-end will not give the best orbits and it should be used only for quadrupolar measurements.

- Dedicated DOROS front-end(s) for low frequency beam stability measurements next to the experiments
  - Such measurements not compatible with precision orbit measurements (calibration switching not possible)
  - Details being discussed

- Radiation robustness evaluation
  - Installing a second front-end in a place with a larger radiation, probably P7

- Request from the CCC SPS island to have the SPS DOROS front-end acquiring synchronously to the SPS Frev for beam studies (currently synchronously to the LHC Frev …)
  - Requires minor hardware modifications and some FPGA changes
  - The plan: “We will do our best”

- Laboratory:
  - Oscillation measurements: a front-end prototype with beam oscillations in µm (and reduced sensitivity)
  - Fine gain control with pin diodes: a front-end with such a control
  - Attempting bunch gating “à la BBQ”

Summary

The 2017 news:

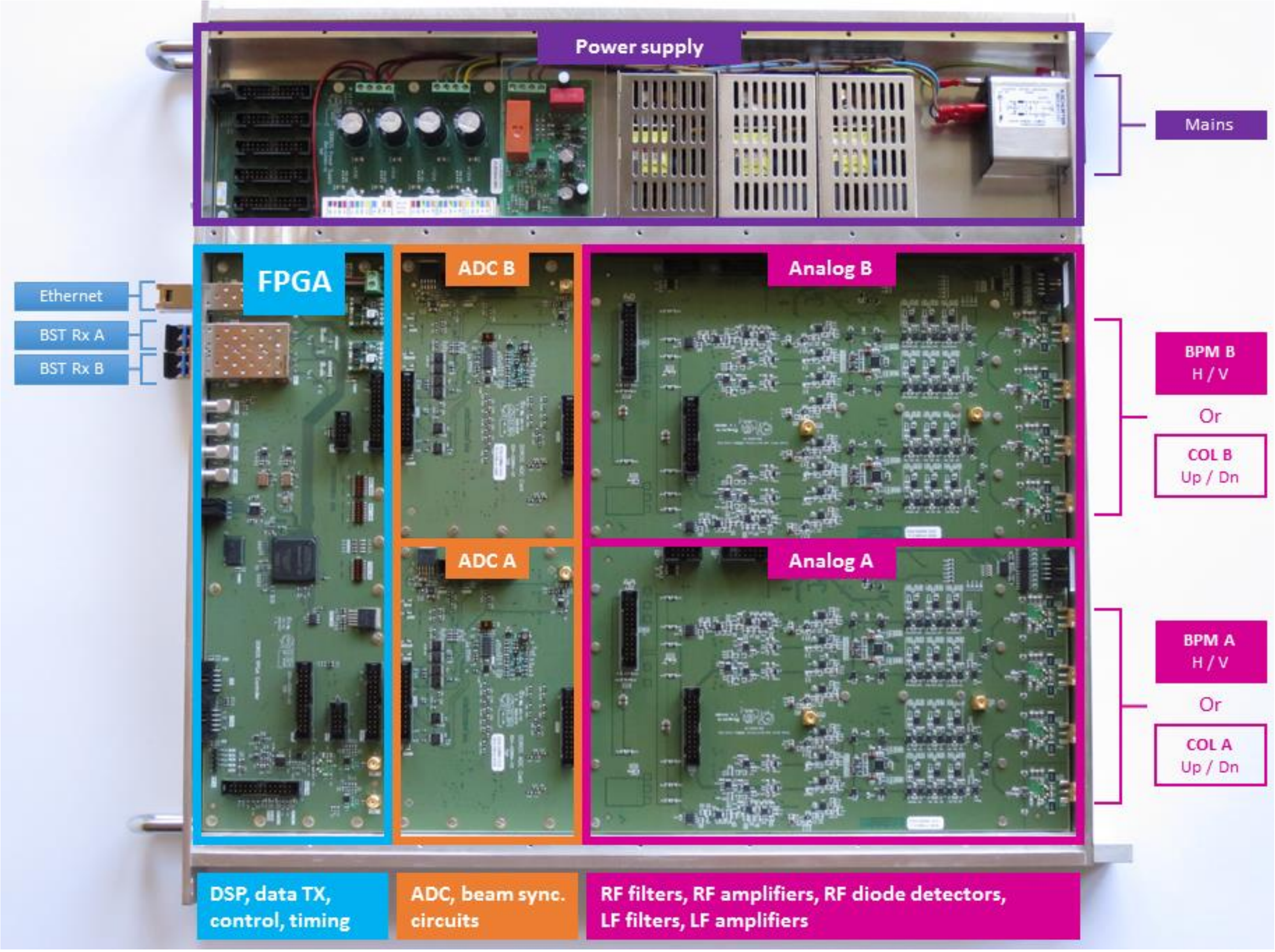
- Progress in the FESA software
- Excellent reliability
- Real-time linearity correction to reduce systematic errors
- Very promising quadrupolar measurements
- 2 SPS BPMs equipped with DOROS electronics and used for MDs and the hardware evaluation with SPS beams
- One DOROS front-end installed in the LHC tunnel in P4 for radiation robustness evaluation
- Laboratory studies of the sensitivity of the oscillation measurements: orbit detectors vs. oscillation detectors
- Fine gain control of the DOROS RF amplifiers with pin diode attenuators

The 2018 plans:

- Redundancy of the collimator SIS front-ends
- A dedicated DOROS front-end for the quadrupolar measurements of Apostolos
- Dedicated DOROS front-end(s) for low frequency beam stability measurements next to the experiments
- Radiation robustness evaluation
- Frev sampling in the SPS DOROS front-end
- Oscillation measurements: a front-end prototype with beam oscillations in µm (and reduced sensitivity)
- Fine gain control with pin diodes: a front-end with such a control
- Attempting bunch gating “à la BBQ”

Spare slides

DOROS front-end



- All DOROS front-ends are identical and they are distinguished only by their IDs
- The ID is a unique 16-bit number programmed manually with DIP switches
- One extra DIP switch for channel configuration if the front-end uses 6, 4, or 2 channels (standard 8 channels)

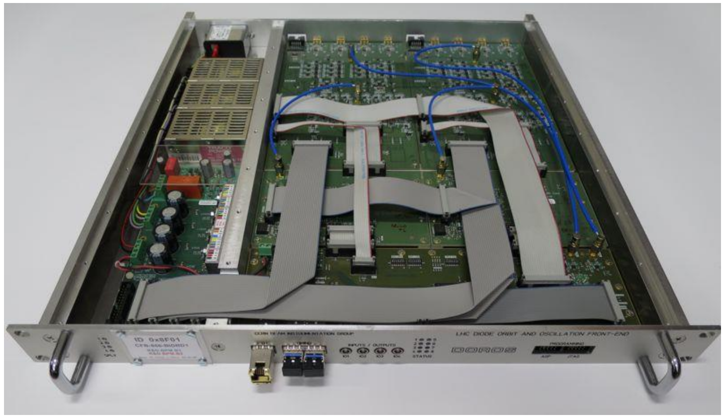
Diode Orbit part

- 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}
- Real-time UDP streaming of the processed ADC data from the DOR channels
  - Raw electrode data IIR filtered, decimated and sent to a FESA server at a 25 Hz rate
  - Cut-off of the IIR filter can be programmed in the range 0.01 Hz – 2 kHz.
  - FESA server computes DOR data and absolute beam orbits in mm;
they are published at 1 Hz rate with 1 s latency.
  - Data is logged and available in Timber
  - A faster asymmetry calibration switching is under study to reach data rates and latency compatible with the current orbit feedback operation (12.5 Hz)
- 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 from FESA 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 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 FESA

Diode Oscillation part

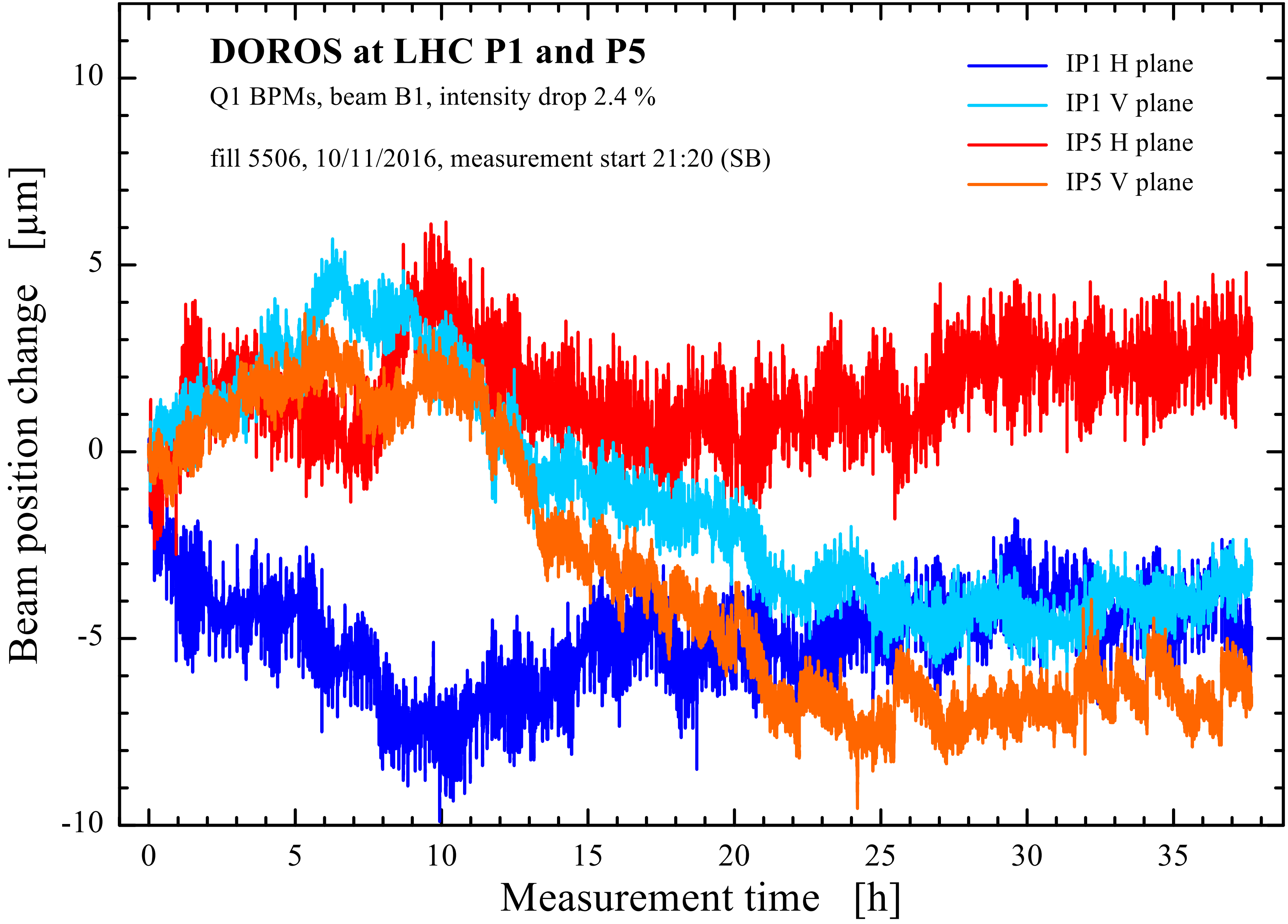
- Optimised diode detectors for measuring small beam oscillations in 3 – 5 kHz frequency range
- Processed analogue signals sampled simultaneously with 24-bit ADCs at the LHC f_{rev}
- Option to synchronize phase of the ADC sampling clocks between the front-ends
- On-demand "Capture/Freeze" mode:
  - Electrode ADC samples stored at f_{rev} rate in the front-end memory.
  - Rolling turn-by-turn buffer depth of more than 1.8 million turns (up to 3.5 minutes @ f_{rev})
  - Capture triggered with dedicated Beam Synchronous Timing (BST) event
  - Optional capture/freeze triggers from FESA commands
  - Data can be used to compute beam position spectra in the bandwidth 0.05 – 0.5 f_{rev}.
- 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 along with the orbit data.
- Sampling of the ADCs in each DOROS front-end can be synchronised to the BST or BPM beam signals

Front-end production and testing



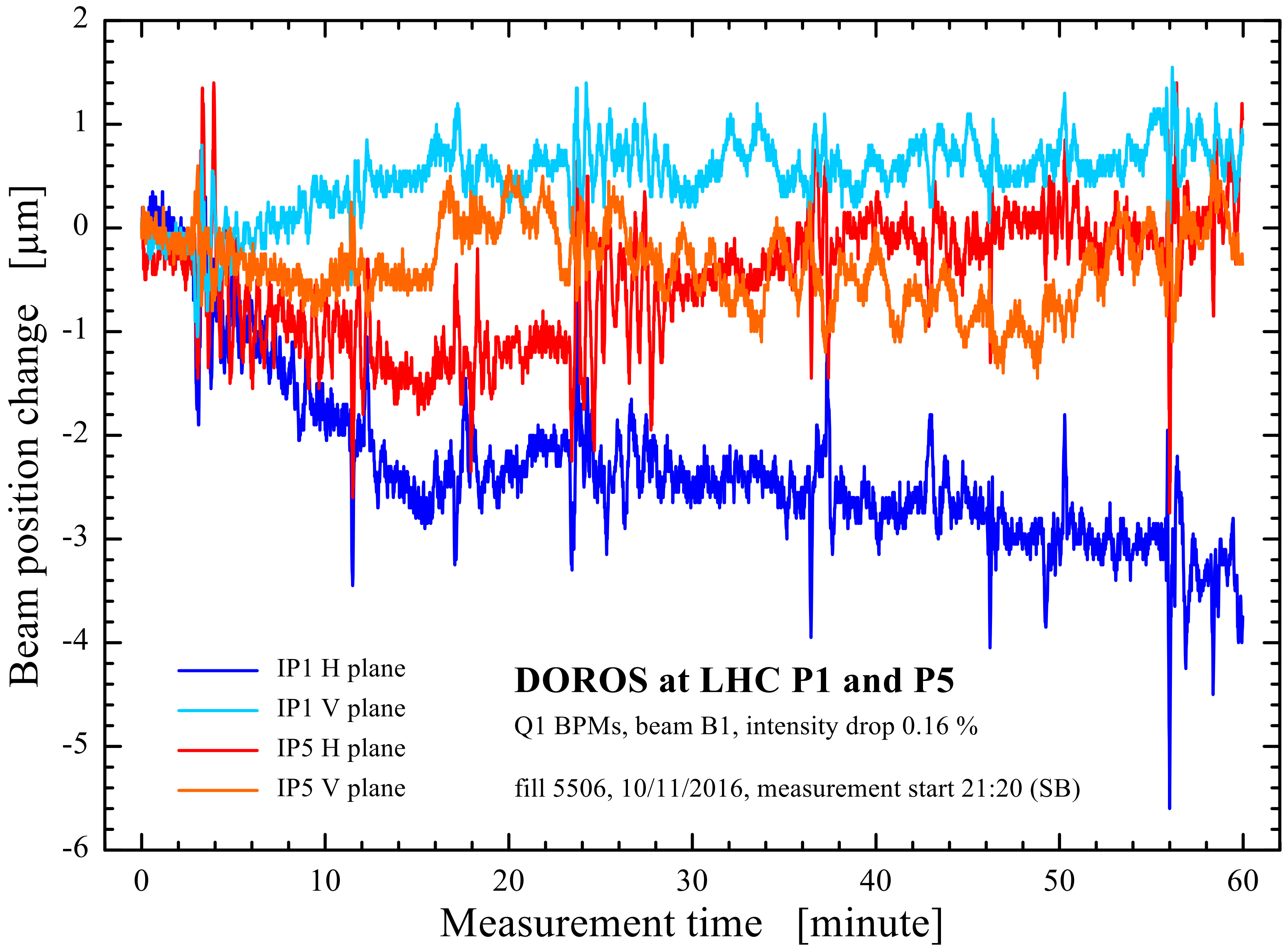
- DOROS accommodates 4 board types:
  - Analog board (two per front-end)
  - ADC board (two per board)
  - FPGA board
  - Power supply
- After production the cards are tested for power consumption only (a minute per board).
- Just after power tests, the ADC cards have the ADC PLL VCO adjusted (a minute per board). This is the only requirement adjustment.
- Front-end box is assembled and equipped with power supplies.
  At this time also flat cables are prepared.
- Once the whole front-end is assembled, the FPGA is programmed (a few minutes).
- The front-end is checked first “as is” without any external signals.
  There are checked noise levels and response to built-in tests signals (a few minutes).
- Then a signal generator is used to simulate beam signals.
  The front-end is checked with one 5 ns pulse simulating one bunch and the same pulse every 25 ns to simulate the full machine. For the time being the checking is manual and takes some 30 minutes.
  Mark works on an automatization of these tests.
- Once the front-end passes the tests, it is good for installation.
  Before the installation the front-end has its ID setup with DIP switches.
  It is 16 bits, which also are the last 16 bits of the front-end MAC address.
- So far we built a few dozens of front-ends. We had only a few PCBs which had not worked right away.
  Typically they had one bad soldering.
- So far we have not had a case of a front-end which stopped operating.

Measurement examples

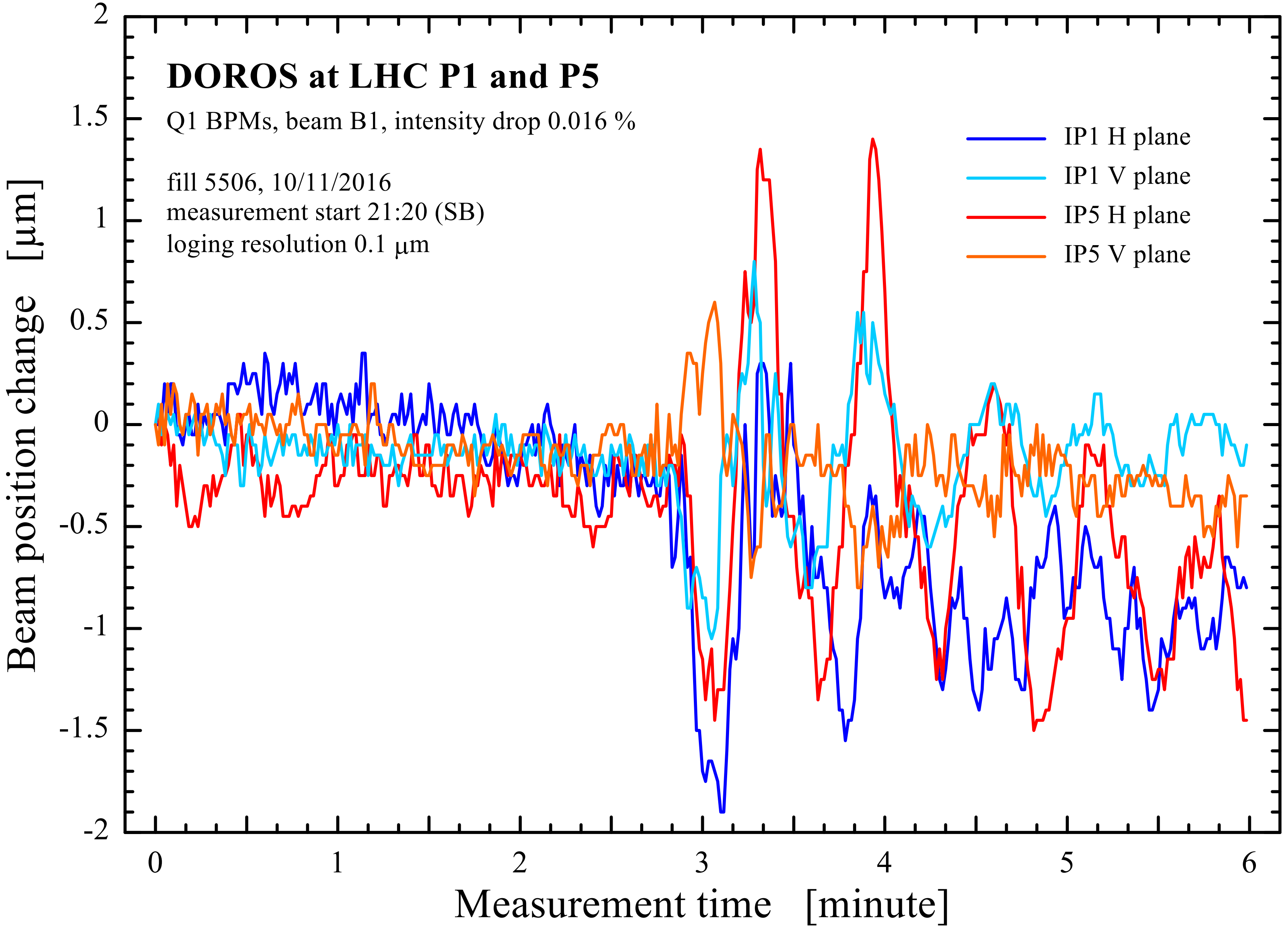


DOROS at LHC P1 and P5
Q1 BPMs, beam B1, intensity drop 2.4 %
fill 5506, 10/11/2016, measurement start 21:20 (SB)
IP1 H plane
IP1 V plane
IP5 H plane
IP5 V plane
Beam position change [μm]
10
5
0
-5
-10
0
5
10
15
20
25
30
35
Measurement time [h]

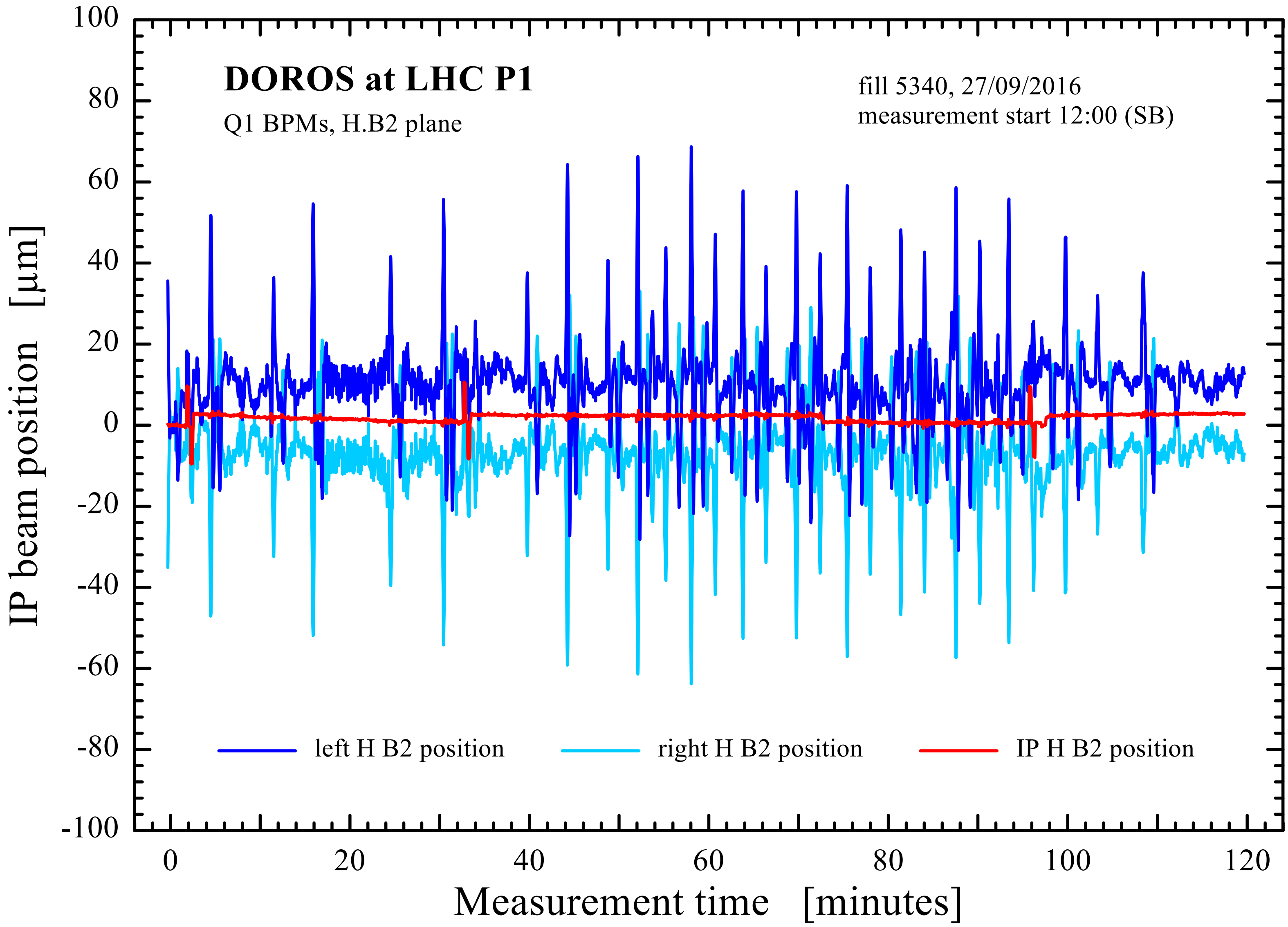
DOROS stability with (almost) constant beam intensity



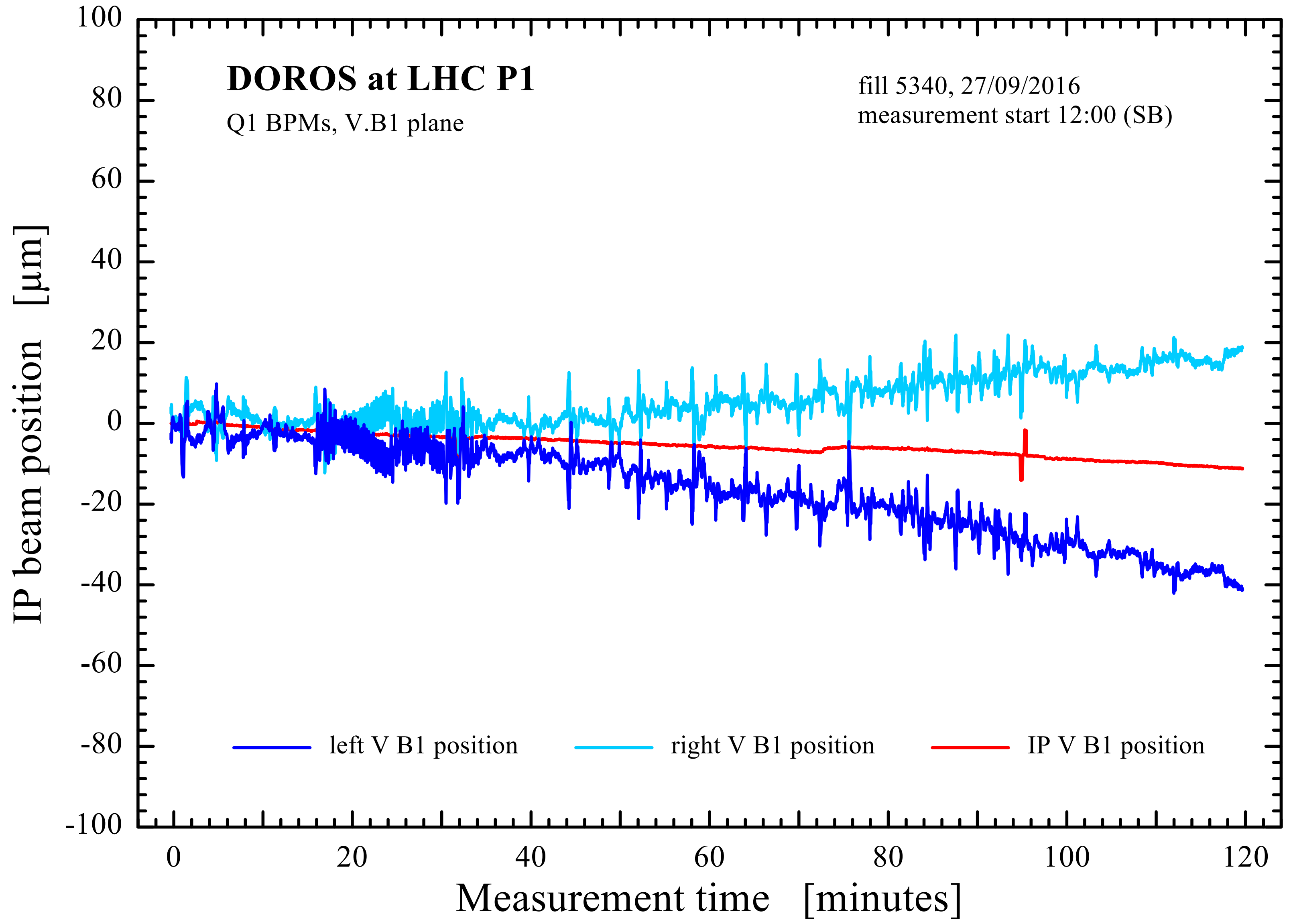
DOROS stability with (almost) constant beam intensity



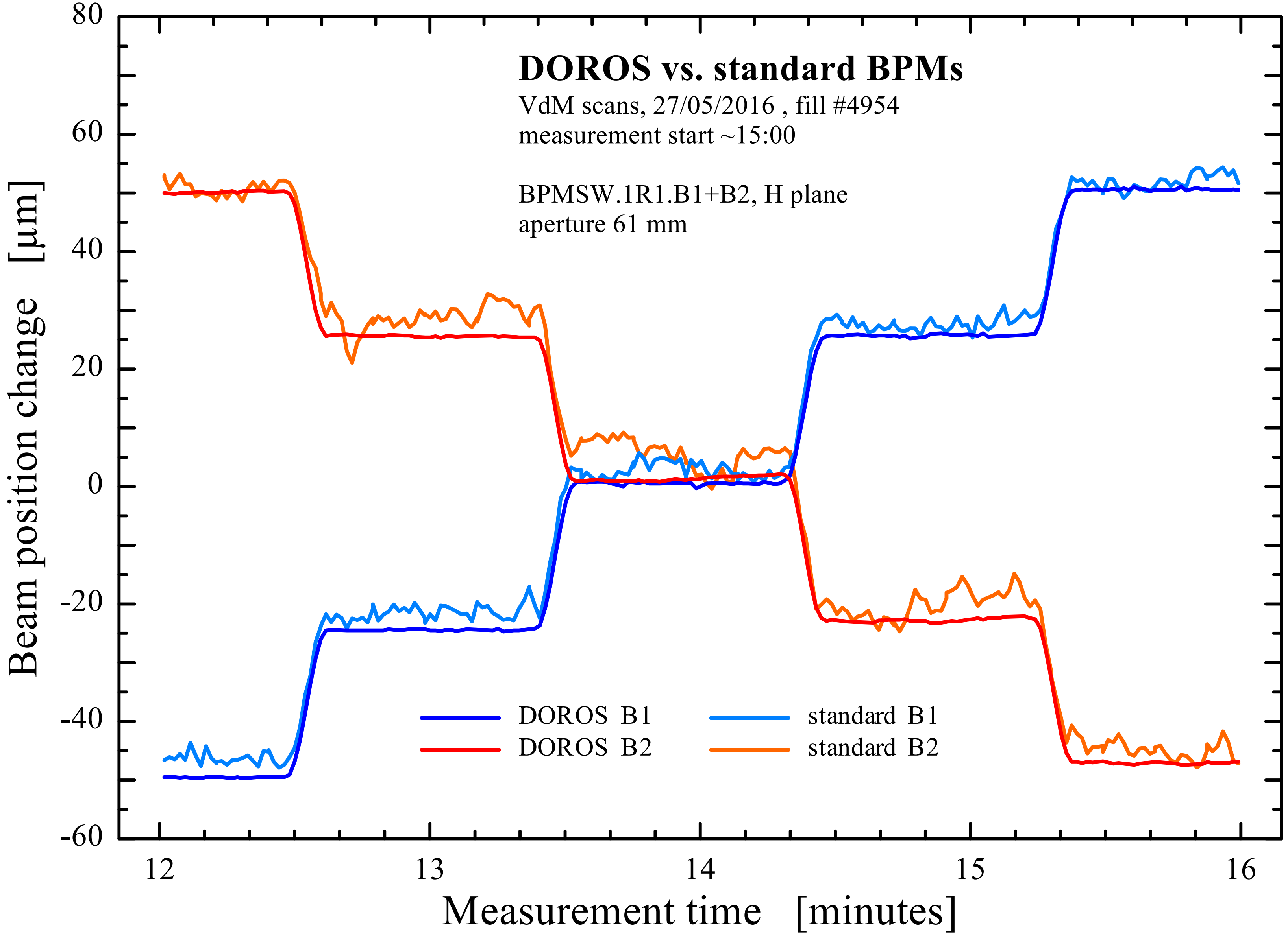
Beam noise seen by the DOROS



Beam noise seen by the DOROS

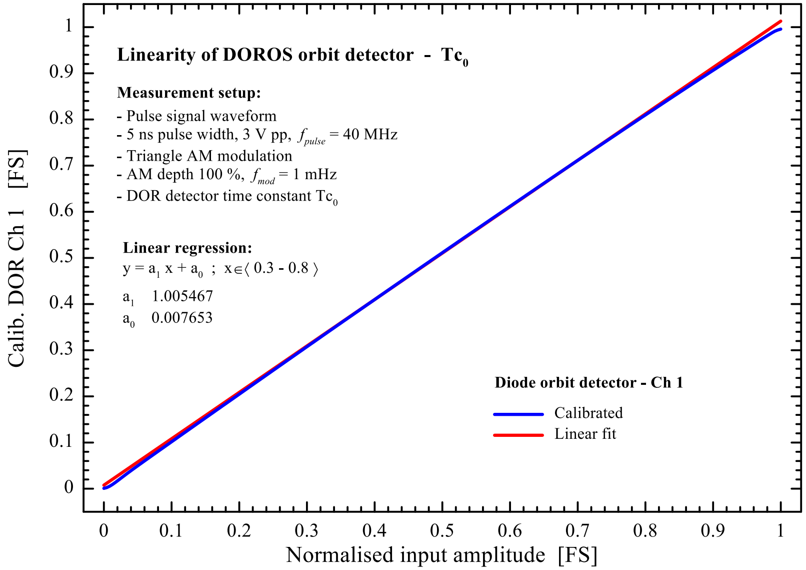


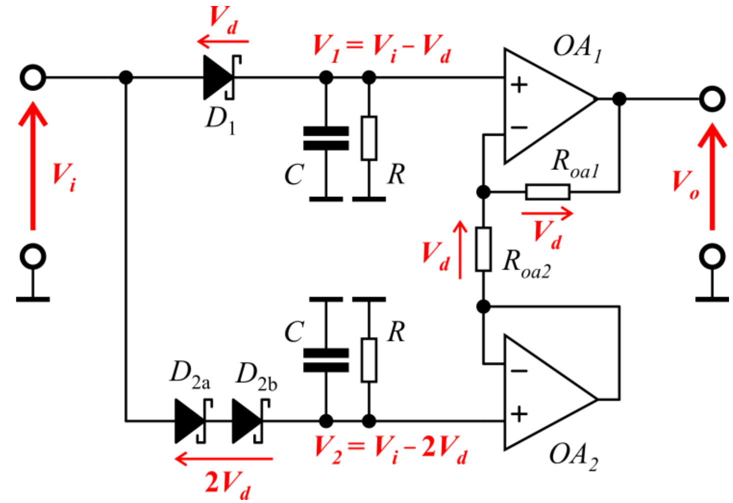
DOROS vs. standard BPMs for orbits



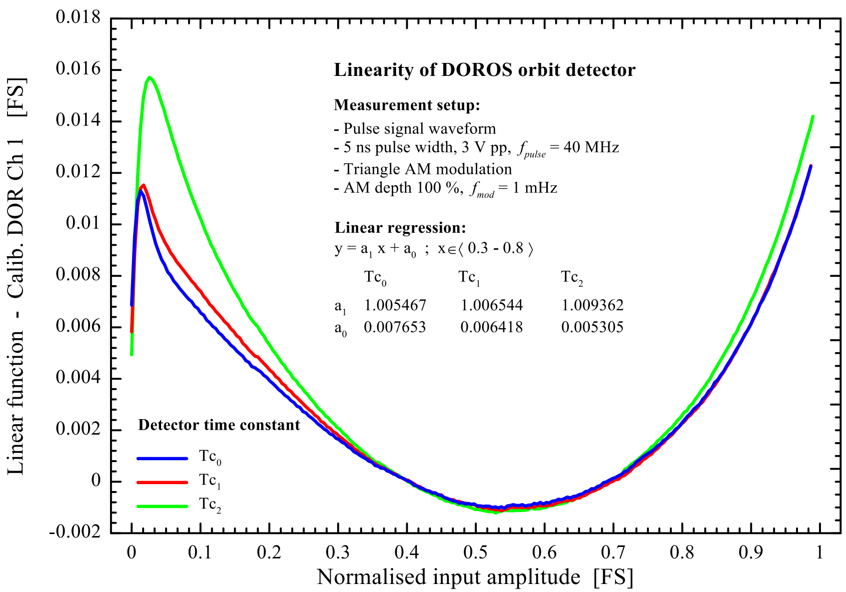
Nonlinearity correction

Linearity of DOROS orbit detectors





Simplified schematic of the DOROS compensated diode detector



- The upper plot shows a laboratory measurement of the detector linearity together with its linear fit.
- The lower 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. For few bunches the time constant with the smallest discharge should be used (TC_0) and for physics beams with many bunches it should be the largest discharge (TC_2).
- The linearity correction coefficients should be different for each time constant and applied automatically according to the time constant being is use.

Linearity of DOROS orbit detectors

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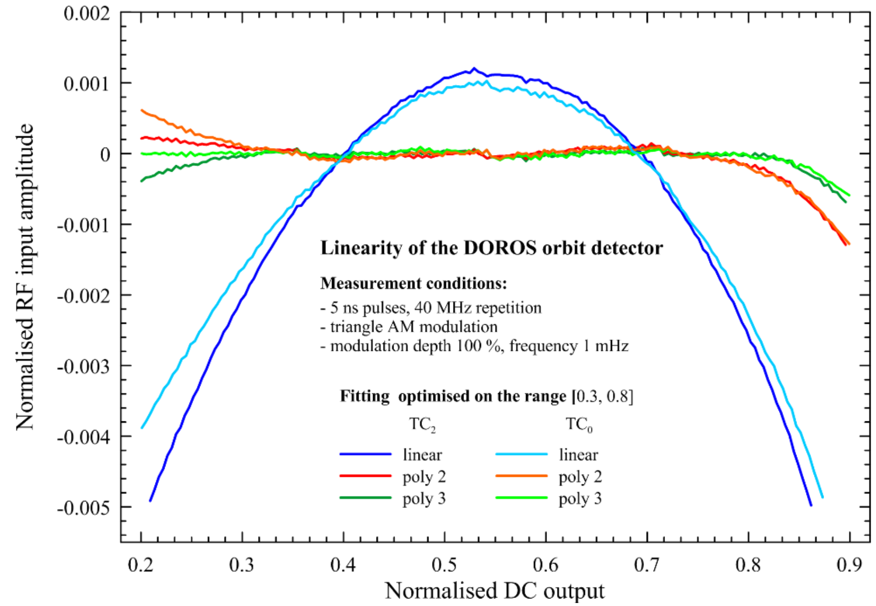
- The plot shows the "inverse" fitting of the detector characteristic, i.e. the RF input as a function of the DC output.
  The 3rd order polynomial can be used to calculate the unknown RF input amplitude of the detector from its known and measured DC output.
- The tables list coefficients of two 3rd order polynomials, the "standard" one $V_{outDC}=f(V_{inRF})$ and the "inverse" one $V_{inRF}=f(V_{outDC})$.
- The "standard" polynomial $V_{outDC}=f(V_{inRF})$ is used in position error calculations.
- The "inverse" polynomial $V_{inRF}=f(V_{outDC})$ is used to calculate the correction coefficients for the position formula with improved linearity, as shown on the next slide.



$$V_{oDC} = c_3 V_{iRF}^{\ 3} + c_2 V_{iRF}^{\ 2} + c_1 V_{iRF} + c_0$$

The "standard" polynomial

Time constant	c_3	c_2	c_1	c_0
TC_0	-0.018087	-0.017291	1.040780	-0.002546
TC_1	-0.021612	-0.013334	1.041260	-0.003984
TC_2	-0.015230	-0.030556	1.056704	-0.007784

$$V_{iRF} = d_3 V_{oDC}^{\ 3} + d_2 V_{oDC}^{\ 2} + d_1 V_{oDC} + d_0$$

The "inverse" polynomial

Time constant	d_3	d_2	d_1	d_0
TC_0	0.021950	0.009651	0.963073	0.002162
TC_1	0.025644	0.005135	0.963090	0.021950
TC_2	0.020509	0.019873	0.949088	0.007064

Position calculation with improved linearity

Normalised position from the input RF amplitudes

$$p_i = \frac{a-b}{a+b}$$

Normalised position from the output DC amplitudes

$$p_o = \frac{A-B}{A+B}$$

"Standard" polynomial mapping the detector DC output to the RF input

$$A = c_3\, a^3 + c_2\, a^2 + c_1\, a + c_0$$

$$B = c_3\, b^3 + c_2\, b^2 + c_1\, b + c_0$$

"Inverse" polynomial mapping the detector RF input to the DC output

$$a = d_3\, A^3 + d_2\, A^2 + d_1\, A + d_0$$

$$b = d_3\, A^3 + d_2\, B^2 + d_1\, B + d_0$$

$$p_i = \frac{A-B+\alpha_1 (A^2-B^2)+\alpha_2 (A^3-B^3)}{A+B+\alpha_0+\alpha_1 (A^2+B^2)+\alpha_2 (A^3+B^3)}$$

The final "corrected" formula to calculate normalised positions with improved linearity

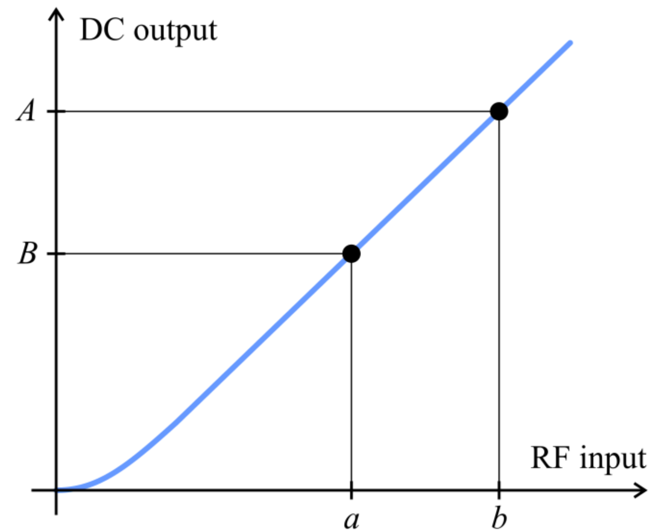
$$\alpha_0 = \frac{2d_0}{d1}, \alpha_1 = \frac{d_2}{d1}, \alpha_2 = \frac{d_3}{d1}$$

The linearity correction coefficients calculated from the "inverse" polynomial coefficients

Time constant	α_2	α_1	α_0
TC_0	0.022792	0.010021	0.004490
TC_1	0.026627	0.005332	0.045582
TC_2	0.021609	0.020939	0.014886

Used quantities:

a, b – signal amplitudes at the detector RF inputs
A, B – detector DC output digitised signals
p_i , p_o – normalised positions on the detector input and output, respectively
c_0 , c_1 , c_2 , c_3 – polynomial coefficients of the detector characteristic
d_0 , d_1 , d_2 , d_3 – polynomial coefficients of the inversed detector characteristic
α_0, α_1, α_2 – linearity correction coefficients



Calculation of the absolute position

- The absolute beam position is calculated from a 2D polynomial also taking into account the normalised position from the perpendicular plane.
- The listed coefficients correspond to the Q1 stripline BPMs of type BPMSW with 61 mm aperture.
- For more details please see:
  A. Nosych, “Geometrical non-linearity correction procedure of LHC beam position monitors”, EDMS 1342295.

$$p_A[\mathrm{mm}] = c_{50}\, p^5 + c_{30}\, p^3 + c_{10}\, p + c_{32}\, p^3 p_\perp^2 + c_{14}\, p\, p_\perp^4 + c_{12}\, p\, p_\perp^2$$

where:

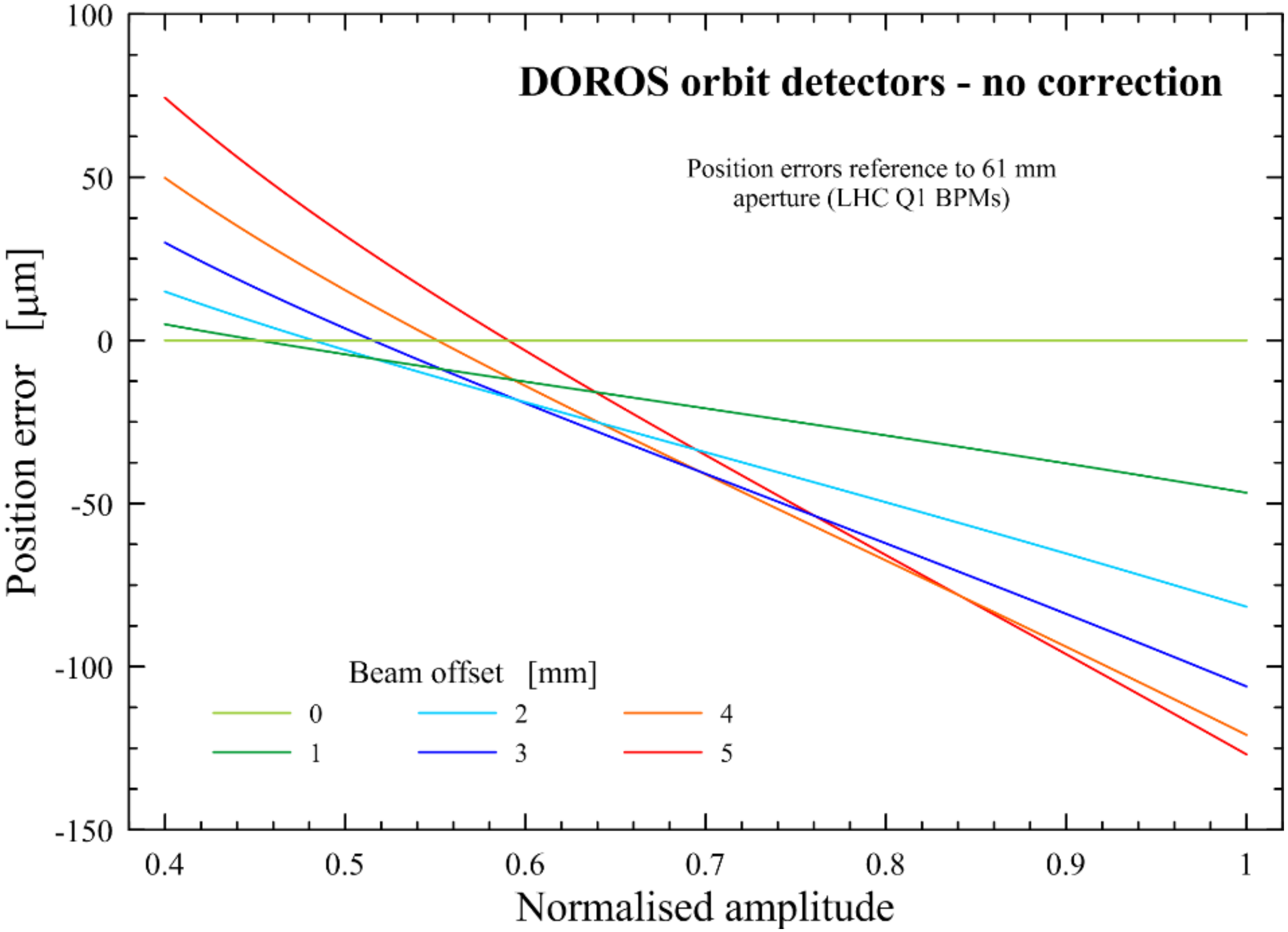
p_A – absolute beam position
p – normalised beam position for the calculation plane
$p_\perp$ – normalised beam position for the perpendicular plane

$c_{50} = 5.1631$	$c_{32} = 8.8287$
$c_{30} = 3.0715$	$c_{14} = 5.3447$
$c_{10} = 17.1037$	$c_{12} = 1.7684$

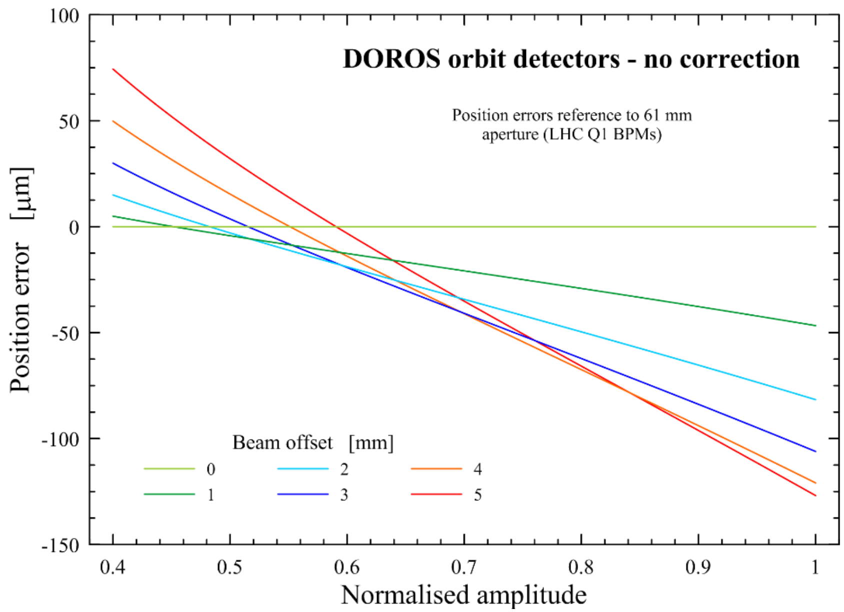
Coefficients for 120 mm BPMSW striplines with 61 mm aperture

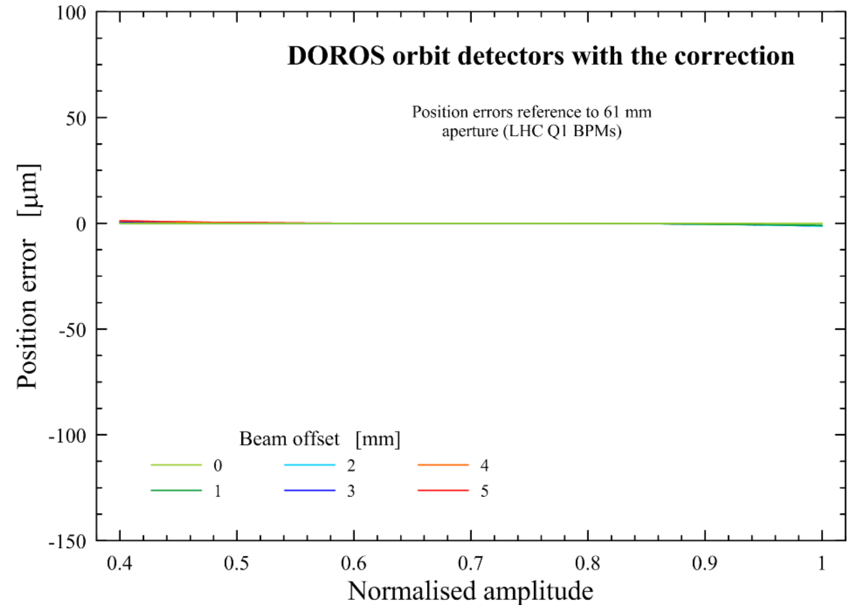
"Natural" DOROS performance

- The transfer characteristic of the DOROS orbit detectors $V_{outDC}=f(V_{inRF})$ is not perfectly linear, with the nonlinearity in the order of 1 %.
- This nonlinearity combined with beam intensity changes results in systematic errors for larger beam offsets.
- The error estimates are presented on the plot below for Q1 BPMs (striplines with 61 mm aperture).
- The errors are in the order of 50 µm, for larger beam offsets and signal variations limited by the automatic gain control to some 20 %.

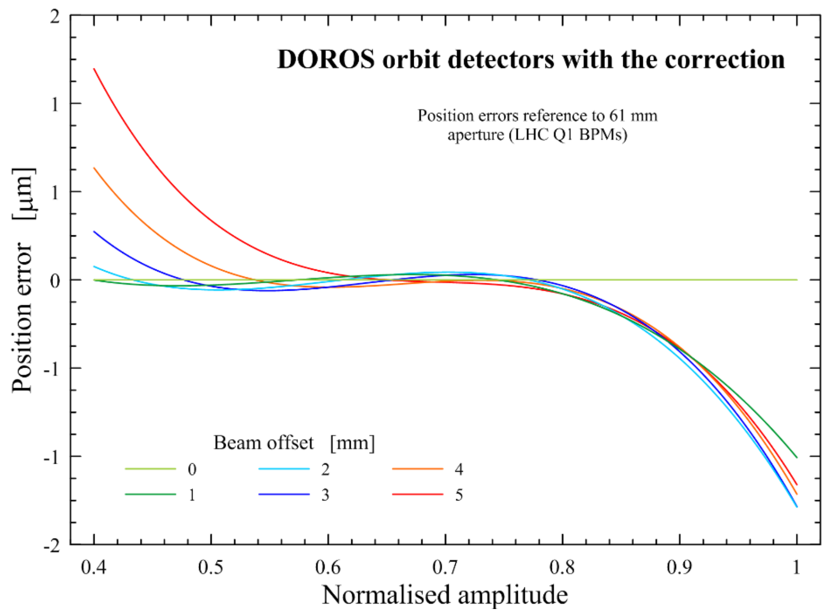


Linearity correction



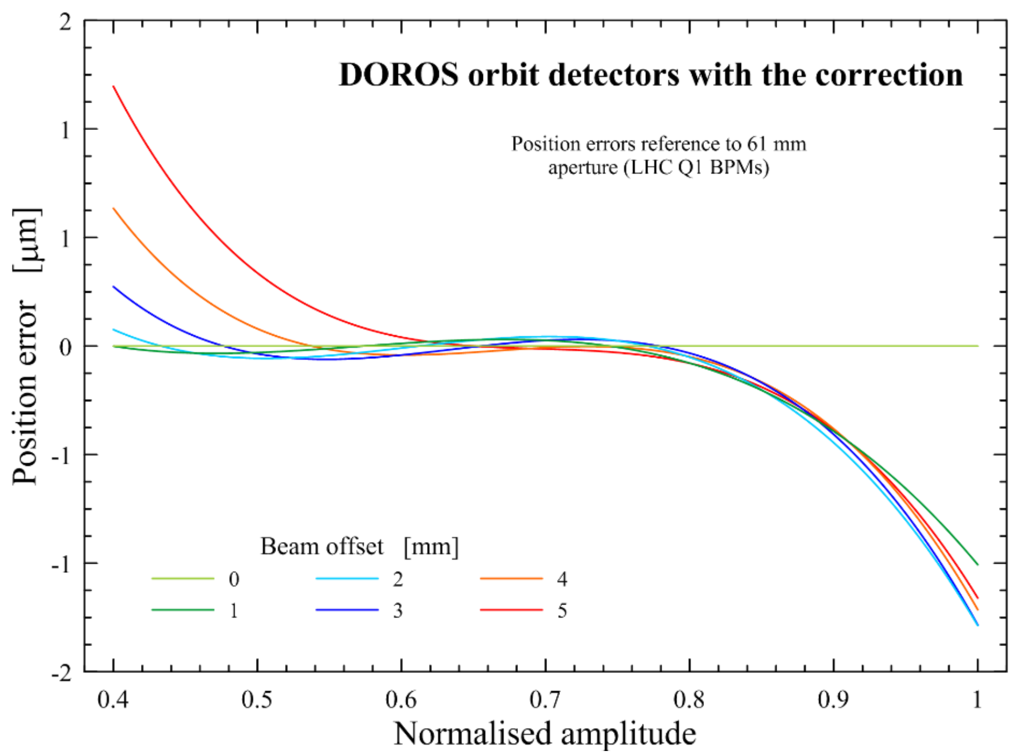


- The upper left plot shows the position errors without the linearity correction.
- The upper right plot shows the position errors with the linearity correction in the same scale as the left plot.
- The lower plot shows the position errors with the linearity correction and the optimised vertical axis scale.



The best improvement of the quality of the DOROS orbit measurements was achieved using the following procedure:

- The transfer characteristic $V_{outDC}=f(V_{inRF})$ of the orbit detectors was measured. The largest challenge of the method is this measurement, as it requires the linearity of the RF signal changes to be much better than 1 %.
- The "inverse" transfer characteristic $V_{inRF}=f(V_{outDC})$ was approximated by a 3rd order polynomial and this polynomial was used to calculate the normalised beam position. The correction is assumed to be identical for all DOROS front-ends.
- The normalised position was used to calculate the absolute position using the standard 2D polynomial.
- The performance of the correction is shown below. It can be seen that the errors are reduced to single micrometres.
- The real performance of the method is worse, as it assumes that all the detectors have the characteristics identical to the one measured in the lab.

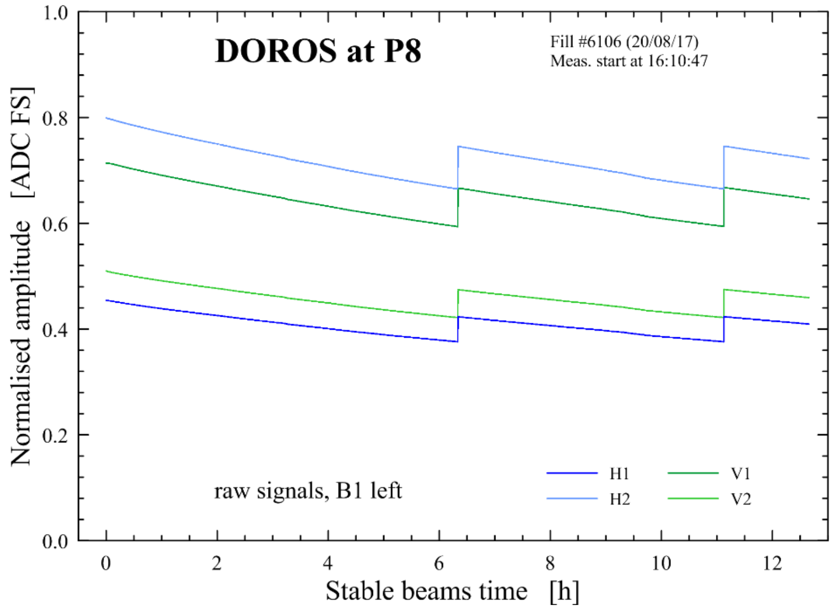


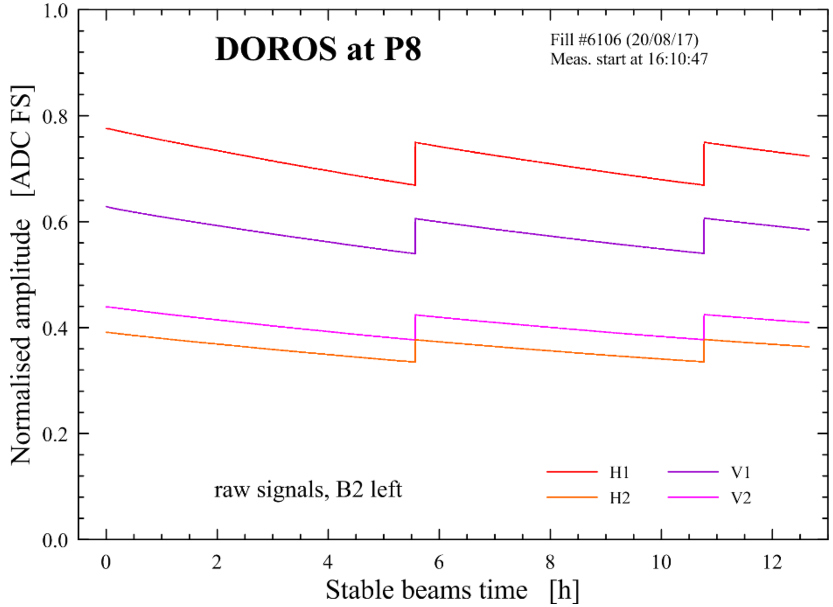
DOROS with improved linearity – example on fill 6106

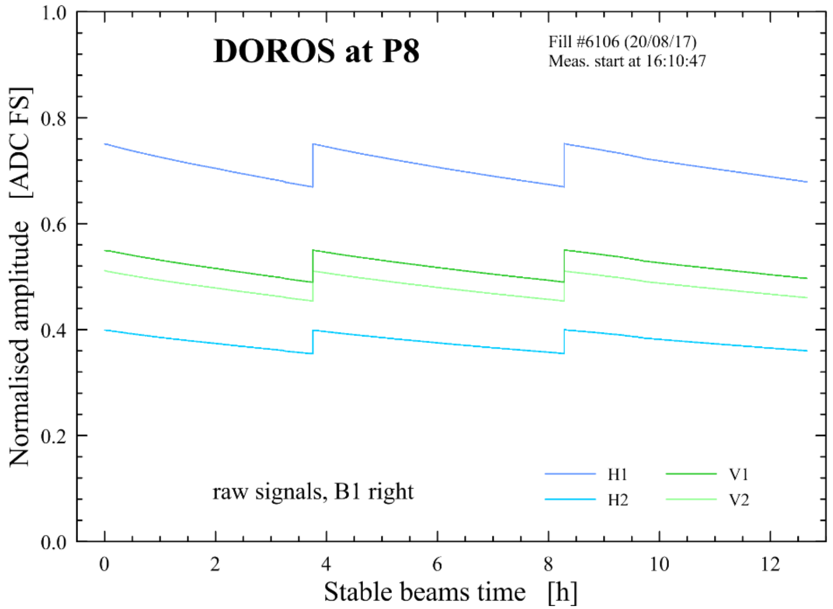
- The following slides show the performance of the linearity improvement method for the stable beams period of fill 6106.
- First P8 is presented in more detail, as there the beam offsets are the larges, causing the biggest errors.
  Then the performance is shown for P1, P2 and P5.
- The correction performance is nicely seen when the gain of the RF amplifiers is increased (1 dB step $\approx$ 12 % gain change).
  Without the linearity correction the gain steps induce large position changes for the planes with important beam offsets.
  These false position changes are largely reduced when the linearity correction is used.
- The performance of the correction is limited by the spread in the detector characteristics and the fact that the characteristics are measured in the lab assuming the number of bunches (1, 100 and full machine for the three time constants). The polynomial used to correct the linearity was calculated upon one laboratory measurement
  and it is used for ALL DOROS front-ends.
- The method will be studied further.
- The presented results probably justify introducing the method into the operational system, as it reduces the systematic errors by approximately one order of magnitude.

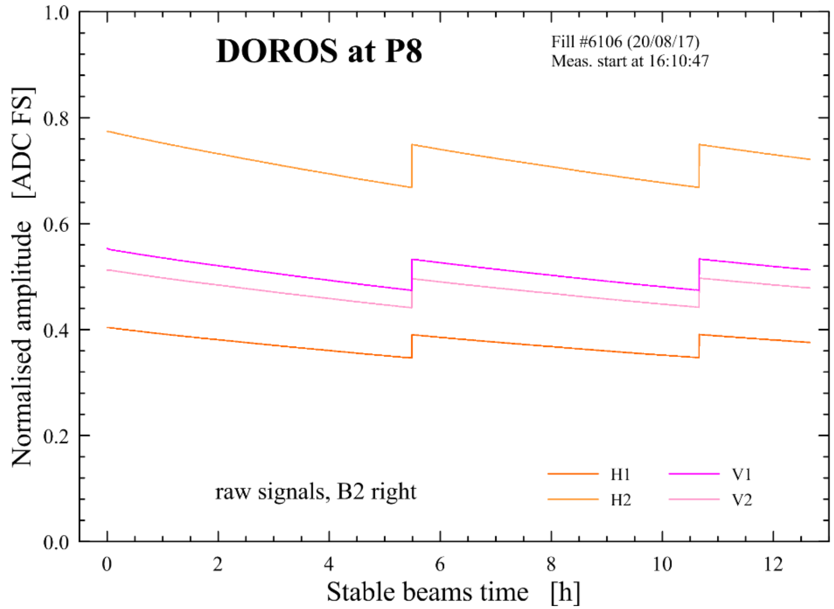
Fill 6106 had the following parameters:

- Stable beams started at 16:10:47 on 20/08/17 and lasted 12 hours and 40 minutes
- 1740 bunches
- B1 intensity 1.8×10^{14}, B2 intensity 1.8×10^{14}

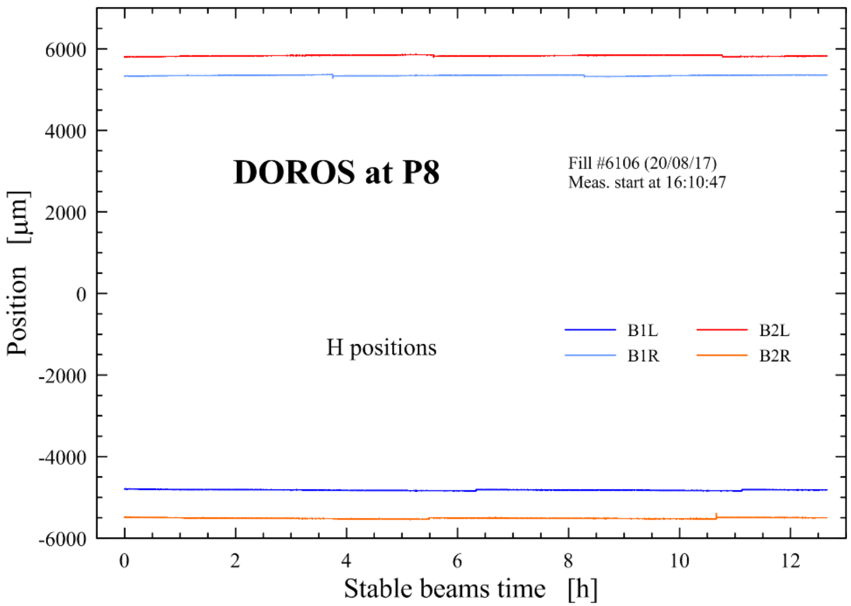

DOROS at P8
Fill #6106 (20/08/17)
Meas. start at 16:10:47
Normalised amplitude [ADC FS]
Stable beams time [h]
raw signals, B1 left
H1
H2
V1
V2

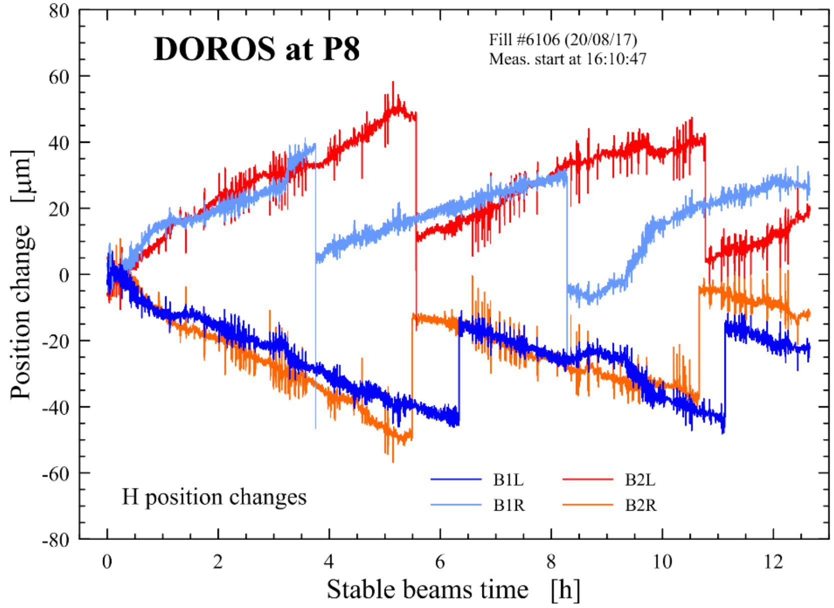

DOROS at P8
Fill #6106 (20/08/17)
Meas. start at 16:10:47
Normalised amplitude [ADC FS]
Stable beams time [h]
raw signals, B2 left
H1
H2
V1
V2

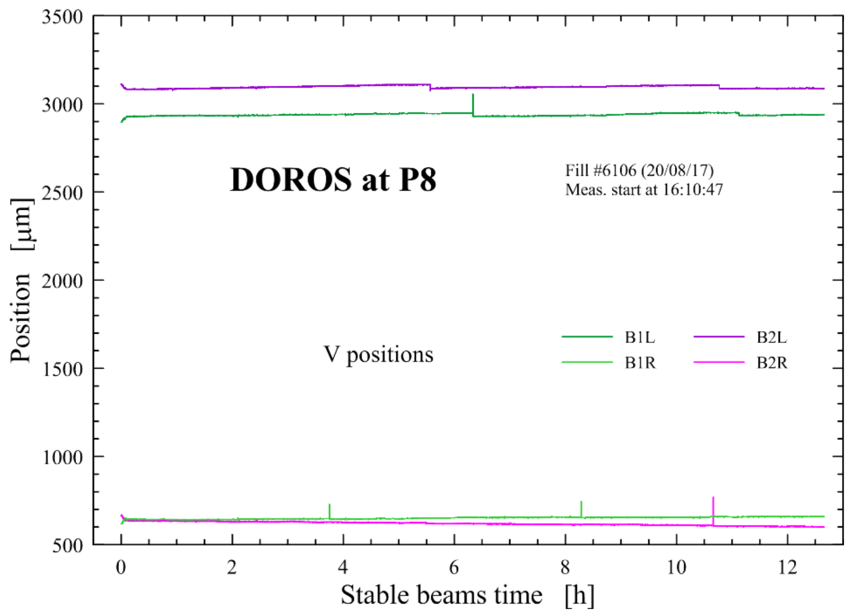

DOROS at P8
Fill #6106 (20/08/17)
Meas. start at 16:10:47
Normalised amplitude [ADC FS]
Stable beams time [h]
raw signals, B1 right
H1
H2
V1
V2

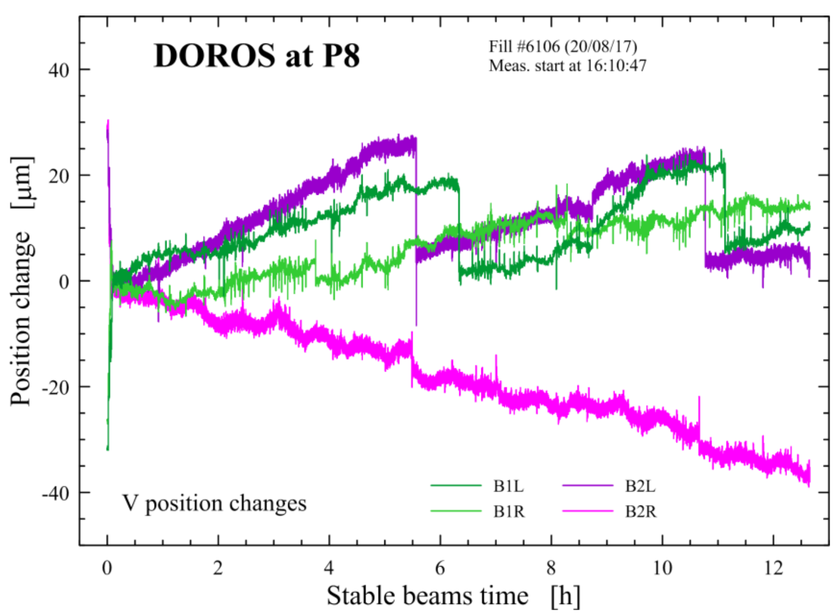

DOROS at P8
Fill #6106 (20/08/17)
Meas. start at 16:10:47
Normalised amplitude [ADC FS]
Stable beams time [h]
raw signals, B2 right
H1
H2
V1
V2

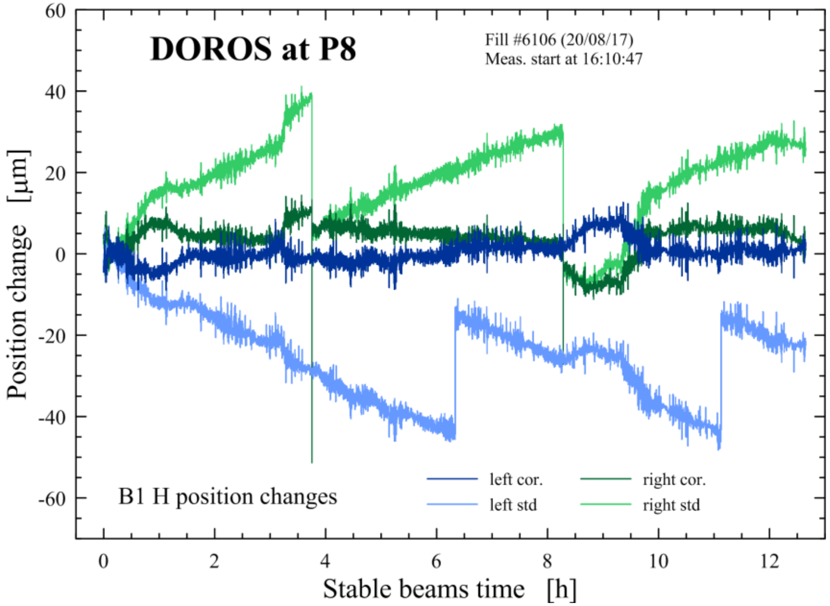
P8: “Standard” positions

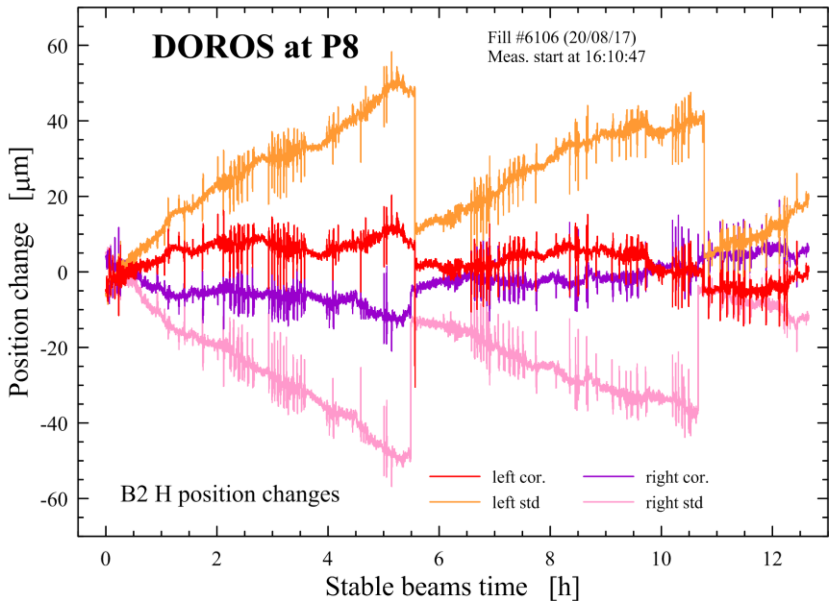


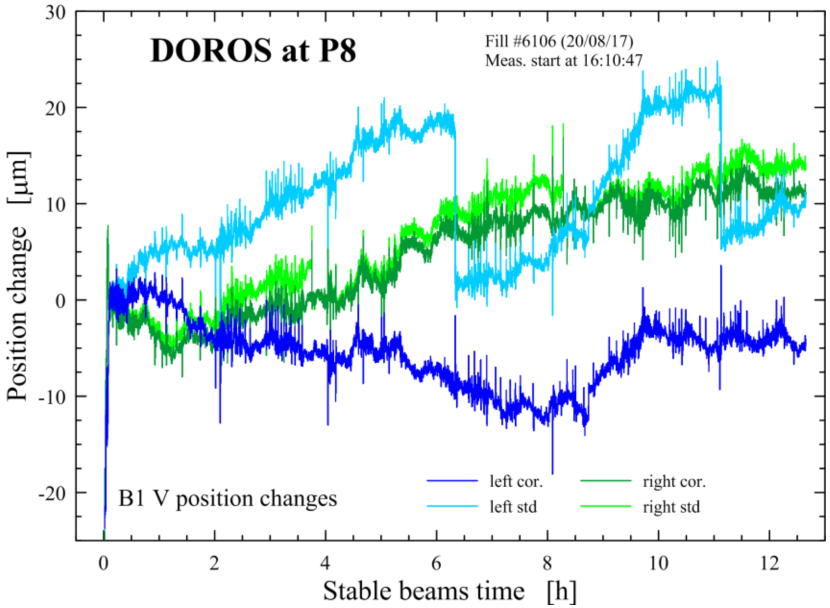


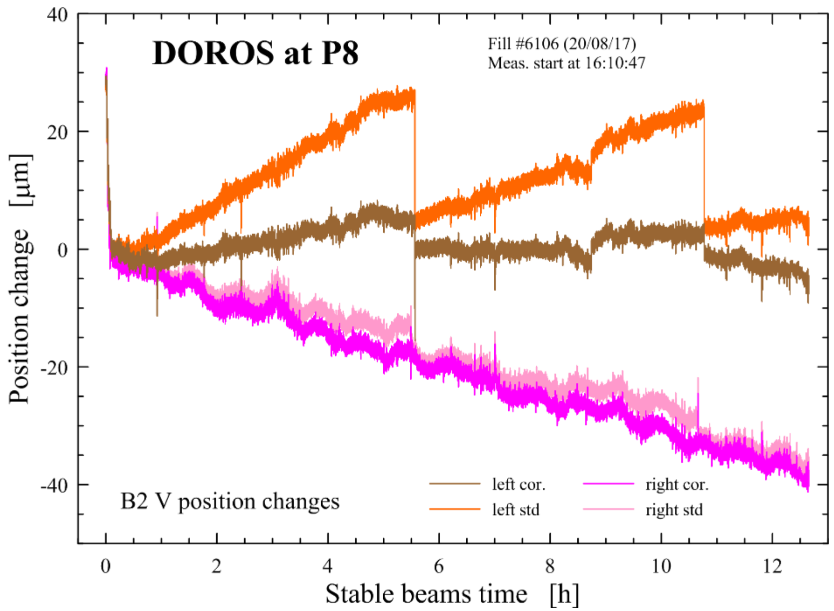




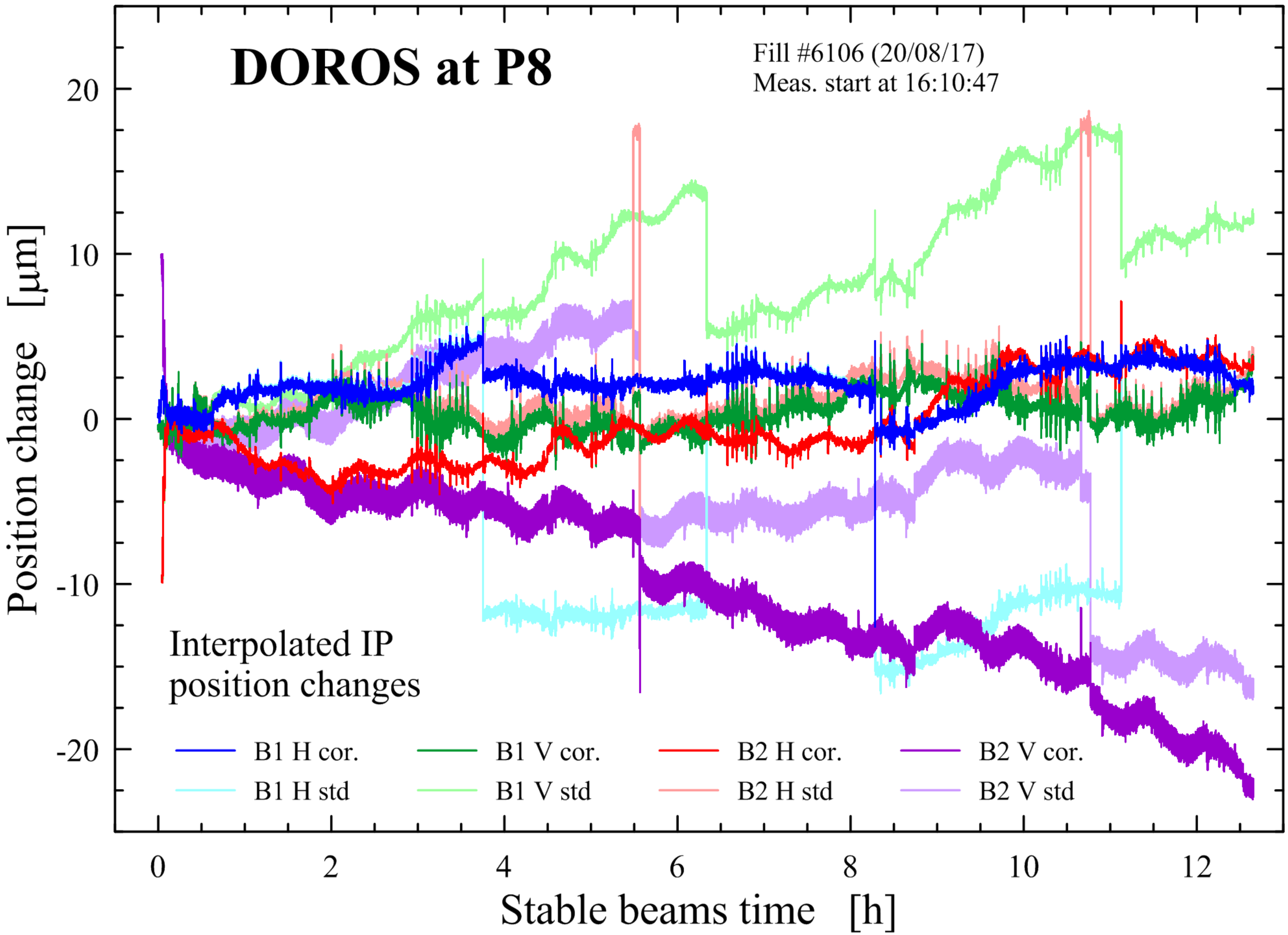

DOROS at P8
Fill #6106 (20/08/17)
Meas. start at 16:10:47
B1 H position changes
left cor.
left std
right cor.
right std
Position change [µm]
Stable beams time [h]


DOROS at P8
Fill #6106 (20/08/17)
Meas. start at 16:10:47
B2 H position changes
left cor.
left std
right cor.
right std
Position change [µm]
Stable beams time [h]

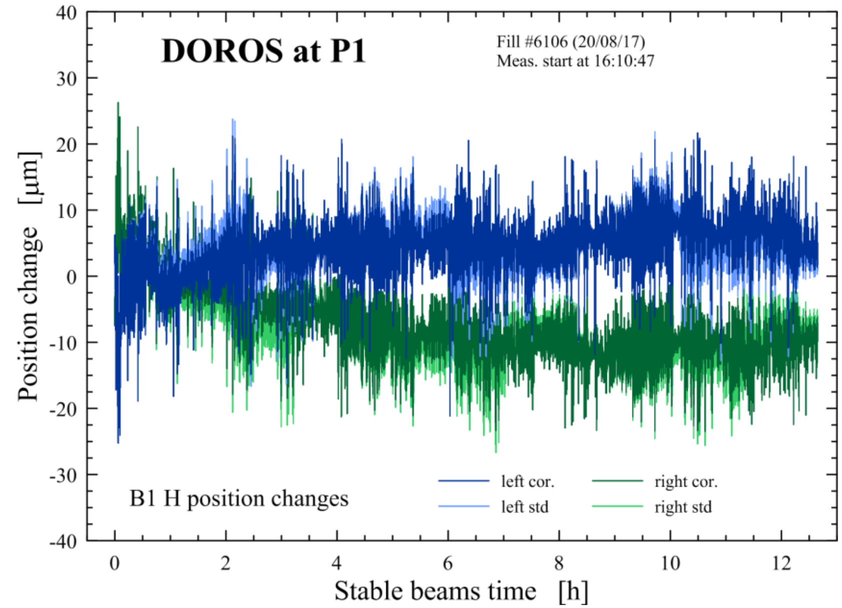

DOROS at P8
Fill #6106 (20/08/17)
Meas. start at 16:10:47
B1 V position changes
left cor.
left std
right cor.
right std
Position change [µm]
Stable beams time [h]

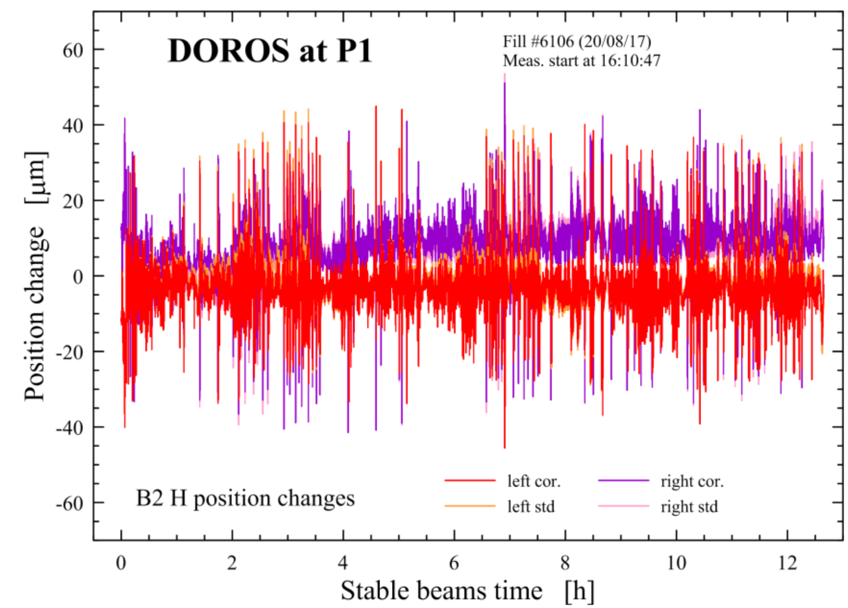

DOROS at P8
Fill #6106 (20/08/17)
Meas. start at 16:10:47
B2 V position changes
left cor.
left std
right cor.
right std
Position change [µm]
Stable beams time [h]

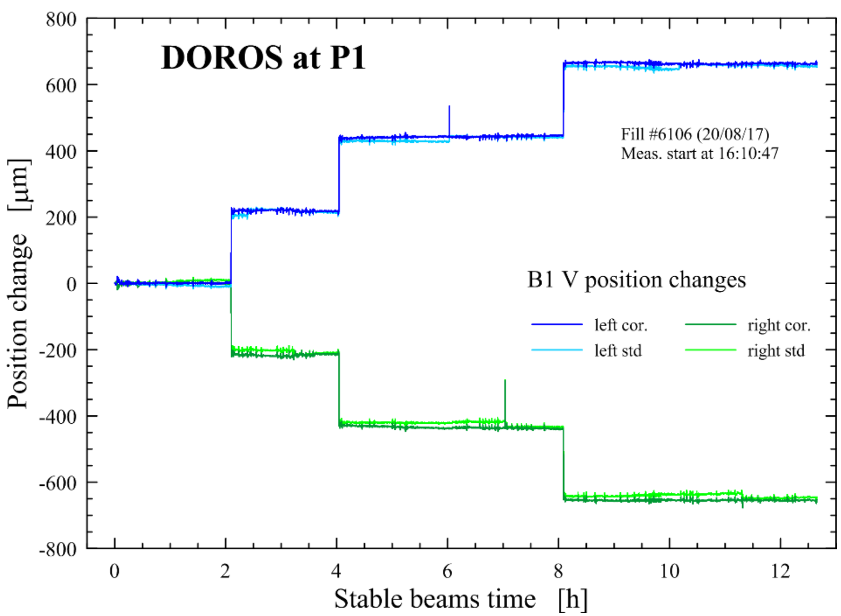
P8: corrected IP positions vs. "standard"

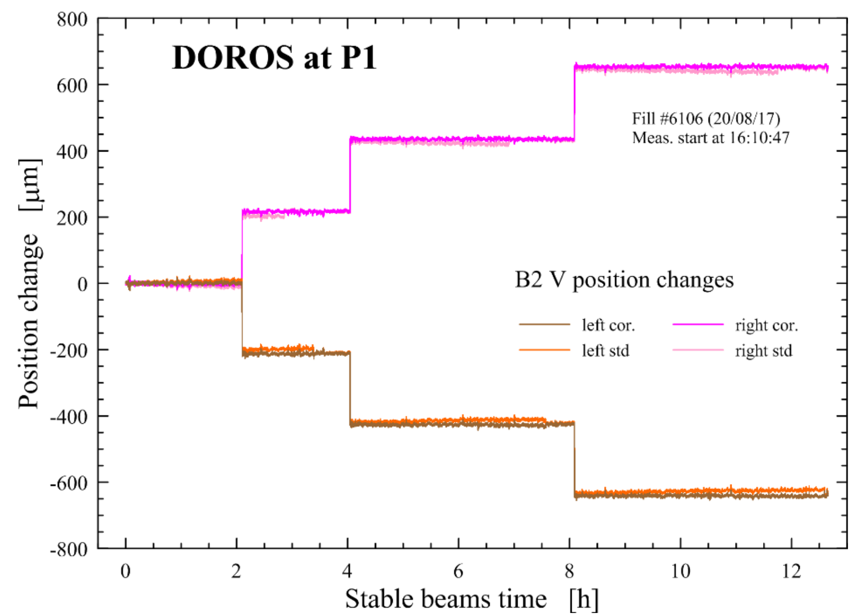


P1: corrected positions vs. “standard”

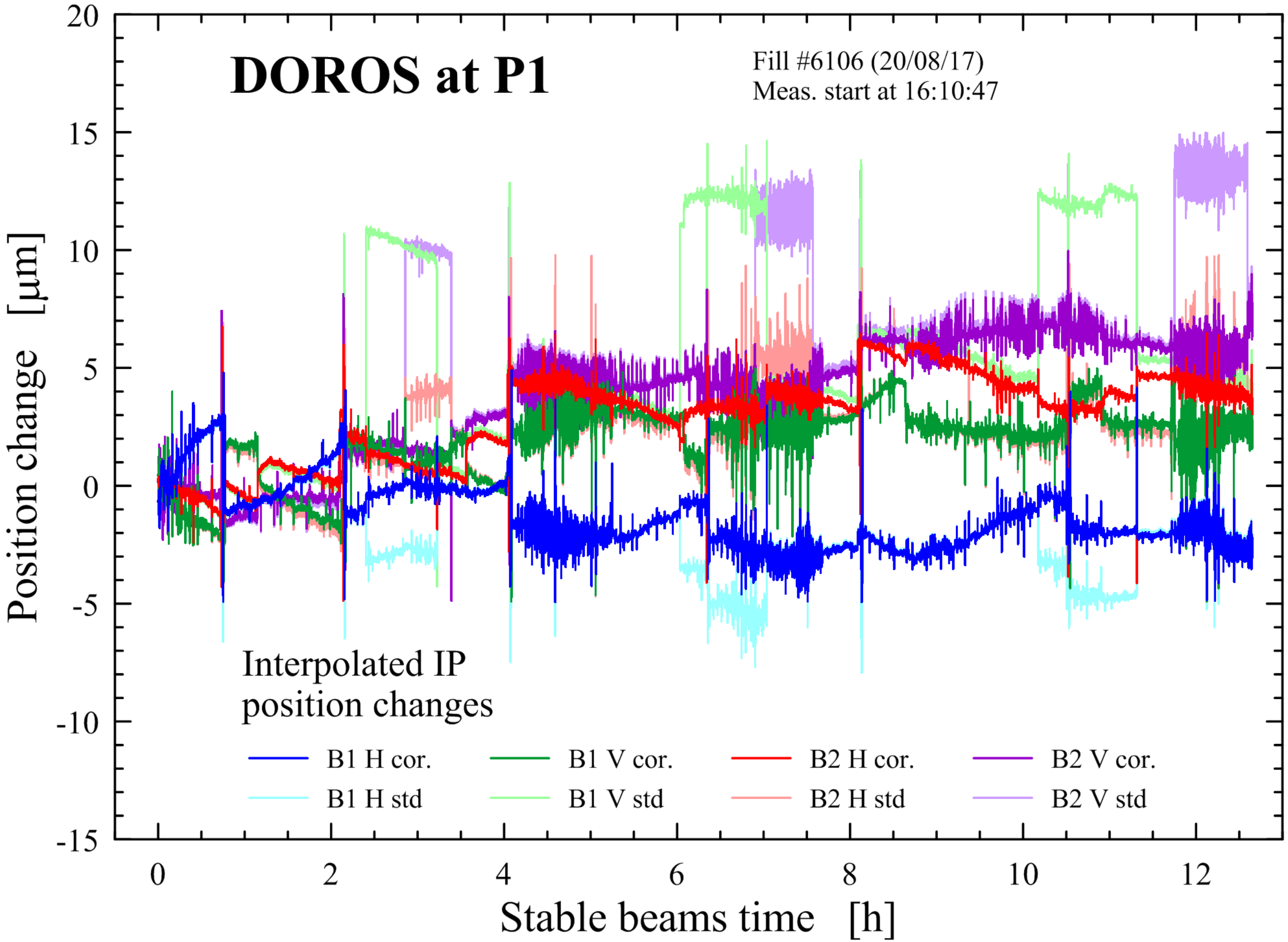




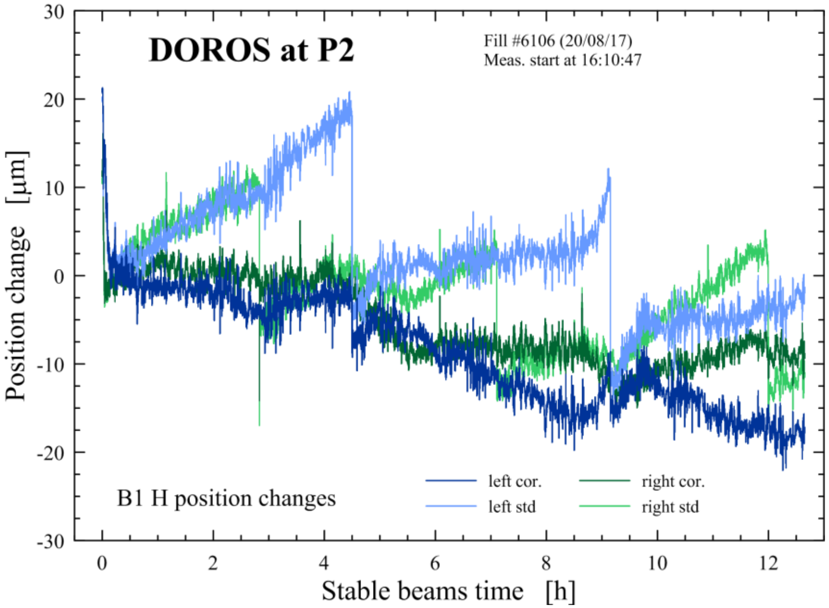


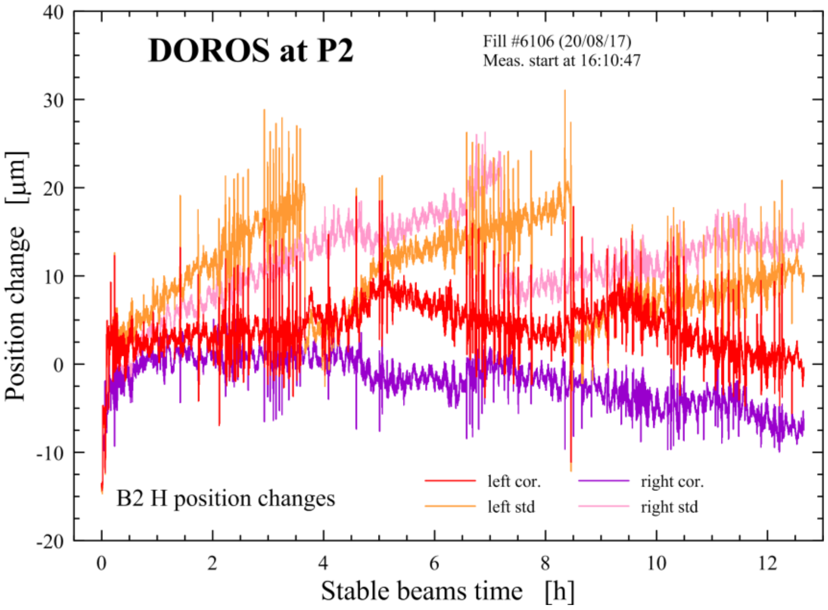


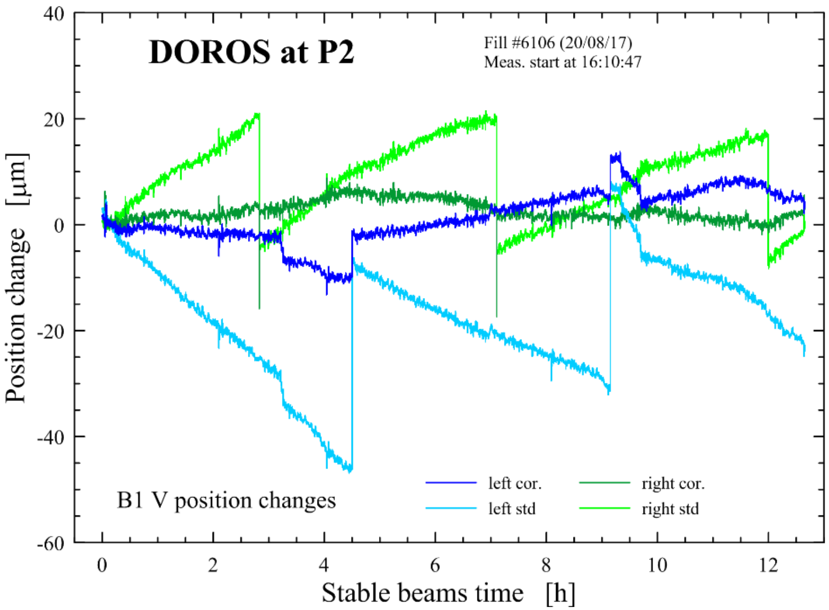
P1: corrected IP positions vs. “standard”

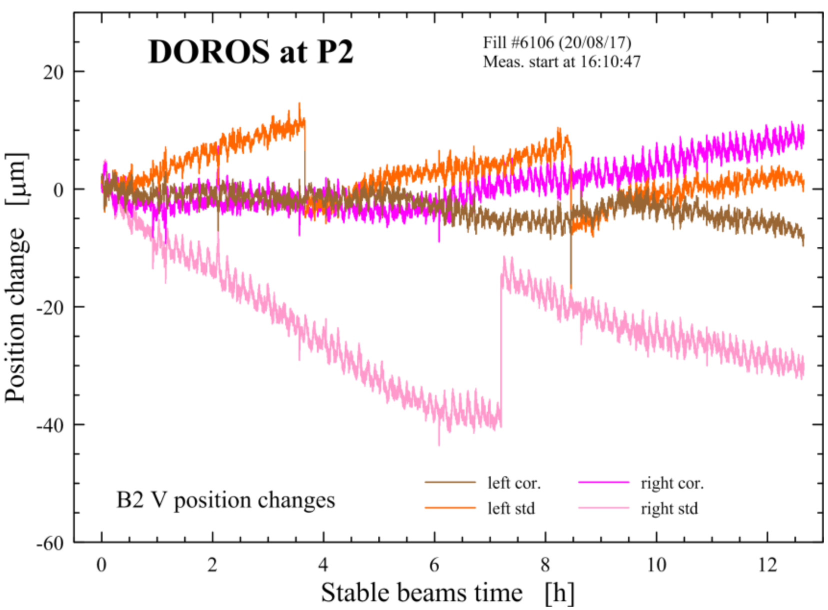


P2: corrected positions vs. “standard”

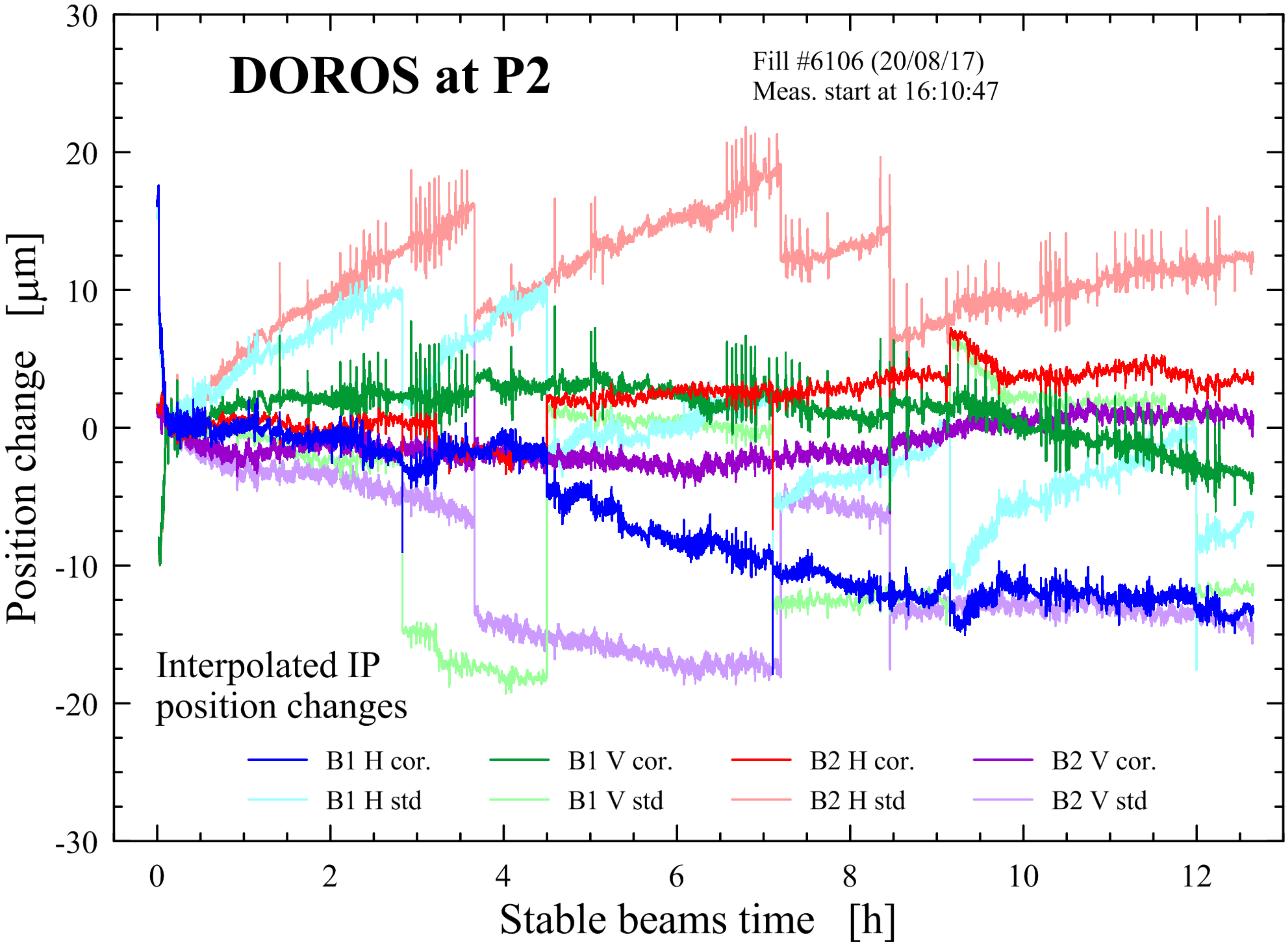


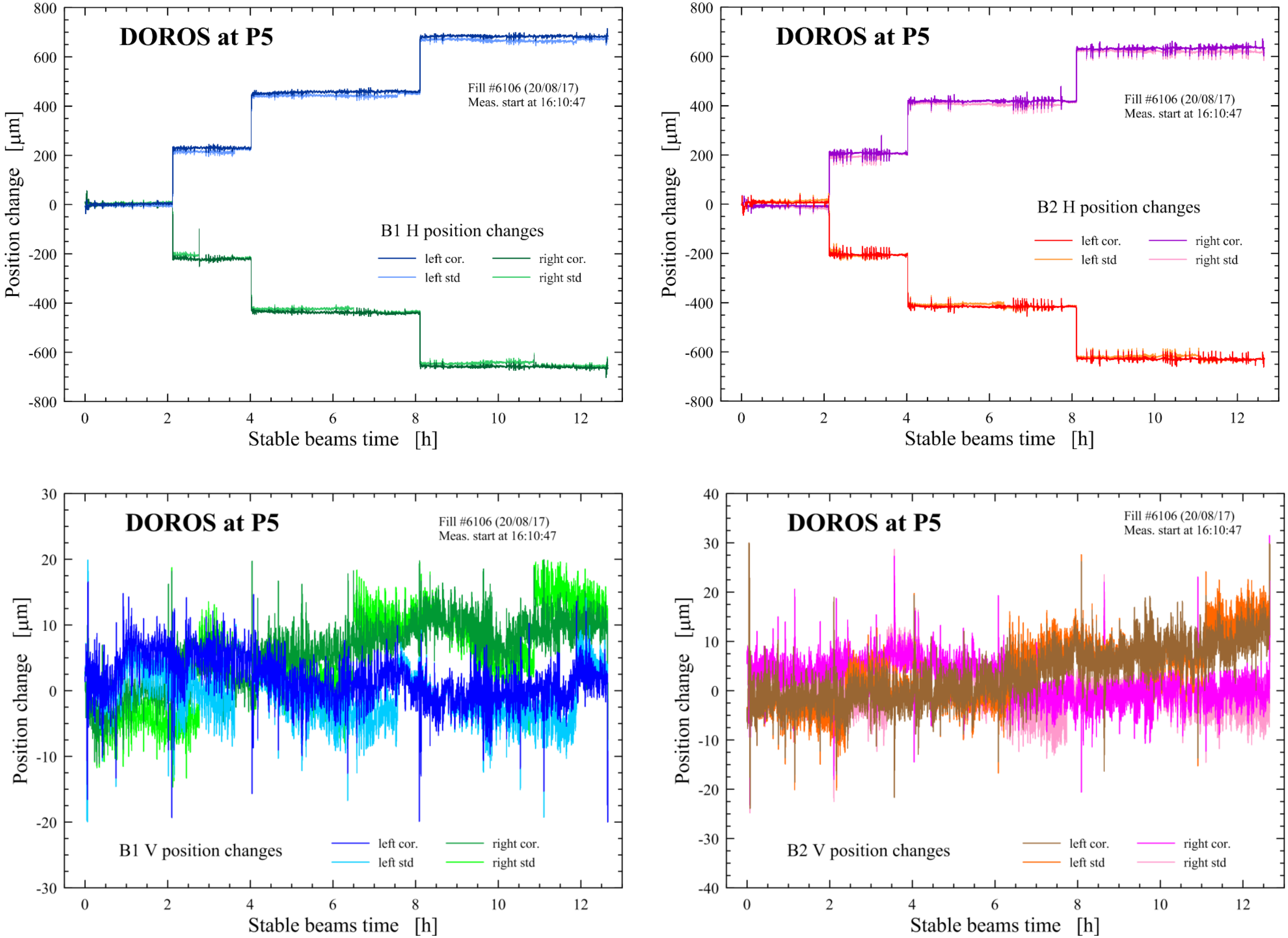




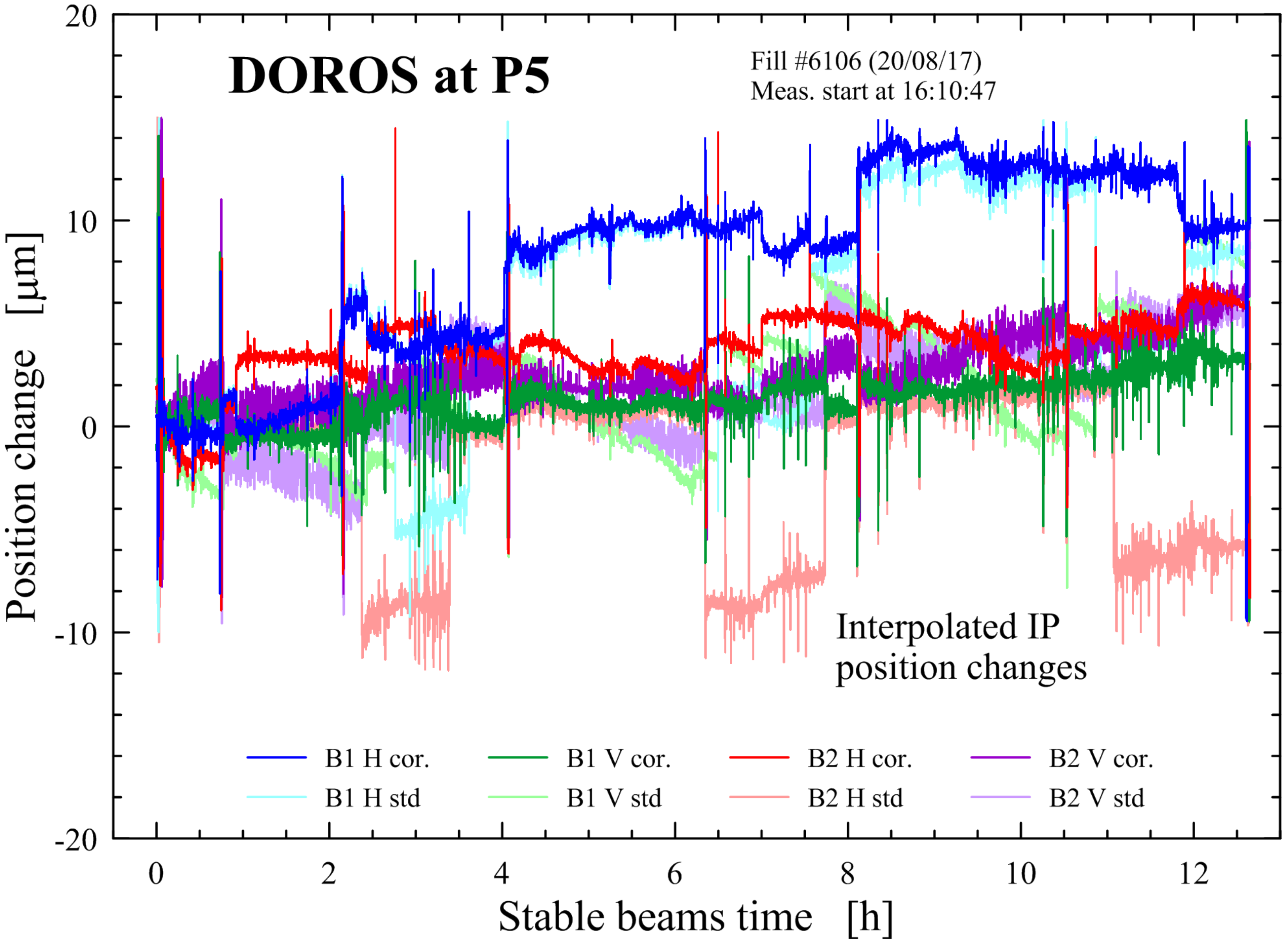


P2: corrected IP positions vs. “standard”



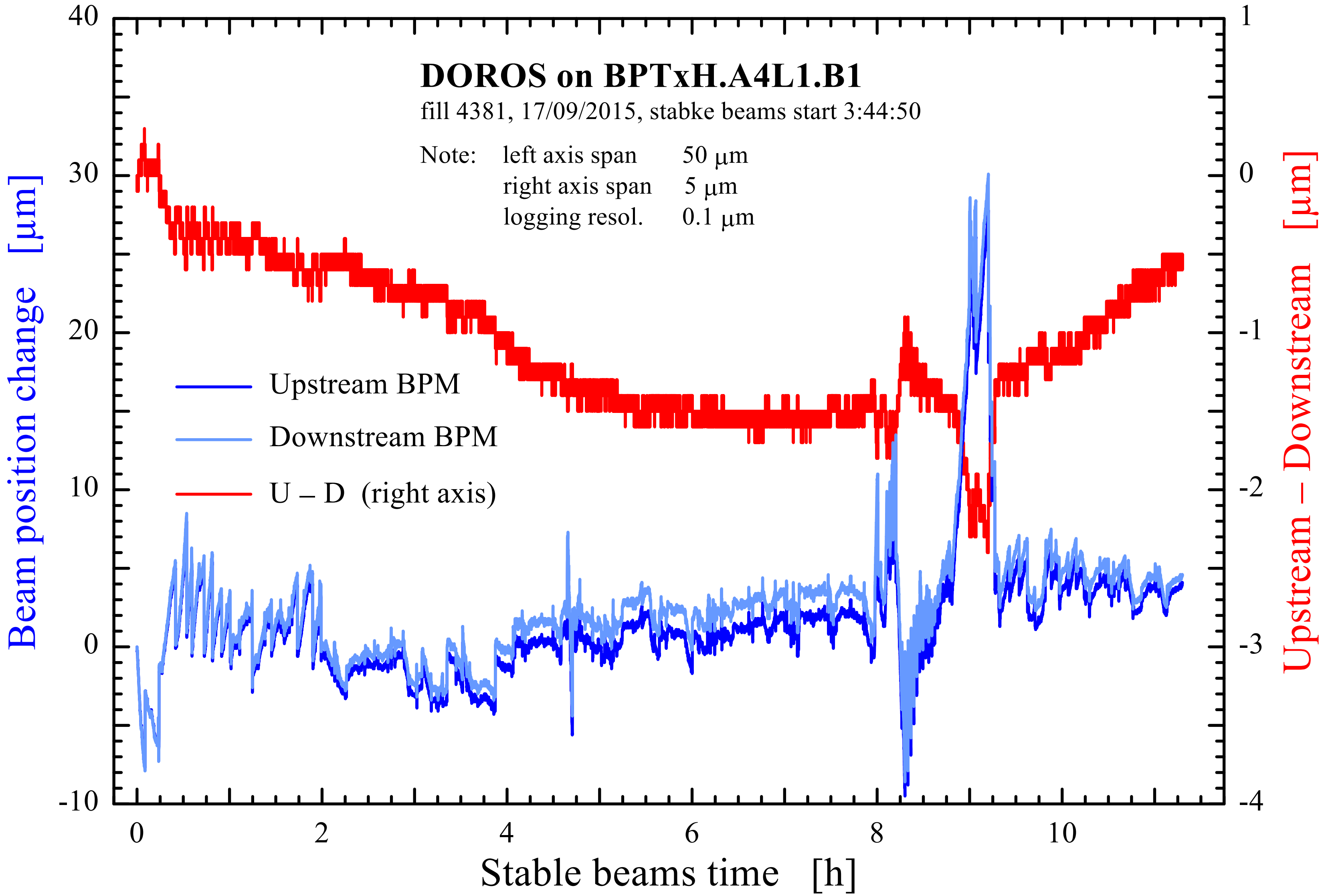

DOROS at P5
Fill #6106 (20/08/17)
Meas. start at 16:10:47
B1 H position changes
left cor.
left std
right cor.
right std
Position change [µm]
Stable beams time [h]
DOROS at P5
Fill #6106 (20/08/17)
Meas. start at 16:10:47
B2 H position changes
left cor.
left std
right cor.
right std
Position change [µm]
Stable beams time [h]
DOROS at P5
Fill #6106 (20/08/17)
Meas. start at 16:10:47
B1 V position changes
left cor.
left std
right cor.
right std
Position change [µm]
Stable beams time [h]
DOROS at P5
Fill #6106 (20/08/17)
Meas. start at 16:10:47
B2 V position changes
left cor.
left std
right cor.
right std
Position change [µm]
Stable beams time [h]

P5: corrected IP positions vs. “standard”



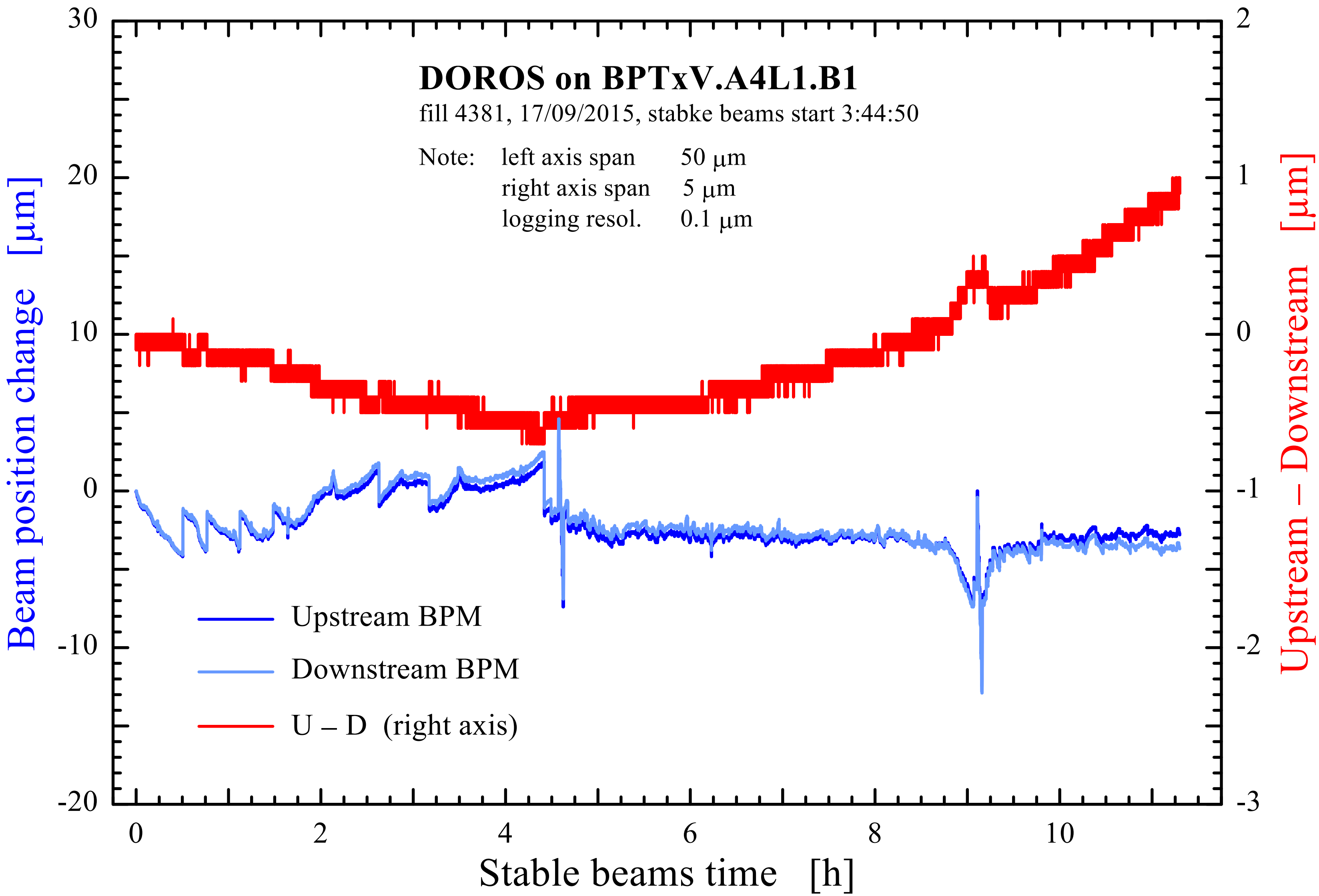
Collimator measurements

DOROS on collimator BPMs: H.L1.B1

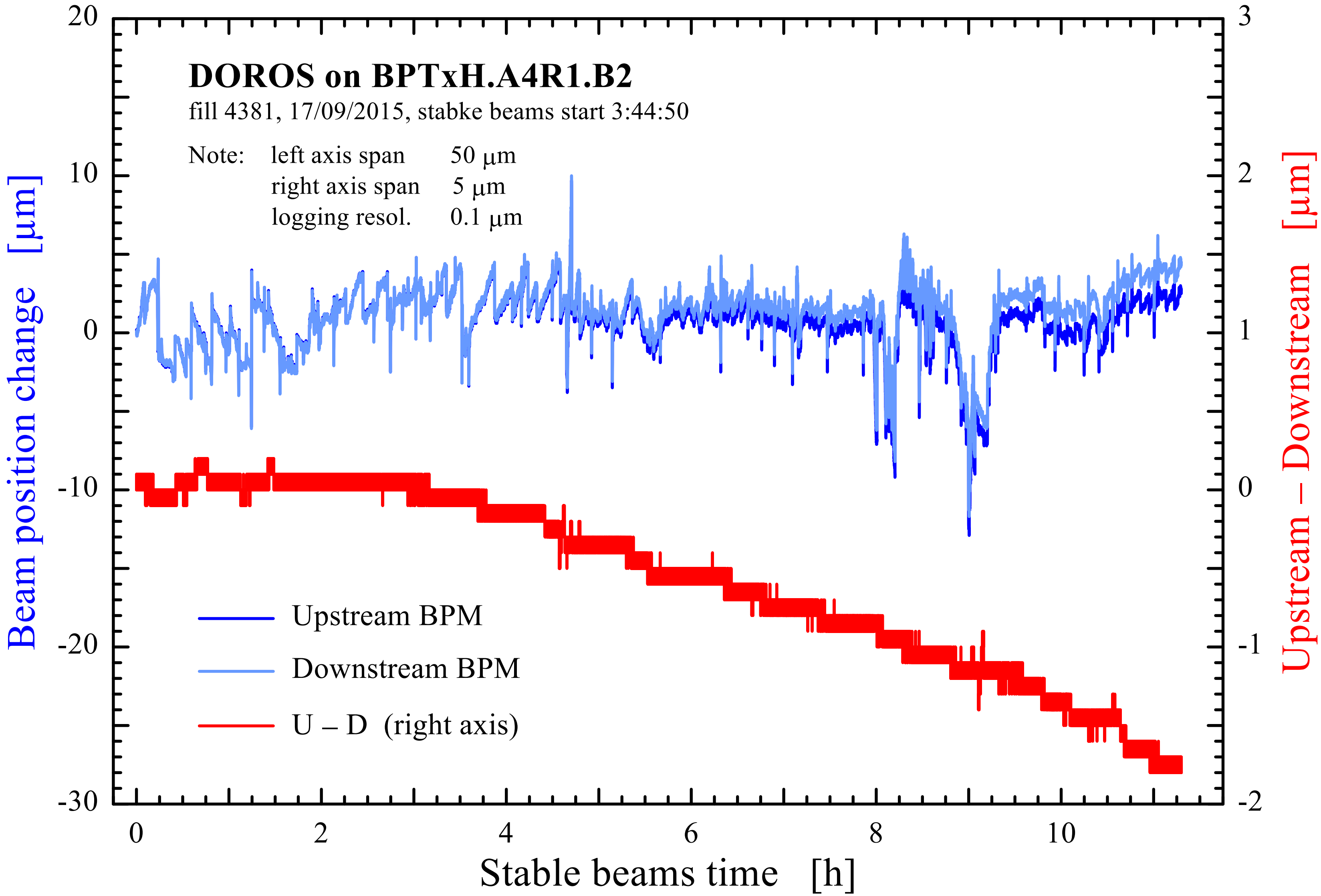


Note: Logging resolution of 0.1 μm seen on the difference between the upstream and downstream BPMs.

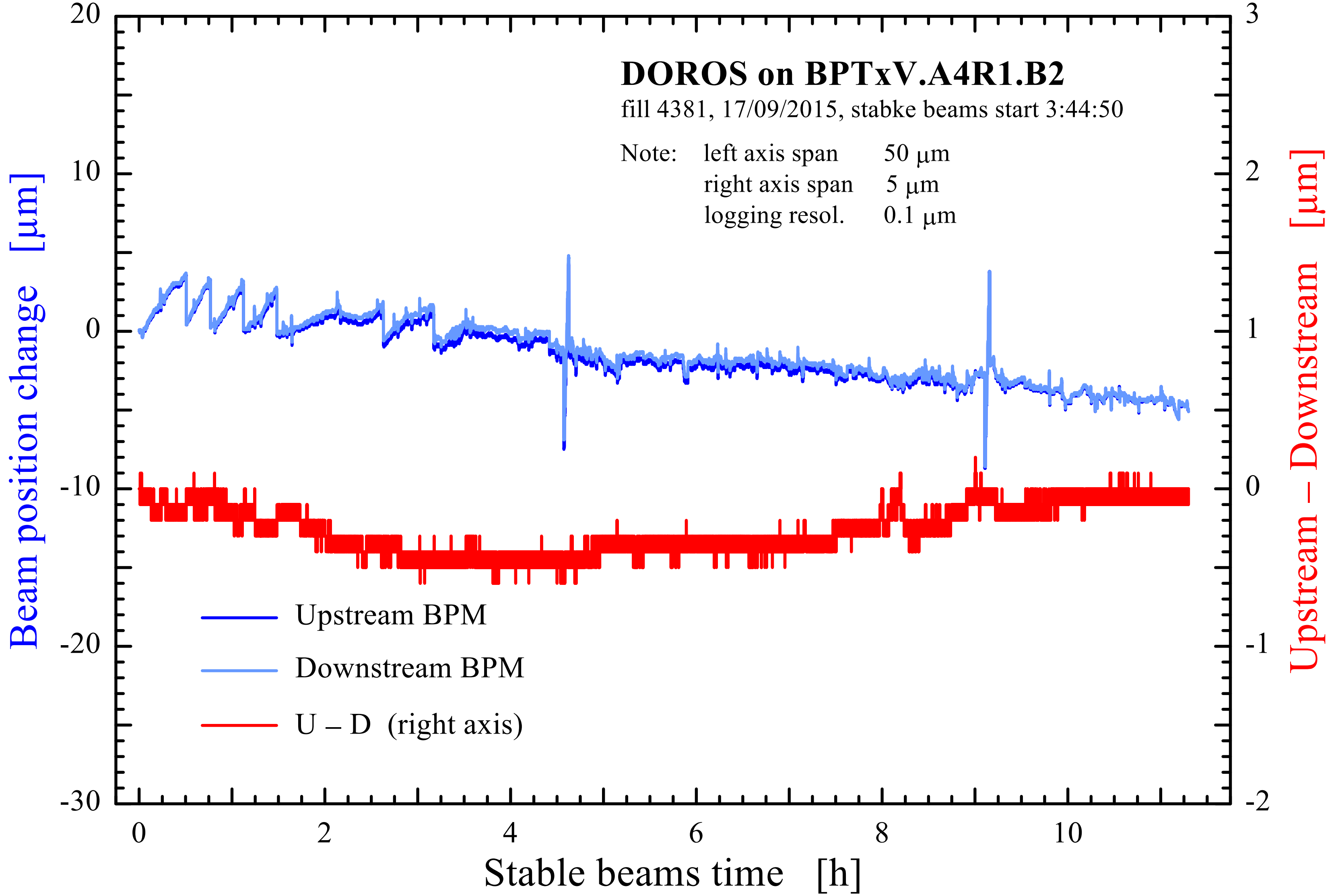
DOROS on collimator BPMs: V.L1.B1



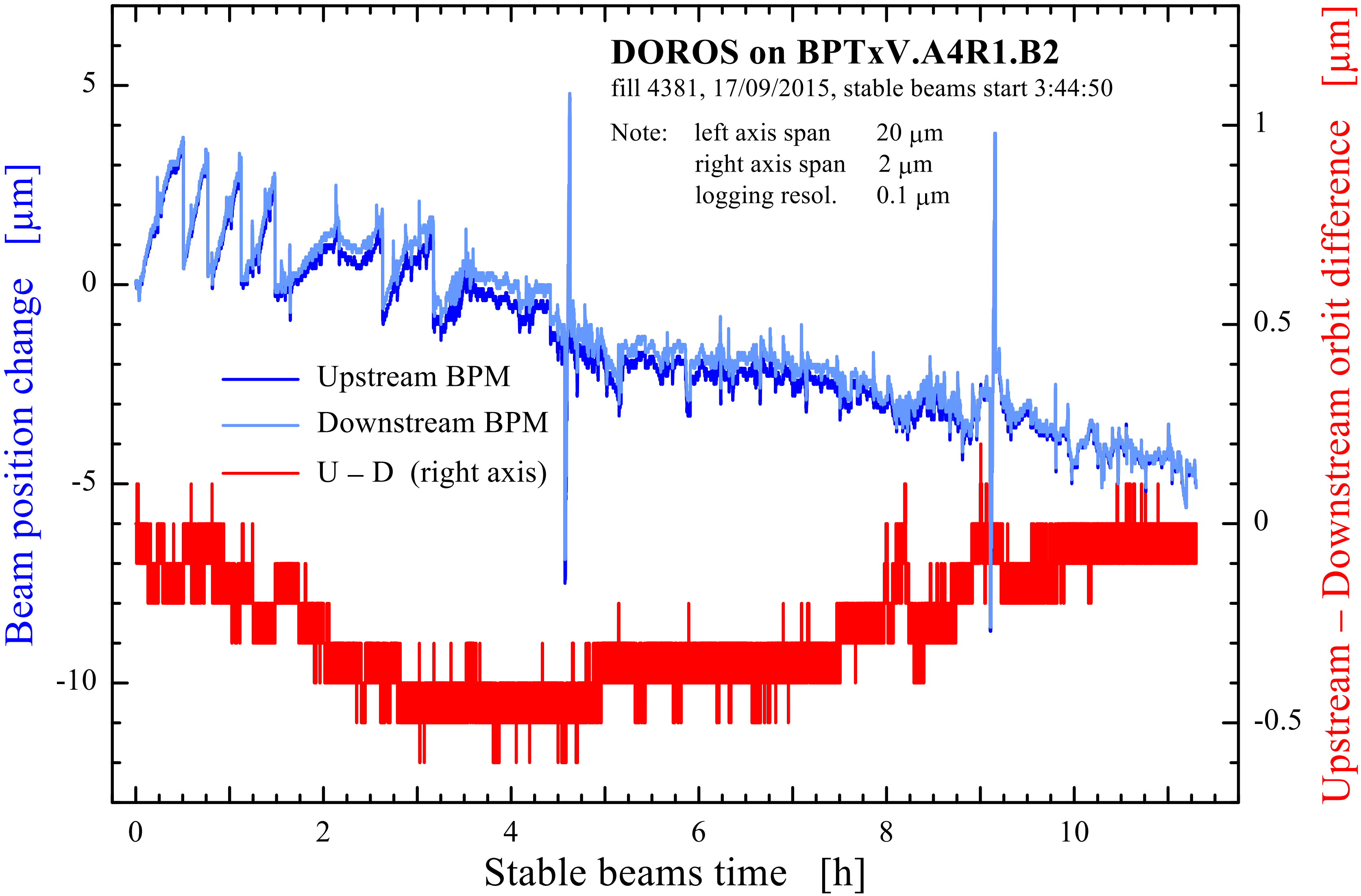
DOROS on collimator BPMs: H.R1.B2



DOROS on collimator BPMs: V.R1.B2

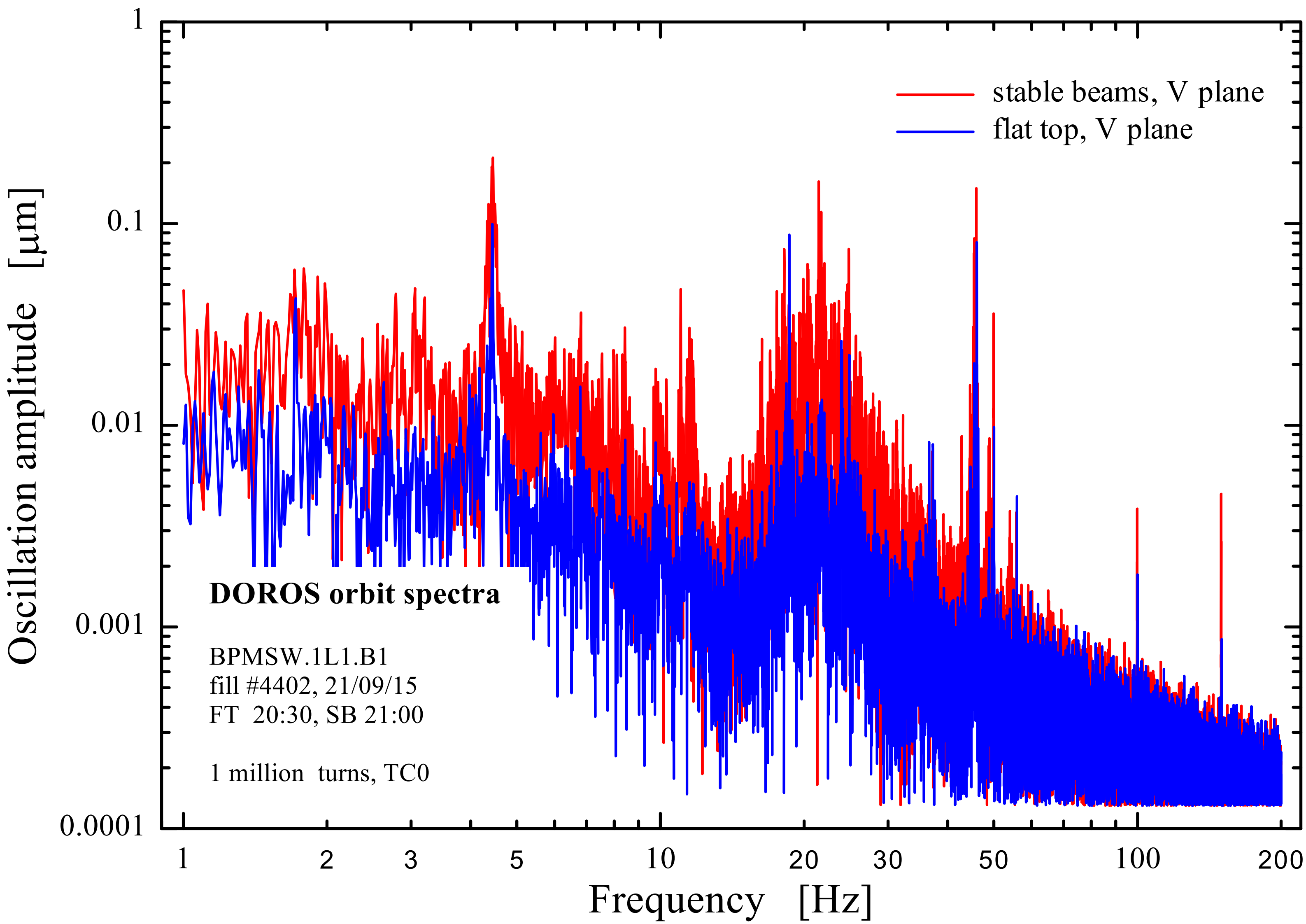


DOROS on collimator BPMs: V.R1.B2



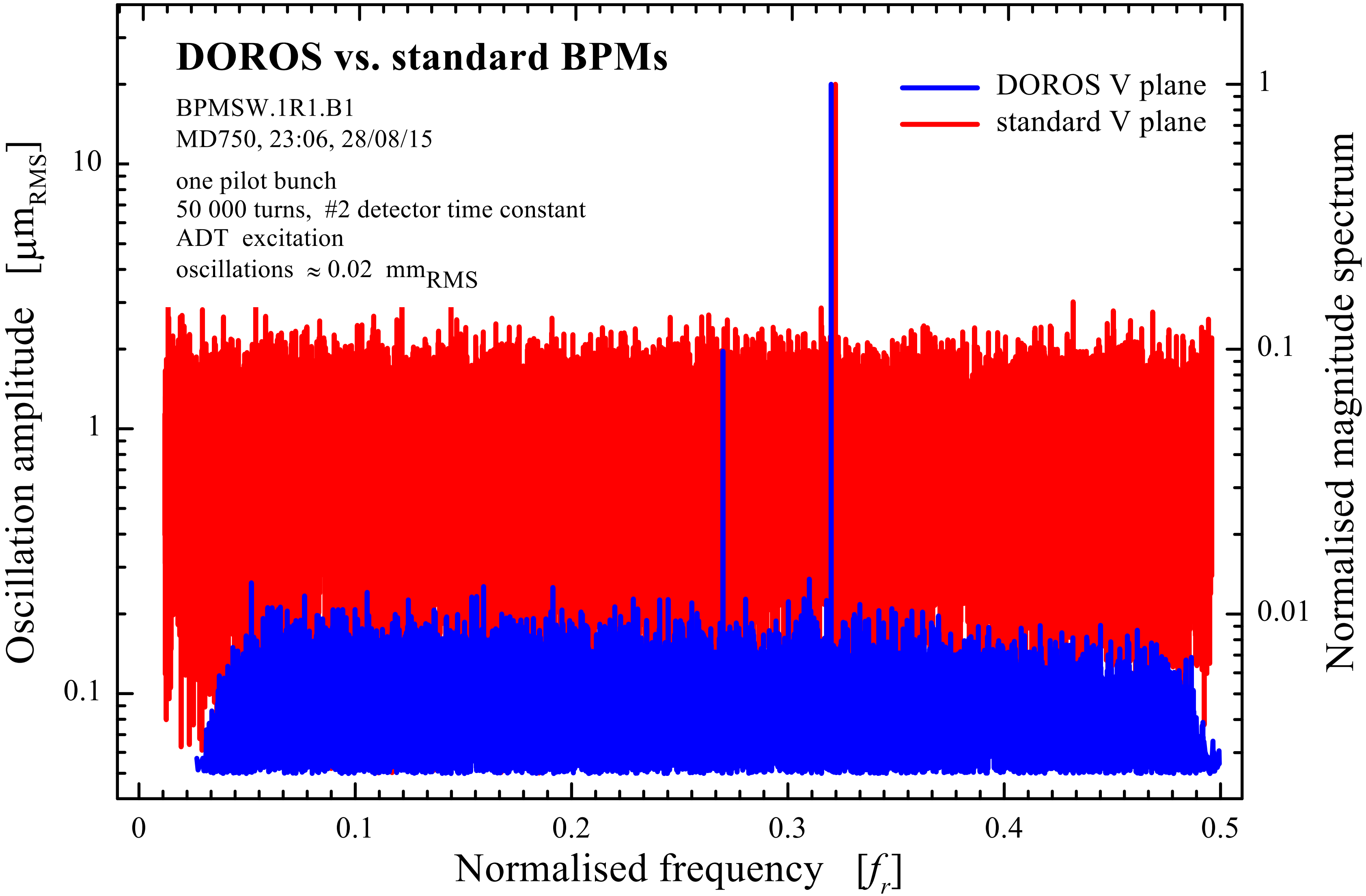
Oscillation measurements

Spectra of the DOROS orbit data



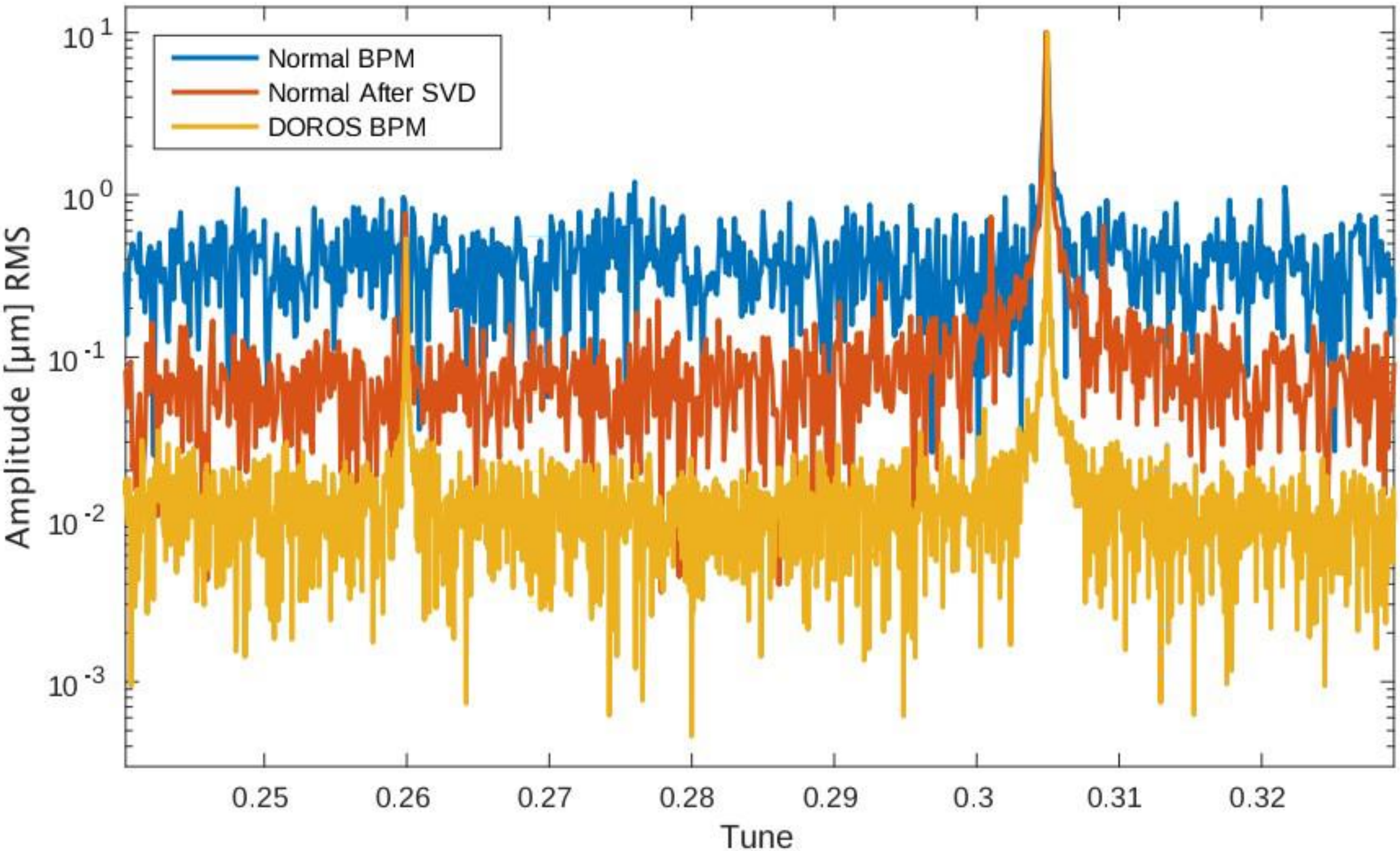
NOTE: The vertical axis is scaled in the equivalent time domain amplitudes of harmonic components.

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



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 nominal)



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

Hardware

DOROS web info

Marek GASIOR - Home p

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

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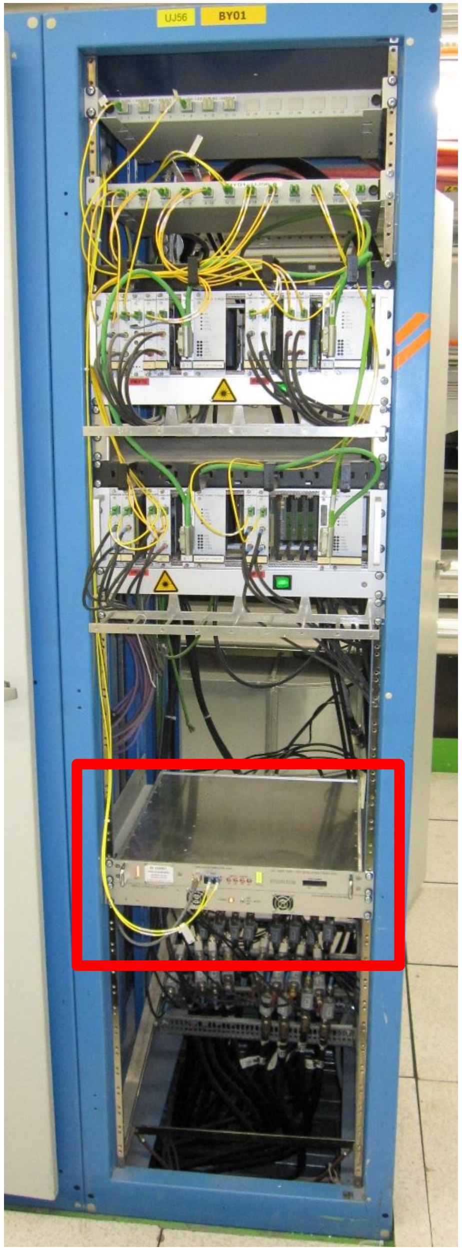
Documents on the DOROS system

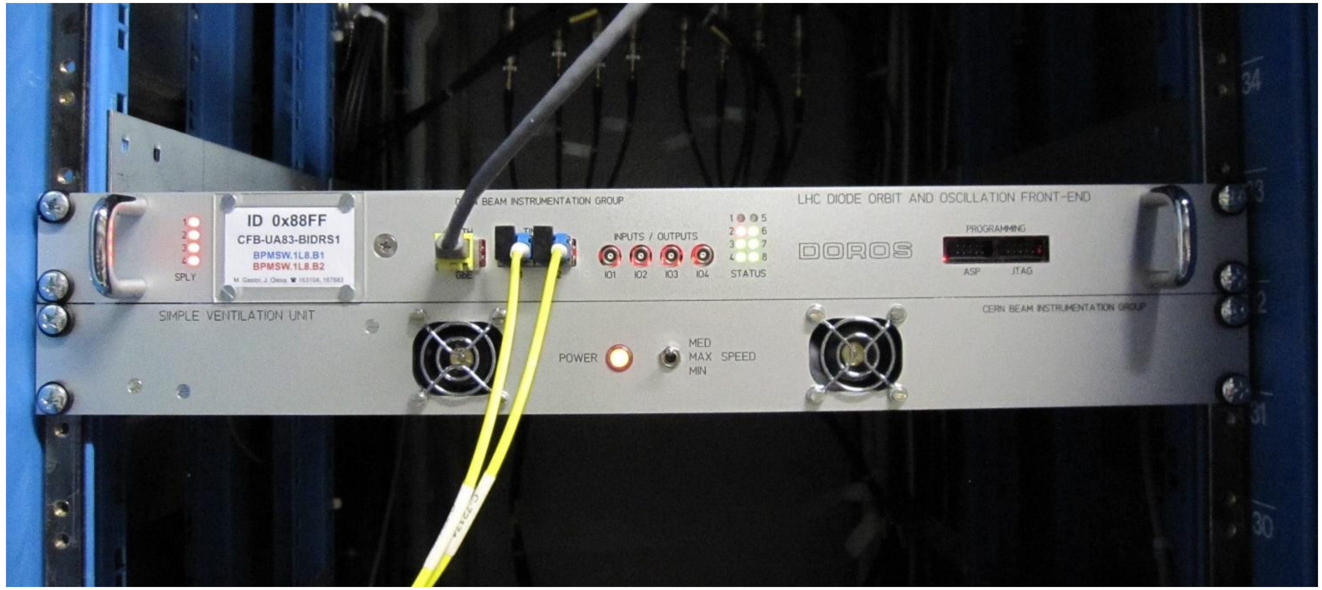
- Introduction to the DOROS system
- DOROS front-ends declared in the CERN network database (login required):
  - list of all DOROS front-ends
  - front-ends on the standard BPMs, system DOROS-S
  - front-ends on the collimator BPMs, system DOROS-C
  - development front-ends, system DOROS-D
- Inventory 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

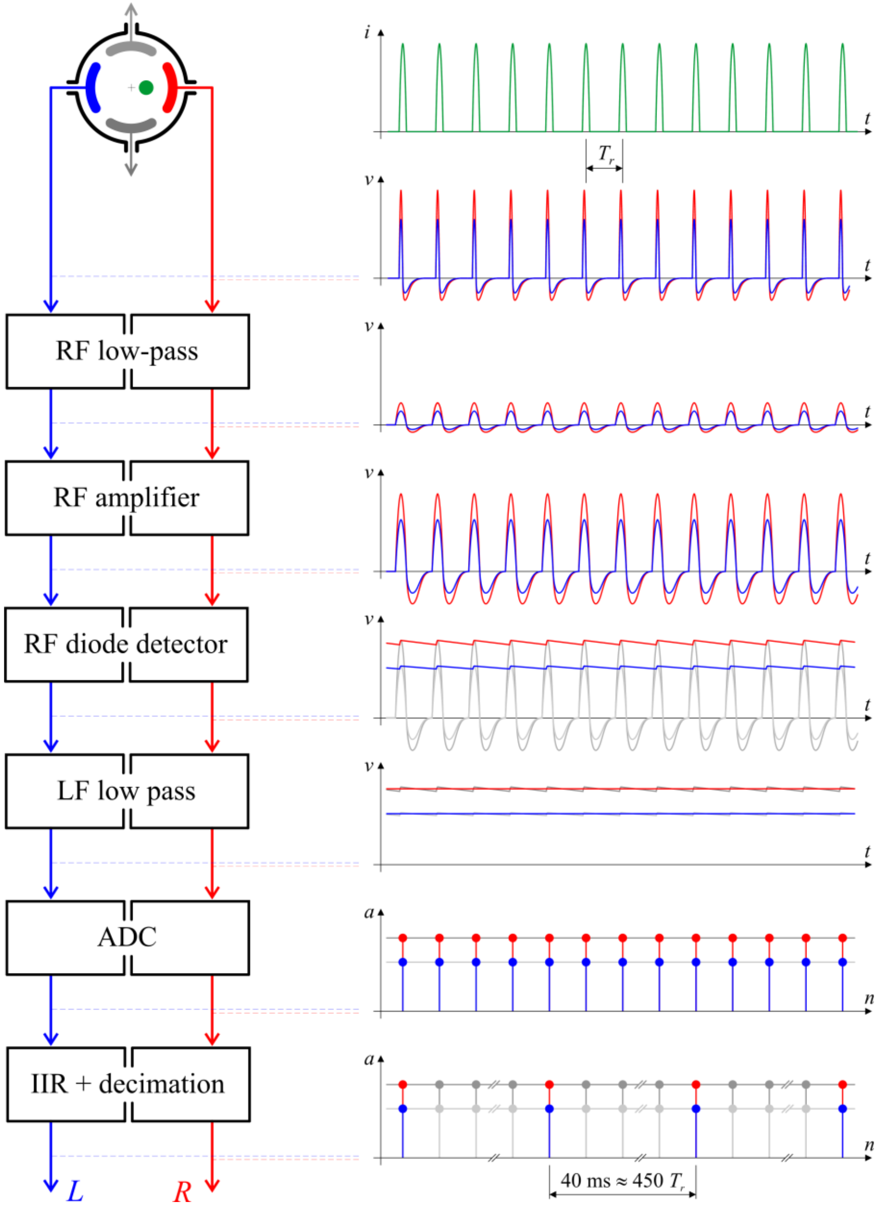
- DOROS experts: Marek 163104, Jakub 167883, Guillaume 167317.
- Localise the rack of a DOROS front-end on the GIS Portal .
  Just type the network front-end name in the search window.
- Vistar info LHC page 1
- LHC access conditions
- LHC logbook
- LHC morning meetings
- Software tools on the BI-SW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

Typical DOROS installation





- One DOROS front-end is a 1U 19” “pizza” box and has:
  - 8 beam signal inputs (SMA, rear panel)
  - Ethernet (RJ45, front panel)
  - Two BST optical sockets (B1 + B2, front)
  - 4 general purpose digital I/O (Lemo, front)
  - 8 digital control lines (optocoupler galvanic isolation, 10-pin header, rear panel)
- One FE can process signals from two dual plane BPMs or two collimators with BPMs
- Collimator BPMs are connected directly to the front-end beam inputs
- Signals from the standard BPM electrodes are divided into two paths with passive splitters, one part goes to the standard electronics and the second to a DOROS input
- The front-ends are accompanied with 1U simple ventilation units to assure a small air flow. Each front-end dissipates about 40 W. Temperatures of the front-end PCBs are typically between 30 and 40 °C.
- The photos show the Q1 FEs in UJ56 and UA83



- Short pick-up pulses go through input low-pass filters to limit their slew rate and reduce peak amplitudes
- RF amplifiers with programmable gain maintain optimal amplitude of the pulses on the compensated diode detectors
- Diode detectors convert pulses into slowly varying signals
- Low frequency low-pass filters are anti-aliasing filters
- 24-bit ADC digitises detector signals at the f_{rev} rate
- 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)
- Signal is decimated to 25 Hz for compatibility with the LHC orbit feed-back system

- Normalised horizontal and vertical positions p_H, p_V are calculated as:

$$p_H = \frac{R-L}{R+L} \qquad p_V = \frac{U-D}{U+D}$$

where R, L, U and D are signal amplitudes on the right, left, up and down BPM electrodes, respectively.

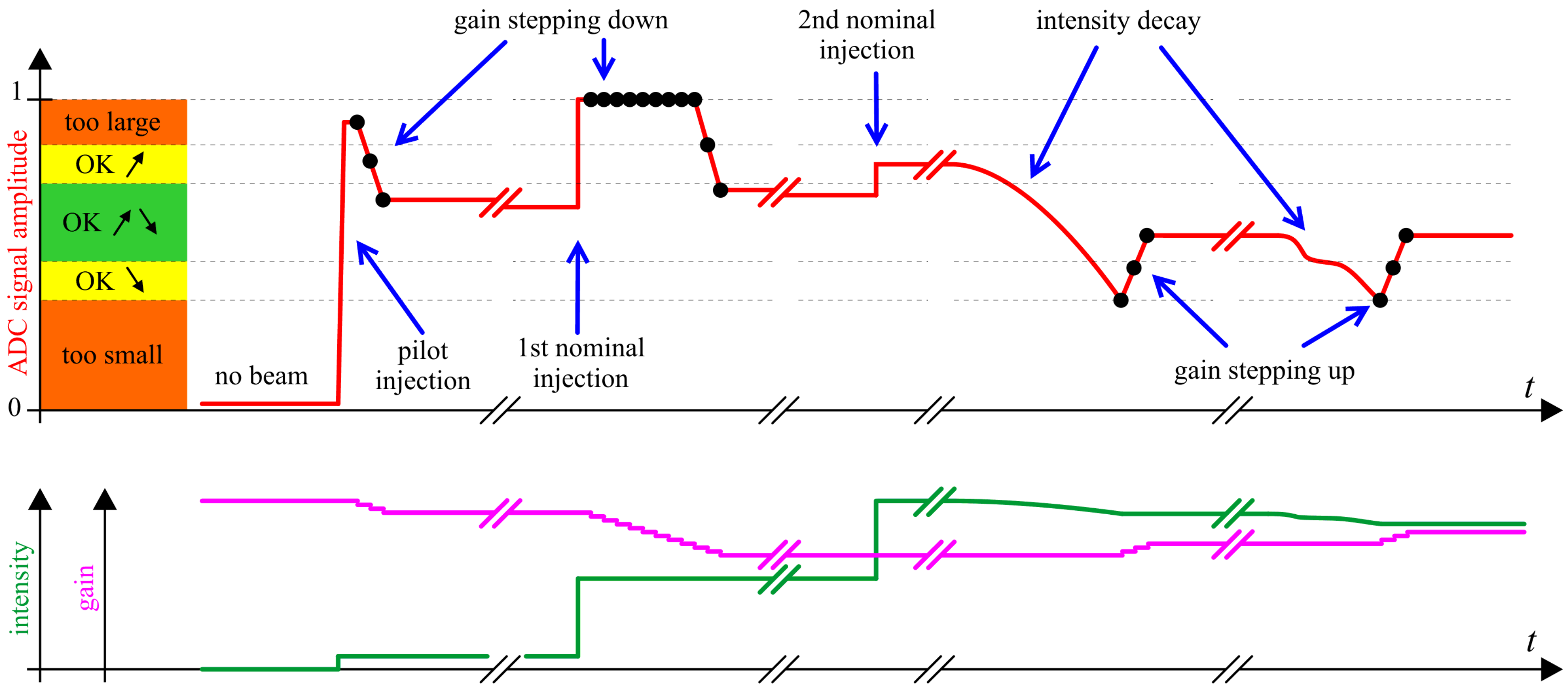
- Absolute beam positions in mm using linear approximation:

$$P \approx \frac{d}{4}\, p$$

- Absolute beam positions in mm:

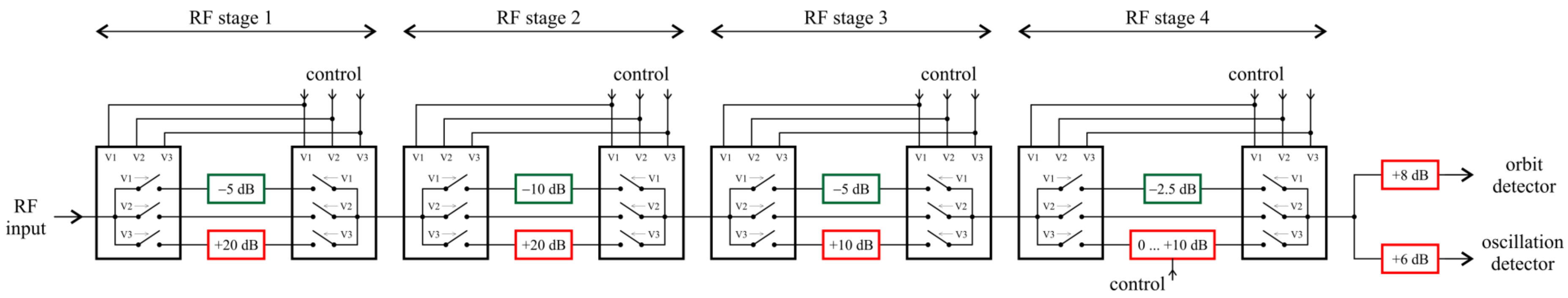
$$P \cong \frac{d}{4}\, f\left(p_H, p_V\right)$$

DOROS – automatic gain control (basic mode)



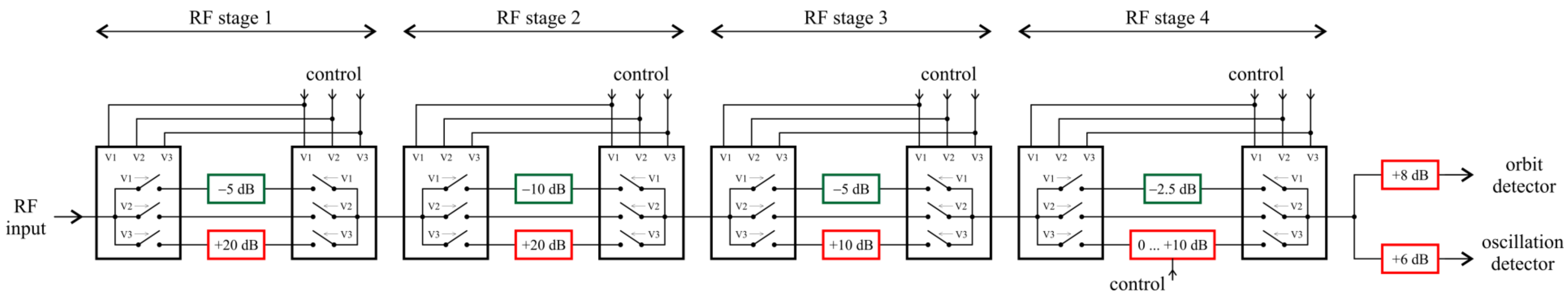
- Four channels of one pick-up have the same gain
- Gain control is based on the largest signal of all four electrodes
- The gain is adjusted to cause the largest signal to have the amplitude in the green zone
- The gain control levels are programmable and can be changed according to actual beam conditions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

RF amplifier



- RF amplifier of one of the 8 DOROS channels is shown
- Each RF amplifier is identical
- It 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 -12 dB to 68 dB in 1 dB steps,
  covering an 80 dB dynamic range (4 orders of magnitude)

Whole gain table (-24 … 70 dB)



period 1: gains -∞ .. 0 dB (index 0 .. 25)

overal gain	stage 1	stage 2	stage 3	PGA	gain index
- ∞	bypass	bypass	bypass	bypass	0
-24	-5	-10	-5	-4	1
-23	-5	-10	-5	-3	2
-22	-5	-10	-5	-2	3
-21	-5	-10	-5	-1	4
-20	-5	-10	-5	0	5
-19	-5	-10	-5	1	6
-18	-5	-10	-5	2	7
-17	-5	-10	-5	3	8
-16	-5	-10	-5	4	9
-15	-5	-10	-5	5	10
-14	-5	-10	-5	6	11
-13	-5	-10	-5	7	12
-12	-5	-10	-5	8	13
-11	-5	-10	-5	9	14
-10	-5	-10	-5	10	15
-9	-5	-10	-5	11	16
-8	-5	-10	-5	12	17
-7	-5	-10	-5	13	18
-6	-5	-10	-5	14	19
-5	-5	-10	-5	15	20
-4	-5	-10	-5	16	21
-3	-5	-10	-5	17	22
-2	-5	-10	-5	18	23
-1	-5	-10	-5	19	24
0	-5	-10	-5	20	25

period 2+3: 0 .. 20 dB (index 26 .. 47)

overal gain	stage 1	stage 2	stage 3	PGA	gain index
0	-5	0	-5	10	26
1	-5	0	-5	11	27
2	-5	0	-5	12	28
3	-5	0	-5	13	29
4	-5	0	-5	14	30
5	-5	0	-5	15	31
6	-5	0	-5	16	32
7	-5	0	-5	17	33
8	-5	0	-5	18	34
9	-5	0	-5	19	35
10	-5	0	-5	20	36
10	0	0	0	10	37
11	0	0	0	11	38
12	0	0	0	12	39
13	0	0	0	13	40
14	0	0	0	14	41
15	0	0	0	15	42
16	0	0	0	16	43
17	0	0	0	17	44
18	0	0	0	18	45
19	0	0	0	19	46
20	0	0	0	20	47

attenuation **bypass** **gain**

period 4+5: gains 20 .. 40 dB (index 48 .. 69)

overal gain	stage 1	stage 2	stage 3	PGA	gain index
20	0	0	10	10	48
21	0	0	10	11	49
22	0	0	10	12	50
23	0	0	10	13	51
24	0	0	10	14	52
25	0	0	10	15	53
26	0	0	10	16	54
27	0	0	10	17	55
28	0	0	10	18	56
29	0	0	10	19	57
30	0	0	10	20	58
30	0	20	0	10	59
31	0	20	0	11	60
32	0	20	0	12	61
33	0	20	0	13	62
34	0	20	0	14	63
35	0	20	0	15	64
36	0	20	0	16	65
37	0	20	0	17	66
38	0	20	0	18	67
39	0	20	0	19	68
40	0	20	0	20	69

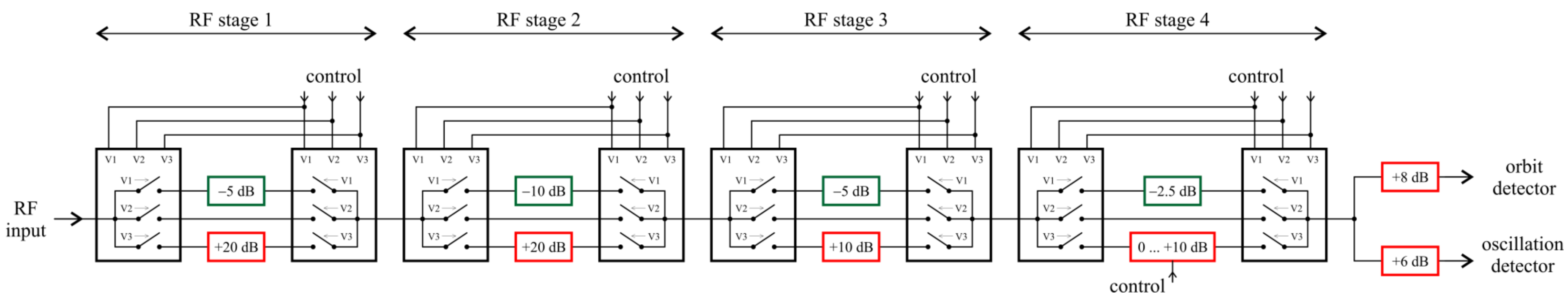
period 6+7: gains 40 .. 60 dB (index 70 .. 91)

overal gain	stage 1	stage 2	stage 3	PGA	gain index
40	0	20	10	10	70
41	0	20	10	11	71
42	0	20	10	12	72
43	0	20	10	13	73
44	0	20	10	14	74
45	0	20	10	15	75
46	0	20	10	16	76
47	0	20	10	17	77
48	0	20	10	18	78
49	0	20	10	19	79
50	0	20	10	20	80
50	20	20	0	10	81
51	20	20	0	11	82
52	20	20	0	12	83
53	20	20	0	13	84
54	20	20	0	14	85
55	20	20	0	15	86
56	20	20	0	16	87
57	20	20	0	17	88
58	20	20	0	18	89
59	20	20	0	19	90
60	20	20	0	20	91

period 8: gains 60 .. 70 dB (index 92 .. 102)

overal gain	stage 1	stage 2	stage 3	PGA	gain index
60	20	20	10	10	92
61	20	20	10	11	93
62	20	20	10	12	94
63	20	20	10	13	95
64	20	20	10	14	96
65	20	20	10	15	97
66	20	20	10	16	98
67	20	20	10	17	99
68	20	20	10	18	100
69	20	20	10	19	101
70	20	20	10	20	102

Gain table used on LHC (0 … 60 dB)



period 2+3: 0 .. 20 dB (index 26 .. 47)

overal gain	stage 1	stage 2	stage 3	PGA	gain index
0	-5	0	-5	10	26
1	-5	0	-5	11	27
2	-5	0	-5	12	28
3	-5	0	-5	13	29
4	-5	0	-5	14	30
5	-5	0	-5	15	31
6	-5	0	-5	16	32
7	-5	0	-5	17	33
8	-5	0	-5	18	34
9	-5	0	-5	19	35
10	-5	0	-5	20	36
10	0	0	0	10	37
11	0	0	0	11	38
12	0	0	0	12	39
13	0	0	0	13	40
14	0	0	0	14	41
15	0	0	0	15	42
16	0	0	0	16	43
17	0	0	0	17	44
18	0	0	0	18	45
19	0	0	0	19	46
20	0	0	0	20	47

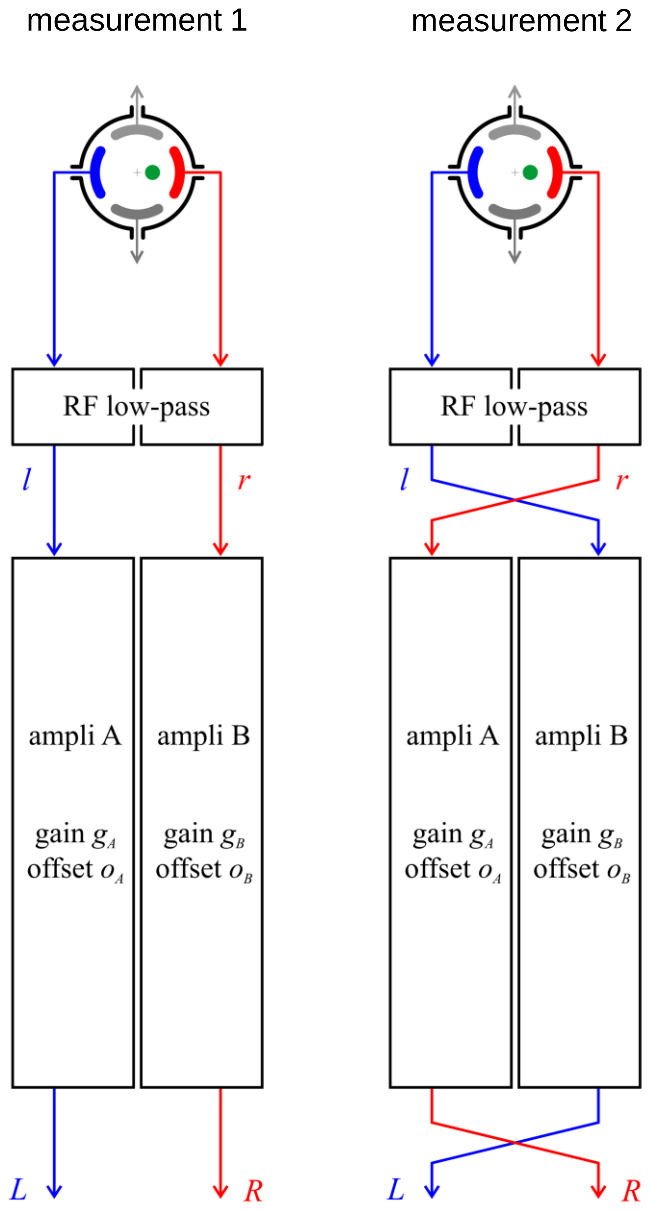
period 4+5: gains 20 .. 40 dB (index 48 .. 69)

overal gain	stage 1	stage 2	stage 3	PGA	gain index
20	0	0	10	10	48
21	0	0	10	11	49
22	0	0	10	12	50
23	0	0	10	13	51
24	0	0	10	14	52
25	0	0	10	15	53
26	0	0	10	16	54
27	0	0	10	17	55
28	0	0	10	18	56
29	0	0	10	19	57
30	0	0	10	20	58
30	0	20	0	10	59
31	0	20	0	11	60
32	0	20	0	12	61
33	0	20	0	13	62
34	0	20	0	14	63
35	0	20	0	15	64
36	0	20	0	16	65
37	0	20	0	17	66
38	0	20	0	18	67
39	0	20	0	19	68
40	0	20	0	20	69

period 6+7: gains 40 .. 60 dB (index 70 .. 91)

overal gain	stage 1	stage 2	stage 3	PGA	gain index
40	0	20	10	10	70
41	0	20	10	11	71
42	0	20	10	12	72
43	0	20	10	13	73
44	0	20	10	14	74
45	0	20	10	15	75
46	0	20	10	16	76
47	0	20	10	17	77
48	0	20	10	18	78
49	0	20	10	19	79
50	0	20	10	20	80
50	20	20	0	10	81
51	20	20	0	11	82
52	20	20	0	12	83
53	20	20	0	13	84
54	20	20	0	14	85
55	20	20	0	15	86
56	20	20	0	16	87
57	20	20	0	17	88
58	20	20	0	18	89
59	20	20	0	19	90
60	20	20	0	20	91

attenuation **bypass** **gain**



$$L_1 = g_A l + o_A$$
$$R_1 = g_B r + o_B$$
$$L_c = \frac{L_1 + L_2}{2}$$
$$L_2 = g_B l + o_B$$
$$R_2 = g_A r + o_A$$
$$R_c = \frac{R_1 + R_2}{2}$$

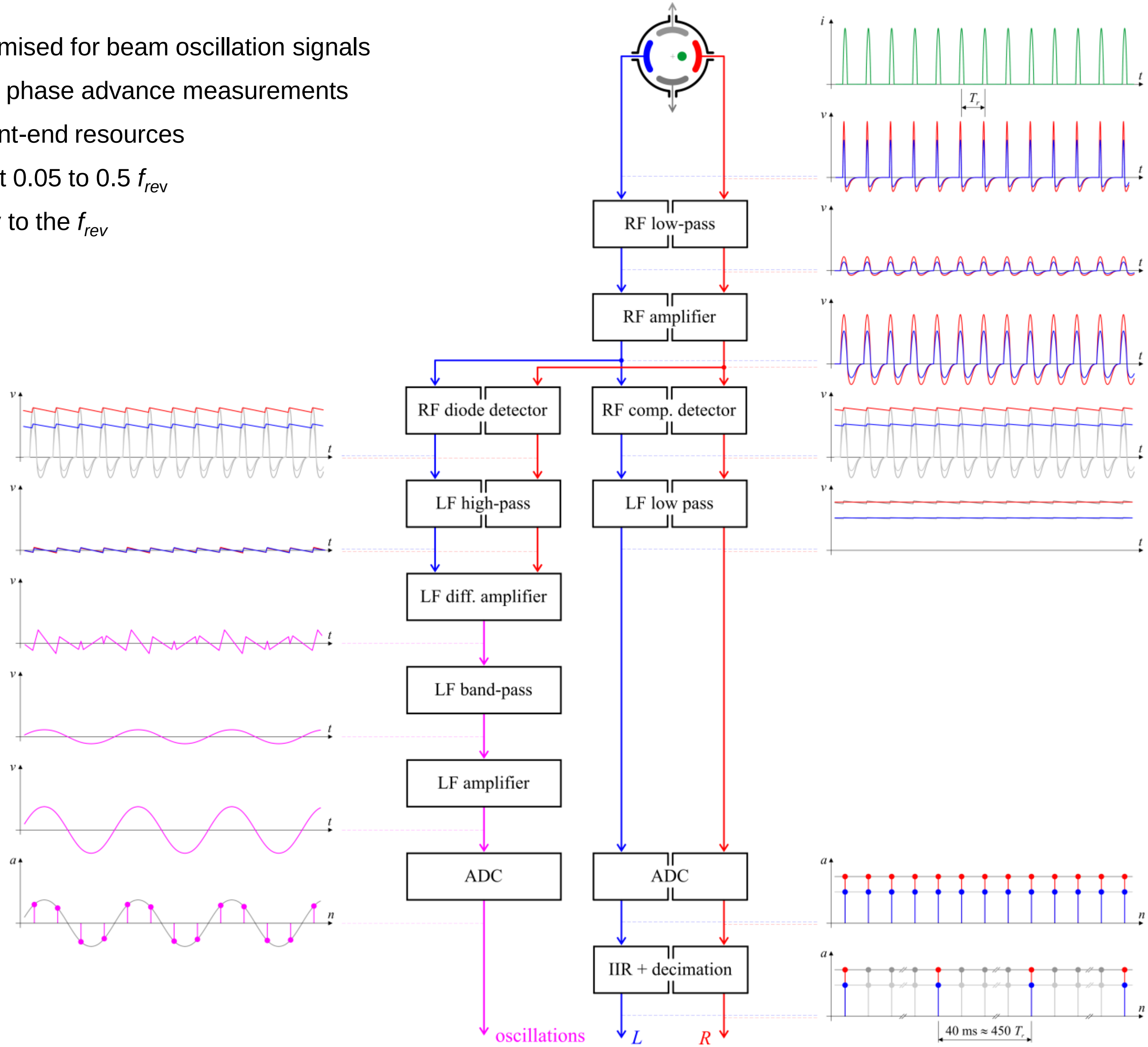
$$p_{Hc} = \frac{R_c - L_c}{R_c + L_c} = \frac{(g_A + g_B)(r - l)}{(g_A + g_B)(r + l) + 2(o_A + o_B)} \cong \frac{r - l}{r + l}$$

- Channel switching is done typically every 1 s
- 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):

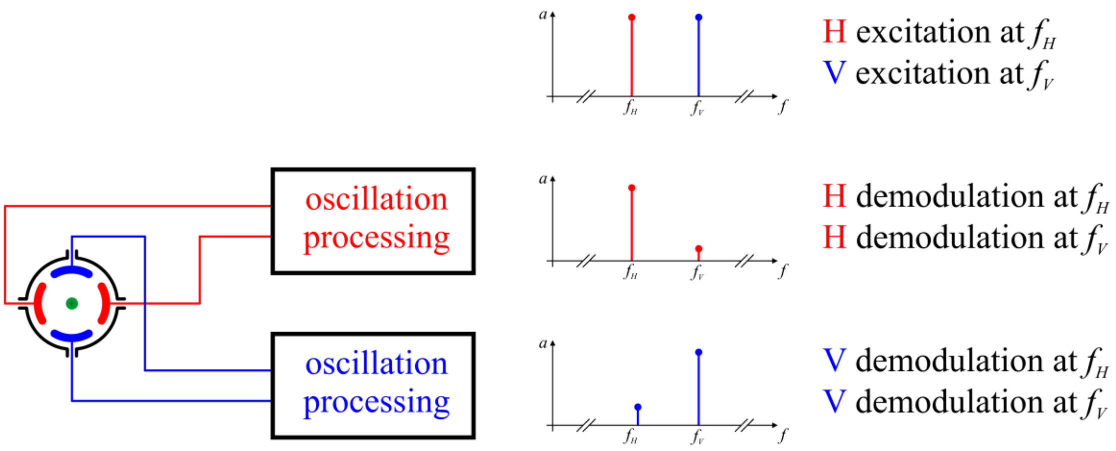
- Perfect amplifiers ($g_A = g_B = 1$ and $o_A = o_B = 0$):
  for $l = 0.5$, $r = 1$, $p_H = 0.3333$ and $P_H = 5.083$ mm for Q1 BPM with $d = 61$ mm.
- Assume amplifiers with $g_A = g_B = 1.05$ and $o_A = o_B = 0.001$:
  $p_H = 0.3329$ and $P_H = 4.927$ mm, resulting in an error of 6 μm

- 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}



Local betatron coupling

- Harmonic beam excitation at a separate frequency for each plane
- Beam signal demodulation at both frequencies for each plane
- From the four amplitudes and four phases the coupling amplitude and phase is calculated for the BPM location



Betatron phase advance

- Harmonic beam excitation at a single frequency
- Beam oscillation phase evaluated for each BPM w.r.t. a common reference
- Phase advance between two BPMs calculated as the difference of the phases w.r.t. the common reference