DOROS system

Marek Gasior, Jakub Olexa, Guillaume Baud, Marc Lasch

Last updated 6/05/2017

Outline:

- Introduction
- Principles
- Measurement examples

Basics

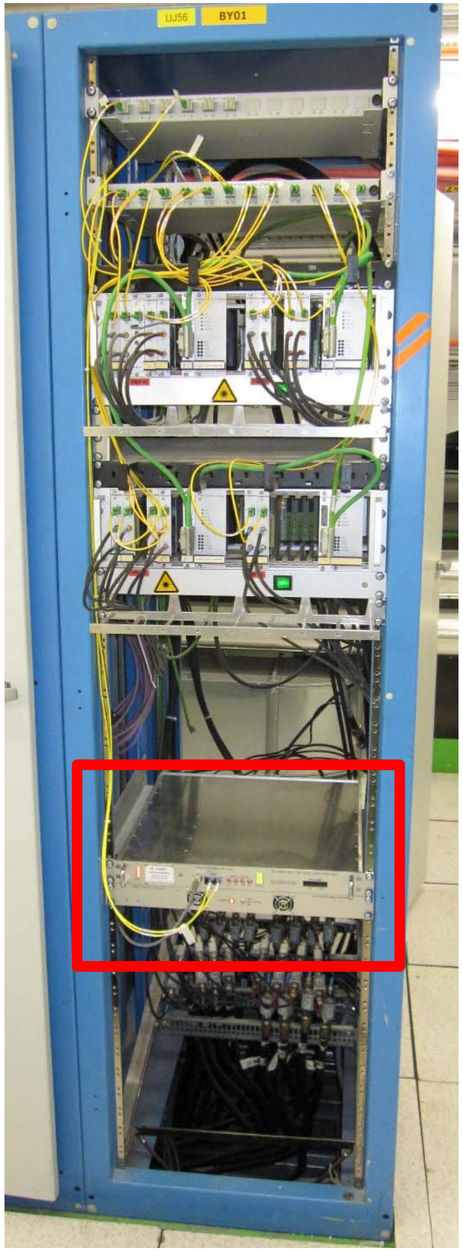
- DOROS is a system for
  - orbit measurement (“averaged” position of all bunches) with sub-micrometre resolution
  - local betatron coupling measurement with micrometre beam excitation
  - beta-beating measurement with micrometre beam excitation
- The system is composed of stand-alone “pizza box” front-ends processing BPM signals and sending the results over Ethernet
- Probably this is the first system with split analogue processing optimized separately for high resolution orbit and beam oscillation measurement
- The orbit measurement sub-system is based on compensated diode detectors, converting the amplitudes of the short beam pulses from the BPM electrodes into DC signals, which can be digitized with very high resolution
- The oscillation measurement system is based on RF diode detectors (“à la BBQ“), demodulating the amplitude modulation of the beam pulses from the BPM electrodes. The detectors are followed by high pass filters, removing the DC content related to the beam offset. This allows subsequent large amplification of only the signals related to the modulation, resulting in a high sensitivity of the beam oscillation detection.
- DOROS = Diode ORbit and OScillation
- DOROS was primarily designed for the LHC collimator BPMs and optimised for:
  - high resolution, precise beam orbit measurement for small beam offsets
  - robustness and simplicity
  - orbit measurements without any prior beam set-up
  - orbit operation without any external timings
- Price to pay: DOROS does not distinguish bunches
  - bunch-by-bunch not possible “by design”
  - bunch gating could be potentially implemented in the future at the expense of the obligatory synchronisation to the turn clock

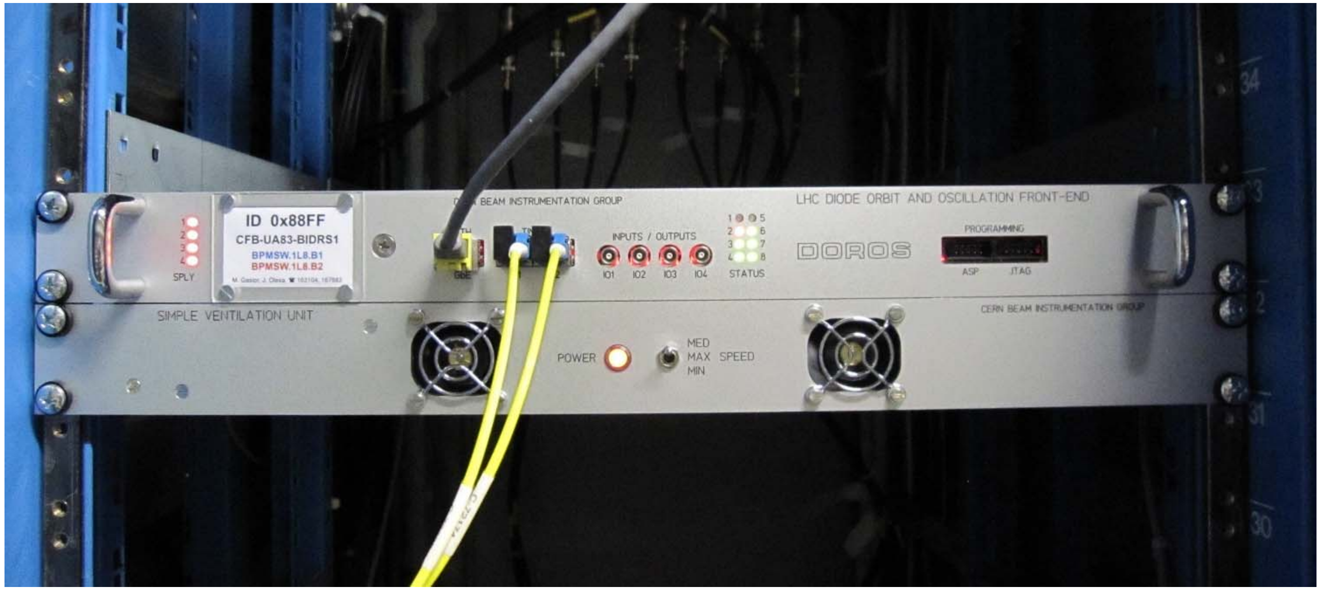
DOROS installations

- DOROS is used as an operational system on all LHC collimators with in-jaw BPMs.
  New in 2017: Two collimators in P7 and two BBLR collimators in P5.
- DOROS is installed as a development system on
  - Q1 BPMs in P1, P2, P5, P8
  - Q7 BPMs in P1
  - AFP BPMs in P1 (**new in 2017**: BPMSA.A6L1.B2)
- DOROS front-ends on standard BPMs share the signals with the regular LHC BPM electronics
  - passive splitters used, optimised for symmetry of signals from each BPM electrode pair
- DOROS on the standard BPMs is still considered as an R&D system
  - work on the FESA level goes on
  - work on the GUI level goes on

- DOROS test front-ends on the SPS:
  - LHC collimator prototype with 4 buttons (one DOROS front-end, LHC type)
  - ALPS (= MOPOS replacement) R&D: one DOROS front-end processing signals from the ALPS prototype
  - **New in 2017**: ALPS R&D: one DOROS front-end processing signals from two SPS BPMs (BPCEH 41801, BPCEV 41931); the front-end has been modified for the SPS beam parameters. Its circuits are very similar to those on the ALPS diode orbit PCB being produced.

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

DOROS front-ends

- All DOROS front-ends are identical and they are distinguished only by their IDs
- A FE does not know to which BPMs it is connected, only FESA knows
- The FE unique ID is a 16-bit number programmed manually with DIP switches according to a convention describing:
  - the system (collimator BPMs or standard BPMs)
  - location: LHC point, SPS, lab
  - a serial number, positive or negative, respectively for the FEs on the right and left side of the LHC point
  - examples: 0x1501 = collimator BPM FE in LHC point 5, serial number 1, i.e. 1st on the right IP side
    0x82FF = standard BPM FE in LHC point 2, serial number -1 (FF in U2), i.e. 1st on the left IP side
    0x1A01 = collimator BPM FE in the SPS, serial number 1
- DOROS FEs are Ethernet devices with well defined names, for example:
  - CFB-UJ14-BIDRS1 = standard BPM FE #1 in UJ14
  - CFB-USC55-BIDRC2 = collimator BPM FE #2 in USC55
- DOROS system received from the CERN Network Services its 16-bit MAC address space (08:00:30:F6:xx:xx)
- The last 16 bits of the MAC address are the front-end ID
- If a DOROS FE is exchanged, its replacement receives the same ID resulting in the same MAC, so it can be plugged to the network without any changes in the databases
- All control as well as data acquisition, processing and transmission are done by an FPGA. Its code can be exchanged remotely in a fail-safe way: if the new code does not boot correctly, the system automatically returns to the old code; the FPGA code download takes a few minutes, the start-up with the new code only a few seconds.
- Each front-end is equipped with a few watchdogs, monitoring its operation and power supply voltages.
  In case of any anomaly (e.g. a single event upset, a radiation induced hardware latch-up) the front-end undergoes a cold reset (complete 230 V switching off). The whole reboot takes a few seconds.
- Each front-end can receive BST of B1 and B2; the FE hardware is “White Rabbit ready”.
  However, the most important task of orbit measurement can be performed without any timing.

DOROS data and control

- DOROS data is sent as UDP frames at 25 Hz. The UDPs can be synchronised to the BST "orbit data triggers"
- One UDP frame has some 1.5 kB, resulting in the data rate of 40 kB/s for one DOROS front-end with 2 dual-plane BPMs
- DOROS UDP frames contain:
  - the front-end ID, the FPGA code version, the UTC time stamp, the number of turns from the beam injection
  - 8 BPM electrode amplitudes sent as 32-bit integers used to calculate 4 orbits in FESA (H+V for two BPMs)
  - 8 amplitudes and phases, demodulation results for 4 planes (H+V × 2 BPMs) and 2 frequencies for local coupling and phase advance measurement (valid only when beam is excited at precise frequencies)
  - configuration of the front-end (e.g. actual gains, modes of operation, auto-calibration settings)
  - actual phase error between the BST turn clock phased to the beam and the beam itself
  - power supply voltages
  - temperatures of 5 front-end PCBs
  - statuses of the front-end gear (e.g. Ethernet, BST, system PLLs)
- The UDP data can be sent to 4 destinations (2 fixed IPs + 2 remotely configurable IPs)
- DOROS FEs are controlled by receiving UDP commands programming system registers setting-up the FE functionality. The commands are accepted only from the programmed IPs.
- DOROS FEs decode BST triggers (post-mortem, dedicated "DOROS capture" triggers)
- The most important data is logged, the FE parameters will be logged soon
- LHC experiments receive DOROS orbits in DIP
- **New in 2017**: DOROS front-ends are equipped with two post-mortem buffers for B2 and B1, storing locally the UDP frames, in parallel to their normal 25 Hz transmission. The post-mortem circular buffers store some 1.5 minute of UDP frames for each beam. The buffers are stopped 10 s after the PM trigger. The client decides how much post-mortem data is read. The PM buffers can be stopped upon reception of a dedicated UDP command or the BST trigger.

Turn-by-turn data

- Turn-by-turn data is stored in dedicated buffers and transmitted after the acquisition is finished
- There are stored for each beam:
  - 2 oscillation channels (H+V planes) for local coupling and phase advance measurement)
  - 4 electrode amplitudes used to calculate orbits and low frequency beam spectra
- The turn-by-turn buffer can operate in two modes:
  - capture: data recording starts upon trigger and finishes after programmed number of turns;
  - **New in 2017**: freeze: data is stored in circular buffers all the time and recording stops upon trigger. Then one can read from the buffers required number of turns.
- **New in 2017**: Oscillation and orbit data is stored always turn-by-turn. Data can be decimated upon request during the readout.
- Length of the buffers is some 3.7 minutes (about 2.3 million turns).
- B1 and B2 buffers have independent triggers.

DOROS front-ends declared in the CERN network database

- Naming convention:

…-BIDRC-… = Collimator front-end

…-BIDRS-… = Standard BPM front-end

…-BIDRD-… = Development front-end

- Three independent systems, namely C, S and D
- Each system has its own FESA run on a separate server

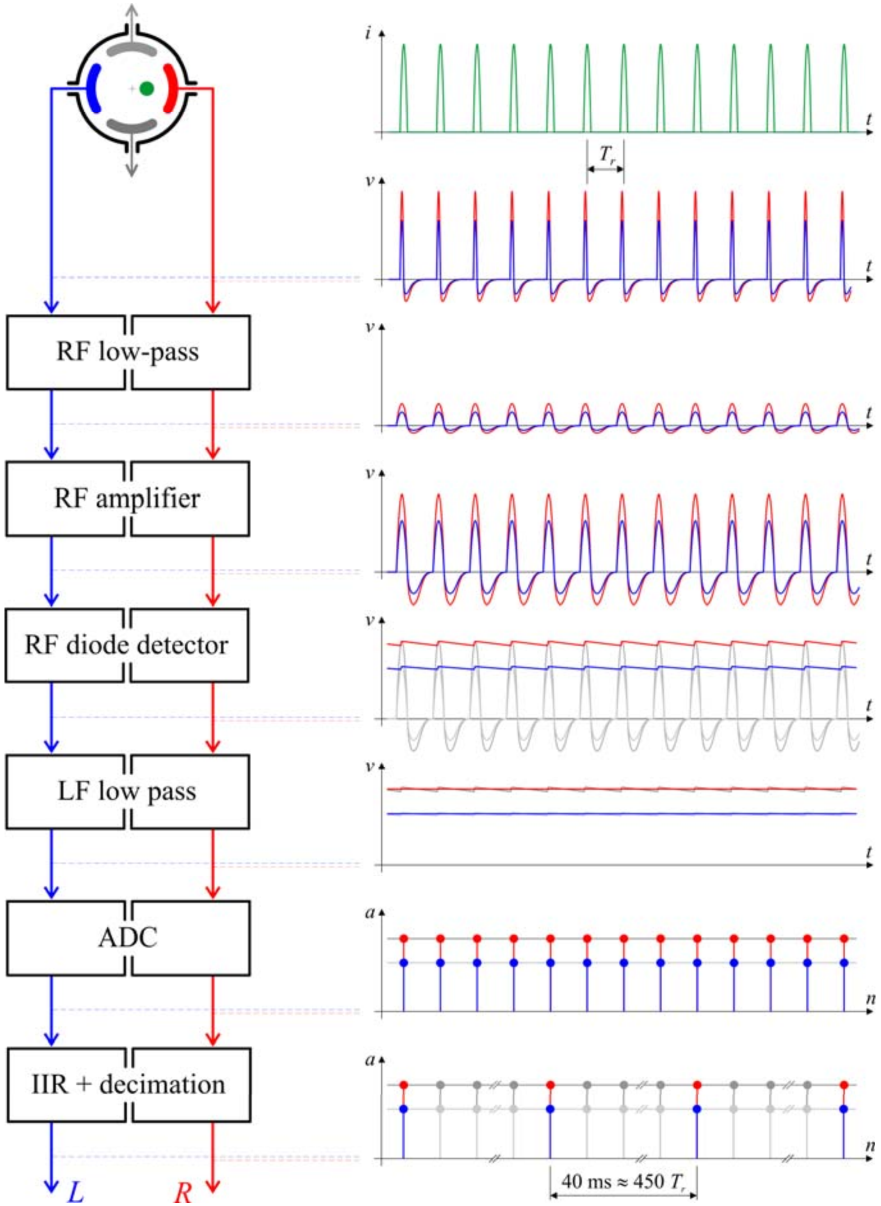
? Please select a Device matching DeviceName(CFB%BIDR%):

I have found one or more devices matching DeviceName(CFB%BIDR%). Please select one of them:
Each line describes a device with its Location, Manufacturer, Type, Operating System and CERN Network Domain

- CFB-272-BIDRC1 0272 R-0005 CERN DOROS2 UC-OS GPN
- CFB-866-BIDRD1 0866 1-0A17 CERN DOROS1 UC-OS GPN
- CFB-866-BIDRD16 0866 1-0406 CERN DOROS1 UC-OS GPN
- CFB-866-BIDRD17 0866 1-0406 CERN DOROS1 UC-OS GPN
- CFB-866-BIDRD18 0866 1-0406 CERN DOROS1 UC-OS GPN
- CFB-866-BIDRD2 0866 1-0A17 CERN DOROS1 UC-OS GPN
- CFB-866-BIDRD3 0866 1-0A17 CERN DOROS3 UC-OS GPN
- CFB-BA5-BIDRC1 0872 R-0009 CERN DOROS1 UC-OS TN
- CFB-ECA5-BIDRC1 0899 S1-2325 CERN DOROS1 UC-OS TN
- CFB-HCA4-BIDRD1 0921 S2-0001 CERN DOROS1 UC-OS TN
- CFB-RR13-BIDRS1 3110 U0-0001 CERN DOROS1 UC-OS TN
- CFB-RR13-BIDRS2 3110 U0-0001 CERN DOROS1 UC-OS TN
- CFB-RR17-BIDRS1 3141 U0-0001 CERN DOROS1 UC-OS TN
- CFB-RR17-BIDRS2 3141 U0-0001 CERN DOROS1 UC-OS TN
- CFB-RR77-BIDRC1 3732 U0-0001 CERN DOROS1 UC-OS TN
- CFB-RR77-BIDRC2 3732 U0-0001 CERN DOROS1 UC-OS GPN
- CFB-UA23-BIDRC1 2218 R-0000 CERN DOROS1 UC-OS TN
- CFB-UA23-BIDRS1 2218 R-0000 CERN DOROS1 UC-OS TN
- CFB-UA27-BIDRC1 2239 R-9708 CERN DOROS1 UC-OS TN
- CFB-UA27-BIDRS1 2239 R-0000 CERN DOROS1 UC-OS TN
- CFB-UA27-BIDRS3 2239 R-0000 CERN DOROS1 UC-OS TN
- CFB-UA63-BIDRC1 2618 R-5304 CERN DOROS1 UC-OS TN
- CFB-UA67-BIDRC1 2639 R-4804 CERN DOROS1 UC-OS TN
- CFB-UA83-BIDRC1 2818 RA-0000 CERN DOROS1 UC-OS TN
- CFB-UA83-BIDRS1 2818 RA-0000 CERN DOROS1 UC-OS TN
- CFB-UA87-BIDRC1 2839 RA-0000 CERN DOROS1 UC-OS TN
- CFB-UA87-BIDRS1 2839 RA-0000 CERN DOROS1 UC-OS TN
- CFB-UJ14-BIDRS1 2119 0-0000 CERN DOROS1 UC-OS TN
- CFB-UJ16-BIDRS1 2137 0-0000 CERN DOROS1 UC-OS TN
- CFB-UJ56-BIDRS1 2537 1-0000 CERN DOROS1 UC-OS TN
- CFB-UJ76-BIDRC1 2737 U1-0001 CERN DOROS1 UC-OS TN
- CFB-US152-BIDRC1 2127 2-0A01 CERN DOROS1 UC-OS TN
- CFB-US152-BIDRC2 2127 2-0A01 CERN DOROS1 UC-OS TN
- CFB-USC55-BIDRC1 3524 1-0000 CERN DOROS1 UC-OS TN
- CFB-USC55-BIDRC2 3524 1-0000 CERN DOROS1 UC-OS TN
- CFB-USC55-BIDRC3 3524 1-0401 CERN DOROS1 UC-OS TN
- CFB-USC55-BIDRS1 3524 1-0000 CERN DOROS1 UC-OS TN

Listed 37 entries.

Network.Support@cern.ch Generated on Mon Apr 10 15:15:41 2017



- 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.

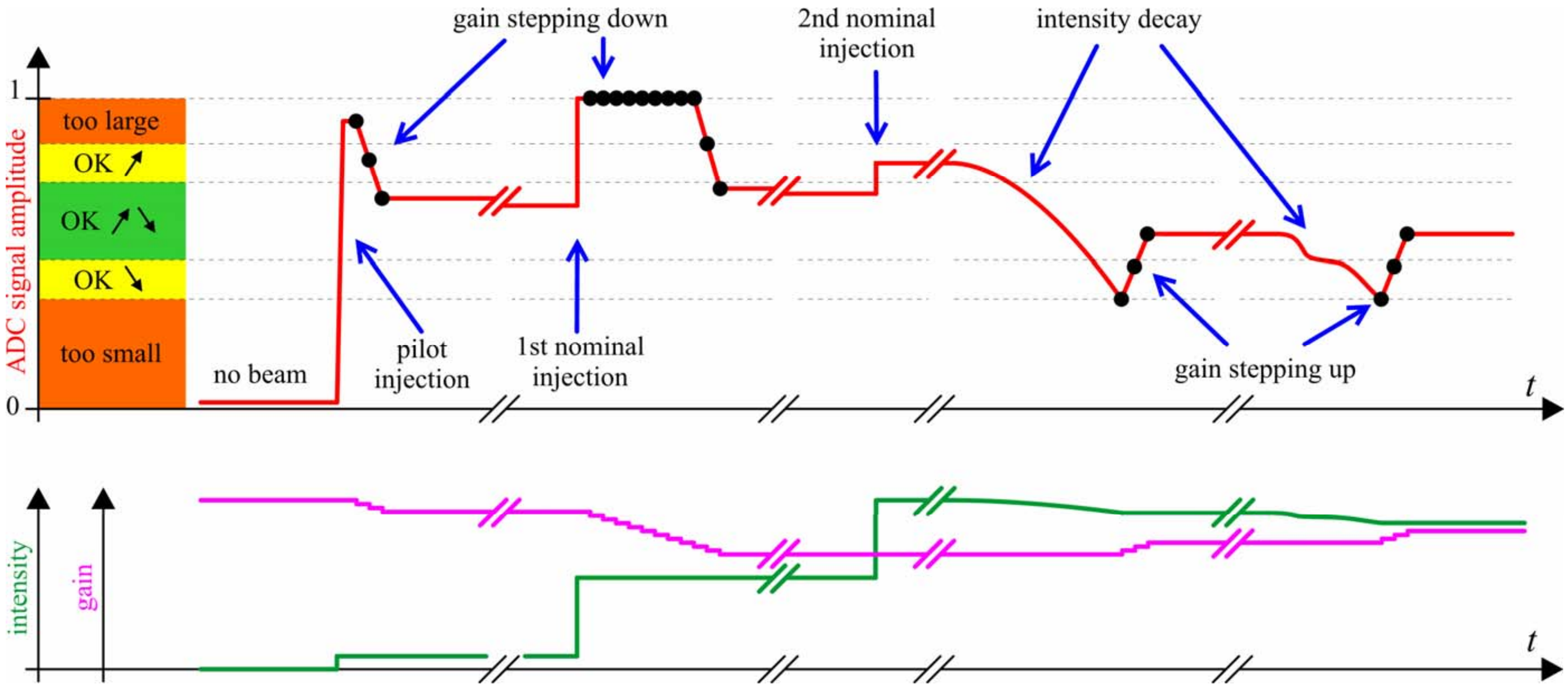
- Absolute beam positions in mm using linear approximation:

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

- Absolute beam positions in mm:

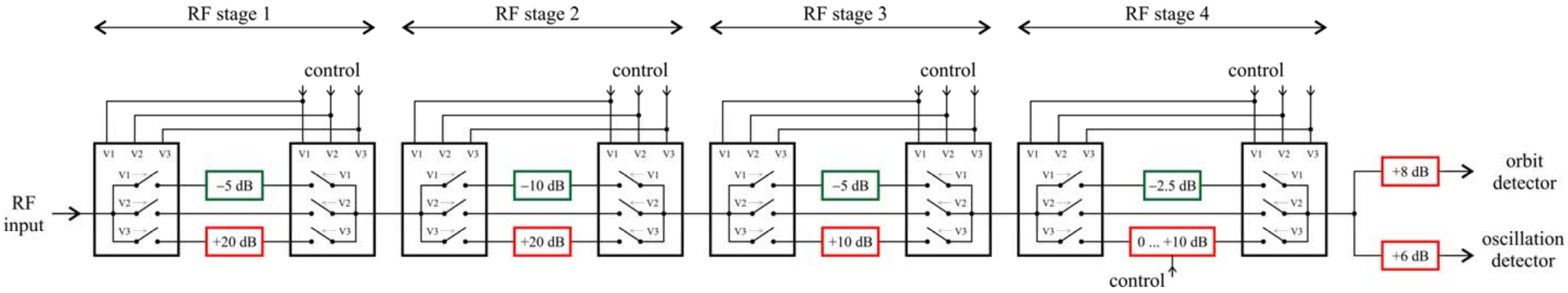
$$P \cong \frac{d}{4} f(p_H, p_V)$$

DOROS – automatic gain control (basic mode)



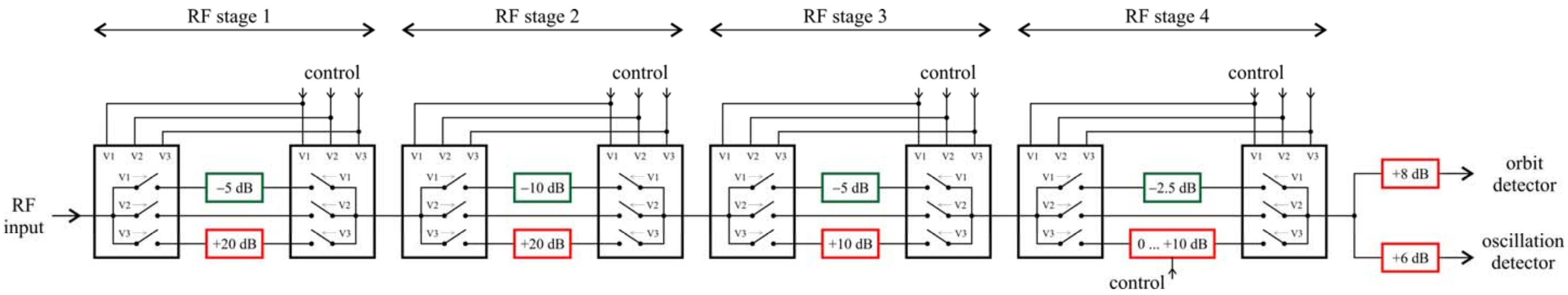
- Four channels of one pick-up have the same gain
- Gain control is based on the largest signal of all four electrodes
- The gain is adjusted to cause the largest signal to have the amplitude in the green zone
- The gain control levels are programmable and can be changed according to actual beam conditions
- 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)

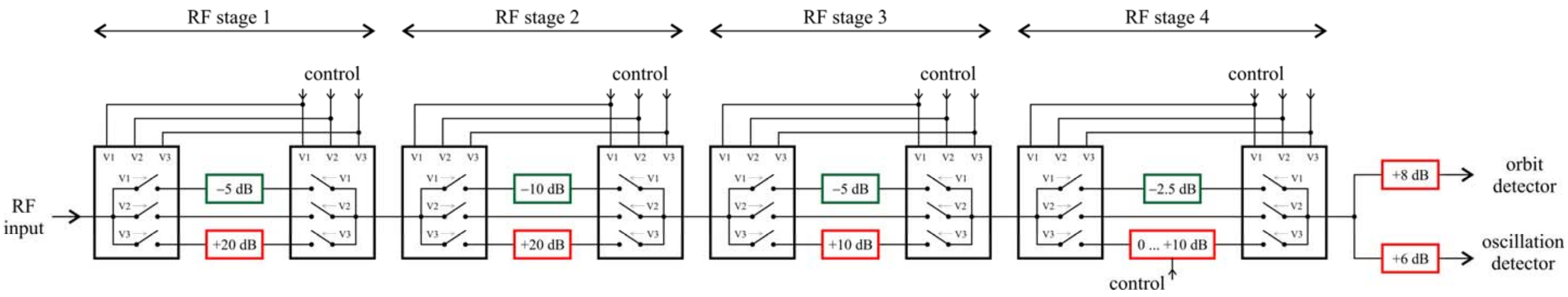
overal gain	stage 1	stage 2	stage 3	PGA	gain index
20	0	0	10	10	48
21	0	0	10	11	49
22	0	0	10	12	50
23	0	0	10	13	51
24	0	0	10	14	52
25	0	0	10	15	53
26	0	0	10	16	54
27	0	0	10	17	55
28	0	0	10	18	56
29	0	0	10	19	57
30	0	0	10	20	58
30	0	20	0	10	59
31	0	20	0	11	60
32	0	20	0	12	61
33	0	20	0	13	62
34	0	20	0	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



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

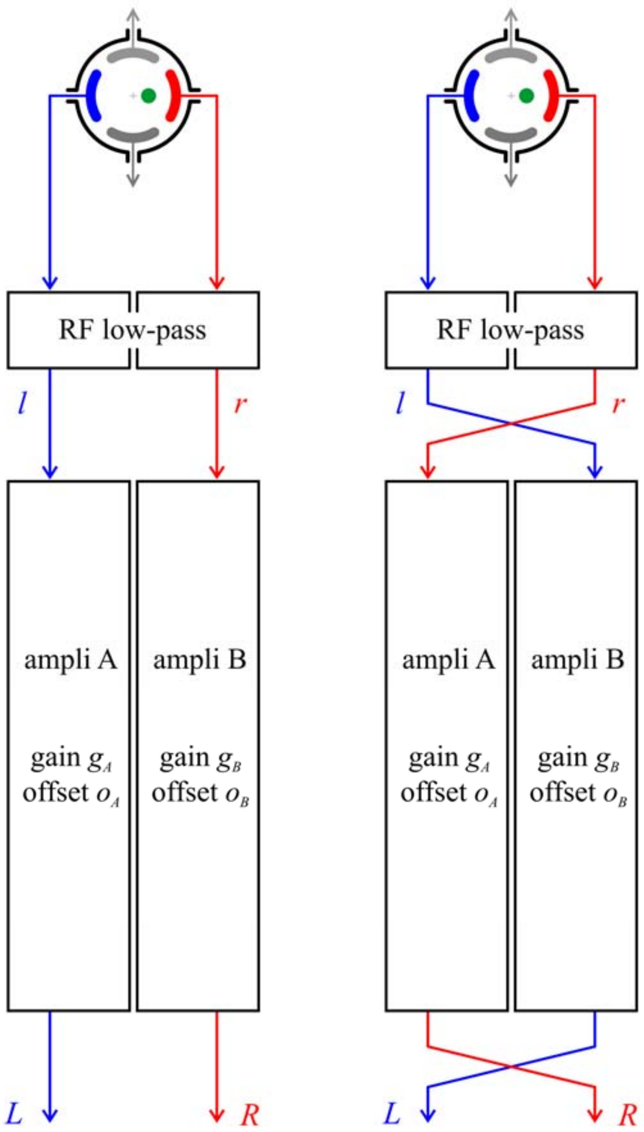
period 6+7: gains 40 .. 60 dB (index 70 .. 91)

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**

Orbit auto-calibration

measurement 1 measurement 2



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

$$R_1 = g_B\, r + o_B$$

$$L_2 = g_B\, l + o_B$$

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

$$L_c = \frac{L_1 + L_2}{2}$$

$$R_c = \frac{R_1 + R_2}{2}$$

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

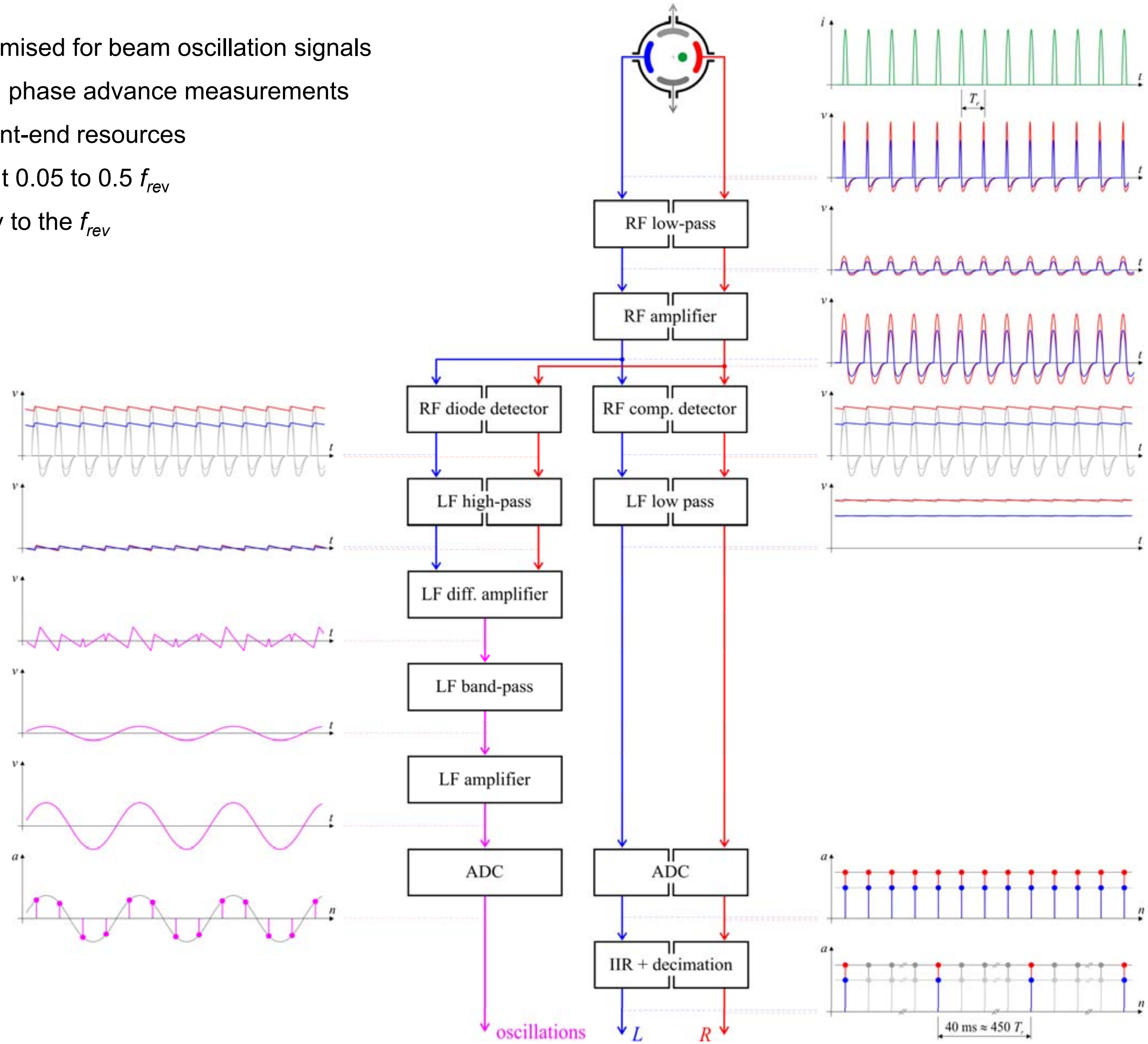
- Channel switching is done typically every 1 s
- One calibrated measurement comes from two simple ones using moving average = one calibrated measurement every 1 s with 1 s delay
- Typically g_A, $g_B \in [0.95, 1.05]$, o_A, $o_B \in [-0.001, 0.001]$

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

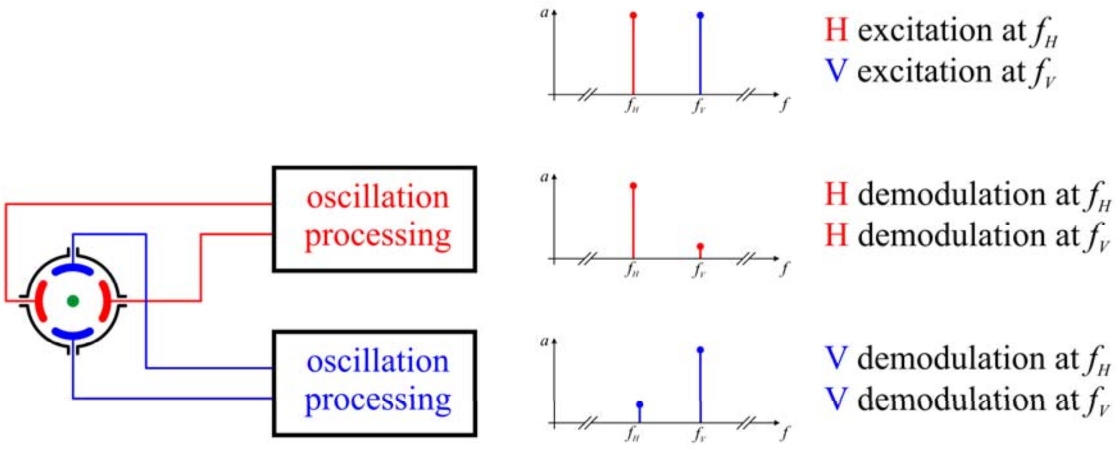
DOROS – oscillation part

- 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}



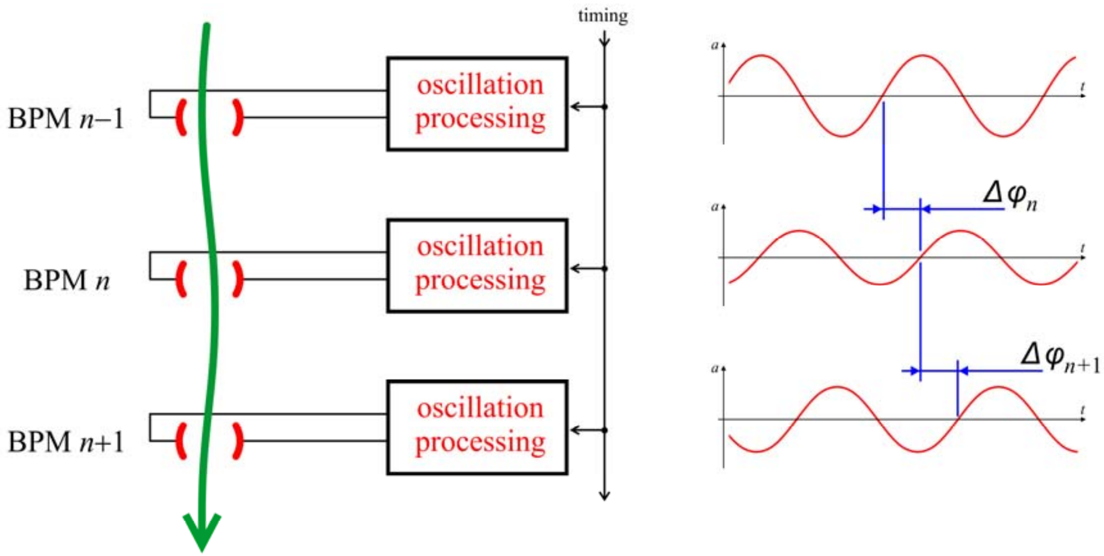
Local betatron coupling

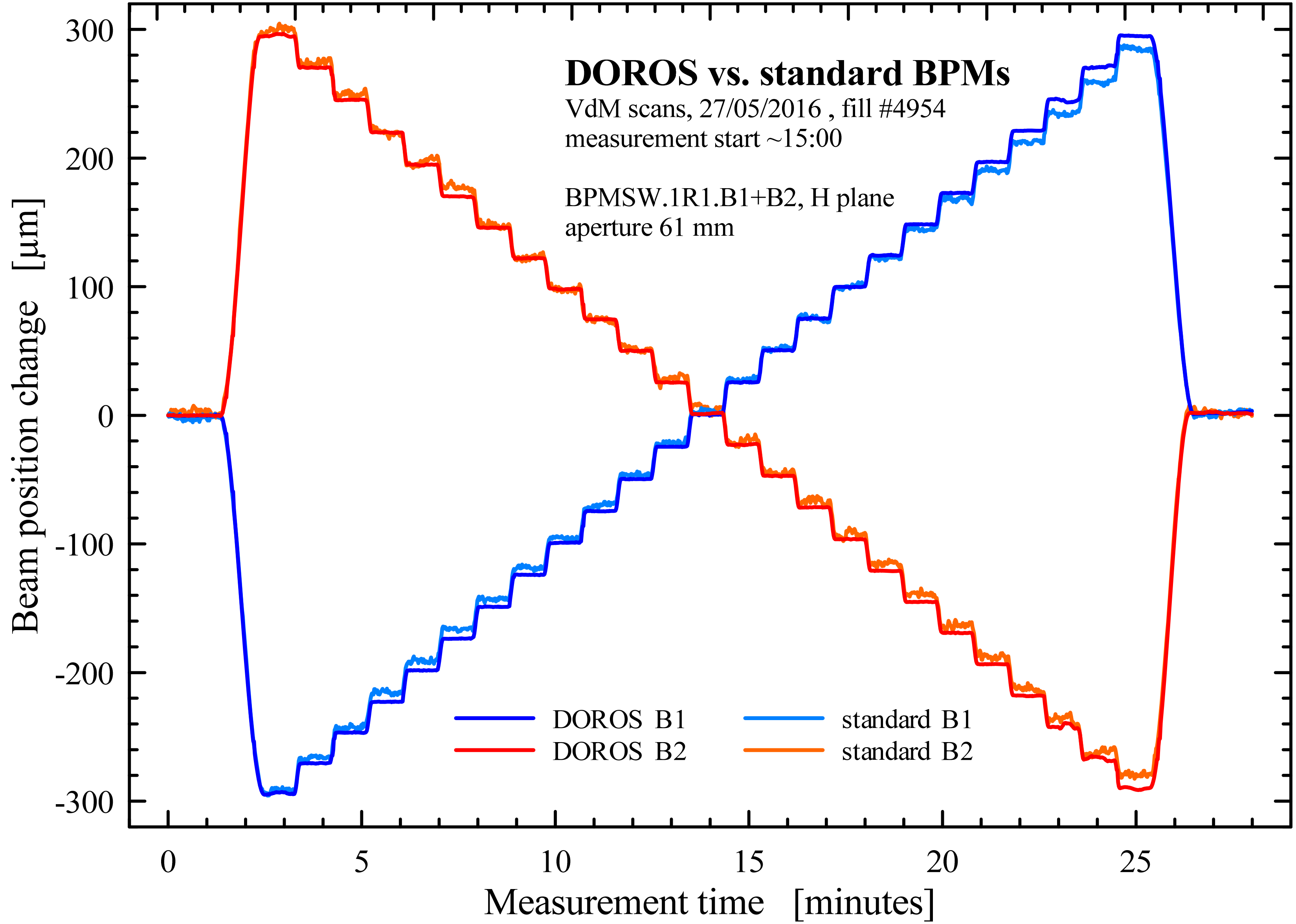
- Harmonic beam excitation
  at a separate frequency for each plane
- Beam signal demodulation at both frequencies for each plane
- From the four amplitudes and four phases the coupling amplitude and phase is calculated for the BPM location



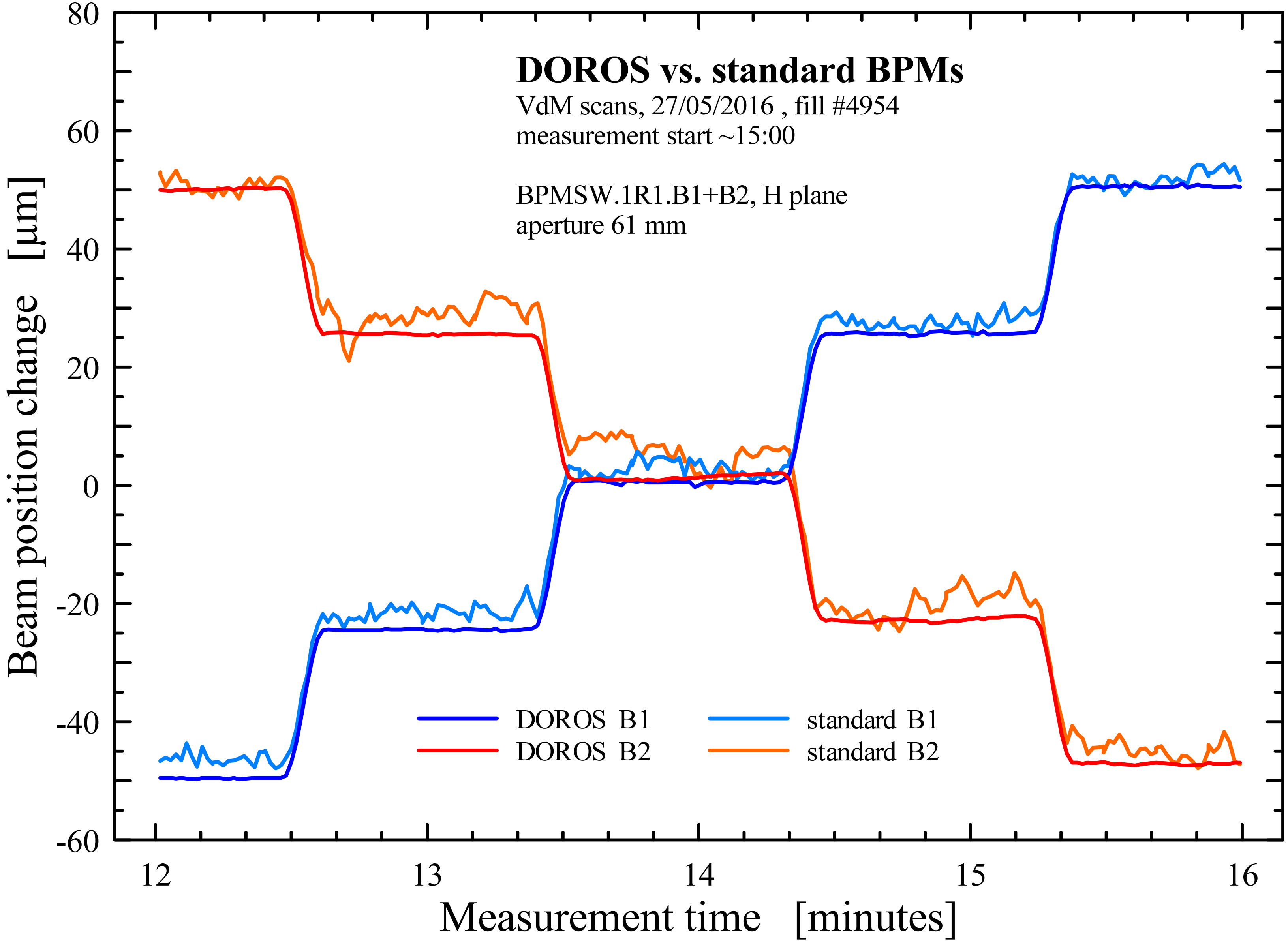
Betatron phase advance

- 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

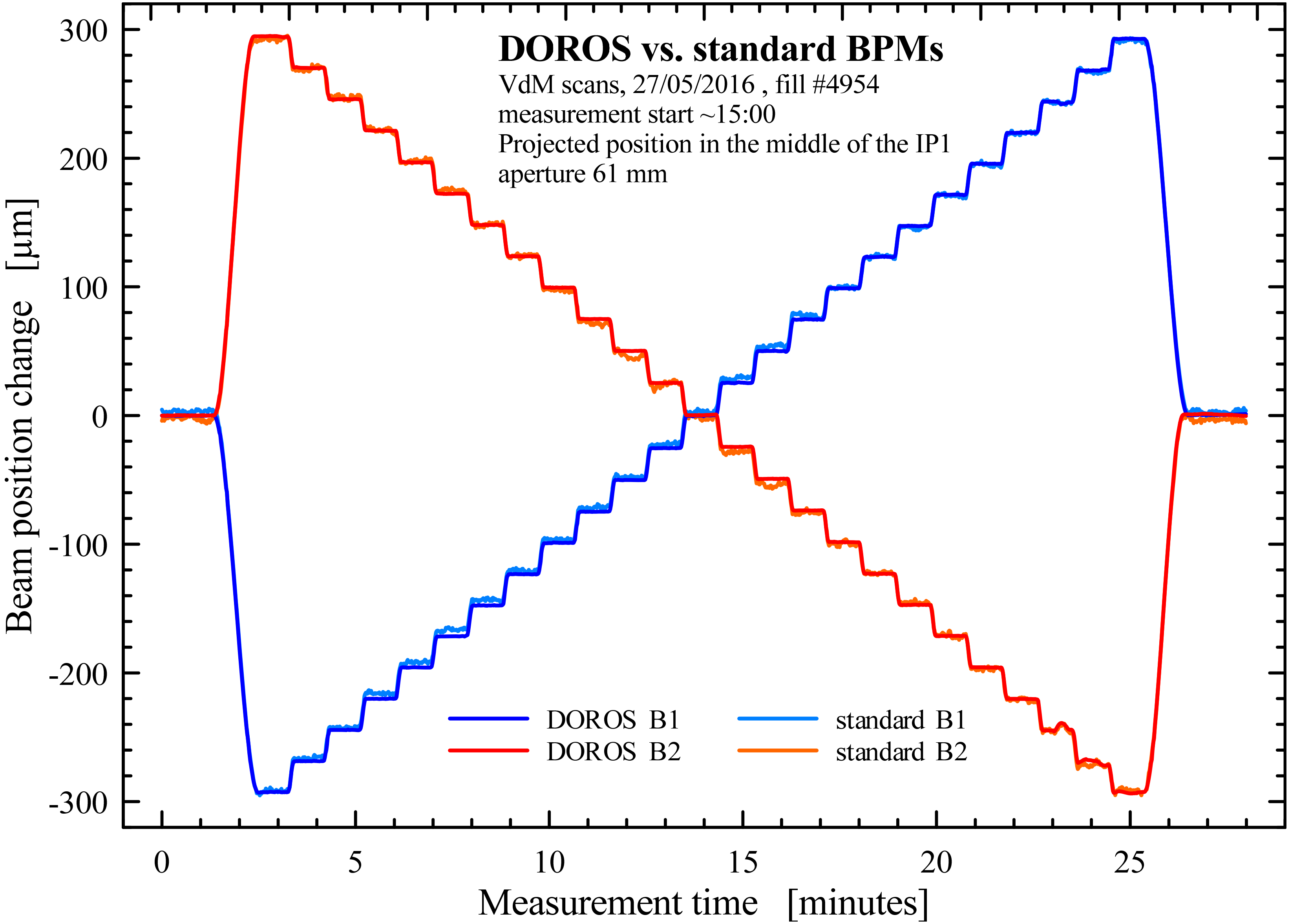



DOROS vs. standard BPMs
VdM scans, 27/05/2016 , fill #4954
measurement start ~15:00
BPMSW.1R1.B1+B2, H plane
aperture 61 mm
DOROS B1
DOROS B2
standard B1
standard B2
Beam position change [µm]
300
200
100
0
-100
-200
-300
0
5
10
15
20
25
Measurement time [minutes]

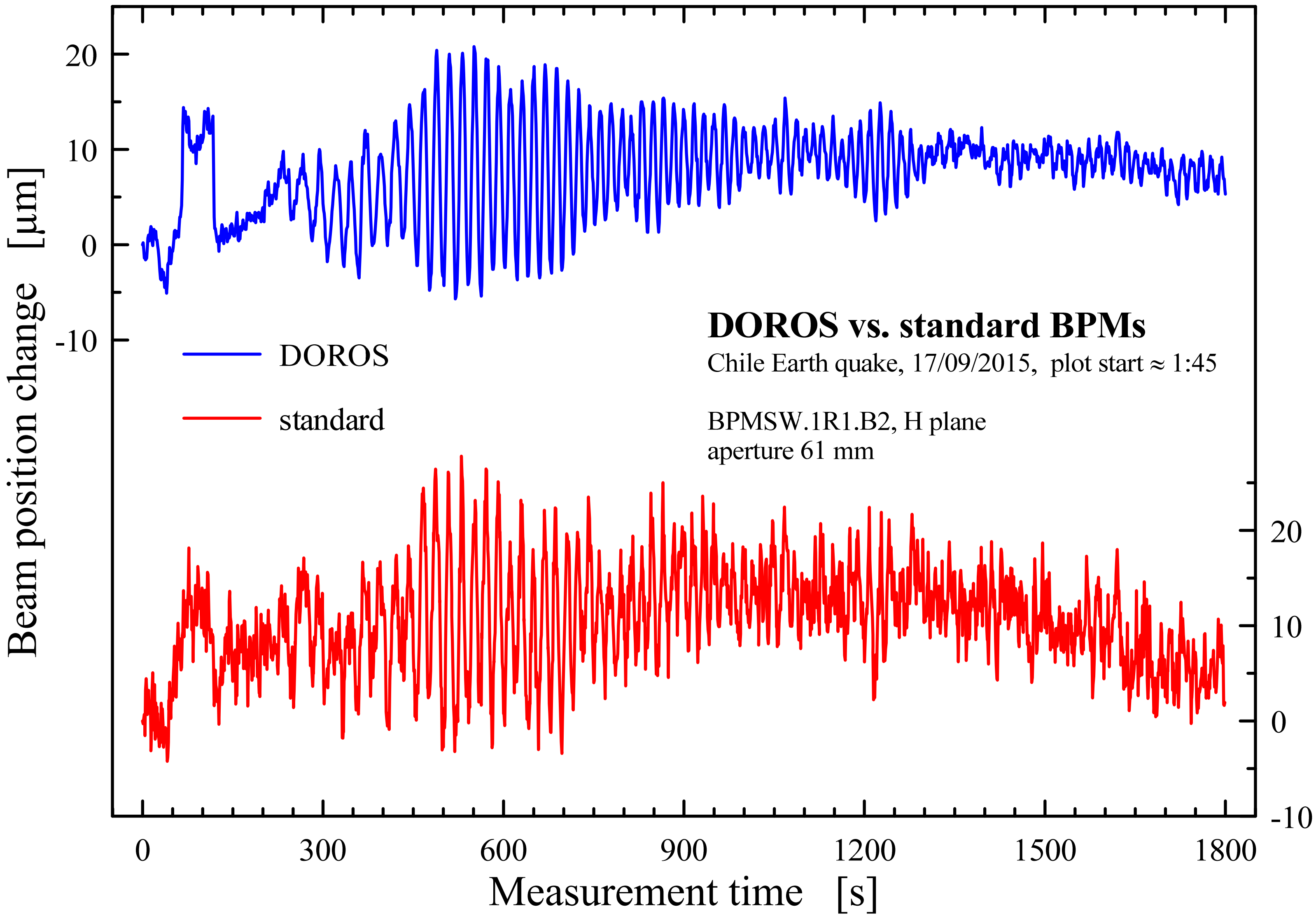
DOROS vs. standard BPMs for orbits



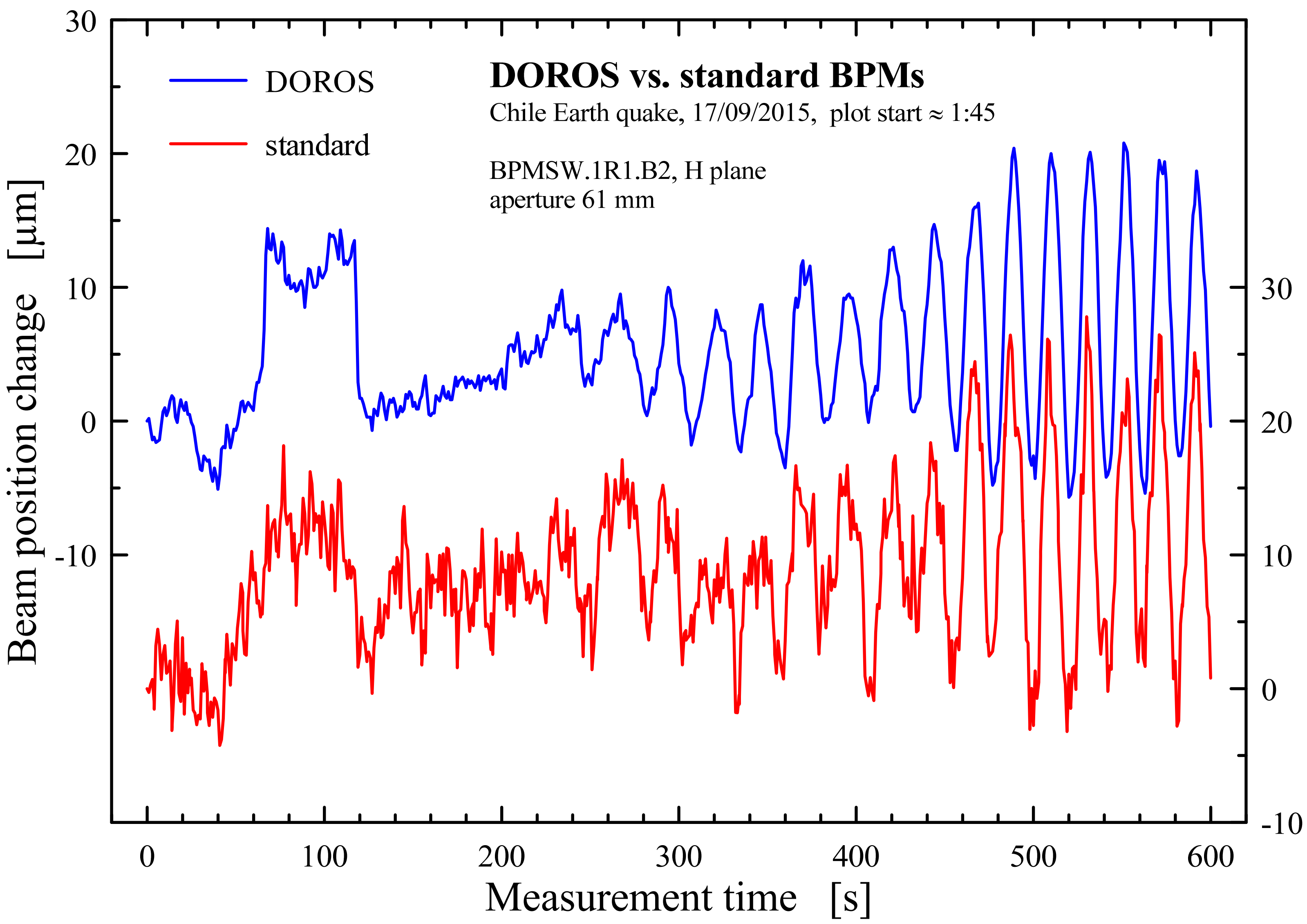
DOROS vs. standard BPMs for orbits



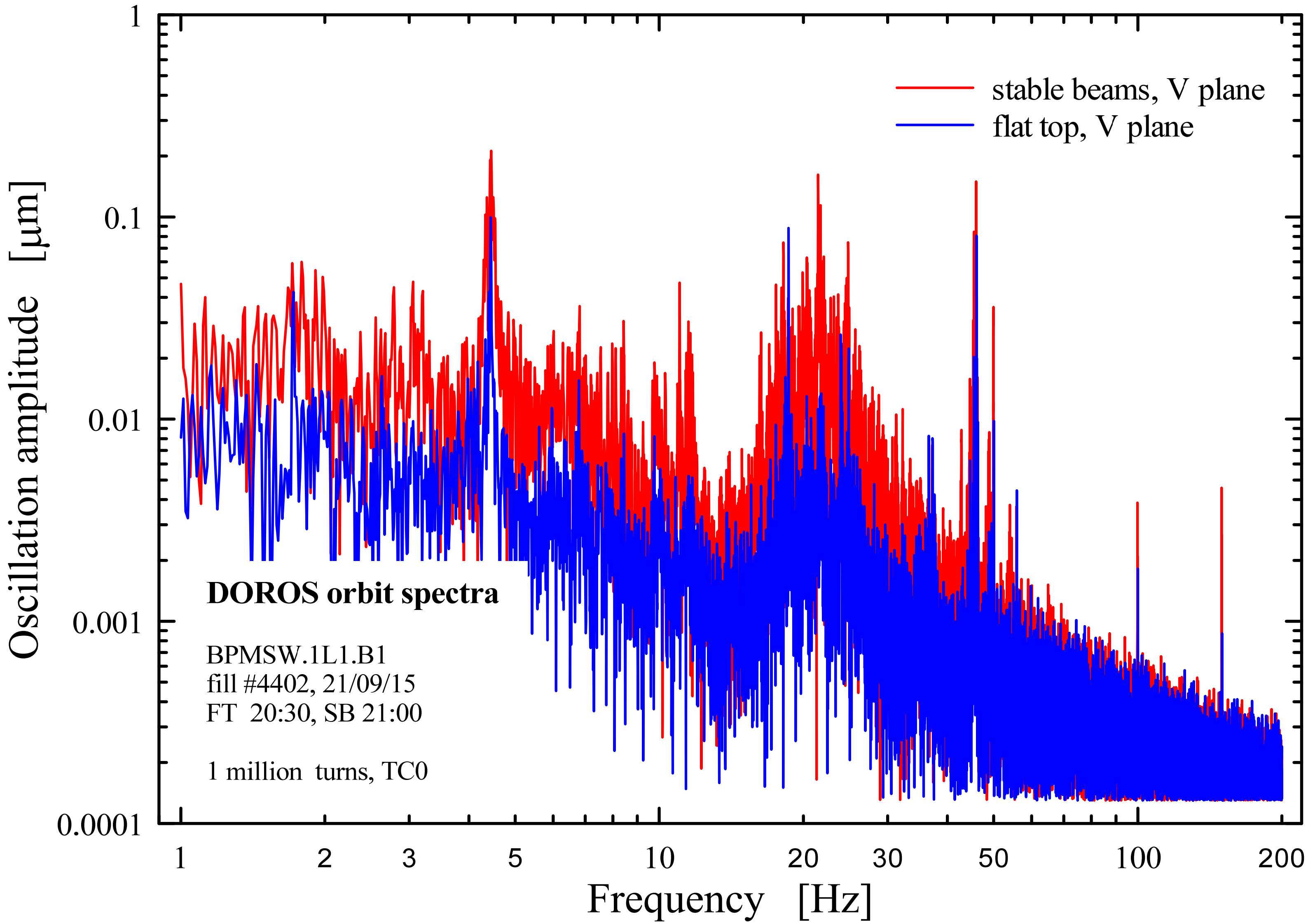
DOROS vs. standard BPMs for orbits



DOROS vs. standard BPMs for orbits

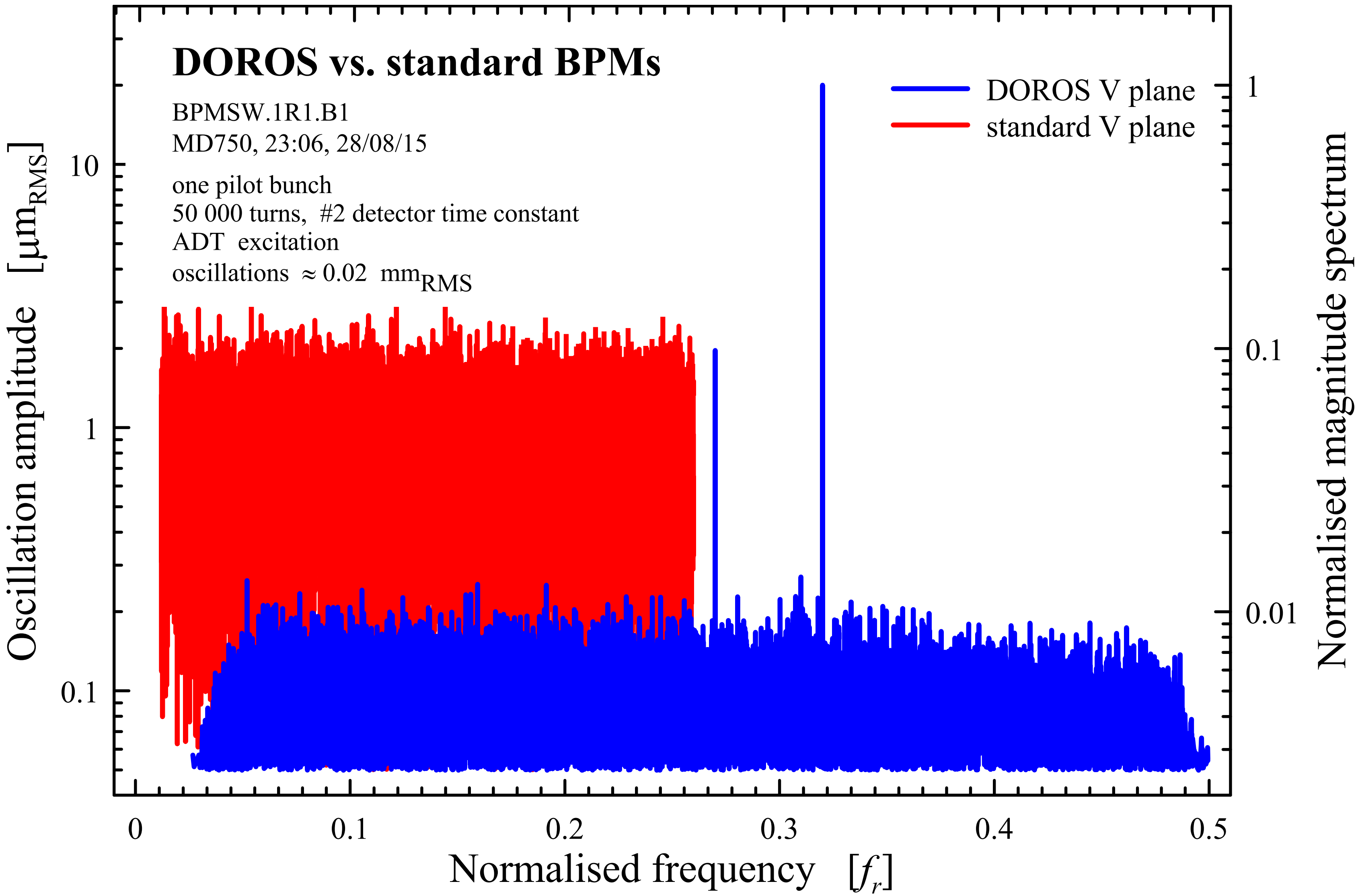


Spectra of the DOROS orbit data



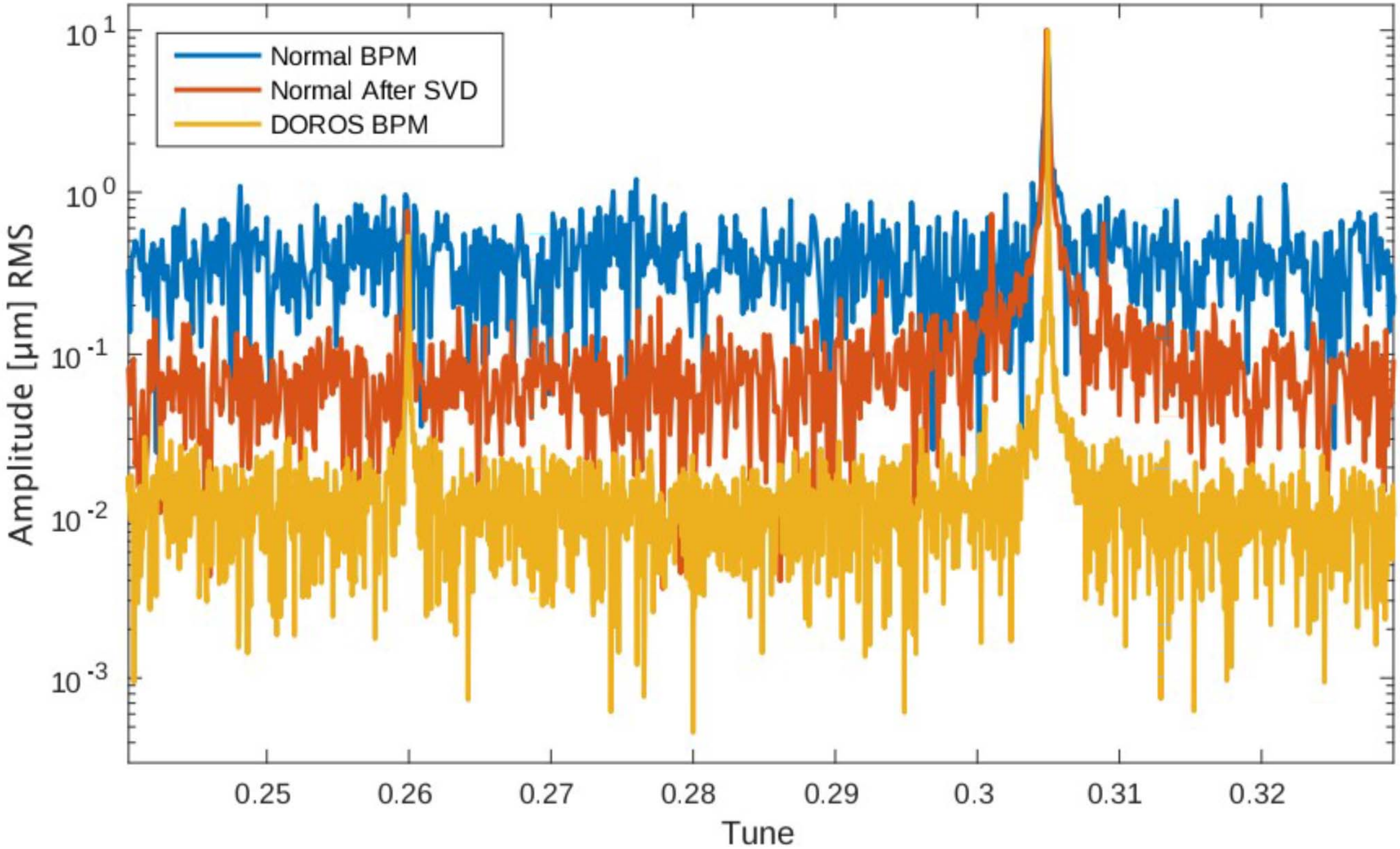
NOTE: The vertical axis is scaled in the equivalent time domain amplitudes of harmonic components.

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



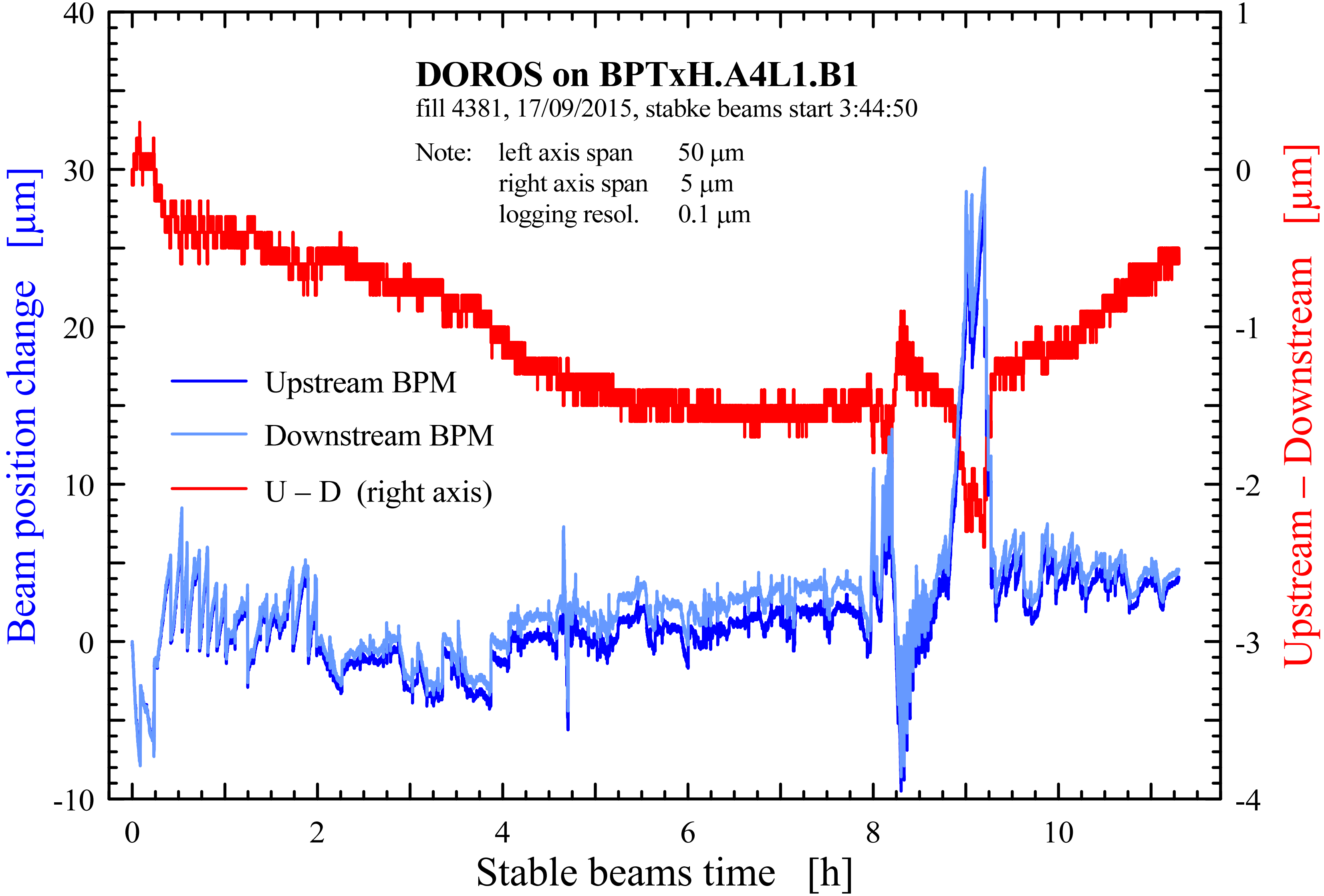
Notes: The vertical axis is scaled in the equivalent time domain amplitudes assuming harmonic components.
For better visibility the upper frequency axis for the standard BPM data is slightly shifted with respect to the bottom axis of the DOROS data.

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



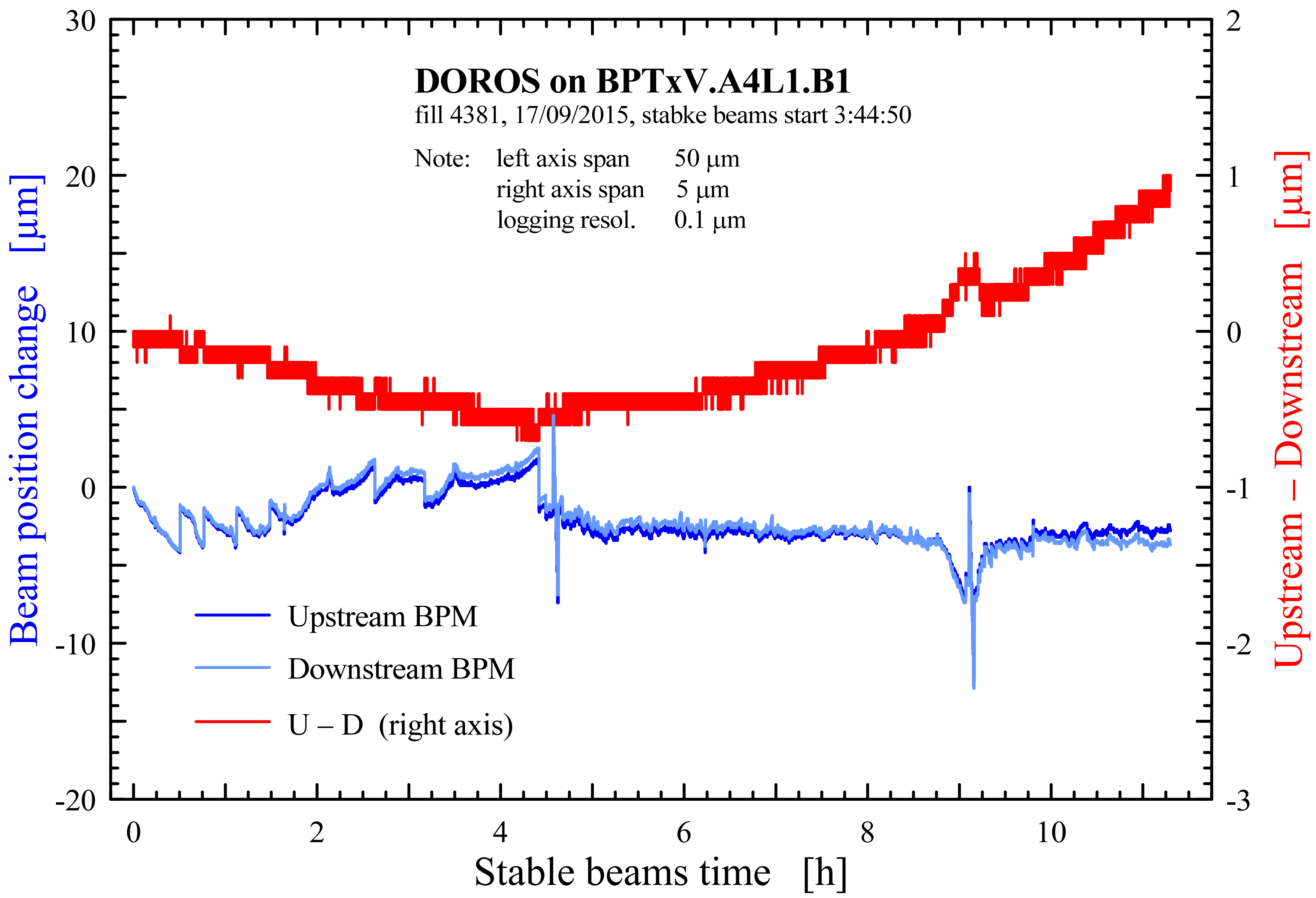
T. Persson, “Online coupling measurement: Method and Experience”, LBOC 7/03/17

DOROS on collimator BPMs: H.L1.B1

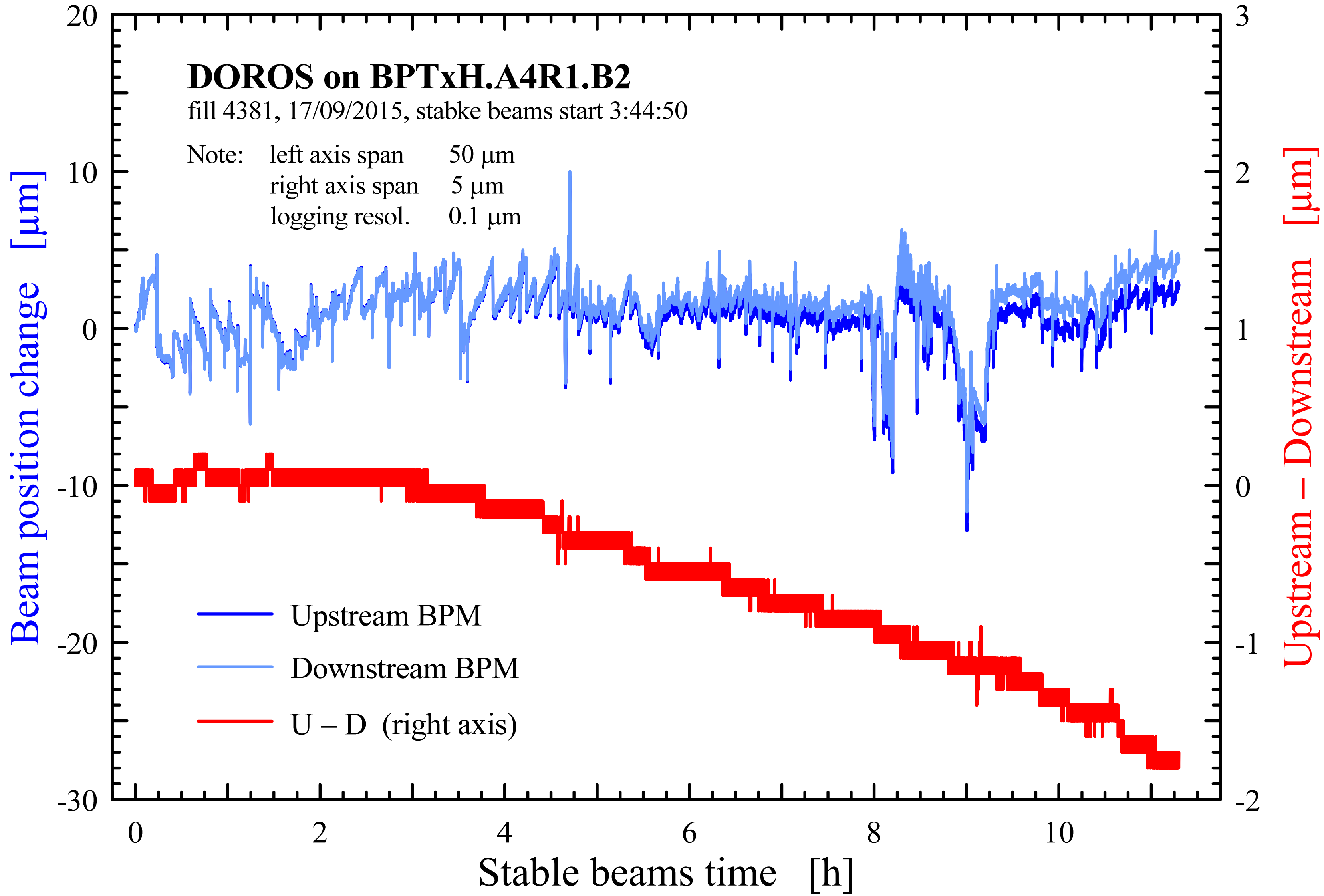


Note: Logging resolution of 0.1 µm seen on the difference between the upstream and downstream BPMs.

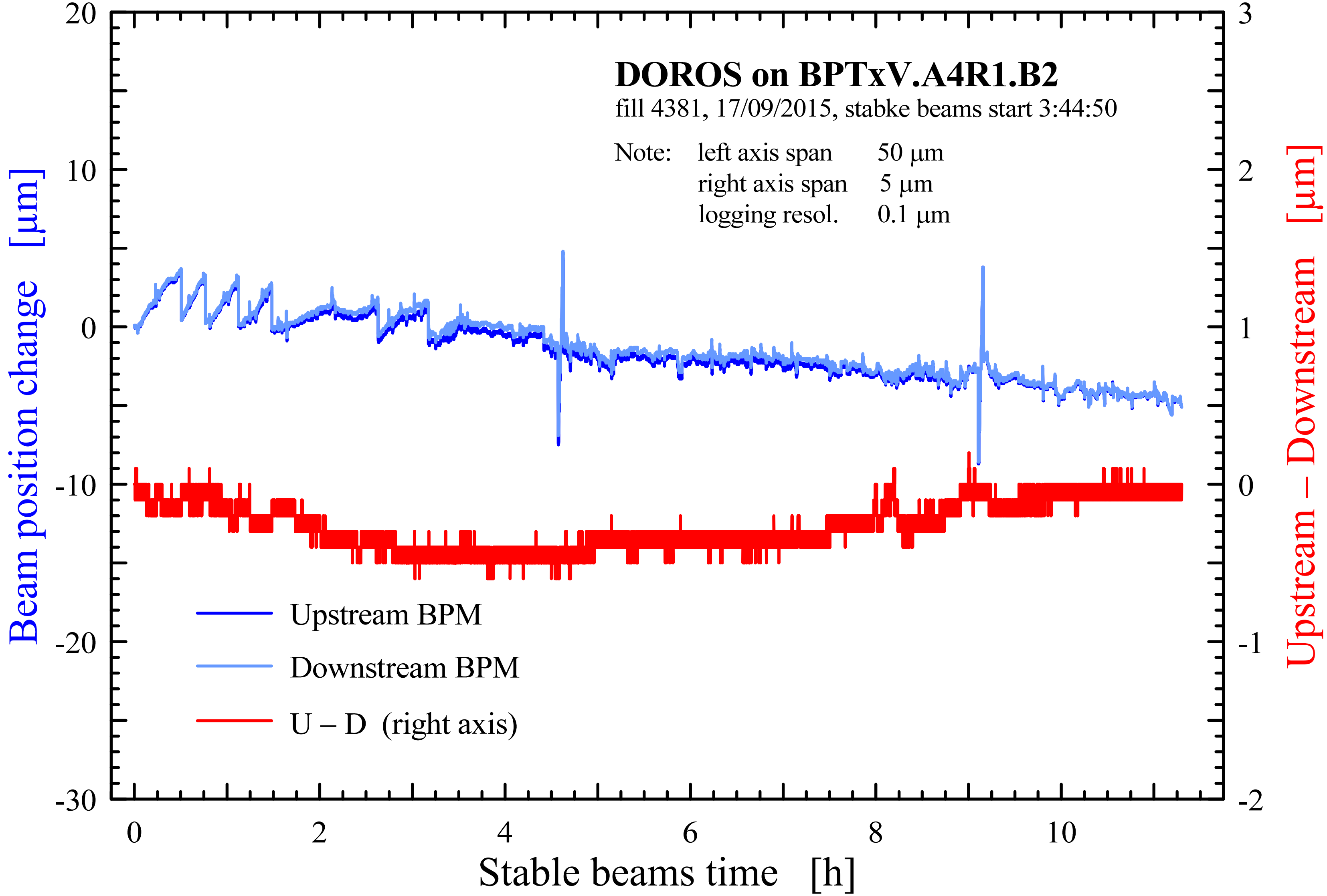
DOROS on collimator BPMs: V.L1.B1



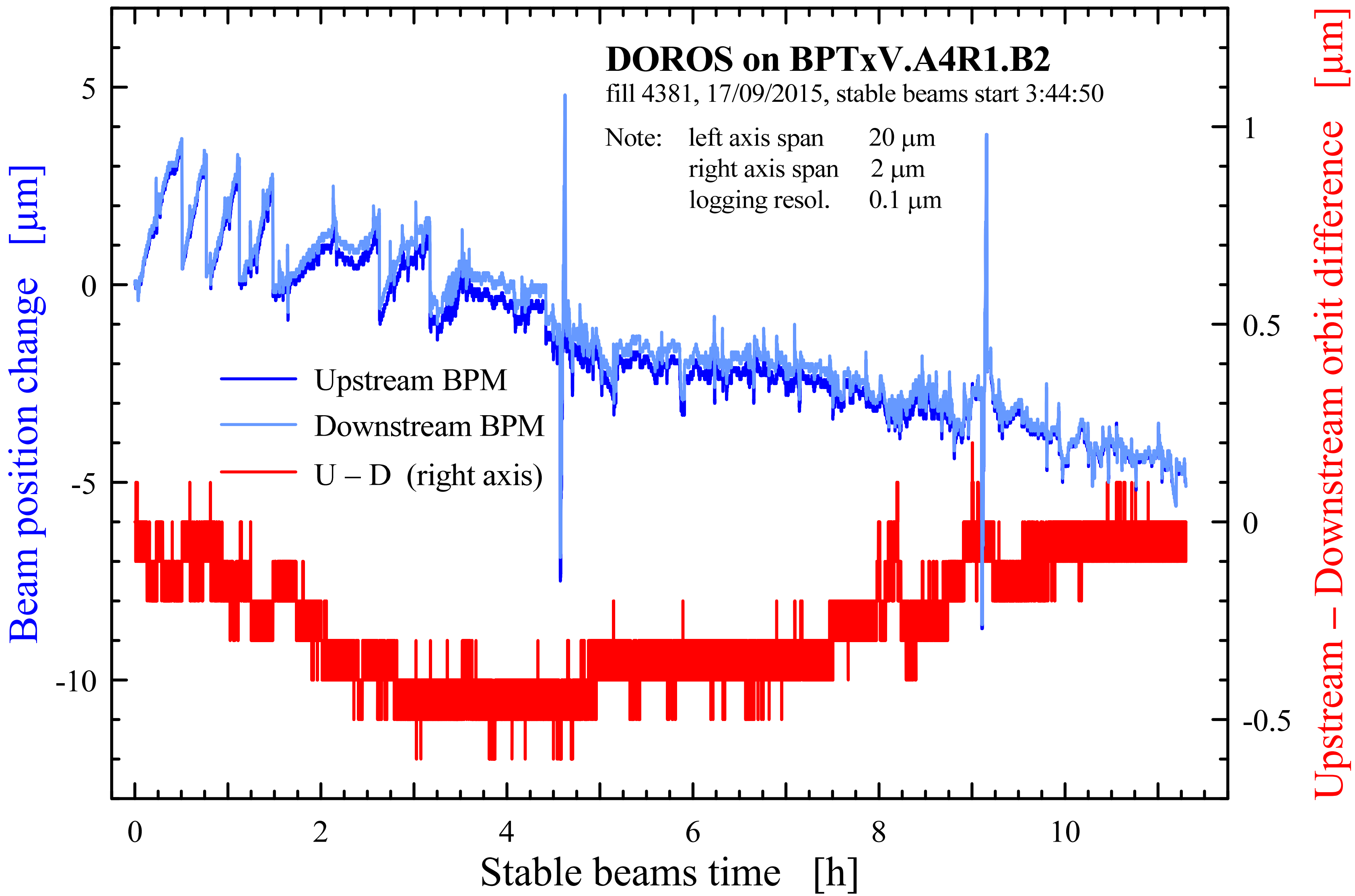
DOROS on collimator BPMs: H.R1.B2



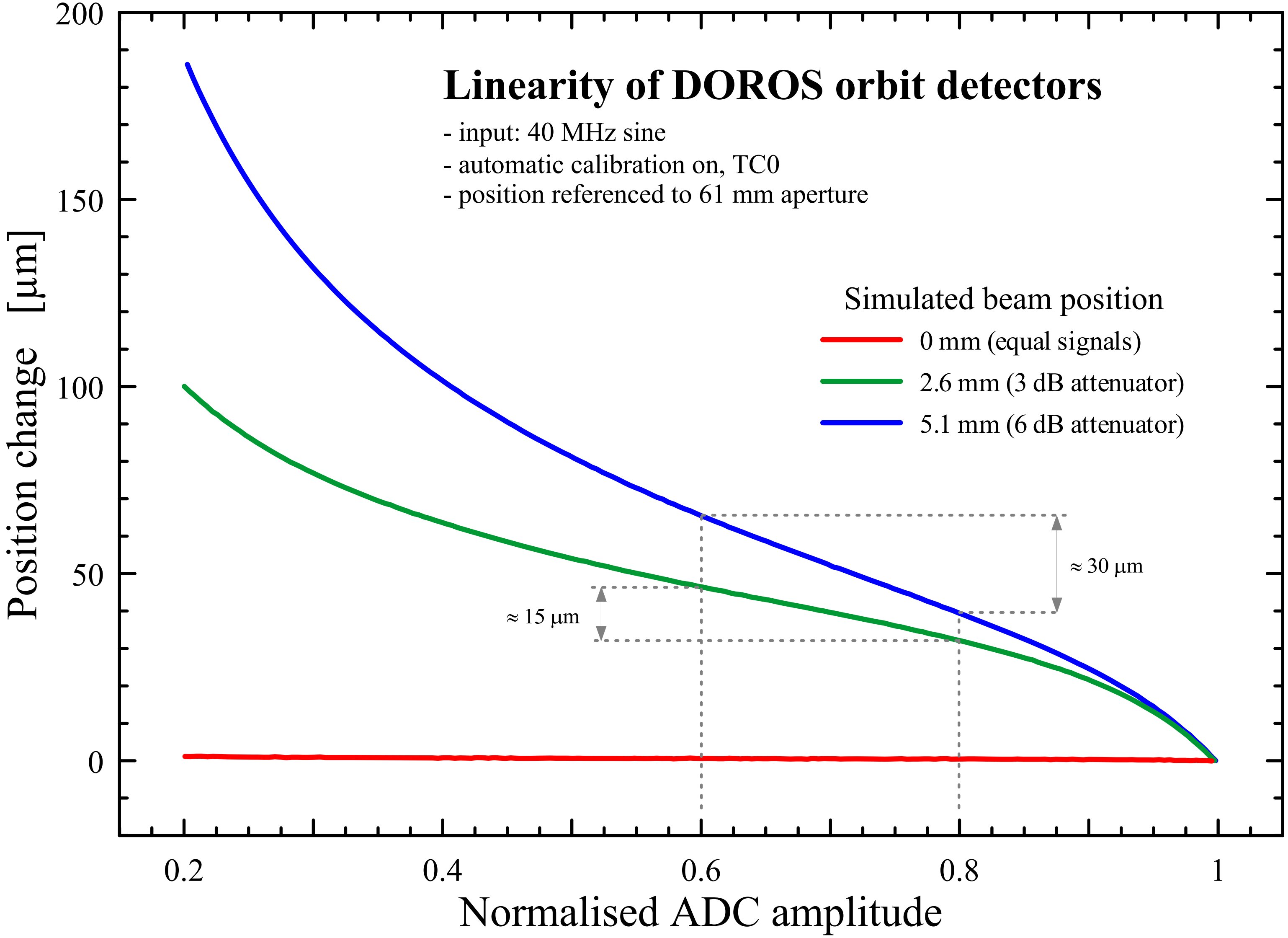
DOROS on collimator BPMs: V.R1.B2



DOROS on collimator BPMs: V.R1.B2

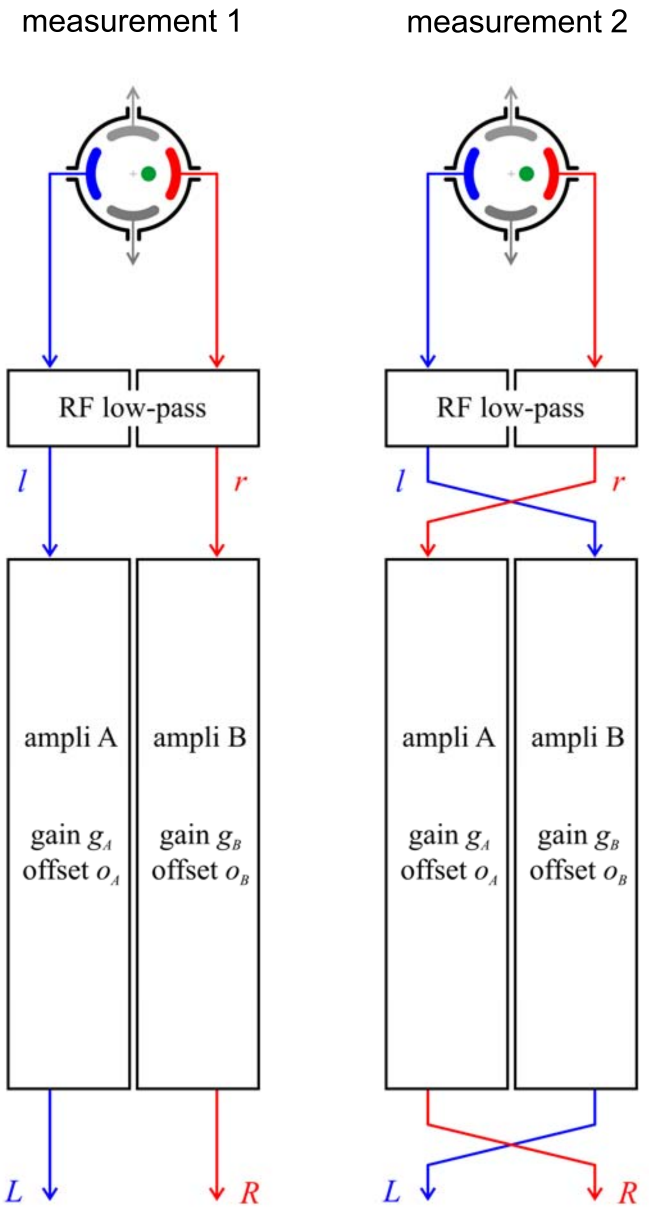


Linearity of the orbit diode detectors



Plot in: M. Gasior et all., „First operational experience with the LHC Diode ORbit and OScillation (DOROS) system", IBIC 2016; here slightly modified for the linearity studies

Limits of the orbit auto-calibration



$$L_1 = g_A\, l + o_A \qquad L_2 = g_B\, l + o_B \qquad L_c = \frac{L_1 + L_2}{2}$$

$$R_1 = g_B\, r + o_B \qquad R_2 = g_A\, r + o_A \qquad R_c = \frac{R_1 + R_2}{2}$$

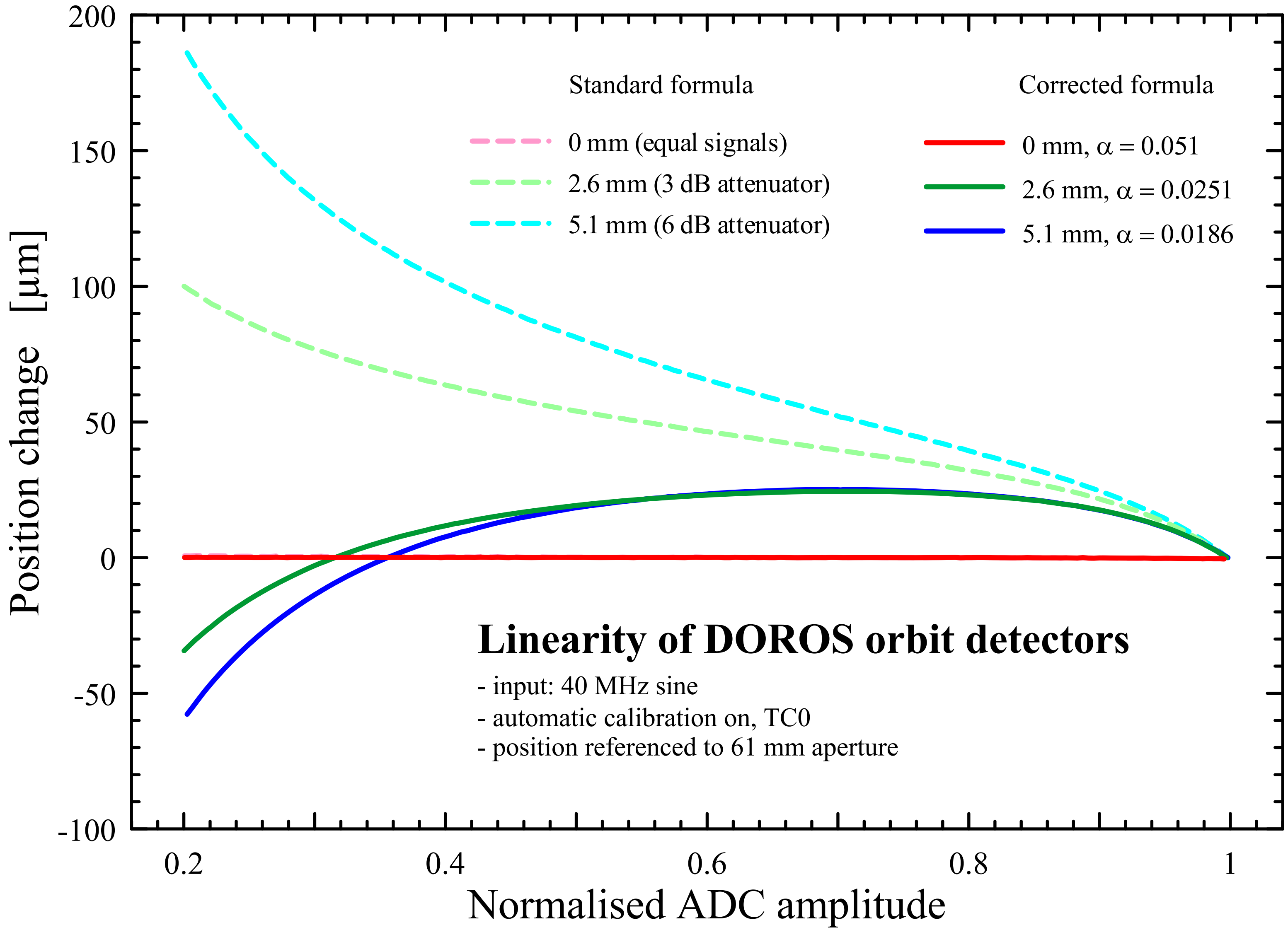
$$p_{Hc} = \frac{R_c - L_c}{R_c + L_c} = \frac{(g_A + g_B)(r - l)}{(g_A + g_B)(r + l) + \boxed{2(o_A + o_B)}} \cong \frac{r - l}{r + l}$$

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

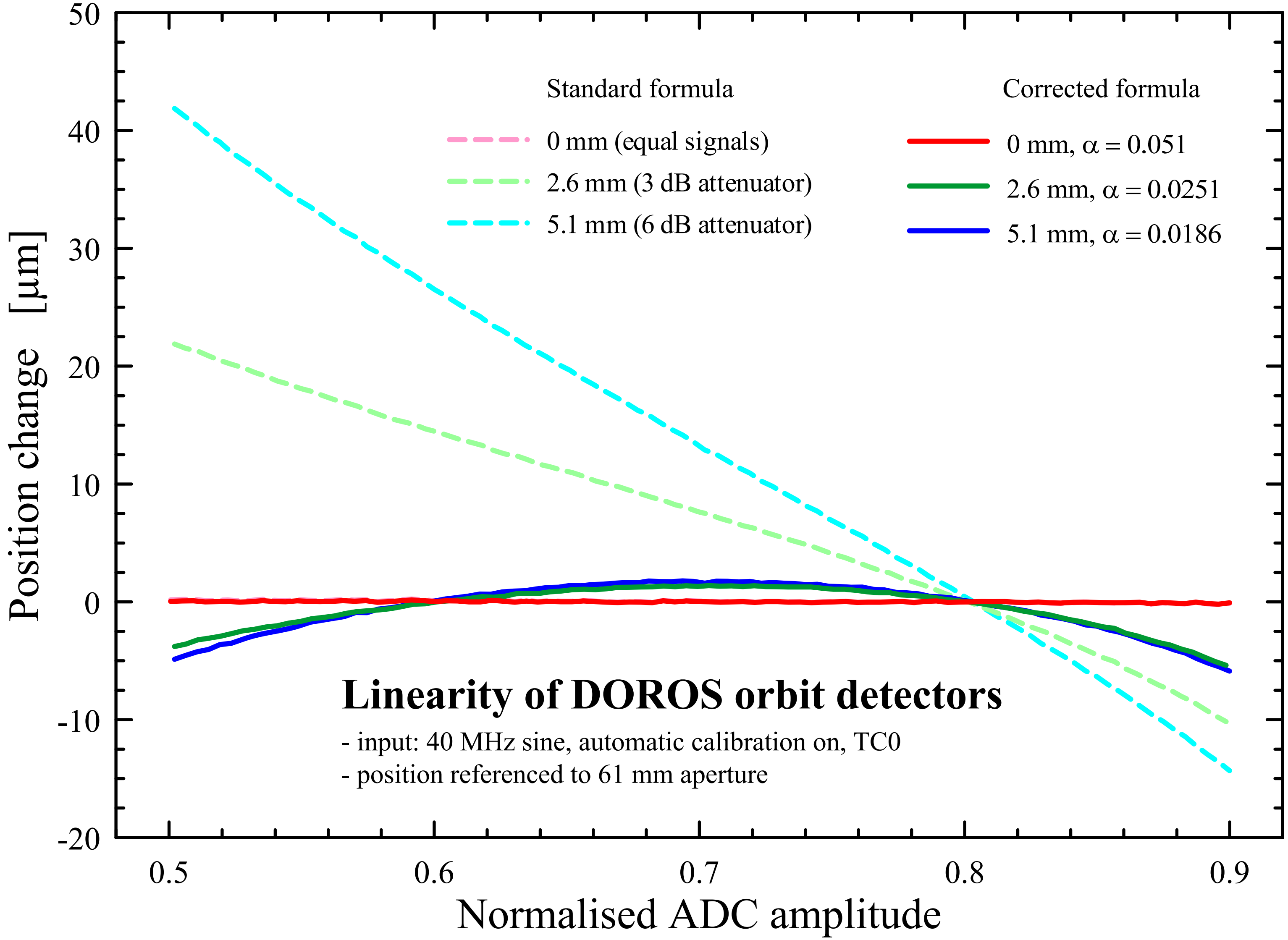
$$\text{for } \alpha = -2(o_A + o_B)$$

- The auto-calibration corrects the gain and the offset errors in the nominator.
- In the denominator only the gain errors are removed, the offset errors stay.
- It is proposed to compensate the “offset error” by a correction term *α*.
- The optimal *α* can be found by minimising the artificial position step induced by the input signal change (in practice caused by the gain change)

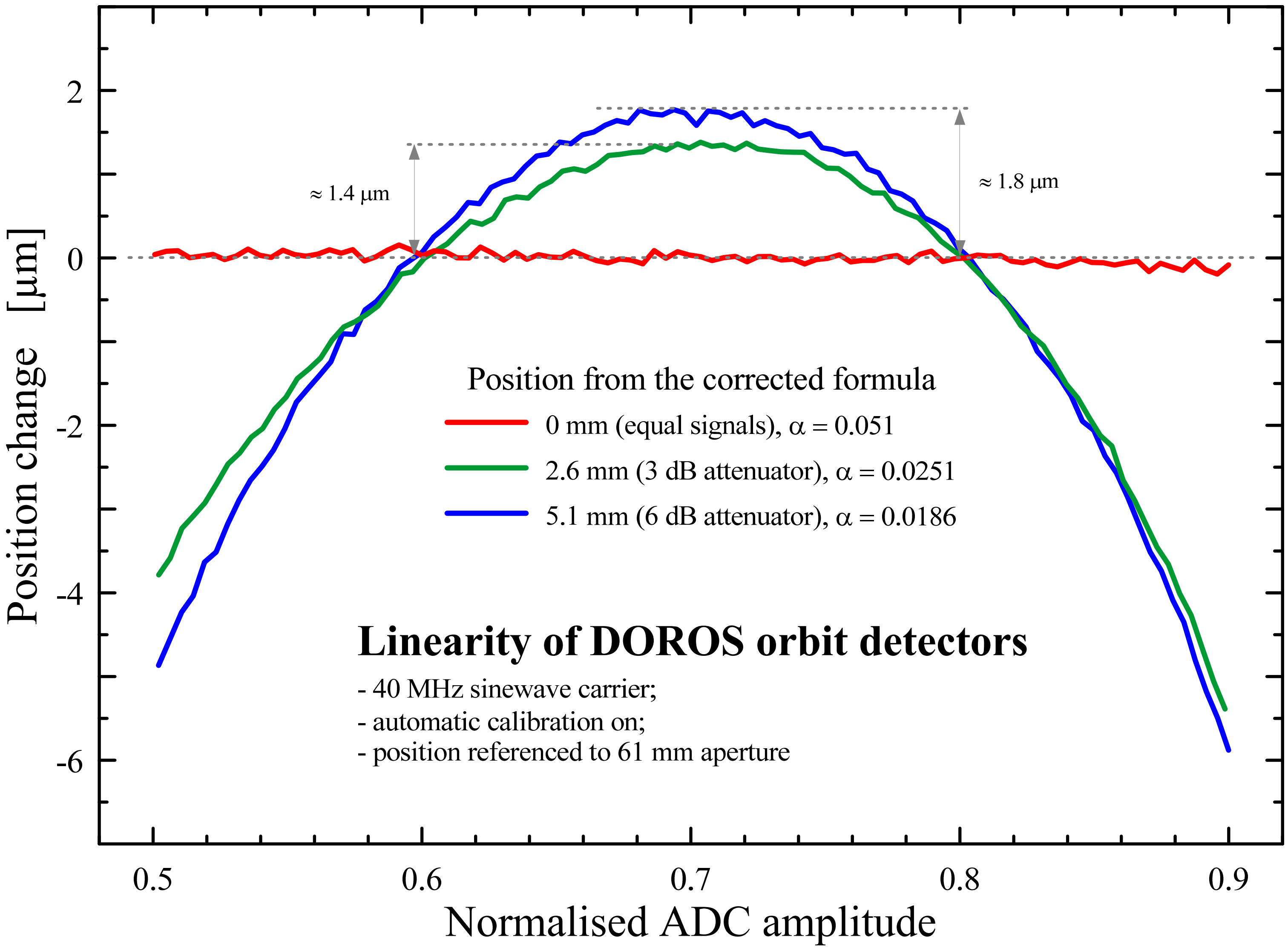
“Standard” linearity of the orbit diode detectors



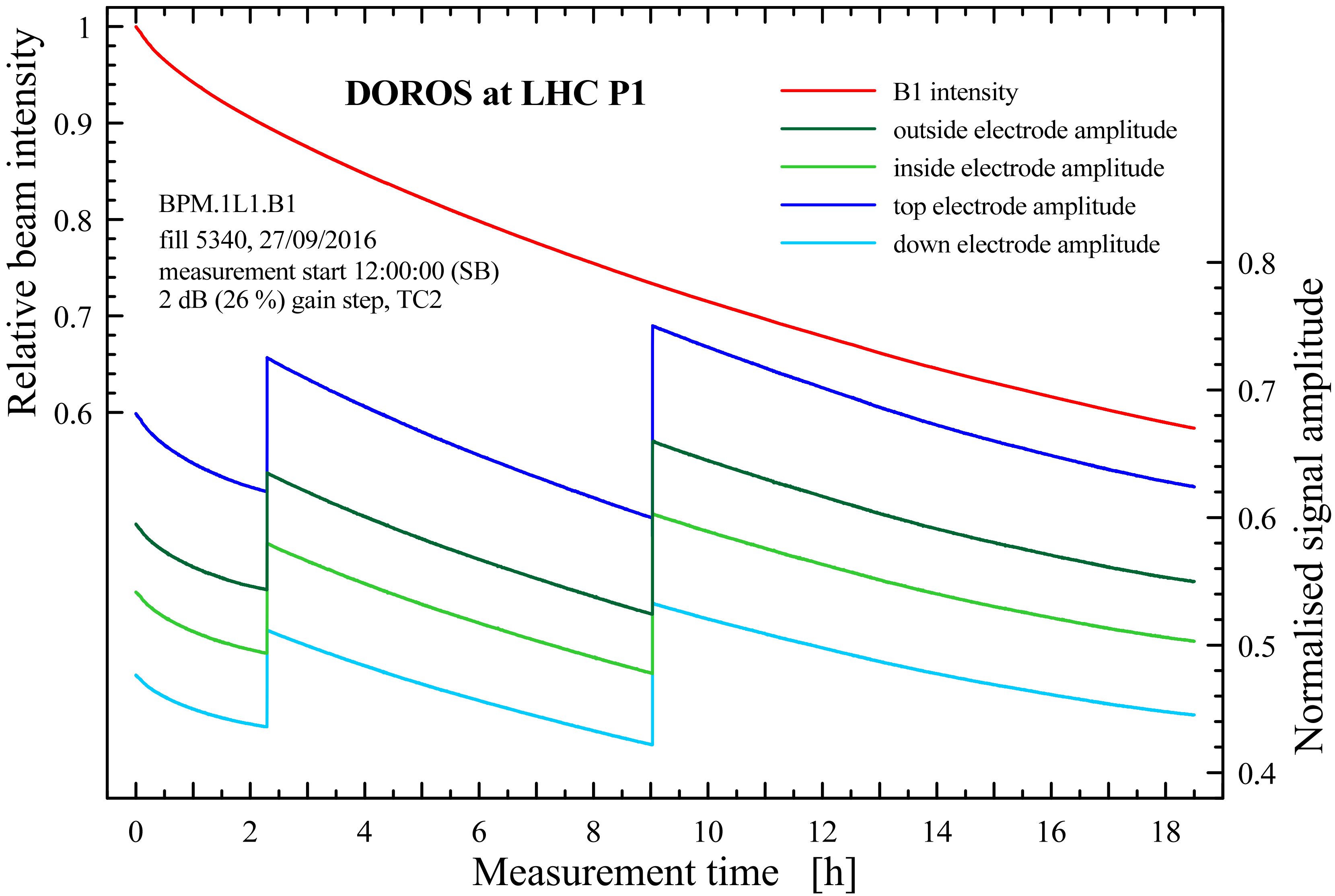
Improved linearity of the orbit diode detectors



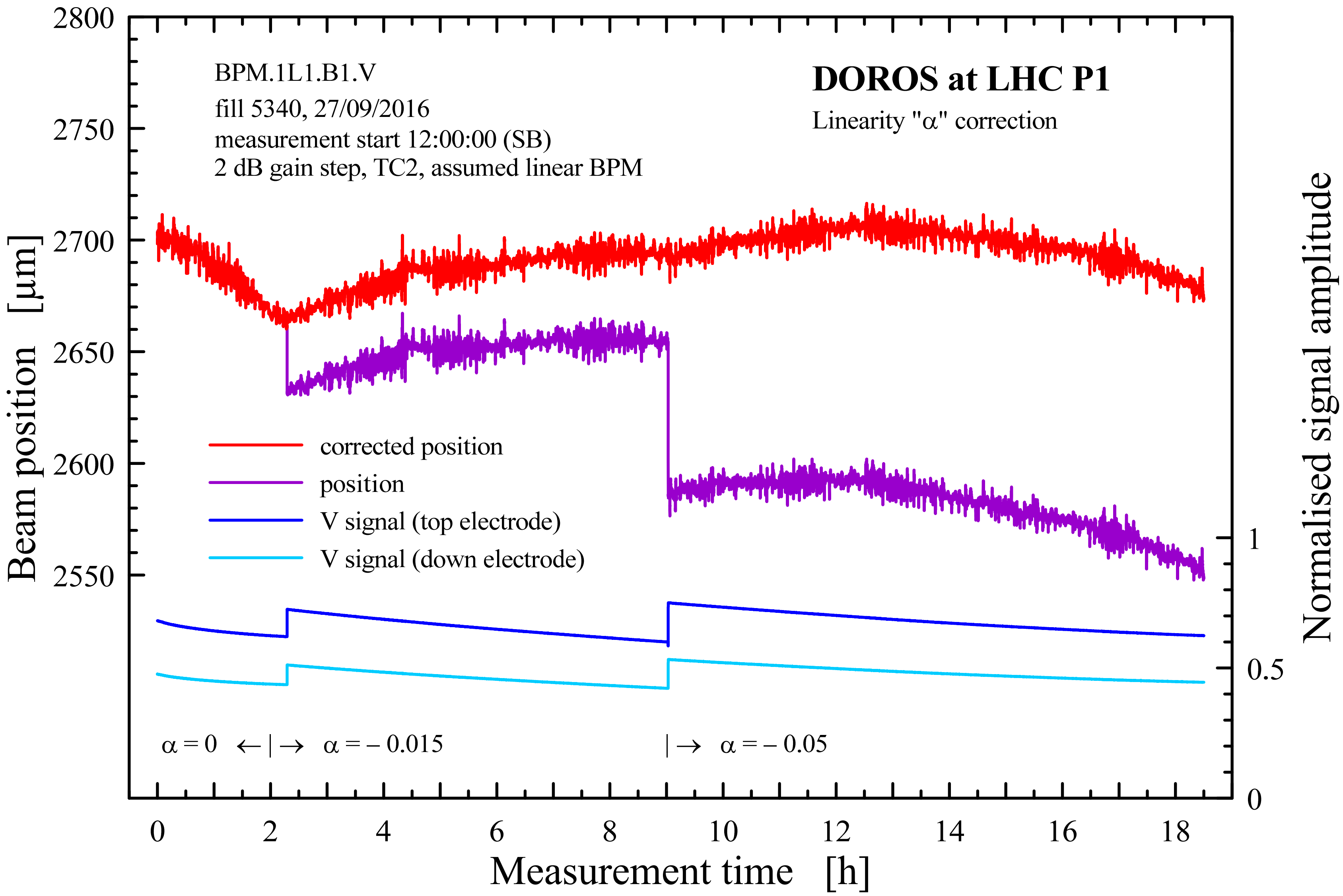
Improved linearity of the orbit diode detectors



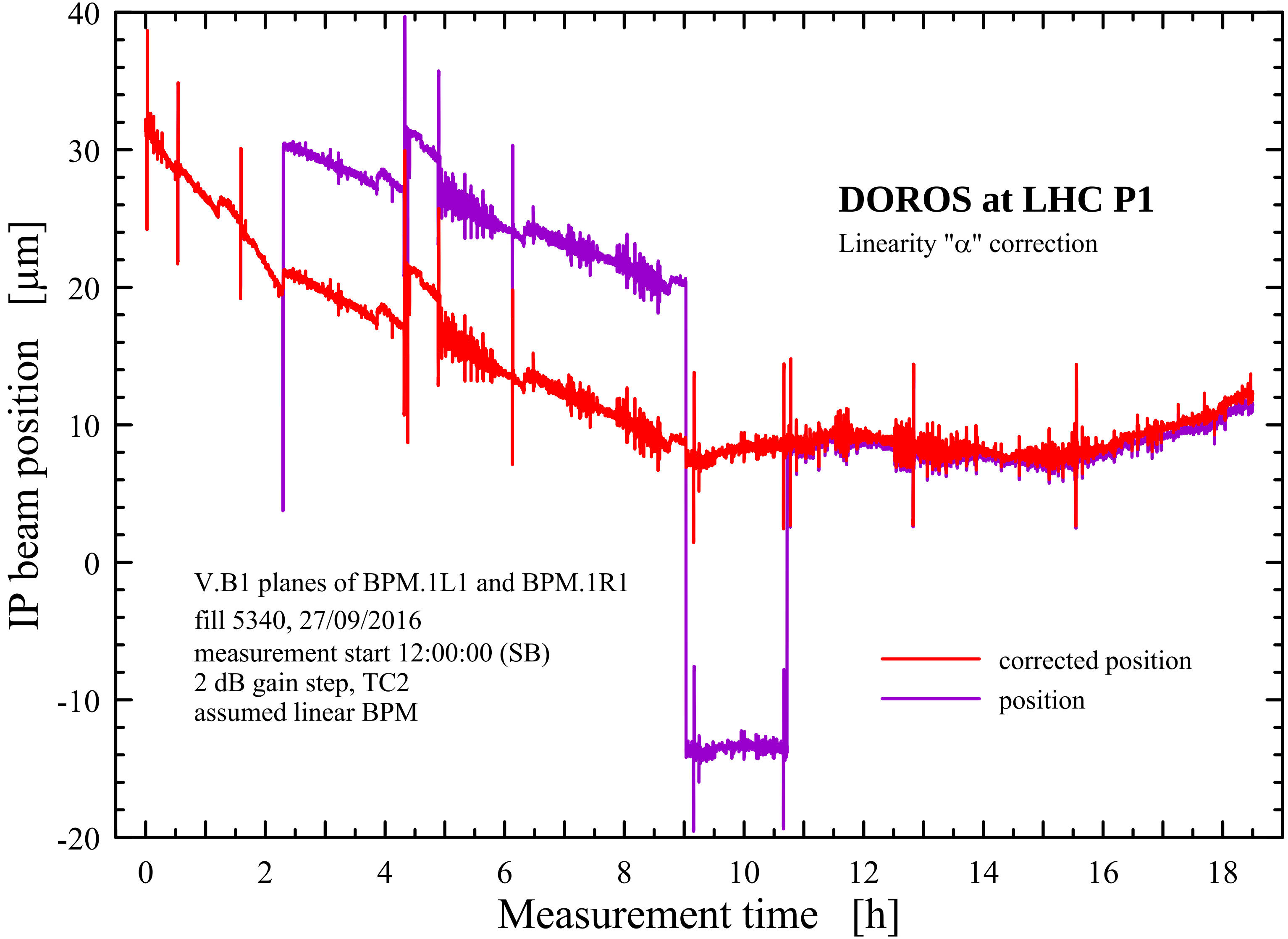
The automatic gain control during a long fill



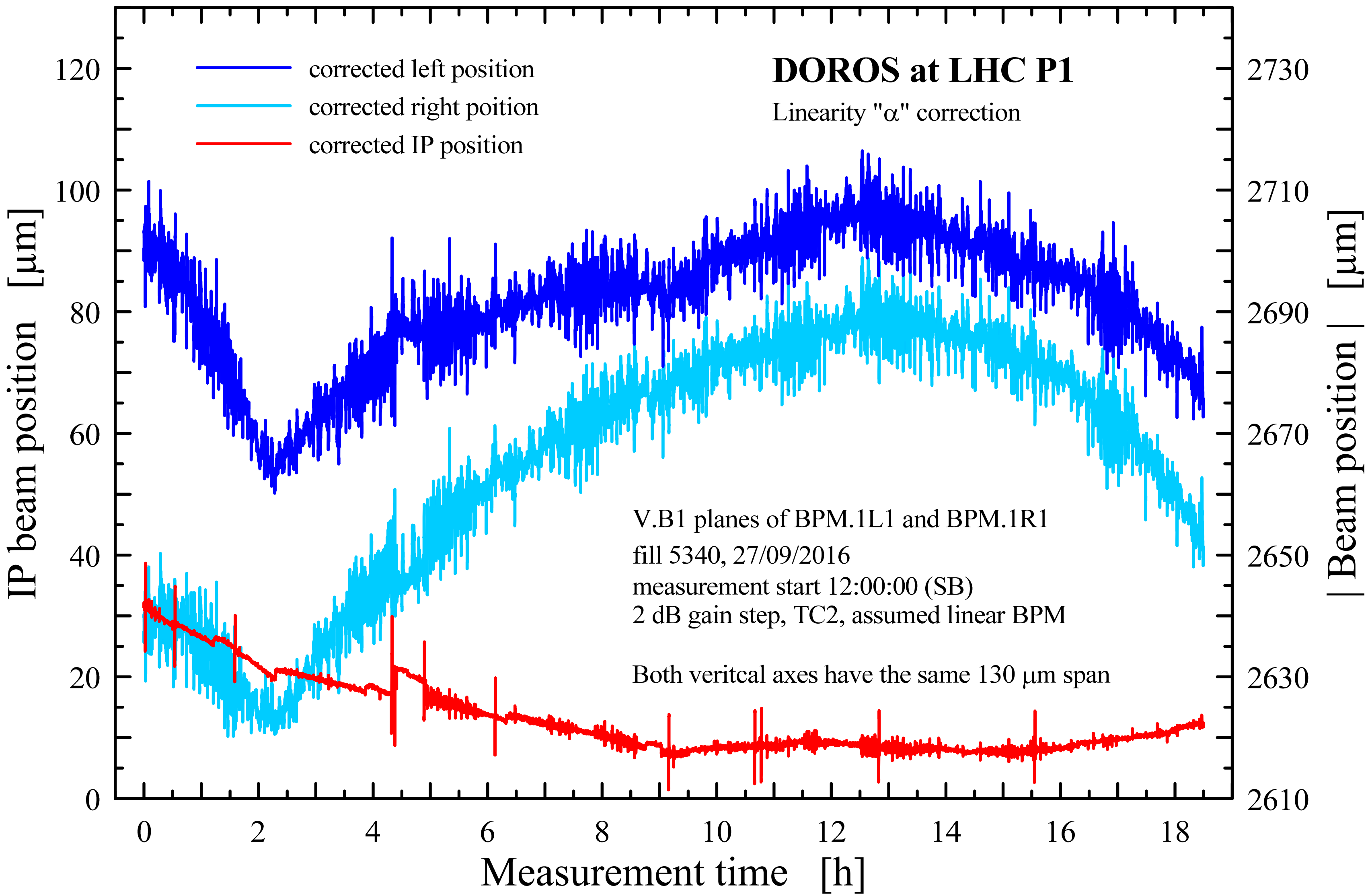
Linearity correction on the beam data (off-line)



Linearity correction on the beam data (off-line)



Linearity correction on the beam data (off-line)



Detector nonlinearity correction with gain switching

- The correction of the residual nonlinearity of the orbit detectors is based on changing the signal levels on the detectors by a short gain change. Before starting the nonlinearity correction the automatic gain control (AGC) loop operates normally and the signal levels are optimal. The auto-calibration works in a regular way.
  The nonlinearity correction procedure is the following:
  - The AGC is turned off. The electrode signals are measured, giving values A_1, B_1.
  - The gain is reduced by one step (1 dB). The electrode signals are measured, giving the values A_2, B_2.
  - The gain is increased by one step (1 dB) to return to the optimal signal levels on the orbit detectors.
  - The AGC is turned on.
- From the two measurements there are obtained two positions, including the required linearity correction α:

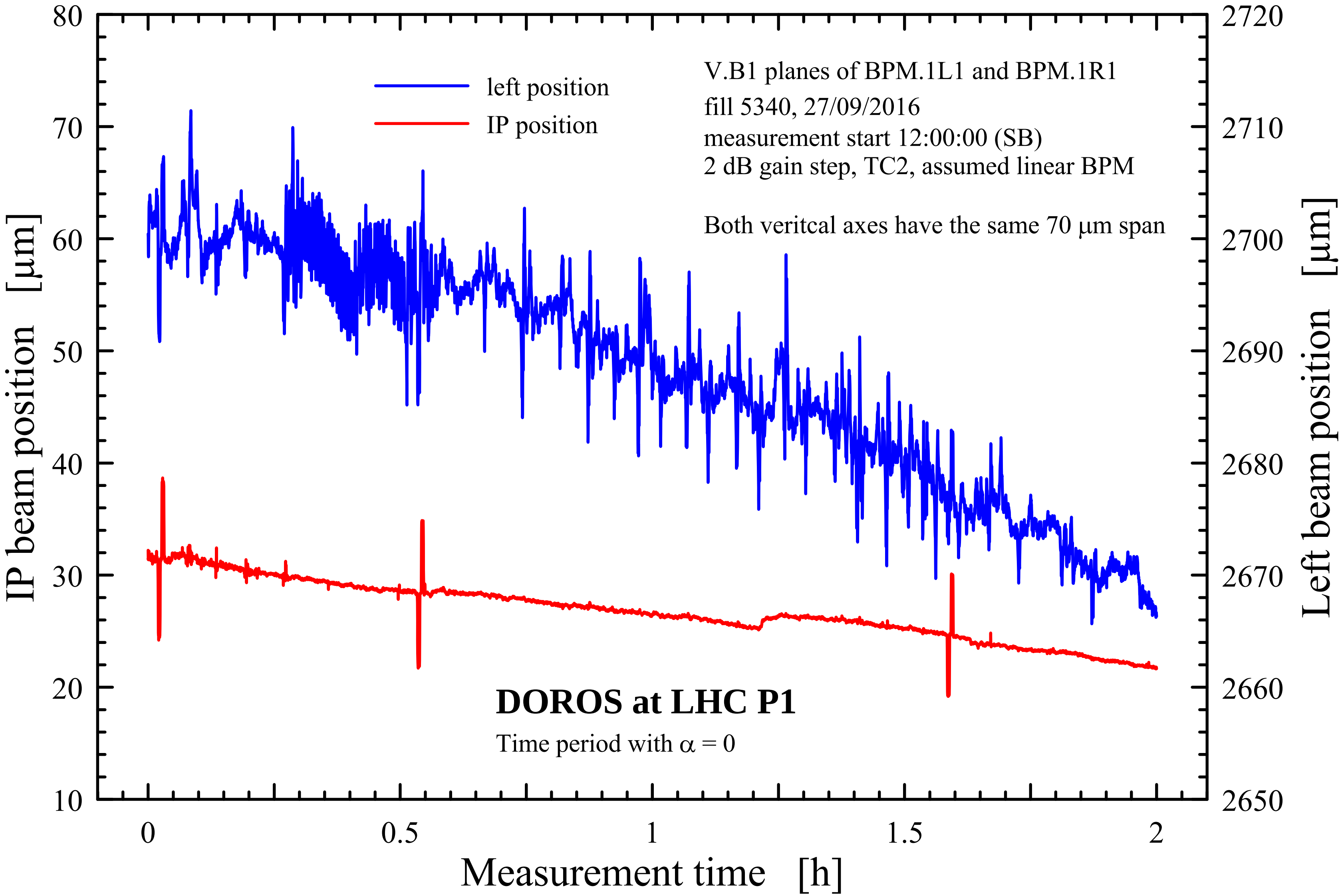
$$p_1 = \frac{A_1 - B_1}{A_1 + B_1 + \alpha} \qquad p_2 = \frac{A_2 - B_2}{A_2 + B_2 + \alpha}$$

- The beam position during the signal level change should stay unchanged, thus $p_1 = p_2$.This allows calculating α as

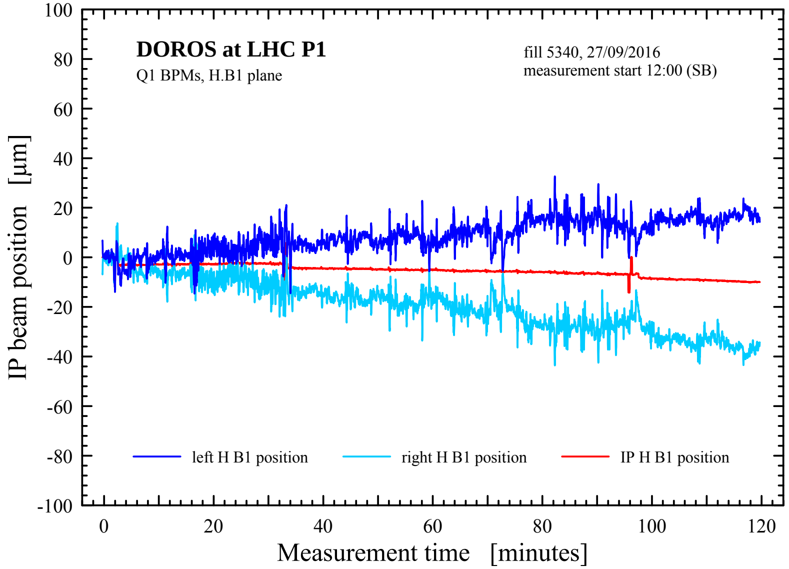
$$\alpha = 2\frac{A_2 B_1 - A_1 B_2}{A_1 - A_2 - \left(B_1 - B_2\right)}$$

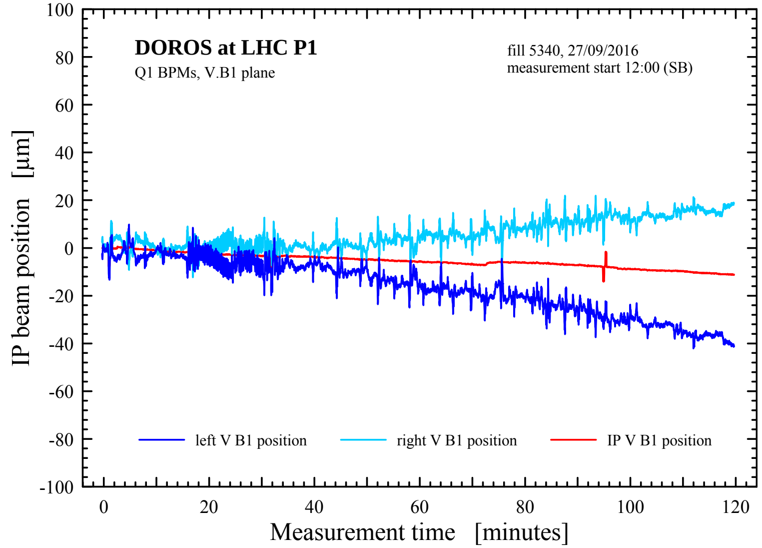
- The following orbit calculations are performed using the calculated parameter α.
- The procedure works only if the denominator is not too small. This requires that the changes of the signal levels on each detector should not be too similar. Thus the procedure works better for larger beam offsets, where the nonlinearity is an important issue.
- For fairly centred beams the procedure must not be used (e.g. a check of the denominator value).
  However, in such cases also the nonlinearity is less of a problem.

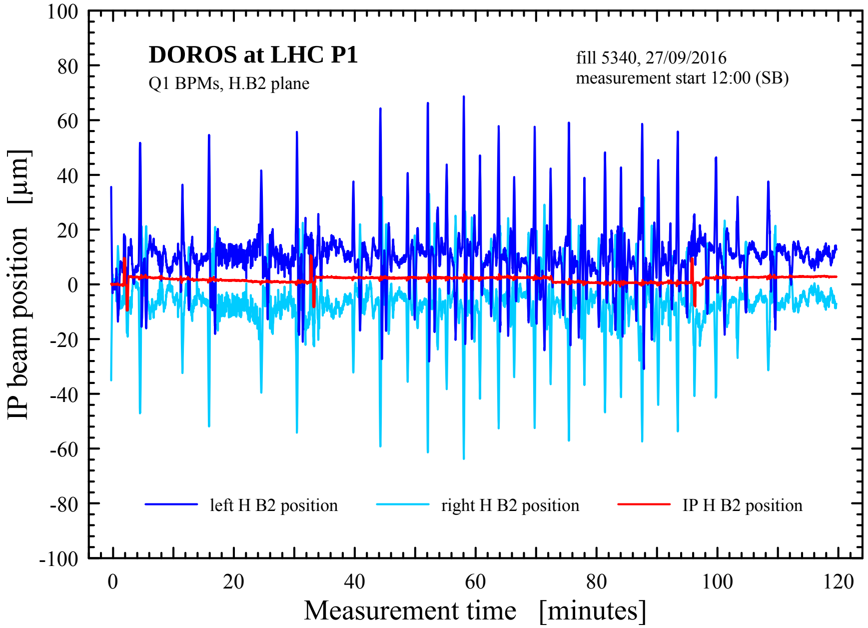
Beam position noise on the Q1 BPM and in the IP1

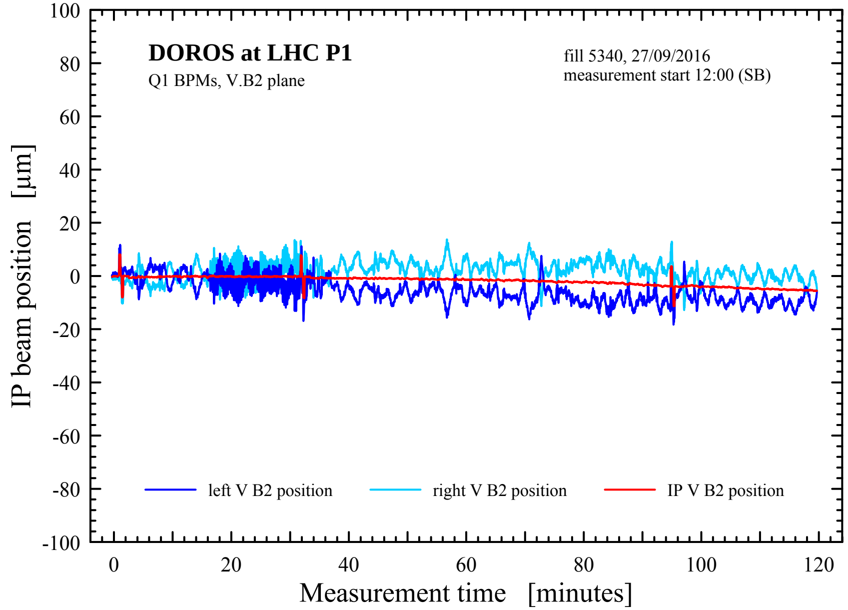


Beam orbit stability and noise

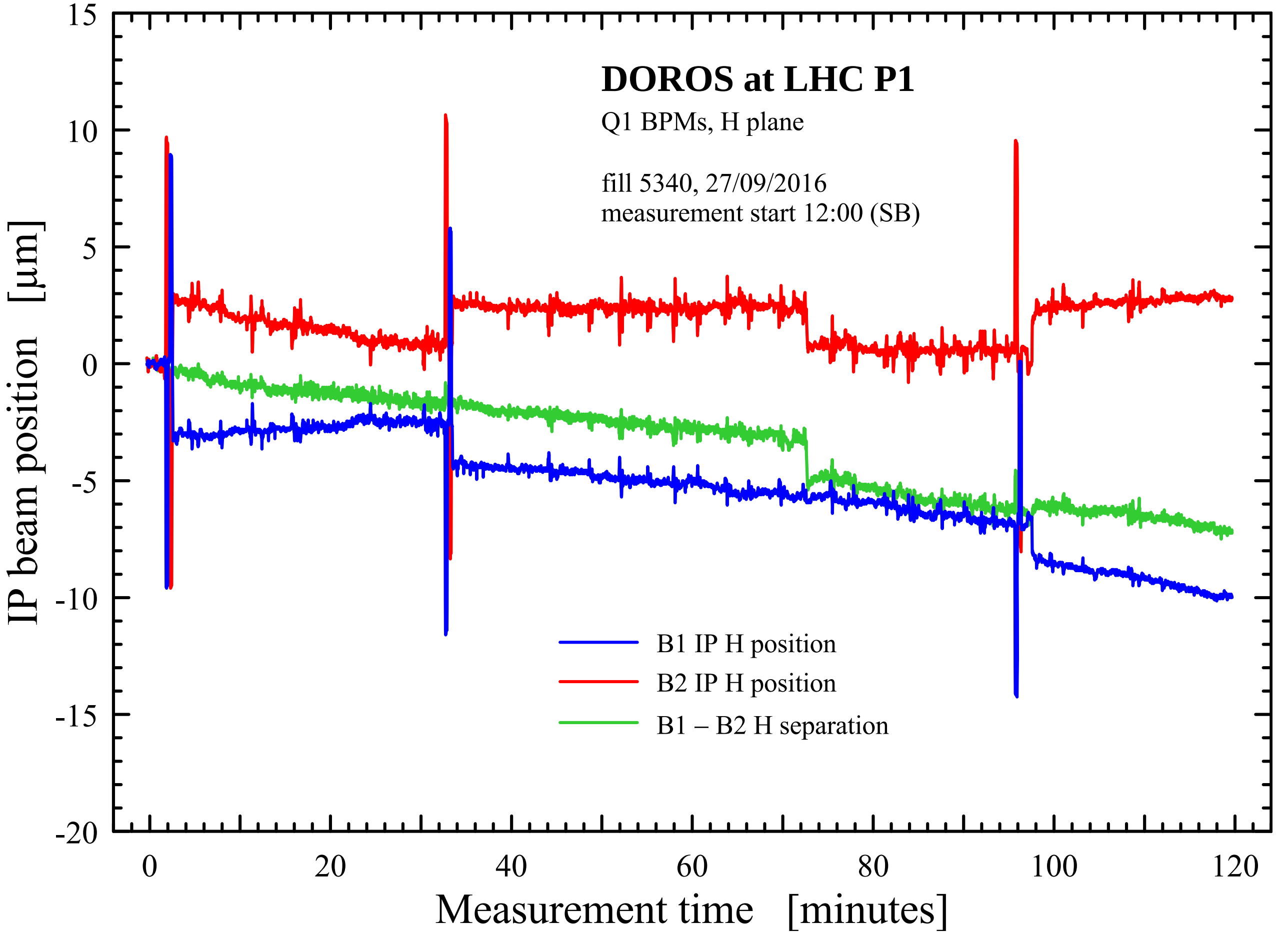




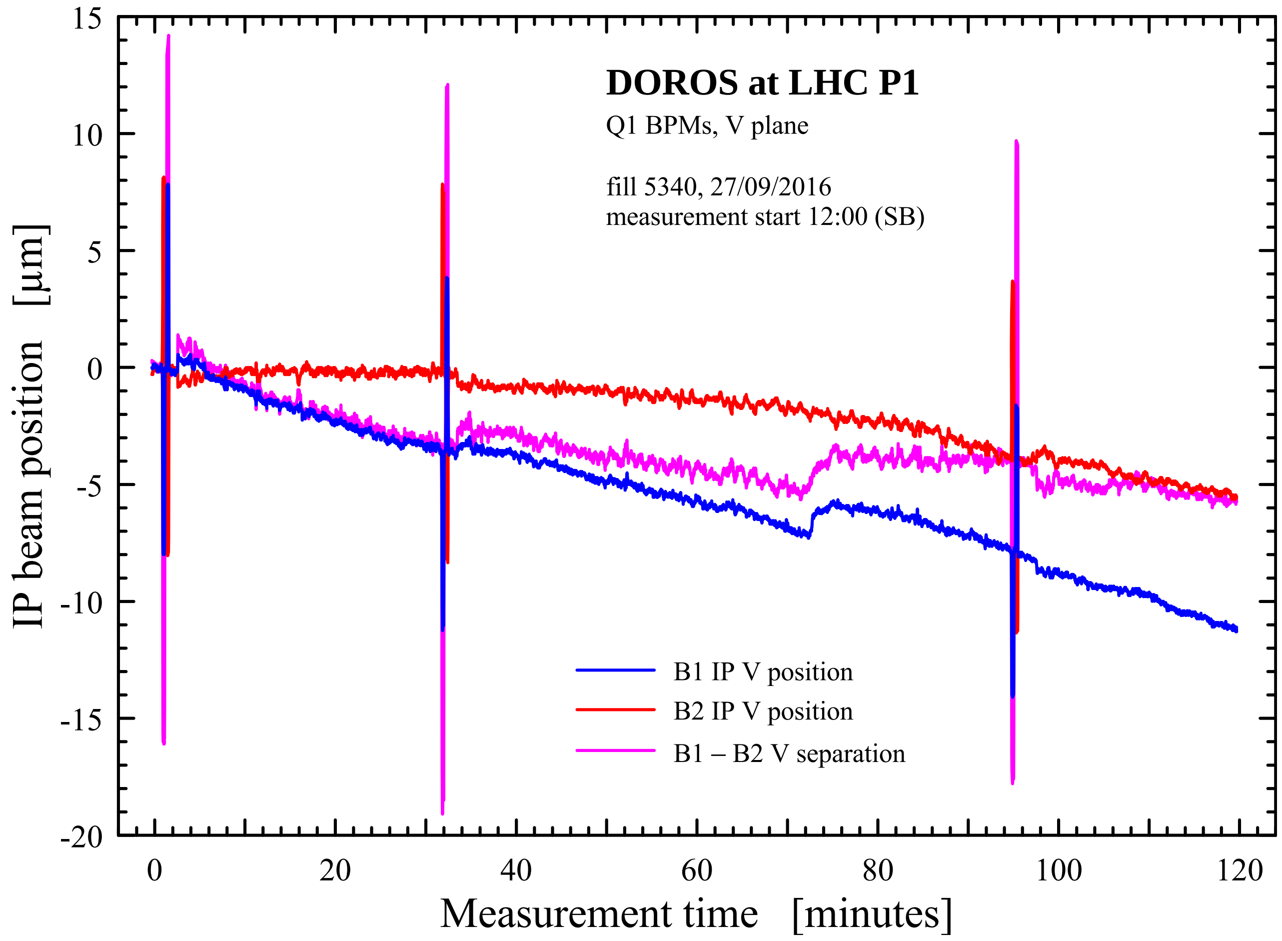


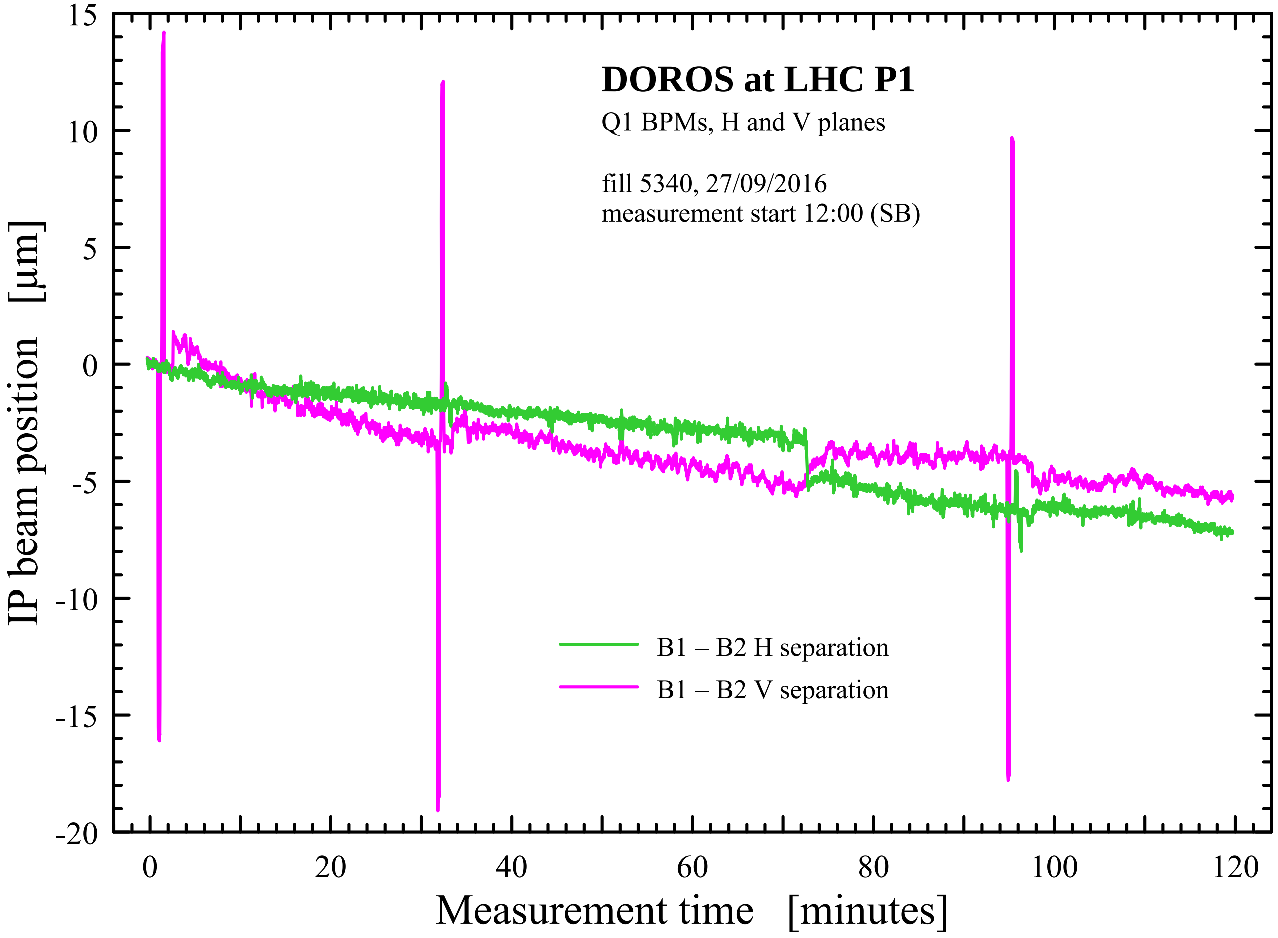


Beam orbit stability and noise

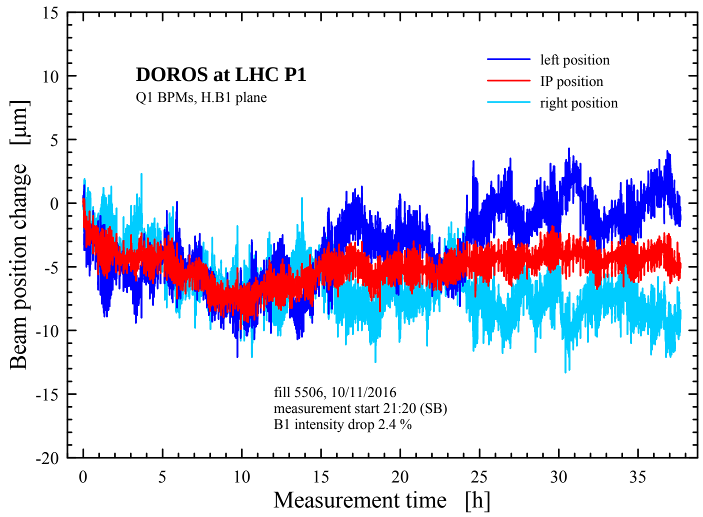


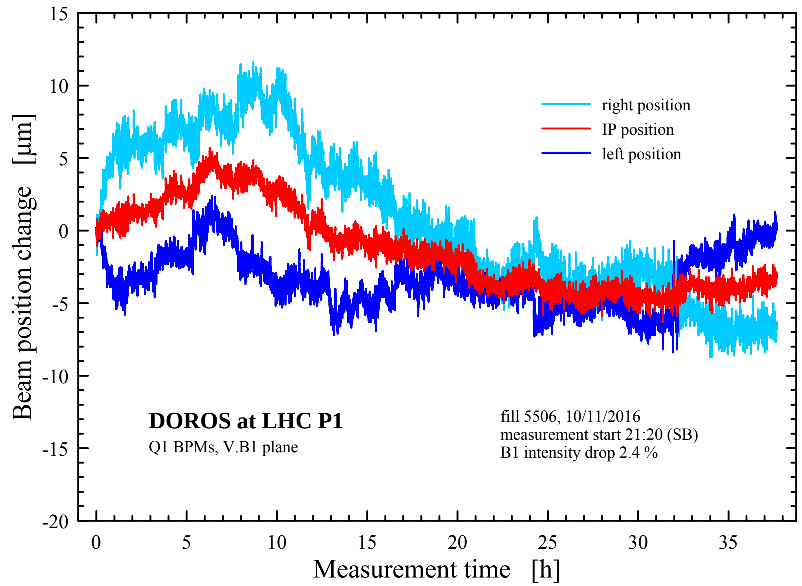
Beam orbit stability and noise

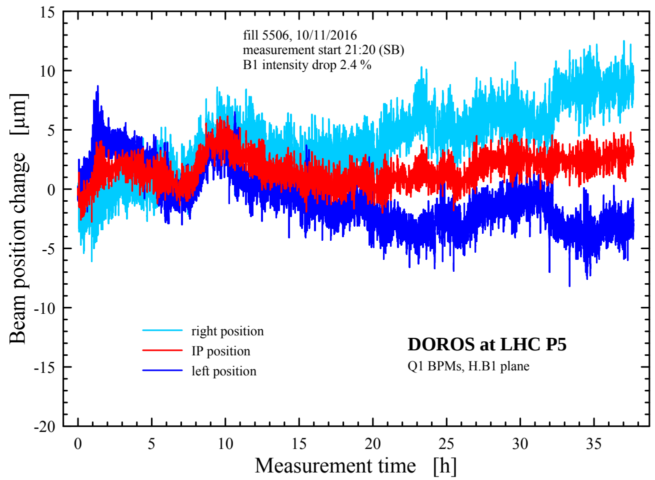


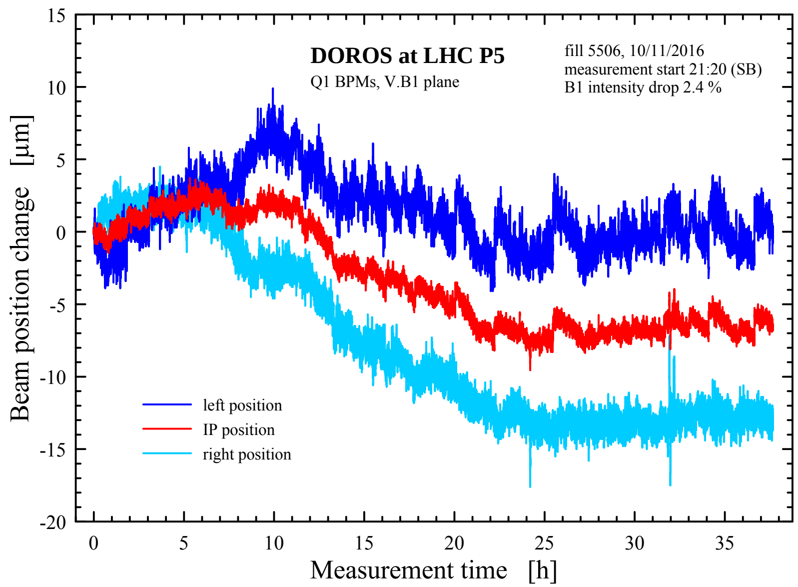

DOROS at LHC P1
Q1 BPMs, H and V planes
fill 5340, 27/09/2016
measurement start 12:00 (SB)
B1 – B2 H separation
B1 – B2 V separation
IP beam position [µm]
Measurement time [minutes]
15
10
5
0
-5
-10
-15
-20
0
20
40
60
80
100
120

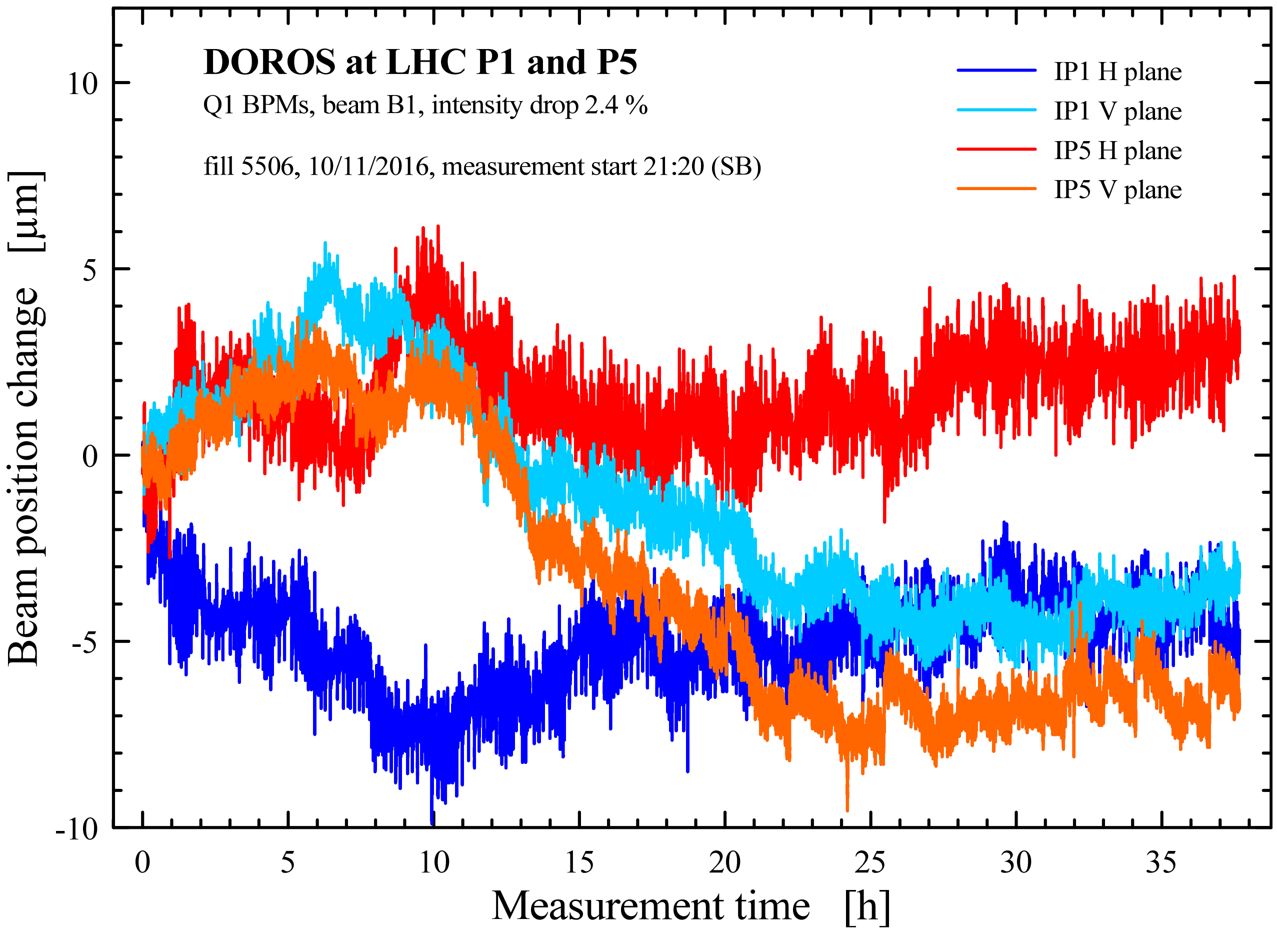
Stability with (almost) constant intensity





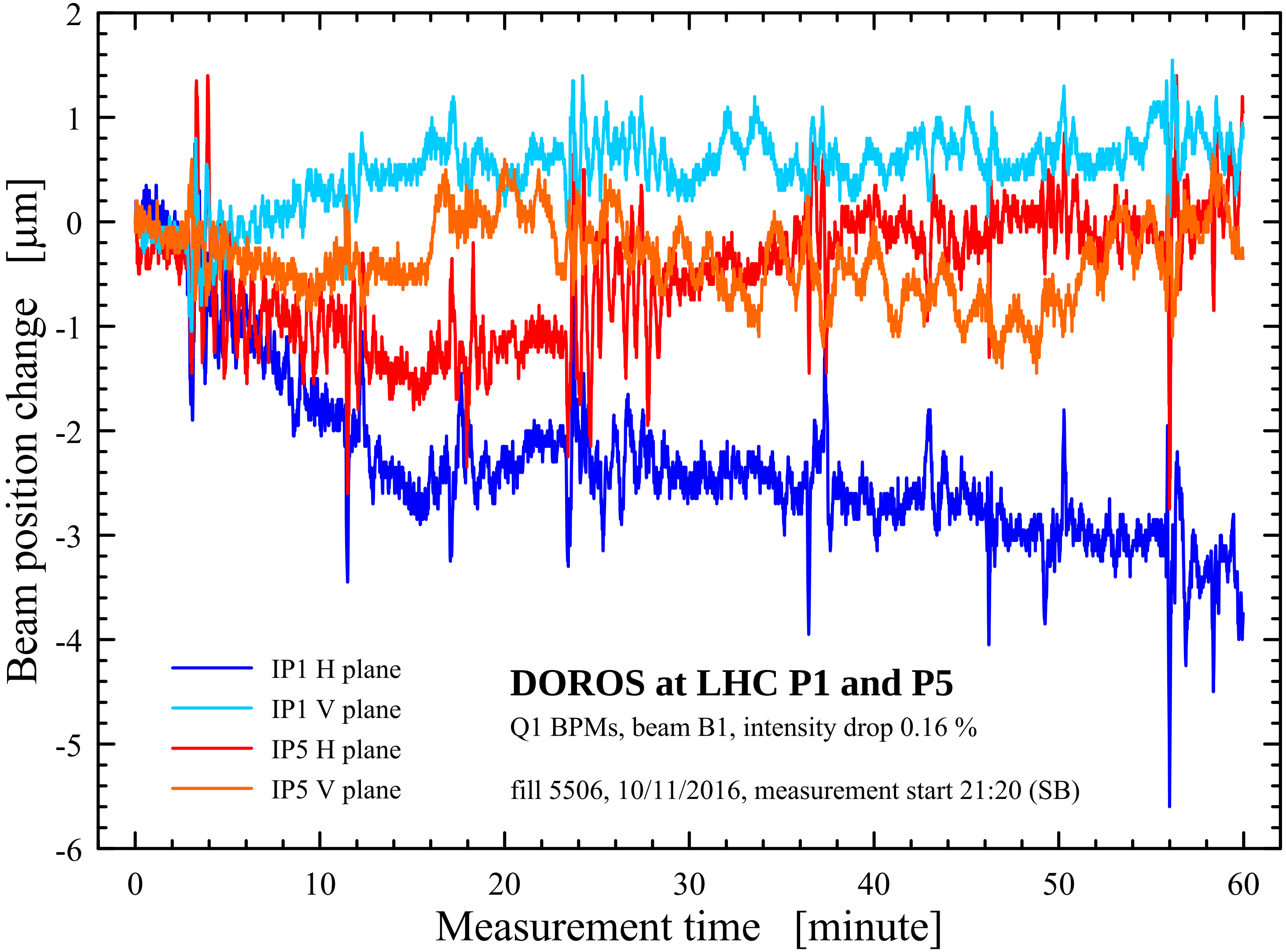




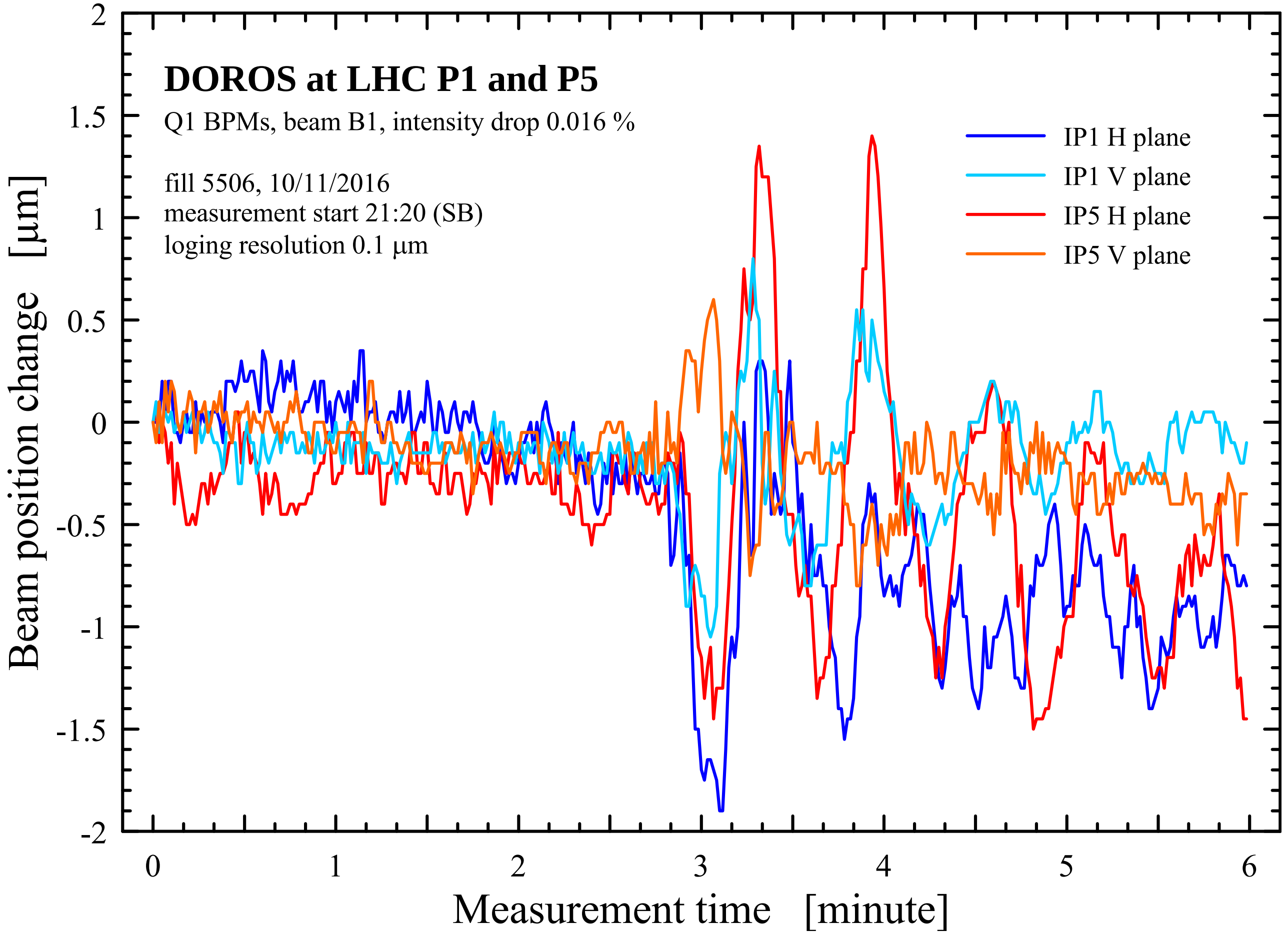


DOROS at LHC P1 and P5
Q1 BPMs, beam B1, intensity drop 2.4 %
fill 5506, 10/11/2016, measurement start 21:20 (SB)
IP1 H plane
IP1 V plane
IP5 H plane
IP5 V plane
Beam position change [µm]
Measurement time [h]
10
5
0
-5
-10
0
5
10
15
20
25
30
35

Stability with (almost) constant intensity



Stability with (almost) constant intensity



Plans for 2017: Collimator DOROS system

- **<u>New in 2017:</u>** Software interlocks on the orbit drifts in the collimator BPMs.
  Orbit measurement quality and reliability evaluated during 2016 run and considered as good for driving interlocks.
- Interlock settings proposed by the Machine Protection Team:
  - Dump if upstream and downstream BPM readings are out of tolerance for 6 s
  - If data on one BPM missing, no action, carry on with one BPM
  - If no data, dump after 60 s
  - If data coming, but with no valid orbits: dump after 60 s
- Work to be done before the interlocks are activated :
  - FESA: check compatibility with the 2017 FPGA code
  - FESA: Implementing FE parameter setting from scripts triggered by the LHC sequencer
  - FESA: Automatic reloading of the FE settings upon its startup (after power cut or self power cycle)
  - FESA: Handling of lost packets and gain switching
    (optimal orbit calculation with some missing data and masking invalid data)
- Work to be done during the year:
  - FESA readout of the hardware post-mortem buffers (**<u>new in 2017</u>**)
  - FESA handling of the “freeze mode” of the turn-by-turn buffers (**<u>new in 2017</u>**)
    These buffers could be frozen upon a post-mortem trigger to make available turn-by-turn orbit and oscillation data
- Studies on getting beam size from collimator scans
  - Very promising calculations, simulations and beam data analysis by Apostolos
  - MD beam measurements to be done in the 2017 run
- Supporting MDs for the BBLR project
- Purchasing critical components for DOROS production for “after LS2 collimator BPMs”.
  Current estimate: some 40 collimators (24 TSPM, 10 TCTPM, 5 TCLD), requiring some 40 DOROS FEs (including spares).

Plans for 2017: Standard BPM DOROS system

- The standard system will profit from the FPGA and FESA upgrades done for the collimator system (post-mortem buffers, freeze mode, scripts, exception handling, …)

- Studying with beam the linearity correction algorithm

- **New in 2017:** Increased bandwidth of the orbit detectors (by factor 10)
  - Work on smooth change of the operation mode: slow switching, fast switching, no switching. Test software algorithm in the lab and then implement in FESA.
  - Measure beam orbit spectra with increased bandwidth. Work on optimising this bandwidth (target: maximum without deteriorating the orbit measurement).

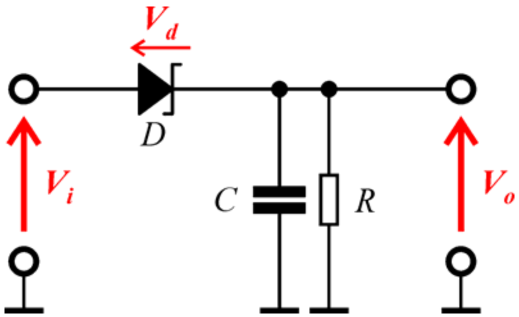
- Supporting MDs on:
  - Q1 stripline directivity
  - Optics measurement
  - Low frequency “beam vibration” measurements

- Attempting bunch gating (“à la BBQ“), at least in the lab. If time permits, installing one FE in P5 for beam tests.

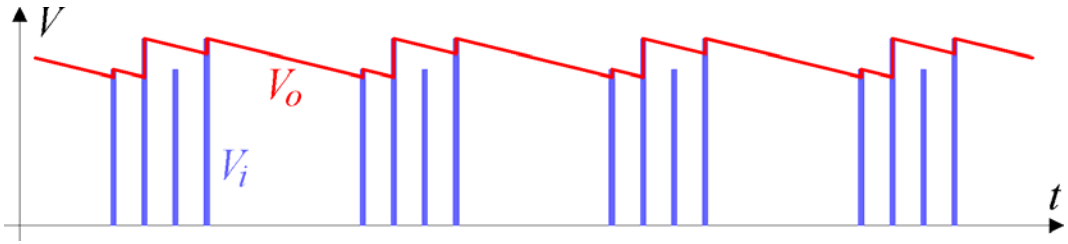
- SPS ALPS development:
  - Testing the analogue board (5 PCBs in production)
  - Continuing radiation testing of the components for the ADC board
  - Designing, producing and testing the ADC board

Spare slides

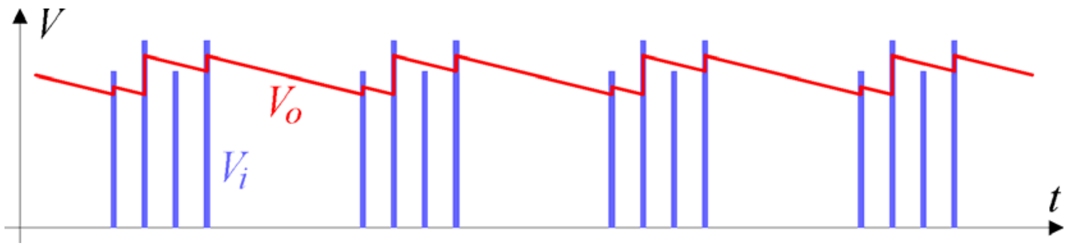
Why diode detectors ?



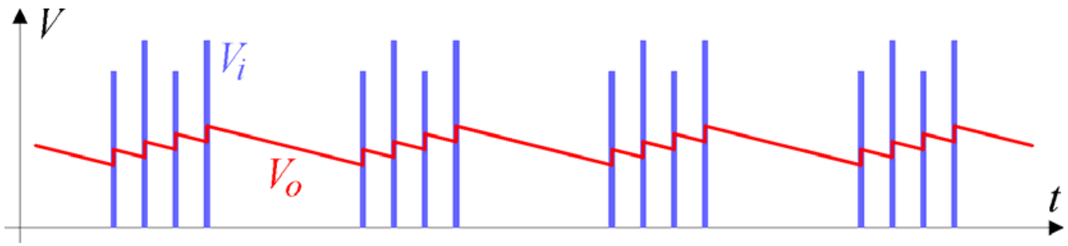
- Diode detectors can be used to convert fast beam pulses from a BPM into slowly varying signals, much easier to digitise with high resolution. In this way amplitudes of ns pulses can be measured with a lab voltmeter.
- As the diode forward voltage V_d depends on the diode current and temperature, the output voltage of a simple diode detector also depends on these factors.
- The detector output voltage can be proportional to the peak amplitude or an amplitude average of the input pulses.



Input (V_i) and output (V_o) voltages of a peak detector with an ideal diode

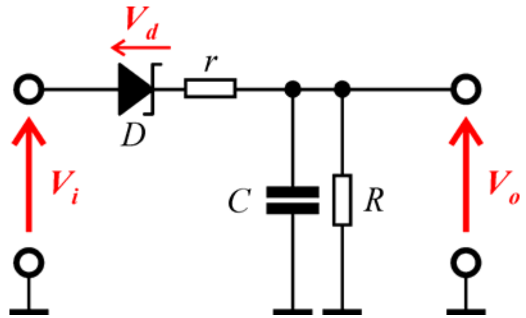


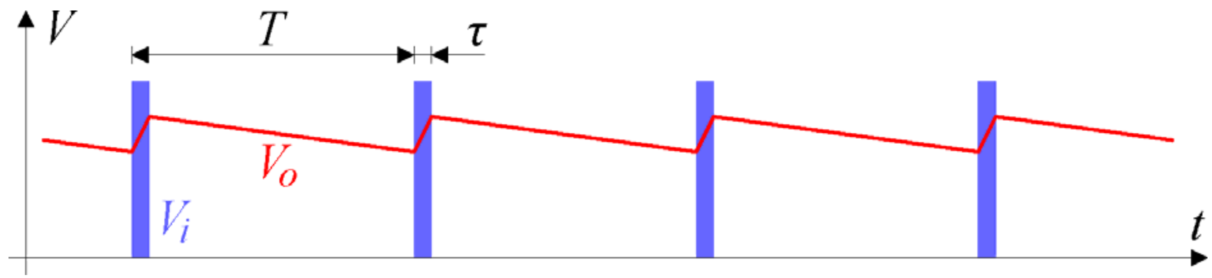
Input (V_i) and output (V_o) voltages of a peak detector with a real diode



Input (V_i) and output (V_o) voltages of an average-value detector

Simple diode detectors





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.

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

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

- $V_i >> V_d$
- *n* bunches

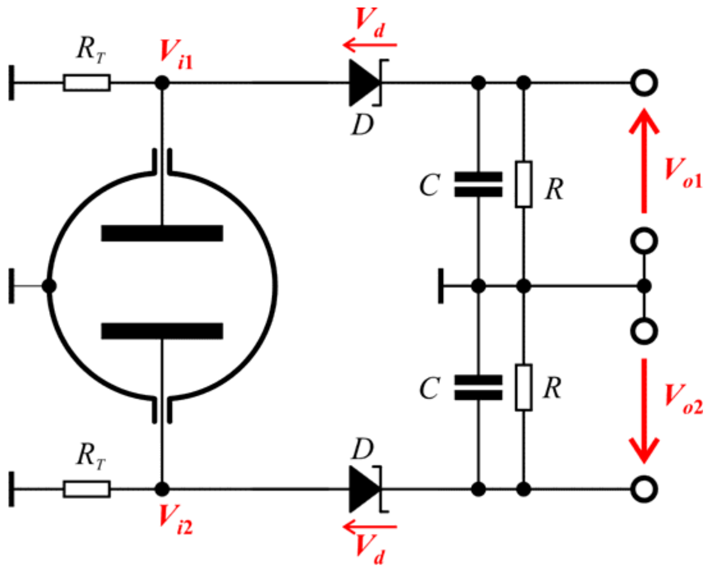
$$\frac{V_o}{V_i} = \frac{1}{1 + \frac{r}{R}\cdot\frac{T}{n\tau}}$$

A numerical example: LHC, one bunch.

For LHC $\tau \approx 1$ ns and $T \approx 89$ µs, so for $V_o \approx V_i$ one requires R/r $> T/\tau$.
Therefore, for $r \approx 100\ \Omega$, $R > 8.9$ MΩ.

- For large T to τ rations peak detectors require large R values and a high input impedance amplifier, typically a JFET-input operational amplifier.
- The slowest capacitor discharge is limited by the reverse leakage current of the diode (in the order of 10 nA for RF Schottky diodes).

Simple diode detectors for BPM signals



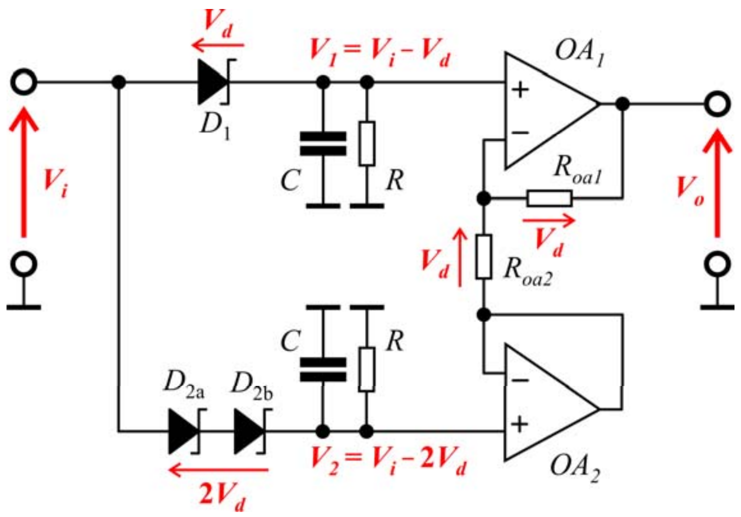
$$\text{ideal}: \quad p_{12} = c_{12} \frac{V_{i1} - V_{i2}}{V_{i1} + V_{i2}}$$

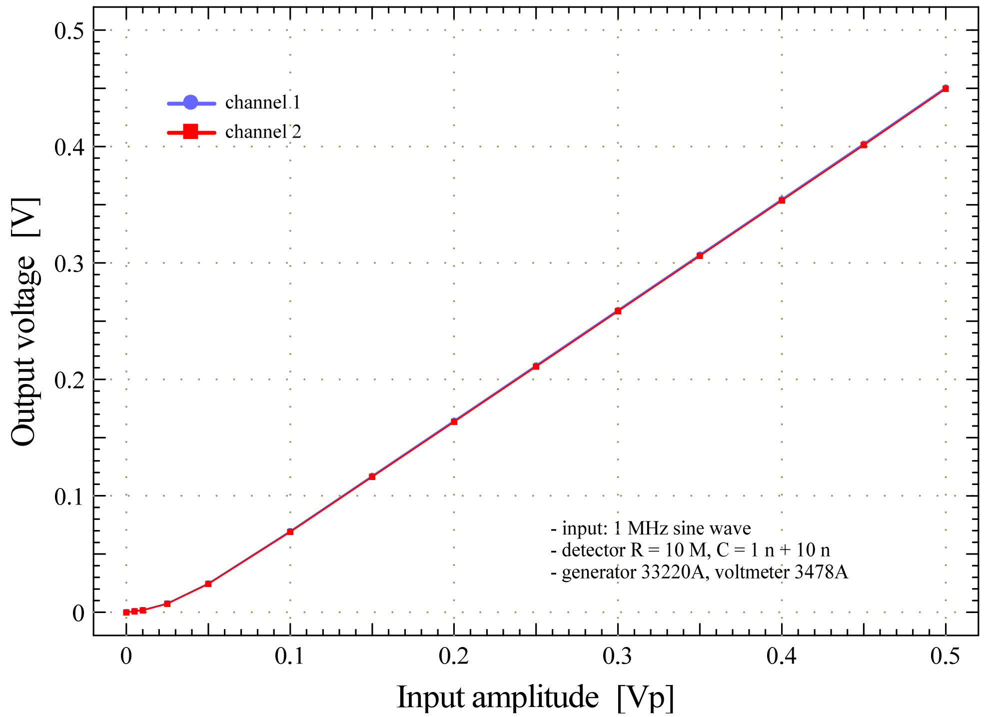
$$\text{real}: \quad p_{12} = c_{12} \frac{V_{o1} - V_{o2}}{V_{o1} + V_{o2}} = c_{12} \frac{V_{i1} - V_{i2}}{V_{i1} + V_{i2} - 2V_d}$$

- One diode detector for each BPM electrode.
- Subtracting signals before the detectors (e.g. by a 180° hybrid) is no good, as the resulting signals would be:
  - smaller (→ larger nonlinearities);
  - changing signs when crossing the BPM centre.
- The diode forward voltage V_d introduces a significant position error.
- V_d depends on the diode current and temperature.
- Simple diode detectors are good for applications when the signal amplitude is not that important.

- Two examples:
  - Tune measurement systems
  - An LHC safety system: Beam Presence Flag

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.
- This is the simpler and most promising scheme, found in a very popular text book on electronics.
- To get an “ultimate peak mode operation”, the discharge resistors can be omitted. In this case the discharge is done by the reverse leakage current of the diodes.
- The asymmetry in the charging conditions becomes less important for larger input voltages.