DOROS – a new system for LHC beam position measurements

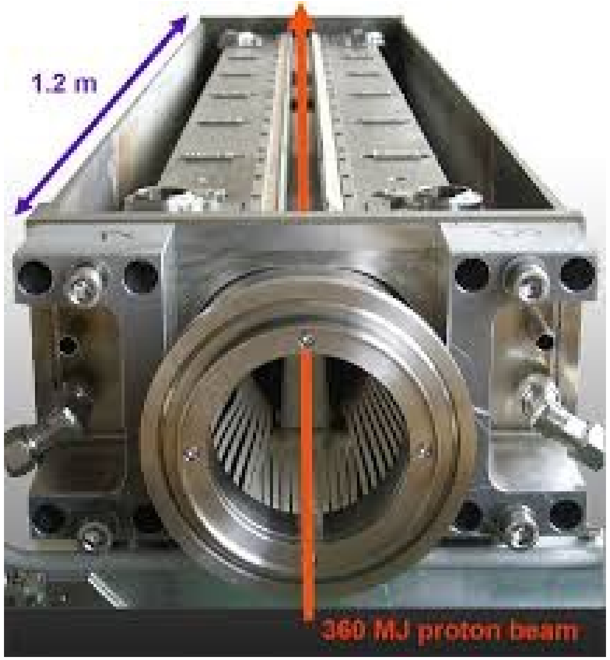
Jakub Olexa

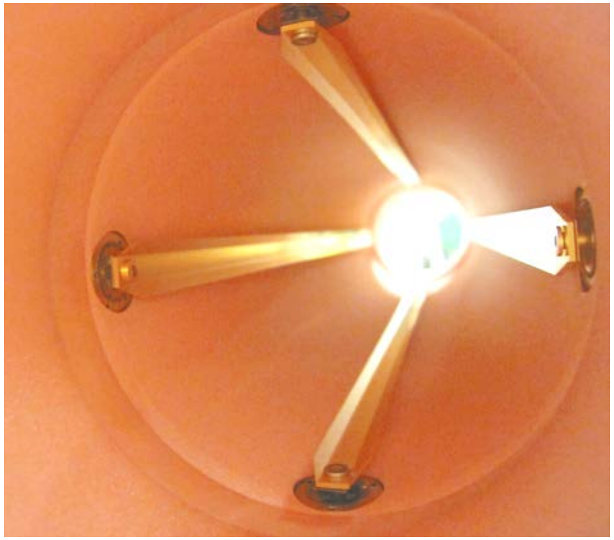
for the BI DOROS team (G. Baud, M. Gasior, J. Olexa)

- Motivation
- Principle
- Hardware
- Measurements and results
- Conclusions

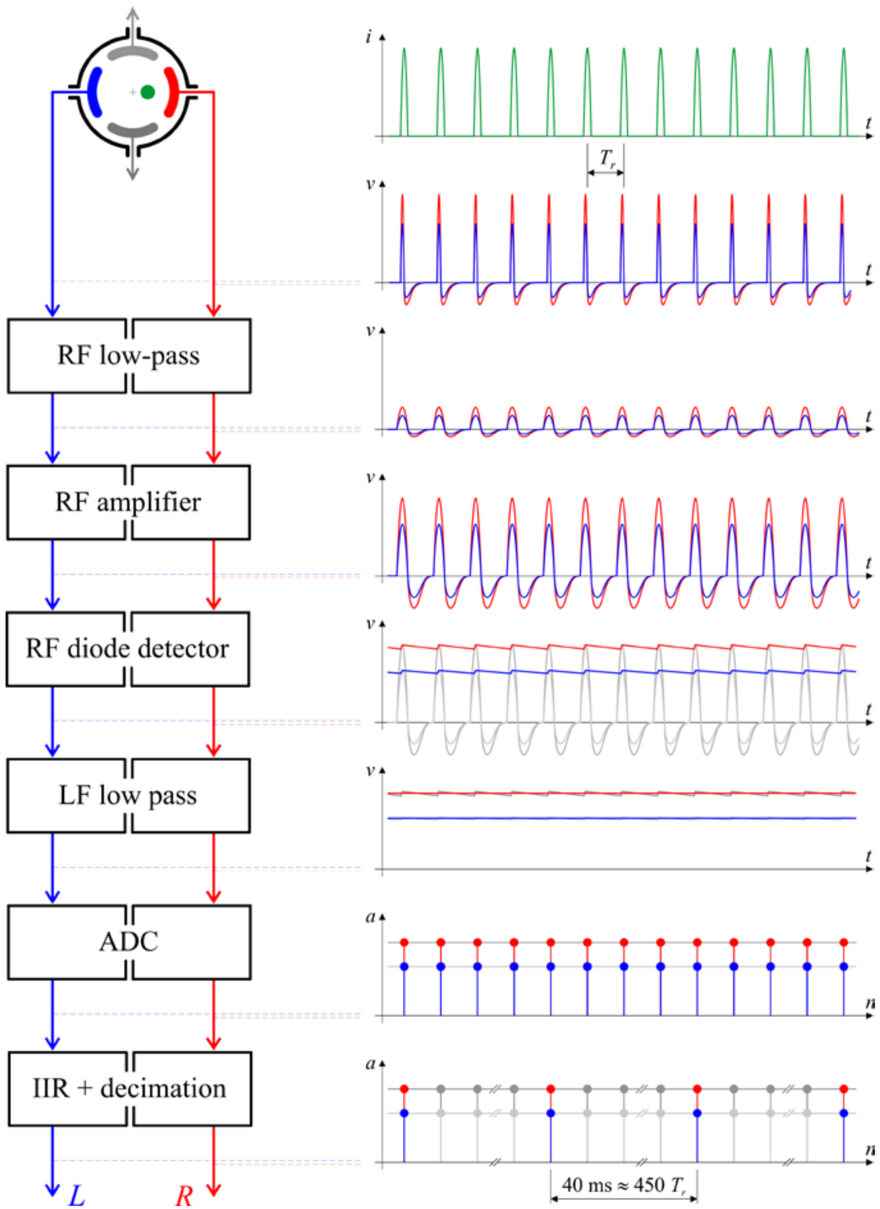
Motivation and DOROS origins

- New generation of LHC collimators installed during LS1:
  - Beam Position Monitors (BPM) integrated in the jaws
  - Allowing fast and precise jaw alignment
- New requirements for BPM electronics:
  - Very precise beam orbit measurement, but only for small beam offsets
  - Slow measurements sufficient for slow jaw motion
  - Potential usage for orbit interlocks, so robustness, reliability and simplicity are highly welcome
- DOROS = Diode ORbit (DOR) and OScillation (DOS)
- New electronics based on a novel technique of compensated diode detectors optimised for precise and reliable orbit measurements
- DOROS strengths:
  - Sub-micrometre orbit resolution and micrometre long-term stability
  - Simplicity and robustness
  - Precise timing not needed for orbit measurements
- DOROS weaknesses:
  - One orbit for all bunches
- Early measurements showed that the technique can be also quite interesting for regular BPMs, even with larger beam offsets
- Finally DOROS used with standard BPMs in the most critical locations (e.g. next to the experiments)





Diode ORbit processing



- Short pick-up pulses undergo low-pass filtering to limit their slew rate and reduce peak amplitude
- 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 reduce 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:

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

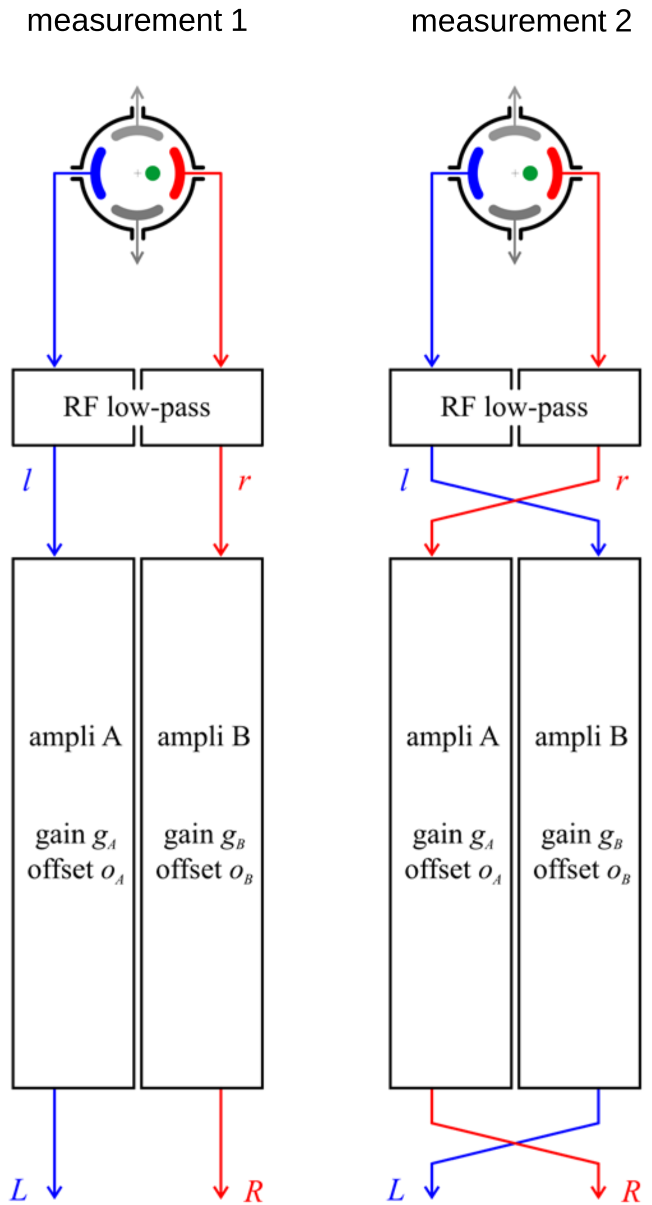
- Absolute beam positions in mm with simplest linear approximation:

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

- Absolute beam positions in mm:

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

Orbit auto-calibration



meas. 1:

$$L_1 = g_A\, l + o_A$$
$$R_1 = g_B\, r + o_B$$

meas. 2:

$$L_2 = g_B\, l + o_B$$
$$R_2 = g_A\, r + o_A$$

meas. 1 + 2:

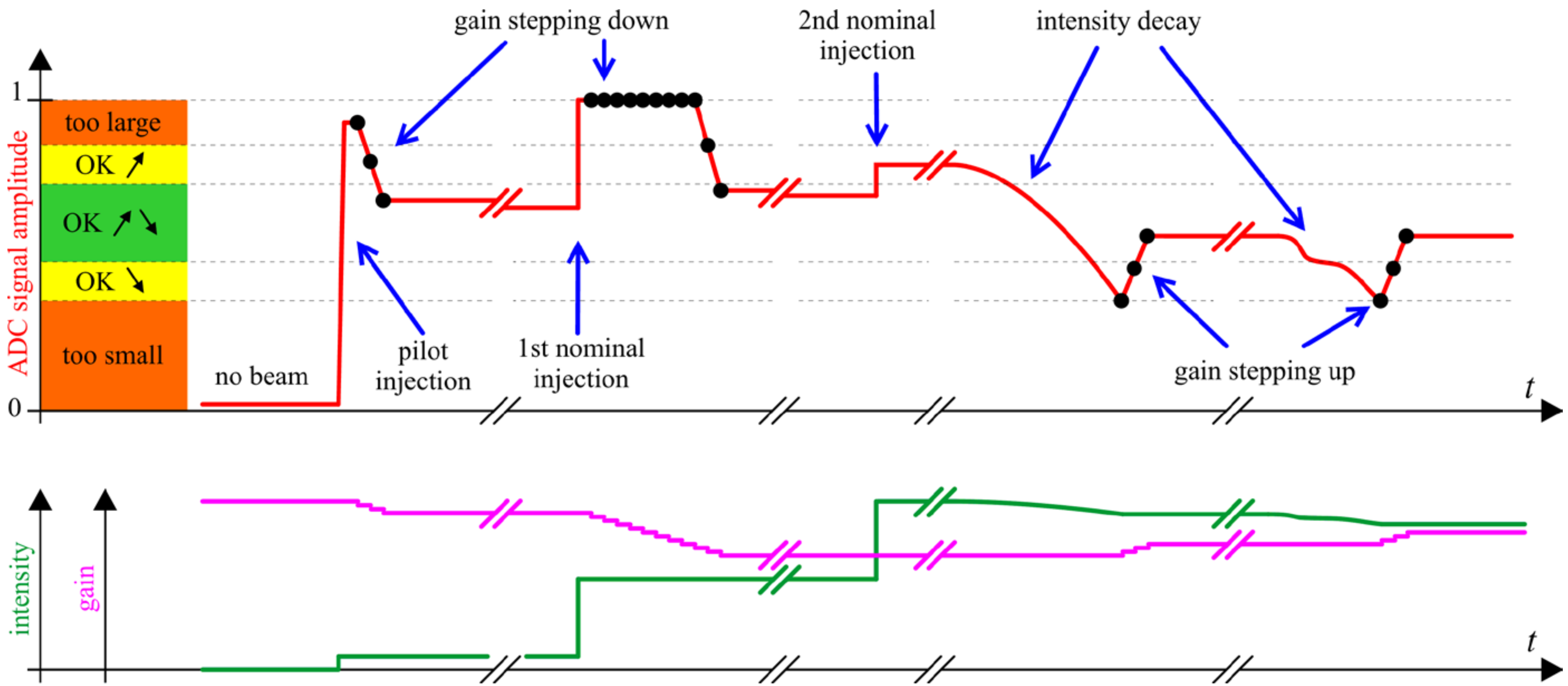
$$L_c = \frac{L_1 + L_2}{2}$$
$$R_c = \frac{R_1 + R_2}{2}$$

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

- 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):

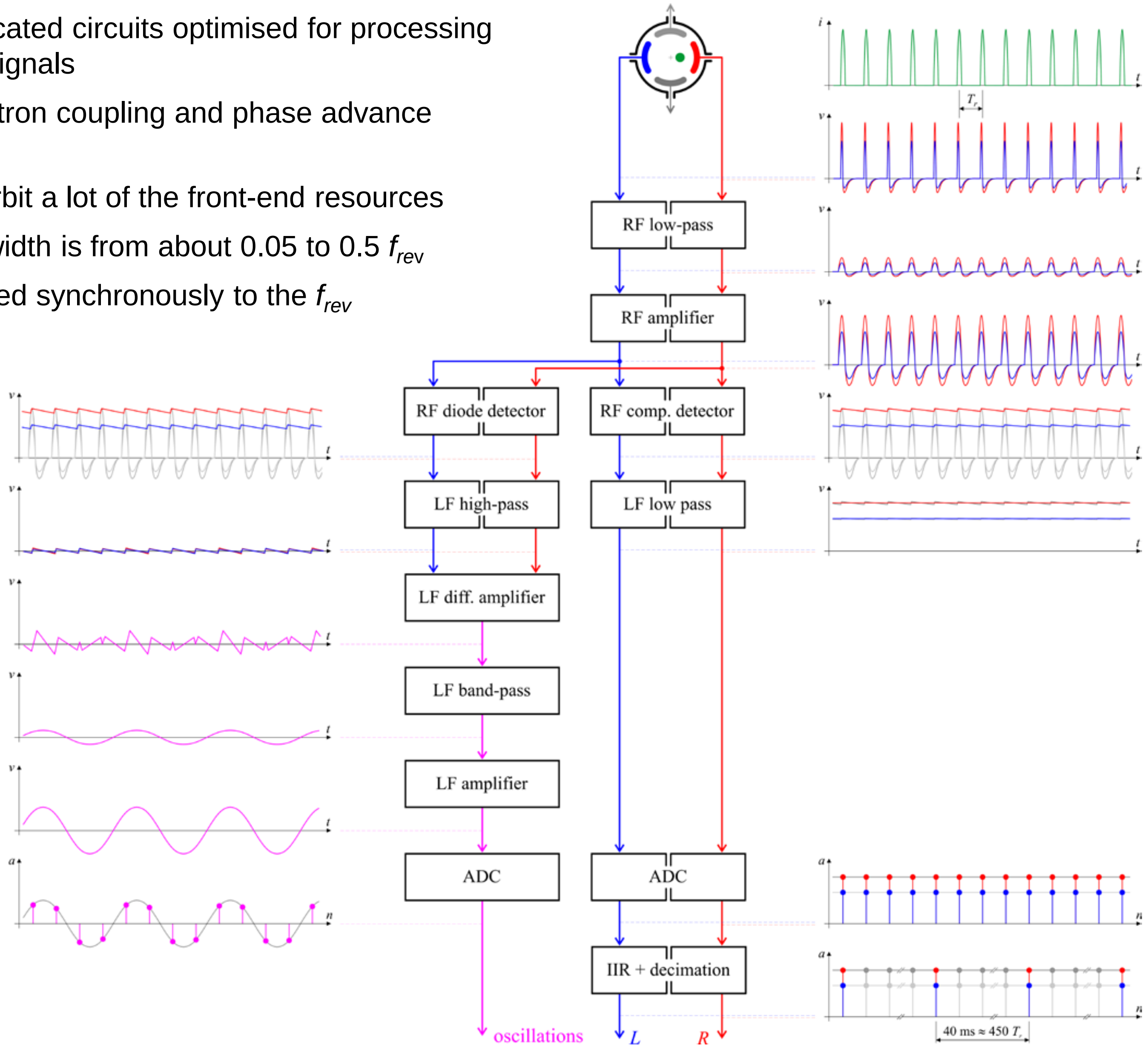
- Perfect amplifiers ($g_A = g_B = 1$ and $o_A = o_B = 0$):
  for $l = 0.5$, $r = 1$, $p_H = 0.3333$ and $P_H = 5.083$ mm for Q1 BPM with $d = 61$ mm.
- Assume amplifiers with $g_A = g_B = 1.05$ and $o_A = o_B = 0.001$:
  $p_H = 0.3329$ and $P_H = 4.927$ mm, resulting in an error of 6 μm



- 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)
- Four channels of one pick-up have the same gain
- Gain control is based on the largest signal of all four electrodes

Oscillation signal processing

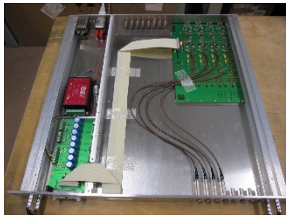
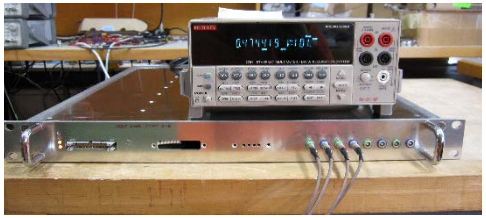
- DOROS has dedicated circuits optimised for processing beam oscillation signals
- Designed for betatron coupling and phase advance measurements
- Shares with the orbit a lot of the front-end resources
- Processing bandwidth is from about 0.05 to 0.5 f_{rev}
- Signals are digitised synchronously to the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



Hardware development history

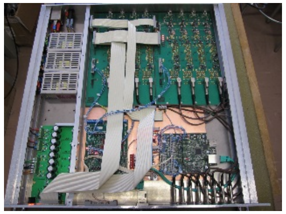
- **2009** – First DOROS R&D and a proof-of-principle

- **2010** – A prototype implementing 4 DOR channels measured with a voltmeter. Tested in SPS beams.

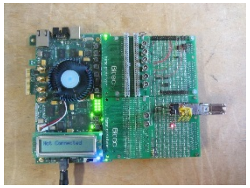
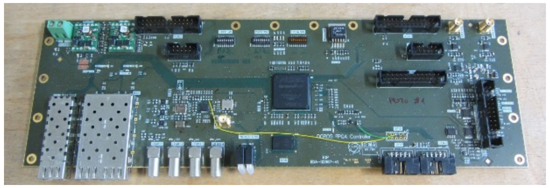



- **2011** – First standalone prototype using 8 CH 24-bit ADC and an MCU. Tested in SPS and LHC beams.

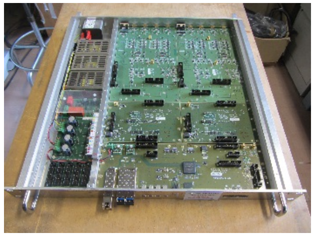
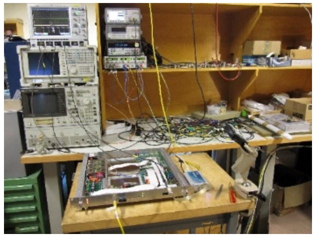
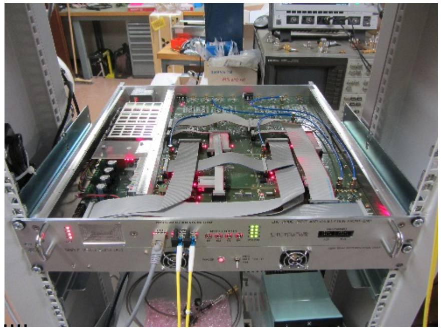
- **2012** – First prototype implementing DOR and DOS. Tested with LHC beams.




- **2013 – 2014** – Development of an FPGA control board, its firmware, software and FESA class.

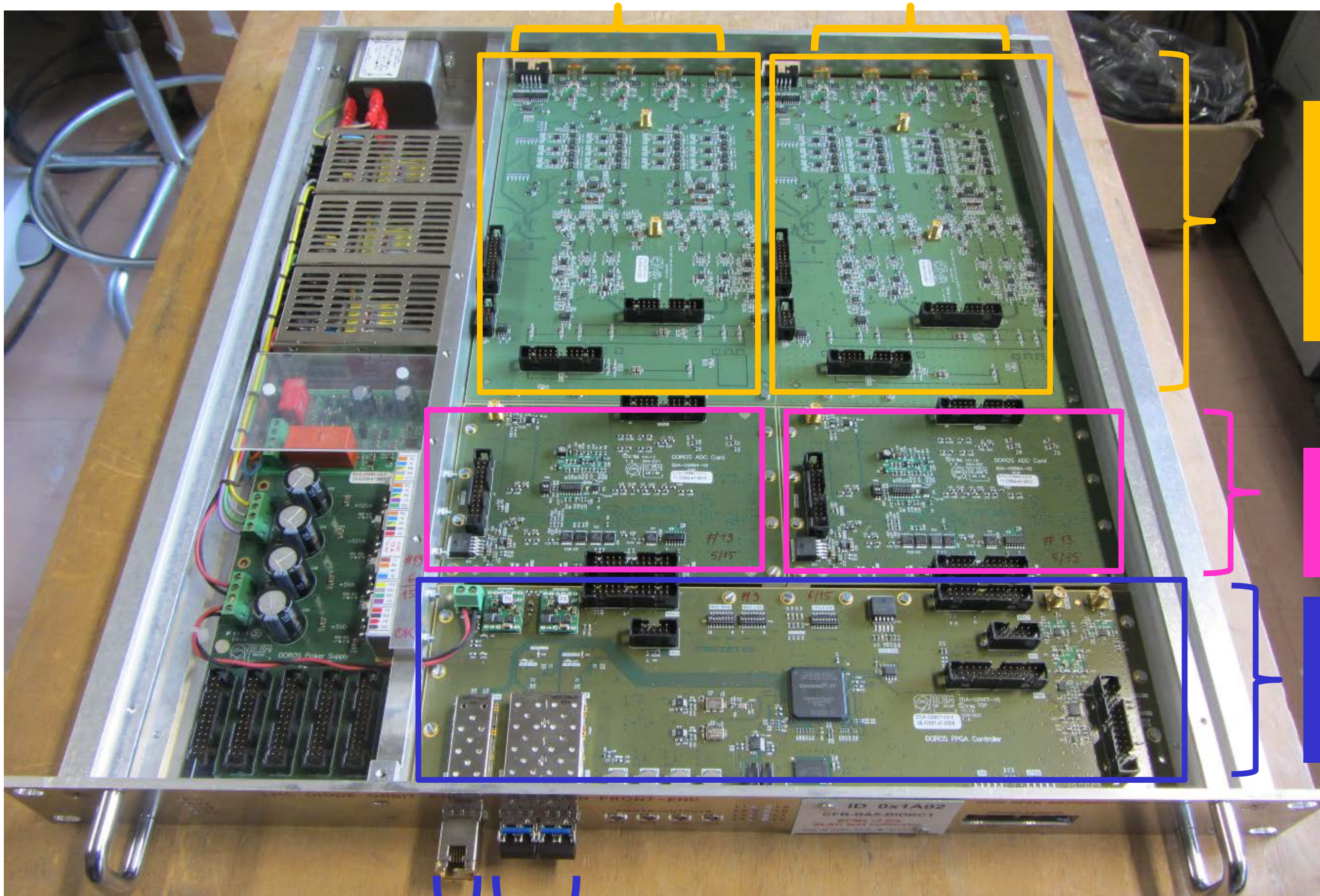
- **2015** – First batch of some 10 operational DOROS front-ends installed in LHC collimators and standard BPMs.

- **2016 – now** – Optimisation of the FPGA code and operation of the hardware with beam

Front-end hardware

2 x 4 BPM channels = 2 x Collimator U/D BPMs Or 2 x Standard H/V BPMs



RF filters, RF amplifiers, Diode detectors, LP filters, Signal buffers

ADC, beam sync. circuits

DSP, Data TX, Control, Timing

RJ 45 Ethernet

2 x BST optical receivers

Front-end functionality

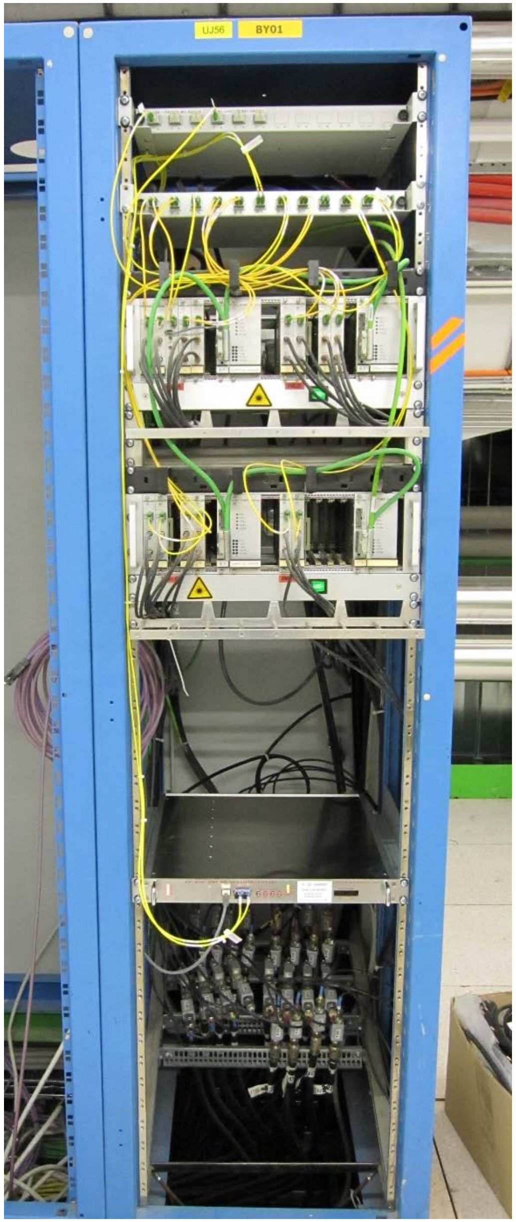
- Orbit measurement with programmable bandwidth down to 0.01 Hz, synchronous to orbit trigger (25 Hz)
- Capture of beam oscillation signals from the bandwidth 0 – 250 Hz (turn-by-turn orbit channels)
- Capture of beam oscillation signals from the bandwidth 0.5 – 5 kHz (turn-by-turn oscillation channels)
- Post-mortem buffers for orbit and oscillation signals
- Automatic gain control of the RF amplifiers
- Auto-calibration with beam signal

- UDP streaming to up to four servers (data + system information)
- UDP commands receiving from FESA servers
- TCP transmission of capture and post-mortem data
- Failsafe remote FPGA code exchange and booting over Ethernet (patent-pending with CERN KT)
- Monitoring of all hardware resources (voltages, temperatures, statuses, statistics, …)
- Decoding and synchronisation to B1 and B2 BST timings (White Rabbit ready)
- Local generator of test signals (programmed 3 amplitude levels, number of bunches, simulation of betatron modulation)

Work in progress:

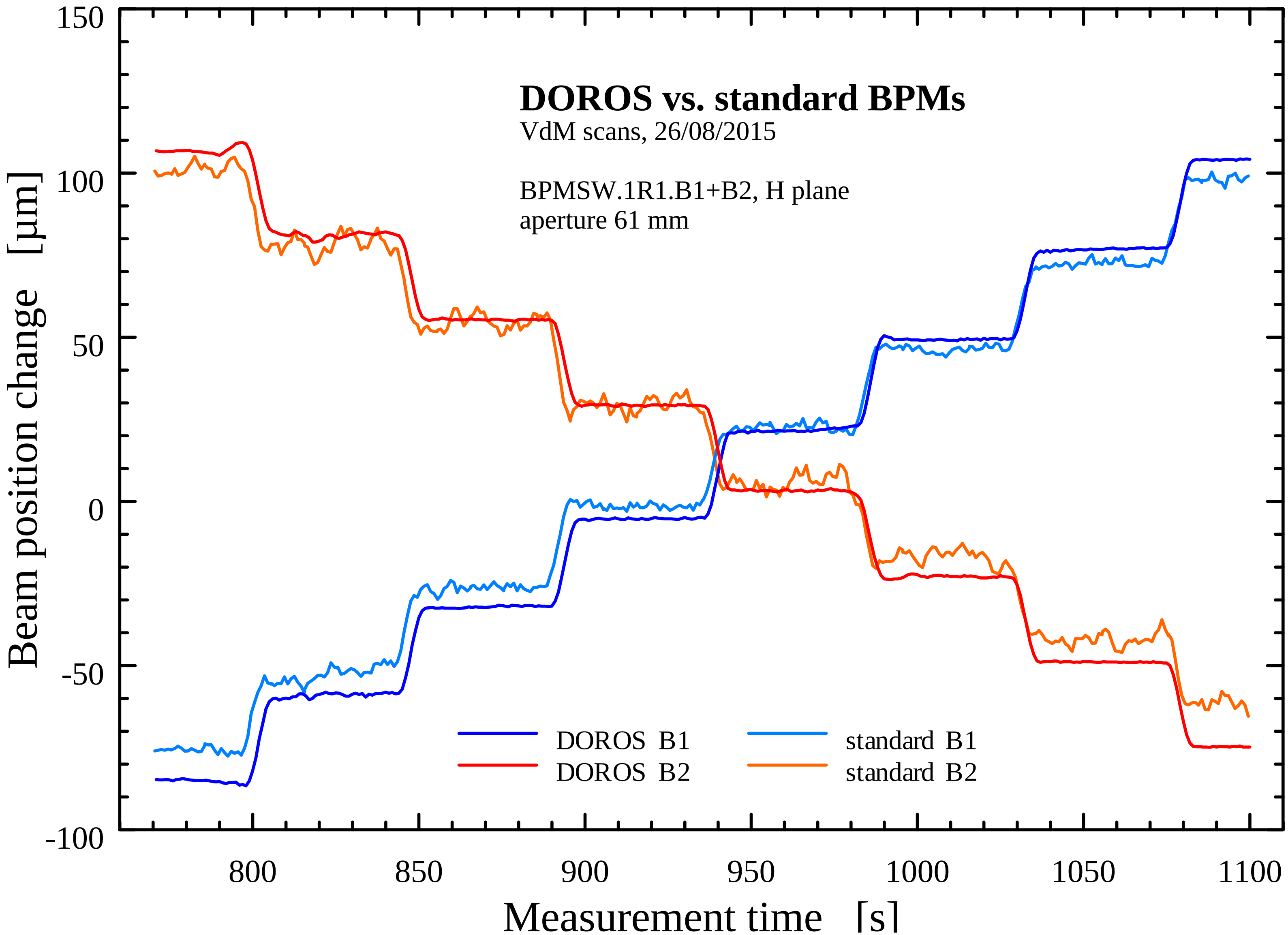
- Full integration to the CERN control infrastructure (FESA, logging, timing, …)
- Real-time demodulation of beam oscillation signals for local coupling and phase-advance measurements

Current installations

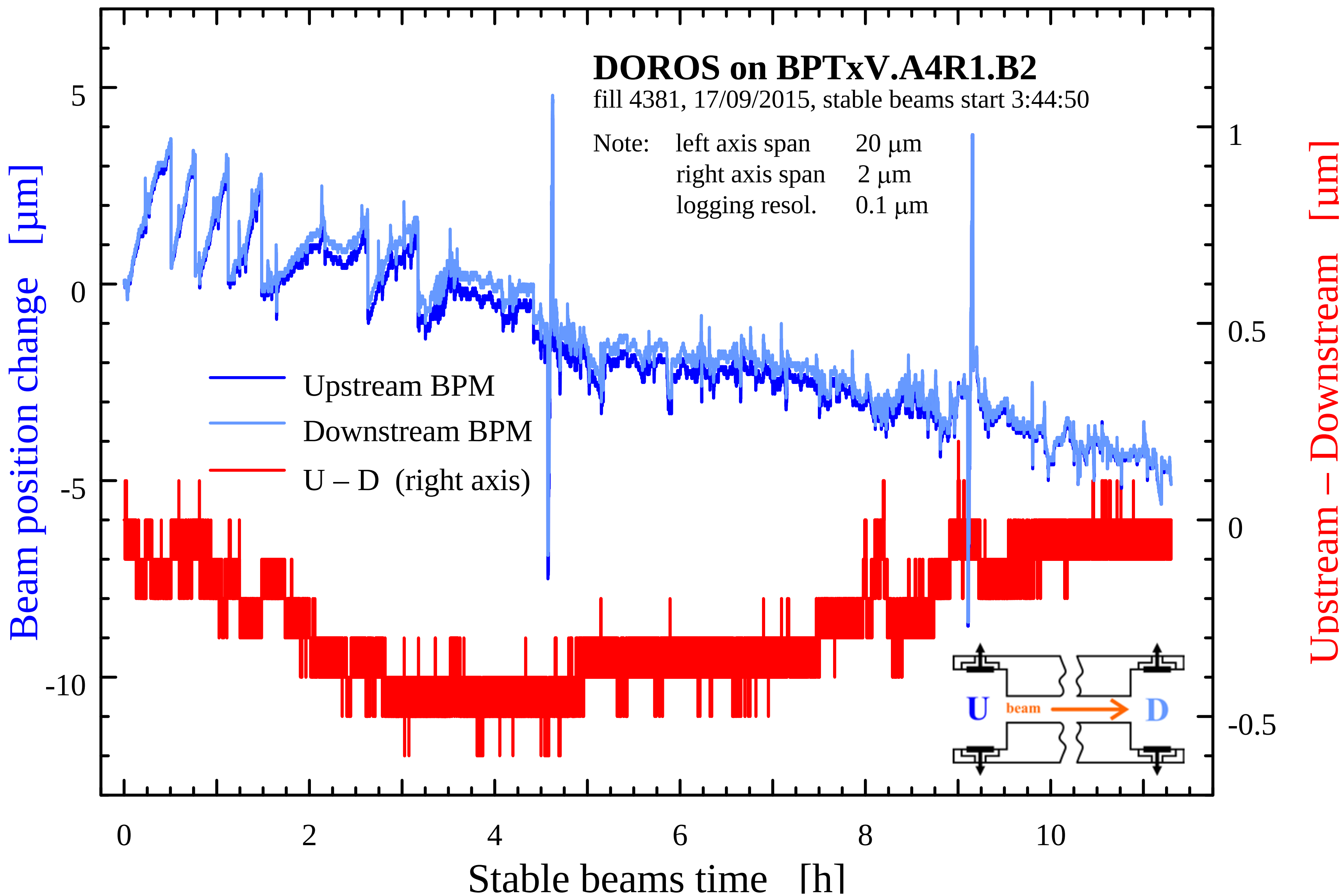


- DOROS installations for the 2016 start-up:
  - 10 front-ends for collimators in LHC points 1, 2, 5, 6 and 8
  - 11 front-ends for standard BPMs in LHC points 1, 2, 5, 6 and 8
  - A few R&D in LAB and SPS

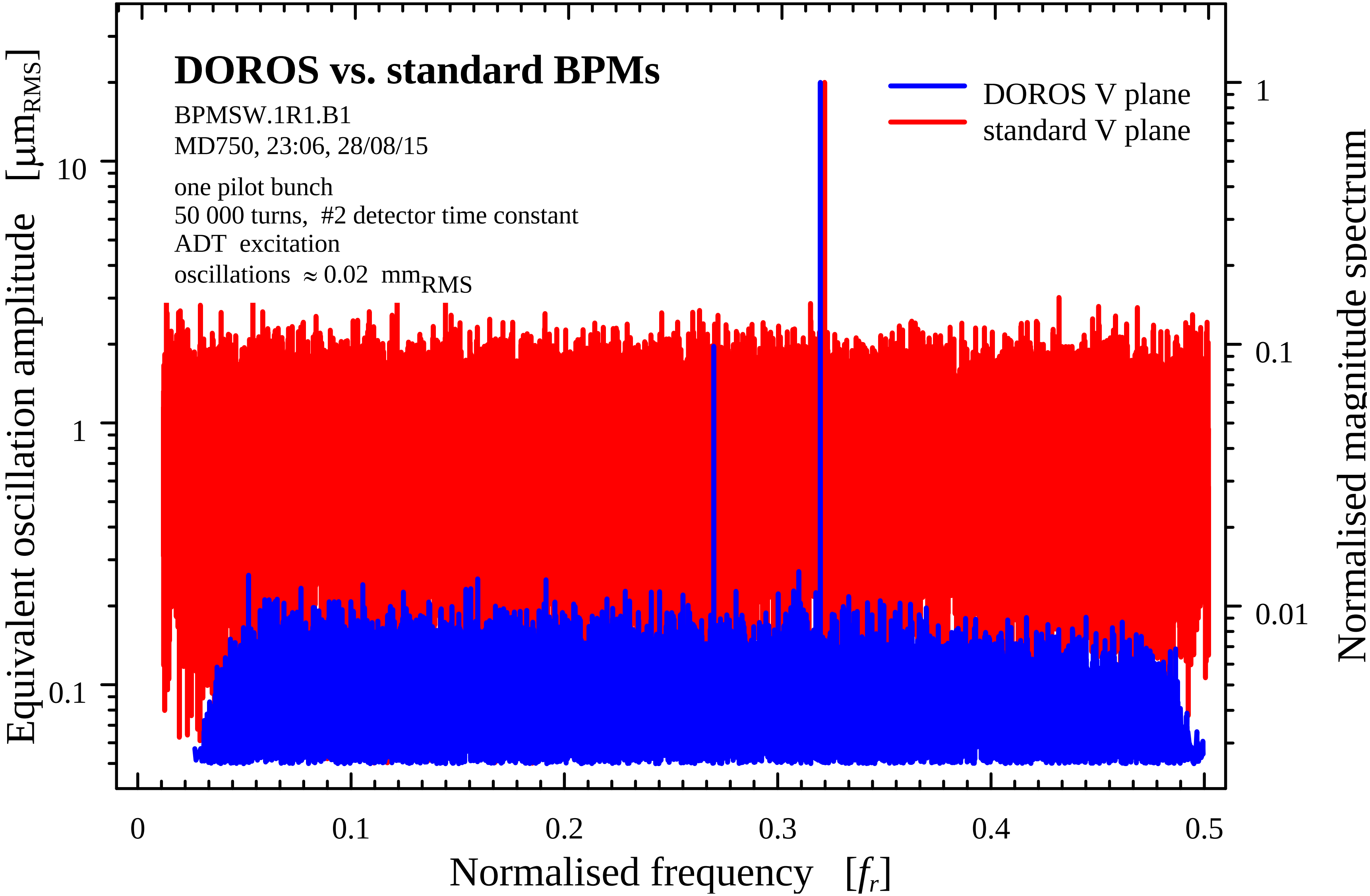
DOROS vs. standard BPMs for orbits



DOROS on collimator BPMs: V.R1.B2



DOROS vs. standard BPMs for beam oscillations



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.

Conclusions and outlook

- The DOROS is a new BPM system optimised for turn-by-turn measurements of beam orbits and oscillations.
- DOROS front-ends are installed on new LHC collimators with BPMs embedded in their jaws. The system has been operational from the 2015 run.
- Identical DOROS front-ends are installed on BPMs in the most critical LHC locations. They are operated in parallel to the standard LHC BPM system.
- DOROS systems were evaluated with beam during 2015 showing very good initial performance.

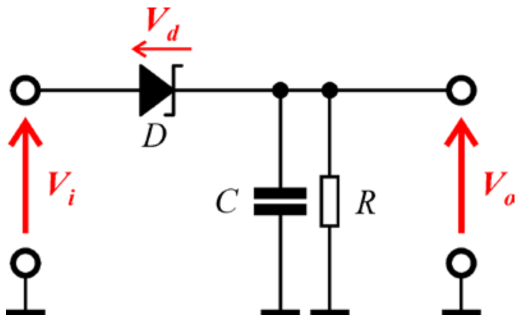
Ongoing:

- Integration of all DOROS functionalities with the FESA framework.
- Functionality optimisation in the laboratory and with LHC beams.
- Real-time processing of beam oscillation signals.
- Adaptation of DOROS hardware for implementation in the new SPS MOPOS system.
- Studies towards a radiation-hard version.

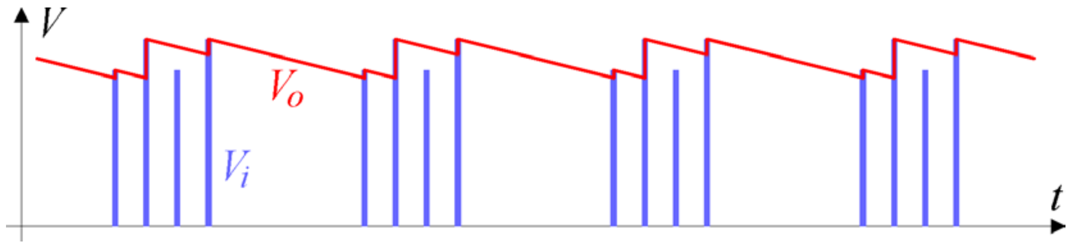
Thank you for your attention!

Question(s)?

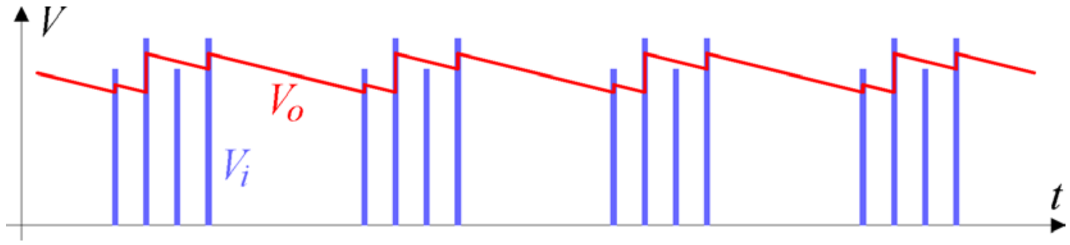
Spare slides



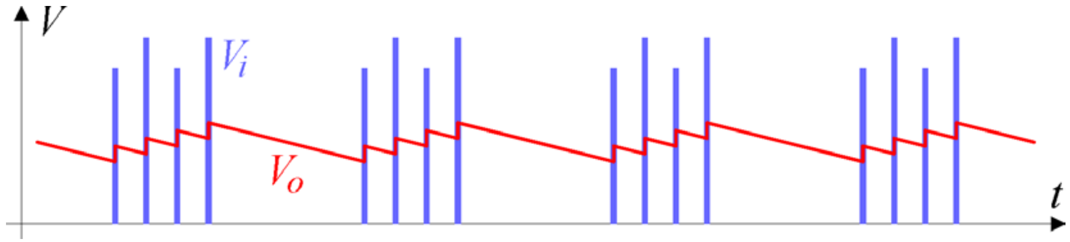
- Diode detectors can be used to convert fast beam pulses from a BPM into slowly varying signals, much easier to digitise with high resolution. In this way amplitudes of ns pulses can be measured with a lab voltmeter.
- As the diode forward voltage V_d depends on the diode current and temperature, the 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

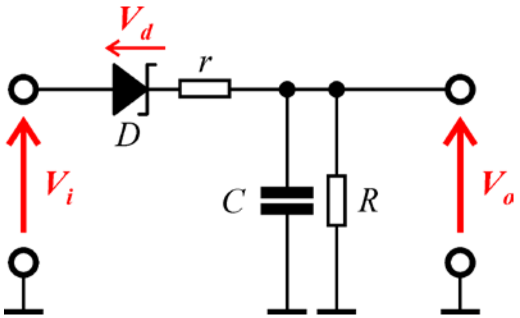


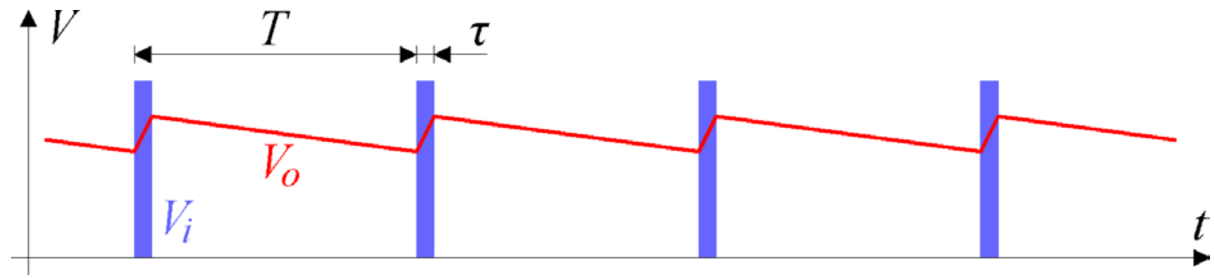
Input (V_i) and output (V_o) voltages of a peak detector with a real diode



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.

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

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

A numerical example: LHC, one bunch.

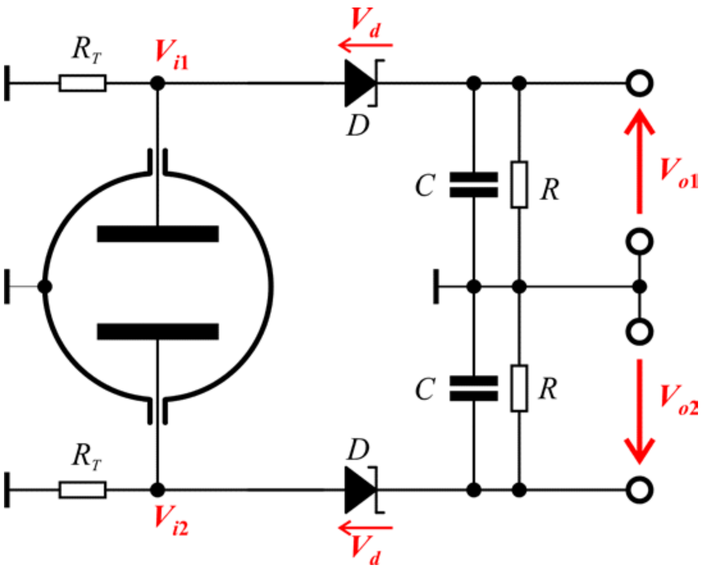
For LHC $\tau \approx 1$ ns and $T \approx 89$ µs, so for $V_o \approx V_i$ one requires R/r > T/τ.
Therefore, for $r \approx 100\,\Omega$, $R > 8.9$ MΩ.

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

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

- 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

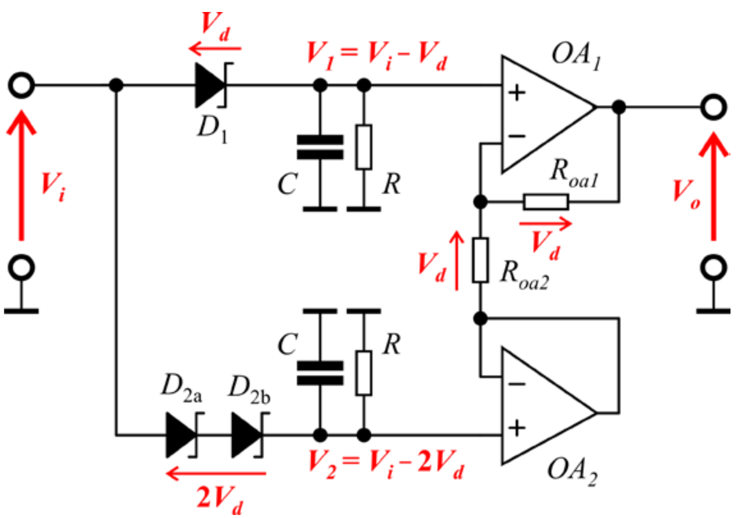


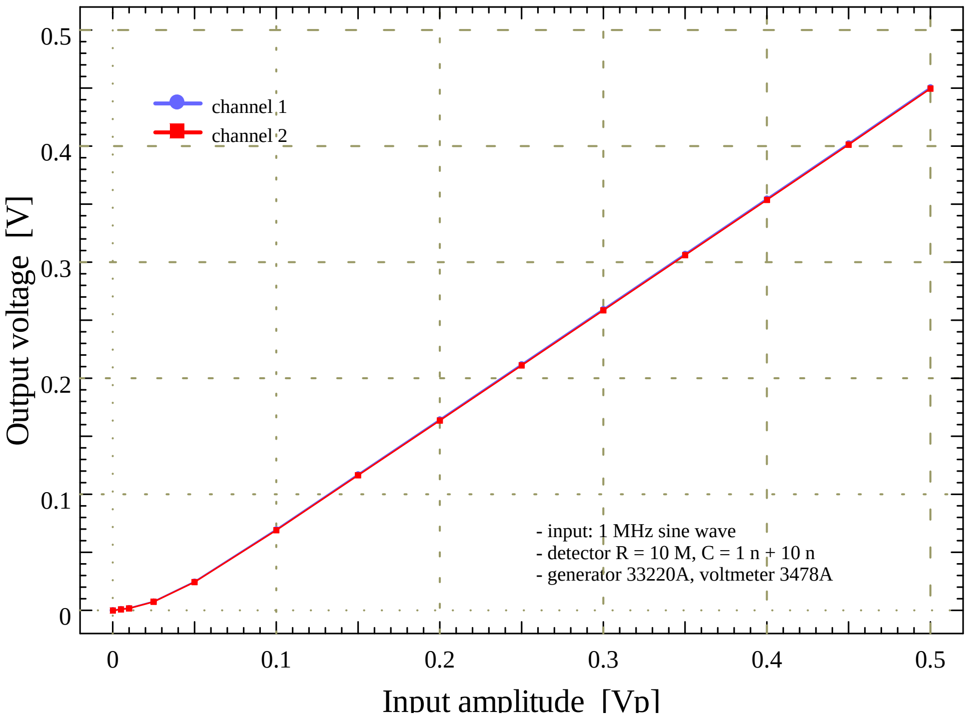
$$\text{ideal}: \quad p_{12} = c_{12} \frac{V_{i1} - V_{i2}}{V_{i1} + V_{i2}}$$

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

- 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 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.