FIRST OPERATIONAL EXPERIENCE WITH THE LHC DIODE ORBIT AND OSCILLATION (DOROS) SYSTEM

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Abstract

The LHC started high-energy operation in 2015 with new tertiary collimators, equipped with beam position monitors embedded in their jaws. The required resolution and stability of the beam orbit measurements linked to these BPMs were addressed by the development of a new Diode ORbit and OScillation (DOROS) system. DOROS converts the short BPM electrode pulses into slowly varying signals by compensated diode detectors, whose output signals can be precisely processed and acquired with 24-bit ADCs. This scheme allows a sub-micrometre orbit resolution to be achieved with robust and relatively simple hardware. The DOROS system is also equipped with dedicated channels optimised for processing beam oscillation signals. Data from these channels can be used to perform betatron coupling and beta-beating measurements. The achieved performance of the DOROS system triggered its installation on the beam position monitors located next to the LHC experiments for testing the system as an option of improving the beam orbit measurement in the most important LHC locations. After introducing the DOROS system, its performance is discussed through both, beam and laboratory measurements.

INTRODUCTION

The Diode ORbit and OScillation (DOROS) system has been primarily designed and optimised for processing signals from the beam position monitors (BPMs) embedded into the jaws of the LHC collimators [1-3]. The system provides orbit readings used for the automatic positioning of the collimator jaws symmetrically around the beam, which reduces drastically the time needed to set-up the collimators and ensures that the collimation hierarchy is always maintained [4].

The DOROS processing for one BPM electrode pair is schematically shown on the block diagram in Fig. 1. It contains four main parts, namely RF processing, orbit processing, oscillation processing and the FPGA controller. The role of the RF processing is to deliver signals with sufficiently large amplitudes to the orbit processing, whose key components are the compensated diode detectors [1]. The detectors convert the amplitude of RF beam pulses into DC voltages which can be measured with very high resolution by the system ADCs. As the orbit processing does not have sufficient bandwidth to cope with signals at LHC betatron frequencies (around 3 kHz), the system is also equipped with a dedicated circuitry optimised for beam oscillation signals.

The RF processing starts with 80 MHz non-reflective filters to reduce the peak amplitudes of the BPM signals, followed by an isolation RF transformer. The transformer cuts ground loops between the LHC machine and the racks where DOROS front-ends are installed, allowing a very clean transmission of the BPM signals. The signals then pass through a calibration switch, which periodically swaps the BPM electrode signals. This way each electrode

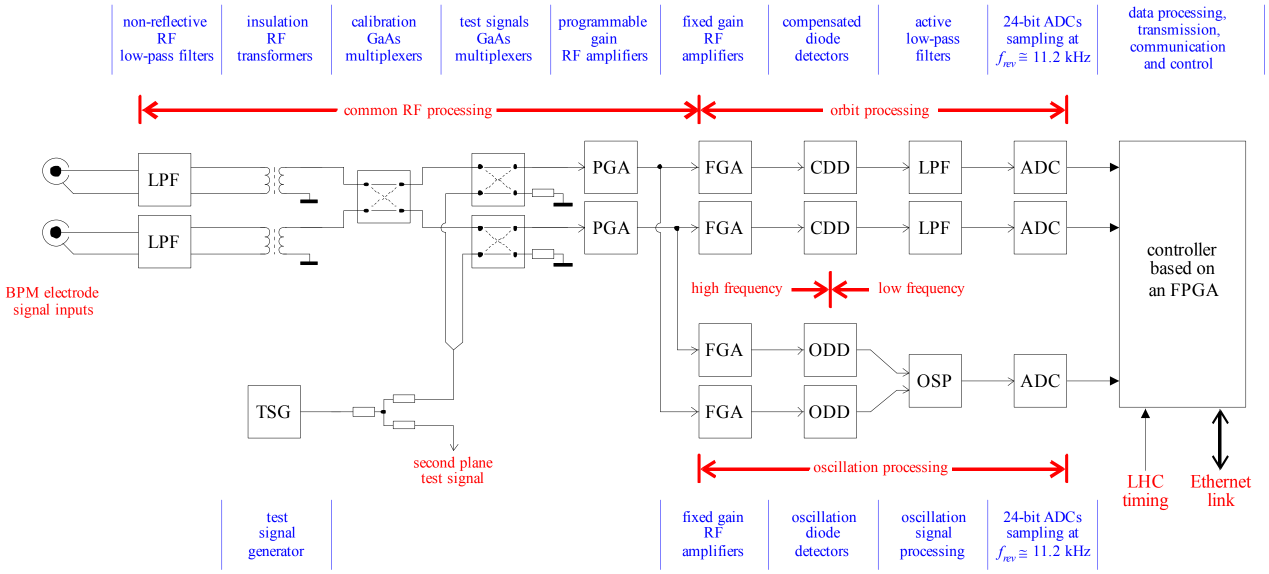

Figure 1: Block diagram of two channels of a DOROS front-end processing signals from one pair of BPM electrodes. LPF – low-pass filter, TSG – test signal generator, PGA – programmable gain amplifier, FGA – fixed gain amplifier, CDD – compensated diode detector, ODD – oscillation diode detector, OSP – oscillation signal processing.

ISBN 978-3-95450-177-9

signal is measured twice in either configuration of the switch. The resulting amplitudes are combined to make the calculated beam position independent of the residual asymmetry between both channels [5].

The test multiplexers allow injection of locally generated signals used to check the functionality of the system without beam. They are followed by programmable gain amplifiers, whose gain can be changed from −15 to +50 dB in 1dB steps. The gain is automatically set according to the actual beam intensity by the system FPGA controller to maintain optimal signals on the diode detectors.

The orbit processing starts with fixed gain amplifiers driving the compensated diode detectors. Their output signals go through 100 Hz low pass filters prior to being digitised by the ADC sampling at the LHC revolution frequency (f_{rev}, about 11.2 kHz). For orbit processing the ADC samples are filtered in IIR filters implemented in the system FPGA, decimated and transmitted over Ethernet as UDP packets.

The oscillation part implements signal processing similar to tune measurement systems based on diode detectors [6]. It starts with fixed gain amplifiers driving the oscillation diode detectors. They are followed by oscillation signal processing, consisting of amplifying and filtering the differential detector signal to the bandwidth 0.05–0.5 f_{rev}, which is then digitised at f_{rev} synchronously to the orbit signals. The oscillation ADC samples are processed in the system FPGA, resulting in amplitudes and phases, which are sent in the common UDP packets [7].

The oscillation part requires special timing and synchronisation circuitry to relate the beam oscillation signals acquired with many DOROS front-ends distributed around the LHC ring [8]. A detailed description of the DOROS system and of its performance can be found in a Ph.D. thesis [9].

DOROS SYSTEMS

The DOROS processing is implemented in front-ends built as 1U 19” modules. Each front-end can process signals from four BPM electrode pairs. This typically means the upstream and downstream single-plane BPMs of two collimators or the horizontal and vertical electrode pairs of two stripline BPMs. All DOROS front-ends are identical and transmit both the amplitudes of BPM electrode signals and beam oscillation data. The front-ends continuously send data as UDP packets every 40 ms upon triggers received over optical fibre distributing the LHC beam synchronous timing. A dedicated DOROS server receives this data and converts it into beam parameters, based on the geometry and location of the corresponding BPMs. The server also sends control commands to the DOROS front-ends, performs data logging and monitors the proper operation of the front-ends.

Each DOROS front-end is declared in the CERN Ethernet network as an independent device identified by a programmable 16-bit ID. This ID also defines the front-end MAC address, allowing for an easy exchange of the front-ends, as the new front-end gets the same ID and MAC address as its predecessor.

The system FPGA runs permanent system checks and is able to reboot its hosting front-end autonomously. The reboot is done by switching off the power of all front-end components, except for a robust passive power supply and simple watchdog circuitry. This way the front-end can recover from a latch-up caused by a radiation-induced single even upset. The system server also checks data consistency and can trigger a reboot of a malfunctioning front-end by sending a reset UDP command.

DOROS front-ends can store in a local memory both orbit and oscillation ADC samples for a few millions of turns, which can be read-out for off-line analysis upon user requests. The front-ends also have a dedicated post-mortem buffer transmitted for analysis after each beam dump.

There are currently three separate DOROS systems installed, each connected to its dedicated server. The first system consists of 10 DOROS front-ends connected to the BPMs of 18 LHC collimators. The second contains 11 front-ends connected to 21 stripline BPMs located next to the LHC experiments, with the signals split between DOROS and the regular LHC BPM electronics [10]. The third system contains a few development front-ends located in both the LHC and the SPS accelerators.

ORBIT MEASUREMENTS

The quality of DOROS orbit measurements is presented in Fig. 2, showing typical orbit drifts from the upstream and downstream BPMs of a collimator, logged during an 11-hour LHC physics fill. The distance between the two BPMs embedded into the collimator jaws is about 1 m. There is a very good correlation between the orbits measured by both BPMs indicating that the observed drifts, in the order of 10 μm, are indeed caused by the beam. The two abrupt position changes are related to orbit scans performed to optimise the LHC collisions.

The stability of the DOROS orbit measurements can be assessed from the difference between the orbit readings of the upstream and downstream BPMs. This variation can be seen to be of the order of 0.5 μm, as shown in red curve of Fig. 2. The 0.1 μm granularity of the variation is defined by the resolution of the logging database from which the orbit data was taken. The resolution of the DOROS orbit measurements is about an order of magnitude better [3].

DOROS system works very well with the collimator BPMs for which it was designed, where the beam is always quite close to the BPM centre resulting in similar signals on the opposing electrodes. For the standard BPMs it is not generally the case, especially for the stripline BPMs installed next to the LHC experiments, where both beam travel in the same beam pipe with an intentional separation between them. Artificial orbit drifts in the order of a few tens of micrometres have been observed on these stripline BPMs during typical LHC physics fills. The drifts are caused by the combination of a large beam offset, the residual nonlinearity of the compensated diode detectors

ISBN 978-3-95450-177-9

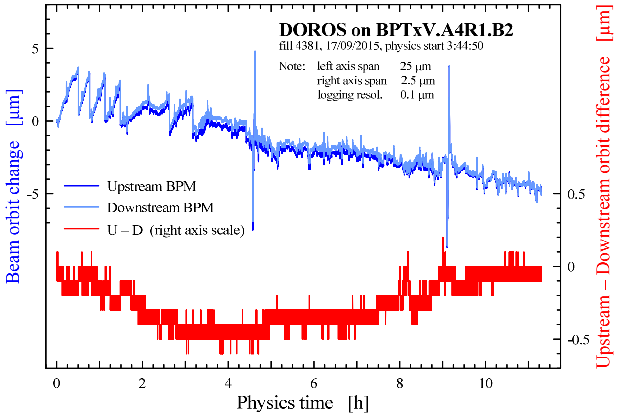

Figure 2: Orbit measurements on two BPMs embedded in the jaws of a collimator.

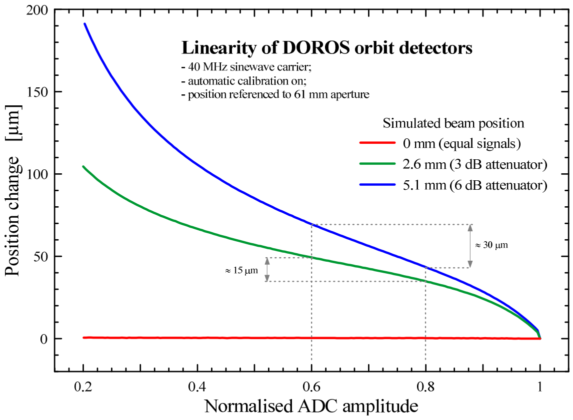

Figure 3: Position change caused by the nonlinearity of the compensated diode detectors (laboratory).

and the beam intensity decay during the physics fill. This effect can be reproduced and has been studied in the laboratory. Figure 3 shows measurements performed by operating a DOROS front-end using a generator signal with a linearly decreasing amplitude to simulate the beam intensity change. The signal was split between the two channels and attenuated to produce signals with different amplitude ratios, simulating three different beam positions. As the position calculation involves signal normalisation, the quality of the generator signal was not critical for the measurements.

The plot shows three measurements with the simulated positions referenced to a stripline with 61 mm aperture, the same as for the LHC BPMs equipped with the DOROS electronics. It can be seen that for the centred beam the nonlinearity of the detectors has little influence, as it is common to both signals. This is why the collimator BPMs work very well. However, for an offset position significant orbit drifts are observed as the beam intensity decreases.

During typical physics fills the LHC intensity can halve, causing a proportional drop in the BPM signals. Most of this drop is compensated automatically by increasing the gain of the DOROS RF amplifiers. The gain can be increased in 1 dB steps (some 12 %) and is controlled by an automatic algorithm (switched off for the measurements of Fig. 2) to maintain the amplitudes measured by the ADCs within a certain window. To estimate the orbit error due to the intensity decay with an offset position one can assume that the larger electrode signal is maintained between 0.6 and 0.8 of the ADC full scale. Variations within this window would result in an orbit error of up to 15 µm for a beam offset by 2.6 mm and 30 µm for a beam offset of 5.1 mm. The orbit drifts observed with beam are compatible with this estimate. These drifts currently prevent the use of DOROS for orbit feedback to maintain optimal collisions. Dedicated studies are therefore ongoing to precisely characterise the nonlinearity of the orbit detectors, with the aim of performing adequate software corrections on the system server prior to calculating the beam orbits.

An example of the use of the orbit data stored in the DOROS local memory is presented in Fig 4. The plot shows magnitude spectra calculated from 1 million turns of orbit data. The data was acquired from a BPM located next to the LHC ATLAS experiment. Two spectra are shown, one where the beta function at the BPM is relatively small (flat top) and one after the beta squeeze, where the beta function is much larger (physics). Comparing these spectra allows deducing the origin of the oscillations observed on the beam, with those originating from the mechanical vibration of the quadrupole magnets of the experimental insertions expected to be enhanced with the change in machine optics. This knowledge is crucial both for optimising the machine and for the design of the next generation of focusing quadrupoles foreseen for the high-luminosity LHC upgrade.

OSCILLATION MEASUREMENTS

Due to optimisation of the orbit detectors for stability and resolution their bandwidth is limited to some 100 Hz. To analyse beam motion at higher frequencies one can use data from the oscillation processing. A comparison of the vertical plane magnitude spectra calculated from DOROS oscillation data with that from the standard LHC BPM electronics is presented in Fig. 5. Both systems were connected to the same stripline BPM, to compare their relative sensitivities for a single pilot bunch. The beam excitation with the amplitude of some 20 $\mu\mathrm{m}_{\mathrm{RMS}}$ was provided by the transverse damper system.

The spectral line corresponding to the vertical excitation at $0.32\,f_{rev}$ is visible in the spectra from both systems. However, the much smaller line corresponding to the horizontal excitation at $0.27\,f_{rev}$, present in the vertical spectrum due to the betatron coupling, is only seen with the DOROS system, whilst it is completely immersed in the noise when measured with the standard BPM electronics. With the order of magnitude higher sensitivity shown by the DOROS system it is hoped that on-line local coupling and optics measurement with LHC physics beams might become a reality [11]. Such measurements currently rely on the standard BPM system, requiring excitation at the millimetre level, which can only be used with few bunches in the machine.

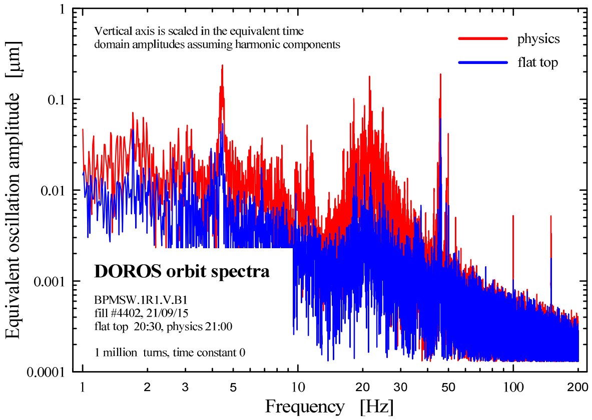

Figure 4: Low frequency vertical beam spectra calculated from DOROS orbit data.

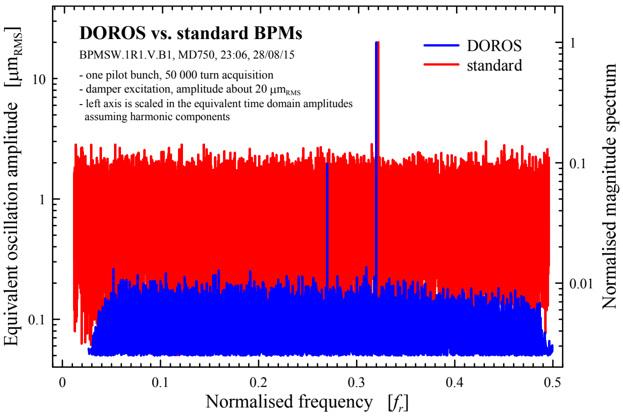

Figure 5: Comparison of vertical beam spectra from the DOROS and standard BPM electronics.

CONCLUSIONS AND OUTLOOK

The DOROS system was designed for measuring beam orbits in the BPMs embedded in the LHC collimators jaws. The goal of achieving sub-micrometre orbit resolution and micrometre stability was achieved with relatively simple and robust hardware, despite the relatively low signal amplitudes available from the small button electrodes of the collimator BPMs. The system is now operationally used for automatic positioning of the collimator jaws and for the continuous monitoring of the beam position at the collimator locations [4]. Further developments involving the generation of beam interlocks from collimator BPMs are ongoing.

The same system was installed on some 20 LHC BPMs located around the LHC interaction regions for comparison with the standard LHC BPM system. It was found that the residual nonlinearity of the orbit diode detectors causes systematic orbit errors at the level of tens of micrometres when the beam has large orbit offsets or when the beam intensity varies. Extensive studies are currently being carried out to linearize the detector characteristics.

The DOROS system can also be used for observing beam spectra and deriving beam parameters from driven beam oscillations. Beam spectra in the frequency range from DC to some 100 Hz can be analysed using DOROS orbit data while the range from 0.5 to 5 kHz can be covered with the oscillation data.

The most advanced application of DOROS oscillation data is for local coupling measurement, which has been demonstrated with very small beam excitation. In the future it is also planned to use DOROS for beta-beating measurements using the synchronous detection implemented in the DOROS FPGAs [7].

The DOROS principle is planned to be implemented in the new SPS BPM electronics and in the longer term it is considered also as a candidate for orbit processing of new LHC BPM electronic. Recent studies have also shown that using BPM electronics based on diode detectors may improve the orbit measurement accuracy in stripline BPMs working with counter-propagating beams [12].

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ISBN 978-3-95450-177-9