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Autoreferát dizertačnej práce

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Abstract

The Large Hadron Collider (LHC) accommodates some 100 collimators whose role is to perform beam cleaning and protect the machine from dangerous particle losses. The collimators are mechanical devices consisting of moveable jaws. Precise positioning and control of the jaws is critical for the cleaning efficiency. Therefore, after the first long shut-down, the LHC was equipped with 18 collimators of a new type. Movable jaws of the new collimators have embedded beam position monitors (BPM) which allow their precise positioning with respect to the circulating beam. However, the existing electronic systems for BPM signal processing could not achieve the required resolution and precision of the position measurements.

In addition to the new collimator BPMs, the LHC accommodates more than 1000 BPMs for measuring the transverse positions of the two counter-rotating beams. The standard LHC BPM system uses these BPMs to measure the orbits and oscillations of the beam. The most important BPMs are located next to the LHC experiments. The beam measurements in such locations are the most challenging as the two beams have to be controlled at a fine precision in order to achieve their efficient colliding. Improving the resolution and precision of the position measurements can contribute to the improvement of the machine performance. Performance of the LHC also depends on the magnet optics. Important machine parameters like betatron coupling, beta-beating and phase advance are obtained by exciting the transverse beam oscillations and measuring the amplitudes and phases of the beam response using BPMs. The standard BPM system requires millimetre-order beam excitation to obtain the measurements of a sufficient quality. For machine protection reasons these measurements can be performed only with special beams and dedicated machine set-up.

The main task of this doctoral work was to design, prototype, build and optimize a new electronics system for beam position and oscillation measurements in LHC. The system called DOROS (Diode Orbit and Oscillation was primarily designed for the new LHC collimators. The same system was also used to provide high-resolution orbit and oscillation measurements in the selected LHC BPMs. The DOROS systems consist of front-ends, each processing signals from up to two BPM sensors composed of horizontal and vertical transverse plains or to two collimators consisting of upstream and downstream BPMs. The RF signals in a front-end are first filtered, amplified and then split into two diode detector sub-systems which work in parallel.

A so called Diode Orbit (DOR) subsystem, based on novel compensated diode detector technique, was designed to perform beam orbit measurements. This thesis describes the analogue processing channels followed by the digital signal processing of the turn-by-turn data and real-time algorithms. The algorithms provide beam based calibration of the channel asymmetries as well as autonomous gain control of the front-end amplifiers. The DOR subsystem was characterized with the laboratory measurements and its performance was demonstrated on a number of beam measurements, showing the achieved sub-micrometre resolution, precision, and long-term stability. The position readings from selected front-ends are also used by the LHC interlock system which terminates operation with beams if the beam positions exceed safe limits.

A so called Diode Oscillations (DOS) subsystem, which is based on direct diode detection technique, was designed and optimised to measure small beam oscillations. This thesis describes both the analogue and digital signal processing in a front-end as well as its synchronization and timing circuits. The sampling of the ADCs can be synchronized to the beam allowing to perform precise measurements of the beam coupling and phase advance.

The front-end units continuously transmit the measurement readings over Ethernet at 25 Hz rate to the system servers synchronously to the LHC timing. Together with the measurement readings the front-ends transmit also statuses and other data important for diagnostics and reliability of the system. At the same time the acquisition data is stored in parallel to the front-end buffers for detailed turn-by-turn and post-mortem signal analysis.

Abstrakt

Kolimátory časticových zväzkov vo Veľkom Hadrónovom Urýchľovači (LHC) sú mechanické zariadenia pozostávajúce z pohyblivých čeľustí, ktorých úlohou je chrániť urýchľovač pred nebezpečnými stratami častíc, a tak zabrániť jeho poškodeniu. Presné umiestnenie kolimačných čeľustí vzhľadom na cirkulujúci časticový zväzok je teda kritické pre efektivitu kolimácie a čistenia zväzkov. Celkovo sa v LHC nachádza približne 100 kolimátorov v hierarchických zoskupeniach umiestnených v kritických lokalitách urýchľovača. Počas prvej dlhej odstávky bol LHC urýchľovač vybavený 18 kolimátormi nového typu. Pohyblivé čeľuste týchto kolimátorov majú zabudované senzory merania pozície zväzkov (BPM), ktoré slúžia na ich presné umiestnenie vzhľadom na cirkulujúci zväzok. Potrebné rozlíšenie a presnosť merania pozície zväzkov nebolo možné dosiahnuť s existujúcimi elektronickými systémami na spracovanie BPM signálov.

Okrem BPM senzorov v nových kolimátoroch je LHC vybavené viac ako 1000 BPM senzormi na meranie transverzálnej pozície oboch protibežných zväzkov. Štandardný LHC BPM systém je elektronický systém, ktorý spracúva signály z týchto senzorov a umožňuje merať orbity a oscilácie zväzkov v LHC. Najdôležitejšie BPM senzory sa nachádzajú v blízkosti LHC experimentov. Pozície oboch cirkulujúcich zväzkov v týchto lokalitách musia byť ovládané s vysokou presnosťou pre dosiahnutie efektivity kolízií v experimentoch. Zvyšovanie dosiahnuteľného rozlíšenia a presnosti systémov merania pozície zväzkov tak môže priamo prispieť ku vylepšeniu výkonnosti LHC urýchľovača. Táto tiež úzko súvisí s optimálnym nastavením magnetovej optiky. Dôležité parametre ako napríklad transverzálne väzby, beta-beating alebo fázové posuny oscilácií, je možné merať pomocou budenia transverzálnych oscilácií a merania amplitúdovej a fázovej frekvenčnej odozvy zväzku pomocou BPM systémov. Na dosiahnutie adekvátnej kvality merania je potrebné budiť oscilácie zväzkov s rádovo milimetrovými amplitúdami. Spomenuté merania je teda možné vykonávať v LHC len so špeciálnymi nastaveniami urýchľovača a typmi zväzkov.

Hlavnou úlohou tejto dizertačnej práce bolo navrhnúť, zostrojiť a optimalizovať nový typ elektronického systému slúžiaceho na merania pozície a oscilácií časticových zväzkov pomocou BPM monitorov v urýchľovači LHC. Tento systém, nazývaný DOROS, bol navrhnutý primárne pre nový typ LHC kolimátorov so zabudovanými BPM senzormi. Identický DOROS systém bol taktiež použitý na presné merania orbity a oscilácií zväzkov vo vybraných BPM senzoroch v LHC nachádzajúcich sa najmä v oblasti experimentov. Oba systémy DOROS pozostávajú z elektronických jednotiek, takzvaných front-endov. Každá jednotka umožňuje spracovávať rádiofrekvenčné signály a merať pozíciu zväzkov v dvoch BPM senzoroch. Tieto signály sú najskôr filtrované, zosilnené a potom rozdelené na následné spracovanie dvomi paralelnými podsystémami založenými na princípe rádiofrekvenčných diódových detektorov.

Diode Orbit (DOR) podsystém bol navrhnutý a optimalizovaný na meranie orbity zväzkov. DOR podsystém je založený na novej technike kompenzovaných diódových detektorov. Táto práca sa zaoberá analógovým ako aj digitálnym spracovaním signálov a algoritmami vykonávanými v reálnom čase. Dynamický rozsah signálov je automaticky regulovaný pomocou autonómneho algoritmu na ovládanie vstupných zosilňovačov. Asymetrie medzi jednotlivými analógovými kanálmi sú minimalizované pomocou kalibračného algoritmu využívajúceho signály z BPM senzorov. Výsledný DOR podsystém bol charakterizovaný pomocou laboratórnych meraní. Táto práca taktiež prezentuje niekoľko meraní realizovaných so zväzkami v LHC urýchľovači. Rozlíšenie, presnosť a dlhodobá stabilita merania pozície zväzkov bola dosiahnutá rádovo menej ako jeden mikrometer. Niektoré DOROS jednotky sú taktiež využívané LHC interlock systémom, ktorý slúži na ukončenie činnosti LHC, ak merané hodnoty pozície zväzku prekročia limity stanovené pre bezpečný chod urýchľovača.

Diode Oscillation (DOS) podsystém, ktorý je založený na princípe priamej diódovej detekcie, bol navrhnutý a optimalizovaný na meranie mikrónových oscilácií zväzkov. Táto práca sa zaoberá analógovým a digitálnym spracovaním signálov oscilácií zväzkov, ako aj súvisiacimi synchronizačnými obvodmi. Vzorkovanie oscilačných signálov v ADC prevodníkoch môže byť synchronizované so zväzkom, čo umožňuje vykonávať presné merania fázového posunu a transverzálnej väzby zväzkov.

Každá DOROS jednotka posiela spracované hodnoty jednotlivých meraní prostredníctvom Ethernetového protokolu s frekvenciou 25 Hz. Táto komunikácia je synchronizovaná časovacími signálmi z LHC. Každý datagram taktiež obsahuje informácie o stave jednotky, ako aj iné dáta slúžiace na diagnostiku a spoľahlivosť systému. Hodnoty z ADC prevodníkov sú zároveň ukladané do lokálnej pamäte nachádzajúcej sa v každej DOROS jednotke. Tieto dáta sú prístupné prostredníctvom Ethernetového protokolu a je ich možné využiť pri takzvanej turn-by-turn alebo post-mortem analýze.

Contents

1 Introduction to the research field of the thesis

The Large Hadron Collider is the world's largest accelerator with the circumference of almost 27 km [1]. It was built in a tunnel of the former Large Electron Positron collider (LEP). Particle beams of positively charged protons or heavy ions are injected into the LHC passing first through a chain of smaller accelerators. The LHC accelerator schematically shown in Fig. 1-1 consists of a ring with two beam lines. The two LHC beams are accelerated to high energies with opposite direction of the beam circulation. Their paths are crossed in the interaction regions in order to collide the particles inside the four main experiments, namely the ATLAS [2], CMS [3], ALICE [4] and LHCb [5]. The physics run in years 2010 - 2013 [6] yielded enough experimental data to discover the Higgs Boson [7].

The LHC ring contains some 1200 superconducting dipole magnets that bend the trajectory of both beams into closed circumference inside of the accelerator vacuum pipes. The dipole magnets can produce magnetic fields of more than 8 T required for beam bending in the horizontal plane. The magnet power supplies deliver current of more than 11 kA controlling the magnetic fields. Some 400 main superconducting quadrupole magnets are distributed on the LHC circumference. The quadrupoles allow controlling the transverse beam sizes in the machine as well as focus the beams in the experiments. Apart of the main dipole and quadrupole magnets, the LHC also contains some 7000 other corrector magnets for controlling beam dynamic effects [1].

The particle beams are bunched and accelerated by a system of superconducting RF cavities. Alternating electro-magnetic fields provide accelerating energy and keep injected particles inside bunches. The beams circulate at revolution frequency f_{rev} of approximately 11.2 kHz defined by the RF system. The revolution period is then equal to some 89.3 µs. The LHC can store about 2800 bunches in each of its two beam lines [1]. All bunches over the accelerators circumference are organised in a so called bunch pattern. Bunch spacing used in physics operation is typically 25 ns. Bunch intensity is a parameter defining number of particles in a bunch. Beam intensity defines a sum of all particles in the machine. A so called a pilot bunch has intensity of 5×10^9 elementary charges [1]. Such beam intensity is safe for the machine even during abrupt particle losses at injection energy. A so called nominal bunch has intensity of more than 1×10^{11} which is required for large production of particle collisions in the experiments [1]. Beams consisting of many nominal bunches are therefore used in physics operation.

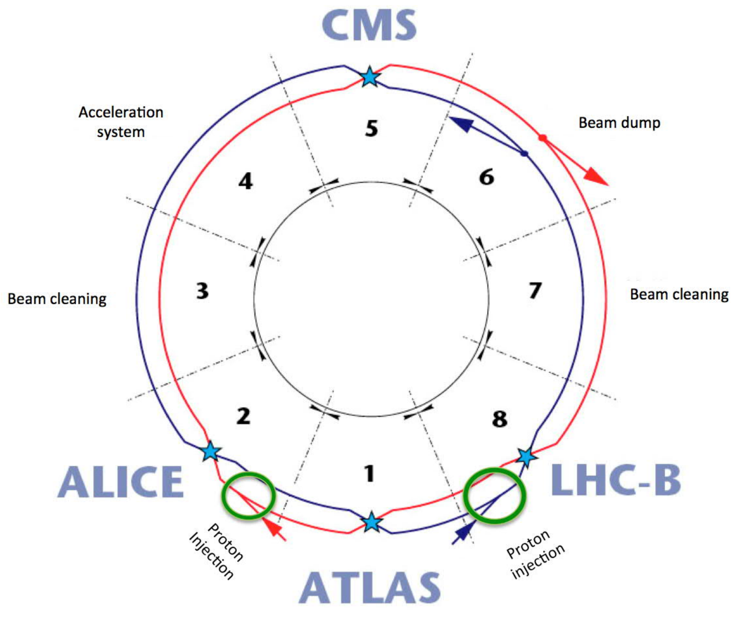

Fig. 1-1 *Schematic diagram of the Large Hadron Collider ring with its two beam lines and four main experiments [10].*

Particle losses in the machine cannot be completely avoided due to imperfections in the magnet alignments as well as many beam dynamic effects. Excessive beam losses on superconductive can cause magnet quench, an effect of sudden loss of superconductivity. Uncontrolled particle losses pose potential risk of damaging superconducting magnets and other sensitive equipment, rendering the machine inoperable for long time. The LHC collimation system was designed to protect the superconductive magnets and other sensitive equipment by intercepting unstable particles from the beam. The collimation system is a beam cleaning system arranged in multiple stages. Each stage consists of a collimator device installed in the dedicated locations on the LHC circumference. This system is critical for safe and reliable operation of the accelerator.

A typical LHC cycle used for physics operation is composed of a few phases [1]. The cycle begins with preparation of machine for the beam injection. A single pilot is first injected in order to validate the machine settings. The nominal bunches are then injected and distribute on the LHC circumference according to the required bunch pattern. After the injection phase is finished the machine is prepared for the energy ramp. Both beams are then accelerated to the programmed energy. Once the acceleration phase is finished the LHC optics is prepared and adjusted for the beam collisions. Physics data taking period, a so called stable beam phase can last for more than 24 hours. During this time, the intensity of the beam naturally decays. Once reaching the threshold of optimal machine run the beams are ejected into the beam dump and the magnetic fields are ramped down for the next machine cycle.

The primary purpose of the LHC is to produce large number of particle collision events that the main experiments can process. Luminosity is a quantitative measure of the accelerator performance and efficiency in production of the collision events. Optimisation of the luminosity production [8] in the LHC depends on a number of machine settings and beams parameters such as the number of bunches, beam intensity, beam sizes or turnaround time.

Knowledge of the transverse position of a particle beam inside the beam pipe plays a crucial role in the operation, performance, reliability and safety of an accelerator. Systems measuring beam position provide means to control, diagnose and study many important beam parameters such as beam trajectory, orbit, tune and other derived quantities. More than 1000 BPM sensors are required in the LHC to measure the transverse positions of the beams [1]. A BPM sensor is a device composed of a system of sensing electrodes which allow non-invasive measurements of the beam position in the transverse plane. Majority of the BPM sensors in the LHC have four electrodes which allow measuring both horizontal and vertical beam positions in the vacuum pipe [9]. Dedicated electronics systems then process the BPM signals and provide position readings used by a number of monitoring and control systems. Measurement data is also stored in the logging databases for offline analysis.

1.1 Beam orbit and trajectory

Position of a bunch can be measured each time it passes through a BPM sensor. A BPM system able to measure positions of individual bunches is referred to as a bunch-by-bunch BPM system. Beam orbit can be defined as an average position of bunches. The averaging can be defined over a given number of bunches and beam revolutions also called turns. The orbits in the LHC are measured as an average of all bunch positions over a few hundred turns. A system optimised for measuring the positions on a one turn basis is referred to as a turn-by-turn system. A system optimized for position measurements over many turns is referred to as a multi-turn system.

As a bunch is advancing through the accelerator ring, the reading of its position can be obtained at each BPM location. Acquired readings from all BPMs on the circumference represent a trajectory of the bunch. Example of a trajectory measurement is displayed in Fig. 1-2. The measurement was acquired by the standard LHC BPM system [11] during the first LHC commissioning in 2008. The figure depicts beam position readings of the horizontal and vertical planes from more than 500 locations on the LHC circumference.

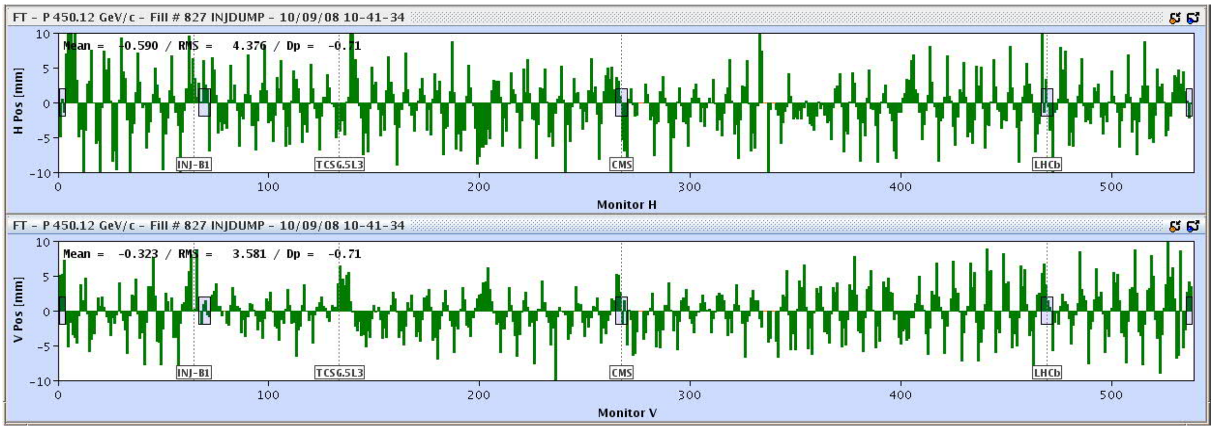

Fig. 1-2 *Horizontal and vertical beam trajectories measured during the first LHC commissioning. The measurements on the top (horizontal plane) and botom (vertical plane) plots were obtained by the standard LHC BPM system. The vertical axis displays the beam position offset in milimetres. The horizontal axis displays the indices of the BPM monitors on the LHC circumference [33].*

Precise measurements of the LHC orbits are the most important around the interaction regions. There the beam orbits have to be controlled within a few micrometres so that the two beams can collide. Some systems use the position readings for real-time feedback corrections. For example the LHC Orbit Feedback system maintains and controls the stability of the beam orbits in the machine [12]. The orbit measurements are also important for protection of the accelerator. For example, if the orbit exceeds safe limits the beams have to be automatically ejected to prevent potential damage. Performance of the LHC can be therefore limited by the resolution, long-term stability and accuracy of the measurement systems.

1.2 Betatron coupling and phase advance

In theory of the transverse beam dynamics, each particle undergoes oscillatory-like trajectory around its orbit when passing through the magnet optics. The resulting motion, referred to as betatron oscillations, is defined by the periodically alternating focusing and defocusing magnetic fields in the machine. The frequency of the betatron motion, referred to as the tune, is an observable parameter which is important for the beam stability and accelerator performance. Envelope of the betatron oscillations, a so called betatron function, describes beam size at any point of the circumference. Phase of the betatron oscillations along the circumference, so called phase advance, is an observable parameter which is inversely proportional to the betatron envelope [13].

Measurements of the optics parameters such as the betatron coupling or phase advance are typically based on transverse beam excitations [17]. The natural beam motion has typically very small amplitudes which is changing over time. Therefore such signals are not suitable for precise optics measurements. Exciting the beams with appropriate frequency and amplitude allows reliable measurements of the beam response, necessary for calculating the optics parameters. Principle of such optics measurements is illustratively explained in Fig. 1-3. A dedicated system drives harmonic beam oscillations with amplitude A_{exc} period T_{exc} around the closed orbit. The example depicts the excitation only in the vertical plain. As the bunch passes through the BPM sensor it induces signals on the BPM electrodes. The beam response is then obtained as an amplitude modulation of the BPM signals. Amplitude and frequency of the excitation are set such, that the resulting beam response can be measured by the BPM electronics. The minimum amplitude is usually limited by the required signal-to-noise ratio (SNR) of the measured signals. The maximum excitation amplitude is often limited by the requirements for the optimal and safe operation of the accelerator. The frequency is set around 0.3 f_{rev} [1] which is close to the fractional part of the horizontal and vertical tunes [14] of the machine.

One of the measured beam parameters is the betatron coupling. The beam oscillations can couple between the horizontal and vertical planes due to magnet misalignments and other sources such as the skewed magnets or solenoids [15]. The measurements in the LHC can be performed by exciting the beam at two different frequencies in each plane. The beam response is then measured by a BPM system. The data is used to compute the coupling in each BPM sensor and to apply necessary corrections to the respective magnets. Local corrections of the betatron coupling are important for the beam quality and lifetime [15]. Another measureable LHC parameter is the betatron phase advance, denoted as $\Delta\varphi$ in the Fig. 1-3. It can be measured as a phase difference between the measured beam responses obtained at two BPMs in two different locations. The parameter depends on the focusing and defocusing forces of the magnet optics. The most important are the BPMs around the experiments where the optics settings change the most. The strong focusing and defocusing forces in these locations result in large betatron functions [14]. Measurement results can be compared to the numerical models yielding maximum relative deviation of the betatron function, a so called beta-beating. This is an important measure of the quality of the machine setup. The beta-beating also serves as a figure of merit for performance optimisations [16], [17].

The local betatron coupling and phase advance measurements in the LHC are usually using the standard BPM system providing position measurements from many BPM sensors in the LHC. To obtain sufficient SNR the amplitude of the excitation is typically in a millimetre range. The optics measurements are therefore limited to dedicated machine setup and beams typically composed of a few bunches. Duration of these measurements of a few thousand turns is typically limited by the allowed length of the excitation at millimetre amplitudes as well as the size of the memory in the acquisition systems. Experimentally achieved resolution of the phase advance measurements in the LHC is around 1° [18]. The resolution can be improved by using different algorithms, usually based on combining measurements from several BPM sensors [16], [17]. Increasing sensitivity of the position measurements to small beam oscillations can potentially allow to use smaller excitation amplitude, resulting in improved machine safety and quality of the optics measurements. Increasing the acquisition length would allow to compute longer averages and resulting in further improvement of the SNR in the local optics measurements.

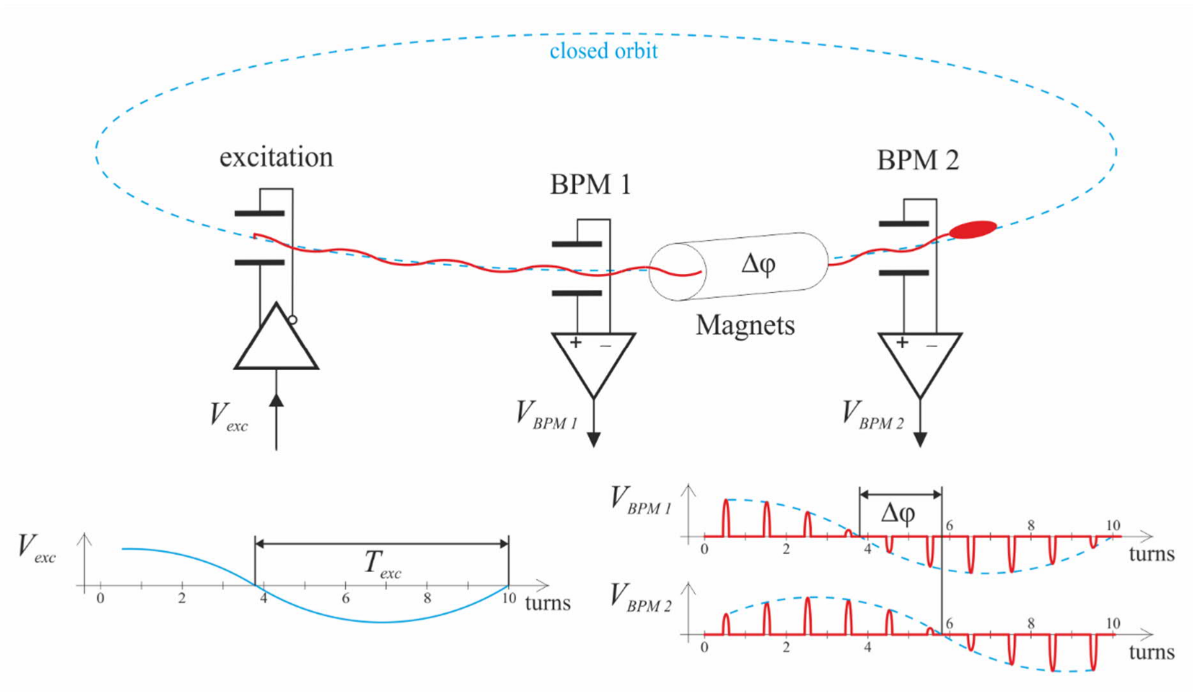

Fig. 1-3 *Illustration of excited beam oscillations and the observed response on two BPM sensors. The illustration in the picture is not in scale.*

1.3 Fundamentals of the beam position measurement

Particles in the LHC beams travel inside the beam pipes emptied to the ultra-high vacuum [1]. The pipes are round and metallic, typically made of stainless steel. The beam particles induce image charge of opposite polarity on the pipe walls. The charge density on the pipe surface is defined by the distribution of the particles in a bunch as well as their distance to conductive surface. As the particles propagate at the speed very close to the speed of light the image charge forms a so called image current. The BPM sensors are devices which allow sensing the induced image charge and measure the transverse beam position [34]. The simplest BPM sensors consist of 4 capacitive electrodes arranged in the horizontal and vertical pairs. The setup allows measuring the transverse beam position in both axis. The bunch charges are marked in red and the image charges are marked in blue. As seen in the example the transverse position of the bunch is vertically displaced from the centre of the BPM. The position offset causes a difference between the induced charges on the opposing electrodes. The image charge of each bunch is converted on the capacitance of the electrode into a voltage pulse (marked in orange). Difference of the pulse amplitudes A_1 and A_2 from the opposing BPM electrodes is proportional to the transverse position of the bunch. The pulse amplitudes are equal from all electrodes if the bunch was located in the centre of the BPM. The amount of the image charge also depends on the intensity of the bunch. Therefore a sum of the amplitudes A_1 and A_2 yields a quantity which is proportional to the bunch intensity. Depending on the geometry and type of the sensor the pulse amplitudes in the LHC can range between tens to hundreds of volts. Construction of a BPM sensor affects also other parameters like its bandwidth or sensitivity. The most common BPM sensor types used in the LHC are the so called button and stripline BPMs [1].

The electrode signals undergo often quite complex signal processing in order to obtain the normalised position offsets. In general, the normalised position p can be computed on an axis between two opposing electrodes using the corresponding pulse amplitudes A_1 and A_2 as:

$$p = \frac{A_1 - A_2}{A_1 + A_2}. \tag{1-1}$$

The equation (1-1) can be used to compute positions in both horizontal and vertical BPM axis. The example showed in the picture would result in a negative p values as the pulse amplitude A_2 would be larger than A_1. If the beam passes through the centre of the axis the p value would be equal to 0 as both amplitude A_1 and A_2 would be equal. The relationship between the measured normalised position p and real position of the beam in millimetres is described by the geometrical characteristic of the BPM sensor. The characteristics for a button and a stripline BPMs are non-linear. In addition, the normalised positions p measured in the horizontal and vertical axis are mutually dependent. The errors resulting from the cross-plane coupling have to be then corrected in the signal processing.

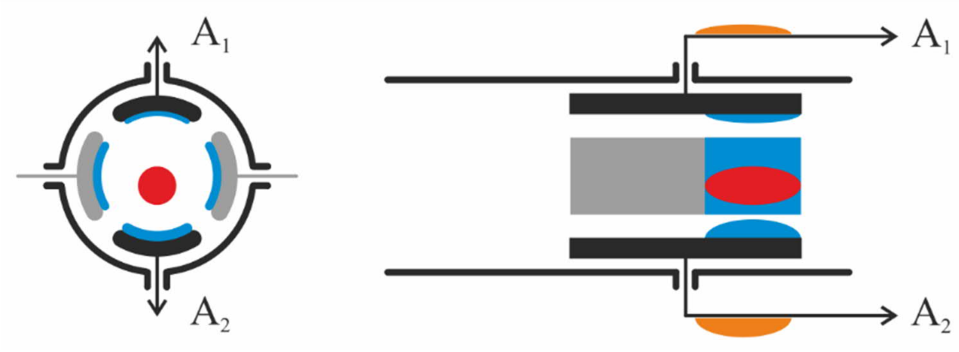

Fig. 1-4 *Illustration of a beam position measurement principle. The particle bunch (red) induces image charges (blue) on four electrode plates of a BPM the sensor. The image charge on each electrode is converted into a voltage pulse (orange).*

1.4 Standard LHC BPM system

The standard LHC BPM system is an instrumentation system used to process the BPM signals in the LHC. It was commissioned during the LHC start-up in 2008. The system consists of electronics that equips more than 1000 BPMs in the machine. The signal processing is based on a so called wide-band time normalisation (WBTN) technique [19]. In principle the WBTN converts the individual bunch position into a time difference between two pulses. This operation is realised on analogue front-end cards located close to the BPM sensor in the LHC tunnel. The front-end has processing bandwidth of 70 MHz. The dynamic range of the system is about 35 dB in each of the two possible sensitivity ranges [11]. The bunch position is encoded into a time interval between two laser pulses and transmitted over optical fibres to the acquisition system located on the surface. After receiving the signals from the front-end electronics, the acquisition system converts the time interval into voltage using analogue integration. The resulting voltage is then digitized by a 10-bit self-triggered ADC. The digital data then undergoes further processing in order to obtain position readings. The system can perform bunch-by-bunch and turn-by-turn acquisitions. The orbit measurements are computed as average positions of all bunches over a few hundred turns. The results are sent at 25 Hz rate to the data concentrators. Position resolution in the orbit mode is around 5 µm [11]. The front-end electronics can be calibrated with 3 different position offsets using test signals generated in the dedicated electronics. The temperature sensitivity of the position measurements is about 20 µm/˚C [11] when applying a software correction algorithm.

1.5 LHC collimation system

Uncontrolled particle losses in the machine may damage the magnets and as well as other radiation sensitive equipment. The LHC collimator system is designed to perform beam cleaning by intercepting beam particles in dedicated locations of the machine. The system consists of many collimator devices arranged in several beam cleaning stages with a strict hierarchy. The photograph on the Fig. 1-5 (a) depicts an example of an LHC collimator composed of a pair of 1 metre long moveable jaws inside a tank. The beam enters the collimator through an upstream port and exits through a downstream port, as indicated in the picture with the red arrow. Positioning of the jaws around the beam axis is controlled by dedicated electric motors. As shown in Fig. 1-5 (b), the motors at each side of the collimator allow control of the distance between the jaws. Each jaw position can be set with micrometre resolution. The collimators are designed to withstand high particle losses, high radiation, slow wear-out of the movable parts, and at the same time provide good RF and vacuum properties [20].

(a) *(b)*

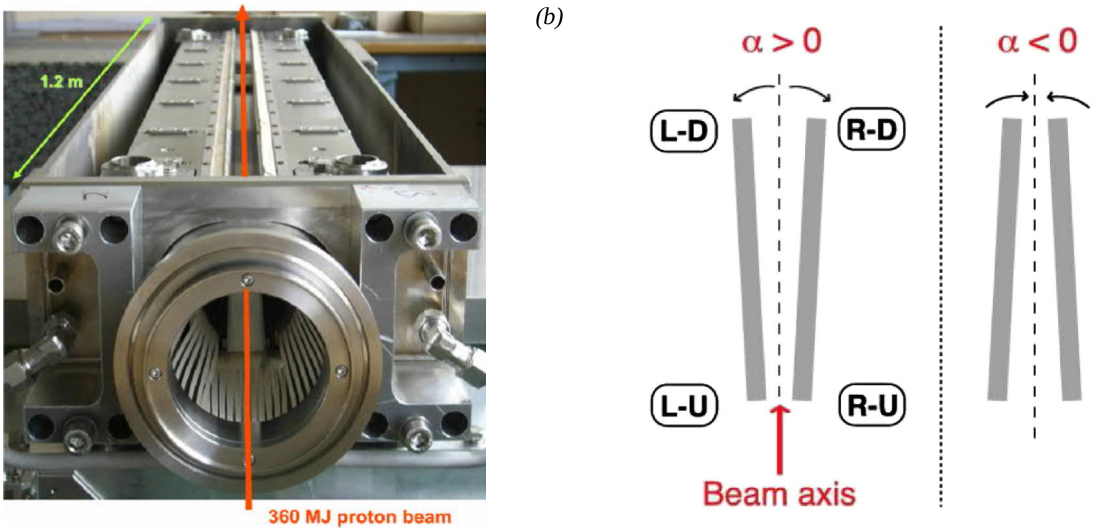

Fig. 1-5 *(a) LHC collimator with two movable jaws enclosed by a 1.2 m long tank. (b) Picture showing an example of the jaw positioning with respect to the beam axis [22]. The red arrow represents a particle beam passing through the collimator.*

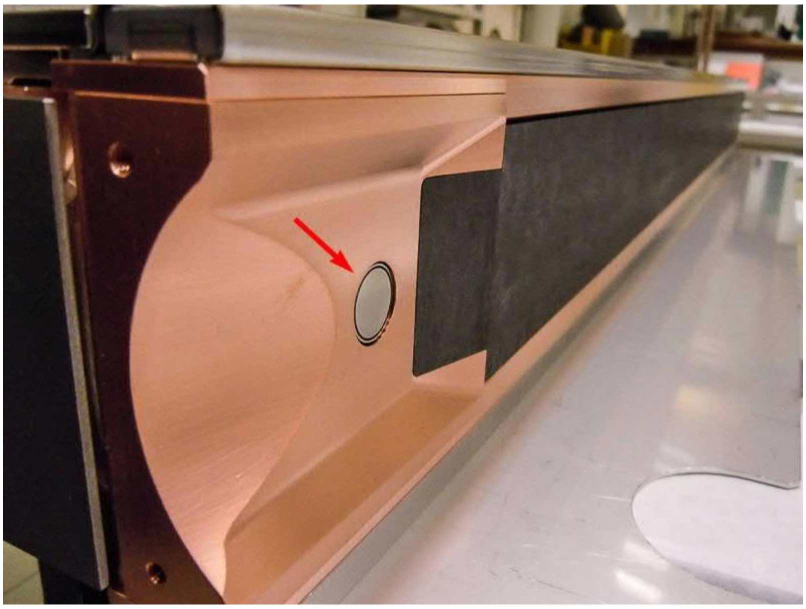

Fig. 1-6 *Photograph of a LHC collimator jaw with embedded BPM electrodes. (Courtesy of CERN)*

Collimator alignment is a process of moving the jaws to a certain distance from the beam. Resulting gap between the jaws is opened for the beam to pass through so that the particles which are outside of the aperture can be absorbed by the collimation surfaces on the jaws. Precise alignment of the jaws is therefore important for proper beam cleaning. A so called Beam Loss Monitor (BLM) based alignment is a method used to align the collimator jaws. It is based on moving each jaw towards the beam until a distinctive particle loss pattern is observed [21]. This happens when the jaw starts to intercept sufficient amount of particles from the beam. Obtained jaw positions are then used as a reference for their further positioning. The method relies on the long-term beam stability and for safety reasons cannot be performed with physics beams. In addition the procedure allows alignment of only a few collimators at a time requiring human supervision which renders the process time consuming. The semi-automated alignment procedure [22] of some 100 moveable collimators requires more than 30 hours [23].

To overcome these limitations the next generation of the LHC collimators features BPM sensors embedded on each side of the jaw [24], [25], as showed in Fig. 1-6. The sensors in a form of retracted button-like electrodes allow to continuously measure the beam position. As a result, both jaws could be aligned using a BPM system without need to create the particle losses as is the case in the BLM-based method. The BPM-based method aims to allow faster and more precise jaw alignments which could be performed even with nominal beam conditions within seconds [26].

The first prototype of such a collimator was tested in the Super Proton Synchrotron (SPS) accelerator. This special type of BPM application required new type of signal processing system which could meet requirements for precision and robustness. After the prototyping phase some 18 new collimators were built and installed in the LHC during its first long shutdown during 2013 - 2015 [27]. Aligning the collimators with the BPMs has a number of advantages:

- fast and precise collimator alignment within seconds,
- all collimators can be aligned at the same time,
- the alignment can be verified during with all types of beams,
- improved collimation efficiency and performance.

2 Motivations and aims of the thesis

Performance of the beam instrumentation systems has strong impact on achieving high quality of the particle beams and performance of the LHC. The introduction chapter presented multiple fields where improving and optimising the performance of the position measurements can improve the beam diagnostic methods, machine commissioning tools, efficient beam cleaning, interlock protection or feedback systems for real-time corrections.

The main goals of the dissertation work can be summarized in the following points:

- Participation in the design and development of a new beam position measurement system, in particular its front-end electronics. Signal processing in the front-ends is split into two separately optimized subsystems which are dedicated for:
  - Precise and accurate measurements of LHC particle beam orbits based on novel diode detector technique [29], in a so called Diode Orbit subsystem (DOR);
  - Processing of beam oscillations based on dedicated diode detectors, in a so called Diode Oscillation subsystem (DOS), to allow measurements of the local betatron coupling and phase advance with minimal beam excitation.
- Building, testing and installing the new system composed of several front-end units used for operational purposes in the LHC.
- Commissioning, measurement analysis and performance optimisation of the new system in laboratory and with beam signals in the LHC.

The most important application of the Diode Orbit and Oscillation system (DOROS) is to provide precise orbit readings for automatic jaw alignment and interlock operation of the new LHC collimators. Another challenging application of the DOROS system is to provide high-resolution orbit and high-sensitivity oscillation measurements in the important BPMs next to the interaction regions of the LHC experiments. In such locations the new system based on identical front-end hardware can be used to measure various beam parameters, such as the orbit drifts in the interaction points, low frequency orbit oscillations, betatron oscillations, local betatron coupling, phase advance and beta-beating. The results of this work had an important impact on the performance, safety and reliability of the LHC operation.

2.1 Orbit measurement

The most important innovation of the new system is the compensated diode detector technique, to the author's knowledge used for the very first time in beam instrumentation applications. The feasibility of this technique was demonstrated with a prototype that was built and tested in the CERN SPS accelerator [29]. The author took part in the development of the following prototypes. The first version was tested during the years 2011-2013 of the first LHC run and achieved sub-micrometre resolution of the orbit measurements [30]. The final design further improves and optimises the performance of the prototype for operational use in critical applications. The DOR subsystem was therefore designed and optimised for:

- large dynamic range accommodating all LHC beam types,
- sub-micron orbit resolution for small and large beam offsets,
- calibration of the systematic errors of the electronics,
- linear response for every beam offset,
- long-term stability and small systematic errors,
- sufficient measurement bandwidth for observing low frequency oscillations,
- robustness and simplicity of the system,
- compatibility with other instrumentation systems,
- reliable operation even without external timings and prior adjustments.

2.2 Measurements based on the excited beam oscillations

The actual LHC BPM system can be used for reliable measurements of the betatron coupling and beta-beating only with beam excitation in the millimetre range. Such excitation amplitudes are allowed for the LHC only under certain conditions requiring special beams, and dedicated machine settings. Therefore, the optics measurements with physics beams, normally the most important for machine optimisation, were not possible [16], [31].

It became obvious during the early development stages that adding a separate subsystem optimised for turn-by-turn beam oscillation measurements would significantly improve the functionality of the system. In addition the oscillation subsystem does not increase the overall system complexity as it shares most of the hardware resources. The first prototype of the oscillation subsystem was built and tested in laboratory to proof its feasibility. This work has been done as a part of the author's diploma thesis [32] finalized in 2013. It was demonstrated that the oscillation part of the new system can operate with low beam excitation, potentially allowing optics measurements with LHC physics beams. The DOS subsystem was designed and optimised for:

- sensitivity of the subsystem to small beam oscillations,
- synchronisation of the ADC sampling frequency and phase,
- flexibility of the oscillation measurements,
- compatibility with the DOR subsystem.

Achieved performance of the hardware and the digital signal processing was verified with laboratory measurements. Obtained results were confirmed with selected beam measurements obtained from the operational system in the LHC.

3 BPM signal processing based on RF diode detectors

Diode detectors can be used to convert amplitudes of the BPM electrode pulses into slowly varying signals. A schematic diagram of a diode detector is shown in Fig. 3-1. Principle of its operation is demonstrated in Fig. 3-2 (a) on two different input signals consisting of voltage pulses with a repetition period *T* and amplitudes V_{i1} and V_{i2}. The pulse amplitudes are proportional to the bunch intensity and transverse position. In the LHC the repetition period of a single bunch is approximately 89 µs [1]. The response signals on the output of the diode detector is illustrated in Fig. 3-2 (b). Static model of a diode is approximated with a constant forward resistance *r* and a constant forward voltage V_d.

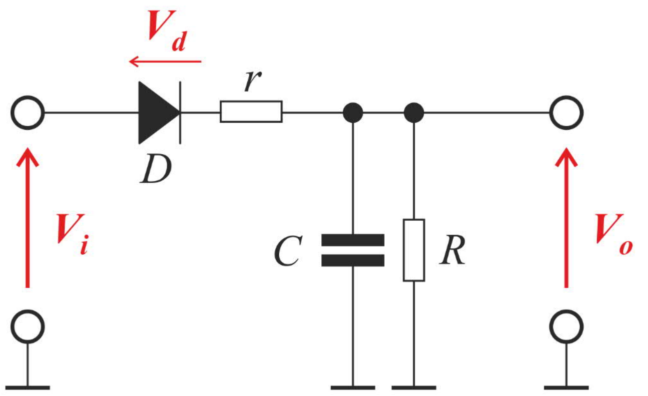

Fig. 3-1 *Schematic diagram of a simple RF diode detector showed in the picture. Resistor r indicates the dynamic resistance of the diode.*

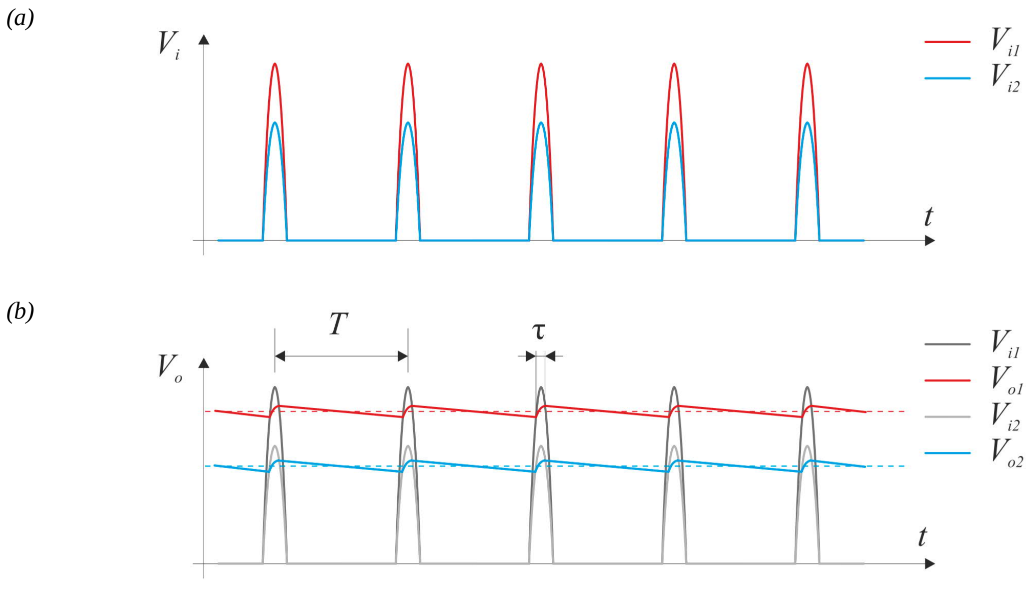

Fig. 3-2 *(a) Example illustration of the electrode signals with two amplitudes Vi1 and Vi2 applied on the input of the RF diode detector. (b) Response of the diode detector in the steady state. Average voltage is indicated with dashed lines.*

Two example plots shown in Fig. 3-3 (a) and Fig. 3-3 (b) illustrate the effect of different values of the discharge resistor *R* on the output signals. Displayed plots allow comparing the response of the diode detector (in red, blue and green) for two pulse repetition periods T_1 and T_2. The dashed lines indicate the average signal level at the detector output. The plot Fig. 3-3 (a) shows the detector responses for the input pulses (in grey) with repetition period T_1. Large discharge resistor value R_1 causes slow capacitor discharge such that the output signal in the steady state is found close to the input peak voltage. Decreasing the resistor to value R_2 or R_3 causes an increase in the capacitor discharge rate as well as the output voltage ripple. As a consequence the average output voltage is decreased. The plot Fig. 3-3 (b) shows the detector responses for the input pulses with repetition period T_2 which equals $2T_1$. The example also depicts a transition T_1 into the new steady state with T_2. The average voltage on the detector output decreases with increased discharge time. The voltage ripple around the average value is increased. The plot also displays the detector signals with smaller resistor values R_1 and R_2 where $R_1 > R_2$. Using a fast discharge rate the output signal may even drop close to zero when the repetition rate of the BPM pulses is too low. In such cases the detector output depends on the pulse duty cycle. This effect also depends on the pulse amplitudes. An example of such scenario could be found with the LHC pilot beams with the maximal repetition period equal to T_{rev}. As can be seen in the plot, the average signal (dashed line) does not drop to zero but stays at some constant level. The dependency on the duty cycle may dominate in the signal which can lead to large errors in the measurements. Such effect can be avoided by using slow detector discharge when measuring low number of bunches grouped on the circumference. The detector is then operated in a so called peak detection mode.

Examples of the diode detector signals with two different bunch patterns are illustrated in Fig. 3-4 (a) and Fig. 3-4 (b). The plot (a) shows an example of a typical distribution of bunches with equal pulse amplitudes. In this scenario the diode is in the conducting state for all bunches in the machine. However, when the amplitude distribution in the pattern becomes asymmetric the detector will measure mostly bunches which produce dominant pulse amplitudes. If the discharge rate of the detector is slow (e.g. the R_1 is large) the remaining bunches producing smaller amplitudes will be ignored and thus will not contribute to the output signal. Such effect can be avoided by using fast detector discharge when measuring BPM signals with important asymmetry in the amplitude distribution. The detector is then operated in a so called averaging mode.

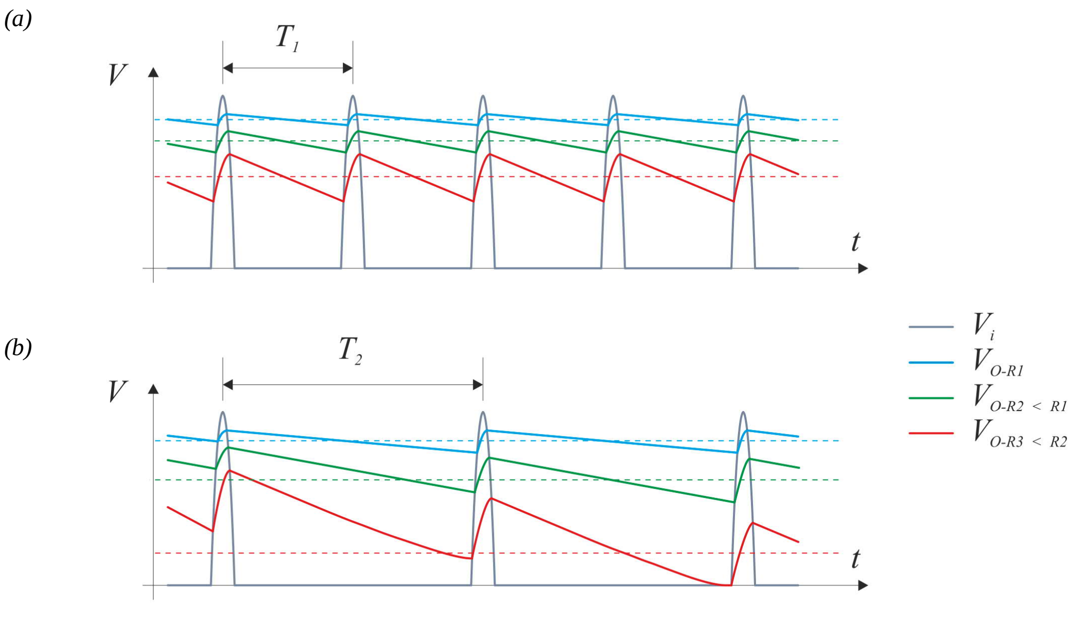

Fig. 3-3 *Example illustrations of the diode detector output signals displayed for two bunch repetition periods T_1 and T_2 and different discharge resistors R_1, R_2 and R_3. The pulse amplitude is constant in both examples. The relationship between the resistor values is $R_1 > R_2 > R_3$. Average voltage in the steady state is indicated with dashed lines.*

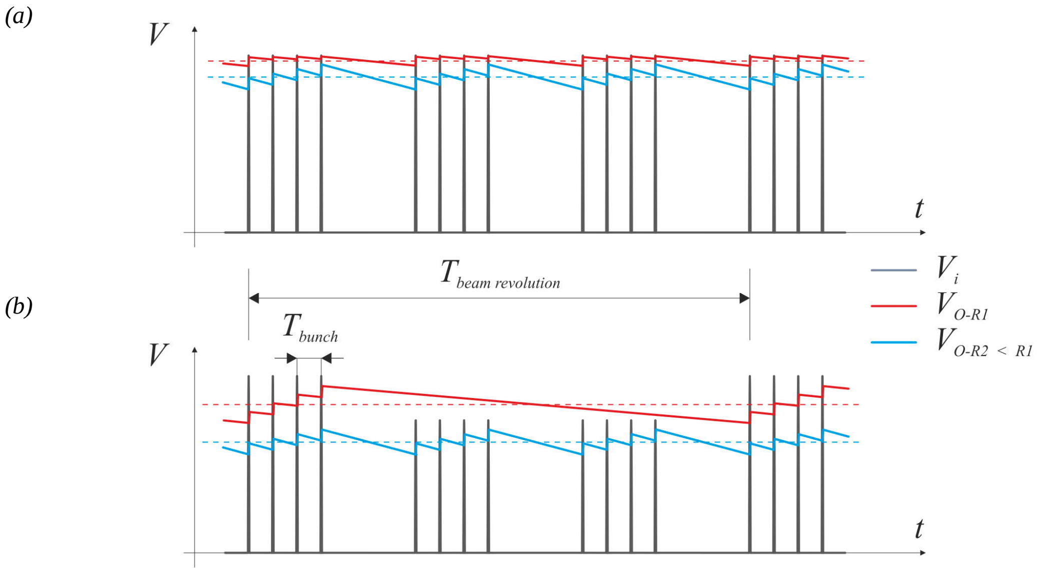

Fig. 3-4 *Example of the diode detector signals for different amplitude distribution in the bunch pattern. Bunches repeat every beam revolution T_r with T_{bunch} spacing between them. The plot on the top displays 16 pulses with equal amplitudes. The plot on the bottom illustrates pattern where the amplitudes of 8 pulses in the middle is decreased. Output signals are displayed for discharge resistors R_1 and R_2. The relationship between the resistors is $R_1 > R_2$. Average voltage in the steady state is indicated with dashed lines.*

3.1 Beam position measurement

The diode detectors can be used to process electrode signals from a BPM in order to measure the transverse position and oscillations of the LHC beams. Schematic diagram in Fig. 3-5 illustrates a setup of the diode detectors used to process BPM signals V_{i1} and V_{i2} from the two opposing electrodes. The resistors R_T provide impedance matching on the detector inputs. Each electrode signal is then processed by a dedicated diode detector producing output signals V_{o1} and V_{o2}. The voltage drop across the diode is denoted with V_d. As indicated in the picture the two diode detectors are assumed to be identical.

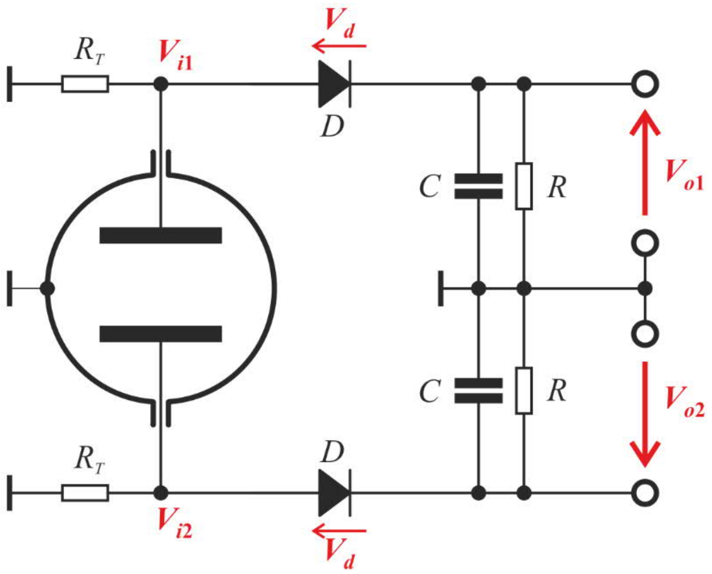

Fig. 3-5 *Example schematic of a diode detector setup used to process* V_{i1} *and* V_{i2} *signals from two BPM electrodes.*

The relative position error p_{err} as measured by the simpla RF diode detectors can be expressed as:

$$p_{err} = \frac{2V_d}{V_{i1} + V_{i2} - 2V_d} \ . \tag{3-1}$$

In practical example the amplitudes of the input signals V_{i1} and V_{i2} equal to 5 V and diode voltage drop V_d equal to 0.2 V, the position error p_{err} is calculated to about 5 % which is more than 0.8 mm when projected on a 61 mm BPM aperture. In addition, the parameter V_d depends on the diode current, temperature and production spread. Typical change of the V_d with temperature can be about 2 mV/°C which would translate in this example into a 1 % position error. These limiting factors were addressed by the V_d compensation scheme described in the following chapter.

The simple RF diode detectors can be however designed and optimised for achieving high sensitivity to the relative position change such as the betatron oscillations [35]. Schematic diagram of the oscillation signal processing based on the RF diode detector is illustrated in Fig. 3-6 along with the example signals in important nodes. In the LHC the amplitude of the BPM signals can reach more than 100 V with an amplitude change typically smaller by a few orders of magnitude. Diode detectors can be designed to process such voltages when built with several diodes in series. Schottky RF diodes are suitable for such applications for their fast switching times, low input capacitance and low voltage drop V_d. The detectors then down-convert the small oscillations into the base-band. An important part of the energy of the betatron harmonics appears in the base-band which results in a large betatron signal gain. In order to achieve high sensitivity, the dominating DC part is removed on the series capacitors. The oscillations are then measured after the following operational amplifier and filtering stages. The band-pass filter smooths the charging and discharging of the detector capacitors, attenuates the low frequency background components as well as the revolution frequency components which could potentially saturate the following stages. Described oscillation signal processing based on the RF detectors was implemented in the LHC base band tune system (BBQ) [37]. The unprecedented sensitivity of the system allows to measure frequency of the natural beam oscillations with amplitudes in the order of nanometres and frequency resolution in the order of 10^{-5} [36]. The RF diode detection technique has number of advantages when measuring relative position changes:

- large dynamic range,
- wideband signal processing,
- sensitivity to very small beam signals,
- no external triggering required,
- no biasing required,
- simplicity and robustness of the circuit.

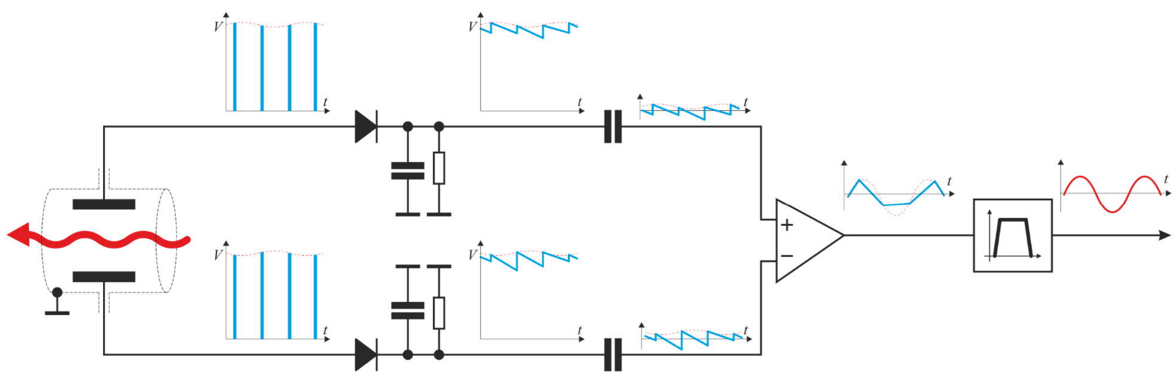

Fig. 3-6 *Schematic diagram of an oscillation signal processing based on a diode detector principle. The diagram displays the example signals in the important nodes [36].*

3.2 Compensated diode detectors

The RF diode detectors can be designed to process BPM signals and provide output signals which are proportional to the beam position. However, as observed in equation (3-1), using a simple RF diode detector for orbit measurement would result in systematic errors that depend on the diode forward voltage V_d. This voltage drop can be compensated using a circuit similar to the classic diode detector described in a popular electronics book [38]. The circuit showed in Fig. 3-7 is composed of two RF diode detectors connected to the same input signal V_i. A so called 1D diode detector branch is built with a single diode D_1. Its output voltage V_1 is thus smaller by the diode voltage V_d as indicated in the diagram. A so called 2D diode detector branch has two diodes D_{2a} and D_{2b} in series. Its output voltage V_2 is smaller by $2V_d$. The output signals from the two sub-detectors are processed by two operational amplifiers OA_1 and OA_2. Voltage drop $2V_d$ is derived from the V_1 by the amplifier OA_1. It is then added to the output voltage of the amplifier OA_2 which functions as a follower for the V_2. Output voltage V_o can thus be expressed as:

$$V_o = \left(1 + \frac{R_{oa1}}{R_{oa2}}\right) V_1 - V_2 \,. \qquad (3\text{-}2)$$

Approximating the detector voltages V_1 and V_2 as the input voltade V_i decrased by the voltage drop V_d and assuming identical resitors R_{oa1} and R_{oa2} the output voltage V_o in equation (3-2) can be then expressed as:

$$V_o = [2V_i - V_i] + [2V_d - 2V_d] = V_i \,. \qquad (3\text{-}3)$$

As seen in the equation, the voltage drop is compensated when the amplifier gain is equal to the voltage drop ratio of the 1D and 2D detectors. For the compensation scheme to work the diode in the circuit have to have identical characteristics and working conditions. Differences of component spread can be minimized by using three diodes in a single package. The impact of the thermal drifts is also minimized this way. The amplifier feedback resistors R_{oa1} and R_{oa2} should be selected with precision better than the symmetry between the diodes in the circuit. As shown in the Fig. 3-7 the compensation scheme is built with the same R and C component values in both detector branches. Difference in the diode voltage drop between the two branches results in different charging and discharging currents between the two sub-detectors.

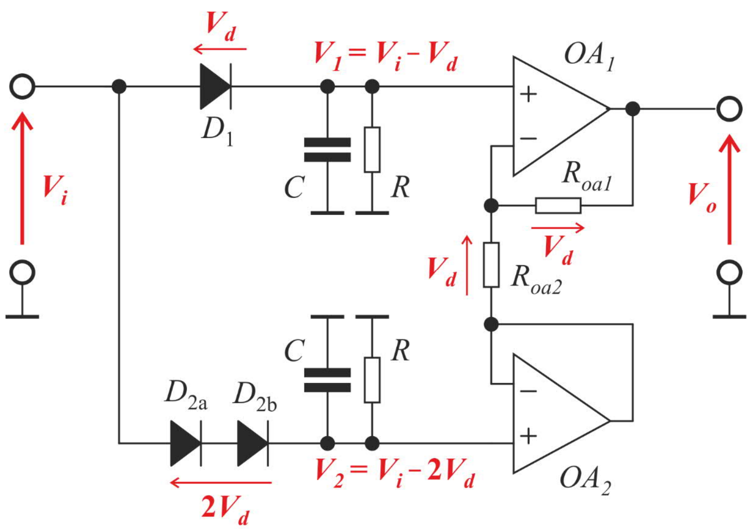

Fig. 3-7 *Schematic of a compensated diode detector. Voltage drop over forward biased diode D_1 is compensated by a parallel circuit containing two diodes D_{2a} and D_{2b}. Their voltage is subtracted by an operational amplifier resulting in the output voltage Vo which is equal to the input voltage V_i.*

Example of the input-output voltage characteristic of the compensated diode detector is showed in Fig. 3-8. The plot displays results from the laboratory measurement using 1 MΩ and 10 MΩ discharge resistors. As seen in the plot the asymmetry becomes less important when the amplitudes of the input pulses are sufficiently large. The non-linearity of the detector characteristic is also more important when the input pulses are below 0.2 V. The dynamic range of the input signal has to be therefore controlled within certain limits for the best measurement results. The dynamic range can be controlled by a set of amplifiers placed in front of the diode detectors. The slowest time constant of the detector can be achieved by omitting the discharge resistors. The capacitors are then discharged through the reverse currents of the diodes and the leakage currents of the amplifier inputs. In this mode of operation the circuit acts as a peak detector with the longest time constant.

The compensated diode detectors have a number of advantages. Carefully optimized design can be used to build BPM electronics providing beam orbits measurements with sub-micrometre resolution and wide dynamic range. In addition, the technique allows measuring the peak voltages of each BPM electrode separately and compute the beam positions in the digital domain. Digital signal filtering and calibration techniques can further improve the precision and accuracy of the position measurement. The simple construction of the circuit allows to build a robust BPM system with guaranteed operation even without external timing. The technique is thus suitable for safety critical application requiring high position resolution measured over multiple turns.

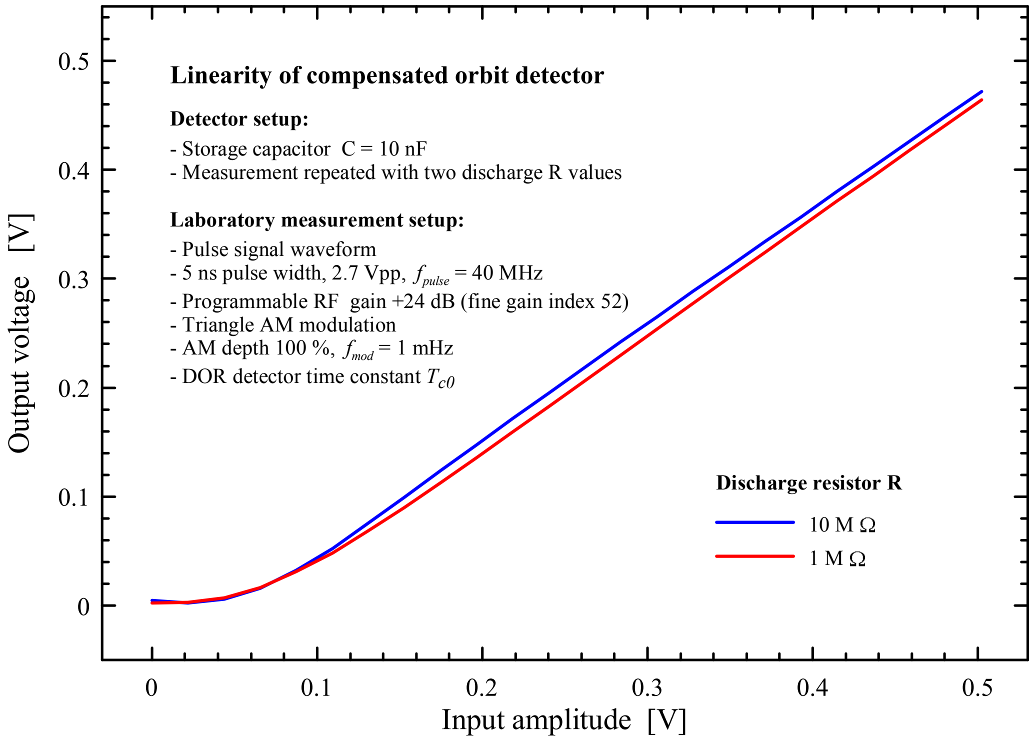

Fig. 3-8 *Input-output voltage characteristic of a compensated diode detector zoomed to a 0.5 V amplitude of the input signal. The characteristic was measured with constant capacitor value 10 nF and discharge resistor values of 1 MΩ and 10 MΩ.*

4 Architecture overview

Developed DOROS front-end is a stand-alone rack mountable unit built as a 19” 1U box. It consists of six electronics boards and power supply modules as shown in Fig. 4-1. The front-end picture was taken without the top cover and without the internal cabling which would otherwise cover the electronics. The boards are mounted on aluminium bars attached to the chassis. The housing was designed to provide solid structural support as well as good heat dissipation. When closed, the entire box surface serves as a heat sink which can be cooled actively by an external airflow.

Two analogue processing boards A and B can be seen on the right side of the picture. Each board is processing inputs from four BPM electrodes. The inputs can be connected to the upstream and downstream electrode pairs of a collimator or to the horizontal and vertical electrode pairs of a dual-plain BPM. The electrode signals are filtered by the input RF filters, which are followed by the programmable RF amplifiers. The resulting signals are then processed by the respective diode detector subsystems. The orbit subsystem is dedicated and optimized for the beam orbit measurements. The oscillation subsystem is dedicated and optimized for beam oscillation measurements. The low frequency signals from the detectors are further filtered and sent over a flat cable to the ADC board A and B respectively. The ADC board contains an 8-channel 24-bit sigma-delta ADC which is simultaneously sampling the analogue signals from four orbit, two oscillation and two auxiliary channels. The board also contains timing and synchronization circuits as well as other circuits dedicated to the voltage and temperature monitoring. Data from the ADC is sent to the FPGA controller over a dedicated SPI bus.

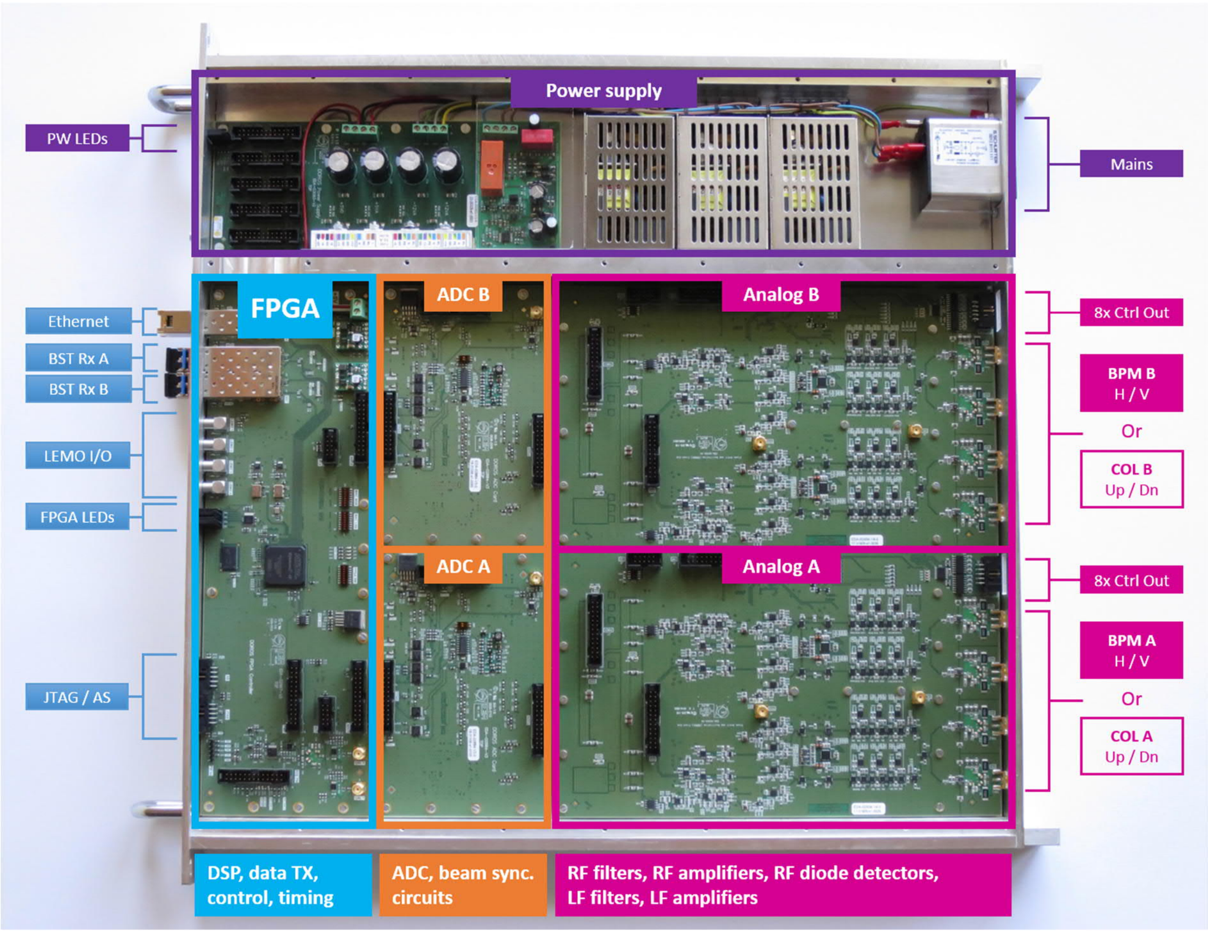

Fig. 4-1 *Top view photograph of a DOROS front-end with removed cover and internal cabling.*

The FPGA Controller board can be seen in Fig. 4-1 left. The board implements the communication and control interfaces, external timing receivers, on-board oscillators, memories, test signal generator, front-end monitoring and fail-safe recovery. The controller is based on an Altera Cyclone IV FPGA [39] running an embedded system based on a NIOS-II soft-core CPU [41]. The embedded system runs on a Micrium µC real-time operating system providing TCP/IP stack and multi-threading for networking, front-end controls and maintenance applications [42]. The digital signal processing, timing and clock management and hardware interfaces were implemented in the FPGA logic. Dedicated SFP module provides the Ethernet communication over 1000-BaseT link. The DSP data along with other information, such as the system settings and statuses, is streamed over a UDP protocol to the selected servers on the CERN technical network. The ADC samples can be at the same time buffered in a 1 Gb DDR on-board memory. The readout and control of the DDR buffers is implemented using a TCP protocol. The DOROS project was assigned a dedicated 16-bit MAC address space for the usage on the CERN technical network. The front-end hardware is identical for all DOROS systems, simplifying the front-end installations, management of the spare parts and maintenance of the DOROS systems. Each front-end can be addressed by a unique 16-bit ID number set on the on-board DIP switches. Reprogramming of the FPGA memory is provided over Ethernet network and is based on a dedicated fail-safe technology, developed also by the author. This technology undergoes patenting process. In addition, the FPGA code can be also programmed and debugged over JTAG or Active Serial connectors available on the front-panel.

The LHC timing of each beam is provided over a dedicated fibre optics network. The FPGA board has two dedicated SFP ports and clocking circuits for receiving Beam Synchronous Timing (BST) distribution. The front-end can receive timing from two independent BST sources. The SFP ports can be connected to the FPGA transceivers for gigabit communication if the BST functionality is not required. A BST decoder module in the FPGA allows receiving the timing messages and provides beam reference clocks, triggers and timestamps [43]. The reference clocks are used by the dedicated synchronization circuits generating the ADC clocks synchronized to the beam. The controller board has four LEMO IO connectors with programmable direction for receiving external signals and timing over coaxial cables. The front-end can be also clocked from an on-board oscillator. Local timing derived from on-board crystal oscillators can be used when the external timing is not available. The FPGA controller also supports the White Rabbit protocol [44] used to receive synchronous timing over Ethernet.

The FPGA controls and maintains the internal front-end hardware over eight I2C buses, six SPI buses and one parallel bus. Two optocoupler-isolated connectors in the backplane provide 16 pins for controlling any external hardware, such as fans or RF switches. The controller board also contains a test signal generator for simulating LHC BPM signals. To simulate different beam intensities, the test pulses can be configured with 3 different amplitudes. In order to simulate betatron oscillations the pulse amplitudes can be modulated by a dedicated DAC. The test signals can be injected to the front-end beam inputs using GaAs switches.

The front-end power supplies can be seen in Fig. 4-1 on the top of the picture. There are three AC/DC converters each supplying 25 W power. Two 12 V AC/DCs are dedicated for the positive and negative voltages used mostly by the analogue circuits. The board seen on the left provides the primary linear regulation and filtering. Important analogue circuits are powered from a second regulation stage implemented locally on the boards. The third AC/DC produces 5 V power supply used mostly by the digital circuits such as the Ethernet transceivers, memories or oscillators. The FPGA has dedicated power supplies provided from additional DC/DC regulators.

4.1 Signal processing overview

Diagram in Fig. 4-2 shows signal processing of one BPM electrode pair inside the DOROS front-end. The signal processing of the second electrode pair on the analogue board is identical and thus is not displayed in the plot. The processing can be divided into the following parts:

- RF signal processing,
- diode orbit processing (DOR),
- diode oscillation processing (DOS),
- digital signal processing and Ethernet communication and control,
- ADC clocking, timing and synchronization.

As seen in the diagram, the RF part of the signal processing is common for the following blocks. It consists of input circuits that receive the BPM electrode signals, programmable gain amplifiers and the test signal generator. The input stage also contains RF signal multiplexers used for calibrating the asymmetries of the orbit measurement channels. The output of each programmable RF amplifier is used by the DOR and DOS subsystems, as well as the timing circuit generating the beam reference signal. The signals on the inputs of each subsystem are buffered by additional RF amplifiers with fixed gains.

The DOR channels are based on a Compensated Diode Detector (CDD) optimized to measure beam orbits in the frequency range from DC to 100 Hz. Each electrode signal is processed by one CDD. Each DOR channel is digitized by a dedicated ADC channel. The beam positions are computed upon the processed ADC samples. The DOS channel which is based on the RF diode detector is optimized for high sensitivity to small beam oscillations in frequency range from 0.05 f_{rev} to 0.5 f_{rev} (approximately 0.05 - 0.5 kHz). One DOS channel measuring oscillations in one BPM plain consists of two diode detectors, differential amplifier and filtering stages. Its output is sampled by a dedicated ADC channel.

To accurately measure the beam oscillations the ADC sampling frequency has to be synchronized to the beam revolution. The synchronized f_{ADC} clock, common for all ADC channels, is provided from the synchronization circuits (SC). As showed in the diagram, the reference clock can be provided either from the BST receiver, front-panel LEMO connectors or an on-board oscillator. The SC uses one of these clocks as a reference for the ADC sampling. The beam reference derived from the BPM electrode signals, allows synchronization of the ADC sampling clock to the beam.

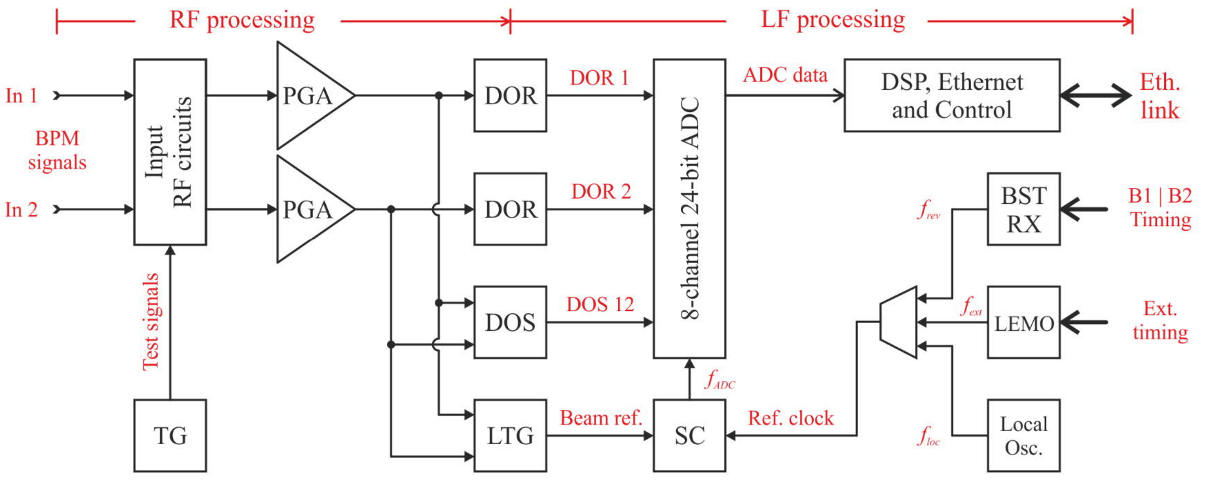

Fig. 4-2 *Schematic diagram of DOROS front-end signal processing and synchronization of two BPM electrode channels.* ***Abbreviations****: RF – Radio Frequency, LF – Low Frequency, PA – Programmable RF Gain Amplifier, DOR – Diode Orbit channel, DOS – Diode Oscillation channel, LTG – Local Timing generator, SC – Synchronization circuits, BST RX – Beam Synchronous Timing receiver, TG – Test signal Generator, DSP – Digital Signal Processing, LEMO – external front-panel connectors.*

The diagram in the in Fig. 4-3 shows the signal processing, control and communication blocks implemented in the FPGA logic. The ADC samples is transmitted over SPI bus in so called sample frames. A single frame contains serialized samples from all eight channels. The FPGA controller has two dedicated SPI buses allowing to read the frames from both ADCs in parallel.

Readout of each sample frame is initiated upon a data ready (DRDY) signal from the respective ADC. The DRDY signal is synchronous to the selected ADC reference clock. The SPI block receives the frames from the ADCs and provides the de-serialized samples from the ADC channels to the corresponding DSP blocks. Both DOR and DOS subsystems have dedicated processing blocks performing signal filtering and decimation. The output data rate is reduced and adapted to the UDP transmission rate.

Results from the DOR and DOS subsystems are merged in a single UDP buffer using a dedicated DSP Direct Memory Access (DMA) unit. The UDPs are transmitted over Ethernet at a 25 Hz rate. The sending frequency is compatible with other LHC instrumentation systems, such as the standard LHC BPM system [11]. The transmission can be synchronized to a dedicated Tx trigger received over the BST protocol [43]. The UDPs from the DOROS front-ends are then received and concentrated by a dedicated server machine. Synchronized transmission allows minimizing the spread in the UDP arrival time. The DOROS server can then synchronously provide the processed data to the logging databases as well as to other servers and applications (e.g. Orbit Feedback System [12]). A single UDP datagram contains also other information describing the current state of the front-end such as hardware configuration, PCB temperatures, state-machine settings, statuses or power supply voltages. This information can be used in a server application for monitoring and diagnostics of the system. A copy of each UDP datagram can be streamed to five servers.

The IP addresses of the operational servers are hardcoded in the FPGA code. The remaining IPs of the development and monitoring servers can be configured over Ethernet and stored in a non-volatile memory accommodated on the FPGA board. The memory stores also other information such as the number of power-cycle counts, status reports, error codes and other diagnostics information.

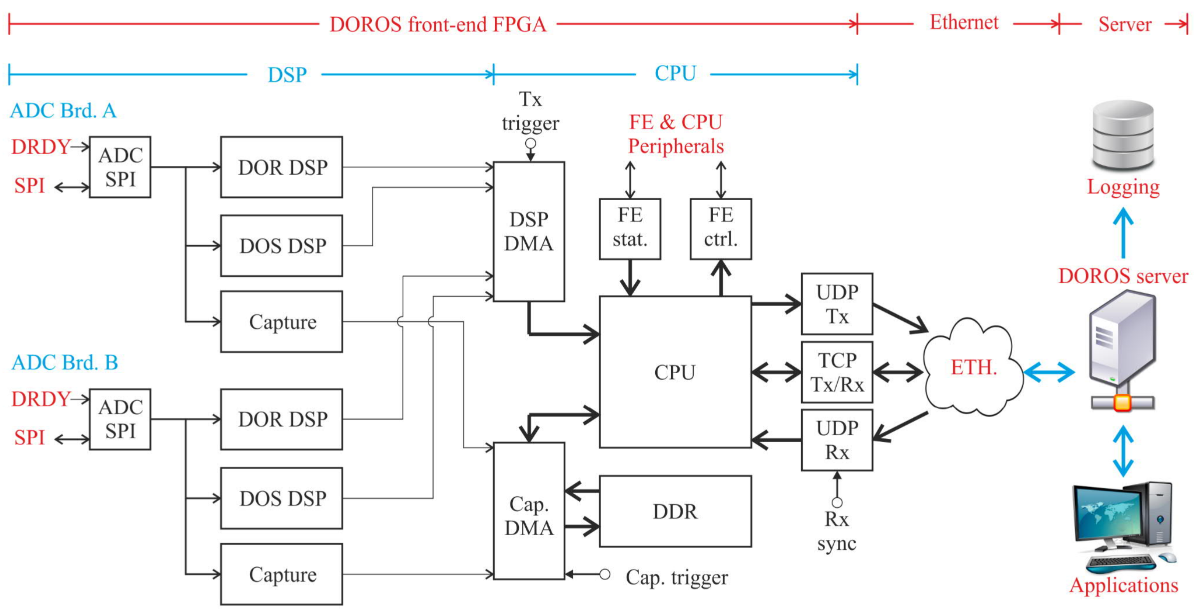

Fig. 4-3 *Diagram of DOROS FPGA blocks performing digital signal processing, communication and controls.*
***Abbreviations**: SPI – Serial Peripheral Interface, DOR – Diode orbit processing, DOS – Diode Oscillation Processing, DRDY – Data Ready signal from ADC, DSP – Digital Signal Processing, DMA – Direct Memory Access, CPU – Central Processing Unit, ETH – Ethernet, UDP – User Datagram Protocol for Ethernet data streaming, TCP – Transmission Control Protocol for Ethernet communication*

The front-end can also buffer the UDP payload data in so called Post-Mortem buffers located on a dedicated address space mapped in an on-board DDR memory. The buffers allow storing some 4500 UDPs sent at 40 ms rate, which is equivalent to some 3 minutes of the front-end operation or 2 million LHC beam revolutions. The data and control of the buffers is provided over a reliable TCP connection for further offline analysis. The readout can be triggered upon safety critical events, such as the beam injection or beam dump.

The raw ADC samples can be also stored in the local DDR memory. The de-serialized and formatted ADC samples from the SPI modules are buffered at the sampling rate without further digital treatment. A so called capture DMA unit stores the channel data from both ADCs in individual circular buffers mapped in a dedicated address space in the DDR memory. The DMA provides input FIFO buffering and the DDR access arbitration on a "first-come-first-serve" basis. This functionality allows clocking the two ADC boards from independent clock domains. Typically, the ADC board A can be clocked from the LHC beam 1 timing and ADC board B can be clocked from the LHC beam 2 timing. The DMA unit offers two modes of operation:

- Capture – The acquisition is started using hardware or software triggers and finishes after programmed amount of ADC frames. The buffers are then available for readout.
- Freeze – The data is acquired continuously in the circular buffers. New data overwrites the old data after each buffer overflow. A freeze command will stop the buffer pointers and make them available for the readout. The buffering is resumed once the data readout is finished.

The circular buffers store the data from four DOR and two DOS channels for each of the two ADCs. The maximum length of an acquisition is about 1.8 million LHC beam revolutions which is equivalent to some 3.5 minutes. The CPU can control the DMA, trigger the acquisition and access the memory to read the circular buffers after they are stopped. The data is then available "on-request" to the servers through a TCP protocol. The capture functionality is suitable for measurements requiring extended observation bandwidth. The freeze mode can be also triggered after each beam dump for extended post-mortem analysis.

Front-end settings are controlled by dedicated servers over the UDP protocol. A single UDP datagram can contain up to 255 command messages, each consisting of 5 bytes. The command messages are executed in the same order as inserted in the UDP payload. The first byte of the message is interpreted as command ID, which is a unique index identifying the command. The command ID field can address up to 255 different functions to control. The remaining 4 bytes in a message are allocated for control data. The execution of the commands can be synchronized to one of the following sources:

- 25 Hz UDP transmission trigger (provided from BST, local or external source),
- 1 Hz trigger (provided from BST, local or external source),
- Immediately, without waiting for the triggers.

If the selected trigger is not available, the commands will execute after a programmed timeout. The CPU performs a number verifications before the payload is accepted for further processing. This includes checking the information, such as the packet length, signatures or UDP ports. The CPU can also perform a simple IP address filtering. Reception of the command datagram is reported in the UDP data stream providing a simple handshake mechanism. The server can thus monitor the command status without opening additional connections.

5 Summary of results and future outlooks

The main subject of this doctoral thesis was to develop and optimise an electronics system called DOROS. The BPM signal processing in this system is based on two diode detector types which were separately optimised for beam orbit and oscillation measurements of the LHC particle beams. The DOROS project started as a simple circuit built in 2009 showing that the diode detectors could be used for BPM signal processing. The following prototyping and first beam measurements showed that a BPM system based on the diode detector techniques could reach resolution of the position measurements better than a micrometre. In the beginning of the doctoral project in 2013 it was decided to develop and deploy a fully operational system dedicated to precise orbit measurements for automatic alignment of the LHC collimator jaws with embedded BPM electrodes. These are critical devices assuring safety and reliability of the LHC. At the same time it was foreseen to test the system on a few selected BPMs around the experiments in the LHC to see if such approach could be used for precision measurements. There the resolution and stability of the position readings is important for a number of measurements, crucial for optimising the luminosity in the experiments and pushing forth the performance limits of the LHC machine. The first DOROS front-ends were installed and commissioned for beam operation in 2015 and more were added over the years of operation. The hardware and firmware in the DOROS front-ends is identical to that of the collimator system which simplifies the maintainability of the two systems.

As of beginning of 2018, the current collimator DOROS system consists of 20 front-end units equipping 22 LHC collimators with the jaws-embedded BPMs located in LHC points 1, 2, 5, 6, 7 and 8. The system is used for precise beam-based alignment of the jaws. This technique allowed to reduce the collimator setup time from several hours to just a few seconds. The system has been used during many machine studies [27], [28], [45] and [46], which were targeting the performance and reliability improvements of the LHC beam cleaning system. Other studies are focusing on the so called wire collimators and their precise alignment for compensating the beam-beam effects during the collisions in the experiments [47]. In addition, the position readings from a few selected DOROS front-ends are used by the LHC interlock system to terminate the LHC operation with beams if the beam positions measured in the collimators exceed safe limits. This functionality became operational since September 2017 without a single malfunction which would trigger a false beam dump and prevent beam injection into the LHC. A lot of effort was put into optimising the system reliability and robustness on both the hardware and software layers. In addition the interlocked system was made redundant with two DOROS front-ends for each collimator BPM to prevent blocking the LHC operation in case of a hardware failure. Each front-end performs a number of sanity checks, including its FPGA-embedded system running an real-time operating system as well as all Ethernet communications with the data concentrators and control servers. In case of a detected hardware or software failure, the front-end can automatically reset and resume operation within some 10 s. The current MTBF estimate of the DOROS system reaches more than 60 years.

The current standard DOROS system consists of 21 front-ends which equip 40 BPMs in the LHC. The system has been installed on the most important Q1 BPMs around the four LHC experiments as well as on a few selected Q5, Q6 and Q7 BPMs located in LHC points 1, 2, 4, 5, 6, and 8. The signals from these BPMs were split between the standard LHC BPM and the DOROS system allowing to evaluate and compare their performance. The standard DOROS system is operationally used for optimisation measurements such as the Van der Meer scans or local betatron coupling measurements. The system was also used during many LHC beam studies such as β^* levelling [40], stripline BPM directivity [47] or beam oscillations at frequencies below 100 Hz [48]. Most of these studies are targeting the LHC high luminosity upgrade necessary for increasing its discovery potential. A recent beam study is focusing on a non-invasive measurements of the quadrupolar moment during the beam energy ramp using the BPM signals. Both the standard and collimator DOROS systems have become important beam instrumentation tools used for the LHC beam diagnostics and performance optimisation.

The main contributions and results of this dissertation work can be summarized as follows:

- **Design, development and optimisation of a new BPM signal processing system based on diode detectors.**

The developed DOROS system described in the thesis consists of front-ends realised as 19” 1U rack units which can process signals from eight BPM electrodes. The BPM signals are first filtered and amplified before they can be processed by the diode detectors. The RF amplifier consists of four stages controlled by the FPGA to provide variable dynamic range of about 90 dB controlled in 1 dB steps. The beam orbit and oscillation signal processing is then addressed by two separate subsystems, each containing specifically optimised diode detector processing. The analogue signals from each subsystem are digitized by an 8-channel 24-bit sigma-delta ADCs and processed in DSP channels implemented in the FPGA logic. The results are then transmitted over Ethernet network to the respective servers. The data transmission at the 25 Hz rate is synchronous to the external triggers received over the LHC BST networks. The ADC sampling is synchronized to the LHC beam revolution frequency f_{rev} of approximately 11.2 kHz using the BST clocks phase-aligned to the local clock reference generated from the BPM signals. At the same time the raw ADC data is stored at the f_{rev} rate in the circular buffers in the local DDR memory. The data is then available for capture or post-mortem analysis. The FPGA system controls the functionality of the front-end such as the calibration switching, automatic gain control, test signal generator, synchronization circuits, status monitoring or the fail-safe reprogramming and recovery system.

- **Design and optimisation of signal processing dedicated to the beam orbit measurements in the LHC based on compensated diode detector technique.**

The most important innovation of the new system is the compensated diode detector technique, to the author’s knowledge used for the very first time in beam instrumentation applications. This technique is used in the so called DOR subsystem in the front-end for measuring beam orbits and low frequency beam oscillations. A typical BPM sensor in the LHC can produce pulses with time duration of about 1 ns, repeating every 25 ns. Depending on the bunch intensity and the BPM type, the peak amplitudes can change by some four orders of magnitude, typically between 0.1 V and 100 V. Measurement of a 1 µm position change on a 100 mm aperture BPM would require resolving a change of the peak amplitude in an order of 10^{-5}, which is equivalent to a voltage change of 10 µV on 0.1 V peak amplitude. The RF diode detectors have a number of advantages for measuring small beam position changes:

- fast response,
- sensitivity,
- no external triggering required,
- simplicity and robustness.

It was shown that beam positions computed from the RF diode detector signals depend on the voltage drop seen across the diode detector which can change according to the current flowing through the diode, temperature or the production spread. The compensation scheme minimizes these dependencies, reducing the temperature drifts and offset errors in the measured beam positions. Precision and accuracy of the measurement are influenced by the gain and offset asymmetries between the respective analogue channels. In order to minimise such asymmetries using only the beam signals, a so called automatic calibration switching method was developed. This technique is based on periodic signal multiplexing between the front-end analogue channels followed by further signal treatment in the DSP and a calibration algorithm computing the calibrated positions on the remote server. The automatic calibration switching minimizes the systematic position errors which depend on the RF gains as well as drifts in the analogue electronics. The calibration switching is important especially for the collimator jaw alignments or the long-term measurements during the LHC stable beams.

The dynamics of the diode detectors can be changed with their time constants controlled by the FPGA system. Three DOR time constant settings T_{c0}, T_{c1} and T_{c2} are available. The T_{c0} is the slowest and the T_{c2} the fastest capacitor discharge rate set by a switchable resistor network in each detector. These settings affect number of parameters such as the detector bandwidth, the frequency characteristic or the transient response during the calibration switching. Slow transient response of the diode detectors limits the maximum switching frequency and the minimum latency of the calibrated measurements.

Transient response with different time constant settings were analysed. The duration of the transient with the slowest time constant T_{c0} was measured to be some 0.4 s which would limit the maximum calibration frequency to less than 2.5 Hz. A transient speed-up method was developed to decrease the transient duration by means of automatic control in the FPGA system. The speed-up is based on temporal increase of the detector discharge rate after each transient which is achieved by dynamic control of the time constants. The data affected by the transients is then rejected in the position computation algorithm. The presented laboratory measurements showed that this technique helps to decrease the transient duration to some 0.15 s. Consequently, the calibration switching rate with the slowest time constant can be increased to more than 5 Hz.

Frequency characteristics and the bandwidth of the compensated diode detectors were measured in laboratory and presented in the thesis. It was shown that the time constant T_{c0} sets the smallest measurement bandwidth, up to some 10 Hz. Due to its slow discharge rate, this time constant setting should be used for input pulses with low repetition rates, such as the LHC pilot beams consisting of a single bunch. Time constant T_{c2} provides the largest bandwidth of the DOR detectors, up to some 500 Hz. However, the measurement bandwidth is limited by the output analogue filters to 100 Hz. This setting is more suitable for higher pulse repetition rates, such as the LHC physics beams which typically consist of more than thousand bunches. As opposed to the T_{c0}, the frequency response of the detectors with T_{c2} is flat and therefore more suitable for measurements such as orbit oscillations.

Precision and accuracy of the calibrated orbit measurements was evaluated in laboratory and presented in the thesis. The measurements were performed with a signal generator simulating the LHC BPM signals. The analysis was focused on evaluating the systematic errors and noise of the position signals measured with different RF amplifier settings and pulse repetition rates. The quality of the calibrated measurements was compared to the raw measurements without calibration. The position computation assumed 61 mm BPM aperture. The offset errors of the absolute positions was estimate to be around ±150 µm when the calibration was not used. Such offset error would be translated as alignment error of the collimator jaws induced by the position measurement system. It was also observed that, depending on the RF gain settings, these errors changed by more than 50 %. The calibration switching reduced these offset errors to less than 30 µm which is equivalent to around 0.1 % asymmetry between two DOR channels. Obtained results were also independent of the RF gains. It was shown that the calibration switching helps to improve the resolution and decrease the low frequency drifts caused by slow changes of the gain asymmetries. The position drifts were reduced by the calibration switching by more than factor 2. The position noise was estimated in the calibrated measurements to less than 0.5 μm_{RMS}. For favourable conditions the noise level was estimated to be less than 0.05 μm_{RMS}. This result could be achieved with high pulse repetition rates on the signal generator and low gain settings in the RF amplifier. Similar settings are typically used during physics beams with nominal intensity bunches.

Sensitivity of the position measurements to the induced temperature change were evaluated and presented in the thesis. After 4 hours of stable measurement conditions, the temperature changes were induced by opening the front-end unit and exposing its electronics to the temperature fluctuations. The following measurement was performed with a forced air flow over the electronics with an external ventilation unit. The temperature change during the test reached 15 ˚C, which is much more than the typical operating conditions observed in the LHC tunnel. It was showed, that the temperature sensitivity without the calibration switching can reach about 1 µm/˚C. Applying the calibration switching at 1 Hz rate reduced the dependency of the measurement on the temperature change by an order of magnitude.

Performance of the DOR subsystem was evaluated with beams using the DOROS systems in the LHC. The upstream and downstream BPM electrode readings of the collimator DOROS system were used to estimate the noise and long-term stability with the LHC beams. The orbit resolution estimated over 11 hours of measurements with physics beams was better than 0.1 µm. The offset drift most probably caused by the DOROS electronics was estimated to less than 0.5 µm. Long-term stability of the DOR subsystem was also demonstrated with the standard DOROS system acquiring orbits measurements during a 37 hour LHC physics fill. The beam orbits were measured in the BPMs located on the left and right side of the ATLAS and CMS experiments. The projected orbit signals to the middle to the experiments changed during this measurement by less than 15 µm. It was observed that the beam position drifts are correlated between the ATLAS and CMS interaction regions. The position results from the standard DOROS system were used in comparison with the standard LHC BPM system. Presented measurement examples were acquired during the Van der Meer position scans in the ATLAS experiment. The largest discrepancy between the absolute beam positions was measured around 400 µm which is equivalent to 0.6 % error on the BPM aperture. Part of the orbit measurement was used to estimate and compare the precision of the two systems. In this comparison the DOROS system achieved improvement of more than factor 6 in both the standard deviation and peak-peak noise estimation. This comparison assumed that the estimated noise was dominated by the measurement system. Further beam measurements showed that the standard DOROS system measures oscillatory-like beam motion with amplitudes in the order of a few micrometres and frequency in the order of 0.01 Hz. It was also observed that the measured oscillations have negative impact on the collision rates in the experiments.

As the compensated diode detectors consist of non-linear elements, the linearity of the position measurement has been measured and analysed. The presented laboratory measurements showed that when the simulated beam is centred and the pulses from the electrodes have equal amplitudes, the influence of the signal amplitude changes on the measured positions is very small. This is typically the case for the collimator system where the BPM-embedded jaws are aligned symmetrically with respect to the beam. In such conditions the diode detectors of each channel pair operate with very similar signals, reducing the influence of the residual nonlinearity of the detectors. In the least favourable conditions when the diode detector operates with T_{c2} and the signal amplitude changes by 50 % of the ADC full-scale, the position change was measured to be less than 1 µm. The calibration switching helps to suppress most of the asymmetries between the two channels processing signals from the BPM electrode pair and thus also improve the linearity of the measurement with centred beams.

The systematic errors of the beam position measurements become more important with increasing beam offsets. In such conditions the signals for the opposing BPM electrodes have much different amplitudes, causing the corresponding diode detectors to operate at quite distant part of their characteristics. Then the residual nonlinearities of the characteristics are converted into systematic position errors changing with the signal amplitudes driven by the beam intensity decay. Depending the detector time constant and position offset the position error for a 50 % amplitude drop could reach more than 100 µm. The linearity errors were decreased by compensating of the amplitude drop using the automatic gain control with 1 dB gain steps in the RF amplifier. The automatic gain control can reduce the signal change on the detector inputs to about 12 %. The position error was reduced to some 25 µm when using the time constant T_{c0} and setting the automatic gains to maintain the signal levels within 0.6 - 0.8 ADC FS range. It was also showed that the smallest systematic errors can be achieved with the slowest detector discharge T_{c0} achieving more than 20 % position error reduction in comparison to the T_{c2}. However, using only the T_{c0} time constant is not optimal in all operational conditions. An example of such a case is a physics fill lasting several hours. During this time the diode detectors start measuring the orbit of non-colliding bunches, whose nominal intensity decays slower. The problem was solved by using the faster discharge constant T_{c2} to operate the detectors in the averaging mode.

Further improvements can be achieved by linearization of the diode detector characteristic using the correction polynomials obtained from the laboratory measurements. The fitting and correction coefficients were computed up to the 5th order polynomials for all three detector time constants. Performance of the linearization method and its impact on the precision of the orbit measurement was evaluated with the LHC beams. Without additional corrections the non-linear errors became apparent especially in the BPM planes where the beam offsets were larger than 3 mm. Each 1 dB increase in the RF gains caused some 20 µm discontinuity in the orbit measurements which significantly limited the operational precision. Proposed linearization polynomials obtained from the laboratory measurement were used to correct the non-linear effects observed in the beam measurements. Obtained results of the 3rd order polynomial correction showed that all the orbit discontinuities caused by the gain change were minimized to less than 1 µm. The non-linearity correction is currently performed as part of the position computation in the DOROS server. The same correction coefficients are used for all DOROS front-ends. This simplification results in the error increase to some 5 µm when comparing the performance of all standard DOROS front-ends.

In addition to the calibrated orbit processing, the DOROS systems can acquire the DOR signals from each BPM electrode using the data capture in the front-end memory. The main advantage is that the capture mode allows to acquire the raw ADC samples at the turn-by-turn rate for a few millions of LHC beam revolutions. The increased measurement bandwidth is suitable for observing orbit oscillations at higher frequencies than the calibration switching. Depending on the time constant of the diode detectors the observation bandwidth can be increased to some 100 Hz. For such measurements the calibration switching has to be temporarily turned off to measure the oscillations with fine frequency resolution in the frequency domain. An example of the orbit spectra measured with the three time constants was also presented in the thesis. This mode became useful for diagnostics of low frequency beam spectra [48].

- **Design and optimisation of signal processing and synchronization of the beam oscillation measurements.**

The so called DOS subsystem in the DOROS front-ends was designed and optimised to perform measurements of the excited beam oscillations and related beam and machine optics parameters, such as betatron coupling or phase advance. The beams during these measurement are excited at a frequency close to the fractional LHC tunes. Processing of the DOS signals can be thus focused only on the excited oscillation components rather than on the whole frequency spectrum. The narrow-band signal processing allows to increase the sensitivity of the system and simplify the data processing. The oscillation signal processing of a BPM electrode pair is based on two RF diode detectors. An AC coupling removes the dominant DC part of the signals related to the beam intensity and thus increase the dynamic range. The oscillation parts of the BPM signals are then subtracted on a differential amplifier, allowing to measure the relative position changes in frequency range from approximately 500 Hz up to some 5 kHz. The DOS signals are sampled by the multichannel 24-bit sigma-delta ADC shared with the DOR subsystem. The DOS data is then processed by dedicated DSP channels transmitted at 25 Hz rate over Ethernet. This design did not significantly increase the overall system complexity as most of the hardware resources are shared with the DOR subsystem, such as the RF filters and amplifiers. The proper signal levels on the input of the DOS detectors are guaranteed by the automatic gain control used by the DOR subsystem. The presented laboratory measurements were focused on characterisation of the DOS performance with a signal generator simulating the BPM signals. The beam oscillations were simulated with amplitude modulation of the pulses. The measurement results showed, that the SNR of the narrowband DOS signals depends on a few parameters, such as the:

- pulse amplitude modulation depth, which represented the oscillation amplitude,
- pulse repetition rate, which represented the bunch spacing,
- generator signal amplitude, which represented beam intensity,
- and FFT length, which also represented duration of the beam measurement.

Large beam excitations applied for very long time lead to increasing beam size resulting in decreasing efficiency of the collisions. It was estimated with laboratory measurements, that a single nominal bunch in the LHC with excited oscillations of only 10 µm amplitude for 1 s duration would yield some 40 dB SNR in the DOROS oscillation measurements. By increasing number of the simulated bunches to the full capacity of the LHC, the same SNR could be reached within the 1 s duration with less than 1 µm oscillation amplitude.

The standard DOROS system was used to measure excited beam oscillations in the LHC in order to evaluate the local betatron coupling. The beam excitation was chosen such that both the DOROS and the standard LHC BPM system can detect and measure the beam oscillations. As the DOS part of the DOROS system measures only the position change, the standard BPM system was used to estimate amplitude of the oscillations in micrometres which was then used to scale the DOS results. The noise floor of the DOS subsystem was estimated to 0.1 µm. In comparison to the standard BPM system, the DOS achieved sensitivity improvement by an order of magnitude. This improvement was important in a few cases when the sensitivity of the standard system was not sufficient to detect the beam oscillation. Obtained results from the local beam coupling analysis [48], [49], [50] showed very good agreement between the two BPM systems.

Timing circuits described in the thesis allow synchronization of the DOROS front-ends to a common reference clock derived from the BPM signals synchronous to the beam. The local timing generator circuit was designed and optimized to derive the LHC revolution clocks using a fast comparator and a hold-off circuit implemented in the FPGA logic. A beam synchronous reference clock is generated locally in each DOROS front-end from a selected bunch in the bunch train, common for all front-ends. It was shown that the threshold level of the input comparator can be optimised based on the orbit signals measured by the DOR subsystem. A change in the threshold level controlled by a DAC introduces a delay in the reference clock maximum about 1 ns. Proper setting of the threshold level according to the DOR signals improves robustness of the produced beam reference clock.

The beam-based clock reference is not available for all beam conditions and front-end settings. Therefore, another clock reference is received from the BST network with guaranteed operation in all beam conditions. However, the phase synchronism with beams is not guaranteed causing systematic errors in the phase advance measurements. Therefore, the phase of the revolution clocks received from the BST can be adjusted in 100 ps steps by a PLL-based phase shifter. Such small phase differences are difficult to be reliably measured by classical counting methods. The thesis also presents a dedicated phase detector circuit which has been developed and optimized to detect small phase difference between two f_{rev} clocks and allow their precise phase alignment. Its phase-to-voltage characteristic was designed to have an extremum when its two input signals are exactly in phase. In this condition all its digital signals are of 50 % duty cycle so that the circuit characteristic does not have a dead zone. This feature allows a precise indication of the zero-phase condition, which is independent of the detector power supply and the offset of its ADC readout. The laboratory measurements demonstrated that the differential phase detector circuit is capable of detecting the zero-phase condition with resolution well exceeding the minimum phase step of 100 ps. The peak-peak noise of the phase measurement was estimated at the zero-phase condition to less than 30 ps. The nominal performance can be reached only with the circuit enclosed inside the front-end. The temperature sensitivity of the phase detector signal was estimated to 1.6 µV/˚C which can be expressed as an equivalent time delay of around 22 ps/˚C. The signals from the phase detector can be thus used for the long-term monitoring of the phase alignment.

At the time of finishing this doctoral work, further studies and developments are performed on the DOROS systems. One of the developments targets a radiation tolerant version of the DOROS electronics. Such system could be installed in the LHC tunnel where the ionising doses may reach levels harmful for regular electronics.

Length of the coaxial cables from the BPM sensors that would allow to place the electronics to safe locations may become an important factor for the overall system cost and performance. The study investigates the tolerance of the individual components to the ionising radiation and its impact on the measurement performance.

Another study looks into developing a version of the DOROS system optimised for the SPS accelerator. There the beam revolution frequency is four times higher than in the LHC, which would require to increase the ADC sampling as well as the bandwidth of the input RF filters and amplifiers. In addition the SPS cycle is much faster. A typical cycle can last only a couple of seconds depending on the type and purpose of the SPS beam. Therefore the bandwidth of the signal processing, including the digital signal processing part, has to be appropriately adapted to provide more orbit samples especially for short SPS cycles.

6 Conclusions

The DOROS systems developed at CERN have become an important part of the LHC beam instrumentation. This doctoral thesis demonstrated that a BPM measurement system based on novel diode detector circuits can be built and optimised for achieving submicron resolution of beam orbit measurements as well as sensitivity to micrometre-order beam oscillations. Presented development and measurements were realised at CERN as part of the beam instrumentation research and development.

The first part of the DOROS system was optimised for measuring the beam orbits. This doctoral thesis presented new signal processing techniques developed and optimised to continuously calibrate the symmetries between the channels. The techniques are crucial for minimising the systematic errors and drifts of the electronics as well as maximising the precision and response of the position measurements. Linearity of the orbit measurement system was optimised with careful settings of the automated gain control algorithms, and at the same time using the correction functions obtained from the laboratory measurements. The calibration and linearity corrections are applied in real-time obtaining the beam position readings at 1 Hz rate.

The second part of the DOROS system was developed and optimised to measure transverse beam oscillations with high sensitivity. Dedicated timing circuits and signal processing were implemented in the system to allow synchronisation of the acquisition and the oscillation signal processing to the LHC beam revolution. The oscillation signal detection and synchronization techniques studied in the thesis are important for precise measurements of the magnet optic parameters, such as the local betatron coupling, phase advance and beta-beating, using only very small beam excitation amplitudes.

The DOROS systems have been commissioned and operationally involved in many beam measurements used to optimise the performance, reliability and safety of the LHC accelerator. The main application of the collimator DOROS system is precise orbit measurements for alignment of the collimator jaws with the beam. This system provides measurements to LHC interlock system which can cut off the operation with beams if the measured beam position exceeds safe limits.

In addition, the DOROS system is also used to provide precise orbit and oscillation measurements in the most important BPMs around the four main LHC experiments. This system is operationally used for optimisation measurements such as the Van der Meer scans or local betatron coupling measurements. This system was also used during many LHC beam studies such as the β^* levelling, stripline BPM directivity or low frequency beam oscillations. These studies are targeting the LHC high luminosity upgrade which is necessary for increasing the LHC discovery potential.

7 Resumé

Hlavnou úlohou tejto dizertačnej práce bolo vyvinúť a optimalizovať elektronický systém s názvom DOROS. Spracovanie BPM signálov v tomto systéme je založené na dvoch druhoch diódových detektorov, ktoré boli oddelene optimalizované na meranie orbity a oscilácií časticových zväzkov v urýchľovači LHC. Projekt DOROS začal v roku 2009 prototypom jednoduchého obvodu, ktorý ukázal, že diódové detektory môžu byť použité na spracovanie BPM signálov. Následný vývoj prototypov a prvé merania so zväzkami ukázali, že BPM systém založený na technológii diódových detektoroch môže dosiahnuť rozlíšenie merania polohy zväzkov lepšie ako jeden mikrometer. V roku 2013 bolo rozhodnuté vyvinúť a inštalovať plne funkčný systém, ktorý by umožnil presné zarovnávanie čeľustí LHC kolimátorov pomocou integrovaných BPM senzorov. Takzvaný kolimátorový DOROS systém je kritický pre bezpečný chod a spoľahlivosť urýchľovača LHC. Idea použitia diódových detektorov na presné merania pozície zväzkov bola súčasne testovaná na niekoľkých vybraných BPM senzoroch v okolí LHC experimentov. Rozlíšenie a stabilita meraných hodnôt v týchto lokalitách LHC predstavujú dôležité parametre pre množstvo meraní, ktoré sú kritické pre optimalizáciu luminozity jednotlivých experimentov a prekonávanie limitov LHC. Prvé DOROS zariadenia boli nainštalované a uvedené do prevádzky v roku 2015. Takzvaný štandardný DOROS systém bol potom postupne v priebehu rokov rozširovaný o ďalšie jednotky v rôznych lokalitách LHC. Hardvér a firmvér je identický vo všetkých DOROS zariadeniach v LHC, čo umožňuje ich jednoduchšiu údržbu.

Súčasný kolimátorový DOROS systém sa skladá z 20 jednotiek, ktoré umožňujú merať pozíciu zväzkov v 22 LHC kolimátoroch s integrovanými BPM senzormi. Tento systém sa používa na presné zarovnanie čeľustí vzhľadom na meranú pozíciu zväzku. Čas potrebný na nastavenie kolimátorov bol pomocou DOROS systému rádovo zredukovaný z niekoľkých hodín na niekoľko sekúnd. Systém bol použitý počas viacerých štúdií [27], [28], [45] a [46] zameraných na zlepšenie výkonnosti a spoľahlivosti kolimácie zväzkov v LHC. Ďalšie štúdie sú zamerané na presné zarovnanie "wire" kolimátorov, ktoré slúžia na kompenzáciu efektov vznikajúcich počas kolízií zväzkov v experimentoch [47]. Merané hodnoty z niekoľkých vybraných DOROS jednotiek sú taktiež používané takzvaným LHC interlock systémom, ktorý slúži na ukončenie operácie LHC v prípade, ak meraná pozícia zväzku v kolimátoroch prekračuje bezpečné limity. Tento ochranný mechanizmu bol uvedený do prevádzky v septembri 2017. Akákoľvek dlhodobá porucha DOROS jednotky môže zbytočne prerušiť a prípadne zablokovať operáciu LHC. Z tohoto dôvodu bolo vynaložené úsilie na zabezpečenie dostatočnej spoľahlivosti a odolnosti systému na hardvérovej ako aj softvérovej úrovni. Kritické časti systému boli implementované redundantne pomocou dvoch nezávislých DOROS jednotiek, aby sa zabránilo blokovaniu prevádzky LHC v prípade zlyhania hardvéru. Každá DOROS jednotka taktiež automaticky monitoruje svoj stav, vrátane FPGA systému s implementovaným procesorom s operačným systémom v reálnom čase, ako aj všetku Ethernetovú komunikáciu s koncentračnými a riadiacimi servermi. V prípade detekcie poruchy je jednotka automaticky resetovaná a jej operácia je obnovená do približne 10 sekúnd. Súčasný odhad MTBF systému DOROS dosahuje viac ako 60 rokov.

Súčasný štandardný DOROS systém pozostáva z 21 jednotiek, ktoré boli inštalované v LHC a slúžia na merania pozície zväzkov v 40 BPM senzoroch. Tento systém bol inštalovaný na najdôležitejších BPM senzoroch v LHC, vrátane BPM Q1 nachádzajúcich sa pri kvadrupólových magnetoch v okolí štyroch experimentov, ako aj na niekoľkých vybraných BPM Q5, Q6 a Q7 nachádzajúcich sa v LHC bodoch 1, 2, 4, 5, 6 a 8. Signály z týchto BPM boli rozdelené medzi štandardný LHC BPM systém a systém DOROS, čo umožňuje vyhodnotiť a porovnať merané výsledky z týchto dvoch systémov. Štandardný DOROS systém sa využíva na optimalizačné merania v LHC, akými sú napríklad takzvané Van der Meer skeny alebo meranie lokálnej betatrónovej väzby. DOROS systém bol tiež použitý počas viacerých štúdií, akými sú napríklad takzvaný β^* leveling [40], direktivita BPM stripline senzora [47] alebo merania nízkofrekvenčných oscilácií zväzkov [48].

Väčšina týchto štúdií je zameraných na vylepšenia LHC, ktorých cieľom je zvýšenie a optimalizácia luminozity v experimentoch. Nedávna štúdia sa začala zaoberať neinvazívnymi meraniami kvadrupolárneho momentu zväzkov pomocou BPM signálov. Takéto merania sú dôležité najmä počas akcelerácie v LHC, kedy dochádza k zvyšovaní energie zväzkov. Štandardné a kolimátorové DOROS systémy sa stali dôležitými nástrojmi na meranie a diagnostiku zväzkov ako aj na optimalizáciu výkonnosti LHC urýchľovača.

Hlavné prínosy tejto dizertačnej práce možno zhrnúť do nasledujúcich bodov.

- **Návrh, vývoj a optimalizácia nového systému spracovania BPM signálov založeného na báze diódových detektorov.**

Systém DOROS opísaný v tejto práci pozostáva z hardvérových zariadení realizovaných ako 19 "1U jednotky, ktoré dokážu spracovať signály z dvoch BPM senzorov pozostávajúcich zo štyroch elektród. Signály z BPM senzora sú najskôr filtrované a zosilnené predtým, než sú spracované diódovými detektormi. Implementovaný rádiofrekvenčný zosilňovač pozostáva zo štyroch blokov ovládaných pomocou FPGA. Dynamický rozsah signálov tak môže byť ovládaný v rozsahu 90 dB s 1 dB krokom. Signály orbity a oscilácií zväzkov sú potom spracovávané oddelene pomocou dvoch samostatných podsystémov obsahujúcich špecificky optimalizované diódové detektory. Analógové signály z oboch podsystémov sú potom digitalizované pomocou 8-kanálového 24-bitového sigma-delta prevodníka. Digitálne signály sú spracovávané v paralelných DSP kanáloch implementovaných v FPGA logike. Spracované výsledky sa potom posielajú prostredníctvom Ethernetovej siete na príslušné servery. Opakovacia frekvencia posielania datagramov rovná 25 Hz je synchrónna s externým LHC časovaním (takzvaným BST) distribuovaným prostredníctvom optických vlákien. Vzorkovanie ADC pri frekvencií približne 11.2 kHz je synchronizované s obletom LHC zväzku. Synchronizácia vzorkovania medzi DOROS jednotkami je založená na stabilnom hodinovom signáli z BST, ktorý je možné fázovo zarovnať vzhľadom na referenčný hodinový signál generovaným zo samotných BPM signálov. Jednotlivé ADC vzorky sú ukladané taktiež v nespracovanej forme do DDR pamäti nachádzajúcej sa v každej DOROS jednotke. Tieto dáta sú k dispozícii serverom prostredníctvom TCPIP protokolu a umožňujú merať a analyzovať oscilácie zväzkov. Systém FPGA riadi aj ostatné funkcie DOROS jednotky, akým je napríklad kalibrácia merania orbity, automatické riadenie zisku vstupných RF zosilňovačov, generátor testovacieho signálu, riadenie synchronizačných obvodov, monitorovanie stavu alebo aj preprogramovanie FPGA na diaľku prostredníctvom Ethernetovej siete.

- **Návrh a optimalizácia spracovania signálu na meranie orbity LHC zväzkov pomocou kompenzovaných diódových detektorov.**

Najdôležitejšou inováciou nového systému je metóda kompenzovaných diódových detektorov, ktorá podľa autorovho poznania bola prvýkrát použitá v aplikácií na meranie pozície časticových zväzkov. Táto technika sa používa v DOR podsystéme na meranie orbity a nízkofrekvenčných oscilácií zväzkov. Typický BPM senzor v LHC môže produkovať impulzy s časovým trvaním približne 1 ns, ktoré sa opakujú každých 25 ns. V závislosti od intenzity zväzku ako aj typu BPM senzora sa môžu amplitúdy výsledných pulzov meniť približne o štyri rády, typicky v rozmedzí 0.1 V a 100 V. Meranie 1 μm zmeny pozície zväzku v transverzálnej rovine pomocou BPM senzora s 100 mm apertúrou by bolo potrebné detekovať zmeny amplitúdy pulzov v oblasti rádovo 10^{-5}, čo je ekvivalentné 10 μV zmene napätia BPM signálu s 0.1 V amplitúdou. Použitie RF diódových detektorov na meranie takýchto malých zmien signálov má niekoľko výhod:

- rýchla odozva,
- vysoká senzitivita,
- nevyžaduje externé časovanie,
- jednoduchosť a robustnosť.

Bolo ukázané, že pozícia zväzku vypočítaná zo signálov na výstupe RF diódových detektorov závisí od poklesu napätia na diódach. Toto napätie sa mení v závislosti od teploty, prúdu, ako aj od výrobného procesu, v dôsledku ktorých sa mení aj výsledná chyba merania. Kompenzované detektory minimalizujú závislosť výstupných signálov od napäťového poklesu na dióde, čo je dôležitým predpokladom pre maximalizáciu presnosti a stability meraní. Presnosť merania je taktiež ovplyvnená asymetriami medzi príslušnými analógovými kanálmi. Aby bolo možné minimalizovať chyby vyplývajúce z takýchto asymetrií, bola vyvinutá automatická kalibračná metóda, založená len na BPM signáloch. Táto technika využíva periodické multiplexovanie signálov na vstupe príslušných DOR kanálov. Po následnom spracovaní signálov v analógovej a digitálnej časti DOROS jednotky je možné vypočítať kalibrované hodnoty pozície z prijatých dát na serveri pomocou kalibračného algoritmu. Automatické kalibrovanie umožňuje minimalizovať systematické chyby merania, ktoré závisia od zisku RF zosilňovačov, ako aj od teplotných a iných zmien v analógovej časti. Kalibrácia merania je kritická pre presné nastavovanie čeľustí kolimátorov, ako aj pri meraní pozície zväzkov počas kolízií v LHC experimentoch.

Dynamiku diódových detektorov je možné meniť pomocou časových konštánt, ktoré je možné spínať pomocou FPGA systému. V každom DOR detektore sú k dispozícií tri nastaviteľné časové konštanty, konkrétne T_{c0}, T_{c1} a T_{c2}. Nastavenie T_{c0} určuje najpomalšiu a T_{c2} najrýchlejšiu rýchlosť vybíjania pamäťových kondenzátorov v detektoroch. Tieto nastavenia ovplyvňujú viacero parametrov, akými sú napríklad šírka frekvenčného pásma, frekvenčná prenosová charakteristika alebo prechodová odozva počas kalibračného multiplexovania signálov. Pomalá prechodová odozva diódových detektorov obmedzuje maximálnu frekvenciu multiplexovania, čo má za následok zvýšenie latencie kalibrovaných meraní.

Prechodové odozvy detektora v jednotlivých nastaveniach časovej konštanty boli merané a analyzované pomocou laboratórneho zapojenia. Dĺžka trvania prechodu s najpomalšou konštantou T_{c0} bola odhadnutá na približne 0.4 s, čo by obmedzilo maximálnu frekvenciu multiplexovania signálov na menej ako 2.5 Hz. Z tohoto dôvodu bola vyvinutá nová metóda urýchlenia prechodových javov využívajúca automatické riadenie časových konštánt pomocou FPGA systému. Táto metóda je založená na urýchlení vybíjania detektora pomocou dočasného nastavenia T_{c1} alebo T_{c2} konštanty pri každom multiplexovaní vstupných signáloch. Merané dáta, ktoré sú ovplyvnené prechodovými javmi, sú neskôr vyradené kalibračným algoritmom na výpočet kalibrovanej pozície. Laboratórne merania ukázali, že táto technika pomáha znižovať trvanie prechodov na približne 0.15 s. V dôsledku toho môže byť frekvencia multiplexovania s konštantou T_{c0} zvýšená na viac ako 5 Hz.

Frekvenčné prenosové charakteristiky a šírka frekvenčného pásma kompenzovaných diódových detektorov boli taktiež zmerané v laboratórnych podmienkach. Najmenšie frekvenčné pásmo merania sa pohybuje od DC do približne 10 Hz v prípade nastavenia T_{c0} konštanty. Vzhľadom na pomalé vybíjanie kondenzátorov v detektoroch by sa toto nastavenie malo používať pre vstupné signály s nízkymi opakovacími frekvenciami, akými sú napríklad pilotné zväzky v LHC. Nastavenie konštanty T_{c2} poskytuje naopak šírku frekvenčného pásma až do 500 Hz. Výsledné frekvenčné pásmo merania je však obmedzené analógovými filtrami na 100 Hz. Nastavenie T_{c2} je teda vhodnejšie pre vyššie opakovacie frekvencie vstupných signálov, akými sú napríklad zväzky využívané pri interakciách v LHC experimentoch. Frekvenčná odozva s nastavením T_{c2} je na rozdiel od T_{c0} plochá, a preto je vhodnejšia pre merania nízkofrekvenčných oscilácií zväzkov.

Presnosť kalibrovaných signálov bola vyhodnotená pomocou laboratórnych meraní. Tieto boli realizované pomocou signálového generátora, ktorý simuloval signály z BPM senzora v LHC. Analýza bola zameraná na vyhodnotenie systematických chýb a šumu, ktoré boli merané s rôznymi nastaveniami vstupných RF zosilňovačov ako aj frekvenciou opakovania pulzov. Kvalita kalibrovaných meraní bola porovnaná s meraniami bez kalibrácie. Výpočet pozície sa vzťahuje na 61 mm apertúru BPM senzora. Bez použitia kalibrácie bola absolútna odchýlka merania v meracom zapojení simulujúcom nulovú odchýlku odhadnutá na približne ±150 μm.

Takáto odchýlka merania by sa napríklad prejavila ako chyba nastavenia kolimátorových čeľustí vzhľadom na zväzok. Bolo tiež ukázané, že v závislosti od nastavenia zisku v RF zosilňovači sa tieto chyby menili o viac ako 50 %. Kalibračná metóda zredukovala tieto odchýlky na menej ako 30 μm, čomu zodpovedá približne 0.1% asymetria medzi dvoma analógovými kanálmi. Tento odhad chyby zároveň zahŕňa asymetrie, ktoré nie je možné kalibrovať pomocou multiplexovania signálov, akými sú napríklad vstupné RF filtre alebo aj samotné pripojenie generátora k DOROS jednotke. Dosiahnuté výsledky kalibrovaných meraní boli tiež nezávislé od nastavenia zisku v RF zosilňovači. Bolo ukázané, že kalibračná metóda pomáha znižovať šum ako aj pomalé zmeny medzi analógovými kanálmi, ktoré boli zmenšené o viac ako 2-krát. Hladina šumu v meraní kalibrovanej pozície bola odhadnutá na menej ako 0.5 μm_{RMS}. Za priaznivých podmienok merania bola táto hladina nižšia ako 0.05 μm_{RMS}. Tento výsledok bol dosiahnutý pri laboratórnom nastavení s vysokými opakovacími frekvenciami generovaných pulzov a relatívne nízkymi hodnotami zisku vo vstupnom RF zosilňovači. Takáto konfigurácia simuluje LHC zväzky s nominálnou intenzitou, ktoré sú používané pri kolíziách v experimentoch. Senzitivita merania pozície zväzkov na indukovanú zmenu teploty bola zmeraná a vyhodnotená v laboratórnych podmienkach. Po 4 hodinách merania v stabilných podmienkach bola vnútorná elektronika v DOROS jednotke vystavená vonkajším teplotným zmenám. Následná zmena teploty v jednotke bola vykonaná pomocou externej ventilačnej jednotky umožňujúcej prietok vzduchu ponad exponovanú elektroniku v DOROS jednotke. Celková dosiahnutá zmena teploty počas tohoto laboratórneho testu dosiahla 15 ˚C, čo je oveľa viac, ako bolo pozorované v DOROS systémoch pri typických prevádzkových podmienkach v LHC tuneli. Bolo ukázané, že senzitivita merania pozície na teplotné zmeny môže dosiahnuť približne 1 μm/˚C v prípade, ak nie je použitá kalibračná metóda. Meranú senzitivitu merania bolo možné znížiť o jeden rád s použitím kalibračnej metódy pri 1 Hz frekvencií multiplexovania vstupných signálov.

Výkonnosť DOR podsystému bola vyhodnotená pomocou LHC zväzkov. Na odhad šumu a dlhodobú stabilitu merania boli použité údaje z kolimátorového DOROS systému. Rozlíšenie merania orbity bolo odhadnuté na menej ako 0.1 μm počas 11 hodín nominálnej operácie LHC. Zmena odchýlky merania počas celej dĺžky merania bola odhadnutá na menej ako 0.5 μm. Dlhodobá stabilita podsystému DOR bola ukázaná taktiež na meraniach orbity zväzkov so štandardným DOROS systémom realizovaných počas 37 hodín nominálnej operácie LHC. Orbity zväzkov boli merané v BPM senzoroch umiestnených na ľavej a pravej strane ATLAS a CMS experimentov. Extrapolované pozície zväzkov do stredu oboch experimentov sa menili menej ako 15 μm počas celej dĺžky merania. Pozorovaný priebeh meranej orbity v oboch experimentoch bol navzájom korelovaný. Výsledky merania so štandardným DOROS systémom boli porovnané so štandardným LHC BPM systémom. Prezentované výsledky meraní boli získané počas takzvaných Van der Meer skenov v ATLAS experimente. Najväčší rozdiel medzi absolútnymi hodnotami merania pozície zväzkov z oboch BPM systémov bol približne 400 μm, čomu zodpovedá 0.6 % chyba v rámci 61 mm BPM apertúry. Toto meranie bolo taktiež použité na odhad a porovnanie presnosti týchto dvoch BPM systémov. V tomto porovnaní dosiahol systém DOROS 6-krát menší šum ako štandardný LHC BPM systém za predpokladu, že šum meracieho zariadenia dominuje nad šumom pozície samotného časticového zväzku. Detailnejšia analýza meraní ukázala, že štandardný DOROS systém dokáže zaznamenať nízkofrekvenčné vibrácie zväzku s amplitúdou rádovo niekoľkých mikrometrov a frekvenciou rádovo 0.01 Hz. Bolo tiež pozorované, že tieto oscilácie majú negatívny vplyv na počet kolízií v experimentoch.

Linearita merania predstavuje dôležitý parameter, ktorý bol meraný a analyzovaný v laboratórnych podmienkach pomocou signálového generátora. Výsledky týchto meraní ukázali, že v prípade, keď majú pulzy z BPM elektród rovnaké amplitúdy, je vplyv zmeny týchto amplitúd na výsledné nameranie pozície veľmi malý. Takéto podmienky merania sú pozorované v kolimátoroch, keď sú čeľuste so zabudovanými BPM elektródami symetricky umiestnené vzhľadom na meraný zväzok a signály z týchto senzorov majú rovnaké amplitúdy. Diódové detektory DOR podsystému potom pracujú s veľmi podobnými signálmi, čím sa znižuje vplyv ich nelinearity na meranie.

V najmenej priaznivých podmienkach, kedy diódové detektory pracujú s nastavením T_{c2} a amplitúda signálu sa mení v 50 % rozsahu ADC, bola meraná zmena pozície v dôsledku nelinearity menej ako 1 µm. Kalibrácia merania pomáha potlačiť väčšinu asymetrie medzi kanálmi, čím tiež zlepšuje linearitu merania. Pri zvyšujúcich sa odchýlkach pozície zväzkov od stredu medzi dvomi BPM elektródami sa v dôsledku nelinearity zvyšujú systematické chyby merania orbity. V takýchto prípadoch majú signály z protiľahlých BPM elektród rozdielne amplitúdy, čo spôsobuje, že príslušné diódové detektory pracujú v odlišných bodoch prevodovej charakteristiky. Reziduálna nelinearita charakteristiky je tak konvertovaná do systematickej chyby merania, ktorá závisí od amplitúdy BPM signálov. Táto amplitúda závisí od intenzity zväzku, ktorá sa môže v rámci jedného LHC cyklu výrazne meniť. V závislosti od nastavenia časovej konštanty v detektoroch ako aj od pozície zväzku môže chyba merania pri 50 % poklesu amplitúdy dosiahnuť viac ako 100 µm. Takúto chybu merania je možné znížiť kompenzáciou poklesu amplitúdy BPM signálov pomocou automatického ovládania zisku v RF zosilňovači s krokom 1 dB. Zmena amplitúdy signálov na vstupoch detektorov je tak zredukovaná na približne 12 %. Pri použití časovej konštanty T_{c0} a automatického udržiavania úrovní signálu v rozsahu 0.6 – 0.8 ADC FS bolo dosiahnuté zníženie chyby merania na približne 25 µm. Bolo taktiež ukázané, že najmenšie chyby vyplývajúce z nelinearity diódových detektorov možno dosiahnuť s nastavením T_{c0}, kedy je vybíjanie kondenzátorov v detektore najpomalšie. Optimalizáciou časovej konštanty je možné dosiahnuť približne 20 % redukciu nelinearity v porovnaní s T_{c2}. Limitovanie nastavenia časovej konštanty iba na T_{c0} počas celého LHC cyklu však nie je vždy optimálne. Príkladom, kedy nastavenie T_{c0} nie je vhodné pre meranie pozície predstavuje prípad viac hodinových kolízií zväzkov experimentoch. Od určitého momentu začnú diódové detektory merať orbitu časticových grúp (takzvaných bunch), ktorých menovitá intenzita klesá pomalšie ako je priemerná intenzita grúp podieľajúcich sa na kolíziách. Tento problém bol vyriešený pomocou nastavenia T_{c2}, ktoré umožňuje znížiť senzitivitu diódových detektorov na zmeny intenzity medzi časticovými grupami v rámci jedného obletu zväzku.

Ďalšie zlepšenia linearity merania bolo možné dosiahnuť pomocou linearizácie prechodovej charakteristiky diódových detektorov pomocou takzvaných korekčných polynómov. Fitovacie a korekčné koeficienty polynómov až do 5. rádu boli získané z laboratórnych meraní pre tri možné nastavenia časových konštánt detektora. Metóda linearizácie prechodovej charakteristiky a jej vplyv na presnosť merania bola vyhodnotená pomocou meraní zväzkov štandardným DOROS systémom v LHC. Chyby linearity bolo možné pozorovať najmä v meraniach, kde bola pozícia zväzku vzhľadom na stred BPM senzora väčšia ako 3 mm. Pri každom zvýšení zisku v RF zosilňovači o 1 dB dochádzalo ku približne 20 µm zmene meranej orbity v dôsledku nelinearity detektora. Polynómy získané z laboratórneho merania boli potom aplikované na korekciu pozorovaných zmien orbity. Bolo ukázané, že linearizačná metóda dokáže minimalizovať pozorované chyby merania na menej ako 1 µm pomocou polynómu 3. rádu. Vzhľadom na tento výsledok bola táto linearizačná metóda implementovaná ako súčasť výpočtu pozície na DOROS serveri v reálnom čase. Táto implementácia využíva rovnaké korekčné koeficienty pre všetky DOROS jednotky. Takéto zjednodušenie sa však prejavilo pri porovnaní výsledkov zo všetkých štandardných DOROS jednotiek vo zvýšení reziduálnej chyby merania na približne 5 µm.

DOROS systémy umožňujú okrem kalibrovanej orbity zväzkov zároveň merať DOR signály v širšom frekvenčnom pásme pomocou ADC vzoriek ukladaných do DDR pamäti. Jednotlivé vzorky sú ukladané pri vzorkovacej rýchlosti ADC prevodníka, ktorá je synchrónna s frekvenciou obletu LHC zväzkov. Uložené dáta je možné pozorovať a analyzovať po dobu niekoľkých minút, čo predstavuje rádovo niekoľko miliónov obletov zväzku v LHC. Zvýšená šírka pásma merania na približne 100 Hz je vhodná na pozorovanie oscilácií orbity v rádovo vyšších frekvenciách, ako by bolo možné pozorovať pomocou kalibračnej metódy. Pri takomto type meraní musí byť multiplexovanie vstupných signálov dočasne vypnuté, aby bolo možné počítať spektrá signálov s dostatočným frekvenčným rozlíšením. Príklady takýchto meraní boli užitočné pri diagnostike nízkofrekvenčného spektra orbity zväzkov [48].

- **Návrh a optimalizácia spracovania signálov a synchronizácie merania oscilácií zväzkov.**

DOS podsystém v každej DOROS jednotke bol navrhnutý a optimalizovaný na detekciu budených transverzálnych oscilácií zväzkov a meranie súvisiacich parametrov urýchľovača, akými sú napríklad betatrónova väzba alebo fázový posun oscilácií. Časticové zväzky sú počas týchto meraní vybudené na frekvencii blízkej k vlastným osciláciám zväzkov v LHC. Z tohoto dôvodu môže byť spracovanie DOS signálov zamerané len na konkrétne frekvenčné komponenty. Spracovanie signálov v úzkom frekvenčnom pásme umožňuje zvýšiť citlivosť systému a taktiež zjednodušiť spracovanie dát. Táto práca opisuje implementované spracovanie signálov oscilácií zväzkov v DOS podsystéme. Detekcia oscilácií v každej BPM rovine je založená na dvoch RF diódových detektoroch. Dominantná DC časť signálov, ktorá je úmerná intenzite a orbite zväzku, je odstránená pomocou blokovacích kondenzátorov, čím je umožnené zvýšiť dynamický rozsah a senzitivitu merania. Signály z oboch diódových detektorov sú potom odčítané pomocou diferenciálneho zosilňovača, čo umožňuje merať relatívne zmeny pozície. Následná nízkofrekvenčná časť obmedzuje výsledný frekvenčný rozsah merania na pásmo od 500 Hz až po približne 5 kHz. Signály DOS sú potom vzorkované pomocou viackanálového 24-bitového sigma-delta ADC prevodníka, ktorý je spoločný s podsystémom DOR. Jednotlivé vzorky z kanálov DOS sú spracovávané v DSP kanáloch a výsledky sú posielané spolu s ďalšími dátami na DOROS serveri prostredníctvom Ethernetovej siete. Keďže väčšina signálového spracovania, ako napríklad RF filtre a RF zosilňovače je zdieľaná s podsystémom DOR, implementácia podsystému DOS výrazne nezvýšila celkovú zložitosť systému. Automatické ovládanie RF zosilnenia využívajúce signály DOR garantuje správne nastavenie úrovne signálu aj na vstupe DOS detektorov. Laboratórne merania boli zamerané na charakterizáciu podsystému DOS pomocou signálového generátora simulujúceho signály z BPM senzora. Oscilácie zväzkov boli simulované pomocou amplitúdovej modulácií pulzov. Výsledky merania ukázali, že odstup signál-šum v meraných úzkopásmových signáloch závisí od viacerých parametrov, ako napríklad:

- hĺbky amplitúdovej modulácie, ktorá predstavuje amplitúdu oscilácií zväzkov,
- opakovacej frekvencie pulzov, ktorá predstavovala rozstup jednotlivých časticových grúp,
- amplitúde pulzov, ktorá predstavuje intenzitu zväzku,
- dĺžke FFT, ktorá súvisí s trvaním merania.

Excitované oscilácie zväzkov s veľkými amplitúdami a príliš dlhým trvaním nepôsobia priaznivo na kvalitu zväzkov v dôsledku čoho je znižovaná účinnosť kolízií v experimentoch. Laboratórne merania ukázali, že je možné pomocou DOROS systémov dosiahnuť 40 dB odstup signál-šum, ak je amplitúda budených oscilácií iba 10 μm a ak meranie trvalo aspoň 1 s. Toto laboratórne meranie simulovalo zväzok skladajúci sa len z jednej časticovej grupy vo zväzku. Pomocou toho istého laboratórneho zapojenia bolo ukázané, že zvýšením počtu časticových grúp na plnú kapacitu LHC (približne 2800 grúp) by bolo možné dosiahnuť rovnakého odstupu šumu s amplitúdou oscilácie menšou ako 1 μm. Takáto amplitúda meraných oscilácií by zároveň predstavovala rádovo nižšiu perturbáciu kvality zväzku počas excitácie.

Štandardný DOROS systém bol použitý na meranie excitovaných oscilácií zväzkov slúžiacich na merania lokálnej betatrónovej väzby v LHC. Amplitúda budenia zväzku bola zvolená tak, aby systém DOROS ako aj štandardný LHC BPM systém dokázali detekovať oscilácie zväzku. Keďže DOS podsystém umožňuje merať iba zmenu pozície a nie jej absolútnu hodnotu, bol na odhad absolútnej hodnoty amplitúdy oscilácií v mikrometroch použitý štandardný BPM systém. Pomocou zmeraného škálovacieho koeficientu bolo možné odhadnúť hladinu šumu v DOS na 0.1 μm. V porovnaní so štandardným BPM systémom bola dosiahnutá citlivosť podsystému DOS vyššia o jeden rád. Toto zlepšenie bolo dôležité v prípadoch, keď citlivosť štandardného systému nebola dostatočná na detekciu oscilácií zväzkov, kedy je získané meranie neplatné. Analýza výsledkov merania lokálnej betatrónovej väzby ukázala veľmi dobrú zhodu medzi oboma BPM systémami [48], [49], [50].

Vyvinuté a implementované obvody časovania umožňujú synchronizáciu DOROS jednotiek s referenčným hodinovým signálom odvodeným z BPM signálov. Tento referenčný signál s frekvenciou približne 11.2 kHz je tak intrinzicky synchrónny s obletom zväzku. Obvod časovacieho generátora bol navrhnutý a optimalizovaný na odvodenie synchronizačného hodinového signálu z BPM signálov pomocou rýchleho komparátora a hold-off obvodu implementovaného v FPGA logike. Synchronizačný signál je vytvorený v každej DOROS jednotke a slúži predovšetkým ako referencia fázy pre jednotlivé ADC prevodníky. Bolo ukázané, že porovnávacia úroveň vo vstupnom komparátore môže byť optimalizovaná pomocou subsystému DOR. Týmto spôsobom je možné zvýšiť robustnosť výsledných referenčných hodín. Porovnávaciu úroveň je možné nastavovať pomocou DAC prevodníka, ktorým je zároveň možné riadiť oneskorenie referenčných hodín v rozmedzí približne 1 ns.

Synchronizačný signál odvodený z BPM signálov však závisí od konfigurácie zväzkov ako aj od nastavenia DOROS jednotky. Spoľahlivosť tohto referenčného signálu za každých okolností tak nie je možné garantovať. Z tohoto dôvodu má každá DOROS jednotka prístup k externému hodinovému signálu BST, ktorého spoľahlivosť je garantovaná počas celého LHC cyklu. Fáza BST signálov však vzhľadom na oblet zväzku nie je zaručená, čo spôsobuje chyby pri meraniach fázového posunu oscilácií zväzkov. Z tohto dôvodu bol implementovaný mechanizmus umožňujúci posuv fázy referenčných BST hodín v 100 ps krokoch. Výsledné fázové rozdiely dvoch 11.2 kHz hodinových signálov počas jednotlivých krokov je náročné spoľahlivo merať pomocou klasických metód. Z tohto dôvodu bol vyvinutý obvod diferenčného fázového detektora, ktorý bol optimalizovaný na merania malých fázových rozdielov medzi dvoma nízkofrekvenčnými hodinovými signálmi, čím je potom umožnené ich presné fázové zarovnanie. Prevodová charakteristika tohto detektora bola navrhnutá tak, aby mala extrémum v prípade, keď sú oba vstupné hodinové signály presne vo fáze. V tomto bode charakteristiky majú všetky hodinové signály v detektore 50 % striedu, čo zvyšuje presnosť detekcie a výrazne redukuje závislosť meraného fázového rozdielu na rýchlosti spínania hradiel v detektore. Prezentovaný fázový detektor umožňuje presnú detekciu nulového fázového rozdielu, ktorý nie je závislý od napájacieho napätia detektora ani od ofsetu na vstupe ADC. Laboratórne merania ukázali, že diferenčný fázový detektor je schopný detekovať fázové rozdiely s rozlíšením presahujúcim minimálny ovládací krok fázového posunu. Špičkový šum meraného fázového rozdielu z detektora bol odhadnutý pomocou laboratórneho merania na menej ako 30 ps. Tento výsledok bolo možné dosiahnuť iba ak bol fázový detektor uzavretý vnútri DOROS jednotky. Senzitivita fázového detektora na teplotné zmeny bola odhadnutá na 1.6 μV/°C, čo môže byť taktiež vyjadrené ako časový rozdiel medzi dvoma hodinovými signálmi rovný približne 22 ps/°C.

V čase dokončovania tejto kandidátskej práce sa na systémoch DOROS uskutočňoval ďalší vývoj. Jedna zo štúdií sa zameriava na nasledujúcu generáciu DOROS elektroniky tolerantnej voči radiácií. Takýto systém by mohol byť inštalovaný na miestach v LHC, kde môže hladina radiácie dosahovať úrovne, ktorá predstavuje problém pre štandardnú elektroniku. Typickými miestami sú práve v blízkosti samotných kolimátorov alebo v blízkosti magnetov v oblúkových sektoroch LHC, kde dipólové magnety ohýbajú trajektóriu zväzkov. Dĺžka koaxiálnych káblov z BPM senzorov, ktorá by umožnila inštalovať senzitívnu elektroniku v bezpečnejších lokalitách, by v týchto prípadoch mohla predstavovať dôležitý faktor v celkových cenových nákladov na inštaláciu. Spomenutá štúdia skúma senzitivitu jednotlivých komponentov v DOROS jednotke na ionizujúce žiarenie ako aj vplyv na celkovú presnosť merania a spoľahlivosť systému. Ďalšia štúdia sa zaoberá vývojom verzie systému DOROS, ktorá by bola optimalizovaná na meranie orbity v SPS akcelerátore. Frekvencia obletu zväzku v SPS je štyrikrát vyššia ako v LHC, čo by vyžadovalo zvýšenie vzorkovacej frekvencie ADC ako aj rozšírenie frekvenčnej šírky pásma vo vstupných RF filtrov a zosilňovačov. Okrem toho je SPS cyklus omnoho kratší. V závislosti od typu a účelu zväzku môže typický SPS cyklus trvať len pár sekúnd. Frekvenčná šírka pásma v nízkofrekvenčnej časti spracovania signálov ako aj DSP musia byť adaptované tak, aby bolo možné zvýšiť počet meraní orbity zväzkov, najmä počas krátkych SPS cyklov.

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