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UPGRADE OF THE CERN SPS BEAM POSITION MEASUREMENT SYSTEM

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Abstract

The CERN Super Proton Synchrotron (SPS) is a fast cycling hadron accelerator delivering protons with momenta of up to 450 GeV/c for the Large Hadron Collider (LHC), fixed target experiments and other users such as the AWAKE plasma acceleration experiment. It is also used to accelerate heavy ions.

This paper presents the upgrade initiative for the SPS beam position measurement system in the frame of the CERN LHC Injector Upgrade (LIU) project. The new SPS beam position read-out electronics will be based on logarithmic amplifiers, using signals provided by the 216 existing beam position monitors, the majority of which are based on split-plane "shoebox" technology. It will need to cover a dynamic range sufficient to manage the wide range of SPS beam intensities and bunch formatting schemes to provide turn-by-turn and averaged beam orbits along the SPS acceleration cycles. In order to avoid long, expensive coaxial cables, the front-end electronics, including the digitization, will be located inside the accelerator tunnel, with optical transmission to surface processing electronics. This represents an additional challenge in terms of radiation tolerance of electronics components and materials.

INTRODUCTION

Since 1999 the beam orbit of the Super Proton Synchrotron (SPS) is measured using the Multiturn Orbit Position System (MOPOS) [1, 2], processing the signals of 216 beam position monitor (BPM) pickups which are distributed around the 6.9 km circumference of the machine.

Since 2008 dedicated LHC filling cycles with optimized beam optics have been added, delivering high intensity proton and lead-ion beams for the Large Hardon Collider (LHC). As a consequence, the levels of residual ionizing radiation increased in recent years, the typical annual dose is in the order of 100 Gy/y in the SPS tunnel, but varies a lot along the cell positions. While the MOPOS read-out electronics – located in surface buildings – is well protected, the up to 800-meter-long coaxial signal cables connected to the BPM pickups in the tunnel receive a large radiation dose, degrading the signal quality and the required phase matching between Δ and Σ signals. Repairs, maintenance and calibration of the current SPS MOPOS electronics is also becoming an issue due to the lack of spares, availability of electronics components and short maintenance periods.

A Logarithmic Position System (ALPS), foreseen to replace the current MOPOS electronics, as well as its associated long coaxial signal cables, is currently under development. Figure 1 shows a simplified layout for a single read-out channel, which consists of the following:

BPM pickup One of 102 horizontal or 94 vertical split-plane, so-called "shoe-box" BPMs, in alternating arrangement, or a horizontal or vertical channel of one of the 19 dual-plane strip-line BPMs located in some parts of the straight sections.

Front-end electronics The front-end electronics is the core element of the ALPS BPM system, and is installed inside the accelerator tunnel, typically in close proximity to each BPM pickup. It provides the required analog signal conditioning, digitalization, data acquisition and data transmission via optical fiber.

VFC-HD Back-end Located in surface buildings, the open-hardware VME64x FMC carrier board [3] holds the SFP+ optical fiber transceivers that obtain the transmitted data from the tunnel, after which it is post-processed in a large FPGA to provide the position information. Each VFC-HD processes four BPM channels and labels the BPM data according to the CERN beam synchronous timing (BST) information.

SPS BEAM CONDITIONS AND BPM PICKUP SIGNALS

Table 1 summarizes some of the typical beam conditions in the SPS, representing the core information for the conceptual layout and design of the BPM read-out system upgrade. The RF frequency is ~200 MHz, which results in a harmonic number of $h = 4620$ and a revolution time of $T_{rev} \approx 23$ μs. The variety of different beam formats, as well as the variation in bunch length and intensity limits the choices for the read-out technology, which is required to be able to measure single bunches to a full machine, provide turn-by turn and batch-by-batch signal position information, as well as a continuous beam orbit measurement mode.

The BPM pickups remain unchanged for this upgrade and define minimum and maximum signal levels at the input of the analog signal conditioning electronics for the different SPS beam conditions. While the electrode geometry of the horizontal and vertical split-plane BPM pickups differ substantially (see Fig. 2), electromagnetic analysis shows an almost identical transfer impedance for frequencies below 500 MHz, i.e. supplying the same signal levels into a 50 Ω load impedance.

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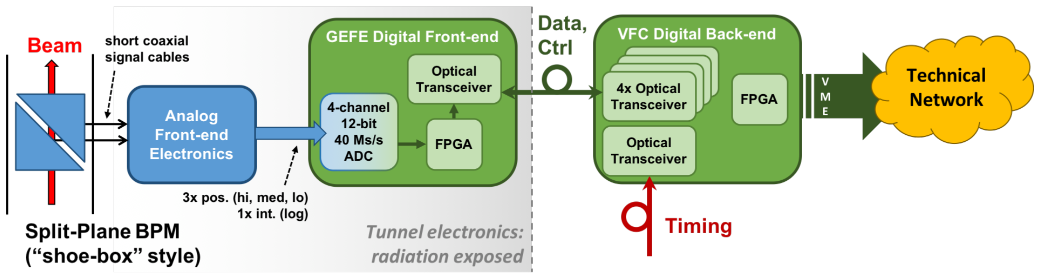

Figure 1: Simplified layout of the ALPS BPM read-out electronics – one channel shown.

Table 1: Typical SPS Beam Conditions

	protons	ions
bunch int.	>2e9 (min, SB) 1.5e10 (max, 5 ns MB) 2.6e11 (max, 25 ns MB) 3.5e11 (max, 50 ns MB)	>2e9 (min) 5e9 (typ) 2e10 (max)
typical beam formats	single bunch (SB) multibunch (MB) batches: 5 ns: 6…2000 bunches 25 ns: 1…12 batches (max 288 bunches) 50 ns: 1…6 batches (max 144 bunches)	50 ns & 100 ns: 1…12 batches (max 60 bunches)
bunch length (4σ)	1.65 ns (min, 400 GeV/c* or 450 GeV/c*) 4 ns (26 GeV/c,* proton injection) 5 ns (14 GeV/c,* ion injection)	
f_{RF}	199.95 MHz (inj.) 200.40 MHz (extr.)	197.02 MHz (inj.) 200.39 MHz (extr.)

* Beam momentum given for protons. For ions, 5 GeV/c/u (injection) and 177 GeV/c/u (extraction).

However, the position sensitivity at 200 MHz, i.e. the response of the two electrodes to a change in the beam position, is different, about 0.2 dB/mm for the horizontal and 0.4 dB/mm for the vertical split-plane pickup.

Figure 3 (left) compares the oscilloscope signal of a proton bunch at injection energy, measured after ~100 m of low-loss coaxial cable with a wakefield simulation of a vertical split-plane BPM for a bunch length of 3 ns, both scaled to $1 \cdot 10^{10}$ protons/bunch and correcting for various insertion losses, power splitter, impedance matching network, etc. Figure 3 (right) shows a simulation of the bunch length dependence of the pickup output signal in the frequency domain, indicating an optimal signal response in a range 50 MHz to 200 MHz. The electromagnetic simulation (*CST Studio* wakefield solver) is seen to give a good agreement with the beam measurement for the time domain signal response of the pick-up to a single proton bunch.

SPS BPM READ-OUT ELECTRONICS

A first read-out electronics prototype [4] indicated that a logarithmic amplifier based system could meet all the SPS beam conditions and functional requirements of the new BPM system. It was, however, not qualified to operate in

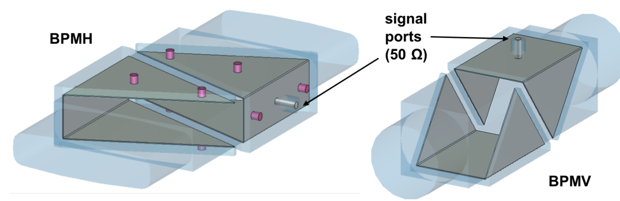

Figure 2: Schematic view or the horizontal (left) and vertical (right) split-plane BPM pickups.

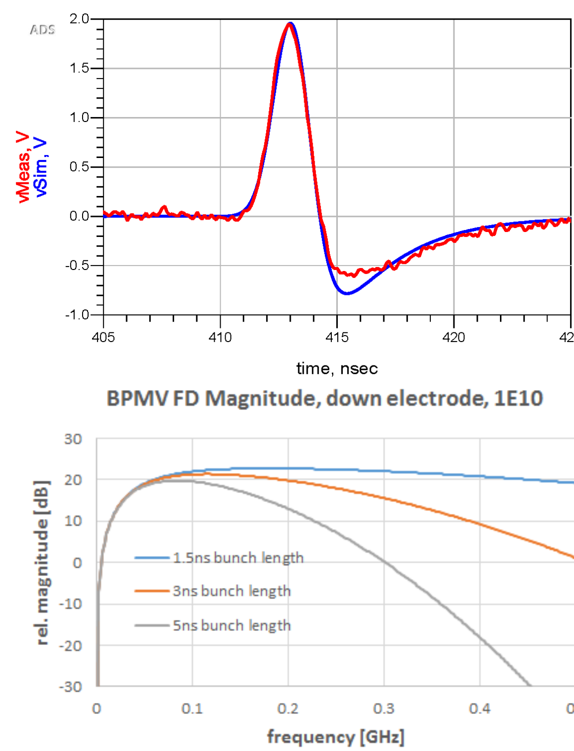

Figure 3: Single bunch signal response of a vertical split-plane BPM in time (left) and frequency domain (right).

a radiation environment. Following the same concept, the final SPS BPM acquisition upgrade is based on narrow-band, 200 MHz RF signal processing, followed by a dynamic range compression and position detection, i.e. AM-demodulation, using logarithmic amplifiers. The digital front-end utilizes 4-channel 12-bit 40 Ms/s analog-digital converters (ADC), a radiation tolerant FPGA for data serialization and pre-formatting, and a radiation hard optical fiber transceiver for

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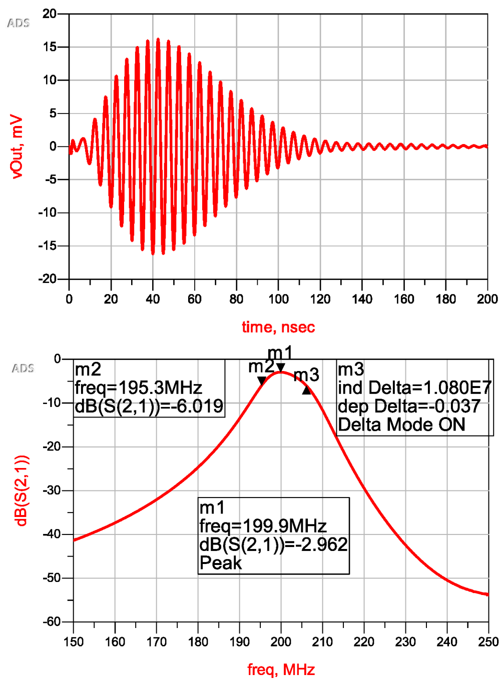

Figure 4: Time (left) and frequency domain response (right) of a prototype hairpin bandpass filter.

the point-to-point optical data transfer to the VME-based back-end located in the surface buildings. All semiconductor and opto-electronic components have been qualified for the required integrated radiation dose of 750 Gy, assuming a minimum lifetime of 10 years.

RF Analog Signal Conditioning

The analog front-end normalizes and conditions the broadband, pulse-like signals of the pickup electrodes to a digitizable waveform, with an amplitude proportional to the beam position, independent of the beam intensity. The dual logarithmic amplifier / detector ADL5519 from *Analog Devices* is used for the normalization:

$$pos = \frac{1}{S_{dB}} 20 \log_{10}\left(\frac{A}{B}\right) = \frac{1}{S_{dB}} 20 \left[\log_{10}(A) - \log_{10}(B)\right] ,$$

where A and B are the signals of the horizontal or vertical electrodes of the BPM pickup, S_{dB} is the BPM pickup calibration constant (in dB/mm), and pos the normalized beam position ()in mm). The demodulated analog position signal – still uncalibrated – is delivered by the ADL5519, utilizing the internal operational amplifier subtraction $\log_{10}(A) - \log_{10}(B)$ output of its two logarithmic amplifier chains.

The logarithmic amplifiers are preceded by a low-loss, low-cost, strip-line, hairpin-style, 3-stage Gaussian bandpass filter that defines the operating frequency of 200 MHz for the electronics, see Fig. 4 (right). A bandwidth of 10 MHz is found to be a good compromise between a sufficiently long single bunch response time (Fig. 4, left) for the acquisition of the demodulated position signal by the asynchronous clocked ADC and sufficient signal level $\gtrsim -50$ dBm at the high sensitivity ADL5519 input to guarantee low intensity single bunch operation.

To cover the entire range of beam intensities in the SPS three ADL5519 chips are used, each with a dynamic range of ~40 dB, with an overlap of ~17 dB, and acquired in parallel by three of the four ADC channels. The fourth ADC channel acquires the sum of all individual logarithmic signals as

$$sum = \log_{10}(A_{hi} \cdot B_{hi} \cdot A_{med} \cdot B_{med} \cdot A_{lo} \cdot B_{lo}) .$$

This is used for a decision algorithm, that computes which sensitivity channel should be used, and which ADC samples contain valid position data. The analog electronics also includes a signal generator for test and calibration purposes with flexible settings for the timing and signal amplitudes of the test pulses.

Digital Front-End Electronics

The digital front-end interfaces the analog frond-end with the digitalization and optical transmission electronics. It is composed of a carrier board that holds two mezzanine cards, one for the digitalization and one for the optical transmission. The BPM digital front-end FMC mezzanine (BDF) holds the ADCs, while the giga-bit transceiver (GBT) based expandable front-end link board (L-GEFE) [3] holds the radiation tolerant components of the GBT link (GBTx and VTRx), a full-duplex optical link, operating at a rate up to 4.8 Gbps. The carrier board itself is an FPGA-based carrier featuring a ProAsic3L from *Microsemi*, acting as a link between the ACD mezzanine and the optical transmitter. During BPM operation, the analogue signals are digitized on the BDF, and the raw data is forwarded to the carrier board FPGA. Here, the data is packaged and in turn forwarded to the L-GEFE, which serializes the raw data, and sends it via the GBT optical link to the back-end located in a surface building. During test and calibration of the analog front-end, control signals are received by the L-GEFE from the back-end through the GBT Link, which are directly forwarded to the RF analog board through the carrier board.

VME Back-End Electronics

The core element of the back-end electronics is the so-called VME FMC carrier board, VFC-HD, a general-purpose digital acquisition card developed by the Beam Instrumentation (BI) group at CERN, under the Open-Hardware License (OHL). The VFC-HD is a FPGA-based VME64x carrier for one high pin count (HPC) FPGA Mezzanine Card (FMC, VITA 57). It contains an *Altera Arria V GX* FPGA linked to 2 GB of DDR3 RAM. It is also equipped with six SFP+, GBT compatible, optical transceivers, and the protocols for decoding the CERN beam synchronous timing (BST), white rabbit timing [5] and ethernet. In BPM operation, four of six optical transceivers acquire the raw data from two horizontal and two vertical BPM front-ends with the timing data provided through the fifth transceiver (see also Fig. 1). The data samples of interest are discriminated in the FPGA using a specific algorithm [6], and processed in a selectable acquisition mode:

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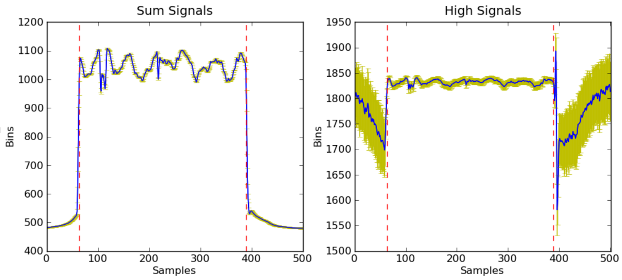

Figure 5: Response of the logarithmic sum (left) and the high sensitivity position channel (right) to a 8 µs proton batch.

Capture trajectory provides the turn-by-turn position of the beam, averaged over a selectable range of bunches, for a predefined number of turns.

Injection trajectory provides the turn-by-turn position of the first 64 turns of a batch after its injection.

Orbit provides the average of the position of all batches in the machine, averaged over a programmable period of time.

During a test and calibration procedure, configurable control signals are generated in the FPGA of the VFC-HD and sent via the GBT link to the front-end electronics.

INITIAL BEAM TESTS & OUTLOOK

Figure 5 shows the raw data of a preliminary beam test of a prototype BPM setup detecting a batch of 1650 bunches, spaced by 5 ns, each ~$1.5 \cdot 10^9$ protons. Some reflection effects are visible as an impedance matching network was still missing in this first beam test setup.

A full SPS sextant will be equipped with a pre-series of 36 BPM front-end electronics linked to the final back-end electronics for performance validation with both proton and ion beams in 2018. The full system is then foreseen to be deployed during the 18 month long shutdown of all CERN accelerators in 2019-2020.

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