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LogAmp Electronics and Optical Transmission for the new SPS Beam Position Measurement System

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Abstract

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ABSTRACT: A new front-end board is under development for the CERN SPS Multi ORbit Position System (MOPOS). Based on logarithmic amplifiers, it measures the beam position over a large dynamic range of beam intensities and resolves the multi-batch structure of the SPS beams. Analogue data are digitized at 10 MS/s, packed in frames by an FPGA and on every turn sent to the readout board, via a 2.4 Gb/s optical transmission link. A first prototype has been successfully tested with several SPS beams. This paper presents an overall description of the system and its capabilities highlighted by the first beam measurements.

KEYWORDS: Front-end electronics for detector readout; Beam-line instrumentation (beam position and profile monitors; beam-intensity monitors; bunch length monitors); Data acquisition circuits; Radiation-hard electronics

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1 Introduction

The SPS orbit and trajectory measurement system relies on 216 Beam Position Monitors (BPM) distributed all around the ring. They are either single plane electrostatic rectangular “*shoe-boxes*”, based on electrodes with a linear response, or *stripline* directional couplers, both providing horizontal and vertical beam signals.

The upgrade of the present MOPOS is required to replace the obsolete electronics and to improve the quality of the position measurements, currently done with a timing resolution of one SPS turn (around $23 \mu\text{s}$) by means of a peak-detector. The project aims at developing a radiation hard (100 Gy/year) electronic system capable of providing both high dynamic range measurements, covering the various beam configurations available in the SPS, and a fast enough data sampling rate to resolve the $2 \mu\text{s}$ long multi-batch structure of the beam.

2 Requirements

The SPS currently accelerates both proton and lead-ion beams, with a wide range of bunch filling patterns and bunch charge as shown in table 1. We call *batch* a bunch train coming from the PS ring and injected in the SPS. The nominal number of batches N_{batch} can vary between 1 and 4 for protons and up to 13 for ion-beams. Because the pick-up provides signals directly proportional to both beam position and beam intensity, the electronic system must cover a dynamic range of more than 70 dB [1]. In addition, due to the different filling patterns and bunch spacing, the bandwidth of the electronics will vary from 40 to 200 MHz. The required resolution for low and high intensity beams is presented in table 2 both for the *orbit mode*, providing a beam position averaged over 1 ms, and for the *trajectory mode*, in case of turn-by-turn acquisitions.

Table 1. SPS beam types.

Beam Type	Bunch Spacing [ns]	Bunch Charge [10^{10}]	Bunch Number
FT / CNGS	5	$0.1 \div 2$	$400 \div 4000$
LHC25NS	24.96	$1 \div 50$	$N_{\text{batch}} \times 72$
LHC50NS	49.92	$1 \div 50$	$N_{\text{batch}} \times 36$
LHC75NS	74.88	$1 \div 50$	$N_{\text{batch}} \times 64$
LHC single bunch	$524.4 \div 2022.6$	$0.2 \div 50$	$1 \div 16$
LHC Ion/Pb ⁸²⁺	100	$0.01 \div 2$	$N_{\text{batch}} \times 4$

Table 2. Beam position measurements: resolution requirements.

	High Intensity Beam ($\geq 10^{10}$ p/bunch)	Low Intensity Beam (ex. LHC pilot: $2 \cdot 10^9$ p/bunch)
<i>Orbit Mode</i> (average on 1 ms)	$100 \mu\text{m}$	$400 \mu\text{m}$
<i>Trajectory Mode</i> (turn-by-turn)	$400 \mu\text{m}$	$1000 \mu\text{m}$

3 Electronics upgrade

A simplified block diagram of the newly developed electronics is presented in figure 1. Each pick-up will be read out using a front-end board located in the SPS tunnel, and exposed to radiation doses of up to 100 Gy per year. Despite the technical challenges imposed by a radiation-hard design, this solution was favoured to avoid the very long and expensive cables which are currently used in the present system. In view of a possible upgrade for two-plane beam position monitors, the front-end electronics integrates two processing channels, for both the horizontal and the vertical planes. On the front-end board, after a first analogue processing stage, signals are digitized locally and transmitted via optical fiber over long distances, of up to 1 km, to a read-out board located in a surface building. The read-out board communicates through a VME interface with the software environment in order to receive commands and send data.

The machine timing is distributed on the read-out boards providing both an injection *pre-pulse* signal, sent around $70 \mu\text{s}$ before each beam injection, and the SPS *Turn Clock*, sent every $23 \mu\text{s}$. The SPS *Turn Clock* pulse is used to synchronize all the data chain locally on the front-end boards. The read-out board is equipped with a powerful FPGA, which provides several data acquisition modes described later in this document. The data are published via our standard control system. In total, the Multi Orbit POsition System has 216 front-end boards and 54 read-out boards.

3.1 Front-end

The front-end board has been designed to be modular with independent analogue and digital circuits connected together. The analogue board is based on bandpass filters and dual logarithmic amplifiers (Analog Devices ADL5519), whereas the digital board consists of an octal 14-bit ADC (Analog Devices AD9252), an FPGA (Xilinx Spartan6) and a Small Form-factor Pluggable (SFP) optical transceiver.

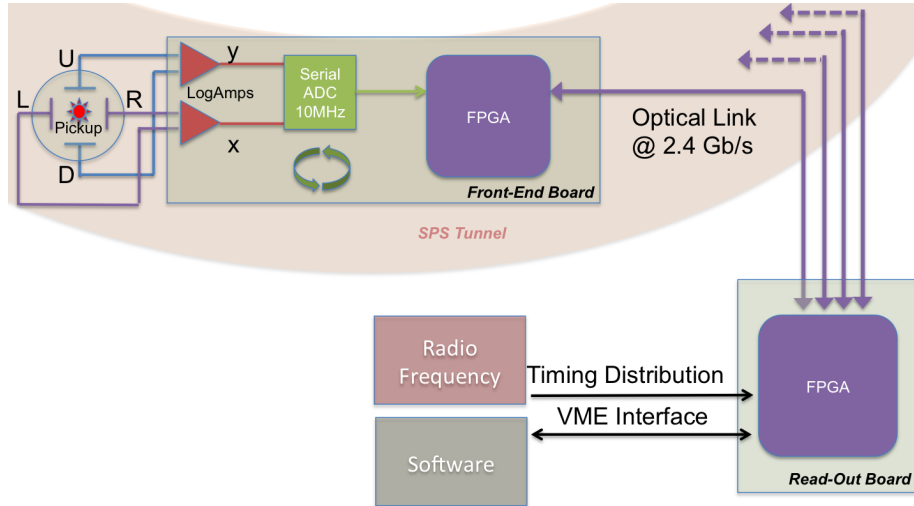


Figure 1. Multi Orbit Position System upgrade: simplified block scheme.

Analogue Front-End. The architecture of a single-plane analogue front-end board is depicted in figure 2. The input signals come either from the pick-up or from a calibrator, which is remotely controlled by the digital front-end board.

The beam displacement y can be derived from the logarithmic difference of the input signals from opposite electrodes U and D as follows:

$$y = \frac{U - D}{U + D} \iff \frac{U}{D} = \frac{1 + y}{1 - y}. \quad (3.1)$$

Consider the series expansion of the natural logarithm:

$$\ln \frac{1 + y}{1 - y} = 2 \left(y + \frac{y^3}{3} + \frac{y^5}{5} + \dots \right). \quad (3.2)$$

Converting to decibels and using the first term leads to:

$$\log \frac{U}{D} \cong 2 \frac{y}{\ln 10}. \quad (3.3)$$

Then, for small beam displacements, the log-ratio gives a good approximation of y :

$$y = \frac{\ln 10}{2} (\log U - \log D). \quad (3.4)$$

For each BPM plane, the input stage is made of a low-pass filter that minimizes the bunch shape variation during acceleration. The signals from each electrode are split into three parallel detection chains with different band-pass filters and gain stages to cover the high dynamic range and the different beam patterns available in the SPS. Signals from opposite electrodes are processed by the same dual logarithmic amplifier, which provide a direct measurement of the beam position. Therefore each plane generates three analogue position signals, called Delta 200 MHz, Delta 40 MHz Low Sensitivity and Delta 40 MHz High Sensitivity. One should however note that only one signal will be used to calculate the beam position, this selection being made in the read-out

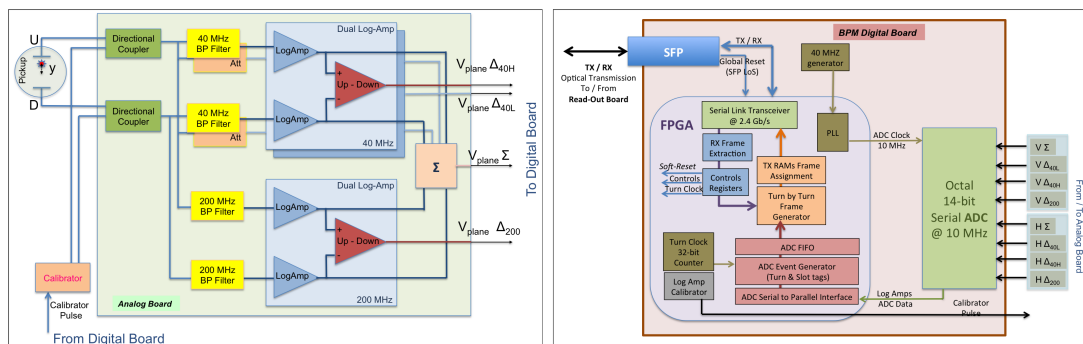


Figure 2. Front-end board architecture: single-plane analogue board on the left; digital board on the right.

board. In addition, all the logarithmic amplifier's outputs are summed together. The corresponding *Sum* signal gives an estimate of the beam intensity and it is used to detect the presence of the beam and to validate the acquisitions.

Digital front-end. The architecture of the digital front-end board is depicted in figure 2. Each BPM plane provides three beam position signals and one beam intensity signal. They are digitized at 10 MS/s and serialized. The on-board FPGA communicates with the read-out board via a 2.4 Gb/s, bidirectional, optical transmission link. Every $23 \mu\text{s}$ it receives from the read-out board a frame of data, which carries the SPS *Turn Clock* information together with some commands used to control the parameters of the calibration system. This timing information is then locally decoded and each ADC measurement is tagged in the FPGA by a time-stamp with respect to the rising-edge of the SPS *Turn Clock*. Data are then packed in a frame every turn and transmitted to the read-out board.

Radiation tests. The front-end board is designed to be located in the SPS tunnel, where it must withstand radiation doses of up to 100 Gy per year. Several commercial components have been tested under radiation in 2012 [2]. Two different setups have been prepared with 1 kGy of total dose targeted for each device under test. In the first setup, logarithmic amplifiers, ADC-drivers and voltage regulators have been tested at the Paul Scherrer Institute (PSI), in the Proton Irradiation Facility (PIF). The corresponding data allowed to select the components to be used in the Multi Orbit POsition System. In the second test setup, several families of bidirectional Small Form-factor Pluggable (SFP) optical transceivers, either single-fiber or double-fiber, have been tested at both PSI-PIF and CERN CNRAD. The test results showed that the SFP components are very sensitive to irradiation and for our current renovation program we are now considering to use specifically designed radiation hard optical transceivers rather than COTS components. For the final version, the FPGA and the ADC have still to be selected.

3.2 Read-out

The read-out board, shown in figure 3, is a custom made VME FMC Carrier, called VFC [3], which has been developed as a general beam instrumentation acquisition board. On the VFC there are two Xilinx Spartan6 configured to manage up to 6 SFP optical transceivers: 2 on the front panel, one of those receiving the Beam Synchronous Timing signals, like the SPS *Turn Clock*, and 4 available

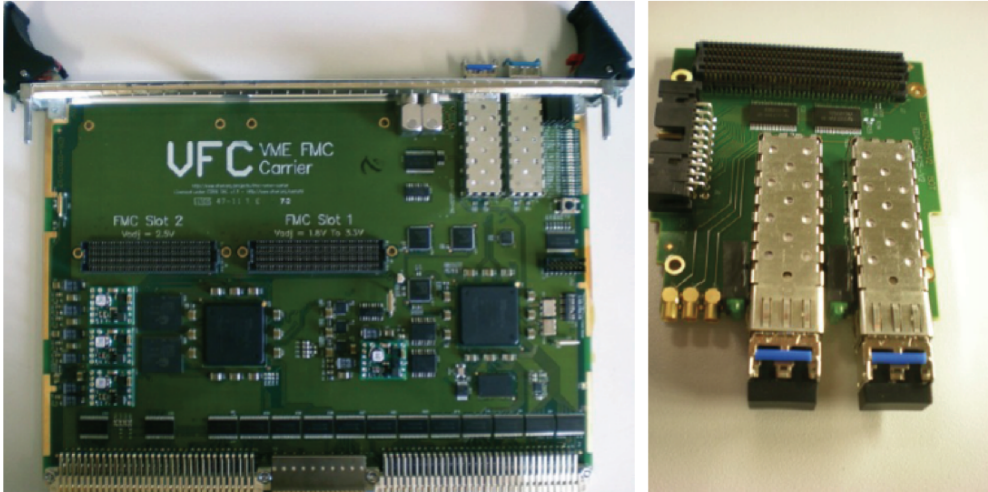


Figure 3. MOPOS read-out electronics: VFC board, on the left; FMC board on the right.

for the FMCs. In order to read out four beam position monitors with one VFC board, a dedicated MOPOS FMC, shown in figure 3, has been developed and produced.

Measurements. From turn-by-turn data, several acquisition modes, presented in table 3, have been implemented in the FPGA of the read-out board. They provide the trajectory and orbit measurements as requested by the SPS operators. For each mode, two parameters must be defined and configured on the FPGA: the number of ADC slots selected per turn, from 1 up to 235, with an ADC sampling rate of 10 MS/s, and the number of turns to be acquired. The *FIFO Mode* is a debugging mode which allows to save all the data for 3 consecutive SPS turns, corresponding to about 70 μ s. The *Capture Mode* is an operational mode used to acquire data over a time window, which can be up to 220 turns, if all the ADC slots are saved for each turn, or up to 64 k turns, when a maximum of 8 ADC slots are selected per turn. The data acquired with the *FIFO* and the *Capture* mode are transmitted to the software without any processing. These two modes have been used to test the first MOPOS prototype with several SPS beams in January/February 2013.

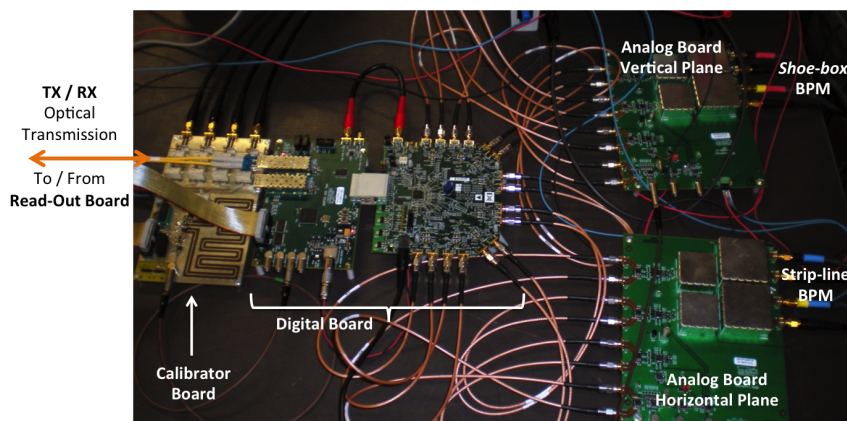
The other acquisition modes, presented in table 3, have been already implemented in the firmware of the read-out board but were not tested with the beam. The main difference with respect to the *FIFO* and the *Capture* modes is that the data are already analyzed by the FPGA firmware, which outputs a mean value to the software. The *Injection Trajectory* contains up to 13 mean position values, one for each batch, which are defined by a certain number of programmable ADC slots. The *Orbit Diagnostic* outputs 235 mean position values, one for each ADC slot. On the contrary the *Global Orbit* gives a value for each turn, averaged on a selected number of ADC slots, which can possibly be non consecutive. Finally the *Continuous Filter* outputs one value per BPM plane every ms, which is the filter response in permanence over all the data received from the front-end.

4 First measurements with beams

The first MOPOS prototype has been assembled and tested in the SPS, with both proton and lead-ion beams, under different conditions, including single bunch, 25 ns and 50 ns bunch trains. During

Table 3. Acquisition modes included in the read-out board firmware.

Measurement Mode	Type	# SPS turns	# ADC slots	Mean Values
FIFO	Debug	3 ($\sim 70 \mu\text{s}$)	All frame	—
Capture	Operational/	220 ($\sim 5 \text{ ms}$)	All slots	—
	Debug	64000 ($\sim 1.5 \text{ s}$)	8	—
Injection Trajectory	Operational	Up to 64 ($\sim 1.5 \text{ ms}$)	Up to 235	13 batches
Orbit Diagnostic	Debug	Up to 255 ($\sim 5.8 \text{ ms}$)	All	One for each slot
Global Orbit	Operational	Up to 255 ($\sim 5.8 \text{ ms}$)	Up to 235	One for each turn
Continuous Filter	Operational	Permanence	All slots	One for each plane

**Figure 4.** MOPOS first prototype setup tested on the SPS: front-end boards.

this test, the front-end, as visible in figure 4, was installed in the same room as the read-out electronics and therefore not exposed to radiation. The analogue boards were connected to a horizontal *Stripline* BPM and to a vertical “*shoe-box*” BPM. The digital front-end is made of an octal-14bit-ADC commercial evaluation board, a calibrator and the FPGA-based acquisition board, which is connected via an optical fiber to the read-out VFC board.

The beam injection oscillations have been successfully measured in both planes. To evaluate the sensitivity of the system, local beam displacements, usually called orbit-bumps, were introduced during the SPS machine cycle using dipolar magnetic correctors. The beam-synchronous *pre-pulse* signal has been used to trigger the acquisition either at injection or during the orbit-bump.

4.1 Injection oscillations

The injection oscillations of a proton batch have been measured and are displayed in figure 5. The left plot presents typical single-bunch oscillations observed at injection on the horizontal *stripline* pick-up using the 40 MHz high sensitivity mode. These oscillations are usually damped within 1 ms when the transverse damper is active. On the right plot, smaller vertical oscillations are shown for the vertical *shoe-box* BPM, which have been measured with the 40 MHz low sensitivity mode for a beam of 48 bunches per batch and 25 ns bunch-spacing.

In figure 6, the left plot shows the beam position and intensity signals of 4 batches containing 36 bunches with 50 ns bunch-spacing and $1.4 \cdot 10^{11}$ protons per bunch. The measurement was done during the injection of the fourth batch, which is clearly off-centre with respect to the other batches.

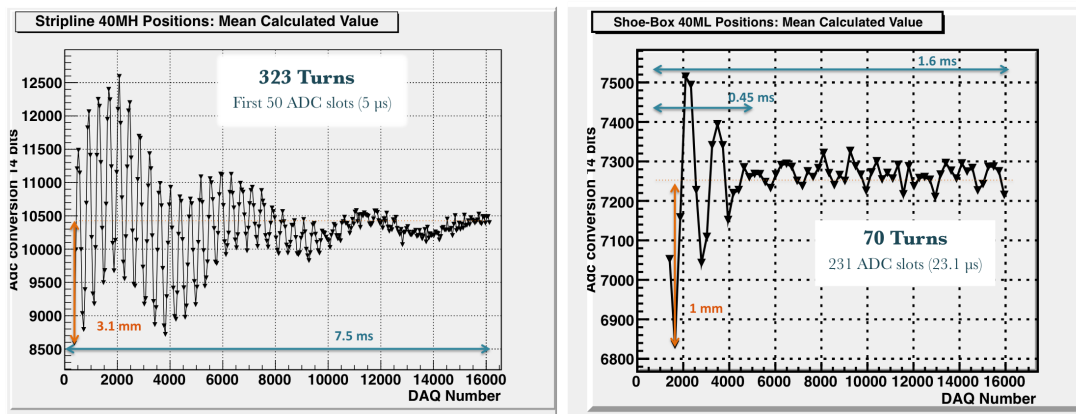


Figure 5. Proton injection oscillations: horizontal plane, single bunch, on the left; vertical plane, 48 bunches spaced at 25 ns, on the right.

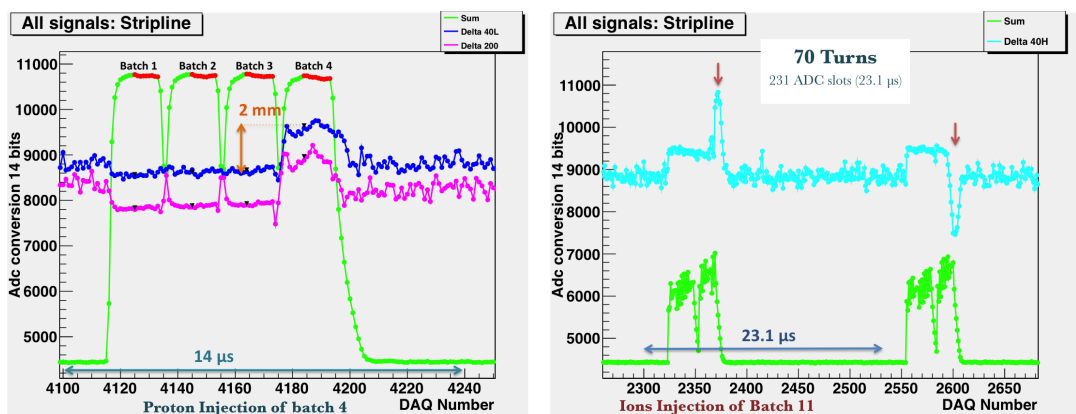


Figure 6. Multi-batch beam injection oscillations: protons on the left; lead-ions on the right.

The acquisition of a lead-ion beam of 10^{10} charges per bunch, when batch 11 is injected, is presented on the right plot in figure 6. The batches of Pb^{82+} ion beams injected in the SPS contained two bunches with 200 ns spacing. Notice that batch 11 is off-centre with respect to the other centred batches. For heavy ion beams, only the 40 MHz High-Sensitivity channel provided useful data; the other channels were dominated by the noise of the logarithmic amplifiers and the associated ADC-drivers.

4.2 Local beam displacements

In order to characterise the performance of the system, local beam displacements of ± 1 mm, ± 2.5 mm and ± 5 mm have been put in place in the vicinity of each BPM under test. Each orbit bump, either in the horizontal or in the vertical plane, is using 3 magnetic correctors. They are programmed to start 1 s after the injection. As depicted in figure 7, the bump is kept stable for 200 ms, with a rise and fall time of 100 ms. For each displacement, three measurements have been acquired: before, in the center, and after the bump.

Both the system sensitivity, which is the number of μm per ADC-bin, and the resolution, typically limited by noise, have been evaluated from these data. The results are shown in table 2.

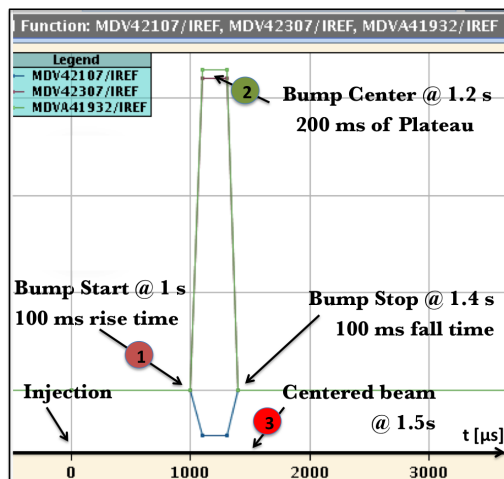


Figure 7. Local beam displacement configuration.

The analogue noise on the 40 MHz high-sensitivity channel, which is active for the single-bunch proton beam acquisitions, was estimated at 150 ADC-bins on a turn-by-turn basis in the worst case, which means about $375 \mu\text{m}$ for the vertical measurements. This noise level needs to be reduced in order to improve the performance of this channel.

A proton beam of 48 bunches per batch with 25 ns bunch-spacing and $1.4 \cdot 10^{11}$ charges per bunch has been used to characterise the 200 MHz and 40 MHz low sensitivity channels. These results confirm that the sensitivity is about $1.7 \mu\text{m}/\text{bin}$ for the *stripline* and $2.5 \mu\text{m}/\text{bin}$ for the “*shoe-box*”, which reflect different BPM apertures. Noise levels, including beam position jitter, limit the estimated resolution to $375 \mu\text{m}$ in *trajectory mode* and $80 \mu\text{m}$ in *orbit mode*, in the worst conditions.

5 Conclusions

The upgrade of the Multi Orbit POsition System is required to replace the obsolete electronics and to improve the quality of the current measurements in the SPS. A prototype of the new electronic system, based on logarithmic amplifiers and fast digital electronics, has been fully tested in the CERN-SPS, allowing the observation of proton and lead-ion beams under various beam conditions. The beam injection oscillations and the multi-bunch structure have been reconstructed. Using local beam displacements, the resolution of the system was estimated to be $375 \mu\text{m}$ for turn-by-turn acquisitions and $80 \mu\text{m}$ in *orbit mode*, which matches the specifications. The system is now being optimized to improve the sensitivity for low charge beams. Several commercial components have been already tested under radiation, while the ADC and the FPGA have not been selected yet.

A pre-production of the new MOPOS system will be installed in 2014 in an SPS sextant. At least for one year, both systems, the current and the new-one, will run in parallel to validate the new MOPOS electronics.

Acknowledgments

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