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COMMISSIONING OF ALPS, THE NEW BEAM POSITION MONITOR SYSTEM OF CERN'S SUPER PROTON SYNCHROTRON

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Abstract

The Super Proton Synchrotron (SPS) is both the final machine in the pre-accelerator chain of the Large Hadron Collider (LHC) at CERN and a machine providing several fixed target experiments with proton and ion beams. In the framework of CERN's LHC Injectors Upgrade (LIU) project, aimed at improving the performances of the pre-accelerators in view of the high-luminosity upgrade of the LHC, the Beam Position Monitor (BPM) system of the SPS was redesigned during Run 2 of the LHC and deployed during the subsequent Long Shutdown 2 (LS2). This new system is called ALPS (A Logarithmic Position System) and acquires the signals from some 240 BPMs. It is designed to improve the system's reliability and reduce the required maintenance with respect to its predecessor. During the restart of the SPS in 2021, the BPM system was a key element of the fast recommissioning of the machine, proving the validity of the chosen design approach and pre-beam commissioning strategy. This paper aims to illustrate the design choices made for ALPS, the strategy for commissioning it with beam in parallel with the machine restart, the commissioning procedure and the results obtained.

INTRODUCTION TO ALPS

The Super Proton Synchrotron (SPS) is the second largest accelerator in the CERN complex. It can accelerate both proton and ion beams to fill the Large Hadron Collider (LHC) but also provides beams to several fixed target experiments. The beams accelerated by the SPS may vary in bunch intensity from 5E8 up to 5E11 protons per bunch, but also in bunch spacing, from single bunch to trains spaced from 5 ns to 75 ns. Table 1 summarises the beam types accelerated in the SPS.

The majority of the pick-ups in the SPS are of the shoeboxe type, with very low sensitivity: 0.1 dB/mm and 0.2 dB/mm respectively for the horizontal and the vertical planes. Because of the limited BPM sensitivity, the system needs to cover the 70 dB dynamic range, mostly deriving from intensity (see Table 1), with an expected resolution in the order of 0.01 dB, corresponding to about 100 µm. ALPS (A Logarithmic Position System) uses logarithmic amplifiers to compress the dynamic range, as described in details in [1]. The chosen amplifiers have a dynamic range of about 40 dB, in which processing errors are acceptable for the system requirements. In order to cover the full 70 dB required, the electrode signal is split in 3 channels with different sensitivity ranges, each separated by about 15 dB [1]. The 3 channels are acquired in parallel and the online processing algorithm automatically selects the ranges which can be used for position calculation.

The logarithmic amplifiers only approximate the logarithm function, and the error function is specific for each amplifier. The mismatch between the error functions in the different channels, as well as the integral error, need to be compensated for in the processing chain to achieve a precision compatible with the target resolution, otherwise they would lead to position- and intensity-dependent systematic errors. This is achieved with a correction polynomial applied in the online processing chain, and computed from calibration measurements performed in the lab on each amplifier. Figure 1 illustrates the residual integral error of the measured power at the input of the front-end after the calibration. ALPS' front-end electronics, both analogue and digital, is indeed installed in the SPS tunnel and exposed to radiation but no digital processing is performed there after digitisation: the digitised signals are directly transmitted to the surface via optical fibres after packaging and serialisation. The front-end as a whole, as well as each of its active components individually, was qualified for radiation with the help of CERN's Radiation to Electronics (R2E) working group and, whenever possible, radiation-tolerant by design ASICs designed by the CERN PH-ESE group were used. As a result, the front-end electronics, installed in small crates located under the beamline itself, is expected to properly operate, i.e. without significant drifts, up to an integrated dose of 750 Gy [2].

The use of radiation-tolerant front-end electronics, with digitisation in the tunnel and optical transmission, eliminated the need for the long cables used in the previous system. Those cables were the main reason for maintenance interventions: due to the low sensitivity of the pick-ups, even small drifts in the cable characteristics had to be measured and compensated for between each run.

Table 1: SPS Beam Types

Spacing	Charges per bunch MAX	Charges per bunch MIN
5 ns	5e10	5e8
25 ns	3e11	1e9
50 ns	3e11	1e9
75 ns	3e11	1e9
single bunch	5e11	1e9

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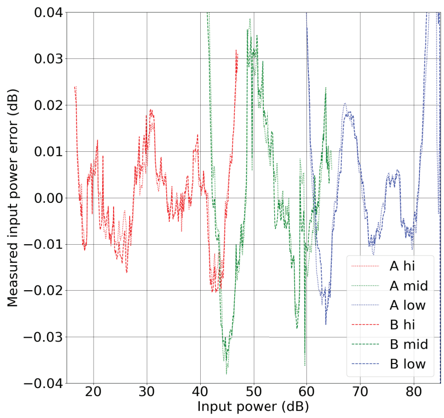

Figure 1: Plot of the residual error on the power level estimation at the input of one of the front-ends after applying the correction polynomials. In the plot, the different sensitivity ranges are depicted in different colours and the result for each of the electrodes is shown with a different line style. The horizontal axis is in dB with an arbitrary offset. It can be observed how the traces for the 2 electrodes overlap, and the absolute error is kept below 0.03dB.

COMMISSIONING CHALLENGES

The SPS was recommissioned in 2021 after a large upgrade program in which several operation-critical systems were totally replaced, including the accelerating radiofrequency system (RF). The BPM system is fundamental for the commissioning of an accelerator from day one: to thread the beam around the machine, to establish a first closed orbit and to perform the first beam-optic checks. For this reason, several of the ALPS acquisition modes were expected to work reliably from first injection. This was possible thanks to an extensive and successful dry run programme organised in collaboration with the SPS operation crew (SPS-OP). This improved not only the readiness of the system, but also SPS-OP's confidence in a system with which they were familiar before the first beam.

INSTALLATION, TEST AND DRY COMMISSIONING

The SPS has ~240 BPMs connected to the ALPS acquisition system. While the front-end electronics is distributed all along the ring, the back-end electronics is grouped in 6 surface buildings called BAs, each serving a sextant of the SPS. The basic building block of the back-end electronics is a VME [3] board called VME FMC Carrier (VFC), which is the standard readout board of CERN's Beam Instrumentation group (SY-BI) [4]. These boards are equipped with a Field Programmable Gate Array (FPGA) in which the samples coming from the front-end are processed in real time to obtain a pseudo position. The transfer function of the specific BPM being read out is required to translate this value, expressed as the difference between the signal amplitudes from 2 opposite electrodes, into an actual position. This operation is performed in software in a PC installed in the same VME crate as the VFCs.

Synchronisation with the machine cycle and events is achieved via the general machine timing (GMT), which is distributed to each VME PC, and the beam synchronous timing (BST), which is distributed to each VFC and embeds the revolution frequency and various triggers in a digital frame.

Each VFC receives the data from 4 front-ends and each crate is equipped with up to 10 VFCs for a total of up to 40 BPMs, covering the needs of a full sextant.

The first BA installation was finalised at the end of 2019, while the remaining 5 were completed and tested in the first half of 2020.

ALPS has several acquisition modes and processes and each of them had to be commissioned:

- **FIFO**: When this mode is activated, any valid position sample detected by the system is stored in a memory with 64 locations. This mode does not depend on timing and is therefore the main tool for the commissioning of the accelerator when the RF is not yet operational.
- **Injection trajectory**: This mode stores the position of each injected train of bunches, considered as a unit (i.e. no bunch-by-bunch information), for the first 64 turns.
- **Capture trajectory**: This mode stores the position of a selected group of bunches, considered as a unit for 1000 turns after it is triggered.
- **Global orbit**: This mode publishes the position of all the bunches averaged over 1 ms.
- **Synchronous orbit**: This mode implements the same logic as the global orbit, but the average is performed only on a selected group of bunches and therefore needs to be synchronised with the revolution frequency.
- **Snapshot**: This mode stores the raw ADC signals, their processed version, and most of the control and synchronisation signals while preserving their relative timings. It is used to measure and compensate for the delay resulting from the different cable lengths and the time of fly of the beam.
- **Trajectory interlock process**: This is not strictly an acquisition mode, but rather a process running in parallel that identifies possible beam instability by monitoring each position sample. If the process identifies a possible instability, the beam is dumped and several buffers intended to identify the beam behaviour that triggered the dump are stored for further analysis.
- **Orbit interlock process**: This is a software check running on the VME PC that monitors the orbit in the location where an extraction bump is prepared. If the orbit is not measured at the expected level after the bump has been prepared, the extraction kicker is not allowed to charge. The same test is performed a few ms before firing the kicker for a final validation. If either of the 2 checks fails, the extraction is not permitted and the beam is sent to the dump line instead.

Each of these modes was tested in the lab to verify the basic functionalities, but as soon as the first BA installation

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(including the associated front-end electronics) was complete, the tests were performed using the actual system and its embedded test circuitry, wherever possible in collaboration with SPS-OP. This approach was originally chosen in order to be able to test the integration of the system in the different software layers, but it also had the advantage of giving the operators more than one year to familiarise themselves with ALPS. This allowed SPS-OP to discover potential operational shortcomings and to look for solutions and improvements as a team with the BI developers, whether to adapt the instruments and the associated tools or to adjust the way they were used. For example, the complex interpretation of the injection trajectory post-mortem data, a group of buffers designed to help analyse the instabilities that caused the beam dump command, benefited from the dry runs and interaction between the two teams. Those interactions resulted in an optimisation of the data stored and better analysis tools.

BEAM COMMISSIONING AND ISSUES

The first beam after the long shutdown was injected in the SPS on 12 April 2021 and was immediately acquired by ALPS with the FIFO mode (see Fig. 2). The position measured made it possible to promptly correct the optics settings and store the beam for several turns, a necessary condition for the start of the RF commissioning.

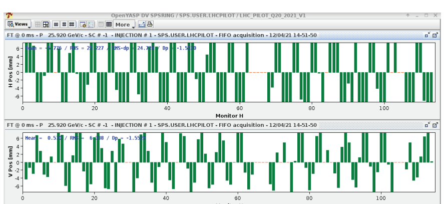

Figure 2: A screen capture of the SPS BPM operational software depicting the first successful injection in the accelerator as captured by ALPS in FIFO mode. The trajectory measured made it possible to promptly correct the optics settings.

Once the RF had captured the beam, making it possible to reliably distribute the BST and triggers, the other acquisition modes of ALPS could be used to further set up the beam. Thanks to the extensive dry runs, the commissioning of the system with beam did not require any dedicated beam time, and all the modes were immediately available.

ALPS' immediate availability and ease of use was such that SPS-OP declared that it enabled them to gain an enormous amount of time compared to previous start-ups.

The only significant issue encountered when testing the system in real conditions was linked to high-intensity single-bunch beams: when the injected intensity of the single-bunch beams was increased to above 1e11, the system started showing increased noise and, depending on the actual intensity, even wrong orbit readings.

It is important to note that the system uses a dedicated processing chain for single-bunch measurements. The analogue front-end does not reach a steady state when excited with a single state and therefore requires dedicated calibration settings; moreover, the sampling frequency of 40 MHz does not guarantee a sample close to the peak of the signal, so a digital up-sampling algorithm had to be implemented in the FPGA [1].

Fortunately, the system was able to reduce the signal levels at the input using the programmable attenuators originally foreseen for calibration purposes. This allowed the SPS commissioning to continue while the ALPS team was investigating the problem.

The issue was found in the programmable parameters used to determine the sample to select for the position measurement. It had not been possible with the laboratory setup, nor with the calibration circuit used for the dry runs, to reliably emulate intensities higher than 1e11, and it had been assumed that the shape of the signal would have been a simple scaling of that obtained for lower intensities. Unfortunately, due to saturation of some components in the channel with higher sensitivity, this assumption turned out to be wrong. Once the issue was identified thanks to analysis of the raw data via 'snapshot' acquisitions, it was easy to correct. The attenuators were nevertheless kept in the chain at their maximum level, 8 dB, as the system performed better than expected for low-intensity beams.

MEASURED RESOLUTION

The resolution of the system depends more on the beam time structure than on beam intensity, as long as the input remains in the calibrated range.

The resolution estimation was performed via Singular Value Decomposition (SVD) analysis [5]. Table 2 shows the estimated resolution for the 2 most common BPM types in the SPS: the shoeboxes BPH and BPV. The table indicates the estimated resolution before SVD analysis, with the data still affected by beam motion, and after removing the first 4 modes identified by the SVD decomposition. The data for this analysis, for a total of 5000 points of turn-by-turn data from each BPM, was acquired during normal operation of the SPS and not in dedicated runs. The multi-bunch beam used was a 10 µs train of proton bunches spaced 5 ns apart, for a total of 400 samples at 40 MHz. As a result, the

Table 2: Turn-by-turn resolution for a single-bunch and a 10us-long multi-bunch beam. The resolution varies with the BPM type due to the different aperture. For the purpose of the analysis, the first 4 modes obtained with SVD have been subtracted to remove the variations linked to the beam motion.

Beam type	**BPH**	**BPV**
Single-bunch: before SVD	600 µm	150 µm
Single-bunch: after SVD	290 µm	140 µm
Multi-bunch (10 µs): before SVD	250 µm	12 µm
Multi-bunch (10 µs): after SVD	80 µm	7 µm

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multi-bunch resolution is expected to be approximately 20 times better than the single-bunch resolution for the same BPM type, simply because of averaging. Another important factor is the different sensitivity of the horizontal and vertical BPMs: as a result, the vertical resolution after SVD should be 2 times better than the horizontal one.

For single-bunch beams, the factor 2 between vertical and horizontal resolution is respected after the subtraction of the beam motion (i.e. after SVD). For single- and multi-bunch beams, it can be observed that the SVD has minimal effect on the estimated resolution in the vertical plane, where the beam is very quiet, as expected, and, after the SVD analysis, the expected factor 20 between the resolution for single- and multi-bunch beams is respected.
In the horizontal plane (BPH), on the other hand, the resolution for the multi-bunch beam after SVD is not in line with expectations. Neither the factor 20 with respect to the single-bunch case, nor the factor 2 with respect to the vertical plane resolution, is respected. This last consideration in particular might suggest that, in this case, the SVD analysis did not succeed in removing all beam-motion components. Bearing in mind that the electronics is the same for the 2 planes, and that the only difference is the sensitivity of the 2 types of electrode (merely a consequence of their different apertures), it can be estimated that the real resolution is better than 24 µm, i.e. 2 times the resolution measured in the vertical plane before the SVD analysis.

CONCLUSIONS

ALPS commissioning started with dry runs one year before the first beam was injected in the SPS in 2021, in the middle of the Long Shutdown 2 (LS2), at a time when some of SPS-OP's software tools were still being developed and some acquisition modes were still being tested. This made it possible not only to test the integration of the system, but also to get the operators used to ALPS and how it should be operated.

The exchanges with SPS-OP during the dry runs highlighted possible use scenarios as well as the associated shortcomings of the system as a whole, leaving the developers on both sides enough time to adapt to and implement the changes required. During this process, SPS-OP had to deal with several iterations of error finding and debugging of the system following new releases, but this actually created a stronger team spirit between the operators and the beam instrumentation team working on ALPS. When the first beam was injected in April 2021, ALPS felt like a familiar system to the SPS-OP team, who already knew how to operate it and what to expect.

However, not everything could be tested without beam. In particular, high-intensity single-bunch beams could not be emulated, and the system's response to them was unexpected. This required a period of investigation, during which the issues linked to the higher intensity could only be mitigated with the use of programmable attenuators, luckily already present in the input line for calibration purposes. The investigation, carried out in parallel with the SPS commissioning, and mostly in parasitic mode, lasted approximately one week: the problem was identified in a set of parameters used to select the sample for the position computation and was easily solved.

The resolution measured in the vertical plane, after the use of SVD analysis is 140 µm for single-bunch beams in turn-by-turn mode and is in line with the estimations based on laboratory measurement. For multi-bunch beams, it has been verified that the resolution scales with the square root of the length of the bunch train measured in slots of 25 ns, proving also the effectiveness of the digital up-sampling and dedicated calibration for the more difficult single-bunch case. In the vertical plane, with the beam being very stable, the effect of SVD analysis is minimal for both single- and multi-bunch beams, but it was nevertheless important to apply it: without the SVD analysis the scaling of the resolution with the number of samples used per turn would not be respected.

In the horizontal plane, the resolution for the single-bunch beams in turn-by-turn mode is 290 µm, a factor 2 worse than in the vertical plane, but this was expected given that the BPM aperture in this plane is twice as big. For multi-bunch beams, on the other hand, the resolution even after SVD analysis remains a factor 5 worse than expected from scaling the single-bunch case. Given that the electronics is the same for both planes, it is believed that this mismatch is an artefact of the SVD analysis, which is not capable of effectively suppressing the strong beam movements in the horizontal plane. Other methods of estimating the resolution are still under investigation in order to confirm this hypothesis.

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