Commissioning of ALPS, the New Beam Position Monitor System of CERN's Super Proton Synchrotron

ALPS
A Logarithmic Position System

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 experiments with proton and ion beams. For this reason it accelerates a variety of beam types:

SPS beam types for protons and ions

Spacing	Charges per bunch MAX	Charges per bunch MIN
5 ns	5E+10	5E+08
25 ns	3E+11	1E+09
50 ns	3E+11	1E+09
70 ns	3E+11	1E+09
Single-bunch	5E+11	1E+09

During CERN's Long Shutdown 2 (LS2) several systems in the SPS were upgraded as part of the LHC injector upgrade (LIU) project: among them the beam position monitoring (BPM).

While the acquisition electronics has been totally replaced, the BPM electrodes have been kept, with the majority being the very linear but low sensitivity BPV and BPH shoeboxes, respectively for the vertical and horizontal planes:

- BPV sensitivity: 0.2 dB/mm
- BPH sensitivity: 0.1 dB/mm

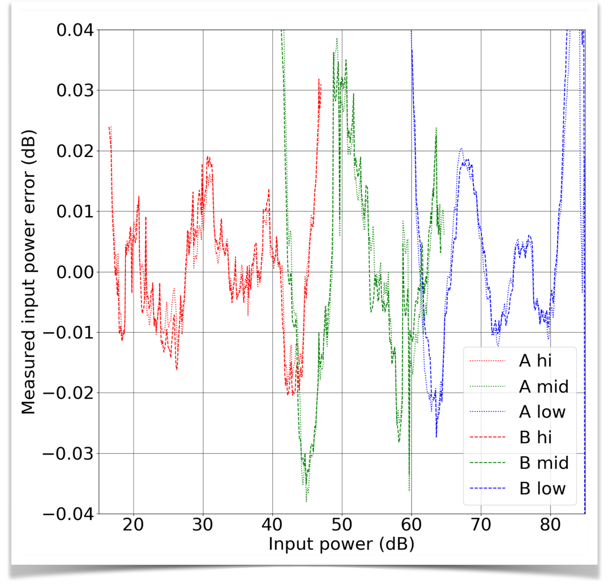
A BPM system for the SPS needs to cover **70 dB of dynamic range**, mostly due to the range of beam intensites injected, with a **resolution in the order of 0.01 dB**, due to the low electrode sensitivity.

ALPS deals with the large dynamic range via:

- Logarithmic amplifiers to compress the dynamic range
- 3 parallel acquisition channels for each electrode, ~10 dB apart

The front-end filters for the electrodes of the same BPM are carefully paired, and the logarithmic amplifiers have 2 channels per chip: this makes it possible to reduce the systematic errors due to asymmetries in the processing chain.

For large displacements, in the tens of mm, the error in the logarithmic function introduces systematic errors that are dependent on the intensity. ALPS controls this error in its online processing chain with correction polynomials computed from the calibration of each amplifier.



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 BPM system is fundamental for the commissioning of an accelerator from day one, and is required for establishing a closed orbit. For this reason, commissioning of several of the ALPS acquisition modes could not wait for the beam, as they had 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.

In addition during LS2, the radiofrequency (RF) acceleration system was also totally renewed, making the 2021 start-up very similar to the start of a new machine, but with the time pressure of the experimental programme waiting to start.

INSTALLATION, TEST and DRY COMMISSIONING

ALPS' front-end electronics is installed in the tunnel, and for this it was qualified up to 700 Gy with the help of CERN's Radiation to Electronics (R2E) project.

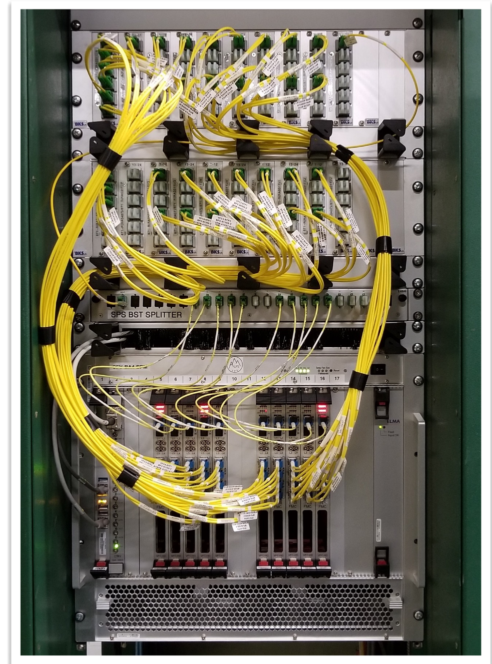
The design used a mix of :

- COTS qualified with the help of R2E
- ASICS designed by the CERN PH-ESE group

At each front-end location a device, called a rad-mon, is placed to monitor the integrated dose.

The processing in the front-end stops at the digitisation: the digitised signals are serialised and transmitted to the back-end on the surface via optical fibres.

About 240 front-ends are distributed along the SPS ring. The electronics is qualified and expected to work without significant variations in the characteristics up to 750 Gy.



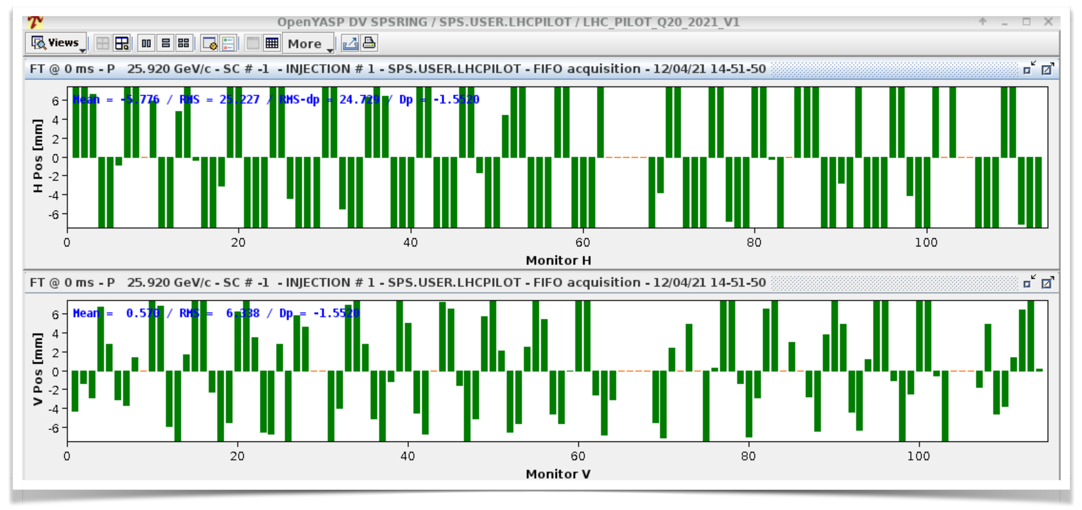
The back-end is based on the CERN SY-BI standard acquisition board: the VME FMC carrier (VFC).
Each VFC receives the continuous data stream from 4 front-ends and from the beam synchronous timing (BST) via optical fibres.
The back-end boards are concentrated in 6 crates, each in one of the surface buildings called BAs.

ALPS implements several acquisition modes and processes:

- **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 and not in a bunch-by-bunch manner, for the first 64 turns.
- **Capture trajectory**: This mode stores the position of a selected group of bunches, considered as a unit and not in a bunch-by-bunch manner, for 1000 turns after it is triggered.
- **Global orbit**: This mode publishes the position of all the bunches averaged over 1 ms.
- **Synchronous orbit**: Like the global orbit but on a programmable group of bunches
- **Snapshot**: A debug and set-up mode storing raw-data samples and trigger signals respecting their relative timing.
- **Trajectory interlock process**: A process aimed at protecting the SPS from instabilities.
- **Orbit interlock process**: A process aimed at protecting the SPS against unsafe beam extraction.

Each of these modes was tested in the lab to verify the basic functionalities, but as soon as the first BA installation (including the associated front-end electronics) was complete at the end of 2019, 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.

BEAM COMMISSIONING and ISSUES



A screenshot of the operational tool used to display the trajectory, measured in FIFO mode by ALPS, of the very first beam injected in the SPS after LS2. The acquisition was used to adjust the optic's settings and quickly achieve circulating beam conditions.

- ALPS did not require dedicated beam time for its commissioning.
- All modes were immediately available thanks to the extended dry run programme.
- 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.
- High-intensity single-bunch beam required adjustment in the configuration: intensities beyond 1E11 could not be emulated in the laboratory or with the embedded test circuitry, and the parameters for the detection of the valid samples had to be adapted.

MEASURED RESOLUTION

- The resolution was computed with the help of SVD analysis to remove the components linked to beam motion: the first four modes were removed from turn-by-turn data.
- The multi-bunch beam resolution, for a train of 10 us, is expected to be 20 times better than the resolution for a single-bunch.
- The resolution in the vertical plane, after subtracting the beam motion, is expected to be 2 times better than the one in the horizontal plane because of the higher sensitivity of the BPV compared to BPH.

Turn-by-turn resolution

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

- The measured resolution for a BPH in the multi-bunch case does not respect any of the expected ratios: because the electronics is the same, the logical conclusion is that the SVD analysis used is not able to isolare the intense beam motion in this plane.
- The expected resolution in the horizontal plane for a 10 us multi-bunch train, scaling it from the single-bunch case or the vertical-plane case, is about 15 um.

CONSLUSIONS

- Thanks to the extended dry run programme:
  - The acquisition modes were tested in almost realistic conditions and with the operational tool
  - The operators become familiar with ALPS
  - A strong team spirit was created between the instrumentation and operation teams.
- ALPS was commissioned without requiring dedicated beam time.
- Some operational conditions, like higher intensities, could not be emulated, requiring adjustment during the first day of the run.
- The resolution in the vertical plane is 140 um in turn-by-turn single-bunch mode and scales as expected with the number of samples.
- The resolution in the horizontal plane needs more investigation.

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