COMMISSIONING THE NEW CERN BEAM INSTRUMENTATION FOLLOWING THE UPGRADE OF THE LHC INJECTOR CHAIN

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Abstract

The LHC injectors Upgrade (LIU) program has been fully implemented during the second long shutdown (LS2), which took place in 2019-20. In this context, new or upgraded beam instrumentation was developed to cope with H^- beam in LINAC4 and the new Proton Synchrotron Booster (PSB) injection systems which would provide a high brightness proton beams in the rest of the injector complex. After a short overview of the newly installed diagnostics, the main focus of this paper will move to the instruments already commissioned with beam. This will include LINAC4 diagnostics, the PSB H^0-H^- monitor, the PSB Trajectory Measurement System and the PS beam gas ionization monitor. In addition, particular emphasis will be given to the first operational experience with the new generation of fast wire scanners installed in all injector synchrotrons.

INTRODUCTION

The LHC Injectors Upgrade (LIU) program [1], aimed at increasing the beam intensity and brightness in the LHC injector chain, to meet the requirements of the High Luminosity LHC project, started in the 2010. It included the development of various new beam diagnostics systems in the whole injector complex, composed of LINAC4, Proton Synchrotron Booster (PSB), Synchrotron Booster (PS) and Super Proton Synchrotron (SPS). After the design phase, in some cases followed by prototyping including beam tests during the LHC Run2, the final diagnostics version has been installed during the second LHC Long Shutdown (LS2) in 2019-20. While a detailed description of the individual systems functionalities and performances is (or will be presented) in separate publications, this paper will give a general overview and some highlights about LINAC4, PSB and PS systems already commissioned with beam in the first part of 2021.

LINAC4 INSTRUMENTATION

After many decades of operation of the CERN hadrons complex with LINAC2 accelerating protons to 50 MeV, the historical milestone of connecting the new 160 MeV H^- LINAC4 to the PSB was reached in LS2. The new linac was re-started at the end of 2020. As for all its construction, commissioning and reliability runs phases, beam diagnostic was essential to setup RF structures and optimize the beam transmission during acceleration while preserving longitudinal and transverse beam parameters. Crucial instruments were surely the Time-of-Flight (ToF) monitoring system and the Bunch Shape Monitor (BSM).

The ToF system [2] was extensively used to tune each RF cavity to its nominal level of acceleration and precisely determine the beam kinetic energy. The method is based on the measurement of the signal phase shift difference while passing through pairs of strip lines Beam Position Monitors (BPM), while scanning the RF phase. During the last year the robustness and automation of the whole monitoring system was highly improved [3,4].

The BSM allows reconstructing the beam longitudinal distribution by converting it into a transverse distribution of low energy secondary electrons emitted by a tungsten wire intercepting the beam [5,6].

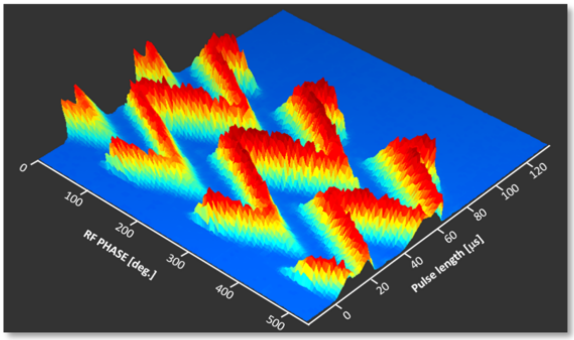

Figure 1: BSM measurement successfully proving the beam energy modulation around 160 MeV, programmed to optimize the multi-turn injection process into the PSB.

Two BSM monitors, one at end of the linac and a second one installed in 2020 at the end of the linac transfer line, after being fundamental for the RF setting up, are now daily used to check the RF stability and to prepare the different H^- beam types required by the PSB, like in the example of Fig. 1.

Transverse emittances are inferred from profile measurements via wire grids and wire scanners, but measurements can be performed only up to beam densities not damaging the wires, which basically prevents measuring pulse lengths longer than 100 µs [7]. We are developing a laser stripping

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emittance meter [8]. This is little invasive (only 7 % of the particles intercepted by the 100 µm laser beam are stripped) suitable to all beam powers. The final system is under commissioning. It allows measuring H and V emittances at two locations and a very recent example of phase space reconstruction is shown in Fig. 2.

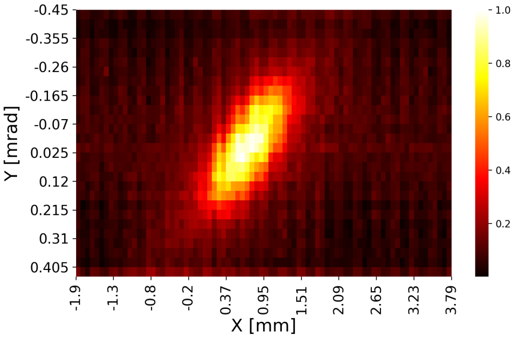

Figure 2: LINAC4 beam phase space horizontal distribution, as measured by the new laser emittance meter, in the L4 - PSB transfer line.

PS BEAM GAS IONIZATION MONITOR

An Ionisation Profile Monitor (IPM) has been developed for the PS to provide continuous bunch-by-bunch transverse beam profile measurements throughout the acceleration cycle. The instrument consists of: an electrostatic field cage to accelerate ionisation electrons onto an electron detector; a 0.2 T self-compensating dipole magnet to maintain the transverse position of the ionisation electrons onto the detector and an ionisation electron detector based on Timepix3 Hybrid Pixel Detectors (HPD) with silicon sensors. Individual ionisation electrons are detected by the Timepix3 HPD with a 1.6 ns time-resolution and a 55 µm pixel pitch. Instruments to measure the horizontal and vertical beam profiles were installed in the PS during LS2. Figure 3 shows the time evolution of the beam profile and position in the horizontal plane during a complete PS cycle. A gas injection has been installed to facilitate turn-by-turn beam profile measurements at particular moments during the acceleration cycle.

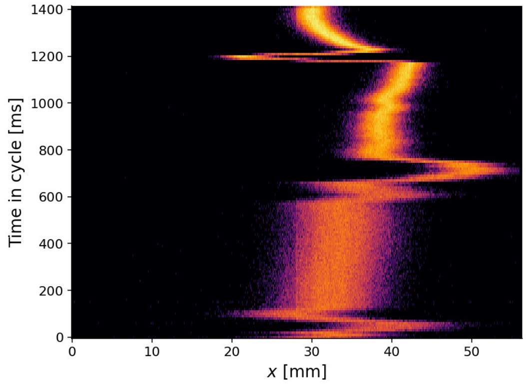

Figure 3: Horizontal beam distribution during a PS acceleration cycle, as measured by the IPM monitor.

PSB AND PS TRAJECTORY MEASUREMENT SYSTEM (TMS)

Both the CERN PSB and PS are equipped with a beam Trajectory Measurement System (TMS) that digitizes BPM signals at 125 MS/s. The digital processing in the dedicated FPGAs converts the data flow into turn-by-turn and bunch-per-bunch positions all along the acceleration cycle. The trajectory data are stored in circular buffers large enough to then display thousands of consecutive turns.

The system uses numerical phase-locked loops to derive its beam-locked timing reference. Programmable state machines, driven by accelerator timing pulses and information from the accelerator control system, control the order of operations. The TMS was essential to quickly restart and have beam circulating in both the PSB and PS in 2021. It routinely delivers turn-by-turn position data of individual particle bunches with a resolution of the order of 100 µm RMS (0.1 % of the machine aperture), and can provide down to 30 µm. It also provides time averaged orbits, trading bandwidth for still better resolution.

PSB H^0-H^- BEAM CURRENT MONITOR

The connection of LINAC4 to the PSB implied the complete change of the PSB injection region. This included the new diagnostics to continuously monitor the amount of non stripped H^- ions that, not injected in the ring, are absorbed by the dedicated dump. The monitor, Fig. 4, consists in 4 titanium plates placed few cm upstream of the dump, intercepting partially stripped (H^0) or not stripped (H^-) ions. The plates' thickness (1 mm) ensures full stripping and the monitor signal results from the electron charge, integrated every 1 µs. This system, via electronics channels acquiring in parallel, is used to continuously monitor any degradation of the stripping foils and to interlock the beam injection anytime the integrated signal exceeds the threshold retained sustainable by the downstream dump. A first commissioning phase consisted in calibrating the monitor w.r.t. an upstream beam current transformer, with low intensity beams and no

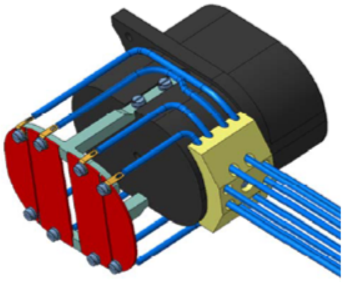

Figure 4: PSB H^0-H^- beam current monitor installed after the H^- striping foil units: four plates integrate the signal from non stripped ions before they are absorbed by the dump.

stripping foil inserted. The monitors are now operational and allow measuring stripping inefficiencies smaller than 1 %, which means few 10^7 particles. An example is shown in Fig. 5. This new system can already be used to study the stripping efficiency with different foil types, as shown in Fig. 6.

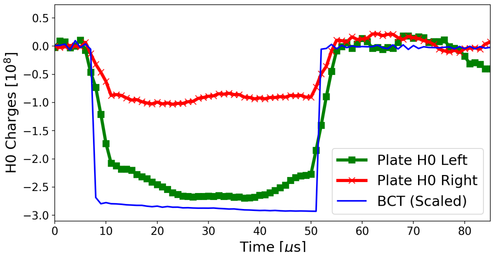

Figure 5: Measurement of the only partially non stripped particles (H^0) as measured by the dedicated monitor in front of the dump.

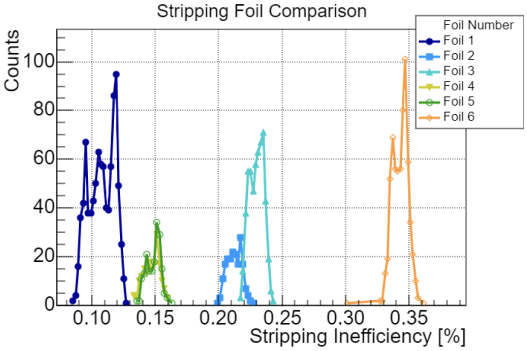

Figure 6: Stripping inefficiency as measured by the H^0-H^- monitor in the PSB Ring 3 during dedicated studies with different foil types (preliminary results).

NEW FAST WIRE SCANNERS

To cope with high brightness beams and renovate a park of instruments operated for decades, the LIU project included the major challenge of designing, testing and producing new fast (up to 20 m/s) wire scanners for the PSB, PS and SPS. This took many years and after the pre-series (one device per machine) validation completed in 2017-2018 [9], 17 new instruments were installed during LS2. The new systems are designed to enhance reliability/availability while improving accuracy, e.g via an in-vacuum optical position encoder used to infer the wire position during the scan. The secondary shower detector and related DAQ, based on 4 PMT coupled to the same scintillator, with different optical density filters in between, is meant to cover the whole park of signals generated by the wire interaction with beams of different energies (from 160 MeV to 450 GeV) and brightness. The PMT signals are digitized by fast FMC ADCs (500 MS/s). With the PSB restart in December 2020, followed by the PS ans SPS commissioning, the new wire scanners have been extensively used by both the beam diagnostic team for setting up/tuning and the operation crew to set up the machines and start qualifying the new LIU beams. This resulted in several thousands of wire scans, as for example summarized in Fig. 7. For the moment the only failure is related to a broken wire, traced down to a known issue with carbon wire copper coating (to ease the wire fixation) experienced by the first systems installed in LS2. Figure 8 shows an example of the ongoing studies to properly setup the systems in the PSB, in which by changing the PMT high voltage, PMT channels with different attenuation agree within 4 % in terms of beam size.

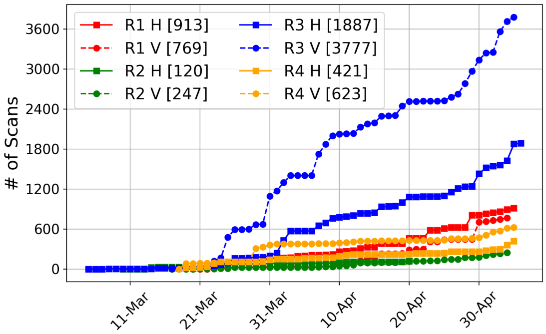

Figure 7: PSB BWS usage statistics since the beginning of the 2021 run.

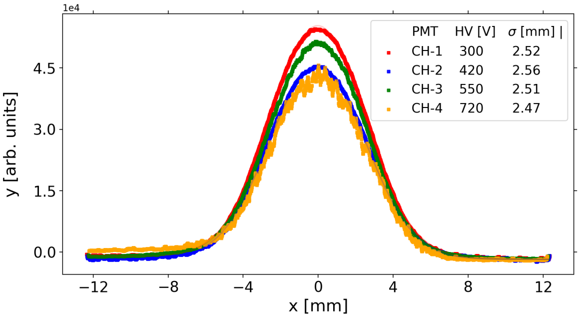

Figure 8: PSB beam profile as measured by one of the new wire scanner systems.

OUTLOOK

After the long shut down started at the end of 2018, the LHC injectors restarted in December 2020 with a large number of new beam diagnostics. In addition to the highlights presented in this paper, it is worth mentioning few other systems. The Beam Loss Monitors underwent major upgrades in all injectors [10] and were already fundamental for machine setup and protection. The PSB and PS optics matching monitors, based on new fast electronics featuring turn-by-turn wire grids acquisition, were not commissioned with beam yet, because of other operational priorities. Finally, the SPS is equipped with A Logarithmic Position System (ALPS) [11], featuring radiation tolerant electronics, accurately monitoring turn-by-turn trajectories at injection and average beam orbits along the acceleration cycle. ALPS worked from the first day of the SPS commissioning.

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