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RECOMMISSIONING OF THE CERN INJECTOR COMPLEX BEAM INSTRUMENTATION

R. Veness*, European Organisation for Nuclear Research (CERN), Geneva, Switzerland

Abstract

During the last two years, the CERN injector complex has been completely renovated with the aim of providing high intensity and smaller emittance beams to the LHC.

A new Linac providing H- has been constructed and major upgrades in the Proton Synchrotrons (PS Booster ring, PS ring and Super PS ring) have been performed. A full suite of new beam diagnostics has been implemented and commissioned. This includes fast wire scanners, beam gas ionization monitors, quadrupolar pick-ups and diamond beam loss detectors. New radiation-hard beam position monitoring system was also successfully deployed in the SPS. This talk will present an overview of the performance of the newly built instruments.

INTRODUCTION

The LHC injectors are the heart of the CERN accelerator complex, producing and accelerating proton and ion beams upto LHC injection energies, as well as producing beams for fixed-target and other facilities on the site.

2019–2020 saw the second major shutdown of the whole CERN accelerator complex since the start of LHC operations, called LS2. This was required principally to complete the LHC Injectors Upgrade (LIU) project [1], with changes across the whole injection chain to produce brighter, more intense beams in preparation for the High-Luminosity LHC (HL-LHC) upgrade [2]. Table 1 shows the target beam parameters for this upgrade at the time of the instrumentation conceptual design in 2014.

Table 1: Achievable LIU Proton Beam Characteristics at Injection

Machine		PSB	PS	SPS	LHC
Kinematic energy	[GeV]	0.16	2	25	449
Number of bunches		1/ring	29.6	1.5	650
Bunch separation	[ns]	-	284	25	25
Bunch intensity	[10^{10} p/b]	29.6	28.1	2.2	2
Transverse emittance	[μs]	1.5	1.6	1.7	1.9
Bunch length	[ns]	650	205	4.2	1.65

The major change has been the construction of a new LINAC (LINAC4) which produces hydrogen ions (H-) at 160 MeV, rather than the 50 MeV protons from the previous LINAC2. These are stripped to p+ with carbon foils and accelerated in the existing Proton Synchrotron Booster (PSB) to 2 GeV. The existing Proton Synchrotron (PS) ring takes this new higher energy injection and accelerates into the Super Proton Synchroton (SPS) at 26 GeV which gives the final boost to 450 GeV for LHC injection.

In parallel with the LIU project, LS2 has also seen a significant consolidation project (called CONS) of the injector systems, taking advantage of the unprecedented access to machines, with the aim of ensuring reliable operations for the HL-LHC era. The injectors have been operating for, in some cases, more than 60 years and were historically separated by machine in instrument design and operations. One of the strategic goals of the Beam Instrumentation group was to use this major upgrade to standardize whole instrument groups across the injector complex, replacing mechanics, electronics and software where possible with the aims of decreasing commissioning time, improving maintainability and coping with reductions in expert manpower.

These LIU and CONS projects have led to a number of new in-vacuum beam instrumentation requirements, coming from the completely new LINAC4 and its injection into the PSB, instruments with a new specification due to the increased energies and intensities in the rings and for the consolidation of obsolete instruments, many of which were 30+ years old. The numbers are summarized in Table 2.

Table 2: In-vacuum Instruments Newly Commissioned Post-LS2

Machine / Complex	'New for old' Replacements	Additional Instruments
LINAC4	–	36
PSB	20	12
PS	9	2
SPS	4	3
LHC	3	1
ISOLDE / HIE	20	11
ELENA	–	31
TOTALS	56	96

A total of 152 in-vacuum instruments were built and newly commissioned post-LS2, plus some 348 new BLM channels. Not all of this work will be covered in this paper, in particular, there are two significant new installations, ELENA, the extra-low energy ion ring and an extension to the High Energy and Intensity isotope separator, HIE-ISOLDE, which have between them 42 new instruments. However, these are not part of the LHC injector chain so will be presented elsewhere. The paper will also cover the new acquisition system for SPS beam positioning system that has been designed, deployed and successfully commissioned with beam.

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* raymond.veness@cern.ch

LINAC4

Construction of the new LINAC4 started in 2008 and the commissioning of the machine and associated beam instrumentation has progressed in stages [3]. Although LINAC4 has been extensively used for testing and reliability, LS2 has seen the final stage of commissioning, with the connection of the LINAC to the new PSB injection and the subsequent recommissioning as the source of protons for all CERN machines from late 2020. The focus since the re-start has been on tuning the RF structures and optimizing beam transmission while preserving longitudinal and transverse emittance. Key to this has been the Time-of-Flight (ToF) and Beam Shape (BSM) monitoring systems [4].

The ToF system [5] 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 (BPMs), during an RF phase scan. Over the last year the robustness and automation of the whole monitoring system was highly improved [6].

The BSM system allows the reconstruction of the beam longitudinal distribution by converting it into a transverse distribution of low energy secondary electrons emitted by a beam-intercepting tungsten wire [7]. Two BSM monitors are in use, one at end of the LINAC and a second one installed in 2020, at the end of the LINAC transfer line. Following an initial period for the RF set-up, they are now regularly used to check the RF stability and to prepare the different H- beam types required by the PSB, with an example given in Fig. 1.

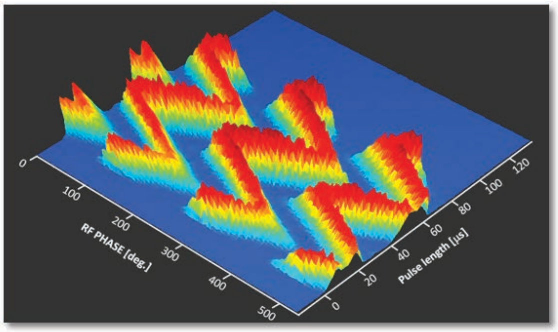


Figure 1: BSM output image showing energy modulation around 160 MeV. Courtesy of [4]

At low beam intensities, transverse emittance is inferred from wire grids and scanners. For beam pulse lengths longer than ~100 µm these instruments are restricted due to wire damage. A newly developed "laser stripping emittance meter" [7], which is minimally-invasive, intercepting only around 7% of particles has been developed and is under commissioning for these measurements.

NEW BOOSTER INJECTION REGION

The region between LINAC4 and PSB was completely re-built during LS2 to accommodate the new H- injection at 160 MeV. The carbon stripping foils which strip H- to p+ are instrumented with insertable observation screens (BTVs) to monitor the process. Improperly stripped particles are absorbed by a dedicated dump. This is instrumented with a "H0/H- monitor" consisting of 4 titanium plates. These measure the charge of partially stripped (H0) and non-stripped (H-) particles to monitor degradation of the stripping foils and interlock the maximum sustainable intensity on the dump [8]. Due to the complexities of the electronics and influence of secondary emission from plates, these monitors were calibrated against beam current transformers (BCTs) and a calibration factor was obtained. These are now fully commissioned and able to resolve stripping inefficiencies below 1%, with a stable error of below 1.5% for all plates in the four PSB rings (see Fig. 2).

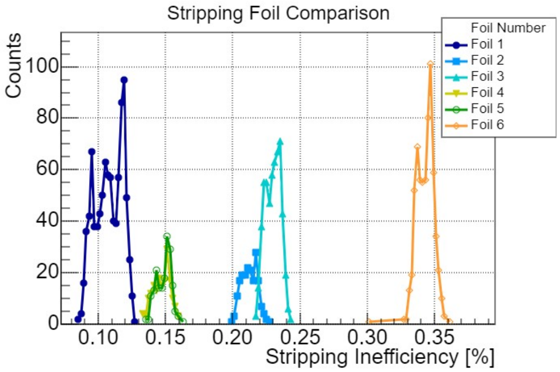


Figure 2: Stripping inefficiency as measured by the H0H- monitor in the PSB Ring 3 during dedicated studies with different foil types (preliminary results). Courtesy of [8]

The renewing of this injection region, with good access to areas that are normally tightly packed with equipment (see Fig. 3) and highly activated due to the injection losses was also the opportunity to replace 17 obsolete BTV monitors which are required for the set-up and commission the injection and extraction lines. These were replaced with a new, common design based on magnetically coupled bellows-free movements. Reliable installation and test before commissioning was important as these instruments were required to transfer the beams into the PSB with a completely new optics layout. The plan is now to re-use this standard BTV design wherever possible in the injector complex.

PROTON SYNCHROTRON

A new ionization profile monitor (called a Beam-Gas Ionisation (BGI) monitor) has been designed and installed in the PS. This, as depicted in Fig. 4, uses Timepix3 hybrid pixel detectors to image beam-gas ionisation electrons. The ionisation electrons are accelerated onto the detector by an electrostatic field inside a 0.2 T dipole field used to maintain the transverse position. A prototype was installed in 2017,

Figure 3: Four BTVs installed in the PSB.

but extensively re-designed and re-installed along with a second device in the vertical plane in 2021. It is the first use of active silicon detectors in the beam vacuum of an injector at CERN and as such has seen extensive off-line testing, both for performance and machine compatibility.

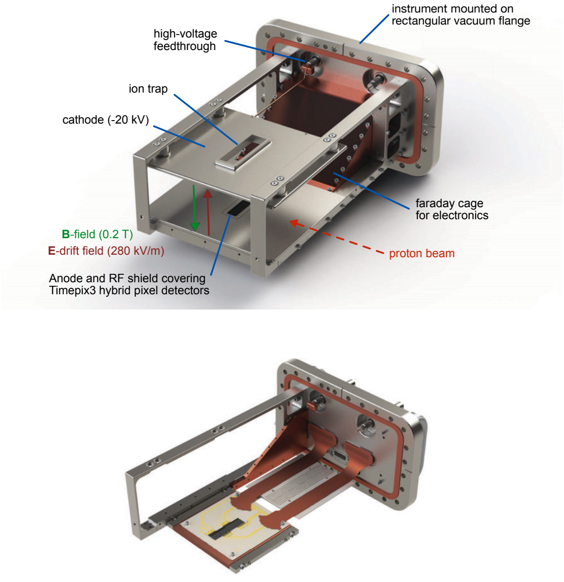


Figure 4: Design of the Timepix3 beam gas ionization monitor.

The instruments and software were available from first beam in the PS commissioning [9]. The fast 2 ms integration time allows for 600 profiles to be registered along the 1.2 s of a single PS beam cycle. The waterfall plot of Fig. 5 shows this complete beam size evolution across a machine cycle. The only significant issue during the commissioning was due to unexpected beam losses in the sector which was tracked down to an unwanted sextupolar field component in the compensation dipole. Magnet simulations have found a corrective shielding plate modification which will be applied in a future shutdown, with a short-term corrective fix in place using other lattice magnets.

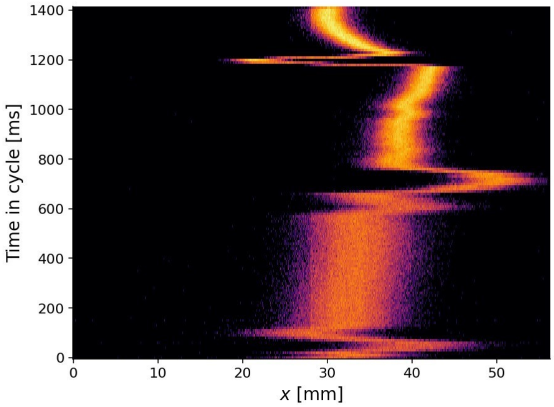


Figure 5: Waterfall plot evolution of the horizontal beam profile and position of a LHC-type bunch along the 1.2 s long PS cycle. Courtesy [9]

The PS ring also saw a number of other instrumentation changes, including a new Secondary Emission Monitor (SEM) grid for setting up the injection and the replacement of three obsolete SEM grids used for emittance measurement during set-up and now also equipped with fast electronics for turn-by-turn injection matching studies.

SUPER PROTON SYNCHROTRON

New Orbit Control Electronics (ALPS)

The SPS orbit system electronics for the 240 Beam Position Monitors (BPMs) in the SPS machine was completely replaced during LS2 [10]. The system, based on the use of logarithmic amplifiers, was specified to cover ~90 dB with a resolution in the order of 0.01 dB. The previous electronics were replaced by radiation tolerant analogue and digital front-ends connected by fibers to 60 back-end boards using the ‘VME FMC Carrier’ (VFC). This was to be the first major use of the new VFC board developed at CERN [11] and since rolled-out to a number of other new systems such as the new fast wire scanners, diamond BLMs, BCTs and tune measurement.

As the BPM system was considered a fundamental requirement for restarting the machine, extensive preparations were made to ensure operability. Components that were radiation tolerant by design were used wherever possible, and all cards underwent burn-in tests and calibration in the lab.

A number of dry runs with the system were also organized and performed with the accelerator operations team. These allowed a user-level test and debug of the system, but also built confidence, both in the system and in the team. The system worked from first beam in the SPS, giving orbit correction sufficient to start RF commissioning. This in turn allowed the use of the orbit acquisition mode to further commission the machine. Figure 6 shows an image of the SPS operational software showing the first successful injection in the accelerator captured by ALPS.

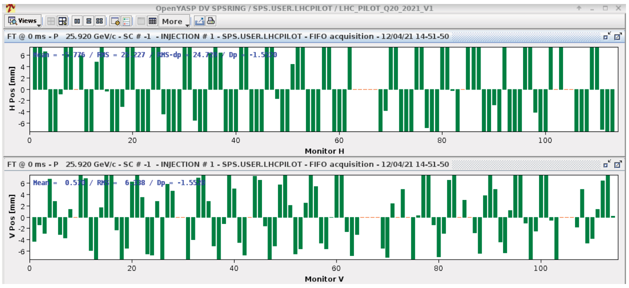


Figure 6: Screen capture of SPS-ALPS operational software. Courtesy of [10]

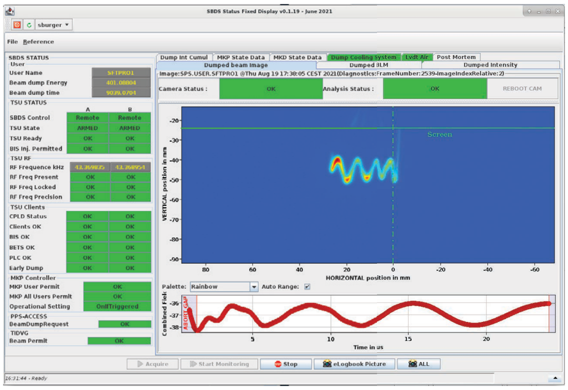
Based on logarithmic amplifiers with a settling time of 100 ns, the resolution of the system is expected to be worse for single bunch than for train of bunches, due to averaging. It was measured with beams in both configurations, and after a Singular Value Decomposition (SVD) analysis [12] resolutions of 140 µm and 7 µm have been demonstrated for single bunch and bunch train length of 10 µs respectively. Close collaboration between electronics, software and operations teams from early specification, through test and finally commissioning was key to the success of this project.

New Beam Dump and Instrumentation

Another major project executed in the SPS during LS2 has been the installation of a new SPS Beam Dump System (SBDS). This involved the relocation, design civil works and installation of a completely new 'in-line' beam dump to accommodate the higher brightness LIU beams in accordance with modern radio-protection standards. This has involved a complete re-distribution of beam instrumentation in two of the six SPS sectors, but more significantly the design of a new imaging system directly in front of the new dump [13].

Due to the exceptional 100% availability requirement and harsh radiation environment, the system was designed around a fixed Chromox screen intercepting the ejected but not circulating beam. The light passes along a 17 m optical line with 5 fixed mirrors to a radiation-shielded bunker containing the digital camera. The acquisition system takes advantage of the long decay time of Chromox to capture multiple images of the same event and perform on-line selection to provide an unsaturated image over a wide range of intensities.

The system was working from first beam and extensively used to evaluate dump kicker and diluter performance. An operational GUI is used in the control room with data showing the 'painting' of the beam on the dump, with an example given in Fig. 7.



SBDS STATUS

User
User Name SFTPRO1
Beam dump Energy 401.08804
Beam dump time 9039.0704

TSU STATUS

	A	B
SBDS Control	Remote	Remote
TSU State	ARMED	ARMED
TSU Ready	OK	OK
BIS Inj. Permitted	OK	OK
TSU RF		
RF Frequence kHz	43.369835	43.368954
RF Freq Present	OK	OK
RF Freq Locked	OK	OK
RF Freq Precision	OK	OK
TSU Clients		
CPLD Status	OK	OK
Clients OK	OK	OK
BIS OK	OK	OK
BETS OK	OK	OK
PLC OK	OK	OK
Early Dump	OK	OK

MKP Controller
MKP User Permit OK
MKP All Users Permit OK
Operational Setting OnlTriggered
PPS-ACCESS
BeamDumpRequest OK
TIDVG
Beam Permit OK

Image:SPS.USER.SFTPRO1 @Thu Aug 19 17:38:05 CEST 2021(Diagnostics:FrameNumber:2539-ImageIndexRelative:2)

Camera Status : OK
Analysis Status : OK

Palette: Rainbow
Auto Range: ☑

16:31:44 - Ready

Figure 7: SBDS operational display. Courtesy of [13]

NEW WIRE SCANNERS

Before the shutdown there were three different designs of wire scanners (BWS) operating in the injectors with maximum scan speeds of between 1 and 20 m.s^{-1}. All were obsolete mechanically, unreliable in electronics and software and not compatible with the smaller, higher brightness LIU beams. A major project saw one new 20 m.s^{-1} device designed and installed, with new control electronics, acquisition and software layer, in 17 locations across the 3 rings [14].

Prototype devices were installed in all three injector rings in the operation years preceding LS2 allowing for test and development of the mechanical instrument and acquisition as well the design of the control system. An emphasis was placed on system testability and maintainability during the design phase, with redundant, easily-accessible mechanics and controls hardware and mechanics designed for rapid diagnosis and validation [15].

During the so-called Individual System Tests (ISTs) periods, it was possible to test and validate all kinematic units without beam. The first instruments to see beam in the PSB required an intense period of firmware and software tests, which, as well as for the DAQ of the secondary shower detectors, were not possible to perform before. At this stage, the benefits of system standardization became apparent as the subsequent PS and SPS commissioning were much smoother, with scans made on the first day of beam, benefiting from the debugging in the PSB. Figure 8 shows data from the operational logbook from the SPS showing beam size and transverse emittance measured over 120 bunches.

Studies and optimisation of this complex instrument are still ongoing in parallel with operation, in particular for optimisation of the acquisition and implementation of the lower scanning speeds needed for the smallest beam sizes in the SPS. These small, high intensity beams will remain a technological limit for this device until improved wires are developed [16].

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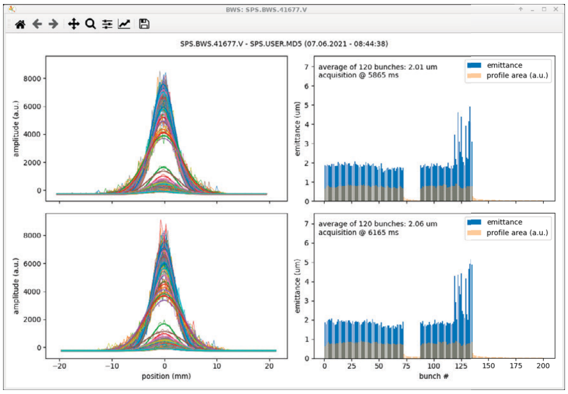

Figure 8: BWS Operational display from the SPS. Courtesy of [15]

BEAM LOSS UPGRADES

2021 sees the global commissioning of a new beam-loss monitoring (BLM) system [17]. The system provides automatic protection to accelerator equipment in case of unexpected beam losses as well as serving as a diagnostic tool for adjustment of machine parameters.

The system consists of 322 detectors of two different ionization chamber designs mounted ex-vacuum along the whole injector chain. Each detector has a dedicated HV power supply and customized coaxial cables to maximize reliability for these accelerator-critical diagnostics. The acquisition control system consists of 14 racks with custom-designed back-plane connecting up to 64 channels. There are two overlapping measurement techniques covering the 2x10^{10} input range with a measurement frequency of up to 2 µs.

Installation and commissioning was distributed over 6 years, starting with prototyping in the PSB in 2015. The LINAC4 system was the first to be fully operational and extensively used in the commissioning. The PSB and PS systems were then fully installed and the legacy units decommissioned during LS2. Figure 9 shows a BLM chamber installed in the PSB and illustrates the challenges of retrofitting such instruments into an existing machine.

Full commissioning was in three phases. Firstly ISTs were used for hardware and connection tests. This was followed by a full system dry-run without beam, testing overall modulation and triggering beam interlocks as well as training operators. The final tests with beam included generating intentional losses to trigger interlocks and measurement of loss signals.

The systems were operational from first beam in all machines and were important in the rapid re-start of the complex. Measurement data from the systems are used to calculate the deposited energy and the ambient radiation, and provide input to dosimetry and FLUKA simulations. Some localized issues of EMI have been observed, both synchronous and asynchronous with the beam, and have been attributed to nearby power cables. Ongoing commissioning activities include the refinement of thresholds for interlocks and mitigation of EM noise. In the longer term, automation of system checks will be made to further enhance reliability.

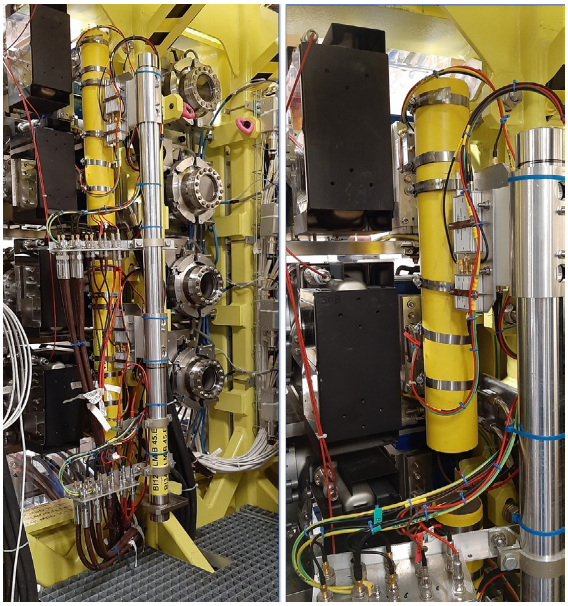

Figure 9: BLM ionisation chambers installed in the PSB.

CONCLUSIONS

The LHC injector complex re-started in January 2021 after two years of the most significant upgrade in it's 60-year history. One hundred and fifty-two new in-vacuum instruments were designed and built and have been commissioned. Major instruments classes such as the fast wire scanners and SPS orbit system have been completely rebuilt along with the addition of innovative new instruments such as the BGI.

Major steps have been taken in the direction of standarisation of hardware and software which will pay-off in the future with reduced expert manpower and spares inventory, partly compensating the increase in the instrument park under the responsibility of the group.

Recommissioning has been a major undertaking due to the many changes, not only to instrumentation, but the layouts and energies of the machines and associated RF and magnet systems. However, all key instruments were available when needed by operations. This can be attributed to a number of factors: whenever possible, prototypes were installed and operated with beam in the run before the start of the shutdown, allowing for the few final design changes which led to major time and cost savings overall; dry-runs both with and without beam using combined BI and operations teams helped gain confidence in startup-critical systems; in the end, global schedule delays due to COVID stretched the final installation and early commissioning periods. This led to less conflict of expert resources in the key times when the same people are needed both in the tunnel and in the control room, often also in more than one machine.

Many lessons will always be learned from this kind of major project. For BI in LS2, the re-start has been relatively smooth to-date and so the lessons not so painful. EM noise, probably due to the inappropriate routing of power and signal cables has caused issues across several instrument classes and some corrective actions will be needed. Finally, restart schedules will always be tight, but dedicated schedule time for commissioning with beam needs to be defended if expectations of good early instrument availability are to be maintained.

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This is a summary paper, relying heavily on the work presented in six other papers at this conference (as well as in earlier conferences) on the commissioning of new instruments. The author would like to thank these others for their support and for sharing their pre-prints.

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