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COMMISSIONING OF THE LHC INJECTORS BWS UPGRADE

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Abstract

A novel generation of fast Beam Wire Scanners (BWS), developed in the framework of the LHC Injectors Upgrade (LIU), has been recently deployed in the 3 LHC injector synchrotrons, accelerating protons from 160 MeV to 450 GeV, during the 2019-2020 LHC long shutdown. The monitors feature high precision motor controllers, high resolution wire position monitoring and wide dynamic range secondary particles detectors. This contribution will document the commissioning of the 17 new systems during the accelerator complex restart in 2021, which is an exciting and challenging phase in the life cycle of an instrument. A summary of the so far achieved levels of reliability, reproducibility, detectors/DAQ bandwidth, and overall accuracy, will be used to revisit the options for further improving the systems' performance in the future.

INTRODUCTION

The LHC Injectors Upgrade (LIU) Beam Wire Scanner (BWS) achieves high performances and reliability with completely new engineering concepts. After more than a decade of research and development within the instrumentation group at CERN [1–5], seventeen systems have been installed in the injectors complex during the second LHC long shutdown (LS2). The commissioning has been following the restart of the injectors in 2021, starting with the Proton Synchrotron Booster (PSB) with eight systems, Proton Synchrotron (PS) with five and Super Proton Synchrotron (SPS) with four. This paper, after introducing the new system features, will focus on the various commissioning stages that allowed to hand over the systems to the various accelerators operation crews.

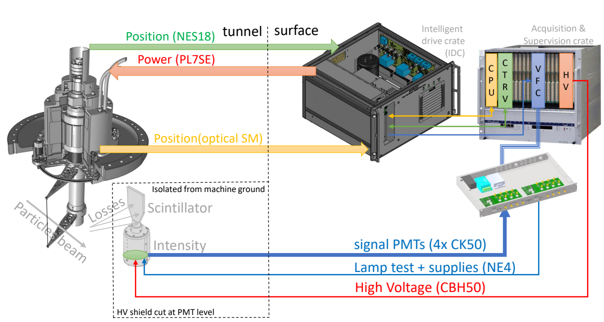

Figure 1: LIU BWS with its electronics at the surface (right) while mechanics and detectors are on the beam line (left).

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INSTRUMENT DESCRIPTION

A wire-scanner monitor is based on a very thin carbon wire made crossing the particle beam at high velocity [6]. This interaction produces a shower of secondary particles, which correlated to the wire position, allows reconstructing the transverse beam profile.

The new BWS features key innovations, with the kinematic unit having moving parts only in vacuum, using magnetic and optical means to transfer power and signaling from and to the air side. The position of the shaft is measured by a solid rotor resolver for trajectory control [7] and by a high accuracy optical encoder, developed in-house, to precisely infer the fork and wire position during a scan [8]. The encoder is based on the analysis of a laser beam focused on and then reflected by reflective and anti-reflective tracks engraved on the optical disc mounted on the shaft. Due to the high acceleration felt by the carbon wire the calibration of this system is essential to compensate for uncertainties of the wire trajectory for predefined speeds [9]. The secondary particle shower detection uses one scintillator coupled to four detectors equipped with different neutral density filters to cover the large dynamic range of beam energies and intensities across the LHC injectors [10]. The output signals are digitised simultaneously at high speed and processed to provide profile measurements for each particle bunch.

Figure 1 shows the instrument architecture. The kinematic unit and particle detectors (left side) are located in the accelerator tunnel. The stand-alone control unit and the VME acquisition system (right side) are in the surface service area. The communication from tunnel to surface is done with cables and optical fibers, with lengths above 150 m in some cases.

Hardware Test Procedures

Emphasis was made on the system testability when designing the LIU wire-scanner. Multiple procedures were implemented to quickly validate the systems after installation and any time a diagnosis is required.

The Open Loop Test (OLT) verifies the cabling, electronics and sub parts of the kinematic unit. The three phases motor is powered without current and position feedback, i.e. in open loop, similar to stepper motors. The scanner moves forward and backward by 3.14 rad in steps and an example of the measured motor currents (blue, green, orange) and shaft angle (red) is shown in Fig. 2. The levels are compared to references to detect any non-conformity. With this procedure, the system hardware commissioning can be carried out from the surface without the need of tunnel access to

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connect test scanner outside the vacuum, as necessary with legacy systems.

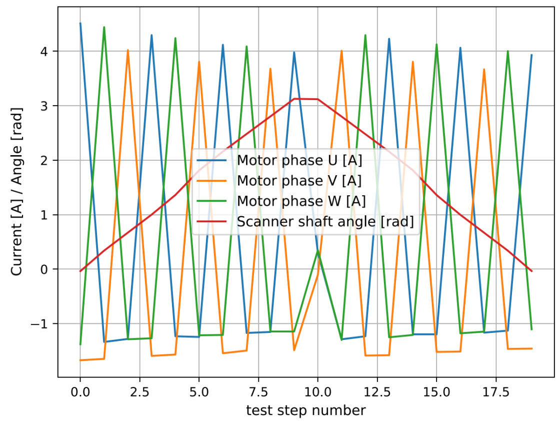

Figure 2: Motor currents and shaft angle of scanner PS.64.V during an Open Loop Test (OLT) checking the scanner connectivity and kinematic unit rotation.

The Scan Without Motion (SWM) performs all the scan procedure without the need for moving the wire in the beam. As during a standard scan, the PMT acquisition is triggered at a predetermined shaft angle, but in this test the angle is simulated with predefined tables. The test generates data from all sensors, from the motor currents to the PMT signals.

The PMT Lamp Test (PLT) uses the incandescent lamp in front of PMTs controlled from the surface and allows verifying the high voltage supply, tunnel pre-amplifier and signal cables to the surface.

The Optical Encoder Test (OET) consist in the optical encoder laser power scans allowing defining the optimal and stable level.

INDIVIDUAL SYSTEM TESTS

The Individual System Tests (IST) at CERN are the overall verification by experts of a system before the HW and Beam commissioning carried out by the accelerator operation crew. This was the opportunity to adjust the wire scanners' settings

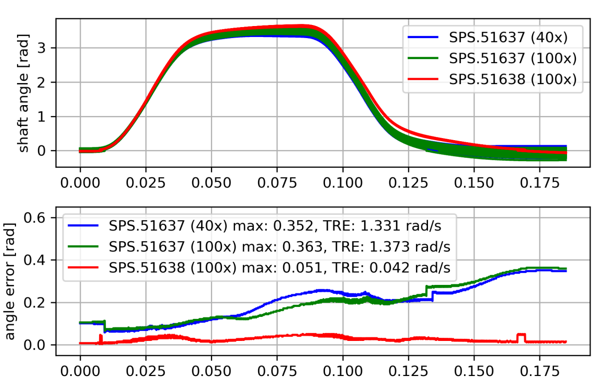

Figure 3: Kinematic unit angular trajectory for sets of scans (top) and the scan to scan variation within the set (bottom).

after their final installation in the various machines. These

Table 1: LIU BWS name (N), accelerator (A), cabling length [m] (L), trajectory reproducibility error [mrad/s] (TRE), PMT noise [bin] (N1) noise @16 kHz [V^2/Hz] (N2).

N	A	L	TRE	N1	N2	scan*
R1H	PSB	60	21	171	0.02	2047
R2H	PSB	60	21	158	0.00	1361
R3H	PSB	60	697	88	0.00	4528
R4H	PSB	60	21	133	0.00	1572
R1V	PSB	55	232	144	0.01	1681
R2V	PSB	55	85	145	0.00	1261
R3V	PSB	55	63	95	0.00	6499
R4V	PSB	55	845	126	0.01	1431
54H	PS	185	63	1706	44.1	2866
64V	PS	230	63	901	8.04	2797
65H	PS	232	106	492	1.04	1028
68H	PS	215	21	522	2.15	331
85V	PS	216	85	1634	19.2	497
41677V	SPS	170	169	487	0.36	4517
41678V	SPS	170	63	155	0.12	325
51637H	SPS	150	1373	378	0.63	2040
51638H	SPS	150	42	2526	0.88	1095

*Total of 35'876 scans (up to 01.09.2021)

tests were performed using expert software tools managing the final version of the stand-alone control unit . This allowed performing OLTs and OETs for all systems, thus validating the connections and mechanics under vacuum. A series of 100 scans per scanner was performed to study the trajectory stability. As an example, Figure 3 shows the motion pattern reproducibility for two SPS scanners, as they move through the beam axis and back. One of the two is less reproducible. Even if there is no evidence that a larger angular spread reduces the overall instrument performance, it is valuable to keep track of it, since it may lead to long term reliability issues with the kinematic unit. Table 1 summaries the Trajectory Reproducibility Error (TRE) for all scanners in mrad/s, indicating at which rate reproducibility degrades.

All secondary shower detection systems were validated using the PLT procedure.

COMMISSIONING WITH BEAM

The BWS development before the 2019-2020 Long Shutdown (LS2) included the test of various prototypes with beam in the PSB, PS an SPS [3, 11, 12]. The commissioning with beam of the final systems in 2021 took several weeks in the PSB, especially to fully deploy and validate the latest FW and SW versions. On the other hand, in the PS and SPS, thanks to the experience in the PSB and benefiting of the systems' standardization, it was possible to acquire beam profiles from the first day of beam operation.

Figure 4 shows an example of a LHC-type beam with 25 ns bunch separation measured in the SPS with the LIU

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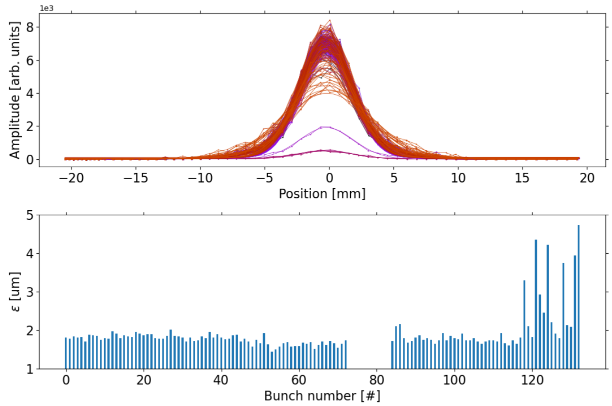

Figure 4: SPS.BWS.41677.V measurement (top) of 25 ns separated bunches (LHC Type beam). The beam emittance growth at the end of the train is due to the electron cloud effect (bottom).

scanner 41677V (top). The growth of the beam emittance at the end of the train is due to the electron cloud effect (bottom).

With the first milestone of handing over all systems to operation, the challenging phase of maximizing availability and optimizing the overall systems' accuracy is ongoing. For the acquisition chain, the following aspects are particularly relevant to set up and characterize in order to assess and improve performance: operating point (PMT high voltage), digital integration phasing, noise reduction/rejection and bandwidth characterization.

Optimisation of the Acquisition Operating Point

The detection of the particles shower uses a plastic scintillator (BC-408) coupled to 4 PMTs (R9880U from Hamamatsu) with custom powering board optimised for large pulse mode and fast recharge. Neutral density filters with different attenuation in front of each PMT allows covering a wide range of beam types, The PMT current outputs are pre-amplified to drive long coaxial cables to the surface

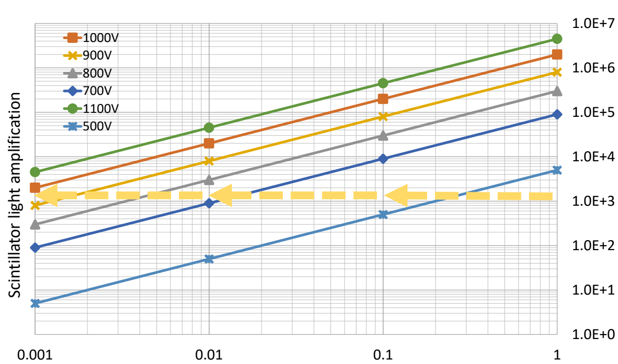

Figure 5: The scintillator light amplification (axis y) combines the 4 PMT optical filters (axis x) and the PMT voltage (colored lines). The dashed line represents an approximation of the amplification set for the measurements in Fig. 6.

where another amplifier stage drives 4 parallel high speed digitizers.

Figure 5 shows the scintillator light amplification as function of filter attenuation (i.e. PMT channel) and PMT voltage. The selection of the acquisition working point requires an optimal balance between competing effects. The beam signal needs to be well above the noise level to achieve enough precision without saturating the digitizers. The PMT must also be run in its linear regime. If too many photons are detected, saturation effects appear and degrade the system performance. The visible consequence of PMT's or digitizer's saturation is an artificial growth of the beam size.

Figure 6 shows measurements of LHC type beams in the PSB for different PMT voltages and channels. For each channel, the emittance is stable for a range of voltage, but grows after a certain threshold. This evidences that at least for this beam type different operating points can be found (all leading to about 1.75 µm) but also that particular care has to be taken to avoid operating in saturation.

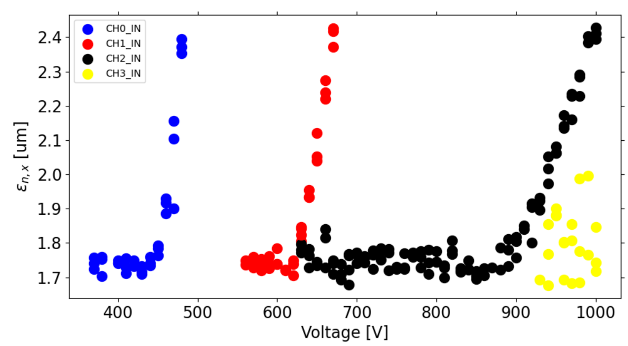

Figure 6: PSB R1V voltage scan, LHCINDIV beam, Intensity: $9.4x10^{10}$ ppb, Energy: 2018 MeV.

Therefore, this type of measurements is very valuable to study linearity, saturation of the analog part of the signal detection and processing (the digital part saturation is easier to detect) and will allow determining if the choice of optical filtera attenuation is adequate to cover all beams, including the ones expected in the future.

Acquisition Integration Adjustment

The PMT signals are captured with a direct-current coupling (DC) digital acquisition system (DAQ) at 500 MHz and 14bit resolution asynchronously to the particle beam. This information is stored into volatile memories with the beam and bunch synchronisation signals. Once the scan is completed, a hardware-based processing integrates the signals to obtain one profile per bunch. This operation requires adjusting the phase between ADC integration windows and beam arrival time. While the phasing is presently performed manually, new FW and SW routines are under development to automatically find the optimal delays for different machines and to be robust against beam phase changes. Figure 7 shows a raw PMT signal of PS-65H (blue), digitally integrated (yellow) using the beam revolution (red) and harmonic reference (green).

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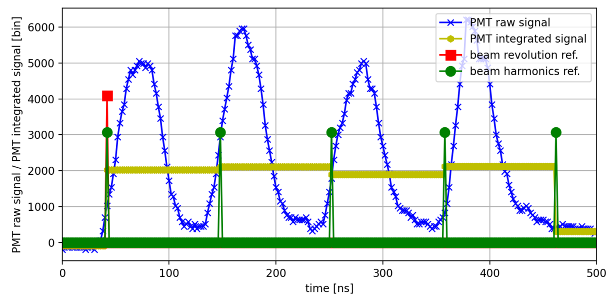

Figure 7: Raw PMT capture of a beam of four bunches with PS.65.H (blue), digitally integrated signal (yellow), beam revolution reference (red) and beam harmonics ref. (green).

Acquisition Noise Characterisation

Noise and electromagnetic interference can heavily affect the wire scanner measurements. In many cases, the data processing and fit filters out most of the stochastic noise when calculating the beam size. Nevertheless, when very small beams are measured, the contribution of low frequency noises is a concern. After inspections, some faulty PMT isolation and ground loops were identified and corrected. The grounding scheme shown in Fig. 1 was finally considered as the optimal.

Figure 8 shows a typical PMT signal power spectrum density without beam (red) and with a common mode noise suppressor based toroid core (green). The main perturbation at 16 kHz has a reproducible phase from scan to scan and is synchronous with the BWS motor driver. It can be attenuated by more than 30 dB with the tested choke, though some resonances between 100-200 kHz are enhanced. This coupling does not take place at the surface, but along the cabling. There is a correlation between noise levels (columns N1, N2) and cable length (column L) visible in Table 1.

Acquisition Bandwidth

The bandwidth of the acquisition system determines the ability of the system to resolve short time structures, in

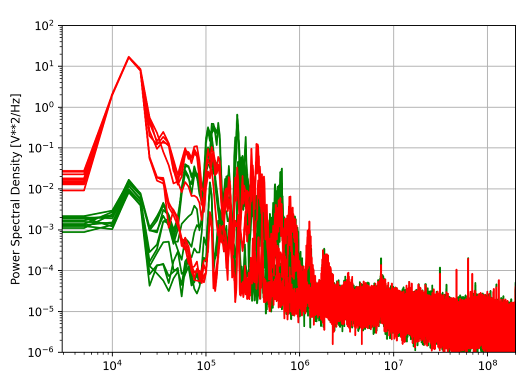

Figure 8: Power Spectral Density of PS-85V PMT signals without beam (9 scans in red) and with a common mode noise suppressor choke (11 scans in green).

our case the bunch by bunch profiles. Beam measurements on the SPS system show few per-cents cross-talk between bunches spaced by 25 ns. A hardware review has revealed bandwidth and stability limitations of the tunnel pre-amplifier, but the beam tests without it did not show improvement in the machine conditions. A second setup with a smaller scintillator volume from a PS legacy system has been tested showing even worse measurement quality without improving the bandwidth. This is shown in Fig. 9, comparing the LIU type scintillator and amplifier (blue-yellow) to the smaller PS-type without amplifier (green-red). The temporal behavior is similar (bottom) , the PS type shows poor quality (top). Further studies are ongoing to optimize the HW and developing SW based corrections to reduce cross-talk.

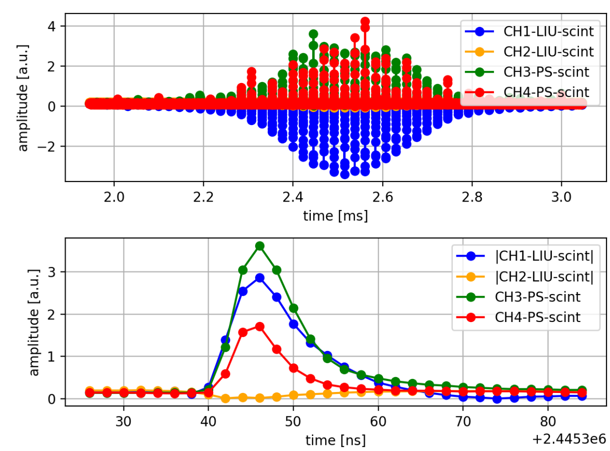

Figure 9: SPS measurements with LIU-type scintillator and pre-amplifier (red, green), and PS-type scintillator without pre-amplifier (blue, yellow). The time structure of a bunch shows similar decay for both systems (bottom) while the PS overall signal is poorer (top).

CONCLUSIONS AND OUTLOOK

The 17 new wire scanners installed in the LHC injectors were all commissioned in a relatively short time given the system complexity. They are daily, extensively used (thousands of scans already in the first few months) by the operation crews, with no major faults. This first operation period already proved the systems' capability to measure 25 ns spaced bunches with few % cross-talk and with a few % statistical error (always difficult to decouple from bunch per bunch and shot by shot beam jitters). More time and dedicated measurements are needed to assess the systems' absolute accuracy and resolution.

Studies are ongoing to tune and optimize PMTs operating ranges, synchronization with the beam, noise and bandwidth. Finally, new features are under development in order to detect PMTs linearity limits, improve the measurement precision by reducing the wire speed, and increase the scan repetition rate up to bursts of several consecutive scans on the same circulating beam.

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