BEAM INSTRUMENTATION FOR THE CERN LINAC4 AND PSB HALF SECTOR TEST

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Abstract

The construction, installation and initial commissioning of the CERN LINAC4 was completed in 2016 with H- ions successfully accelerated to its top energy of 160 MeV. The accelerator is equipped with a large number of beam diagnostic systems that are essential to monitor, control and optimize the beam parameters. A general overview will be complemented by a summary of the most relevant results. This includes transverse profile monitors (wire scanners, wire grids and a laser profile monitor), beam position and phase monitors (whose ToF measurements were essential for adjusting RF cavity parameters), beam loss monitors, beam current transformers and longitudinal beam shape monitors. This contribution will also cover the beam instrumentation for the so-called PSB Half Sector Test, which has been temporarily installed in the LINAC4 transfer line to study H-stripping efficiency. At this facility it was possible to test the new H^0/H^- beam current monitor, designed to monitor the stripping efficiency and an essential element of the beam interlock system once the LINAC4 is connected to the PSB in 2019.

LINAC4 INSTRUMENTATION

During the successful commissioning of LINAC4 up to 160 MeV [1], beam instrumentation was extensively exploited to set up the RF structures, characterize the beam parameters and protect against excessive beam losses. The full LINAC4 diagnostics park is summarized in Table 1. Information about the instrumentation engineering specifications and achieved performance during the LINAC4 commissioning stages at 3,12,50 and 100 MeV can be found in [2–11]. This section will recall the functionality of each system and discuss the most relevant results obtained during the last commissioning period at 160 MeV.

Beam Current Transformers (BCT)

The BCTs consist of a magnetic core with a secondary winding (the beam replacing the primary winding) and a calibration winding. They are designed for the rather long LINAC4 pulses of 400 μs with a droop that does not exceed 1 %. In order to minimize the transformer sensitivity to external magnetic fields, 3 layers of mu-metal and 1 layer of Armco magnetic shielding are employed. The signal is read out by a dedicated VME module (TRIC: TRansformer Integration Card). The signal from the secondary winding

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Table 1: LINAC4 Instrumentation

System Class	#	Beam Observable
Faraday Cup	1	Intensity
BCT	11	Intensity
BPM	26	Position, Phase, Rel. Intensity
SEM Grid	30	Transverse Profile, Emittance
Wire Scanner	24	Transverse Profile
BTV+	1	Transverse Profile
Laser Stripping*	2	Transverse Profile, Emittance
BLM	19	Losses
BSM	2	Longitudinal profile, phase

+ At the stripping foil permanent test stand, also used to image the stripping foil
* Tested at 3,12 and 100 MeV, not at 160 MeV yet

is amplified by pre-amplifiers with 2 different gains and digitized in parallel using two 200 MHz ADC channels in the TRIC card. The samples are then averaged with a user defined time resolution of between 10 ns (successfully used to measure the rise and fall times of the fast chopper) and several μs. The 11 installed BCTs are regularly used to monitor beam transmission along the different LINAC4 sections and trigger the interlock system inhibiting the next pulse in case of high losses. Their use for high precision measurements during the PSB HST discussed below brought to light pre-amplifier saturation effects due to a strong 352 MHz RF component well outside the presumed passband of the transformer. Once identified, this was successfully corrected by the addition of appropriate low pass filters.

Transverse Profile Monitors

The transverse profile and emittance (via the three profile method) are measured using wire grids and wire scanners, equipped with either 30 μm Carbon or 40 μm Tungsten wires. The read-out electronics digitizes the net charge in the wire every 4 μs. The material choice was optimized for different beam energies to ensure adequate signal (dominated by the collected charge of stripped electrons) and minimize wire heating. This last problem limits the use of these instruments to a 40 mA, 100 μs pulse. Such a limit and the non-negligible losses induced by wire grids motivated the design of a much less invasive laser-based transverse profile and emittance monitor. This system, based on the measurement of stripped electrons and photo-detached H^0 generated by scanning a focused ($\approx$100 μm) infra-red laser through the

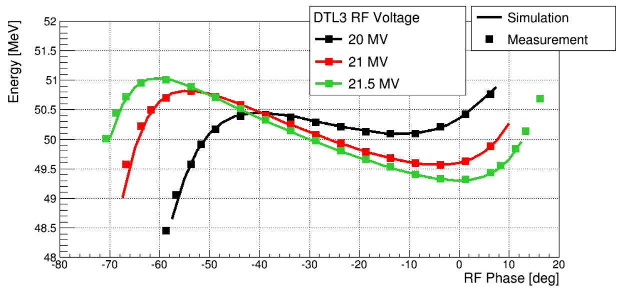

Figure 1: Beam energy measured at the exit of DTL3 via the ToF between BPMs, compared to beam dynamics simulations.

beam, has been successfully tested at 3, 12, 50 and 100 MeV and will be installed at two locations for permanent 160 MeV measurements. The stripping foil test stand at 160 MeV (and the PSB HST) is also equipped by a scintillating for imaging the beam and and the stripping foil units [15, 16].

Beam Position Monitors (BPM)

The BPM sensors consist of shorted strip-line pick-ups that offer the versatility to fit into the limited space available, while ensuring good linearity and sensitivity. They were designed to monitor the beam position with 100 μm resolution and provide the relative beam intensity between two monitors with 200 μA resolution. In addition, they can be used as phase-probe monitors with 0.1 $^{\circ}$ resolution to infer the beam energy through Time of Flight (ToF) between BPM pairs. They have been essential to set up and tune the RF structures (from 12 to 160 MeV) by using the ToF measurements to infer the beam energy at the exit of each cavity. The result of the measurements performed at the exit of the DTL3 cavity (50 MeV) can be seen in Fig. 1, showing the excellent agreement between simulations and BPM measurements for three different RF voltages.

Bunch Shape Monitor (BSM)

The bunch shape monitor (BSM) [12] is designed to reconstruct the longitudinal bunch profile by monitoring secondary electrons emerging from a 100 μm tungsten wire intercepting the beam. It features a phase resolution of 1 $^{\circ}$ and can cover the full phase range (180 $^{\circ}$ at 352 MHz). The two systems (one already permanently installed at the end of the linac and a second tested at the HST facility) are also complementary to the BPMs when used as phase probe monitors. A measurement example can be seen in Fig. 2, showing the bunch intensity as function of phase and time. The signal shape in time reproduced perfectly the BPM measurements, with the BSM providing the added information on longitudinal bunch intensity profile.

Beam Loss Monitors (BLM)

Since a total beam loss in a single location can severely damage the machine and in order to keep operational losses below 1 W/m to minimize accelerator component activation, several BLMs were installed in strategic LINAC4 locations. The detectors are the same Ionization Chambers used for the LHC [13] with a readout system adapted to the CERN Injector Complex requirements [14]. The system has a very high dynamic range, being able to detect currents ranging from 10 pA to 200 mA. Processing is carried out with several integration windows ranging from 2 μs to 1.2 s. For the moment the BLMs have been used only to qualitatively monitor local beam losses. The study of their calibration at different beam energies and the definitions of the thresholds values at each monitored location, which will interlock the beam permit, will be milestones of the LINAC4 reliability run later in 2017.

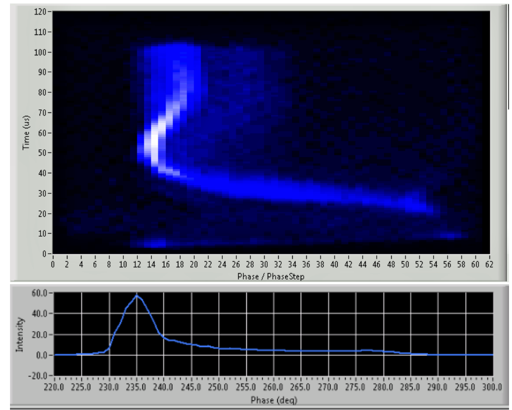

Figure 2: Example of bunch intensity as function of phase and time (top) as measured by the BSM at 160 MeV and its projection on the phase axis (bottom), giving the average longitudinal bunch profile during a linac pulse. The phase axes difference is only an offset set by SW.

PSB HALF SECTOR TEST

The LINAC4 connection to the PSB will imply the modification of the injection region in order to allow H^- stripping before the subsequent proton injection into the 4 PSB rings. Four in-vacuum H^0/H^- Titanium beam dumps, one per ring, will be installed downstream of the stripping foil unit at the exit of the injection chicane meant to separate the injected protons from the unstripped particles. These will intercept the unstripped H^- ions, partially stripped H^0 atoms and

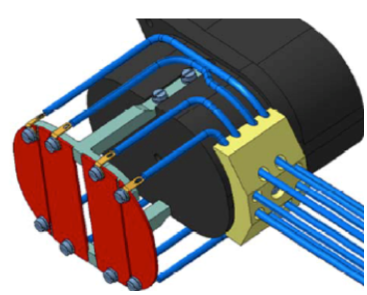

Figure 3: 3D design of the H^0/H^- measurement plates (red) fixed on the unstripped particle dump (black) that will be located after the stripping foil units.

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any H^- ions missing the foil. Each dump will be equipped with a set of 4 Titanium plates, shown in Fig. 3, designed to measure the residual H^0 and H^- beam currents. The 1 mm thickness of the plates is enough to strip all remaining electrons while leaving the resulting protons to easily penetrate and reach the dump. This system will serve to monitor the efficiency of the stripping foil and to protect the dump from a high intensity beam impacts, by providing an interlock signal in case of stripping foil failure. Given the tight schedule for the LINAC4 connection, it was decided to install and test half of the injection region as a dedicated test stand at the end of LINAC4. The so-called Half Sector Test (HST) [15, 16] was comprised of the stripping foil unit, followed by two dipole magnets and the H^0/H^- dump including the H^0/H^- measurement plates.

The first set of measurements consisted of sending a low power H^- beam (i.e. stripping foil not inserted) directly onto the plates. The beam was steered from left to right in order to check the response when almost all the beam was sent to a single plate. For a fixed pulse length (5 μs), the experiment was repeated at different beam peak intensities. Sensitive integration electronics was used to provide the total charge deposited on each plate for each pulse. A calibration factor was calculated for each measurement by normalizing the plate signal to the number of H^- charges measured by an upstream BCT. A summary of all scans is shown in Fig. 4. The calibration factor is seen to remain stable to within ±1.5 % for all plates over all beam intensities.

A second set of measurements was carried out while inserting different stripping foil types. The measured calibration factor was applied to the plate signals to calculate the absolute number of unstripped particles. This value was then normalized to an upstream BCT to infer the stripping efficiency. Figure 5 shows the result of these measurements, for two different foil types, compared to the transmission efficiency between two BCTs, one upstream and one downstream the stripping foil. Such an excellent agreement is obtained by assuming that even in case of 100 % stripping efficiency 1 % of the fully stripped protons were lost before reaching the second BCT. This assumption is supported by the fact that proton losses at this level are expected in the design of the injection system and by tests with high density

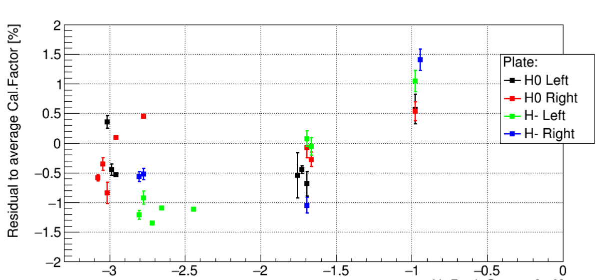

Figure 4: Summary of the H^0/H^- plates calibration in terms of relative variation of the calibration factor (ADC integral / Charges from BCT) compared to its mean value.

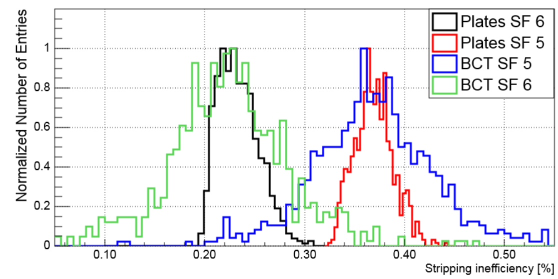

Figure 5: Distributions of the stripping efficiency as measured by the H^0/H^- monitor and by the BCTs over about 700 LINAC4 pulses, with two different Hybrid Boron Carbon (HBC) [16] stripping foils.

foils (e.g. XCF-400 Carbon [16]), during which the BCTs measured 1 % missing protons and the H^0/H^- plates did not record any signal.

The H^0/H^- monitor electronics also provides the integrated sum of all particles on the four plates. This will be used in the PSB as an interlock in case of stripping foil degradation. An example of this output for different beam powers is shown in Fig. 6. A clear linear dependence with beam intensity is observed over a large intensity range.

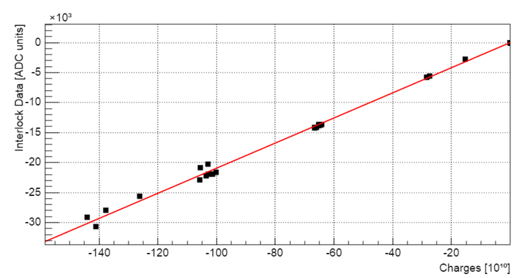

Figure 6: Integral of the summed signal from all 4 plates, as read by the electronics channel that will be part of the PSB interlock system, plotted against beam intensity as measured by the neighbouring BCT.

OUTLOOK

Beam diagnostics were essential for the successful commissioning of LINAC4 up to 160 MeV. The sequential commissioning periods were also extremely useful for verifying the functionality of all instruments, debugging all software and, where necessary, to identify and correct issues, such as the saturation of the BCT amplifiers or faulty channels in wire grids.

The so called LINAC4 'Reliability Run' is due to start later this year, and will allow the few remaining systems to be brought into operation, in particular the BLM system and the laser profile and emittance meters.

Although the HST period was very useful to verify the performance of the H^0/H^- beam current monitors, it was too short to fully establish the absolute accuracy of the device, study in detail the interlock functionality and test the final version of the acquisition electronics. Ways to complete these studies during the reliability run are now being investigated.

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