ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-MOPOST007

SUMMARY OF THE FIRST FULLY OPERATIONAL RUN OF LINAC4 AT CERN

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Abstract

In December 2020 the newly commissioned LINAC4 started delivering beam for the CERN proton accelerator chain, replacing the old LINAC2. LINAC4 is a 352 MHz normal conducting linac, providing a beam of negative hydrogen ions at 160 MeV that are converted into protons at injection into the PS Booster (PSB) synchrotron. In this paper we report on the achieved beam performance, availability, reproducibility and other operational aspects of LINAC4 during its first fully operational year. We also present the machine developments performed and the plans for future improvements.

INTRODUCTION

In LINAC4 negative hydrogen ions (H^-) are accelerated to a kinetic energy of 160 MeV [1]. It is a normal conducting linear accelerator operating at a frequency of 352 MHz. It consists of the following building blocks: caesiated RF source, Low Energy Beam Transport (LEBT), RFQ, Medium Energy Beam Transport (MEBT) including a chopper and 3 bunching cavities, 3 Drift Tube Linac (DTL) accelerating structures, 7 Cell-Coupled Drift Tube Linac (CCDTL) structures and 12 PI Mode Structures (PIMS). The 170 meter transfer line to the PSB is equipped with an additional PIMS cavity known as the debuncher located 42 m from the last accelerating cavity. It operates at zero crossing phase and is used to regulate the beam energy spread.

The project started in 2008 [2]. The commissioning took place from 2013 to 2016 and it was interleaved with installation phases [2–5]. Reliability runs took place in 2017 and 2018. These revealed several issues that would otherwise impossible to discover during commissioning [6, 7]. In December 2020 the beam was injected for the first time into the PSB using a charge exchange technique [8].

The source produces 800 μs long pulses at 35 mA intensity every 1.2 s, resulting in a beam of 28 mA at 3 MeV out of the RFQ (transmission 80-82%). So far, the source was exchanged once per year with one of its 2 identical spares. At every exchange the resulting beam is somewhat different and the LEBT settings need to be slightly re-optimized. The beam chopper defines the accelerated beam pulse length (maximally 600 μs) and, therefore, the total intensity injected into the PSB, which is different for each user. For the operational cycles it ranges from $5 \cdot 10^{10}$ protons per pulse (LHC pilot beam) up to $4 \cdot 10^{13}$ (ISOLDE beam), and it could be increased to a maximum of $6.8 \cdot 10^{13}$. The first 200 μs, called the pulse head, are removed by the chopper because in this part the intensity is not constant, due to the time required for space charge compensation and to ramp-up the intensity of the source. The beam is injected into the 4 superposed PSB rings over a maximum of 150 turns per ring. The chopper removes the bunches falling on the edges of the PSB longitudinal acceptance, which would therefore be lost during the energy ramp, as well as the ones produced while the PSB injection switches from one ring to another.

TRANSFER LINE COMMISSIONING

The commissioning of the transfer line took place during the CERN Long Shutdown 2 (LS2) in 2019-2020. In the first stage, in 2019, when the PSB was still undergoing renovation, the beam was operated up to a dedicated measurement line (the LBE line) located approximately 40 meters upstream from the PSB injection.

For the first time the beam setup was performed as for operational machines with the help of newly developed tools and procedures that were implemented aiming at thorough and time efficient machine commissioning. This included automatised cavity phasing, trajectory steering, optics control using high level parameters, and software applications for the beam measurements of: trajectory response matrix, transverse and longitudinal profiles (showing comparisons to reference curves), emittance and Twiss parameters. As the result of this exercise, the time required for the machine restart after a shutdown has now been determined to be 5 days for the linac and 3 days for the transfer line.

The beam setup went smoothly. Discrepancies in the vertical plane between the optics measurements and the model expectations were found to be due to an error in modelling of the edge focusing of the dipole magnets. They were removed by implementing the correct magnet gap height in the model. With recomputed optics the mismatch factor (Eq. (7.98) in Ref. [9]) was reduced to 0.08, see Fig. 1. The normalised emittance with a beam current of 25 mA was measured to be below 0.3 $\pi \cdot \mu$m in both transverse planes. The design value is 0.4 $\pi \cdot \mu$m for a 40 mA beam current.

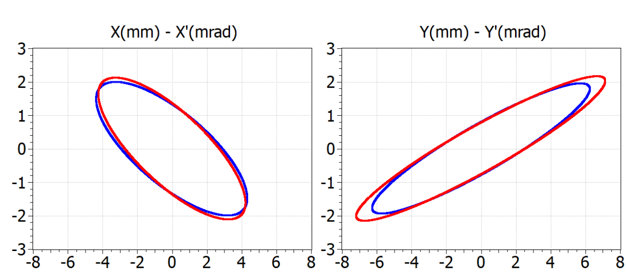

Figure 1: Comparison of the design (blue) and measured (red) phase space ellipses in LBE.

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The Low Level RF includes a Linear Quadratic Gaussian (LQG) regulator and an Adaptive Feed Forward (AFF) [10, 11]. The latter is essential to compensate the transient beam loading at the head of the batch, see Fig. 2. The plot shows the average beam phase along the pulse as measured by the Bunch Shape Monitor located at the end of the linac. The LQG compares the instantaneous cavity antenna with the (constant) voltage set point and generates a TX drive accordingly. Its performance is limited by the loop delay (around 2 µs). It cannot correct instantaneously at the head of the pulse. The AFF memorizes the error over previous pulses and anticipates the correction required on the next pulse. It therefore does an excellent job at the head if the beam pulses are reproducible. To assure a good pulse to pulse stability, the AFF learning speed parameter was set to 97%, i.e. $Corr_{new} = 0.97 \cdot Corr_{old} + 0.03 \cdot Error$. It takes around 10 pulses to flatten the beam energy in case the beam parameters are changed. In LINAC4 one klystron powers a pair of PIMS cavities. Initially the regulation considered only the upstream cavity signal (the blue line on Fig. 2) because it was assumed that the beam loading was identical for the two cavities. However, each cavity is different because their gap lengths must be adapted to the nominal beam energy. Starting from 2020 the regulation used the RF vector sum of the antennas of the two cavities, further improving the energy flatness (the black line in Fig. 2).

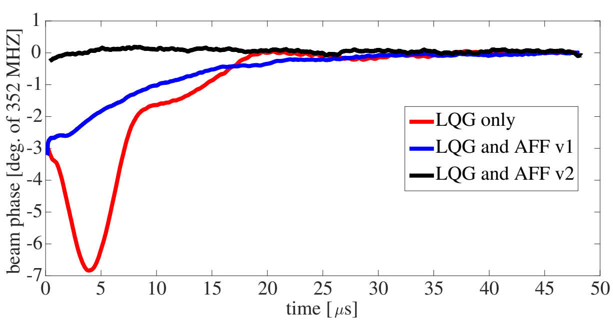

Figure 2: Energy flatness improvement due to AFF as measured by the Bunch Shape Monitor at the end of the linac. See the text for explanation of LQG and AFF v1 and v2.

The pulse position homogeneity in the horizontal plane is well within the specified 1 mm. In the worst case it is measured to be 0.4 mm and the deviation is visible only for the very first couple of microseconds. On the other hand, in the vertical plane it is slightly above 1 mm and the slope is visible all along the pulse. The most likely reasons are the chopper or vertical misalignment caused by the floor movement of the tunnel observed since the construction of the building. Unfortunately, the alignment of the LINAC4's RFQ is extremely delicate to perform and therefore it was decided not to correct it, specially that this deviation is still within the specification limits and does not affect the resulting PSB performance. Currently a new RFQ is under production with improved alignment capabilities.

The shot-to-shot stability is within the defined margins. The specification requires that the intensity, position and energy deviations stay below 2%, 1.5 mm and 100 keV, respectively. A feedback system keeps the measured beam intensity in the LEBT constant by regulating the amplitude of the 2 MHz RF power of the source [12]. This system is also capable of automatically adjusting the intensity in the MEBT, however, it is not enabled for operational beams because no drift in the RFQ transmission was ever observed. A dedicated web service was developed at CERN that provides plots showing evolution of the selected parameters of the accelerators [13]. For LINAC4 it shows plots of beam intensity, transmission, position and phase over a period of the past week, separately for each beam user. The RF amplitudes and phases are plotted for the time period since the beginning of the current run. Results of various statistical analyses are also made available. This helps to monitor the machine status and to detect problems with the machine stability.

ACHIEVED PERFORMANCE

In December 2020 the beam was sent to the PSB for the first time. The charge exchange injection was commissioned according to plan [8]. The related PSB brightness goal was quickly reached and even surpassed the design value [14].

One unexpected issue was the difficulty in beam position measurement at the end of the transfer line for the largest energy spread beams, i.e. above 400 keV r.m.s. It turned out that the debunching is so strong that the 352 MHz signal component in the strip-line BPMs entirely vanishes. A prototype acquisition system based on a higher harmonic signal was developed and successfully tested. The decision was not to proceed with the installation in all the affected BPMs because of the substantial cost, while the machine performance is not affected by this issue. The only resulting complication is that the debuncher RF amplitude needs to be lowered during the trajectory optimisation for this particular optics. Thanks to good alignment the trajectory does not change with the RF amplitude in the debuncher.

In the PSB distributor, which is the element that vertically splits the beam pulse to feed each of the four PSB rings, there is a dedicated in-vacuum beam dump that captures remaining particles from the beam head. It can handle maximally 70 W of beam power and initially it was larger by 40%. A numerical optimiser was developed to adjust the MEBT steering to tune the chopping efficiency [15]. It managed to reduce the pulse head intensity by a factor 3 without reducing the useful beam current.

At the final stage the last LINAC4 subsystem was commissioned, namely the Stray Field Compensation. The transfer line passes only a few meters along the Proton Synchrotron (PS). When the PS beam is at its highest energy of 27 GeV, the magnetic field in the main magnets reaches 1.25 T. The magnets are then fully saturated and a significant fraction of the magnetic field exits the yoke affecting the LINAC4 beam. The induced trajectory error can be as large as 5 mm,

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which is not acceptable for stable PSB injection. The effect exhibits an exponential dependence on the PS magnetic field. The compensation system was re-implemented from scratch using the Software Interlock System technology [16]. During the commissioning phase, for each optics of the transfer line, trajectory correction is computed with the help of a steering program called YASP [17]. Before each pulse, the system looks up what kind of cycle is being played in the PS. It retrieves the magnetic field measurement for the previous instance of this cycle to determine the magnetic field at the moment the LINAC4 beam will be passing next to the PS in order to adjust the scale of the trajectory correction. This works as expected, resulting in trajectory stability at the PSB injection within the specified 1 mm margin. The same effect is created by the magnets of the ion transfer lines between LINAC3 and LEIR. However, in this case it is more static because these magnets are not pulsed and they operate always with the same current. So the trajectory needs to be corrected only occasionally when LINAC3 starts or stops its magnets. Nevertheless, an automatic compensation system is being implemented also for this case such that the trajectory stability is guaranteed at all times.

During winter the beam energy was observed to occasionally fluctuate by a few hundreds of keV. The klystron water cooling system was found to be the main cause. Depending on the outside temperature it uses radiators or cooling towers, because the latter cannot operate when there is a risk of water freezing. The switch is done automatically, however, this provoked temperature fluctuations up to 4 °C. The system was regulated and the amplitude reduced well below 1 °C. On the RF side, the circulators are the most sensitive elements and, during 2021, additional chillers were installed on their cooling system, that entirely solved the issue. Since then, the beam energy stays constant within ±50 keV peak to peak.

For LINAC4 one of the most important performance parameters is availability, because any stop translates to interruption of all the proton based experiments at CERN. In the 2021 run, which spanned over 42 weeks, it was 96.8% and in 2022, at the time of writing, it is 97%. Naturally, the aim is to increase it even further. One discovered weak point was the active mode-anode stabilisation system in the modulators that on several occasions broke when klystrons started oscillating. Each time the repair took around 4 hours. A more resistant passive system was developed and installed for a test in one modulator. After 6 months of operation it proved its satisfactory performance in terms of stability, and all the modulators are now equipped with this passive system. None of them have failed since. In general, all the systems are closely monitored and they keep being improved in order to maximise their availability and performance. Several other problems were already diagnosed and fixed.

Initially the RFQ transmission was of the order of 78%. Naturally, the cavity was very carefully tuned using dedicated RF measurements. The frequency of the RFQ is regulated by adjusting its temperature via cooling circuits. It was found that lowering the temperature by 1.7 degrees increases the transmission to 82.5%. Detailed RF measurements were performed, RF and beam dynamics simulations are still ongoing, but they are not yet conclusive in explaining this effect.

MACHINE PROTECTION

Machine protection is essential in LINAC4. Many signals are monitored online and the Beam Interlock System (BIS) interrupts beam production momentarily if any of the following is out of the allowed range: beam transmission measured between three pairs of Beam Current Transformers, levels of Beam Loss Monitors (BLM), acquisitions of power supplies for critical magnets, temperature of the magnets, status of RF stations and of other critical devices, status from the Software Interlock System (SIS). Within the SIS more sophisticated checks are performed. For example, certain BLM inputs need to be masked for beam measurements with intercepting devices, e.g., wire scanners. SIS will stop the beam if a mask is active for more than an hour. It also watches that during operation all the safety thresholds are at the correct levels, as they may stay lowered after a machine development session. Another example is an automatic pulse shortening when any intercepting device is inserted, because the full pulse length might damage them.

Additionally to BIS and SIS, there are also other mechanisms that can interlock the beam. They are legacy systems developed for the PSB when it was served by LINAC2 and naturally LINAC4 also needs to implement them. While they are all efficient in protecting the machine, the multitude of solutions poses problems in terms of machine operability. The systems are not aware of each other, and when the beam is interrupted, the transmission becomes undefined, and therefore, the BIS also interlocks the beam. In this case it is not straightforward to understand the origin of the problem. The timing schema and also the transmission measurement system were upgraded with additional intelligence to minimise the chances of these chain reactions. Additionally, a software solution is being developed aiming at further simplification of root cause problem detection.

CONCLUSIONS

LINAC4 successfully replaced LINAC2 in providing beam for the CERN proton accelerator chain. All the beam parameters are within specifications: emittance, pulse flatness, shot-to-shot and long-term stability. The expected improvement in the PSB beam brightness and the intensity reach were achieved during the first year of operation. Currently the LINAC4 availability is 97% and developments towards improving it further are ongoing.

ACKNOWLEDGEMENTS

The authors would like to thank all teams involved in the PSB and LINAC4 operation, hardware and beam commissioning for their continuous support and input.

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