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EXPERIENCE WITH THE CERN LINAC4 AND ITS PERFORMANCE DURING THE FIRST FOUR YEARS OF OPERATION

P.K. Skowronski, S. Albright, F. Asvesta, A. Akroh, V. Barbet, G. Bellodi, B. Bielawski, C. Bracco, F. Chapuis, G.P. Di Giovanni, J.-B. Lallement, A. Lombardi, M.F. Marcandella, M. Marchi J. Parra-Lopez, E. Said, J.-L. Sanchez Alvarez, E. Sargsyan, R. Wegner, Y. Wu,
CERN, 1211 Geneva 23, Switzerland

Abstract

Since 2020 Linac4 provides protons for the entire CERN accelerator complex. It accelerates H- ions to a kinetic energy of 160 MeV and injects them into the Proton Synchrotron Booster (PSB) using a charge-exchange injection mechanism. The performance requirements have been successfully met since 2021. This paper presents the operational experience gained, together with availability and reliability statistics for Linac4, during its first four years of operation, and details the key performance indicators for beam quality and stability. It also discusses the main issues encountered and the implemented solutions that have allowed further improvements to be made. Recent developments on the H- ion source have led to an increase of the beam current from the original 35 mA to 50 mA, opening the possibility to increase the intensity delivered to the PSB for the benefit of CERN's experimental programmes. Beam energy modulation in Linac4 has also been developed to increase the PSB bunch intensity for which the results of beam tests are presented.

INTRODUCTION

CERN's Linac4 replaced Linac2 as the first stage of the proton accelerator chain in 2020. It produces negative hydrogen ions H^- at an energy of 160 MeV [1] that are injected into the Proton Synchrotron Booster (PSB), enabling significant improvements in beam brightness compared with Linac2 and paving the way for the High Luminosity LHC and the high-intensity demands of the non-collider experimental program at CERN. With an overall length of about 90 m, Linac4 comprises a sequence of accelerating structures tailored for the acceleration of H^- beams. The layout includes a 3 MeV Radio Frequency Quadrupole (RFQ), followed by three Drift Tube Linac (DTL) structures, seven Cell-Coupled Drift Tube Linac (CCDTL) modules, and twelve Pi-Mode Structures (PIMS). In the transfer line, an additional PIMS cavity is operated with non-accelerating phase. This cavity is used to adjust the energy spread: increasing it to mitigate space charge effects in the PSB or reducing it when producing low intensity "pencil beams". All of the cavities operate at 352.2 MHz.

The source produces 800 μs long pulses every 1.2 s. In 2025 the peak beam current was increased from 35 mA to 40 mA. With the RFQ maximum transmission of 82%, a beam of 33 mA at 3 MeV is produced. This beam is chopped to avoid out-of-bucket losses in the PSB. The first 200 μs, where the beam transmission through the RFQ is lower, is also removed by the chopper. It is due to the fact that in the LEBT, H_2 is injected to maintain a pressure of 5×10^{-6} mbar for space charge compensation. The beginning of the pulse, where this process builds up, therefore has much lower capture efficiency. A pre-chopper installed in front of the RFQ removes the tail of the pulse and controls the pulse length. It therefore, defines the intensity injected to the PSB, which requires different intensities for each experimental facility. It also serves as the principal machine safety element: in case of an interlock it removes the full beam. The main advantage of this solution over inhibiting the source is beam current stability, which would be heavily compromised if the source were interrupted.

Since 2020, Linac4 performance has played a vital role in meeting the beam brightness and intensity targets required for the LHC and experiments at CERN [2–7].

STARTUP, COMMISSIONING, AND OPERATION

Linac4 typically begins yearly operation in March, following a period of beam re-commissioning. Operations conclude in November or December with the start of the maintenance period. In the first week after the end of the yearly run, experts conduct Individual System Tests (ISTs), which include reference measurements, hardware tests that may carry some risk of failure, and software updates. Performing these activities during this period offers two advantages: first, it coincides with radiation cool-down in the accelerator; second, experts have sufficient time to address any issues encountered before the next restart. During the final week of the maintenance period, ISTs are scheduled again to bring all systems back online while access to the Linac4 tunnel is still possible. Subsequently, the operations team assumes control of the machine and carries out one week of hardware commissioning. This phase involves starting and testing all systems using the operational tools from the control room.

The hardware commissioning of Linac4 runs in parallel with the source startup and encompasses coordinated activities across all subsystems. It includes verification of the control system and tools, restarting of modulators, klystrons, and solid-state amplifiers, and ramping the accelerating cavities to nominal voltage with the Low-Level RF (LLRF) in open loop. This is followed by the setup of all 21 LLRF systems and concludes with beam instrumentation checks focused on control and acquisition functionality.

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Before every run, a new source unit is installed. The previous one is disassembled, cleaned, refurbished with new components and the Cs reservoir refilled. Then, it is re-qualified at the test-stand and stored under nitrogen, to become one of the two operational spare units. The H^- source is the first equipment to be recommissioned in the accelerator complex [7].

Beam commissioning typically requires 4–5 days for the linac itself and an additional 2–3 days for the transfer lines. The most time-consuming tasks include interlock tests, cavity phasing, LLRF setup, beam optics verification, and reference measurements. All the quadrupole settings are as designed. Steering is adjusted during each restart to minimize beam losses, particularly in the chopper region where the gap between the plates represents a bottleneck. The chopping efficiency is assessed using time-resolved signals of the beam position monitors (BPMs), and, if required, the steering is corrected. Cavity phasing is performed using Time-of-Flight measurements between two BPMs downstream of a given cavity. The cavity phase is swept and the Time-of-Flight measurements are fitted to simulation for a range of amplitudes to define the required phase and amplitude correction [8]. Because phase scans lead to full beam loss, for the machine safety, the beam pulse is shortened to 100 µs and the peak current is reduced to 7–8 mA at the RFQ output. The current is lowered by reducing the source RF amplitude as much as possible, and also by defocusing the beam with the LEBT solenoids to reduce LEBT and RFQ transmission. The beam optics is verified in the transverse and longitudinal planes using a range of beam diagnostics devices along Linac4 and its transfer lines [9]. The machine features multiple secondary emission (SEM) grids, wire scanners and two bunch shape monitors, allowing longitudinal bunch profiles to be measured. Transverse emittance is measured at the linac exit using four wire scanners placed in sequence without focusing elements in between, and similarly in a dedicated measurement line near the PSB injection point, where three wire scanners are installed for this purpose.

ACHIEVED PERFORMANCE

The measured normalized r.m.s. emittance at 160 MeV is 0.26 π mm mrad in both transverse planes, well within the requirement of 0.4 π mm mrad for a 40 mA beam current. The measured optics mismatch factor, as defined in Eq. 7.98 of [10], is 0.08. Pulse flatness, particularly in terms of bunch position and energy, is a critical parameter. In the horizontal plane, pulse position stability is well within the specified 1 mm; in the worst-case scenario, deviations reach 0.4 mm, and are observable only during the first few microseconds of the pulse. In contrast, in the vertical plane, the deviation slightly exceeds 1 mm, with a visible slope throughout the pulse. This effect is attributed to a droop of the effective chopper voltage, related to charging up effects, and it depends on the chopping patterns of the preceding pulses. Beam current and position oscillations are observable in the second half of the beam pulse. Their origin is not understood and requires further investigations. One hypothesis is that they may be caused by variations in beam parameters or space-charge compensation along the pulse in the LEBT or RFQ. These oscillations do not measurably impact the beam quality provided by the PSB, because long pulses are used for the highest intensity bunches, which are dominated by space charge effects, leading to transverse emittance blow-up. The intensity flatness after the RFQ can be improved at the cost of reduced RFQ transmission. Since the variation is not a concern for the PSB, maximum transmission is preferred.

Beam loading effects in the accelerating cavities are mitigated using feedback and adaptive feedforward (AFF) systems, which operate simultaneously. When either the pulse length or the chopping factor is modified, the AFF correction is automatically reset while the feedback remains active. The AFF generates corrective waveforms based on the deviation of measured amplitude and phase relative to their setpoints. These corrections are then applied to the next pulse of the same type, giving energy deviations below 10 keV at PSB injection.

Pulse-to-pulse stability of beam intensity, position, and energy are well within the defined limits of 2%, 1.5 mm, and 100 keV, respectively. A feedback system regulates the 2 MHz RF source power amplitude to maintain constant source beam intensity [11]. This system can also adjust the intensity in the Medium Energy Beam Transport (MEBT) section, but it is disabled for operational beams, as no significant RFQ transmission drift has been observed.

To monitor the performance, a dedicated web-based Beam Performance Tracking, has been developed at CERN [12]. For Linac4, it provides time-resolved plots of beam intensity, transmission, position, and phase for each type of beam over the past week. Additionally, RF amplitudes and phases are displayed over a rolling 60 day window. It includes various statistical analyses, helping operators and experts to track the machine's condition and promptly identify potential stability issues. For example, the air conditioning in the LLRF room broke, which was not visible in the accelerator control system. The beam energy drifted by more than 100 keV, triggering investigations. Initially, during days when the outside temperature exceeded 25 degrees, the beam energy was oscillating. This was related to the periodic activation of heat pumps, which changed the temperature in the primary cooling circuit too quickly. The problem was subsequently fixed by adding a 3-way valve. In another example growing fluctuations measured at a klystron output indicated the deterioration of a directional waveguide coupler.

In summary, beam stability is fully satisfactory thanks to carefully designed hardware and stabilization mechanisms: feedback systems on the source intensity, cavity tuning, RF amplitude and phase, RF feedforward, automatic breakdown detection and recovery, thermal stability of the cooling circuits and of the building. Continuous monitoring of the beam parameters allows good beam quality to be maintained and to identify issues at an early stage.

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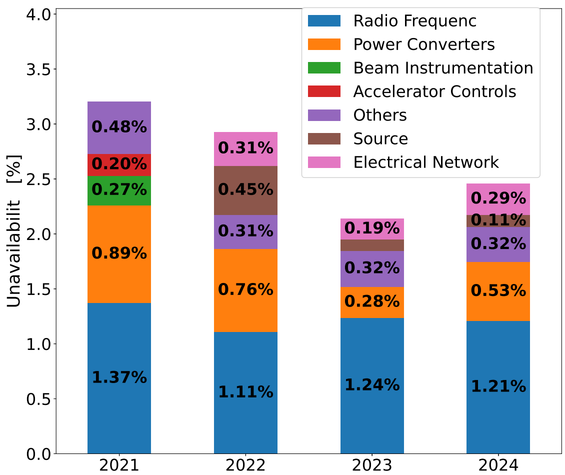

Figure 1: Yearly unavailability of different Linac4 systems.

IMPROVEMENTS

A new extraction system for the ion source was developed in 2022 to reduce transverse emittance and increase transmission, supporting up to 50 mA. The original solution delivered 35 mA peak H^- current, with 27 mA transmitted through the RFQ. It achieved these goals thanks to a simplified design with only three electrodes: plasma, puller, and ground. The puller-dump and einzel lens of the previous source version, which caused undesired emittance growth, were eliminated. The new high voltage system uses one less power supply, which is beneficial for the reliability and availability. Co-extracted electrons are now disposed of at 45 keV onto a dedicated dump after deflection by a permanent dipole magnet housed at the base of the dump. The new source extraction system was thoroughly tested at the Linac4 test stand [13] in 2022 to characterize and validate it for Linac4 operation. Tests with 50 mA showed that increasing the RFQ inter-vane voltage by 5% improved transmission from 76.1% to 83.6%, indicating that the operational voltage is not optimal for a high transmission and should be further studied. To avoid increasing the breakdown rate, which is already in the order of 10^{-5} (about 6 per week), it was decided not to increase it for the moment.

AVAILABILITY AND RELIABILITY

Thanks to continuous improvements, the availability of Linac4, see Fig. 1, has shown an increasing trend over the years and consistently surpasses the 95% target. Major contributors to downtime include the RF systems, modulators, source, and electrical network, with varying impact year to year. Interruptions are logged by the operations crew in the Accelerator Fault Tracking system, which, is complemented by automated fault detection and root cause analysis tools.

The RF and the modulators, i.e. power converters providing around 105 kV for the klystrons, are, not surprisingly, the most challenging systems. The RF system typically operates at 98–99% availability. The biggest issue comes at the interface connecting the modulator with the klystron's electrodes, which contains circuits to measure, stabilize, and protect the modulator. Electrical breakdowns occasionally develop within these systems. Most faults stem from HV breakdowns in klystron tanks, particularly those using a modulation anode. In 2022, active stabilization of the modulation anode was replaced by a passive stabilization following a positive outcome of a pilot installation in 2021. Finally, the voltage was reduced to provide only the necessary power margin for each of the lines. The reliability of the ion source was improved with the introduction of the new source extraction scheme. The 2 MHz source RF amplifier tube lifetime has also been extended by reducing the anode voltage to its rated 15 kV. Before it operated at 18 kV to reach the RF power specification for the initial design. The hydrogen injection valve usually fails once or twice per year. Its replacement takes only a couple of hours but many more hours are then required for the reconditioning. To prevent venting during the exchange, and the resulting 2-3 days reconditioning required in the past, a shut-off valve was added in 2023.

Electrical network faults are rare but noticeable in the statistics. Power cuts sometimes lead to permanent damage of equipment. Glitches, which are frequent during the summer storm season, normally cause only hardware interlocks. Despite largely automated restart procedures it can still take several hours to fully recover.

In conclusion, the most recurring issues have been successfully sorted out and currently the yearly availability depends mostly on the number of major events that take more than 12 hours to repair, such as klystron or source valve exchanges, and faults in the electricity distribution.

CONCLUSION

Linac4 met all the requirements listed in its specification since the start of operation and continues to improve over the years. The key beam performance parameters are very stable throughout the year. In recent years, when restarting after a winter shutdown, from the very first pulse the beam parameters are almost identical to the ones at the end of the previous run. Bunch length is the only parameter showing some degradation over the year with the r.m.s value increasing by 20% and the profile showing higher tails. Thus, beginning of each run the cavity phasing is done.

Currently, Linac4 does not face many operational issues. The beam position oscillation amplitude in the second half of the pulse and the vertical droop are small enough not to impact the quality of the beams produced by the PSB. The hydrogen valve in the source needs frequent adjustments and needs to be replaced once or twice during the run. Linac4's yearly availability is systematically between 97% and 98%, with no repeated failures of single elements. The yearly downtime is driven by the number of unpredictable breakdowns that generally lead to lengthy interventions for equipment exchanges, such as klystrons (1-2 days), transformers (between a few hours to 1 day) or replacement of the hydrogen valve (order of hours, but half a day required to recover the source performance).

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