ISBN: 978-3-95450-219-6 ISSN: 2226-0366 doi: 10.18429/JACoW-LINAC2024-FRXA004

# OPERATIONAL EXPERIENCE AND RELIABILITY OF THE NEW CERN LINAC4

E. Sargsyan*, A. M. Lombardi, G. Bellodi, J.-B. Lallement, P. K. Skowronski, R. Wegner
CERN, Geneva, Switzerland

## *Abstract*

Since its completion in 2017, Linac4, the new 160 MeV proton injector for the CERN accelerator complex, has undergone some tests to assess and improve reliability, until being connected to the Proton Synchrotron Booster (PSB) during the 2018–2020 Long Shutdown 2 (LS2). The performance requirements for the LHC high-luminosity upgrade have been successfully met, and during its first three complete years of operation the linac has shown high reliability figures. Recent improvements of the H$^-$ ion source enable the increase of the beam current from the nominal 35 mA to 50 mA, opening the possibility for increasing the intensity of the Booster beams, for the benefit of the experimental programmes. This paper presents the operational experience and reliability of Linac4 in its first three years of operation.

## INTRODUCTION

Linac4 [1] is a normal conducting linac consisting of a 45 keV caesiated RF H$^-$ ion source, Low Energy Beam Transport (LEBT), 3 MeV Radio Frequency Quadrupole (RFQ), Medium Energy Beam Transport (MEBT) with a chopper and 3 bunching cavities, 3 Drift Tube Linac (DTL) tanks up to 50 MeV, 7 Cell-Coupled DTL (CCDTL) modules up to 102 MeV, 12 Pi-Mode Structure (PIMS) cavities up to 160 MeV, and 1 de-buncher cavity, all resonating at 352.2 MHz. The chopper modulates the beam pulse time structure to reduce beam losses during the beam capture process in the Proton Synchrotron Booster (PSB) and when switching between its 4 rings. The peak beam current from the source is 35 mA, resulting in 27 mA out of the RFQ and 25 mA at the PSB injection with shot-to-shot modulated pulse length of 0–600 μs at 0.83 Hz repetition rate. Linac4 became the injector of the CERN proton accelerator complex in 2020, replacing the 50 MeV Linac2 after 40 years of service. Providing 160 MeV H$^-$ ions, it has been the first step of the LHC Injectors Upgrade (LIU) project [2], implementing a charge exchange injection process and doubling the PSB injected intensity, resulting in a luminosity increase in the LHC injector chain. The commissioning staged in beam energy steps started in 2013, reaching its final beam energy in 2016. Several reliability and performance improvement runs took place [3], until it was finally connected to the PSB. Since then, Linac4 performance and reliability were continuously analysed and improved.

## OPERATIONAL EXPERIENCE

In Dec. 2020, the beam was sent to the PSB for the first time. The charge exchange injection was commissioned according to the plan [4]. The PSB beam brightness goal was quickly reached and even surpassed [5]. The experience from the first year of Linac4 operation is described in [6, 7]. The achieved beam performance is within the specifications [6]. The normalized rms emittance measured at the PSB injection is 0.26 $\pi$.mm.mrad in both transverse planes (the requirement is 0.4 $\pi$.mm.mrad for a 40 mA beam current). The measured optics mismatch factor (Eq. 7.98 in [8]) was 0.08. The pulse flatness in terms of bunch position and energy are one of the key parameters. The beam loading effect in the cavities is compensated by feedback and adaptive feedforward (AFF) systems operating concurrently. When the pulse length or chopping factor are changed, the feedforward correction is automatically reset, while feedback is kept active. By observing deviations in the measured cavity amplitudes and phases from the requested values, AFF develops corrective waveforms that are applied on the subsequent pulse of the same type. This permits to achieve smaller than 10 keV energy deviations at the PSB injection.

The pulse position stability 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 reason is the 3 MeV chopper voltage.

The pulse-to-pulse beam stability in terms of intensity, position, and energy deviations is within the defined margins of 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 [9]. 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 (Beam Performance Tracking) was developed at CERN that provides plots showing evolution of the key accelerator parameters [10]. For Linac4, it shows plots of beam intensity, transmission, position, and phase for the past week for each beam user. The RF amplitudes and phases are plotted for the past 60 days. Results of various statistical analyses are also made available. This helps to monitor the machine status and to detect problems with the machine stability.

### *Startup, Commissioning, and Operation*

Linac4 yearly operation typically starts in March after the beam re-commissioning, when the beam is sent to the PSB, and ends in November, when a year-end technical stop starts to allow for maintenance of the accelerator complex. During the first week after the end of the run, experts

---

* edgar.sargsyan@cern.ch

perform Individual System Tests (ISTs). This includes reference measurements, hardware tests that bear some fault risk, and software upgrades. Doing it during this period has two advantages: first, it is time of radiation cooldown in the accelerator; second, experts have sufficient time to resolve eventually encountered problems before the restart. During the last week of the maintenance period, ISTs are scheduled to restart all the systems while still having a possibility to access the linac tunnel. Afterwards, the operations team takes control of the machine and performs hardware commissioning for 1 week, i.e. all systems are started and tested using the operational tools from the control room. The hardware commissioning of the linac is carried out in parallel to the source startup and consists, among many other activities, of the following:

- Controls and its infrastructure:
  - Verification of timing signals, working sets, applications, logging, etc.
- RF and power converters:
  - Restart of the 14 modulators and 16 klystrons.
  - Restart of solid-state power amplifiers of the 3 buncher cavities, chopper, and de-buncher cavity.
  - Ramp up of the voltage of the 28 cavities to their nominal value, with the LLRF in open loop.
  - Setup of the 21 LLRF systems.
- Beam instrumentation:
  - Checks of the controls and acquisition.

A new source unit is installed at the start of every yearly run. The previous one, after having run during 9 to 10 months, is disassembled, cleaned, and refurbished with new components such as gas injection valve and Cs reservoir, re-qualified at the test-stand and stored under nitrogen, at that point becoming one of the two operational spare units. After every year-end technical stop, the $H^-$ source is the first equipment to restart in the CERN accelerator complex. Its commissioning process follows the following steps: once installed and the vacuum level acceptable, the plasma is started by coupling a 2 MHz RF power of around 25 kW via and external 5-turn antenna and stabilizing it by adjusting the gas pulse duration. The plasma chamber is then conditioned for 2–3 days. The Cs system, including the Cs reservoir, a valve and a transfer-line, is then turned on with the reservoir temperature set to 80 °C (valve and transfer-line always kept 20 °C above) for the initial caesiation phase. The evolution of the process, especially the deposition of the Cs onto the molybdenum plasma electrode is monitored by switching on the extraction voltage from time to time and measuring the ratio between the $H^-$ and co-extracted electron currents (e/H). After a few days under those conditions, the e/H ratio reaches close to 1, the RF power needed to extract 35 mA of $H^-$ ions is generally around 25 to 30 kW meaning the initial caesiation process is completed. The Cs reservoir temperature is reduced to 65 °C (determined empirically) to maintain a continuous caesiation during operation. The team in charge of the source operation proceeds with the last adjustments to reach the required shot-to-shot stability, pulse flatness, et cetera and officially declares the source operational.

At this stage, all the preparations for the RFQ startup are normally completed and the Linac4 beam commissioning can start with the LEBT and RFQ setting up. The LEBT solenoids and steerers strength is varied to maximize the beam transmission through the RFQ. A vacuum pressure of the order of 5e-6 mbar is maintained in the LEBT by injecting hydrogen gas for beam space-charge neutralization, which improves the beam transmission through the RFQ but has a different effect on the head or the tail of the beam pulse, affecting the pulse flatness after the RFQ, as shown in Fig. 1. Oscillations develop toward the end of the beam pulse after the RFQ, which are visible on the BCTs and the BPMs along the machine. This may possibly be due to the beam parameters / space-charge compensation changing along the pulse in the LEBT or in the RFQ and need to be studied. The beam pulse flatness after the RFQ can be improved at the expense of the overall beam transmission.

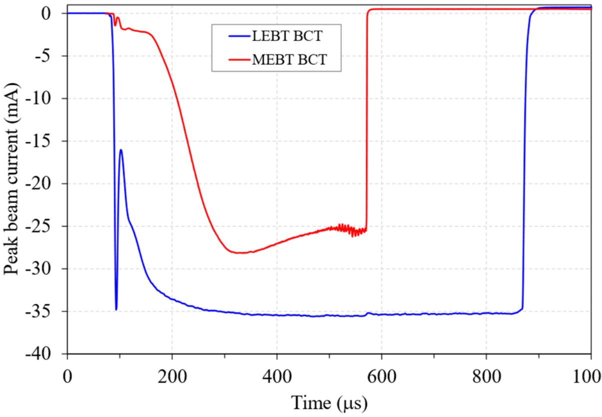

Figure 1: Beam pulse flatness before and after the RFQ.

The beam commissioning of the linac takes 4–5 days, and 2–3 days for the transfer lines. The most time-consuming items are interlock tests, cavity phasing, LLRF setup, beam optics verifications, and reference measurements. MEBT quadrupole settings are usually unchanged as a specific beam optics is required for optimum beam chopping efficiency, whereas the steerers may need adjustment to minimize beam losses in the MEBT, where the gap between the chopper plates is the bottleneck. The MEBT chopper beam dump, which is made of graphite and outgasses when the beam hits it for the first time, is first conditioned with the nominal 27 mA peak beam current from the RFQ and 100 µs pulse length. The chopping is then optimised with the full 600 µs pulse length and the chopping efficiency is measured with the BPMs.

The RF phasing of the cavities is done using Time of Flight measurements between two BPMs after the cavity and comparing them to the characteristic curves [11]. During this process, the beam pulse length is reduced to 300 µs with the pre-chopper in the LEBT and then further reduced to 100 µs with the chopper in the MEBT, dumping the 200 µs head of the beam, which includes the space-charge compensation rise time and transient effects from the source. The beam peak current is reduced to 7–10 mA out of the RFQ by intentionally defocusing the beam with the solenoids and scraping most of it in the LEBT.

ISBN: 978-3-95450-219-6 ISSN: 2226-0366 doi: 10.18429/JACoW-LINAC2024-FRXA004

After the cavities are setup, beam optics verifications are performed in both transverse and longitudinal planes using various beam instrumentation [12] along the linac and its transfer lines. Linac4 is equipped with 2 bunch shape monitors and multiple SEM grids and wire scanners. The transverse emittance is measured at the end of the linac with 4 wire scanners with no focusing elements in between, and similarly, with 3 wire scanners in a dedicated measurement line located close to the PSB injection point.

### *Machine Performance Improvements*

Since its completion in 2017 until end of the run in 2022, Linac4 was operated using an ion source version IS03 [3], which was producing $H^-$ ion beam with a peak current of 35 mA, resulting in 27 mA after the RFQ. Extracting a higher intensity from the source did not result in a higher intensity out of the RFQ mainly due to the extracted beam emittance exceeding the acceptance of the RFQ. The IS03 extraction design, which included a puller-dump electrode at an electric potential of 10 kV, could work with a much higher co-extracted electron current, which allowed the source to operate without caesium. Now that caesiation is routinely used for surface $H^-$ production, a new geometry of the Linac4 source extraction electrodes has been developed and optimised for a higher beam current of 50 mA [13], with the aim of decreasing the extracted beam emittance and increasing the beam current and transmission through the RFQ. The new IS04 source extraction system has a simplified design with only three electrodes: plasma, puller, and ground; the puller-dump and einzel lens of the previous source version causing undesired emittance growth were eliminated. The high voltage system is now utilising one less power supply, which is beneficial for the reliability and the availability of the source and consequently of the linac. 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 has been thoroughly tested at the Linac4 test stand [14] in 2022 to characterize and validate it for operation at Linac4. In the absence of RFQ at the test stand, an RFQ acceptance mask made of 4 consecutive plates with square apertures of different size, which represents the transverse acceptance of the RFQ, has been used. As part of its validation process, the new IS04 source was also installed in the Linac4 tunnel at the end of the run in November 2021 for short tests with the RFQ. The transmission through the RFQ was measured for different source beam currents. The measurements were done with the RFQ operational inter-vane voltage of 81.6 kV and nominal 35 mA beam current from the source resulting in beam transmission of 81.4% through the RFQ. With 50 mA beam from the source, increasing the RFQ inter-vane voltage by 5% (higher than allowed for operation) for a short time, resulted in 10% increase in beam transmission from 76.1% to 83.6%, indicating that the operational voltage is not optimal for a high transmission and should be further studied. On the other hand, the present RFQ already operating 5% above the design voltage, the electric surface fields inside the cavity are very high (estimated 35.6 MV/m or 1.92 Kilpatrick), so that the discharge rate in the order of 1e-5 per pulse (about 1 per 2 days) does not allow a further voltage increase in continuous operation for reasons of machine protection. A summary of these measurements and a comparison to the IS03 source is presented in Fig. 2 and more details are given in [14]. The beam transmission through both the RFQ acceptance mask and the RFQ itself is higher for higher beam currents with the IS04 source compared to the IS03, which confirms a smaller emittance out of IS04 and a better overall performance. The new source is in operation at Linac4 since the start of 2023 run and can reliably provide a higher beam current of up to 50 mA. Nevertheless, the operational beam current from the source remains 35 mA for now, with 27 mA after the RFQ, as this currently provides sufficient beam intensity for all users, and any further increase in intensity would first need some hardware upgrades (e.g., RF klystrons with higher power rating, beam dumps at experiments for higher power) to fully benefit from it.

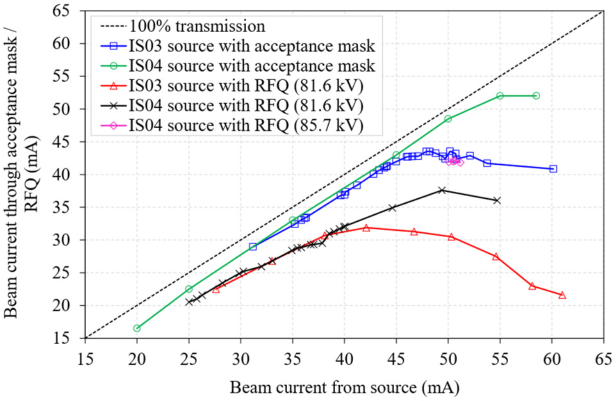

Figure 2: Measured beam current through the RFQ acceptance mask or RFQ vs beam current from the source.

In a machine development session in 2021, the RFQ beam transmission dependence on the cavity tuning was studied. The resonance frequency of the cavity was increased by 7 kHz above the drive frequency of 352.2 MHz, resulting in a beam transmission increase of 4% with the nominal 35 mA beam from the source. This detuning was achieved by lowering the temperature of all vanes homogeneously from 26.0 to 24.7 °C while keeping the body temperature at 26.0 °C. It is not fully understood if the detuning reduces dipolar field components or on the contrary, dipolar components are excited, which then better guide the beam though the RFQ. In the future this optimisation may be used for other RFQs by equipping the cavity with movable tuners and optimising their penetration distribution in operation for maximum beam transmission – a suitable task for a machine learning algorithm.

As the RFQ is operated at a high electric surface field, breakdowns (BDs, discharges in the cavity) occur regularly either as single events, small clusters of a few BDs or as big clusters. To prevent damage to the cavity, a protection system has been developed, which can automatically recondition the cavity when big clusters occur. The system has been introduced for the 2020 run and has been operated successfully since then. In the first years, several external events led to an interruption of the water tuning system which then detuned the cavity and triggered BD clusters. At the start of 2022, an interlock has been implemented to inhibit the operation if the cavity is detuned. Since then, only two external events have been experienced when the LLRF system overdrove the RFQ at the instance of closing the feedback loop. Figure 3 shows that the rate of BDs in the RFQ has been dropping year by year and it seems to stay now constant in the order of 8e-6 per pulse, i.e. about 0.6 BDs per day. BDs triggered by external events have been removed to better visualise long-term trends. In 2023 and 2024, no large BD clusters have occurred anymore.

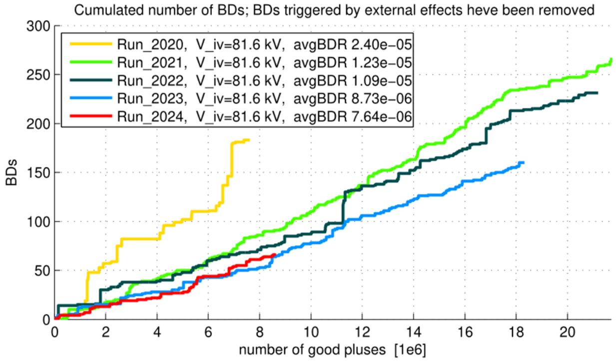

Figure 3: Year-to-year breakdown rates in the RFQ.

In 2021, fluctuations of the cooling water temperature of the CCDTL and PIMS circulators led to a change of RF cavity amplitude and phase of up to 1% and 1° for 3 °C, which was enough to vary the beam energy and trajectory, negatively affecting the beam injection into the PSB. A change of the LLRF loops for one klystron – two cavity systems to lock the voltage vector sum instead of the first cavity's voltage vector only, lead to a significant improvement of the overall stability and reduced sensitivity to the water temperature to an acceptable range. Moreover, the change reduced the beam loading transients.

In Linac4, not surprisingly, the most challenging system is the RF and the modulators, i.e. power converters providing around 105 kV for the klystrons. The biggest issue comes at the interface connecting the modulator with the klystron's electrodes. It also contains circuits to measure, stabilize, and protect the modulator. Electric breakdowns occasionally develop within these systems. In 2022, the active stabilization of the modulation anode was replaced by a passive one in all the klystrons following a positive outcome of a pilot installation during 2021. Finally, the voltage was reduced to provide only the necessary power margin for each of the lines. This of course depends on the maximum beam current the machine should provide during a given period.

## AVAILABILITY AND RELIABILITY

As a result of continuous improvements, the availability of Linac4 has improved from year to year. Some of the main drivers of the availability figures of Linac4, i.e., systems generating most downtime, are the RF, modulators, ion source, and electrical network in varying degrees from year to year, as shown in Fig. 4.

The yearly availability of Linac4 was 96.7%, 97.1% and 98%, in 2021, 22 and 23, respectively, exceeding the target value of 95%. It is a key parameter that is monitored by the operations team and by a dedicated working group [15]. Operations crew registers all machine interruptions in Accelerator Fault Tracking system. In 2023, it was complemented with an automatic fault detection and registration software, helping the operators determine precise downtime periods, affected beam destinations and identify their root cause. The gathered data are continuously analysed to identify the areas requiring improvement. Every year, multiple issues are addressed, and here we can only mention the most important ones. In the following, some details about the availability of selected systems are discussed.

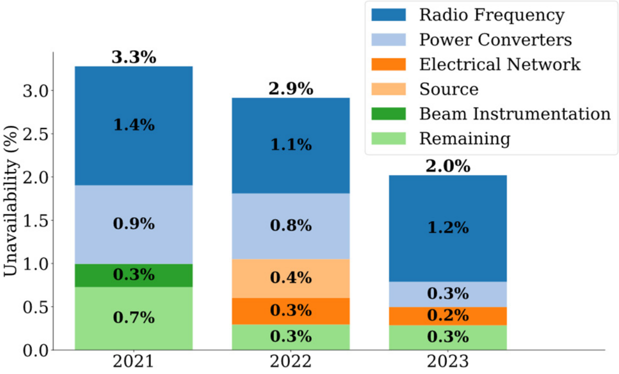

Figure 4: Yearly unavailability of different Linac4 systems. (Plot: courtesy of L. Felsberger, CERN)

The availability of the ion source is mainly dictated by its RF, HV, and gas injection systems. The downtime due to the RF system of the ion source is mainly related to the lifetime of the 2 MHz tube amplifier. In the past, for source development tests at the test stand, the output power of the tube was increased to 100 kW by increasing the anode voltage of the tube from its rated 15 kV to 18 kV, impacting its lifetime. The amplifier was operated in the same manner also at Linac4 until end of 2022 and had to be replaced in March of that year. Since for regular operation, including with a high current of up to 50 mA, the source only requires 30–40 kW of power, it has been decided to reduce the anode voltage back to 15 kV, thus extending its lifetime. We do not yet have sufficient statistics to quantify the lifetime improvements but the operating time of the tube at the time of writing has exceeded 16000 hours, which is the longest the tube has operated in the past before breakdown and replacement, and so far, shows no signs of degradation.

The downtime caused by the HV of the source has been mainly related to 30 kV breakdowns in the einzel lens, which although are automatically reset within a couple of minutes, were rather frequent (32) in 2022. With the IS04 source without einzel lens and consequently one less power supply, this issue is eliminated since 2023. HV breakdowns in the source are now rare.

The source performance and stability depend, among other factors, on the pulse-to-pulse stability of the gas injection valve. Beam current variations from the source depend on the fluctuations of the amount of injected gas. Insufficient amount of gas may lead to plasma instabilities and even extinction (no beam extracted). On the other hand, too much gas may lead to high voltage breakdowns in the extraction system, resulting in downtime. In the past years, we have observed aging of the gas injection valves with increased pulse-to-pulse variation or sudden and random changes in the working point resulting in plasma instabilities that required the intervention of a source expert. In our experience, the lifetime of the pulsed gas injection valve, under normal conditions, is 6 to 12 months. Considering a usual 9 to 10 months run, it was deemed necessary to change the valve preventively during technical stops, which are scheduled once or twice a year. However, after a preventive change of the valve during a technical stop in 2022, the newly installed valve developed a fault after a few hours of operation, requiring a new intervention and replacement of the valve. Although the intervention itself takes 1–2 hours, with the gas injection line configuration before 2023, replacing the valve implied venting the source and, since the caesiation was lost, a consequent source reconditioning was required that can extend to a few days before the required performance for operation could be recovered. This resulted in 134 hours of downtime. Following this incident, a shut-off valve has been installed downstream the gas injection valve at the start of 2023, allowing for its replacement while keeping the source under vacuum and preserving the caesiation, thus reducing considerably the restart time (hours vs days), with a consequent decision against preventive change of the gas injection valve.

The majority of Linac4's equipment are RF systems, comprising 28 cavities, high power couplers, waveguides, or coaxial power lines, 26 circulators, 21 LLRF systems, 16 klystrons, 10 solid-state amplifiers and many sub-components. The klystrons are fed by 14 high voltage modulators. In the past years, the availability of the RF system was impressive, typically between 98% and 99%. Most of the faults occurred in high voltage / high power components. A reoccurring issue (about twice per month for the entire installation) is high voltage sparks inside the high voltage tanks of klystrons, particularly those equipped with a modulation anode. The problem is under investigation, but it is complicated to trace the origin, as located in isolating oil and too rare to reproduce at a test stand.

The last major cause of downtime is the electrical network. Power cuts and glitches only on a few occasions lead to hardware breakdowns (and Linac4 is resistant when compared to other CERN accelerators). Restarting the klystrons and other hardware usually takes more than half an hour to the operations team, despite the process being largely automatized. It is simply the frequency of this events, especially during thunderstorm season, that makes it visible in the statistics.

## HIGH-INTENSITY TESTS

The upgrade to a better performing source in 2023, opened possibilities for high-intensity beam studies both in Linac4 and PSB [16] in the framework of the Physics Beyond Colliders Working Group at CERN, exploring the capabilities of the injector complex in terms of a higher beam intensity for future experimental needs and flexibility in beam production schemes. High-intensity tests were done at Linac4 and its transfer line to PSB during dedicated machine development time in 2023, with the aim of verifying the existence of possible beam transmission bottlenecks, testing the low-level RF system, assessing the available RF power margin of the cavities, as well as preparing for high-intensity tests in PSB. With 52 mA peak beam current from the ion source and 40 mA out of the RFQ at operational voltage, 35 mA peak beam current was transported to the PSB injection line without any rematching in the linac above 3 MeV. With 35 mA peak beam current, the available RF power margin for LLRF regulation was insufficient, requiring an additional beam chopping at 3 MeV. After the RFQ, the main beam transmission bottleneck is the aperture between the chopper plates at 3 MeV, but no beam losses were observed in the rest of the machine. A transverse normalized rms emittance of 0.27 π.mm.mrad was measured with 35 mA in the diagnostics line before the PSB injection. The measured beam phase spread is as nominal, indicating a similar energy spread. With this beam current and 400 µs pulse length, 1.6e+13 protons per ring were extracted from the PSB, which is twice the intensity currently requested by ISOLDE facility. The same intensity can be achieved with the nominal beam current but at the expense of a longer 600 µs pulse length.

## FUTURE PLANS

In view of increasing the beam availability and accelerator complex efficiency for different users, a flexible pulsing of the source with a variable cycle period of 0.9–2.5 s is under consideration, which is challenging for the source pulse-to-pulse stability. Therefore, continuous gas injection and consequently different plasma ignition methods are being explored, since ignition by RF requires higher transient gas pressure than required for source operation, which is the case with the pulsed gas injection. Two plasma ignition methods are being considered: by photoemission using a UV light and dual-frequency operation.

In 2020 an inspection of the RFQ vanes at its low-energy end revealed breakdown craters and changes in surface morphology in some areas, which is not necessarily an issue. Nevertheless, as the RFQ is a single point of failure with a long production time, it was decided to produce a spare, which is identical to the one in operation, with exception of some mechanical parts, like improved support and alignment system. The spare RFQ has been constructed, tunning completed, and is currently at the Linac4 3 MeV test stand for conditioning and beam tests. The RFQ presently in operation may be replaced by its spare during the Long Shutdown 3 (LS3), currently planned for 2026.

## ACKNOWLEDGEMENTS

The authors would like to thank all the teams involved in the Linac4 and PSB operation, hardware and beam commissioning for their continuous support and input.

# REFERENCES

[1] M. Vretenar *et al.,* "Linac4 design report", CERN, Geneva, CERN Yellow Reports: Monographs, CERN-2020-006, 2020. `doi:10.23731/CYRM-2020-006`

[2] K. Hanke *et al.*, "The LHC Injectors Upgrade (LIU) Project at CERN: Proton Injector Chain", in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 3335-3338. `doi:10.18429/JACoW-IPAC2017-WEPVA036`

[3] D. Noll *et al.*, "Linac4: Reliability Run Results and Source Extraction Studies", in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 1090-1093. `doi:10.18429/JACoW-IPAC2019-MOPTS096`

[4] E. Renner *et al.*, "Beam Commissioning of the New 160 MeV H$^-$ Injection System of the CERN PS Booster", in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 3116-3119. `doi:10.18429/JACoW-IPAC2021-WEPAB210`

[5] T. Prebibaj *et al.*, "Injection Chicane Beta-Beating Correction for Enhancing the Brightness of the CERN PSB Beams", in *Proc. 64th Adv. Beam Dyn. Workshop High-Intensity High-Brightness Hadron Beams (HB'21)*, Batavia, IL, USA, Oct. 2021, pp. 112-117. `doi:10.18429/JACoW-HB2021-MOP18`

[6] P. K. Skowro *et al.*, "Summary of the First Fully Operational Run of LINAC4 at CERN", in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 58-61. `doi:10.18429/JACoW-IPAC2022-MOPOST007`

[7] S. Ramberger and R. Wegner, "First Years of Linac4 RF Operation", in *Proc. LINAC'22*, Liverpool, UK, Aug.-Sep. 2022, pp. 25-30. `doi:10.18429/JACoW-LINAC2022-MO1PA03`

[8] T T. P. Wangler, *RF Linear Accelerators*. Wiley, 2008. `doi:10.1002/9783527623426`

[9] M. Peryt, M. Hrabia, D. Noll, and R. Scrivens, "The Linac4 Source Autopilot", in *Proc. ICALEPCS'21*, Shanghai, China, Oct. 2021, pp. 665-670. `doi:10.18429/JACoW-ICALEPCS2021-WEPV018`

[10] V. Baggiolini. "Beam Performance Tracking", `https://bpt.web.cern.ch/`

[11] J.-B. Lallement, "Experience with the Construction and Commissioning of Linac4", in *Proc. LINAC'16*, East Lansing, MI, USA, Sep. 2016, pp. 342-347. `doi:10.18429/JACoW-LINAC2016-TU1A03`

[12] F. Roncarolo *et al.*, "Overview of the CERN LINAC4 Beam Instrumentation", in *Proc. LINAC'10*, Tsukuba, Japan, Sep. 2010, paper THP007, pp. 770-772.

[13] G. Bellodi, H. J. De Grandsaignes D'Hauterives and D. Noll, "Linac4 source extraction re-design for higher current operation", CERN, Geneva, Switzerland, Rep. CERN-ACC-Note-2021-0009, 2021.

[14] E. Sargsyan *et al.*, "Linac4 Source and Low Energy Experience and Challenges", in *Proc. HB'23*, Geneva, Switzerland, Oct. 2023, pp. 290-296. `doi:10.18429/JACoW-HB2023-WEA4I2`

[15] A. Apollonio *et al.*, "Reliability and Availability of Particle Accelerators: Concepts, Lessons, Strategy", in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, Vancouver, BC, Canada, Apr. 4, pp. 5014-5018. `doi:10.18429/JACoW-IPAC2018-FRXGBD1`

[16] T. Prebibaj *et al.*, "Intensity reach in the CERN PSB with the high-current LINAC4 source", presented at the IPAC'24, Nashville, TN, USA, May 2024, paper TUPS31, unpublished.