ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-WEPAF077

# PERFORMANCE EVALUATION OF LINAC4 DURING THE RELIABILITY RUN

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*Abstract*

Linac4 will replace Linac2 as the first element in the CERN proton injector chain from 2020 onwards, following the second LHC long shutdown (LS2). With more than three times higher energy and number of components than Linac2, beam availability is one of the main challenges of Linac4. Intended as a smooth transition from commissioning to operation, a Linac4 Reliability Run was started in July 2017 and is foreseen to last until mid-May 2018. The goal is to achieve the target availability of 95 %. This implies consolidated routine operation and identification of recurring problems. This paper introduces the schedule and operational aspects of the Linac4 Reliability Run, including the developed tools and methods for availability tracking. The paper also summarizes the lessons learned during the first period of the Linac4 Reliability Run with respect to fault tracking and provides an in-depth analysis of the failure modes and observed availability.

## INTRODUCTION

Linac4 will become the sole source of protons for all CERN physics after the long shut down (LS2) in 2019-2020 [1]. The basic architecture of Linac4 is shown in Fig.1. The new injector comprises an $H^-$ source, a low-energy beam transport section bringing the beam to a Radio Frequency Quadrupole (RFQ) structure for capture, bunching and acceleration up to 3 MeV, and three further types of accelerating structures where the particles are accelerated in stages up to 160 MeV.

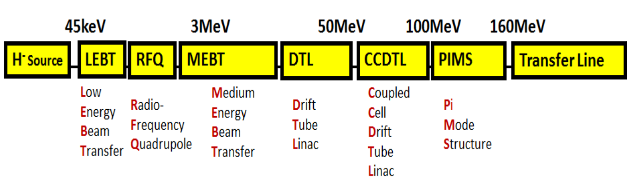


Figure 1: Linac4 basic architecture.

Exiting Linac4, the beam will follow the transfer line that connects Linac4 with the Proton Synchrotron Booster, which is part of the LHC proton injector chain.

Due to the demand of continuous operation and with more than three times higher energy and number of components than its predecessor, Linac4 will have to meet strict requirements in terms of availability, ultimately approaching the availability of Linac2, which is running today with an availability above 98% after many years of operation.

The Reliability Run is intended as a smooth transition between commissioning and final connection of Linac4 to the rest of the CERN accelerator complex. The goal is to achieve an availability above 95% during the Reliability Run. This requires consolidated routine operation and identification of recurring problems. The Reliability Run started in July 2017, after machine commissioning, and is foreseen to last until mid-May 2018.

The CERN standard tool for fault tracking, the Accelerator Fault Tracker [2], in operation for the LHC since beginning of 2015, is used for systematic and consistent Linac4 failure tracking throughout the Reliability Run.

Table 1. Ultimate Linac4 Parameters

| | |
|---|---|
| **Ion Species** | $H^-$ |
| **Output Energy** | 160 MeV |
| **Bunch Frequency** | 352.2 MHz |
| **Max. Repetition rate** | 2 Hz |
| **Beam pulse length** | 400 us |
| **Source Current** | 80 mA |
| **RFQ output current** | 70 mA |
| **Linac output current** | 40 mA |
| **Beam power** | 5.1 kW |
| **Transverse emittances** | 0.4 π mm*mrad |

The collected failure data allow refining of the current Linac4 availability models with measured data. In this paper, the Linac4 performance during the Reliability Run is compared to the predictions obtained from the Linac4 availability model.

## LINAC4 RELIABILITY RUN

The Linac4 Reliability Run provides a unique opportunity to identify weak points and improve operational procedures.

The Linac4 Reliability Run started just after commissioning and was divided into three phases to allow for scheduled Technical Stops. The first phase was from mid-July 2017 to the end of September 2017. A second phase took place from the end of October 2017 to the end of December 2017, and the last phase takes place from mid-April to mid-May 2018. The Reliability Run schedule is shown in Table 2. While the first phase was composed of short periods of operation followed by repairs and optimization,

Table 2. Linac4 Reliability Run Schedule

*C: Commisioning, RR: Relibaility Run, TS: Technical Stop*

| **2017** | | | | | | | | | **2018** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** |
| C | | | **RR** | | | TS | **RR** | | TS | | | **RR** | | TS | | | Spare | | | TS |

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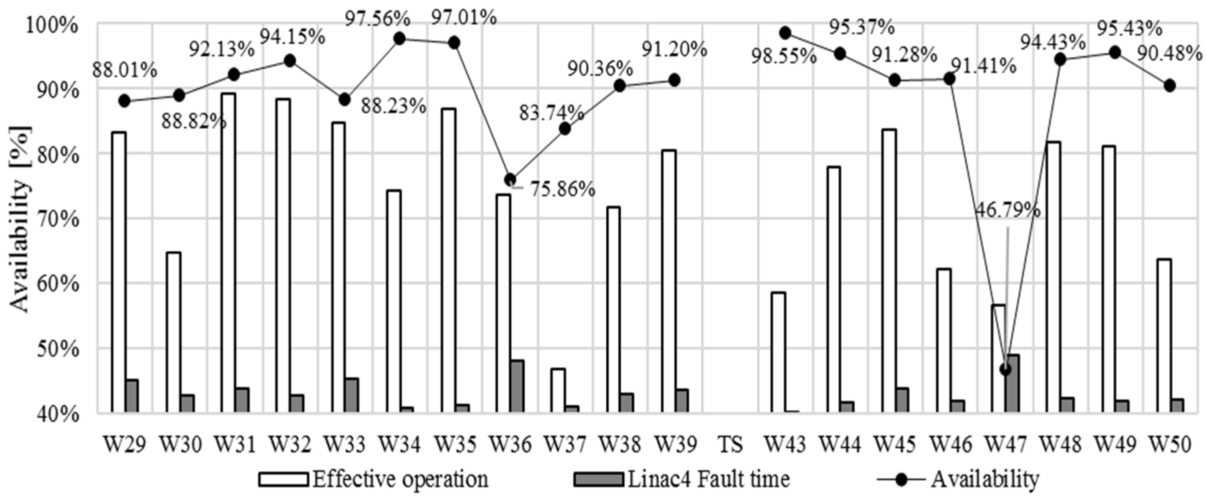


Figure 2. Linac4 weekly availability during the 2017 Reliability Run.

the second phase was composed of longer periods of operation followed by technical interventions, getting closer to realistic operating conditions. In total, 19 weeks have been dedicated to the Linac4 Reliability Run until now, from which 6 weeks were dedicated to specific studies and machine development periods.

From October 2017 onwards, Linac4 was operated from the CERN Main Control Room 24/7 with expert assistance and interventions available only during working hours.

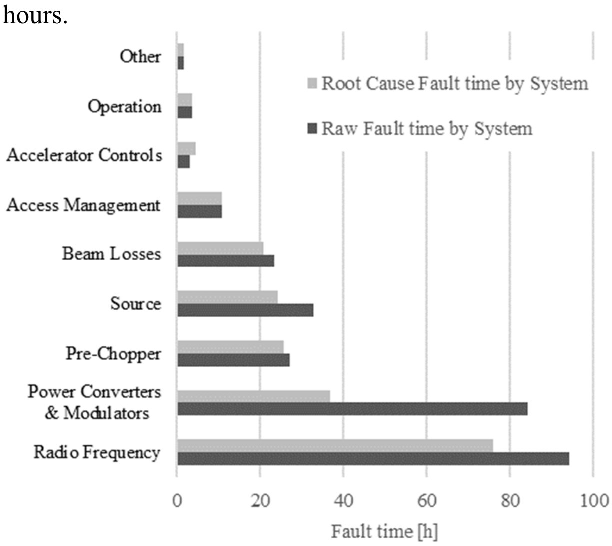


Figure 3. Linac4 systems fault times during the first two phases of the Reliability Run.

## LINAC4 FAULT TRACKING

Following the successful exploitation of the LHC Accelerator Fault Tracking (AFT) system for the LHC [3], the same approach was adopted for Linac4 failure tracking.

The AFT has a web interface, which allows to browse, edit and analyse the fault data collected from the operation e-logbook. A predefined fault tree, defined according to the categories of the Linac4 availability model, is used to classify the faults. In order to ensure reliable data capture, weekly reviews of the faults are done by the Linac4 team. System experts are notified when faults occur and can complement information provided by the operations team or propose changes to the classification, if required.

## FAILURE ANALYSIS AND PERFORMANCE EVALUATION

The results reported here belong to the first two phases of the Reliability Run, which correspond to a total of 13 weeks of effective operation. Table 3 summarizes the main Linac4 performance numbers for the 2017 Reliability Run.

Table 3. Linac4 Availability in the 2017 Reliability Run

| Effective Operation | Availability | Fault Count | Fault Mean Time to Repair |
|---|---|---|---|
| 13 weeks | 90.6 % | 387 | 43 min |

Linac4 was operational 90.6 % of the effective operating time. A total of 387 faults were observed, each of them took on average 43 minutes to notice, understand and repair.

The analysis of the weekly availability as shown in Fig. 2 indicates a weekly availability in line with the set target of 95%, except for some specific weeks, where long faults were observed. In Week 36, two long faults, a controls timing issue and a Radio Frequency (RF) cavity cooling trip due to a defective flow meter, caused a downtime of over 10 hours. Similarly, two long faults caused a downtime of more than 18 hours in week 47. In particular, a failure in a power converter anode module required the replacement of the anode module itself and a HV connector of the Pre-Chopper had to be exchanged. On the other hand, the operating time in week 37 was only one day due to a planned source replacement.

Apart from the few faults that took longer to understand, Linac4 suffered other short but recurrent faults (between 20 and 50 minutes long). These recurrent faults were Power Supply and High Voltage (HV) modulator trips in the RF

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Systems (114 faults), power converter trips in the Correctors and Source High Voltage (65 faults) and 62 stops due to beam losses. In particular, a number of the HV modulator trips were found to be due to aluminium residuals found in the insulator oil used for the 'recycled' LEP klystrons. Systematic filtering of the oil has been performed to avoid this type of failures in the HV modulators in the future.

Overall, the main contributors to Linac4 downtime were the RF systems, Power converters, Pre-Chopper and the Source as shown in Fig. 3. The Raw fault time is the total time the system was down, whereas the Root cause fault time is corrected for parallelism and fault dependencies (i.e. system A inducing a fault in system B).

The following teething problems have either been fixed during the Technical Stop in October 2017 or during the End-of-Year-Technical-Stop, or will be corrected during the Technical Stop in summer 2018:

- Power supply of a klystron vacuum pump in the RF Systems
- Defective flow meter on the RF Systems
- Insufficient radiation hardness of arc detector electronics that originally were not planned to be installed in the Linac4 tunnel
- Source Optimization application, which regulates and optimizes source parameters, but can end up compromising beam stability, will continue to be optimized.

These changes are expected to yield an availability improvement of about 3 %, in the direction of the project goal of 95%.

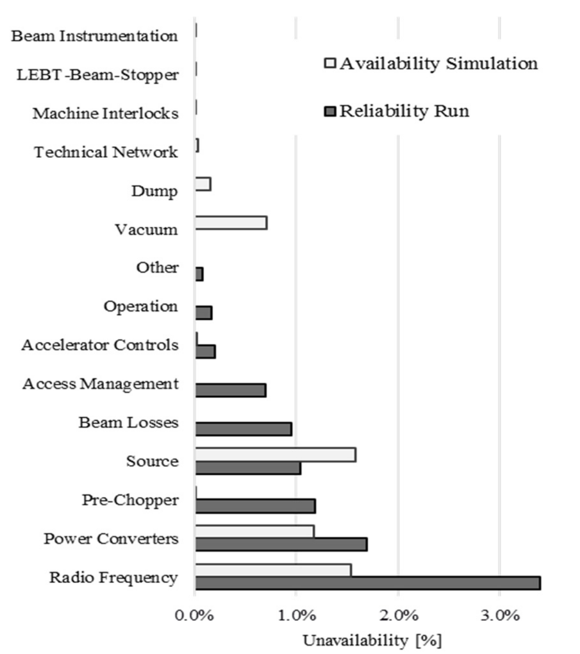


Figure 4. Linac 4 systems unavailability from Reliability Run and simulations.

## RELIABILITY RUN VS AVAILABILITY SIMULATIONS

A Linac4 availability model was developed before the commissioning phase and has been continuously updated since then, following changes in the linac design, with the aim to predict Linac4 availability and reproduce future operation [4]. The Linac4 model simulates steady-state operation, whereas Linac4 has shown still some teething problem that undermined machine performance. Proof of this are the problems discussed above. For this reason, systems with teething problems and unexpected failures, show longer observed fault times than predicted as shown in Fig. 4. This is the case for the RF Systems, Power Converters and Pre-Chopper. Regarding the contributions of the Dump and Vacuum Systems, these are rare failures with very long repair times, which appear in model results due to the high number of runs performed in the Monte-Carlo model. The Accelerator controls caused longer downtime than expected due to the timing issues, which occurred during the first week of operation. There might be two reasons why longer downtime was expected of the Source than observed. Firstly, the Source is operating at about half of the nominal current and secondly, no long duration faults were observed yet. The recovery time of the Source is a function of its downtime; the longer the fault lasts, the longer the expected recovery time to reach the required beam quality.

## CONCLUSIONS

The Linac4 Reliability Run has been a successful experience, allowing the identification of issues beyond the possibilities offered in a commissioning phase. Linac4 achieved a beam availability of 90.6 % of the effective operating time, overall a positive result after only few weeks of operation.

The strategy adopted in this period was to accept increased downtime in favour of fully understanding and identifying the root cause of faults. It was found that aluminium residuals in insulator oil for old LEP klystrons were causing considerable HV modulator faults. In a similar manner, a possible redesign of the HV connector of the Pre-Chopper has been considered. It was also noted that clearer procedures for managing the Source recovery are needed.

Implementation of The Accelerator Fault Tracking system is an important step towards future operation. Huge efforts have been invested in the systematic follow-up of the faults to ensure reliable data capture.

Simulations from the Linac4 availability model show realistic predictions for systems without teething problems. Simulations are expected to correspond better to operational data when Linac4 reaches steady state operation.

As a result of the already foreseen improvements, we expect to achieve a higher availability in the next phase of the Reliability Run, before Linac4 is connected to the CERN accelerator complex.

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## ACKNOWLEDGEMENTS

A special thanks goes to the Linac4 and the PSB operations team at CERN.

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