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# FIRST YEARS OF LINAC4 RF OPERATION

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*Abstract*

Following the construction, commissioning, run-in, and connection, in 2021 Linac4 at CERN saw its successful start-up to full operation. Being composed primarily of RF systems, occupying most of the tunnel and the equipment hall, a coordinated effort has been put in place by four RF teams providing cavities, amplifier chains, low-level RF and general control systems. While all parts came together with impressive performance from day one, many details required a considerable debugging effort to achieve the requested availability of at least 95% from first operation in the synchrotron complex. This contribution focuses on issues in equipment reliability, radiation to electronics, thermal stability, systems interaction, as well as a few aspects of complex low-level RF setup. It will also discuss decisions taken with respect to spare policies and upgrades for the coming years.

## INTRODUCTION

Linac4, the new $H^-$ accelerator at CERN has been constructed as a replacement for Linac2, a proton machine, which was close to its end of lifetime [1]. While the design efforts for Linac4 began in 2004, the actual project was started in 2008. The ground-breaking took place on 16 October 2008, and the inauguration was celebrated on 9 May 2017, following the first beam commissioning of the machine. Linac4 has been designed as part of the LHC injector upgrade with the aim to be able to reach up to twice the beam intensity out of the PS Booster, which is a 4-ring synchrotron following Linac4 and which accelerates the beam from 160 MeV to 2 GeV.

Supporting a rich physics program at the LHC as well as at ISOLDE, AD, and several fixed target experiments, the injector complex is required to almost continuously supply all customers reliably with the requested beam types and beam quality throughout the year. Beam production is based on a complex operation with pulse to pulse modulation (PPM) that must make sure that all facilities are served in parallel with individually tailored beams.

In this context, the performance of the accelerators is primarily monitored in terms of machine availability of non-degraded beam quality. Equipment faults are registered by the operation team in the accelerator fault tracking (AFT) system, analysed by equipment experts, and discussed in weekly meetings [2].

The decision to delay the connection of Linac4 from the long LHC shutdown LS1 (2013–2015) to LS2 (2019–2021), in order to reduce interference with LHC activities, was extremely beneficial for the reliability of the machine. Having been run for almost 40 years, Linac2 was still at an average of 98% of overall availability in the final years. Having the very reliable Linac2 as its predecessor, the challenge for Linac4 was set high, to deliver at its start-up all the previously defined beams at 95% availability despite its about three times higher beam energy and number of RF systems.

In the following sections, a brief introduction to the Linac4 machine and the start-up phase is given. A number of exemplary RF issues that were encountered in the commissioning and early RF operation are described. Operational strategies and spare policies are discussed with an outlook on future RF activities.

## THE MACHINE

As is the case for linear accelerators in general, Linac4 consists primarily of RF systems and equipment required to run these. Linac4 operates at an RF frequency of 352.2 MHz and at about 0.1% duty cycle with a beam-pulse length of up to 600 $\mu$s and a 1.2 s repetition time. The machine has a length of about 80 m. The average operational beam current is up to 23 mA after beam chopping with an emittance of 0.3 $\pi$ mm mrad at 160 MeV.

Cavities in the beamline tunnel are 12 m below the equipment hall where klystrons are located. The equipment hall is about 100 m long and 12 m wide. Connection of RF equipment from the hall to the tunnel passes via shafts with rectangular half-height WR2300 waveguides, and coaxial cables close-by, to keep line-lengths short and at the same environmental conditions. High-voltage (HV) modulators placed next to klystrons, generating the high voltage pulses of up to 110 kV for the klystrons, are taken care of by the power converter group.

The RF structures on the beam line accelerate beam out of the source at 45 keV consecutively with a Radio-Frequency Quadrupole (RFQ) to 3 MeV, 3 Bunchers, 3 Drift-Tube Linacs (DTL) to 50 MeV, 7 Cavity Coupled DTLs (CCDTL) to 102 MeV, and 12 PI-Mode Structures (PIMS) to 160 MeV in the main tunnel, and 1 PIMS-type Debuncher cavity is located in the transfer line tunnel. The RF teams are also in charge of the two chopper structures located in the MEBT line between the first two Buncher cavities and the 2 MHz source amplifier providing about 30 kW RF power to the plasma chamber.

## THE ORGANISATION

The key to the success of Linac4 is the dedication of all teams. Within the RF group at CERN, four of the hierarchical sections are contributing to the operation of the accelerator with each section being responsible for certain parts of the systems, devided into klystrons, controls, feedback, and other linac RF systems. A tight collaboration is also established with other groups at CERN, in particular for power converters, cooling, mains electricity, vacuum, general controls, beam physics, and operation group. The effort within

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the RF group is organised by a Linac4 RF coordinator who mainly takes care of the communication between RF teams, and the operation and beam physics coordination. Part of the assignment is to review faults, analyse corresponding data, and to focus the team effort on critical issues.

In the RF group, three piquet teams for klystrons, other high level systems (solid state amplifiers, chopper, source amplifiers, cavities), and low level RF and controls provide 24/7 on-call support on a weekly rota. All piquet teams have responsibilities for other machines as well. Apart from a team of operators that are on shift work, an on-call machine coordinator out of a team of nine people on a weekly rota follow up the machine issues on the operational side. Three of the machine coordinators are from the operation group, three from the beam physics group and three from equipment providers, whereof one is from the RF group. The benefit is mutual as this responsibility provides a privileged view to the RF group on the operation and to the operation group on the RF. Daily and weekly coordination meetings are organised for the tight follow-up of issues. During year end technical stops, regular maintenance is scheduled, and few technical stops are organised during the year for urgent interventions. A number of software tools provide the formal framework for the follow-up. Among these, the main tools are the e-logbook, and the accelerator fault tracking tool (AFT).

| First Beam Milestones (Beam Physics Group) | | | | |
|---|---|---|---|---|
| 3 MeV | 12 MeV | 50 MeV | 107 MeV | 160 MeV |
| RFQ at test-stand | 1 DTL | 3 DTL | 7 CCDTL + 1 PIMS | 12 PIMS |
| 13 March 2013 | 5 August 2014 | 26 November 2015 | 1 July 2016 | 25 October 2016 |

| Linac4 Beam Commissioning Runs (Beam Physics Group) | | | | |
|---|---|---|---|---|
| Half Sector Test | | Reliability Run | | |
| Oct. – Dec. 2016 | Feb. – Mar. 2017 | July – Sep. 2017 | Oct. – Dec. 2017 | April – May 2018 |
| | During EYETS | Debuncher Inst. | ⇒ YETS | |

| Linac4 Beam Commissioning Runs (Operation Group) | | | |
|---|---|---|---|
| Towards Operation Run | LBE Meas. Line Tests | Run3 Beam Commiss. | Run3 (LHC from 2022) |
| Sep. – Dec. 2018 | Oct. – Dec. 2019 | Aug. – Dec. 2020 | Jan. 2021 – Dec. 2025 |
| ⇒ LS2 | | | |

Figure 1: Linac4 commissioning progressed in three stages with a multitude of runs at each stage.

## THE COMMISSIONING TIMELINE

Linac4 commissioning progressed in three stages with a multitude of runs as shown in Fig. 1. In the first stage of commissioning from March 2013 until end of 2016, milestones in beam energy were reached at 3 MeV (RFQ), 12 MeV (DTL1), 50 MeV (all DTL), 107 MeV (all CCDTL & PIMS01), and 160 MeV (all PIMS), putting the machine consecutively in service. From there on five beam commissioning runs of the full linac led by the beam physics group covered the second stage until summer 2018. Finally on the third stage, three runs led by the operation group until end of 2020 provided for the testing and debugging of the linac up to the connection to the PS Booster synchrotron. These three commissioning stages corresponded to the objectives of the exercise: first to reach the reference beam energy with a first stable beam, then to reach a certain reliability in the equipment operation with full beam and to improve on the beam quality, and finally to reach the required beam quality. [3–5]

The three objectives for Linac4 were in line with the operational reality: for reaching the internal beam dump neither the precise final beam energy nor nominal beam quality are required. When then bending the beam into the transfer line in the second stage, the absolute beam energy and the energy spread needed to be within bounds. At the third stage when sending the beam on the measurement line and later when injecting into the PS Booster synchrotron, a consistent beam quality needed to be achieved.

The transfer of responsibility for beam commissioning to the operation group in the third stage was a natural but important step towards reaching the reliability in the beam parameters. Rigorous debugging with a view towards the downstream machines was undertaken and the standard CERN high-level features like pulse-to-pulse modulation was introduced. The many relatively short operation periods of two to four months interrupted with few months of technical stops were essential for debugging and upgrading systems.

## LOW-LEVEL RF SYSTEMS

The low-level RF systems for Linac4 are a new development. While the design team benefitted from contacts to experts on other linacs namely the SNS at ORNL [6], the operational needs at CERN favoured an individual development. At the time, all other injector linacs at CERN relied on analog low-level cards, and the operational requirements, in particular the pulse-to-pulse modulation scheme used for multi-user beam production, and the specific controls infrastructure required a dedicated implementation.

The hard- and firmware was installed in a Faraday cage in the equipment hall, debugged and upgraded in a staged approach that went all along the commissioning periods of the machines. First the basic feedback loops for tuning, amplitude and phase control were put in operation. Later Kalman filtering and adaptive feed-forward (AFF) were introduced to stabilise the beam head. A polar loop is used to stabilise the klystrons. Detailed descriptions of the systems and algorithms are provided in [7].

Initial difficulties with data persistence increased the start-up time in the first runs. Hardware installations and controls issues repeatedly led to the loss of reference phase values and required the rephasing of the machine practically at every machine start-up. With the automation and debugging of this procedure, the impact could be reduced from about a week to just few hours lost.

The actual phase stability due to thermal variations is continuously being monitored. Early in the design, the installation of a reference line was decided. The RF reference is propagated along the linac tunnel and directional couplers split off reference signals at each cavity which are brought back to the Faraday cage closely following the hollow rectangular WR2300 waveguides through the vertical shafts. While there are absolute seasonal phase changes of few degrees that might be due to humidity variations in the Faraday

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cage, the variations between cavities on the beamline remain within ±1 deg, sufficient for reliable operation.

Very critical for the daily operation also is the recovery of systems after external perturbation like power glitches and outages. At first all systems had to be started individually from the control panel. Klystrons need 15 minutes for heating the filament of the electron gun, and starting all 22 systems by hand required considerable time. The correct start-up of the power systems including the HV modulator and the reliable closure of tuning, phase and amplitude loops in a pre-defined operational state is non-trivial, and the development of a sequencer script required considerable testing and debugging effort. Operators are now able to restart the systems rapidly and reliably. More to this, it is critical for the sequencer to attribute start-up failures reliably to sub-systems in order for the operator to be able to call the right equipment specialist. Further improvements are still on-going. Further effort also still needs to be spent on the energy painting system designed for high intensity beams. The upgrade of the debuncher amplifier to a higher power level might need to be rediscussed.

## RF PROBES

Originally the conditioning of the first DTL structure was foreseen on the RF power test stand, though to gain time, all RF structures were conditioned only in the Linac4 tunnel. When reaching high RF power, and after a good number of RF breakdowns, unfortunately, RF probes occasionally failed with a vacuum leak. The RF probes actually had been recuperated from Large Electron Positron (LEP) main ring cavities [8]. The design was considered fully tested and advantageous as it consists of two individual parts; the power probe, and an RF vacuum window. This way, the RF probe could be exchanged, and its loop angle and thus coupling factor adjusted without breaking the vacuum.

First failures were spread out in time and occurred on the 7.3 m DTL Tank3, but for long did not show up on other RF structure types. Only when all RF structures came on-line and operated at nominal power, it became apparent that there is a correlation with stored energy (24 J for DTL Tank3), and that the problem would need to be treated rapidly to maintain operation.

A new design with a more retracted classic coaxial ceramic feedthrough was developed and installed when available and appropriate. 70 replacement antennas needed to be installed and calibrated, limiting interferences with the Linac4 beam commissioning. The fact that recalibration of RF probes used in feedback loops had an effect on cavity phasing added to the phase issues mentioned before. Microscopic analysis before and after failures could trace cracks in the ceramics as the issue (see Fig. 2). It took almost three years from the first failure to replacing the last probe.

## ARC DETECTORS

In the first months of commissioning up to 160 MeV and with increasing beam intensity, arc detectors on the WR2300

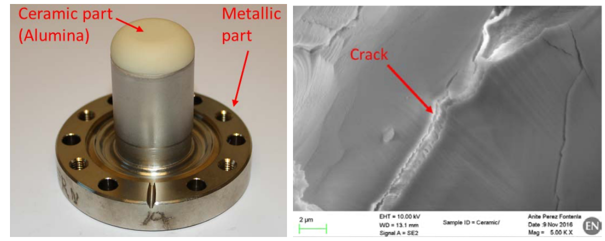


Figure 2: RF probe window (left) analysed by electron microscopy shows a hollow with cracks (right).

rectangular waveguides started detecting false events. Some of the events unfortunately required forcing a power cycle by disconnecting a cable of the control logic. Failures were correlated with beam intensity, beam energy, and radiation levels in the tunnel. The sensors had been built in two parts. The actual detector had been designed radiation hard, and the control logic was foreseen to be installed with long cables far away. Nevertheless, as it was considered easier to do, the control logic was installed in the tunnel close to the detectors. The wrongly made assumption was that the low Linac4 duty-cycle would not lead to radiation failures.

At low beam energies no issues were detected. For higher beam energies, two options were found to remedy the situation a) to shield electronics and to make the control logic radiation hard, and b) to displace the control logic out of the tunnel. It was clear that option a) would allow to go stepwise with minimal investment into hardware, and first to increase shielding in particular locations, to verify with simulations, and to adapt the measures to the needs. Nevertheless it was boldly decided to leave the control logic in place for locations with lower beam energy, and to go for option b) at higher beam energies as potentially debugging the situation at multiple instances also comes at a cost. A sufficient number of spare cable channels from the tunnel were available. By laying cables from the tunnel to existing racks on the surface up to 30 m line length away and moving the hardware, the issue could be treated once and for good. A year after first symptoms the issue was solved, and soon forgotten.

## THE KLYSTRON STRATEGY

The RF frequency of the Linac4 installation of 352.2 MHz was chosen in reference to existing equipment from the former LEP ring, the predecessor of the LHC in the same tunnel. 20 klystrons of nominal 1.3 MW CW output power from three manufacturers with an estimated accumulated remaining lifetime of about 50 years could be recuperated, including waveguides, circulators and dummy loads. In consequence, a layout was defined using some of these LEP klystrons and some new 2.8 MW pulsed klystrons from two manufacturers in order to make sure to reach the required beam performance. [9]

Most RF structures require about 1 MW input power at nominal 40 mA of beam current. At least 25% overhead are required to cover line losses and feedback loop regu-

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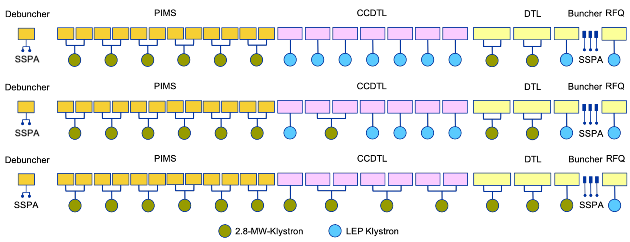


Figure 3: Evolution of the klystron setup - start-up (top), current (middle) and final setup (bottom).

lation. At higher beam energies the space in the klystron hall is too tight for parallel LEP klystrons, and on some RF structures the stably reachable output power from these LEP klystrons limits beam current to 26 mA. In consequence the original setup in Fig. 3 was chosen for the start-up and will be upgraded to the final setup as LEP klystrons reach the end of their lifetime. The lower beam current corresponds to the beam current limits of the $H^-$ source after chopping, and in order to reach the required integrated intensity, the nominal injection into the PS booster synchrotron of nominally 4×100 $\mu$s of beam has been extended to 4×150 $\mu$s, corresponding to roughly 150 turns in the PS booster.

## CIRCULATOR COOLING

In October 2020, a water leak developed in the circulators of the PI-Mode Structure 1 (PIMS01). Due to the fact that it was inside the waveguides, it was discovered only few weeks later, after phase variations in the PIMS02 branch could not be explained other than by a variation on one of the circulators. The two branches powering PIMS01 and PIMS02 are fed by a single high power klystron. The phase and amplitude were controlled on PIMS01 and the phase difference between the structures is adjusted by a phase shifter. As the PIMS01 phase is stabilised, the PIMS02 phase drifted.

When the problem was understood, the water cooling was suppressed and the circulator operated without cooling. Due to the low duty cycle of less than 0.1% water, cooling is not required but a phase variation could still be seen as the two circulators nevertheless depend on a temperature stabilisation. The decision therefore was taken to install chillers for air cooling on the water channels. On the low-level side the amplitude and phase loop is now stabilising the vector sum of the two cavity voltages. Since these two modifications, the systems are back to stable operation.

## THE SPARES POLICY

The spares policy has a direct repercussion on the Mean Time To Repair (MTTR). RF redundancy in normal-conducting ion linacs is limited as all cavities are unique and need to be continuously operational. Nevertheless, the three buncher systems are equipped with a spare amplifier rack and a patch panel which permits to switch from any of the main buncher amplifiers to the spare within a few minutes. A full rack of spare parts was considered necessary in any case and keeping that rack in standby was estimated worthwhile. A similar situation is valid for the debuncher amplifier. It actually consists of two buncher amplifier racks and instead of combining the two, each of the racks can be run individually on the debuncher cavity halving the available power. Currently also a spare chopper structure is being built that can replace either of the two operating units. The potential failure scenario is beam loss on the meander lines of the ceramic buncher plates. Other individual spare units are still being prepared when time is available, and a spare RFQ project has been launched in 2020.

## THE SPARE RFQ PROJECT

At the beginning of 2020, an inspection of the pre-chopper dump in the LEBT line permitted also to inspect the RFQ front face. First endoscope pictures made believe that the RFQ vanes were strongly damaged. Inspection by normal camera after removal of the second solenoid magnet showed that the impact was less severe than apparent from the endoscope images, but changes in surface texture appear to be real. Limited access to the vanes surface made further analysis impossible. While no degradation in the RFQ performance was seen, it was nevertheless decided to build an almost carbon copy spare RFQ (RFQ2). A risk analysis by an expert team during the manufacturing of the first RFQ (RFQ1) in 2015 had concluded that the fact that the RFQ is a monolithic structure makes repairs difficult and favours to have a full spare. Beam and breakdown damage however were not seen as primary reasons for the need of a replacement structure. Raw material had been acquired soon after the study but the decision whether to build a carbon copy or an upgraded version had not been taken until 2020. Within the framework of the Linac4 spare RFQ project, the manufacturing is on-going and the completion of the structure before tuning is expected in September 2022 [10].

The interest in the beam dynamics design to increase the vane voltage needed to be considered relative to the breakdown rate. Early operation showed breakdown rates of $4 \times 10^{-4}$ with frequent bursts of consecutive breakdowns. As breakdowns lead to surface damage, a suppression of these bursts was considered mandatory. To achieve better breakdown performance, first the cavity voltage was reduced, and an effort was made to interlock the operation based on the reflected power caused by the breakdown. Today a linear ramped reconditioning kicks in, that becomes the longer the more consecutive breakdowns are detected. Current operation slightly above the nominal voltage of 35 MV/m is achieved at a breakdown rate of $1 \times 10^{-5}$ which corresponds to a breakdown per day. This performance is considered acceptable by operation. The evolution of breakdowns over the years is shown in the Fig. 4.

In parallel to the RFQ2 manufacturing, a study program was launched to consider the design of a future RFQ3. Building on experience from CLIC studies, materials are being

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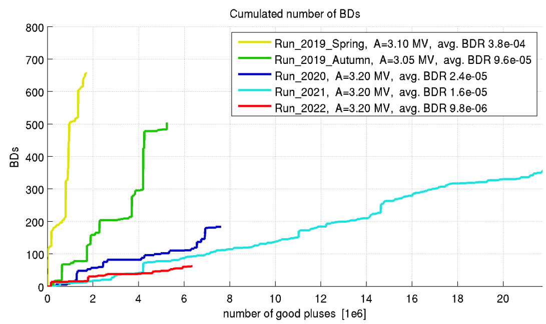


Figure 4: RFQ accumulated number of breakdowns. A breakdown protection considerably improved the situation.

studied with respect to breakdown performance with and without irradiation. First results are described in [11, 12].

## THE AVAILABILITY

The key parameter for the performance of the CERN accelerators is the availability with full beam quality. As mentioned earlier, the performance of all machines at CERN is extracted on a weekly basis and faults are discussed during weekly meetings. Due to the meticulous care in the follow-up of issues and the long start-up phase, the target value of 95% availability could be reached since 2021, as shown in Fig. 5. AFT calculations rely on definitions like the accounting for start and end of a run, for planned interventions, or for multiple interventions undertaken in parallel. In the same way, the fault tracking also strongly depends on what is considered as acceptable beam. Before the beam needed to be injected into the downstream synchrotrons, low-level RF systems were still in the debugging stage, and actual beam quality was not yet checked to be within the same tight limits as it is today. In the figure, a dip in the 2020 availability can be noticed which is due to the issues with the circulator mentioned before.

As a further indication in Fig. 6 the contribution of faults to downtime in 2020 is listed by type of fault. It can be noticed from the graph that most of the faults appear on high-voltage systems like klystrons, and that cavity breakdowns, some source RF and chopper driver issues which are directly related to high voltage faults, account for approximately one third of the downtime. A great effort continues to be made to reduce the impact of breakdowns in RF structures, and a new solid-state amplifier for the source and a new chopper driver are under study. With the replacement of LEP klystrons by new 2.8 MW klystrons, too, it is expected that fault rates improve.

## CONCLUSIONS

Linac4 being the replacement for Linac2 at CERN has shown an impressive performance since its connection to the injector complex, and achieved the key performance target values practically from day one of operation on the accelerator complex. This high performance could only be reached with a long run-in period and the strong dedication

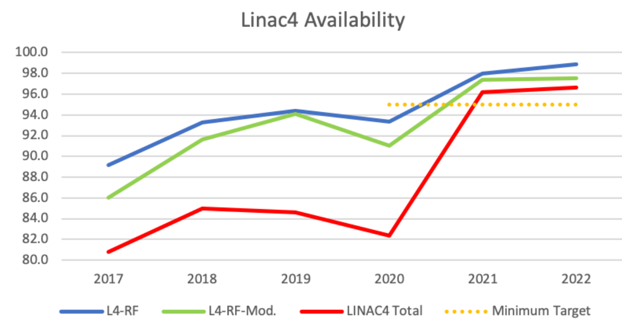


Figure 5: Linac4 availability from 2017 to August 2022: RF (blue), RF plus klystron HV modulators (green), Linac4 total (red), target value of 95% (dotted).

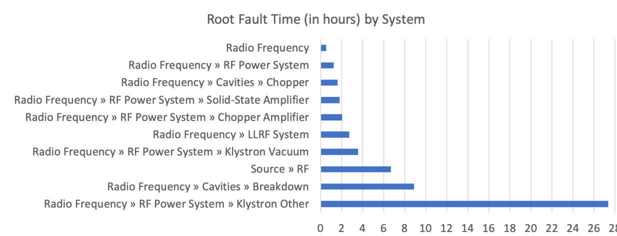


Figure 6: Blocking root faults of the RF systems of Linac4 by categories during the year 2022 until August.

of personnel to sort out issues along the way. The complexity of the operation of such a facility is reflected in that teething issues like failing probes and arc detectors even when treated early, require considerable time to be sorted out completely. Debugging of new systems like the low-level RF controls was time intensive and needed to advance in stages. Data persistence and automatic start-up routines are paramount for reliable operation from the CERN control center.

Organisational structures for treating new issues like piquet teams, regular meetings for interdisciplinary discussion, and a lead to advance on them is now in place. Efforts continue to be made to also secure against future failures and to prepare for upgrades with regular maintenance, and correct numbers and types of spares, in view that beamtime for CERN experiments is precious.

## ACKNOWLEDGMENTS

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