ISBN: 978-3-95450-202-8 doi:10.18429/JACoW-HB2018-MOA1PL03

LINAC4 COMMISSIONING STATUS AND CHALLENGES TO NOMINAL OPERATION

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Abstract

Linac4 will be connected to the Proton Synchrotron Booster (PSB) during the next long LHC shutdown in 2019 and it will operationally replace Linac2 as provider of protons to the CERN complex as of 2021. Commissioning to the final beam energy of 160 MeV was achieved by the end of 2016. Linac4 is presently undergoing a reliability and beam quality test run to meet the beam specifications and relative tolerances requested by the PSB. In this paper we will detail the main challenges left before achieving nominal operation and we will report on the commissioning steps still needed for final validation of machine readiness before start of operation.

INTRODUCTION

Linac4 is a 160 MeV H- linear accelerator that will replace Linac2 as injector of the CERN PS Booster (PSB) and provider of protons to the whole CERN complex as of 2021. The pre-injector part is composed of a RF volume source producing a 45 keV beam at 2 Hz maximum repetition rate, followed by a Low Energy Beam Transport section (LEBT), a Radio Frequency Quadrupole (RFQ) accelerating the beam to 3MeV, and finally a Medium Energy Beam Transport Line (MEBT), matching the beam to the linac. The MEBT is composed of 11 quadrupoles, 3 bunchers and a chopper, formed by two sets of deflecting plates, which are used to selectively remove micro-bunches in the 352 MHz sequence, in order to optimise injection into the 1 MHz CERN PSB RF bucket. The nominal scheme currently envisaged is to chop 133 bunches out of 352, with a consequent current reduction by 40%. After the MEBT, the linac consists of three distinct sections: a conventional Drift Tube Linac (DTL) accelerates the beam to 50 MeV. It is divided in 3 tanks and is equipped with 111 Permanent Magnet Quadrupoles (PMQs). This is followed by a Cell-Coupled Drift Tube Linac (CCDTL), made up of 21 tanks of 3 cells each, accelerating the beam to 100 MeV. The CCDTL was constructed by the Russian Scientific Research Institute for Technical Physics (VNIITF) and the Budker Institute of Nuclear Physics. Focusing is provided by Electro-Magnetic Quadrupoles (EMQs) placed outside each module, and PMQs between coupled tanks. Final acceleration to 160 MeV is done through a PI-Mode Structure (PIMS), composed of 12 tanks of 7 cells each, interspersed with 12 EMQs for beam focusing. The PIMS were constructed within a CERN-NCBJ-FZ Julich collaboration and assembled and tuned at CERN. Both CCDTL and PIMS represent the first such cavities to work in an operational machine. A 70 m long transfer line, including 17 EMQs, 5 dipoles (3 horizontal and 2 vertical) and a PIMS-like debuncher cavity connects Linac4 to the present injection line into the PSB, which will be only slightly modified for the remaining 110 m to the PSB entrance. A sketch of Linac4 is shown in Fig. 1.

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COMMISSIONING

The commissioning of Linac4 was organised in six different phases over 3 years, alternating hardware installation and beam validation periods at increasing energy values. The commissioning was prepared and accompanied by extensive beam simulations, which turned out to be crucial to successfully optimise beam transmission and quality. A key decision was to start simulations with a particle distribution obtained by measuring the beam in the LEBT under different solenoid focusing and back-tracing the measurements to the start of the line.

In the first commissioning stage a dedicated 3 MeV test stand was used for a systematic beam measurement campaign that lasted 6 months. The following stages at higher energies (12 MeV, 50 MeV, 100 MeV and 160 MeV) lasted on average 3 weeks each. Two diagnostics test benches were used during commissioning. The low energy one (used at 3 and 12 MeV), allowed direct measurements of transverse emittance and energy spread via a slit-and-grid system and a spectrometer arm respectively. The high energy bench (used at 50 and 100 MeV) contained 3 profile harps and wire-scanners at 60 deg phase advance from each other for emittance reconstruction; a Bunch Shape Monitor (BSM) and lasing station for beam stripping and two Beam Position Monitors for Time-Of-Flight (TOF) and trajectory measurements.

Table 1: Energy and Beam Intensity Milestones

Energy [MeV]	Date (beam energy)	Record peak current	Date (record current)	2017 operational current
0.045	2013	50 mA	11/2015	40 mA
3	03/2013	30 mA	10/2015	26 mA
12	08/2014	24 mA	11/2016	20 mA
50	11/2015	24 mA	11/2016	20 mA
105	06/2016	24 mA	06/2016	20 mA
160	10/2016	24 mA	10/2016	20 mA

A very important result of the low energy commissioning was the agreement between direct measurements of the beam transverse emittance via the slit-and-grid method and indirect measurements based on emittance reconstruction from profiles, using either a "forward-method" technique or a tomographic reconstruction method [1].

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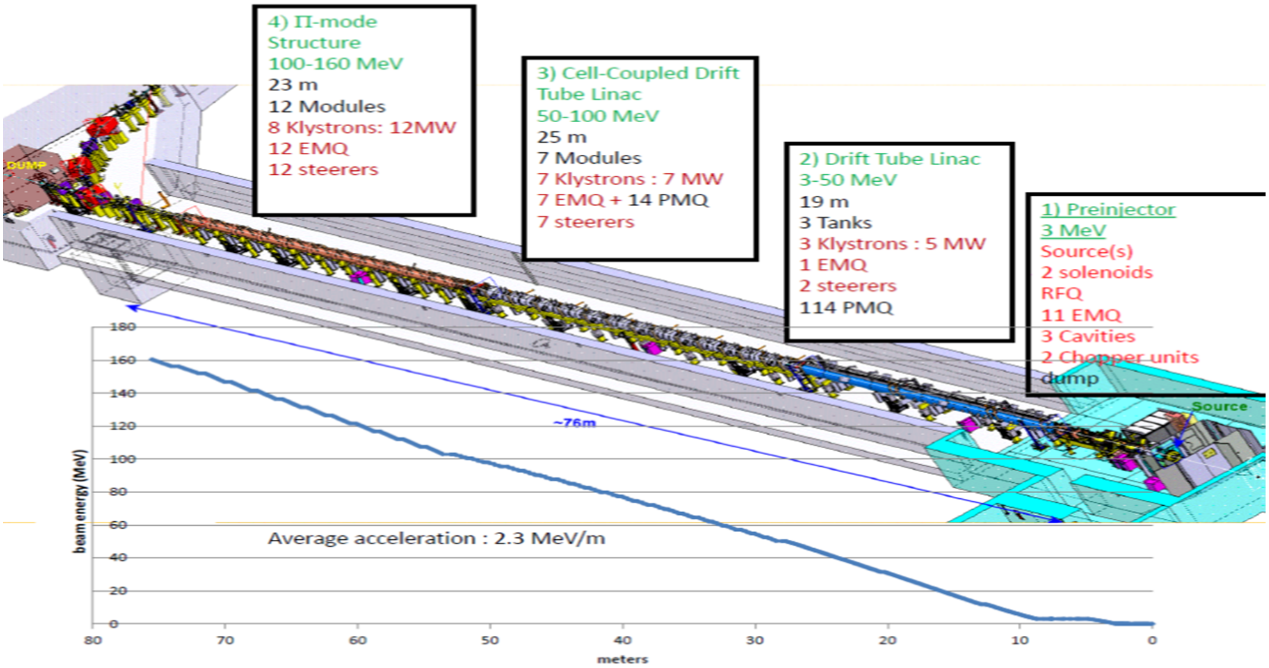

Figure 1: Sketch of Linac4.

We refer to past publications for a more complete description of commissioning measurements [2]; timelines and main milestones of the different commissioning stages are summarised in Table 1. Note that record peak currents were not always taken during the measurement campaign at the corresponding energy. Beam commissioning to the final energy of 160 MeV was successfully completed by the end of 2016.

HALF SECTOR TEST

After achieving this milestone, the 160 MeV beam was used for a few months at the end of 2016 to feed a test set-up of the PSB injection chicane, the Half Sector Test (HST). The purpose of this test was to gain information about the H^-→proton stripping system, to help reduce risks and facilitate the commissioning during the Long-Shutdown-2 (LS2, 2019-2020), when many modifications are foreseen in the framework of the LHC Injectors Upgrade (LIU) programme, and to ensure that the new equipment works according to specifications. The Linac4 connection requires a complete renewal of the PSB injection scheme, due to the energy increase from 50 to 160 MeV and the injection of H^- ions instead of protons as currently done from Linac2. Protons are presently injected via a multi-turn injection process using kickers and an injection septum. After connection, the H^- ions from Linac4 will be injected through a stripping foil located in the centre of the injection bump. Fast kicker magnets will be used for phase-space painting. The new injection scheme will benefit from reduced space charge effects and injection losses (from the current 50% to ~2% due to unstripped or partially stripped particles). The high complexity of integration in a limited space availability, however, justified the proposal for a test installation in the Linac4 transfer line, consisting of a half injection chicane of one PSB ring (see Fig. 2). The installation was composed of:

- a stripping foil system with a loader containing 6 foils and a screen with radiation-hard camera
- half of the injection chicane
- a monitor measuring partially and unstripped particles (H^0/H^-) and the H^0/H^- dump
- beam-loss monitors in vicinity of the dump
- beam current transformers upstream and downstream of the HST for stripping efficiency measurements
- a screen for beam profile and position measurements.

A separate stripping foil test stand was installed at the beginning of the Linac4 transfer line in order to:

- test foil changing mechanisms and interlock functions
- gain experience on foil handling
- test different foil materials and thicknesses
- gain information on foil lifetime.

The HST received first beam at the end of October 2016 and stopped operation in April 2017. Stripping efficiency was confirmed to be >99% for 200 μg/cm² thick carbon foils, fulfilling the design specifications.

A few foil breakages were observed, possibly due to interference with the Beam Televison (BTV) screen, used for beam observation (see a sample measurement in Fig. 3). All the main functionalities were checked and validated. Input was gained on possible design changes to improve measurement precision and stability and for noise reduction. The operational experience gained with equipment handling, controls and interlocks, was crucial for future commissioning phases.

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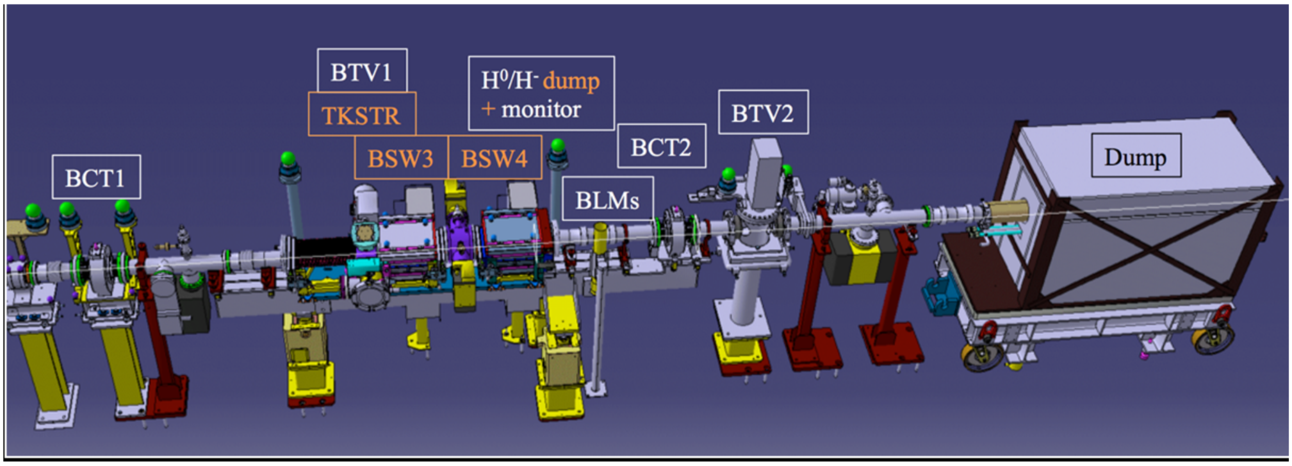

Figure 2: Sketch of the half-sector test installation.

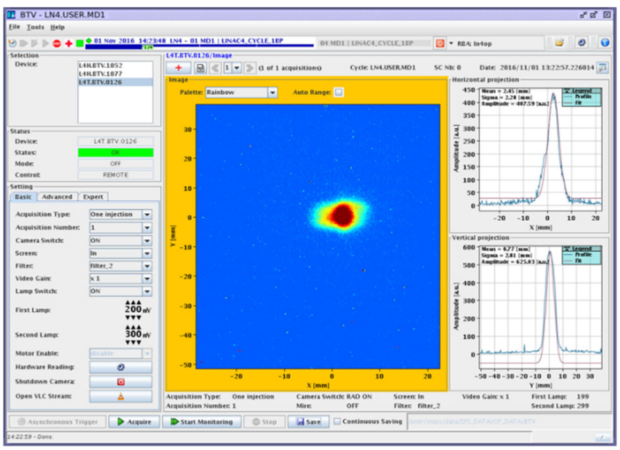

Figure 3: Transverse profile of the beam at 160 MeV measured on the Beam Television (BTV) screen.

RELIABILITY RUN

Once connected to the PSB, Linac4 will be the sole provider of protons to the whole CERN accelerator complex. This sets very high requirements in terms of machine availability, which will ultimately need to match the current performance of Linac2, running today, after 40 years, with an average availability of more than 98%. After successful completion of machine commissioning, a Reliability Run was therefore planned, intended also as a transitional period towards operation. The main aim of the run was essentially consolidation of routine operation and identification of potential recurring problems, thus providing a unique opportunity for early identification of weak points and for improving procedures. The Reliability Run took place from June to the end of December 2017, and it was divided in two phases to allow for scheduled Technical Stops for maintenance and technical interventions. The first phase lasted until the end of September, and it was composed of short periods of operation followed by repairs and optimization. The second phase took place from the end of October to the end of the year, with longer periods of operation followed by technical interventions, to approach more realistic operating conditions. In total, 19 weeks were dedicated to the Reliability Run. The Accelerator Fault Tracking system [3], initially developed for the LHC, was also adopted for Linac4 fault tracking, with some ad hoc adjustments, needed to account for the fact that Linac4 is not yet an operational machine (hence call-out support is not available on a round-the-clock basis). Machine availability and beam-on time was thus calculated manually from logbook entries during working hours only, subtracting scheduled interventions and machine studies.

The analysis of the weekly availability is shown in Fig. 4. The average machine availability over the 19 weeks of the run exceeded 90%. There were 2 specific weeks where long faults were recorded: 1) week 36, with a controls timing issue and a RF cavity cooling problem , and 2) week 47, with the failure of a power converter anode module needing replacement. Apart from these two occurrences, most of the down-time was due to short and recurrent faults, mainly affecting the RF systems, power converters, the pre-chopper and the source. A full fault distribution covering the entire run period is shown in Fig. 5. Some of the problems identified were addressed and fixed immediately during the ensuing End-of-the-Year-Technical-Stop, while others will be corrected during the Extended Technical Stop foreseen in summer 2018.

BEAM QUALITY RUN

The last Linac4 operational period took place between February and May 2018. Substantial RF interventions had taken place during the previous End-of-Year-Technical-Stop (LLRF upgrades, maintenance of high-power RF systems, upgrades of the RF restart procedures etc). The focus of this run was therefore placed on recommissioning all the changes implemented and on the validation of a series of beam quality requirements that had been agreed amongst different groups as necessary for future Linac4 operation with the PSB.

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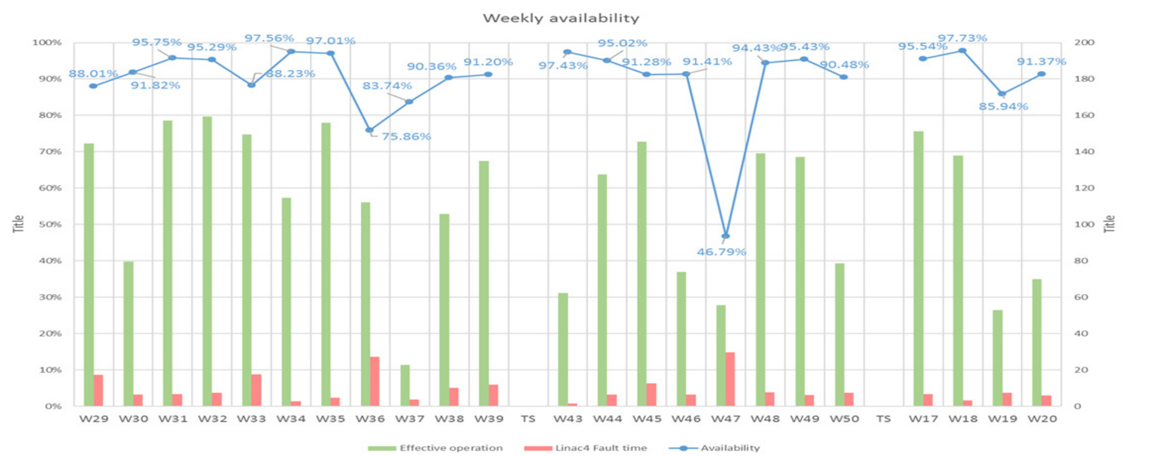

Availability	Fault Count	Operation	Suspended OP	Effective Operation	Fault Mean Time to Repair
91.5%	**449**	23 weeks	~ 8 weeks	~15 weeks	~29 min

Figure 4: Linac4 weekly availability during the 2017/2018 reliability run.

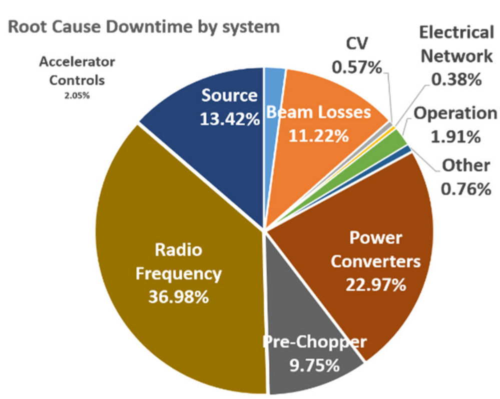

Figure 5: Linac4 fault distribution by system.

The following list of measurements can be earmarked as main achievements of the run:

i) Beam intensity flatness along the pulse and shot-to-shot stability were both confirmed to be within ±2% (excluding the initial current rise time due to space charge compensation build-up at low energy), which is comparable or slightly better than the current performance from Linac2.

ii) Similarly, the horizontal and vertical position variations along the pulse were measured to be contained within ±1 mm (requested margin at the entrance of PSB not to exceed a transverse emittance of 1.7 µm for LHC beams, see Table 3).

iii) The chopper performance was tested in depth, by operating with different (and sometimes extreme) chopping patterns on two parallel users in the machine supercycle. In the first case a LHC-type test beam was used, with a pulse length of 160 µs and a chopping factor of 60% at 352 MHz (equivalent to a ~625 ns long bunch train being accelerated and ~375 ns long bunch train being chopped off and deflected onto the 3 MeV dump). In the second case a substantially different chopping pattern was implemented (3.6 µs beam transmitted, 2.4 µs chopped off), with a longer pulse length. This validated the pulse-to-pulse use of the chopper and was a test exercise to mimic production of different beams in parallel for the LHC and fixed target physics experiments. The remnant current transmitted when the chopper is activated was measured to be ~0.15 mA, which is at the limit of resolution of the measuring devices and amounts to ~1% of the total transmitted beam intensity. Rise and fall times of the chopper signals were confirmed to be within a few ns, in agreement with the technical specifications of the pulse amplifier and PSB requests to minimize losses and reduce activation of the vertical injection septum.

Dedicated time was also set aside to progress with the commissioning of several beam diagnostics devices, particularly the laser emittance monitor [4] and the Bunch Shape Monitor (BSM) [5]. The laser emittance monitor uses a pulsed laser beam delivered to the tunnel by optical fibres to detach electrons from the H^- ions, which are then deflected into an electron multiplier. The resulting neutral H^0 atoms are separated from the main beam and recorded downstream by diamond-strip detectors. By scanning the laser through the H^- beam, transverse profiles can be obtained from the signals on the electron multiplier. The H^0 profiles on the diamond detector allow to determine the beam divergence, which in combination with the laser position, allows the H^- transverse emittance to be reconstructed (see Fig. 6).

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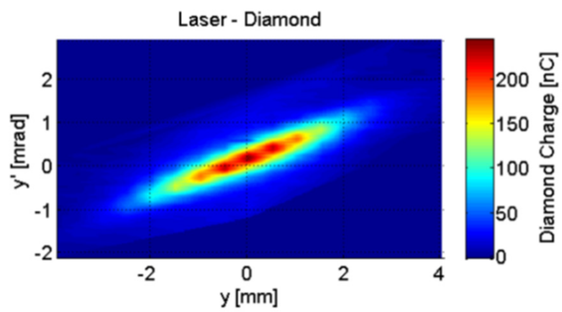

Figure 6: Beam phase space reconstruction at 160 MeV in the Linac4 transfer line using the laser emittance monitor.

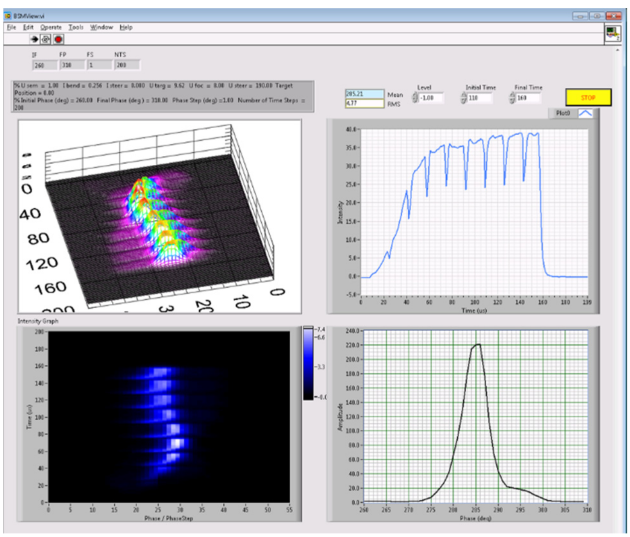

Figure 7: Screenshot from a BSM measurement at Linac4 showing clockwise:1) beam intensity along the pulse length (top right); 2) longitudinal beam phase profile (bottom right); evolution of the phase profile along the pulse length (mountain and cascade plots on the left).

The BSM was developed and fabricated at INR in Russia, to make longitudinal beam profile measurements with a phase resolution of 1° (over a full range of 180° at 352 MHz). Two such devices are installed at Linac4: the first one after the PIMS in the straight line to the dump, and the second one after the debunching cavity in the transfer line to the PSB. Hardware and beam commissioning were successfully completed in varied measurement conditions (changing chopping pattern, pulse length etc- see Fig. 7).

OUTLOOK AND FUTURE PLANNING

Table 2 shows a comparison of the nominal Linac4 beam parameters with the results achieved during the 2017 reliability run. The beam current amounts to 60% of the target value. This intensity limitation occurs in the low-energy pre-injector section and is due to the fact that the beam extracted from the currently installed cesiated RF volume source has an emittance exceeding the transverse aceptance of the RFQ. Target performance for Linac4 after connection to the PSB is to inject via charge-stripping up to 1x10^{13} protons per ring at 160 MeV. The current performance is still sufficient to guarantee the production of LHC-type and fixed-target-physics-type beams (see Table 3), by compensating the lower intensity with a higher number of injected turns [6].

Table 2: Linac4 Design Targets vs Today's Achievements

	Linac4 design targets	**Linac4 achieved**
Peak current in the linac	40 mA	24 mA
Routine current in the linac	40 mA	20 mA
Transverse emittance at 160 MeV	0.4 π mm mrad	0.3 π mm mrad
Energy at PSB injection	160 MeV	160 MeV
Pulse length / rep rate	400 µs/ 1 Hz	Up to 600 µs/ 1 Hz

Table 3: Beam Specifications at the PSB

Beam	Intensity (protons/ring)	Emittance at PSB – [mm mrad]	N° turns at 20 mA beam current
LHC-type	3.4 x10^{12}	1.7	45
Fixed target physics	1-1.2 x10^{13}	10	110-150

A R&D programme has however been launched in parallel on a separate dedicated ion source test stand to study alternative source extraction geometries and plasma generators in order to maximise the current in the RFQ acceptance. This will open the way to upgrades and will allow to exploit the full potential of the linac.

Linac4 has now entered a phase of Extended Technical Stop (ETS) for 3 months until September 2018 to allow the RF team to complete a series of scheduled upgrade and maintenance activities. This will be followed by a re-commissioning run until the end of the year with the aim of validating all changes implemented.

Linac4 will be connected to the PSB during the first semester of 2019, and further commissioning periods are being planned in the following to complete validating the whole installation and its beam performance before the start of official operation in 2021.

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