LINAC4: FROM INITIAL DESIGN TO FINAL COMMISSIONING*

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Abstract

This talk reviews the design, construction, and commissioning effort of CERN's new proton linear accelerator, Linac4, which has recently been commissioned and which is presently undergoing a reliability run. Linac4 will be connected to the LHC proton injector chain during the next long LHC shutdown (LS2) and will then replace the ageing Linac2.

HISTORICAL NOTES

The idea of a high intensity linac dates as early as 1996 [1], and concrete proposals came in 1998-99 [2,3]. The prospect availability of the 352 MHz LEP Radio Frequency (RF) system triggered many different proposals based on its re-use. A high intensity linac based on the 352 MHz system (about 20 klystrons with DC power of 1 MW) could make use of the newly available hardware and modernize CERN accelerators. The initial proposal was for a 2 GeV super-conducting proton linac meant to inject into the PS ring. The layout was studied in details and several versions with different and improved features were proposed between 1998 and 2002 [4, 5], including the function of proton driver for a neutrino factory. In its configuration of 2006 [4,6], the linac included a 180 MeV normal conducting section based on 352/704 MHz structures followed by a 5 GeV superconducting linac based on reduced-beta elliptical cavities at the frequency of 704 MHz.

In its June 2007 session the CERN Council approved the White Paper "Scientific Activities and Budget Estimates for 2007 and Provisional Projections for the Years 2008-2010 and Perspectives for Long-Term", which includes construction of a 160 MeV H^- linear accelerator called Linac4, and the study of a 5 GeV, high beam power, superconducting proton Linac (SPL).

The construction of a new building strategically located on the CERN site to host Linac4 started in October 2008 and lasted for 4 years. Installation of equipment in the tunnel started in 2013 and was followed by alternating phases of equipment installation and beam commissioning at increasing energy. The final energy of 160 MeV was attained in October 2016.

Since 2011 Linac4 became integrated in the framework of the LHC Injector Upgrade program [7] which includes modification to all CERN injectors to allow increasing of the beam brightness delivered to LHC and opens the way to the parameters needed for the High Luminosity LHC [8].

During the LHC Long Shutdown 2 the Linac4 will be physically connected to the CERN PS Booster (PSB) and will inject via charge-stripping up to 3 10^{12} protons per ring at 160 MeV (e.g. an average current of 25 mA along the pulse before chopping, injection over 40 turns of 40 µsec). The beam injected into each ring can be tailored to durations from 1 to 150 µsec, its energy can be dynamically varied by ±1.2 MeV over 40 µsec and the rms energy spread varied from 85 to 450 keV rms. This flexibility is meant to cover all possible beams needed from the PS Booster and will require a conspicuous running in and tuning period for the optimum working point.

LAYOUT

Linac4 is a normal conducting linear accelerator operating at the frequency of 352 MHz. The first element of Linac4 is a RF volume source which can provide a 600 µsec 50 mA H^- beam at 45 keV with a maximum repetition rate of 2 Hz. The beam is then matched to the first stage of RF acceleration (from 45 keV to 3 MeV) in a 3 m long Radio Frequency Quadrupole. At 3 MeV the beam enters a 3.6 meter long Medium Energy Beam Line (MEBT), consisting of 11 quadrupoles, 3 bunchers and two sets of deflecting plates. The beam is "chopped" by removing selected micro-bunches in the 352 MHz sequence to match the beam to the distribution system (which delivers the beam to the 4 superimposed PSB rings) and to the 1 MHz CERN PSB RF bucket. Presently the preferred scheme envisages to chop 133 bunches out of 352 with a resulting average current reduced by 40%. The part described up to now, where the beam quality for the PSB is determined, goes under the name of pre-injector. After the pre-injector the beam is further accelerated to 50 MeV in a conventional Drift Tube Linac (DTL). The DTL, subdivided in 3 tanks, is 19 meters long in total. Each of the 111 drift tubes is equipped with a Permanent Magnet Quadrupole (PMQ). The acceleration from 50 to 100 MeV is provided by a Cell-Coupled Drift Tube Linac (CCDTL). The CCDTL is made of 21 tanks of 3 cells each for a total length of 25 meters. Three tanks are powered by the same klystron, and constitute a module. The focusing is provided by electromagnetic quadrupoles placed outside each module, with PMQs between coupled tanks. The acceleration from 100 to 160 MeV is done in a PI-Mode structure (PIMS). The PIMS is made of 12 tanks of 7 cells each for a total of 22 m. Focusing is provided by 12 Electromagnetic Quadrupoles (EMQ). A 70 m long transfer line, including 17 electromagnetic quadrupoles, 5 dipole bendings (3 horizontal and 2 vertical) and a PIMS-like debuncher cavity connects the Linac4 high energy end to the present injection line into the PSB. The existing line (110 m in length) will not be modified as it can accommodate and match the beam from Linac4 to the new H^- injection system.

A sketch of Linac4 is shown in Fig.1.

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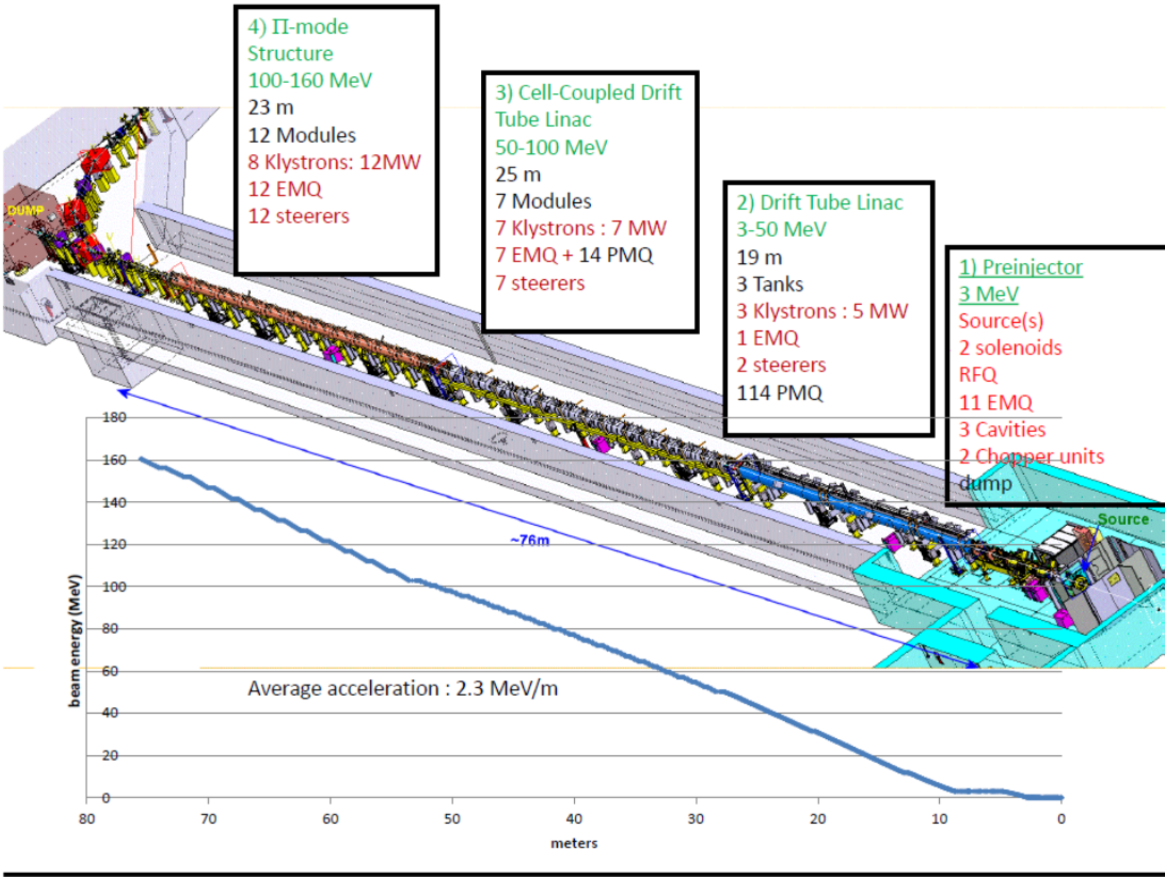

Figure 1: Sketch of Linac4

The integrated gradient of the 158 quadrupoles (of which 127 are permanent quads) and the nominal phase and amplitude of the 260 RF individual accelerating gaps are shown in Figures 2-4.

The design of Linac4 relied extensively on beam dynamics simulation. The actual number of free parameters for optimising the beam during operation are 31 quadrupoles gradients and 25 independent phase and amplitudes. As it can be appreciated from Fig. 2 the flexibility for matching different beams is in the pre-injector after the first stage of acceleration to 3 MeV as well as at the high energy end. Notwithstanding the relatively low number of variable quadrupoles, the Linac4 can accept currents between 0 and 80 mA, can accept both protons and H$^-$ and could potentially deliver to the PSB a beam with energy as low as 50 MeV. Since November 2015 the Linac4 served as emergency back-up for Linac2, in case of an unrecoverable failure. This flexibility has been a design choice from the beginning and special care has been put in an overall start-to-end optimisation of the beam dynamics both in terms of localising the acceptance bottleneck in the pre-injector (to avoid un-necessary irradiation at the high energy end) and in designing a Linac which can be upgraded in the future, as the development of ion sources with higher brilliance will allow even more powerful beams to be produced either for injection into the PSB or for further developments.

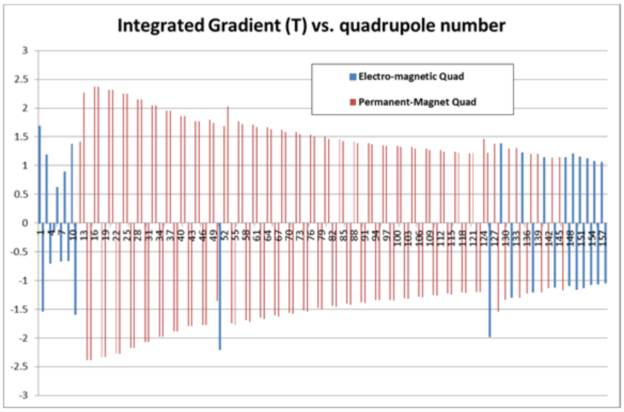

Figure 2: Integrated gradient vs. quadrupole number.

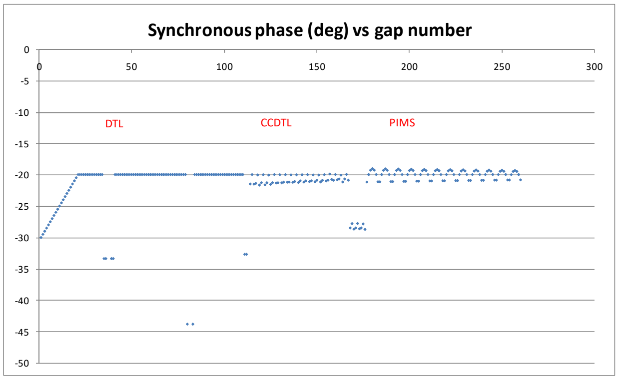

Figure 3: RF Phase vs. gap number.

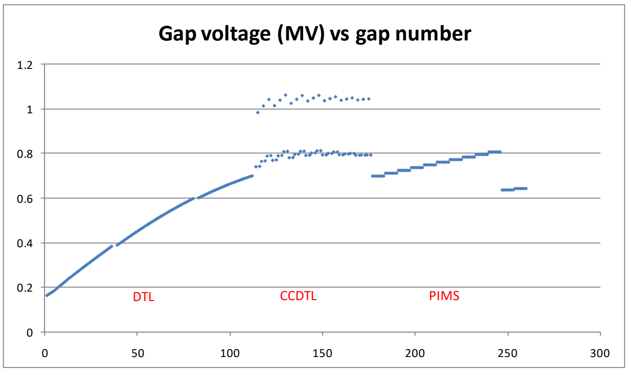

Figure 4: RF Voltage vs. gap number.

Location on the CERN Site

The choice of the location on the CERN site was discussed as soon as the Linac4 construction was approved in 2007. Two locations were considered, one in the existing PS south hall [9] and the second one in a dedicated new location indicated in Fig. 5. The new location [10, 11] implied the construction of a new building but avoided the problem of fitting a Linac in an already crowded area, close to office space. The main reason for the final choice of a dedicated new location was to leave space in front of the Linac for future upgrades to higher energy and the possibility to continue with a multi-GeV Linac. Unfortunately to make this a possibility implied to site the Linac4 2.5 m below the height of the PSB with the consequence of having the beam going through a vertical dogleg. Extensive beam dynamics calculation, also under the influence of errors, have been used to define the best possible arrangement of quadrupoles and dipole bendings to guarantee optimum beam quality, nevertheless a coupling between the horizontal and vertical dispersion is unavoidable and it might pose a limitation for future upgrades.

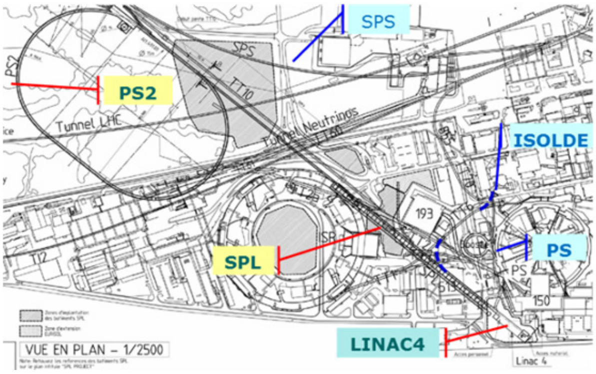

Figure 5: Linac4 location on the CERN site, in blue existing accelerator, in yellow possible future ones.

Accelerating Structures

The Linac4 accelerating systems is made out of 4 different RF structures. The RF acceleration starts with a 4-vane type RFQ, designed and tuned in collaboration with CEA Saclay and build at CERN [12,13]. The MEBT houses 3 single-gap cavities which have the purpose of matching longitudinally the beam between the RFQ and the DTL and as well keeping the 352 MHz structure defined in the RFQ during the chopping. After chopping the beam is accelerated in a Drift Tube Linac [14], designed at CERN and built in industry. The philosophy of the design is “adjust & assemble”: tightly-toleranced Al girders w/o adjustment mechanism once assembled. The PMQ are in vacuum, and particular care has been put in the design of the first gaps to avoid field breakdown enhanced by the PMQ magnetic field.

The CCDTL [15] has been constructed by the Russian Scientific Research Institute for Technical Physics (VNIITF) and the Budker Institute of Nuclear Physics.

The PIMS [16, 17] were constructed within a CERN-NCBJ-FZ Jülich collaboration and assembled and tuned at CERN. Series production could start only after a qualification period of almost 3 years. The critical point was the required precision machining on large pieces of copper (10 - 20 um on 500 mm diameter pieces).

The beam in Linac4 is accelerated with fully synchronous structures (RFQ and DTL) up to the energy of 50 MeV. Up to this energy each of the accelerating gaps (300 cells in the RFQ and 114 gaps in the DTL) are individually tailored and dedicated focusing is provided at each gap. This choice was made to guarantee full transmission, together with the best beam quality and flexibility, for currents up to 80mA. After 50 MeV the choice has been made to use semi-synchronous structures (first the CCDTL tanklets with 3 identical RF gaps and from 100 MeV PIMS cavities with 7 identical RF gaps) equipped with external focusing which is interlaced with acceleration every other 3 or 7 gaps respectively. The phase slippage, consequence of this choice, can be appreciated in Fig. 3. This choice allowed to keep an average effective accelerating gradient of about 2.3 MV/m all throughout the Linac4. Both RF tuning, conditioning and beam commissioning were carried out without major problems. All structures were tuned within the allowed static RF tolerance [18] and work is still ongoing on the Low Level RF system [19] to achieve the field stability of 1% and 1 deg under all possible condition of beam pulse length and beam current. Presently it appears that the achieved levels exceeds the tolerances by a factor of 2.

The CCDTL and the PIMS were successfully employed in an accelerator for the first time.

Magnets

All the electromagnetic elements of Linac4 have been designed in house and produced in industry. Two families of steerer corrector magnets and quadrupoles have been designed, one for the low energy end and one for the high energy end [20,21]. This compromise was the optimum between reducing the number of one-of-a-kind element and adapt the magnet's bore-aperture and length to the varying beam energy and transverse dimensions. The choice of two families turned out to be sufficient. An exception is the MEBT, where out of the 11 quadrupoles there are 4 different types: the quadrupoles used have been recuperated from Linac2 spares. The 5 bending magnets for the transfer lines are standardised and the strict requirements on field quality and field jitter have been met.

Diagnostics

Linac4 is equipped with 15 profile measurements devices (either profile harps or wire scanners) with a time resolution of 6 µsec. This feature is essential to study (and possibly correct) time dependent phenomena like the effect of space charge neutralisation at the low energy and low level RF regulation, which manifest as well as a transverse jitter. Profile harps are used to set-up the correct machine tune and also to measure the beam emittance by combining information from 3 or more profile harps (or from the same profile harp under different focusing settings). The emittance reconstruction method in presence of space charge has been specifically developed for Linac4 [22,23] and it has proven essential during the commissioning of the machine. Whenever possible, at the low energy end, the indirect method has been validated with a direct slit-and-grid emittance measurement. During 2017 a system of laser-and-diamond detector based on photo-detachment of an electron from the H^- and the measurement of the resulting H^0 ions will be installed at the high energy end, thus allowing direct emittance measurement at the end of the Linac. The longitudinal qualities at various energies have been measured either directly with a temporary spectrometer or indirectly via the measurement of the micro-bunch phase spread based on the observation of the time structure of electrons emitted from a wire inserted in the beam with a dedicated instrument provided by INR Moscow [24]. The BSM allows the reconstruction of the beam longitudinal emittance by observing the variation of the micro-bunch phase length when varying the amplitude or phase of a cavity located upstream. Results obtained with this instrument at 50 MeV and 80 MeV compare very favourably with the expectations. A couple of BSMs will be installed in the transfer lines between the Linac4 and the PSB and will be the tools to match the beam longitudinally to the PSB, a much lighter and easy-to-operate system than the present 50 MeV spectrometer magnet that, due to space constraints, could not be upgraded to the increased energy.

Corrector Strategy

Linac4 is equipped with 16 pairs of corrector magnets. The correction system has been defined in combination with the alignment tolerance required for the magnetic elements and a reasonable compromise has been found between the number of correctors, the bore aperture and the tolerance required [18]. During the first years of operation the building is still settling and the more critical part, i.e. the pre-injector needed realignment approximatively every six months. The misalignment induced by the ground movement could be partially compensated with the corrector system but at the price of an unacceptable loss of acceptance. In hindsight more correctors should have been foreseen at the low energy end.

Chopping and Energy Ramping

The 3 MeV line between the RFQ and the DTL houses a fast-switching electrostatic device able to remove 150/352 micro-bunches (and ultimately 3/8 micro-bunches) and a conical-shaped dump to dispose of the chopped micro-bunches [25]. The chopper system is embedded in a system of 5 FODO lattice quadrupoles and three bunchers, the first two FODOs match the beam from a fast phase advance in the RFQ to a slow phase advance in the chopper and the last two FODOs lattice rematch back to a fast phase advance in the DTL. The central FODO which houses the chopper plates and the dump is about 2 m in length, the minimum possible to house the chopper plates (0.8 m) and the dump at an appropriate phase advance of 90 deg from the chopper. The chopper functioning is critical for injection of the Linac4 beam into the PSB and it was fully demonstrated in 2014 [26].

Energy ramping is a special feature of Linac4 to dynamically paint the longitudinal PSB bucket during injection with the aim of obtaining a longitudinal distribution as uniform as possible. To achieve this uniformity a dedicated chopping scheme has to be matched to the energy painting speed and amplitude [27]. Technically the energy painting is achieved by ramping the field in the last two PIMS cavities and by readjusting the phase of the downstream debuncher, to obtain a beam with a controlled average energy variation but with constant energy spread. The speed of the energy variation (nominal 40 µsec), the maximum energy variation (±1.2 MeV) and the micro-bunch energy-spread are correlated and presently the extreme values cannot be achieved all at the same time due to the limited power available in the debuncher. Should that be an issue a more powerful RF source could be purchased as there are no other limitations.

BEAM COMMISSIONING

The beam commissioning was planned in 6 stages of increasing energies at 45 keV, 3 MeV, 12 MeV, 50 MeV, 100 MeV and finally 160 MeV. At each stage a dedicated suite of diagnostics has been temporarily installed to address the specific needs of that particular stage. At each stage the transverse emittance, the average energy and energy spread have been measured, directly until 12 MeV and by reconstruction from profile measurements from 30 MeV. The commissioning was prepared and accompanied by an extensive series of beam simulations which turned out to be the key for speeding up the time needed to optimise the beam transmission and beam quality at the various energies. On average each commissioning stage took about 3 weeks and never more than few days to get the beam through the new segment of the linac. A very well detailed and validated machine model allowed to use diagnostics in an unconventional way by combining information from the diagnostics tools and information from the beam simulations. An example is the setting up of the RF phase of the first DTL tanks based on transmission measurements [25]. Our experience showed that modelling the low energy electric and magnetic elements via a field map was necessary to have a good correspondence with the measured beam qualities, whereas above 3 MeV a lumped-element description was sufficient. The key decision was to start the simulation with a particle distribution obtained by measuring the beam in the LEBT under different focusing and back-tracing to the start of the line. Obtaining this representative cloud of macro-particles implied a thorough measurement campaign at the source test stand for as long as 6 months [28,29] . In the following two representative measurements for the transverse (Fig. 6) and longitudinal planes (Fig. 7) are shown, together with the record beam performance at each energy stage (Table 1). Please note that the record peak current measurement were not taken during the same measurements campaign.

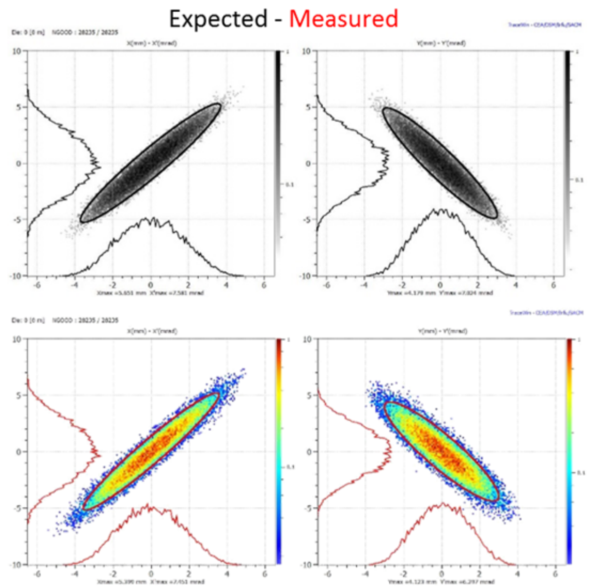

Figure 6: Expected (top) and measured (bottom) transverse emittance at 50MeV

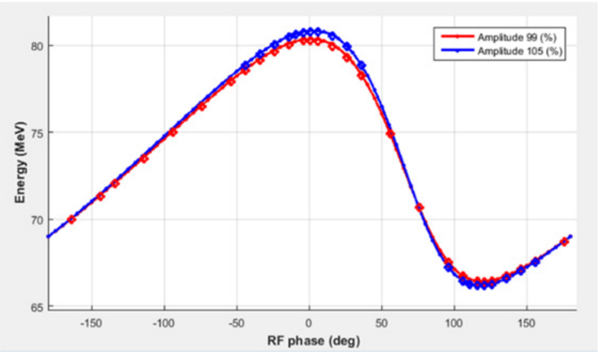

Figure 7: Energy measurement vs phase of the module 4 of the CCDTL for two different field levels

Table 1: Energy and Beam Intensity Milestones

Energy	Date	Record peak current	Date
0.045 MeV	2013	50 mA	Nov 15
3 MeV	Mar 13	30 mA	Oct 15
12 MeV	Aug 14	20 mA	Nov 15
50 MeV	Nov 15	20 mA	Nov 15
105 MeV	June 16	20 mA	June 16
160 MeV	Oct 16	18 mA	Oct 16

The 160 MeV beam has been used since October 2016 to feed a test set-up of the PSB injection chicane, the Half Sector Test [30, 31, 32]. The purpose of this test was to gain information about the stripping mechanism, the H^0 diagnostics and to facilitate the commissioning after the LS2 when many modifications and intervention in the framework of the LIU program are foreseen [33].

POTENTIAL AND OUTLOOK

Linac4 will be connected to the PSB during the LHC LS2 and will deliver initially 3 10^{12} proton per ring. Higher intensity beams can be obtained with longer injection time but their final emittance is still to be evaluated. In parallel a program for the upgrade of the emittance/current of the present source will be deployed over the next 3-4 years. Linac4 is designed to accelerate up to 40 mA average current after chopping, i.e. a source peak current of up to 80 mA. Linac4 has built in a flexibility for what concerns beam intensity, beam longitudinal matching both in terms of chopping and energy painting as well as several possibilities of varying dispersion and matching parameters at injection into the PSB.

The Linac4 has, so far, been working in commissioning mode. From June 2017 it will undergo a reliability run tentatively structured in two stages: a first stage to access the reliability of the individual system by running the beam continuously on the dump in stable and fixed mode, followed by a mock-up of operation with beam production of different beams in terms of intensity emittance and chopping pattern.

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