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LINAC4 COMMISSIONING

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Abstract

This paper 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.

MOTIVATION AND BEAM QUALITY REQUIREMENTS

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 included construction of a 160 MeV H^- linear accelerator called Linac4, and the study of a 5 GeV, high beam power, superconducting proton Linac (SPL).

Since 2011 Linac4 became integrated in the framework of the LHC Injector Upgrade program [1] which includes modification to all CERN's LHC injectors to allow increasing of the beam brightness delivered to LHC and opens the way to the parameters needed for the High Luminosity LHC [2].

During the LHC Long Shutdown 2 (LS2) the Linac4 will be physically connected to the CERN PS Booster (PSB) and will inject via charge-stripping up to 1.3 10^{13} protons per ring at 160 MeV (e.g. an average current of 25 mA along the pulse before chopping, injection over 150 turns of 150 µs). The beam injected into each ring can be tailored to durations from 1 to 150 µsec, and its energy can be dynamically varied by ±0.8 MeV over 40 µs and the rms energy spread varied from 85 to 450 keV rms. The 352 MHz microstructure can be modified by a dedicated beam chopper that can impose patterns between 10 ns and 0.7 µs at the frequency of 1-20 MHz to match the shape of the bucket in the PSB and to further optimise the effect of the longitudinal painting [3]. This flexibility is meant to cover all possible beams needed from the PSB and will require a substantial commissioning and tuning period for the optimum working point once the Linac4 beam is injected into the PSB after LS2.

The Linac4 beam attained the final energy of 160 MeV in October 2016 with a peak current of 18 mA, i.e 70% of the minimum current for the high intensity users. Since then a series of dedicated beam runs lasting typically around three months have been scheduled to further access and optimise the beam quality, to test the injection and stripping mechanism and to access the beam availability and reliability. Before the connection to the PSB, two other beam runs are planned between September and December 2018 and between July and September 2019.

LAYOUT

Linac4 is a normal conducting linear accelerator operating at the frequency of 352 MHz. The first element of Linac4 is a RF ion 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. It contains 16 electromagnets to transport the beam and match the dispersion, two bending magnets and a distributor to send the beam in the 4 superimposed PSB rings.

A sketch of Linac4 is shown in Fig.1.

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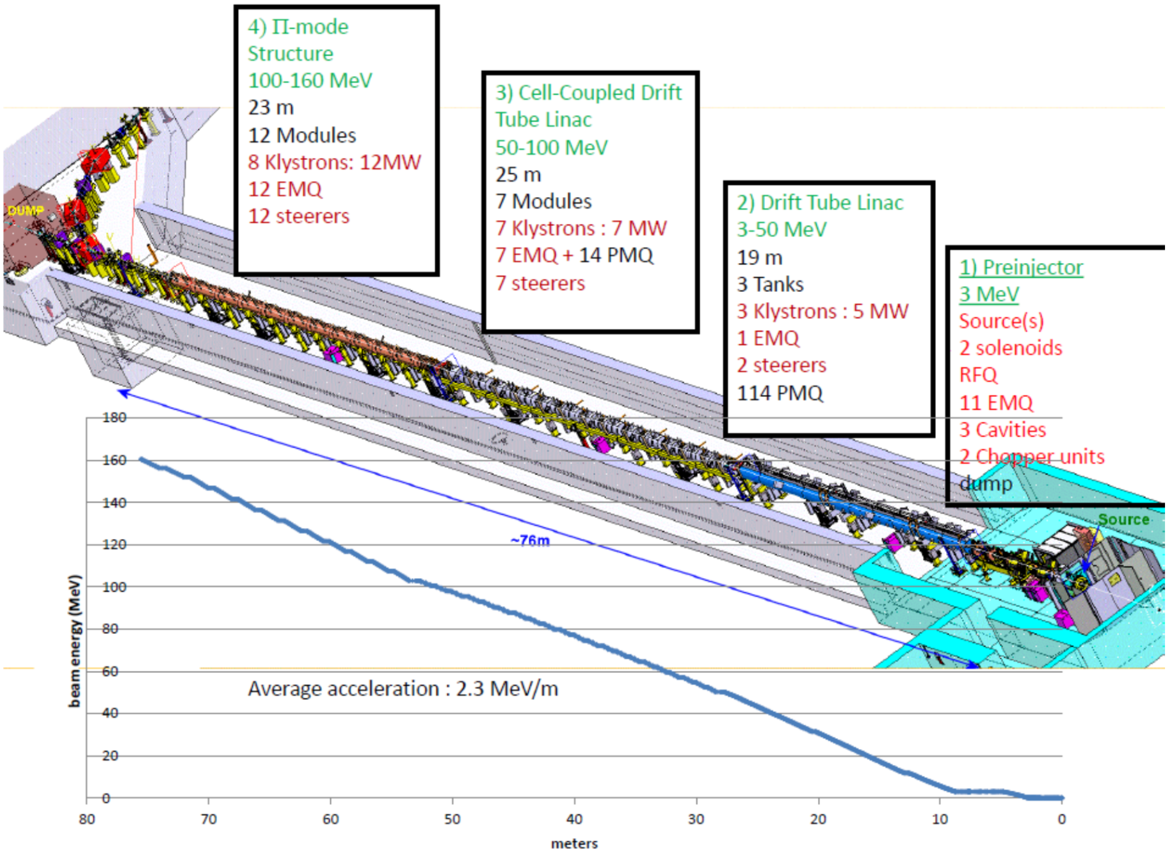

Figure 1: Sketch of Linac4.

All the elements to close the line to the PSB are presently either installed or in-house. The beam can be currently switched between the main dump and a temporary dump in the transfer line. This configuration allows testing of different users on two destinations and especially it allows installing equipment to be tested in one of the parasitic branches. Parasitic test of diagnostics for high intensity linacs but as well for medical application have been performed during beam runs in the line branching off before the main dump that can be seen in Fig. 2. Currently the beam can be disposed of on the main dump or on the temporary dump.

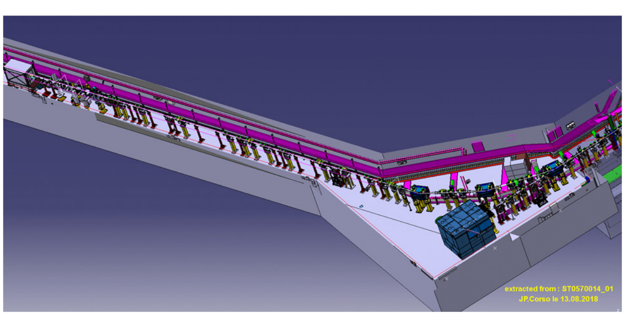

Figure 2: Presently installed hardware in the 160 MeV area. The permanent dump is indicated in blue colour.

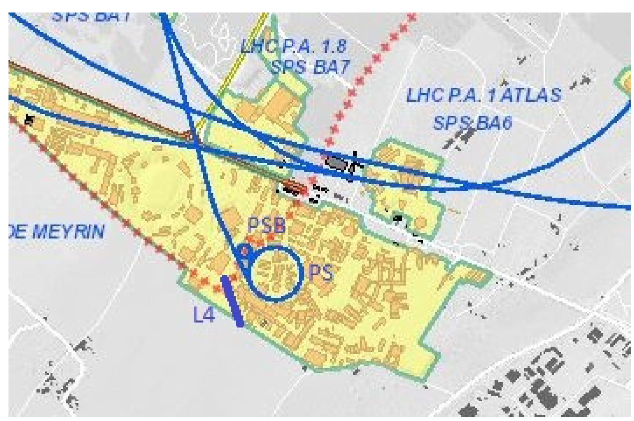

Figure 3: Location of Linac4 on the CERN site.

Figure 3 shows the location of Linac4 on the CERN site. Linac4 lays 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.

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BEAM QUALITY REQUIREMENTS

The injection into the PSB will be heavily changed from protons at 50 MeV to H- at 160MeV, nevertheless the variety and intensity of the beams that the PSB will have to produce will be the same. Linac4 is equipped with a fast chopper, energy ramping and the possibility of intensity variation pulse to pulse. This unprecedented flexibility should be used to the maximum advantage to produce high quality beam with an intrinsically lower current from the source. In this paper, we focus on two typical extreme beams that the PSB routinely produces: the LHC beam that requires 0.34 10^{13} protons per ring in an rms emittance of 1.7µm and the ISOLDE beam, the most demanding in terms of beam intensity which requires 0.9 10^{13} protons per ring in an emittance of 10 µm [4]. It has been recently simulated that such beams are possible with an intensity after the RFQ of 25 mA peak current so this is the value that was targeted during the 2018 beam quality run. The LHC beam will be obtained by injecting 45 turns (=45 µs) in each of the four PSB rings and the ISOLDE beam by injecting 110 turns in each ring The beam quality required at the injection into the PSB is summarised in Table 1.

Table 1 : Target Beam Quality at the PSB Injection

Parameter	Target value
Intensity flatness along the pulse for pulse lengths < 180 µs	±2%
Intensity flatness along the pulse for pulse lengths >180 µs	±5%
Horizontal/vertical position variations along the pulse	±1 mm
Horizontal/vertical injection angle error along the pulse	±0.4 mrad
Current stability shot-by-shot	±2%
transverse emittances rms norm	<0.4 mm mrad
Beam energy	160MeV
Pulse to pulse energy spread	80-600keV
Nominal chopper operation	65% at 1MHz
Energy painting	±0.8 MeV

Most of the parameters have been achieved during the 2018 run. The flatness along the pulse as well as the stability depends mainly from the source settings and the proper regulation of the Low Level RF that is still in progress. In particular the time it takes to attain a stable neutralisation in the low-energy magnetic beam transport at 45keV makes the first 200-300µsec of the pulse severely out of the stability requirements. Whereas future studies will address the effect of gas injection and the perturbation due to the electrical field of the pre-chopper, a practical approach has been adopted which consists in generating a beam about 50% longer than needed and chop off the unwanted part after the RFQ by means of the chopper. A plot of a typical beam at the source and after the chopper is shown in Figure 4.

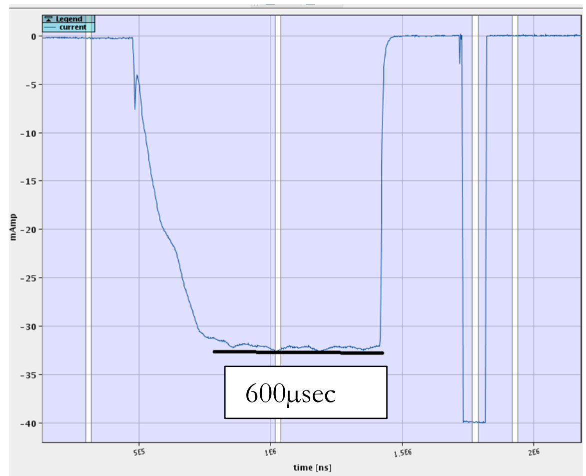

Figure 4: Beam current signal at 45 keV after the source.

The first 350 µs of the pulse the beam is still undergoing time-varying neutralisation effects that result in poor transmission through the RFQ. After 350 µs the beam current (and the beam emittance) is stable. The first 350 µs will be disposed of by the chopper on the inline dump and only the part corresponding to the black line will be transmitted to the PSB.

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 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. 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 [5]. The global beam quality in terms of energy, energy spread, emittance and transmission have been extensively documented in [6] [7] [8]. In the following a representative measurement for the transverse plane (Fig. 5) is shown, to-gether with the record beam performance at each energy stage (Table 2). Please note that the record peak current measurement were not taken during the same measure-ments campaign.

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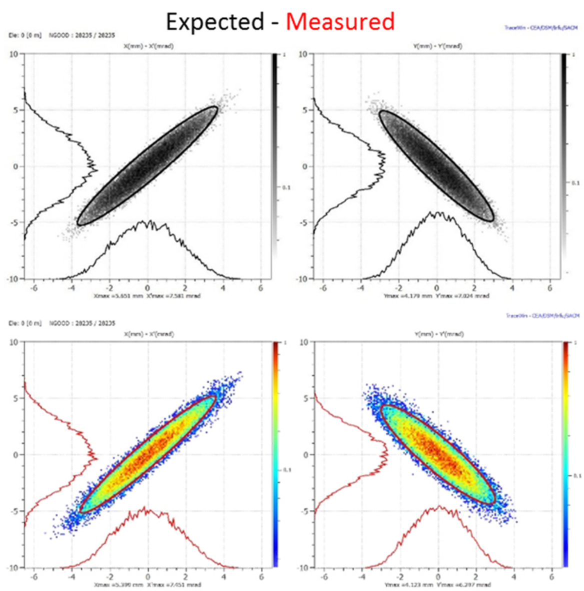

Figure 5: Expected (top) and measured (bottom) transverse emittance at 50MeV

Table 2: Energy and Beam Intensity Milestones

Energy (MeV)	Date	Record peak current (mA)	Emitt rms norm (mmmrad)
0.045	2013	50 mA (Nov15)	0.6
3	Mar 13	30 mA (Oct15)	0.35
12	Aug 14	23 mA (Oct17)	0.3
50	Nov 15	23 mA (Oct17)	0.3
105	June 16	23 mA (Oct17)	0.3
160	Oct 16	23 mA (Oct17)	0.3

BEAM AVAILABILITY

The availability of the beam from Linac is a key parameter in the success of the physics program of CERN, in fact the non-availability of the injectors is the most common cause of down time for the LHC [9]. A demonstrated availability of more than 90% is necessary before connection with the understanding that the more an accelerator is in service the more the availability increases. For example Linac2, that will be serving the PSB until the end of 2018, has in the last year reached an availability of 99%, after 40 years of operation. For Linac4 we have had a first reliability run, from September 2017 to May 2018 articulated in three parts with two technical stops of 3 and 15 weeks respectively for upgrades and repairs. An important effort was made to integrate Linac4 in the CERN Accelerator Fault Tracking system, which keeps tracks of the availability of all accelerators. The results of the availability studies are shown in Figure 6. The average availability over 23 weeks of operation turned out to be 91.5% with main cause of down time the Radio Frequency system followed by the power converters , as expected in the risk analysis reported in [10].

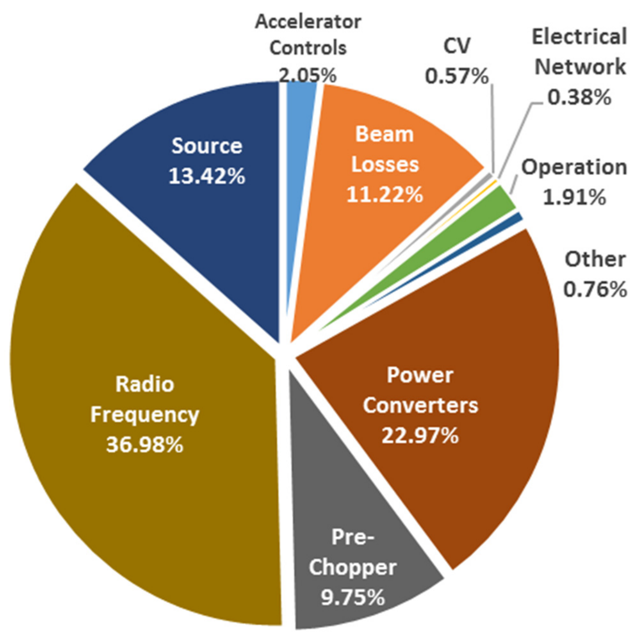

Figure 6: Causes of downtime for the Linac4 during the run 2017-2018. The statistics are taken over 23 weeks of continuous operation.

POTENTIAL AND OUTLOOK

Linac4 will be connected to the PSB during the LS2 and will deliver initially up to 1.25 10^{13} proton per ring. In parallel a program for the upgrade of the emittance/current of the present source will be deployed over the next 3-4 years with the aim of achieving a peak current of 45mA, a value which will allow doubling the intensity of the non-LHC high intensity users (ISOLDE).

ACKNOWLEDGEMENT

Linac4 has been designed, constructed and commissioned thanks to the hard work and the dedication of many people, both at CERN and in collaborating institutes.

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