LINAC4: PROGRESS ON HARDWARE AND BEAM COMMISSIONING

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Abstract

Linac4 has been commissioned, with a temporary source, up to an energy of 12 MeV. The dynamics in the LEBT, in the RFQ and in the chopper line have been verified, as well as the acceleration to 12 MeV with the first DTL tank. Future plans foresee stages of commissioning at the energy of 50, 100 and finally 160 MeV interlaced with periods of installation and followed by a year-long reliability run. In this talk we will present the status of the Linac4 beam commissioning, the status of readiness of the remaining accelerating structures as well as the path to the final source. The possibility of delivering to the PSB a 50 MeV proton beam from Linac4 will be discussed together with its impact on the overall schedule and the achievable beam characteristics

INTRODUCTION

Linac4 will replace the present 50 MeV proton Linac2 as injector of the CERN PS Booster, as a first step of the LHC Injector Upgrade project. A sketch of Linac4 is shown in Fig. 1 and a detailed description of the layout and beam dynamics can be found in [1,2]

The pre-injector includes a source followed by a Low Energy Beam Transport at 45 keV, a Radio Frequency Quadrupole which accelerates the beam to 3MeV and a Medium Energy Beam Transport line (MEBT). The MEBT, 3.6 m in length, houses a fast chopper with the purpose of removing selected micro-bunches in the 352 MHz sequence and therefore avoid losses at capture in the CERN PSB (1MHz). Presently the preferred scheme envisages to chop out 133 bunches over 352 with a resulting average current reduced by 40%. The beam is then further accelerated to 50 MeV by a conventional Drift Tube Linac (DTL) equipped with Permanent Magnet Quadrupoles (PMQ), to 100 MeV by a Cell-Coupled Drift Tube Linac and to 160 MeV by a Pi-mode structure. The focusing after 100 MeV is provided by Electromagntic Quadrupoles (EMQ) whereas between 50 and 100 MeV by a combination of PMQs and EMQs.

Note that the chapter on measurements has been published in the proceedings of LINAC14.

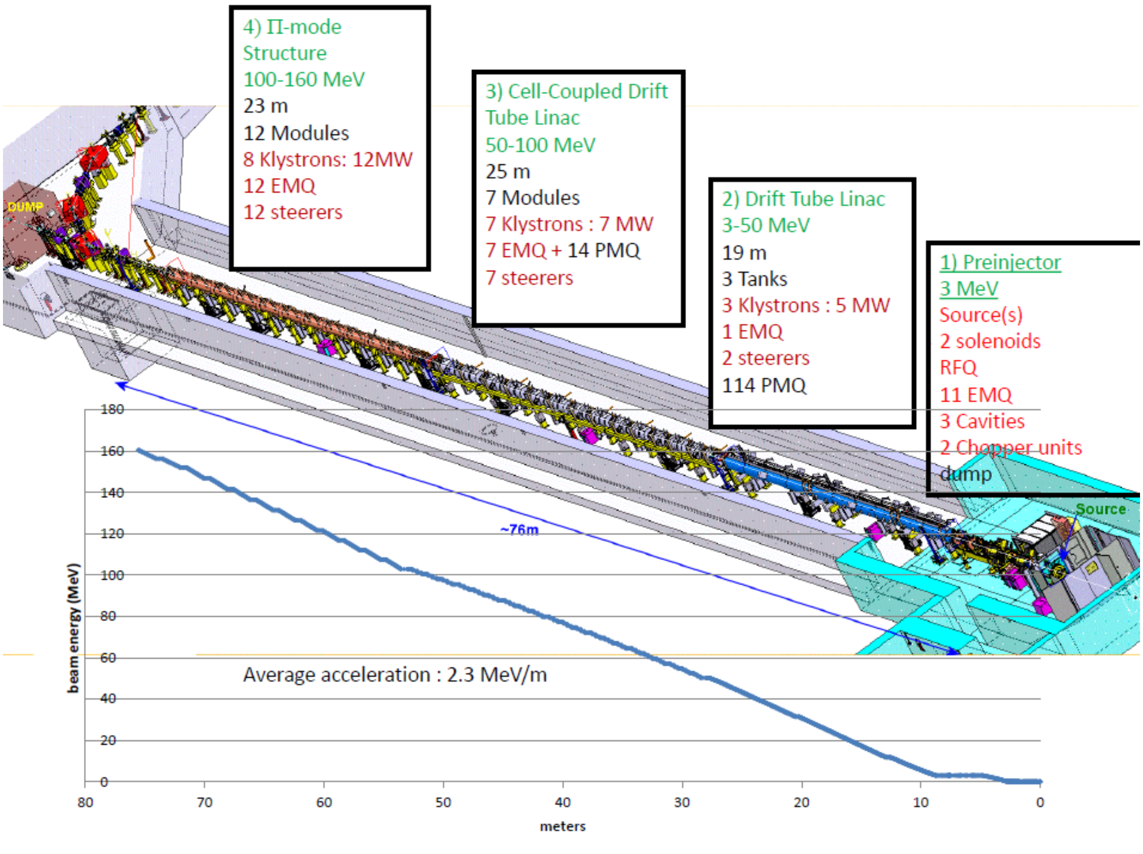

Figure 1: Sketch of Linac4.

COMMISSIONING STAGES

Linac4 is being commissioned with the aim of reaching the final energy in 2015. The commissioning is staged both for simplifying the task as well as for matching the production schedule of the different accelerating structures. The so-called pre-injector, including the source, the Low Energy Beam Transport, the Radio Frequency Quadrupole and the Medium Energy Beam Transport Line has been commissioned in a dedicated test stand before being installed in the final location with the final power supplies and control system. Since October 2013 the commissioning takes place in the final location, the underground tunnel, where periods of beam commissioning are interlaced with period of installation. Six commissioning stages are planned, at the energies of 45 keV, 3 MeV, 12 MeV, 50 MeV, 100 MeV and finally 160 MeV. After the final energy is reached, Linac4 will be run for about 12 months to assess its reliability and to improve it if necessary. At the time of writing, the 12 MeV stage has been started, although with a temporary version of the ion source. 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 and will be measured, with some extra specific measurements which will be detailed in the following.

MEASUREMENTS

Some of the measurements that follow have been taken at a dedicated test stand during the period January 2012-June 2013[3], others in the final location in the tunnel starting October 2013. Unless necessary, the location and time of the measurements are not indicated and the chronological order is not respected.

Measurements at 45 keV

The 45 keV stage comprises a temporary source giving about 20 mA of H^-, two solenoids for matching to the RFQ and a pre-chopper located in between the solenoids. A profile harp and a beam transformer are located between the two solenoids as well. A gas injection system, capable of injecting different gases (hydrogen and nitrogen) and controlling the pressure to 10^{-6} mbar, is used to influence beam neutralisation during transport to the RFQ with the intention of enhancing beam quality. Temporary diagnostics including a slit-and-grid emittance metre and a spectrometer have been installed at different locations along this 2 m long line. Measurements of emittance have been taken under different source regimes, different gas pressures and for different solenoid's settings. The aim of these measurements is to gain an understanding of the dynamics in the LEBT, to correlate the phase space portraits at the RFQ input plane with the solenoid settings and to reconstruct a representative beam distribution to be able to predict with sufficient accuracy the behaviour of the beam further down the accelerator.

The first measurements were done after the first solenoid with the set-up shown in Fig. 2.

Figure 2: Set-up for emittance measurements at 45 keV.

Emittance measurements were taken for different solenoid settings in both transverse planes at a fixed source configuration. A series of 5 measurements, for increasing solenoid field is shown in Fig. 3. For simulations, a beam is created from the measured transverse phase spaces, and populated with a cloud of 500k macro-particles using a dedicated module built into the PATH code [4] and interfaced with the measurement system. The two transverse planes are assumed to be uncorrelated as information on the cross-correlation cannot be gained with a slit and grid system. The cloud of particles mimicking the measured data has been back-traced to the source output. The beam distribution obtained for the five cases of Fig. 3 is shown in Fig. 4. We can notice that the phase space tracked back to the source is consistent for the five cases and most importantly is consistent with what is expected out of the source from IBSimu simulations (a strongly divergent beam with a radius of 25 mm) [5]. After this stage we have an input distribution that very well represents the distribution that comes out of the source. Matching to the next stage of acceleration has been done starting from this input distribution and using statistical computer optimisation techniques to find the solenoid settings that optimise transmission and beam quality into the RFQ acceptance. These settings were confirmed by a series of emittance measurements at the location of the RFQ input plane.

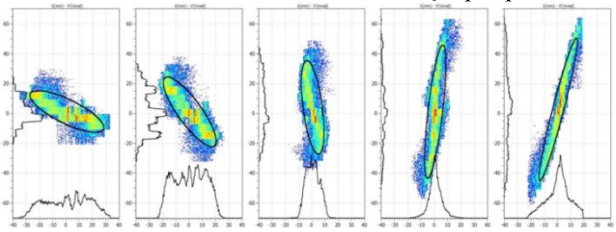

Figure 3: Transverse phase space profile for increasing solenoid field, units of mm and mrad.

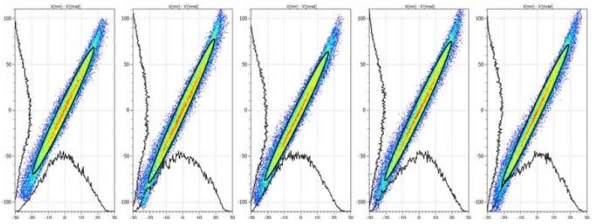

Figure 4: Transverse phase space profile of Fig.3 back-traced at the source output, units of mm and mrad.

At the end of this stage a 16 mA H$^-$ beam was matched to the RFQ acceptance. As the source is not yet the final one, the emittance of the beam exceeds the acceptance of the RFQ and a transmission of about 75% is expected, instead of the nominal 90%.

Measurements at 3 MeV

A beam was very swiftly accelerated to 3 MeV after connecting the RFQ to the LEBT and setting the solenoids to the values predicted by PATH [4]. The maximum expected transmission of 75% was obtained within hours. The correct functioning and the calibration of the RFQ were further confirmed by measuring the transmission of accelerated particles through the RFQ when varying the RF power and comparing it to the expectations from PARMTEQ [6] and TOUTATIS [7]. The results are shown on Fig. 6. A very good agreement is obtained thus validating the RFQ mechanical and conceptual design, the RF calibration and the simulation accuracy. This measurement was repeated after the RFQ was moved into the final location in the tunnel to confirm that no damage had occurred during the transport.

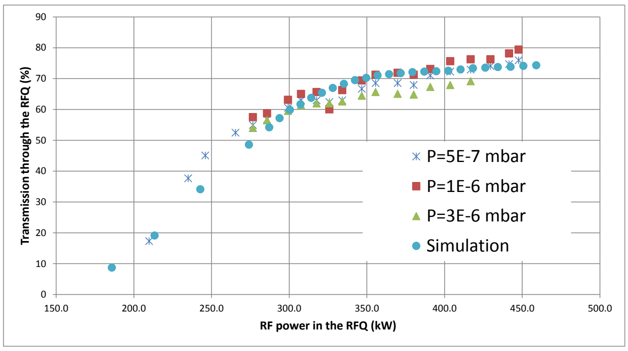

Figure 6: Transmission vs. RF power in the RFQ for different LEBT pressure. The nominal RFQ power is 400kW. Simulations in light blue dots.

After confirming the performance of the RFQ, the 3 MeV beam was passed through the MEBT line and analysed in the temporary diagnostics line. The MEBT line is composed of eleven EMQs, three buncher cavities and an electro-static chopper system integrated in the quadrupoles. Diagnostics including two wire scanners and two beam transformers are located permanently in the line whereas a diagnostics bench comprising a slit-and-grid emittance meter, a spectrometer, a laser and diamond detector, a Bunch Shape Monitor (BSM) and a halo monitor was fitted temporarily at the end of the line. There are multiple issues to address in the MEBT line: first and foremost the correct functioning of the chopping system [8]. The chopping system is composed of 4 plates with a meander line which are meant to selectively kick unwanted micro-bunches so that they are fully separated in phase space at the end of the 800 mm long plates. Subsequently the beam enters a system of three quadrupoles (and a buncher) set such that the separation in phase space is transformed into a separation in real space and the unwanted bunches can be safely disposed of on an in-line dump (a section of a cone that limits the beam aperture over 20 cm). This choice has allowed limiting the voltage needed on the chopper plates and keeping the system as compact as possible but it has the drawback that the dynamics of the through-beam is strongly coupled to the dynamics of the chopped beam, as the same three quadrupoles have to guarantee maximum transmission through the cone for the main beam and maximum extinction factor for the chopped beam. Measurements of the chopping efficiency were a high priority for Linac4. The results are reported in the following.

First the current in a beam transformer downstream the inline dump (BCT04040) has been measured as a function of the quadrupole (L4L.QFC03130) settings between the chopper and the dump. Results are shown in Fig. 7. The top curve shows the transmission of the main beam, the bottom curve the transmission of the chopped beam. It was confirmed that it is possible to maximise the transmission of the main beam and extinguish the chopped beam simultaneously.

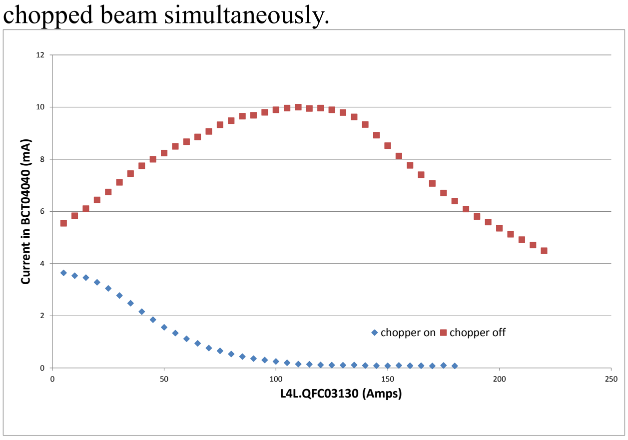

Figure 7: Measured Current in BCT04040 (mA) vs L4L.QFC03130

The two, fully separated beams are also visible at the time-resolved wire scanner located in the vicinity of the dump, see Fig. 8. It was also confirmed that emittance of the main beam didn't change either in orientation or in size when the chopper was turned on.

The transverse emittance of the main beam was measured with three different methods: a traditional slit-and-grid emittance meter, a newly designed laser-plus-diamond detector [9] and an indirect method based on reconstructing the emittance from several profile measurements at varying quadrupole settings[10]. The main purpose of this campaign was to cross-check the indirect method against a direct one as for the higher-energy stages a direct method is not foreseen.

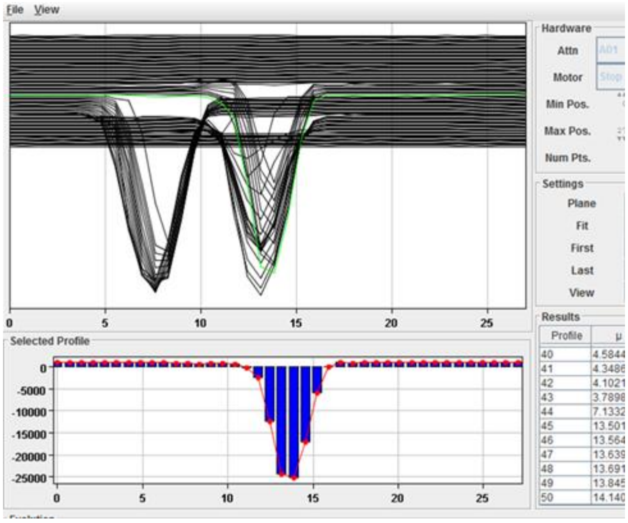

Figure 8: Beam transverse profile on the wire scanner before the in-line dump. Top : A profile (solid black line) is taken every 6 µs. Bottom : Profile of a slice of the main beam . Horizontal scale in mm, vertical a.u.

The values of the emittance obtained with the 3 methods are consistent as all measurements considered are within 10% of each other (see Table 1). The alpha and beta parameters of the measurements differ because they have been taken at different locations of the line, but when tracked to the same location they are consistent as well. The most difficult part in this analysis was to choose the appropriate threshold for each case. Finally the best approach turned out to be choosing the minimum threshold on the raw data, which is not necessarily the same threshold for the three different measurement methods. More details can be found in [10].

Table 1: Transverse emittance

Method	Ex norm rms	Ey norm rms	Threshold
Slit-grid	0.27	0.24	1%
Laser-diamond	0.27	0.27	0.1%
From profiles	0.31	0.34	0.5%

The diagnostics bench is equipped with a Bunch Shape Monitor BSM [11], a device capable of measuring the phase extent of the micro bunch, by analysing the time of arrival of electrons emitted by a wire positioned in the beam. The BSM is located 4.9m from the RFQ and 4.4m, 2.9m and 1.6m from the three buncher cavities respectively. We have used the BSM to measure the beam phase extent for different amplitudes and phases of the second buncher. Starting from those measurements we have been able to reconstruct the **longitudinal beam emittance**, compare it with our expectation from the RFQ simulations and compare the energy spread with the direct measurements at the spectrometer [12]. The results are summarised in Table 2.

Table 2: Longitudinal emittance

Method	ε_{rms} deg MeV	ΔW MeV
simulations	0.19	0.022
From BSM phase profiles	0.16	0.021
spectrometer	-	0.019

Measurements at 12 MeV

Before moving the temporary bench, the MEBT settings for matching the beam to tank1 of the DTL were found. The transverse phase spaces are compared to the matched beam in Fig. 9. The longitudinal matching and the corresponding buncher settings have been found with the help of the BSM and the spectrometer. The expected transmission through the DTL with the measured beam is 95%.

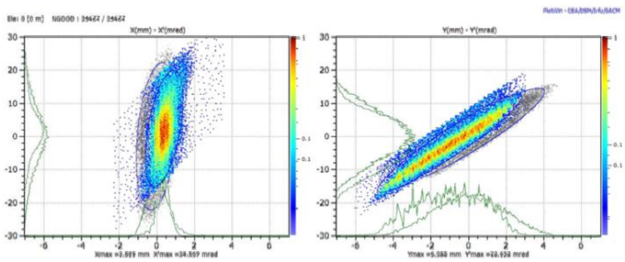

Figure 9: Measured transverse beam phase space (colour) compared to the nominal matched beam (grayscale) at the input to the DTL.

The commissioning of the first DTL tank started with the RF buncher cavities between the RFQ and DTL switched off, with the purpose of sending into the DTL a quasi-continuous beam and sampling the empirical longitudinal acceptance, which is a key to finding the correct longitudinal matching. Preliminary measurements are shown in Fig. 10.

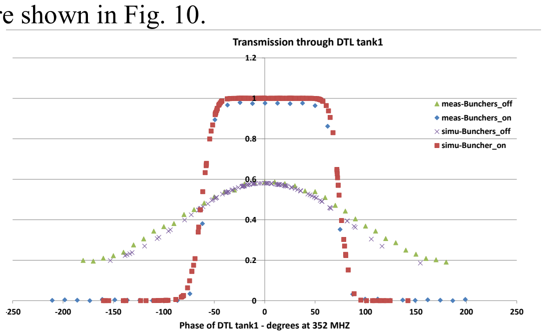

Figure 10: Transmission through the DTL tank1 vs. DTL phase for bunchers off and bunchers on.

THE SOURCE

Linac4 has been commissioned up to the energy of 12 MeV with a temporary source which gives a current of about 15 mA in an emittance that exceeds the RFQ acceptance. In this paragraph we discuss the beam quality needed from the source and the path to the final source.

The source current and emittance were (over-) specified in the Technical Design Report [13]. The requirements on the source at the time were an H- current of 80 mA in an emittance of 0.25 π µm rms norm at RFQ input; at an energy of 45keV (±2keV) and a pulse duration of 400 µsec (100 turns injection into each of the PSB rings). This specification came from the high intensity beam in the PSB, and the aim was to double the intensity for ISOLDE with a 50% extra margin.

The requirement on the source exceeds by far what is obtained in other laboratories and especially what can be safely operated in stable conditions. During the 5 years of R&D at CERN it was found that 80 mA of H- in the acceptance of the RFQ are not an easy target for a conventional non-cesiated source. A source review took place at CERN in 2011 and the reviewer recommended orienting the R&D towards a cesiated source of the type used at the SNS [14] which could reach a stable current in the 50mA range. If higher current was still needed a solution employing a magnetron type source should be explored at a second stage.

Since then the baseline source for Linac4 is a cesiated surface-production RF-source from which we expect a maximum current of up to 50 mA. With such a current there is the added advantage that the space charge is not extreme and the beam can be manipulated more easily in the accelerator and will end up with better beam quality at the PSB injection. Such current will require a minimum of 25 turns injected in the PSB to make $3*10^{12}$ protons per bunch in a 650 nsec bunch as specified in the LIU summary document [15]. With a current of 50 mA from the source an ISOLDE-type beam ($1.3*10^{13}$ ppb) can be obtained by injecting 100 turns in the PSB. Simulations of PSB injection are underway to evaluate the resulting emittance in the PSB.

PROTONS AT 50 MeV FROM LINAC4

The possibility of producing protons at 50 MeV from Linac4 has already been discussed [16]. The hardware necessary includes, besides a complete Drift Tube Linac, CCDTL module number 4. This is needed to adjust the energy spread to the PSB longitudinal. Besides all the quadrupoles of the line, together with the corresponding vacuum pipes need to be operational. It is estimated that from August 2015 all the necessary equipment for a connection will be in place. The switching magnet to be placed at the location of BHZ20 has been documented in [17].

The 50 MeV beam can be produced also after the commissioning to 160 MeV (by detuning all the structures between 50 MeV and 160 MeV), as the beam can pass through these structures without losses.

CONCLUSIONS

Linac4 has been commissioned with a temporary source up to the energy of 12 MeV. Measurements of transmission, emittance and profiles have been taken at several locations along the accelerator with the help of a movable diagnostics bench. The results of the measurements have been compared with the expectation from simulations and a sound model of the beam dynamics in the machine has been obtained.

A new source has been installed and we expect a peak current of 40 mA in the RFQ acceptance.

A 50 MeV proton beam from Linac4 could be available from August 2015.

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