EXPERIENCE WITH THE CONSTRUCTION AND COMMISSIONING OF LINAC4

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Abstract

In the framework of the LHC Injector Upgrade program, CERN is presently commissioning Linac4, a 160MeV H- ion linac, which will replace the present 50 MeV proton linac (Linac2) as injector to the PS Booster during the next LHC long shut-down. The installation of the machine has proceeded in parallel with a staged beam commissioning at the energies of 3, 12, 50, 100 and finally 160 MeV, foreseen for fall 2016. A seven month long reliability run will take place during 2017 to assess potential weak points and find mitigations. The lessons learnt during its construction, the main outcomes of the beam commissioning and the remaining steps toward its connection to the PS Booster are presented in this paper.

THE LINAC4 PROJECT

The Linac4 project started in 2008 with the goal of building a new 160 MeV H^- ion linear accelerator to replace the present 50 MeV Linac2 as injector of the CERN PS Booster (PSB). The main motivations were to increase the beam brilliance in the PSB and in all the LHC injector chain to fulfil the requirements of the High-Luminosity LHC upgrade program [1]. Moreover, the new charge exchange injection into the PSB (H^- ions instead of protons from the Linac2) would reduce the beam losses at injection and increase the operational flexibility.

Linac4 is a pulsed, normal-conducting 80 m long linac. A sketch of the Linac is shown in Fig. 1. It is composed of a 3 MeV pre-injector comprising a 45 keV ion source, a Low Energy Beam Transport (LEBT), a 4 vane Radio Frequency Quadrupole (RFQ) resonating at 352 MHz and a 3.6 m long Medium Energy Beam Transport (MEBT) housing a fast beam chopper. The chopper modifies the beam pulse structure, by removing some selected mircrobunches at 352 MHz with the purpose of considerably reducing the losses during the beam capture at 1 MHz in the PSB. The linac front-end is followed by a conventional 50 MeV Drift Tube Linac (DTL) with a permanent magnet quadrupole focusing channel, a 102 MeV Cell-Coupled DTL (CCDTL) and a 160 MeV π-mode structure (PIMS) [2]. The main Linac4 parameters are given in Table 1.

Figure 1: Linac4 sketch.

The beam commissioning was staged in 6 main steps of increasing energy. At the time of writing, the last step, the commissioning of the PIMS, is about to start. It will be completed by the end of 2016 and will be followed by a 7 month run to improve machine performances and assess reliability. The connection to the PSB will take place during the next LHC Long Shut down (LS2) starting from January 2018. It will then become the sole injector for the CERN proton accelerator complex.

Table 1: Linac4 Design Parameters

Ion Species	H^-	
Length	80	m
Output Energy	160	MeV
Frequency	352.2	MHz
Repetition rate	1.1 (max. 2)	Hz
Pulse length	400 (max. 1200)	μs
Linac pulse current (max.)	40	mA
Chopping factor	62	%
RMS Trans. Emittance	0.4	mm.mrad

LINAC4 BUILDING BLOCKS

Source

The Linac4 caesiated surface ion source driven by an external RF antenna solenoid has reached a stable and reliable performance adequate to the needs of the LHC but is still undergoing developments to improve the current for the requirements of future high-intensity beams in the PSB. Many different prototypes were tested and operated in the past years with constantly increasing performances [3]. It is operated in a pulsed mode at 1.2 s interval, keeping the beam output as stable and reliable as possible. It can today reliably deliver a 50 mA beam out of which 35 mA are within the RFQ acceptance. Optimisation, systematic measurements and prototypes testing are presently on-going on a dedicated test stand, made of a LEBT and an emittance meter (slit and grid). During the last years a very useful tool has been deployed on the source. This system regulates the source parameters (e.g. the gas injection and the RF power) while monitoring some given observables like the electron/H^- ratio with the aim of delivering a constant flat pulse of current of the desired intensity and duration. It will also be used to perform the monthly cesiation needed for the correct functioning of the source.

RFQ

The Linac4 RFQ was designed and manufactured at CERN [4]. Its RF design and tuning has been made in collaboration with CEA Saclay. Consisting of a 3 m long structure made of three brazed sections, it accelerated a first proton beam at 3 MeV in March 2013 after only two weeks of RF conditioning. After having been commissioned in a temporary location, the structure was moved in the Linac4 tunnel for a re-commissioning in situ that took place fall 2013[5]. Since then, it is working very reliably.

MEBT

The MEBT is a 3.6 m long line housing 11 electromagnetic quadrupoles (EMQ), three buncher cavities and a fast beam chopper. It aims to match the beam to the DTL and modify the time structure of the pulse in order to reduce the losses at the PSB injection. The fast chopper is based on an original "low-voltage" concept: the micro bunches that should not be injected in the PSB see a relatively low electric field, generated by two chopper plates. The resulting kick in the phase space is further transferred in the real space by a defocusing quadrupole located at 90° phase advance. The chopped bunches are then collected in a conical aperture beam dump. An extinguishing factor of 100% and a rise/fall time of less than 10 ns were achieved and demonstrated in 2014 [5].

DTL

The DTL [6] has been designed for reliable operation with up to 10% duty cycle; it is composed of rigid self-supporting steel tanks assembled from segments less than 2 m in length. The tank design is almost without welds, heat-treated after rough machining. The FFDD focusing channel (which has been shown to be less sensitive to alignment and gradient errors than FD), is made of Permanent Magnet Quadrupoles. These PMQs are in vacuum for streamlined drift tube assembly. In order to make the design more robust and easier to assemble, the philosophy of the design is "adjust & assemble": i.e. based on tight-tolerance aluminium girders w/o adjustment mechanism once assembled. The tank mounting mechanism (easy to use) has been patented. A picture of the DTL tank 3 and its drift tube alignment girder is shown in Fig. 2. To guarantee reliability of operation, the first cells of tank 1 present an increased gap spacing to reduce the chance of breakdown which could be enhanced by the PMQ fields.

Figure 2: DTL tank3 drift tube alignment girder.

All the above choices have paid off, with a smooth conditioning and an excellent availability during the commissioning phase.

CCDTL

The CCDTL [7] has been constructed by the Russian Scientific Research Institute for Technical Physics (VNIITF) and the Budker Institute of Nuclear Physics (BINP). The quadrupoles, a combination of EMQs and PMQs, are located outside of the RF structure. The structures are made of copper plated stainless steel, and because of high number of C-shaped metal seals, the assembly process was rather time consuming. Each cavity needed around one month of RF conditioning to clean surfaces, after which the full gradient was established without problems. The Linac4 CCDTL is first-ever CCDTL in a working machine and it successfully accelerated the H^- ion beam to 102 MeV in July 2016.

PIMS

The last of the Linac4 RF structures, the PIMS [8], were constructed within a CERN-NCBJ-FZ Jülich collaboration Made out of bulk copper, the cells, consisting in discs and rings were machined and brazed at the Polish National Centre for Nuclear Research (NCBJ) and then tuned and electron beam welded at CERN. They do not contain RF seals. 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 conditioning of the prototype was extremely swift and took only 24 hours; similar conditioning times were required for the other 11 cavities. The PIMS will be the first low-beta π-mode structure to go into an operational machine. A first PIMS module (out of 12 in total) was commissioned with beam together with the CCDTL in summer 2016 and behaved as expected, accelerating the beam from 102 to 107 MeV. The beam commissioning through the 11 other PIMS modules is about the start.

A picture of the Linac4 machine inside the tunnel is shown in Fig. 3.

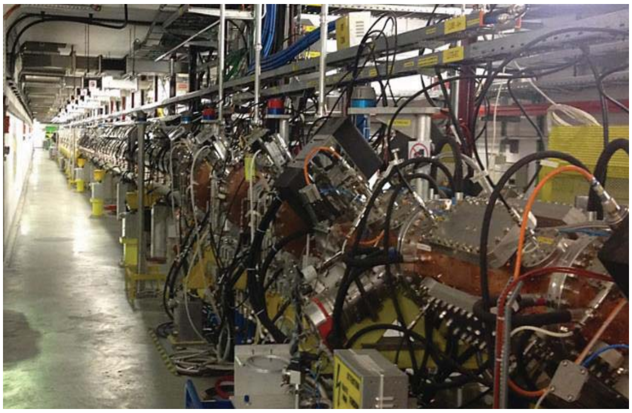

Figure 3: Linac4 seen from the low energy side (RFQ in the foreground).

TIMELINE AND STATUS

The Linac4 project was officially started in 2008. The building and tunnel were completed at the end of 2010 and the infrastructure including all piping and cabling was installed in 2012. The installation of accelerator equipment (klystrons, waveguides, modulators, power supplies and electronics) started in 2013 while the 3 MeV injector was commissioned in parallel in a temporary location. Initial commissioning of the original RF volume ion source showed problems related to the excess of electrons co-extracted with the H$^-$ ions and forced to develop a new source design intended to initially operate in volume mode and finally in surface mode after the addition of a Caesium injection. The new volume source was ready at beginning of 2013 as the RFQ, and after ion source beam measurements and RF conditioning of the RFQ a first 3 MeV proton beam was accelerated in March 2013. The commissioning of the MEBT followed before the 3 MeV front-end was transported to its final location in the Linac4 tunnel and recommissioned with beam in November 2013. The 3 MeV beam tests in the tunnel were completed in March 2014 and preparation for the installation of the other accelerating structures started. In parallel, the new caesiated ion source was commissioned in the test stand; an H$^-$ current up to 60 mA was obtained and a series of reliability tests at 40 mA showed an excellent stability and reproducibility of the ion beam. The first 12 MeV DTL tank was beam commissioned fall 2014. Some difficulties in getting the second and third tanks vacuum tight that were related to the poor quality of the vacuum seals have slightly postponed their commissioning. In order to limit the impact on the general planning, some effort was made to progress and speedup the production, installation and conditioning of the downstream structures during 2015 (CDDTL, PIMS and transfer-line component). The last two DTL tanks were finally commissioned at the end of 2015, with a new cesiated version of the ion source, directly followed by the commissioning of the seven CCDTL modules and of the first PIMS in spring 2016.

At the time of writing, all the accelerating structures are installed and under vacuum. The last PIMS cavities have been conditioned and the 160 MeV commissioning stage is about to start. The Linac4 transfer-line installation is completed, at the exception of a 15 m long section that was kept free for testing there a section of the future PSB charge-exchange injection system including the stripping foil system [9]. This test will take place after the 160 MeV commissioning and continue until February 2017, when the remaining part of the Linac4 to PSB transfer line including the debunching cavity will be installed.

Linac4 aims at a reaching an availability of 95%. In order to identify and solve initial problems and in general terms to assess the reliability of Linac4 prior to its connection to the CERN accelerator complex, a 7 months reliability run will take place in 2017, sending the beam to the main dump during extended periods under the control of the operators. The dates of the main Linac4 milestones are reported in Table 2.

Table 2: Linac4 Project Main Dates

Building completed	2010
Services ready	2013
Source	2011- on-going
3 MeV – @ test stand	04/2013
3 MeV – RFQ-MEBT	01/2014
12 MeV – DTL1	10/2014
50 MeV – DTL2-3	12/2015
107 MeV – CCDTL-PIMS1	07/2016
160 MeV - PIMS	Scheduled 11/2016
Connection to PSB	During LS2 - 2018

COMMISSIONING HIGHLIGHTS

The commissioning of Linac4 has been staged in 6 phases of increasing energy with the aim of matching the schedule of the RF cavities delivery and to be able to assess the beam parameters after each structure with the help of extra diagnostics located on a movable bench. This approach has allowed to progress in beam commissioning before complete installation of the hardware and to optimise the beam throughput at each stage. Most important it has also allowed comparing the information from the permanent diagnostics against more detailed information coming from the diagnostics installed on two dedicated test benches:

- A “low-energy” bench, used at 3 and 12 MeV which allowed direct measurement of the transverse emittance with a slit and grid (or laser and diamond detector) [10] and direct measurement of the energy spread with a 28 degrees bending magnet followed by a profile monitor.
- A “high-energy” bench used for the measurements at 50 and 100 MeV consisting in three profile monitors at the appropriate phase advance (about 60 degrees) for an indirect emittance measurement, a Bunch Shape Monitor [11] and two Beam Position Monitors (BPM) for Time of Flight and beam centre position. The low energy measurements (3 and 12 MeV) results were reported in [5] [12].

Indirect Measurement of the Emittances

At 50 and 100 MeV, both the transverse and longitudinal emittances were measured using indirect techniques developed in the framework of the Linac4 commissioning: the “forward-method” [13] that extends the accuracy of the classic emittance reconstruction techniques to space charge dominated regimes, and the tomographic method that allows phase space density information to be calculated from the profile [14]. The results obtained with these methods were compared, at 3 and 12 MeV, to the one obtained with direct measurements and gave the same orientation of the emittance within a range of 10%. The transverse emittance measured on the high energy test bench is deduced from 3 (or more) profile measurements. Two or three quadrupoles located upstream the 3 monitors were set in order to get the optimal phase advance from monitor to monitor (around 60 degrees). Typical transverse measurements are shown in Fig. 4. The transverse emittances measured at 100 MeV compared to expectation are shown in Fig. 5. The agreement between the measured emittances and our expectation is generally very good. This is due to several factors including an accurate model of the machine, a fruitful exchange of essential information with each of the equipment responsible, a direct participation of RF and Beam Instrumentation experts to the commissioning and most important of all a thorough description of the input beam at the low energy end. The beam 4D distribution after the source has been determined by back tracing to the source a number of measurements taken under different condition at the end of the LEBT therefore creating a beam representative of what is generated from the source, not only in term of distribution but also in terms of source variability.

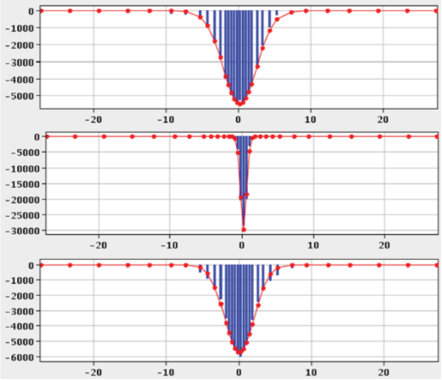

Figure 4: Typical transverse profiles (units of mm) obtained on the 3 profile monitors located on the high-energy measurement bench. The beam is focused on the centre monitor and the phase advance from monitor to monitor is adjusted close to 60 degrees.

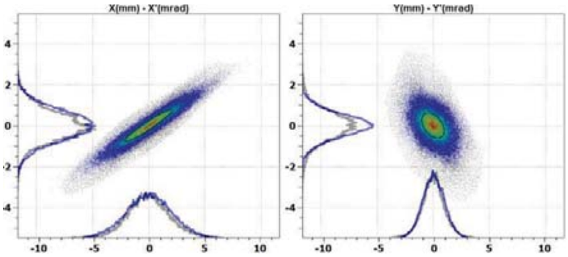

Figure 5: Transverse emittances measured at 100 MeV (color) compared to expectation (grey).

A similar reconstruction technique was used to estimate or measure indirectly the longitudinal emittance. The longitudinal micro-bunch length was measured with a Bunch Shape Monitor for different settings of a RF cavity located upstream. An example is shown in Fig. 6. In that particular case, the measured emittance is twice larger than the one expected from simulation. In fact, while taking the longitudinal profile for the reconstruction, one of the cavity located upstream was not set at the nominal phase, resulting in a longitudinal mismatch and consequently and emittance growth.

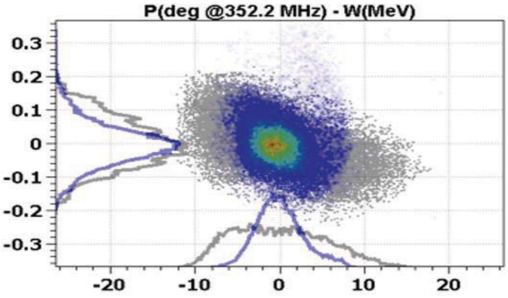

Figure 6: Longitudinal emittance measured at 30 MeV (color) compared to expectation (grey).

Setting of RF Cavities

Linac4 contains 26 independent RF cavities, with 25 phases and 26 accelerating field level to be set without the help of a dedicated longitudinal beam diagnostics. During the commissioning, beam-based measurements giving characteristics signatures were taken for every structures. For the RFQ field level setting, a characteristic curve based on the transmission as a function of the RF voltage is sufficient to find the nominal amplitude. For the 3 MeV buncher cavities, a combination of beam loading observations, (to find the two RF zero crossings) and transverse beam sizes on a wire scanners (RF defocusing) allows to identify the correct phase. The transmission through the DTL RF bucket [5] is also a good indication of the field level and phases of the bunchers. For the DTL, CCDTL and the PIMS a system based on measuring the average beam energy as a function of the cavity phase has been validated as an accurate method. The measurement of the extra power to compensate the beam loading of the cavity is a simple, yet surprisingly precise, method of measuring the beam energy gain through a cavity, as the cavity is regulated such to have a constant field level. Figure 7 shows the power to the cavity as the beam passes through at the accelerating phase or at the decelerating phase. By measuring the difference in power before and during the beam pulse and knowing the beam current at a downstream transformer the energy gain can be derived.

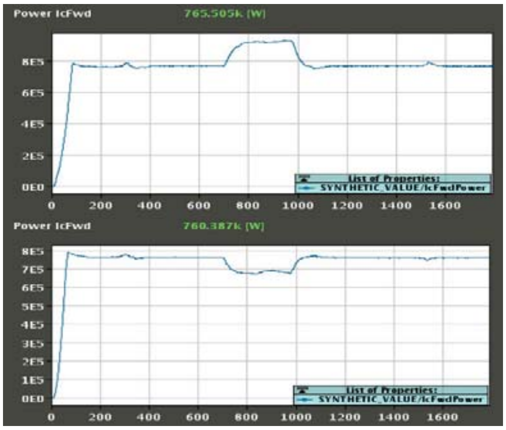

Figure 7: Forward power in CCDTL cavity 3 when the beam is accelerated (top) or decelerated (bottom).

Applying the above technique to the Linac4 DTL, CCDTL and first PIMS has allowed to cross calibrate phase and field levels of the eleven cavities. An example is shown in Fig. 8.

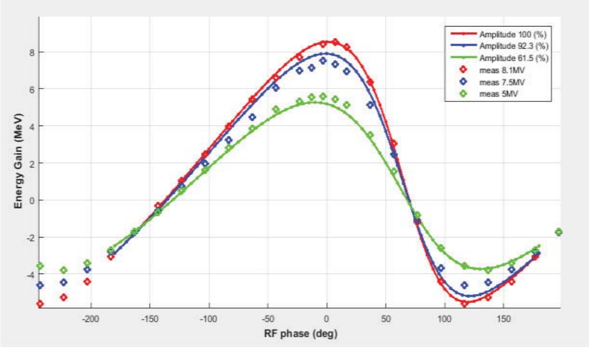

Figure 8: Energy gain in CCDTL cavity number 3 for three different amplitude as a function of phase. Solid lines are simulation and dots are energy measurements deduced from beam loading observations.

In order to set the cavities phase and field more precisely, additional measurements were taken with pairs of pick-ups which allow Time-of- Flight (ToF) measurements. An example is shown in Fig. 9.

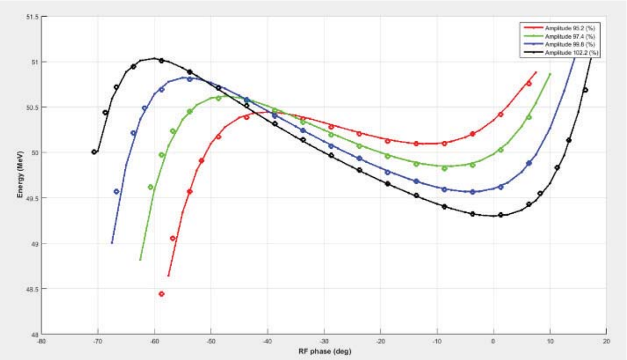

Figure 9: Beam energy measured with the ToF out of DTL tank3 for 4 amplitudes (dots are measurements, solid lines are simulations).

CONCLUSION AND OUTLOOK

The Linac4 installation is completed and the accelerator was commissioned with beam up to the first PIMS cavity, reaching an energy of 107 MeV and a maximum beam current of 25 mA. The measured beam performance at all energy stages corresponds to the expectation from calculations. A robust model of the machine, developed during the first stage of commissioning, has been instrumental to complement diagnostics information and speed up troubleshooting (steering, quadrupole polarity etc…). One of the key factors is the input beam 4D distribution directly measured after the ion source, in the LEBT.

With the completion of the 160 MeV commissioning in the coming weeks, Linac4 will enter a new phase during which its performance and reliability will be improved to meet the LIU requirements. The ion source performance improvement is one of the main challenges for the next years. The source development and the low energy beam characterization will continue, offline, on a dedicated test stand, and will bring us a better understanding of the dynamics in this crucial part of the machine on which the linac overall performances depends.

After the connection work in 2019 and the commissioning of the transfer line and of the new charge-exchange injection system of the PSB that will take place in the following year, Linac4 will become the sole injector for the CERN proton accelerator complex.

ACKNOWLEDGEMENT

Since the Linac4 project was started, in 2008, it has involved more than one hundred colleagues and collaborators inside and outside CERN. The quality of the measurements taken over the last years and the smooth operation of the machine are the direct result of their commitment and dedication. Our sincere thanks go to all of them.

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