FIRST COMMISSIONING EXPERIENCE WITH THE LINAC4 3 MEV FRONT-END AT CERN

J.B. Lallement, A. Akroh, G. Bellodi, J.F. Comblin, V.A. Dimov, E. Granemann Souza, J. Lettry, A.M. Lombardi, O. Midttun, E. Ovalle, U. Raich, F. Roncarolo, C. Rossi, J.L. Sanchez Alvarez, R. Scrivens, C.A. Valerio-Lizarraga, M. Vretenar, M. Yarmohammadi Satri
CERN, Geneva, Switzerland

Abstract

Linac4 is a normal-conducting 160 MeV H^- linear accelerator presently under construction at CERN. It will replace the present 50 MeV Linac2 as injector of the proton accelerator complex as part of a project to increase the LHC luminosity. The Linac front-end, composed of a 45 keV ion source, a Low Energy Beam Transport (LEBT), a 352.2 MHz Radio Frequency Quadrupole (RFQ) and a Medium Energy Beam Transport (MEBT) housing a beam chopper, have been commissioned at the 3 MeV test stand during the first half of 2013. The status of the installation and the results of the first commissioning stage are presented in this paper.

THE LINAC4 PROJECT

Linac4 is a new accelerator, first part of a project to improve the CERN proton accelerator chain [1]. The higher injection energy (160 MeV vs 50 MeV for Linac2) and the H^- charge exchange injection will make it possible to inject more intensity into the PS Booster. The 80 m long accelerator will be housed in a 101 m tunnel, 12 m underground. A view of the Linac in its tunnel is shown in Figure 1. It consists in a 45 keV RF ion source, a 2 magnetic solenoid LEBT; a 352.2 MHz RFQ accelerating the beam to 3 MeV; a MEBT housing a fast beam chopper; a 50 MeV Drift Tube Linac (DTL) composed of 3 tanks; a 100 MeV Coupled Cell Drift Tube Linac made of 7 modules of 3 coupled tanks and a Pi Mode Structure (PIMS) up to 160 MeV. The schematic layout is shown in Figure 2. The Linac will be connected by a 60 m transfer line to the present Linac2-PSB line. Figure 3 represents the integration of Linac4 in the PS complex. The linac positioning was also designed to be compatible with an extension to 5 GeV as part of the Superconducting Proton Linac (SPL) [2].

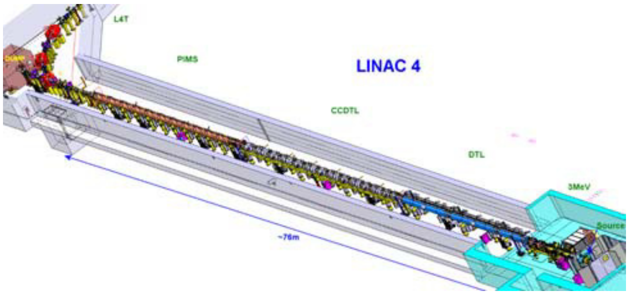


Figure 1: Linac4 in its tunnel.

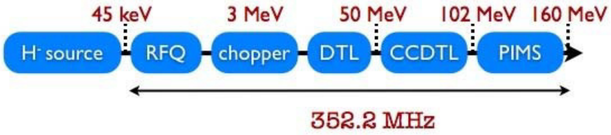


Figure 2: Linac4 layout.

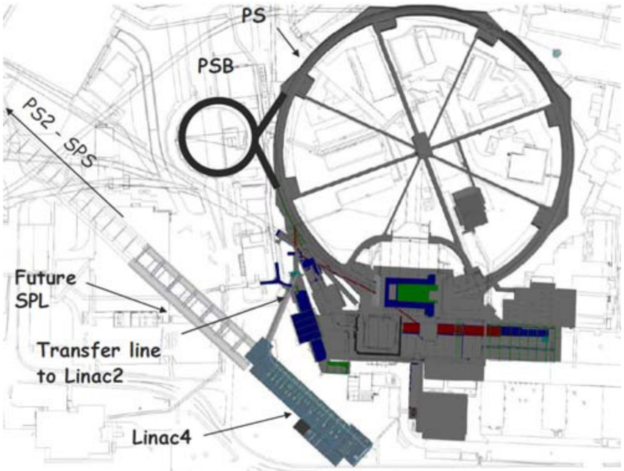


Figure 3: Linac4 integration in the CERN PS complex.

The Linac4 energy and repetition rate (160 MeV, 1.1 Hz) are defined by the PSB while the 352.2 MHz operation frequency is that of the LEP accelerator, from which a large inventory of RF equipment is recuperated. The design parameters are given in Table 1.

Table 1: Linac4 Design Parameters

Ion Species	H^-	
Length	77	m
Output Energy	160	MeV
Frequency	352.2	MHz
Repetition rate	1.1 (max. 2)	Hz
Pulse length	400 (max. 1200)	µs
Chopping factor	62	%
Source current	80	mA
Linac pulse current	40	mA

5 COMMISSIONING STAGES

The commissioning of Linac4 is foreseen in 5 stages at the energies of 3, 12, 50, 105 and 160 MeV, corresponding to the commissioning of the different accelerating structures composing the accelerator [3]. At each stage a dedicated beam diagnostic bench will be temporarily installed.

A first pre-commissioning at 3 MeV was completed in June 2013 in a dedicated test stand before removal and installation of the RFQ and chopper line to the final location in the tunnel. From October 2013, beam commissioning in the tunnel will start with the aim of finishing the commissioning of the 3 MeV part. Once completed, the first tank of the DTL will be installed and the beam should reach an energy of 12 MeV in the first half of 2014. Beam commissioning and machine installation periods will then be interlaced until 2015: Tank 2 and 3 of the DTL to 50 MeV, the 7 CCDTL modules and the first PIMS cavity to 105 MeV and all the PIMS section up to 160 MeV. In order to set the transverse and longitudinal beam parameters, 2 movable diagnostic benches will be used in addition to the diagnostics permanently installed in the Linac. The first bench with an emittance meter and a spectrometer line will be used up to 12 MeV. The second one, with quadrupoles and transverse profile diagnostics (SEM-Grids) for emittance reconstruction with the forward method and with phase pick-ups (BPMs) for Time Of Flight (TOF), will be used at 50 and 105 MeV. This second diagnostic line can be seen in Figure 4. For the last stage, beam commissioning at 160 MeV, the diagnostics permanently installed in the straight line going to the main beam dump will be used.

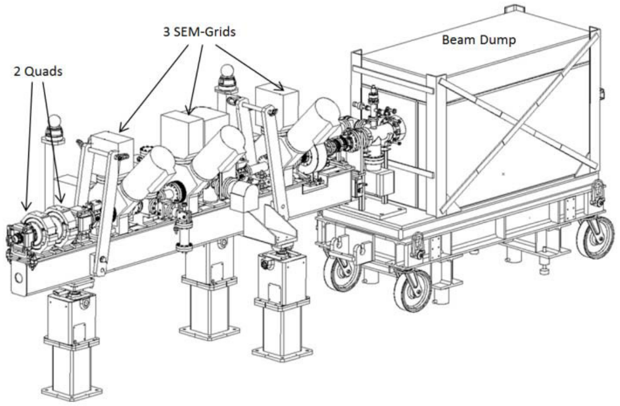


Figure 4: Technical drawing of the 50-105 MeV diagnostic bench attached to the commissioning beam dump.

THE 3 MEV TEST STAND

Experience with other linacs and dedicated beam dynamics studies show that the most difficult part to master is the low energy part, where the beam is strongly influenced by the space charge. This is also the part where there are 2 very critical devices defining the transverse and longitudinal beam characteristics, the ion source and the RFQ. Beam current, distribution and emittance from the source, space charge neutralization in the LEBT, capture and longitudinal emittance in the RFQ, matching and chopping efficiency in the MEBT are all parameters that define the quality of the beam delivered to the PSB. In order to have enough time to study and characterize the low energy beam, it was decided to have a dedicated test stand comprising the ion source, the LEBT, the RFQ, the chopper-line and a temporary diagnostic bench. The test stand was operational in the first half of 2013. Detailed results of the measurement campaign are given in the following paragraphs. A view of the 3 MeV test stand is shown in Figure 5.

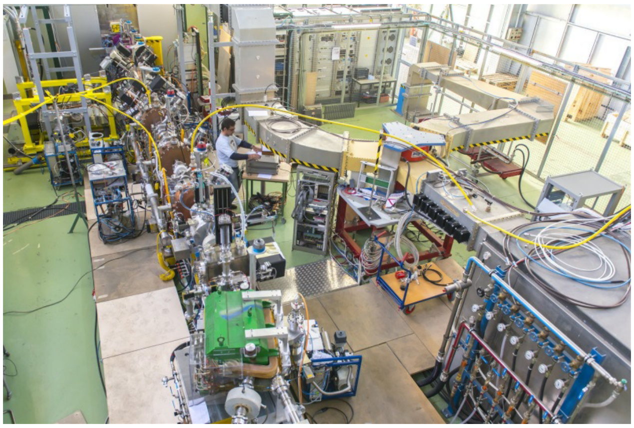


Figure 5: View of the test stand.

In the top-left corner, the 45 keV ion source inside the high voltage cage and the RFQ, followed by the MEBT and the diagnostic bench. On the right, the RFQ klystron and wave guides.

Diagnostic Bench

In addition to the diagnostics permanently installed in the line, a temporary diagnostic bench was designed in order to fully characterize the beam at 3 MeV including:

- Beam Current Transformers (BCTs), for intensity measurements.
- Beam Position Monitors (BPMs) which determine the position of beam as well as its intensity.
- An emittance meter, consisting of a 200 μm slit producing a beamlet whose angular distribution is measured with a wire grid 3 m downstream.
- A spectrometer line to measure the beam energy spread.
- A Bunch Shape Monitor (BSM) [4], which provides a measurement of the longitudinal distribution in a micro bunch.
- A halo monitor [5] used to measure not only the transverse beam halo but also the remaining part of the incompletely chopped bunches (time resolved chopping efficiency).

A detailed drawing of the 3 MeV diagnostic bench, straight line and spectrometer line, is shown in Figure 6.

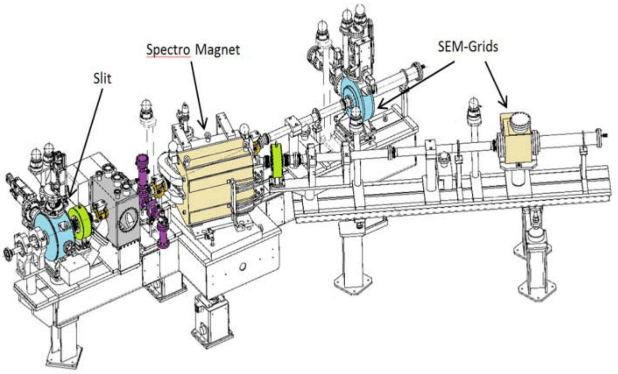


Figure 6: The 3 MeV diagnostic bench.

COMMISSIONING RESULTS

Source and LEBT

The Linac4 ion source consists of a plasma generator and a multi-electrode extraction system (Figure 7). During the commissioning, it was operated in a pulsed mode at 1.2 s interval, keeping the beam output as stable and reliable as possible. During 4 months it was running without any major problems. After typically 2 hours of warming up (stabilization time) it provided stable energy and H- beam current of 16 mA. The source used at the 3 MeV test stand is not the final source of Linac4; the new Cesiated source is presently under construction and test. An operating source with increased performances is due in June 2014.

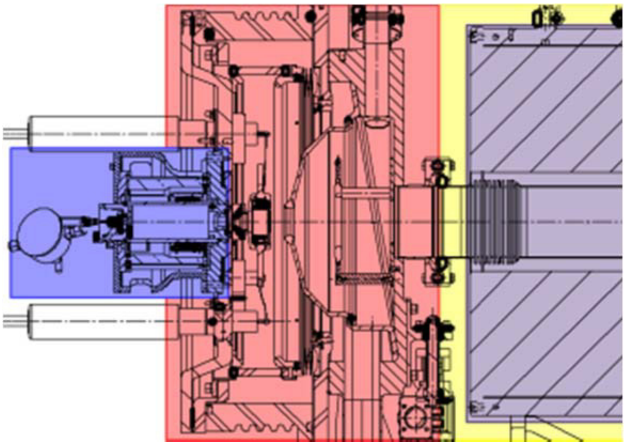


Figure 7: The ion source used at the test stand. Plasma generator (blue), front-end (red) and first part of the LEBT (yellow) including the first solenoid (purple).

The beam transverse emittance was measured with the LEBT emittance meter positioned after the first solenoid for different solenoid settings. These measurements were back-traced with the code Travel [6] to the output of the source, giving a realistic beam distribution further used for simulating the matching to the RFQ. We can see on Figure 8 five different measurements corresponding to different solenoid settings and the respective "back traced" source beam outputs which are all very similar. For the preparation of the RFQ commissioning (matching, transmission studies etc…), the superimposition of these 5 beams was taken as the source beam output distribution for the multiparticle tracking code. The measured RMS normalized transverse emittance out of the source is equal to 0.8 mm.mrad.

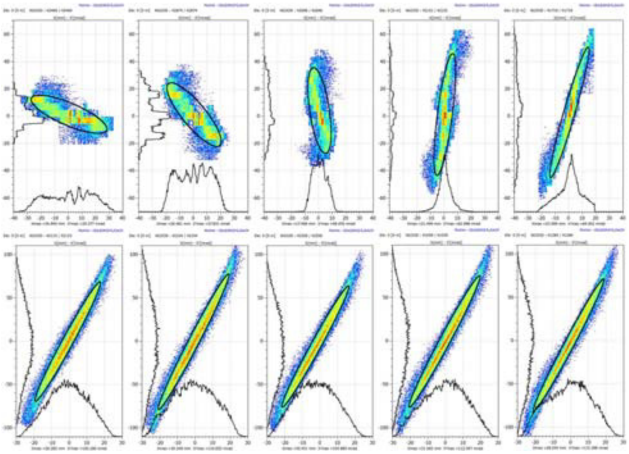


Figure 8: On the top, horizontal emittance measurement for 5 different solenoid settings; on the bottom, the 5 corresponding back-traced source output beam.

In the LEBT, the space charge compensation caused by the secondary particles created by ionization of the residual gas plays an important role in the beam dynamics. The evolution of the transverse emittance ellipse along the beam pulse has been measured for different residual pressures [7]. Figures 9a and 9b show the evolution of the transverse emittance and the Twiss parameter β along the pulse. The stabilization time of the space charge compensation is shorter for high residual gas pressure but the resulting emittance is then larger.

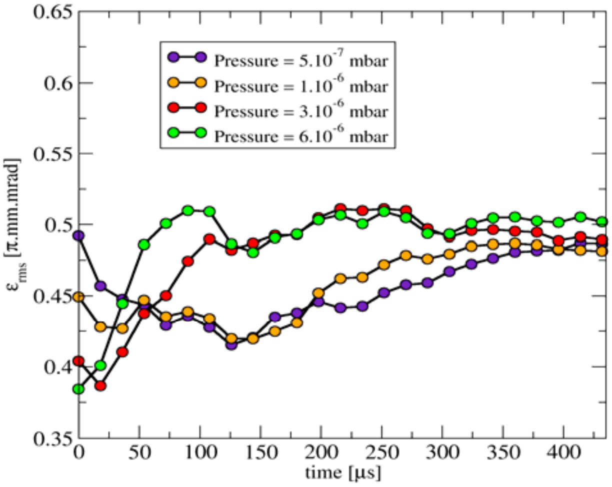


Figure 9a: Transverse emittance evolution along the beam pulse for different residual gas pressure.

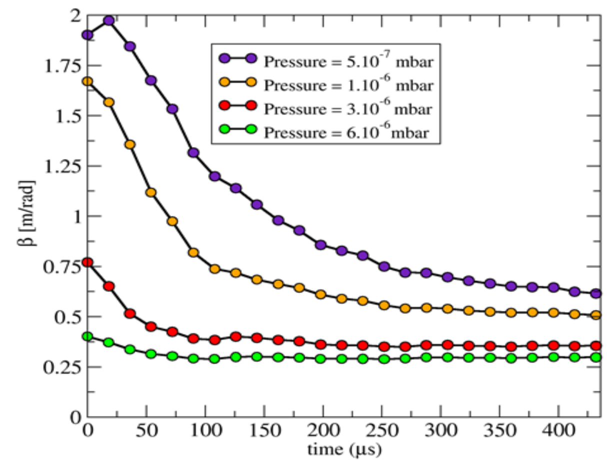


Figure 9b: Beta parameter evolution along the beam pulse for different residual gas pressure.

RFQ

The Linac4 RFQ was designed and manufactured at CERN [8]. The first H- ion beam was injected on March 13th 2013 and the first accelerated beam was observed at the RFQ output after 10 minutes of LEBT solenoids and steerer magnets fine tuning. The empirically optimised solenoid settings were within 3% of the one expected from simulations with Travel code, demonstrating the quality of the RFQ machining and of the LEBT modelling. The first 3 MeV BCT signal observed on that day is shown in Figure 10 (10 mA steady state H- beam current).

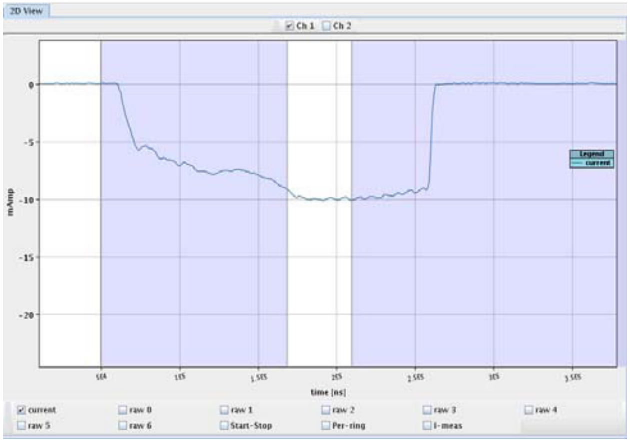
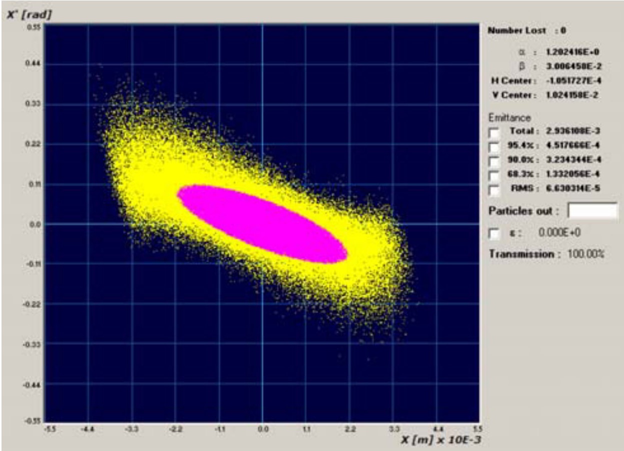


Figure 10: RFQ output beam current – 2013/03/13.

After retuning beam focusing and steering in the LEBT, the RFQ maximum transmission was reached, giving a 12 mA peak current at 3 MeV (75% transmission). The RFQ transmission was studied with Parmteq [9] and Toutatis [10] codes, taking into account the beam parameters measured in the LEBT. Given that the emittance from the source is larger than expected, 25% of the beam from the source is bound to be lost in the first centimetres of the RFQ. Figure 11 shows the comparison of the emittance measured in the LEBT and the RFQ acceptance.



Number Lost : 0
α : 1.202416E+0
β : 3.006458E-2
H Center : -1.051727E-4
V Center : 1.024158E-2
Emittance
☐ Total : 2.936108E-3
☐ 95.4% : 4.517666E-4
☐ 90.0% : 3.234344E-4
☐ 68.3% : 1.332056E-4
☐ RMS : 6.630314E-5
Particles out :
☐ ε : 0.000E+0
Transmission : 100.00%

Figure 11: Comparison of measured emittance (yellow) and RFQ acceptance (pink).

Figure 12 shows a comparison of the simulated RFQ transmission (purple dots) and measured transmission for different gas pressure in the LEBT and RF power. It should be noted that the solenoids and steering magnets were optimized, for the case corresponding to 1.e-6 mbar pressure in the LEBT.

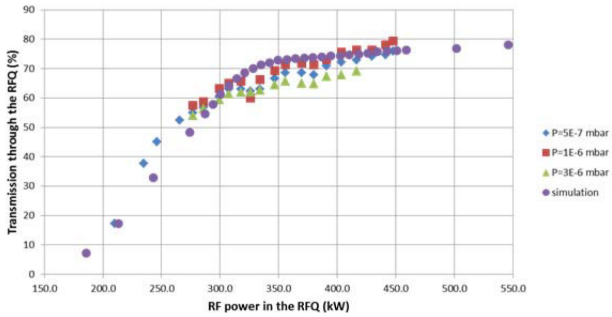


Figure 12: RFQ transmission vs power for different gas pressure in the LEBT.

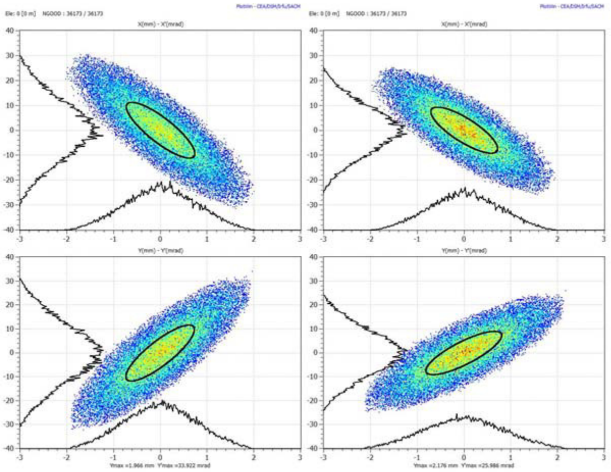


Figure 13: Beam distribution in the Horizontal (top) and vertical (bottom) phase planes at RFQ output; Left: expected from simulation, Right: reconstructed with the forward method.

The transverse emittance was reconstructed after the RFQ with the so-called forward method [3]. The beam profile was measured for different test bench quadrupole settings and the corresponding emittance at the RFQ output computed with the Travel code taking the space charge effects into account. The reconstructed normalized emittance is equal to 0.32 and 0.34 mm.mrad in horizontal and vertical plane respectively compared to 0.36 and 0.37 mm.mrad expected from the simulations. The comparison of the reconstructed and expected phase space distribution is given in Figure 13.

Chopper-Line

The MEBT was installed after the RFQ commissioning was completed. It aims to match the beam to the DTL and modify the time structure of the pulse in order to reduce 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. Figure 14 shows the comparison of the simulated and measured transmission of the chopper-line for chopper ON and OFF varying a MEBT quadrupole gradient. We can see a very good correspondence between simulation and measurements for chopper OFF. For the chopper ON, it turned out that the experimental results are better than simulations, indicating a chopper efficiency better than expected. This could be explained by a coverage factor of the field generated by the chopper higher than expected or by a transverse distribution more Gaussian than assumed in the simulations. The rise and fall time of the chopper is expected to be a few ns; a preliminary measurement with a fast BCT indicates that it is below 10 ns.

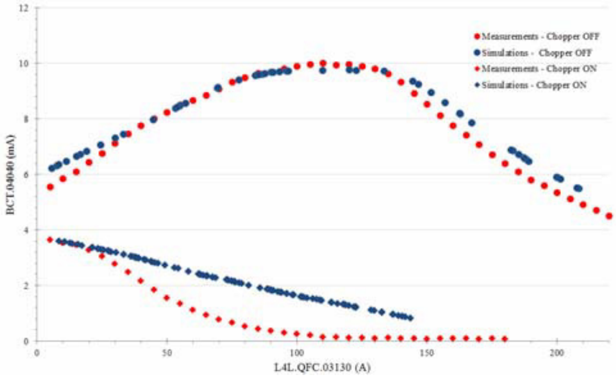


Figure 14: Measured and simulated transmission in the MEBT for chopper ON and OFF.

The longitudinal distribution of the beam was also reconstructed using a method equivalent to the 3 gradients method in the longitudinal plane. The beam phase spread was measured with a BSM for different settings of the second MEBT buncher cavity. As for the transverse plane, we applied the forward method to reconstruct the emittance ellipse in the Phi/E phase space at the output of the RFQ. The measured energy spread is equal to 22 keV RMS compared to the 21 keV expected from simulation.

The matching to the DTL, time resolved measurement with the halo monitor and comparison between TOF and spectrometer measurement will be studied once the line moved in the tunnel.

PROJECT STATUS AND SCHEDULE

The installation of general infrastructure and services is now completed in the Linac4 tunnel. After the successful measurement at the test stand, the 3 MeV line was installed and will be re-commissioned from October 2013. The DTL and CCDTL will be installed and commissioned in 2014, and the PIMS in 2015. A one year reliability run is foreseen in 2016 before the connection of the Linac to the PS Booster foreseen in 2017-18, during an extended stop of the LHC injector chain. Figure 15 shows a view of the Linac4 tunnel in September 2013.

Figure 15: Linac4 tunnel seen from the low energy side. In the foreground, the RFQ and the MEBT.

REFERENCES

[1] F. Gerigk, M. Vretenar (eds.), Linac4 Technical Design Report, CERN-AB-2006-084.

[2] M. Vretenar (ed.), Conceptual Design of the SPL, a high-power superconducting Linac at CERN, CERN 2000-012.

[3] JB. Lallement et al., Linac4 beam commissioning strategy, HB-2012, Beijing.

[4] AV. Feshenko, Methods and instrumentation for bunch shape monitor, PAC 2001, Chicago.

[5] K. Hanke, M. Hori, Design and construction of a Beam Shape and Halo Monitor for the CERN SPL, CERN AB-2005-033 OP.

[6] A. Perrin, JF. Amand, Travel v4.06 user manual, CERN, 2003.

[7] CA. Valerio-Lizarraga et al., Space charge compensation in the Linac4 Low Energy Beam Transport line with negative hydrogen ions, ICIS2013, Chiba.

[8] C. Rossi et al., The RadioFrequency Quadrupole accelerator for the Linac4, Linac08, Victoria.

[9] KR. Crandall, TP. Wangler, PARMTEQ-a beam-dynamics code for the RFQ linear accelerator, AIP, 1988.

[10] R. Duperrier et al., Toutatis, the CEA Saclay RFQ code, Linac2000.