PROFILE AND EMITTANCE MEASUREMENTS AT THE CERN LINAC-4 3 MEV TEST STAND

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Abstract

A new 160 MeV H- Linac named Linac-4 will be built at CERN to replace the old 50 MeV proton Linac. The ion source, the 3 MeV Radio Frequency Quadrupole (RFQ) and the Medium Energy Beam Transport (MEBT) line hosting a chopper, have been commissioned in a dedicated test stand. Wire grids and wire scanners were used to measure the transverse beam profile and a slit/grid emittance meter was installed on a temporary test bench plugged at the RFQ and MEBT exit in different stages. The emittance meter slit was also used as a scanning scraper able to reconstruct the transverse profile by measuring the transmission with a downstream current transformer. On the same measurement bench, a spectrometer in conjunction with a wire grid allowed measuring the energy spread of the particles. This paper summarizes the measurement results that allowed characterizing the 3 MeV beam and discusses the present understanding of monitor performance.

INTRODUCTION

As part of the CERN LHC injector chain upgrade, LINAC4 [1] will accelerate H- ions from 45 keV to 160 MeV. The linac layout is shown in Fig. 1. The ion source, the 3 MeV RFQ and the MEBT line hosting a chopper, have been commissioned in a dedicated test stand [2]. Diagnostic devices are installed both in the MEBT line and in a movable temporary diagnostics test bench which has been plugged at the RFQ and MEBT exit in different stages and which will be removed out of the machine once the beam commissioning has been terminated [3]. The MEBT line, or "chopper line" hosts two Beam Current Transformers (BCT) and two Wire Scanners (WS), which will be permanently installed in the machine. The movable test bench contains two BCTs, three Beam Position Monitors (BPMs), a Bunch Shape Monitor (BSM) a Halo Monitor, an Emittance Meter (EM) consisting of a slit and grid system, and a Spectrometer line. The layout of the 3MeV diagnostic bench is shown in Fig. 2. This paper is focused on the instrumentation for transverse profile and emittance measurements and describes the present understanding of the instrumentation performance. The measurements reported refer to the first commissioning period of the 3 MeV line, which took place in a dedicated test stand. A second, longer commissioning period is foreseen after the permanent installation in the Linac4 tunnel.

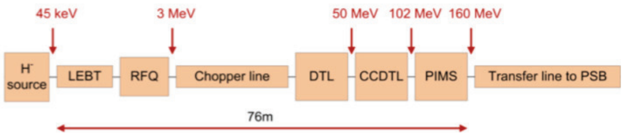

Figure 1: LINAC4 schematic layout.

WIRE SCANNERS IN THE MEBT LINE

The wire scanners installed in the chopper line consist of two 33 µm carbon wires, one horizontal and one vertical, mounted on the same fork support which scans the beam under 45 degrees. Both the horizontal and the vertical profile can then be measured at the same time. The wire signal is amplified and sampled by an ADC with 250 kHz sampling frequency, so that the beam profile can be reconstructed with a time resolution of 4 µs within the beam pulse. In the case of an H- beam, the wire signal is given by the balance between secondary emission and number of charges stopped in the wire, which itself depends on the wire material and diameter and the beam energy [4]. At the 3 MeV energy of the Linac4 MEBT line, with a carbon wire diameter of 33µm, the outermost electrons of the H- ions are stripped in the first nanometres of material with a fraction of them collected by the wire, while the remaining protons are not stopped in the wire. The H- ion entering the wire, the proton exiting the wire and the stripped electrons that are scattered away from the wire also generate secondary emission. The resulting signal at this energy is therefore a balance between the stripped electrons collected in the wire and the secondary emission. For the wire scanners in the chopper line the measured signal was negative, meaning that the deposited electrons were dominant over secondary emission.

The wire scanners were extensively used not only for beam profile measurements and emittance reconstruction, but also to measure the beam displacement when the chopper was switched on. The time resolution of 4µs within the 250 µs beam pulse allowed observing the profiles of both chopped and unchopped beam. In Fig. 3 the beam vertical profiles acquired along the beam pulse in time steps of 4 µs are shown in the case of a chopped

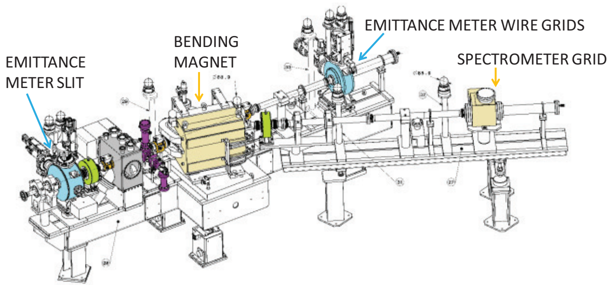

Figure 2: The 3MeV movable diagnostic test bench.

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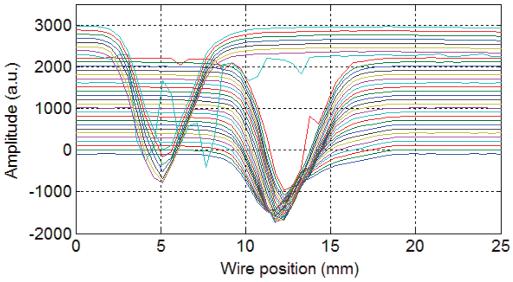

Figure 3: Vertical transverse profiles of the chopped beam acquired with the wire scanner in the MEBT line in time steps of 4µs during the 250 µs beam pulse.

beam, with time going from bottom to top. The displacement in the vertical plane due to the chopper switching-on at the end of the pulse can be clearly seen.

One of the expected problems was the wire heating and extensive model calculations have therefore been performed [5]. In order to measure the beam emittance using a quadrupole scan, a horizontal waist condition was created with a beam size of σ_x=0.3 mm and σ_y=1.8 mm. The beam pulse length was 250 µs, which corresponds to the RF pulse length of the RFQ. The repetition rate was 1 Hz and the average pulse current was about 11 mA. In the upper plot of Fig. 4 the wire signal shape is shown for different wire positions while scanning the beam. While the wire is in the beam halo, the signal is negative and the shape is the expected one. When the wire is approaching the beam center, the signal shape starts being deformed and in the beam centre it turns from negative to positive with very large amplitude after approximately 100-150 µs. This behavior can be explained as due to thermionic emission [6]. Thermal simulations have been performed and show that the wire locally reaches temperatures which are well above the threshold for which thermionic emission becomes significant. In Fig. 5 the temperature profile along the wire is simulated for the described condition, while in Fig. 6 the time evolution of the maximum temperature reached in the wire centre is shown for ten consecutive beam pulses. In the simulation model the wire heating process is due to the energy deposited by the beam particles, while the wire cooling process is due to emitted radiation, thermal conduction along the wire and thermionic emission. Figure 5 shows that cooling due to radiation is the dominant one in the considered setup. For the calculation of radiative energy losses, the wire is treated as a "graybody", which means that the emitted spectrum corresponds to that of a blackbody of the same temperature, but with only a fraction of the emitted power. The emissivity coefficient is smaller than 1, and for Carbon can be assumed as 0.7 and temperature independent [7].

In order to eliminate thermionic emission and the resulting distortion in the acquired beam profile, we tried to limit the pulse length to 150 µs. As can be seen in the second plot of Fig. 4, this was at least partially successful. Simulations, however, show that increasing

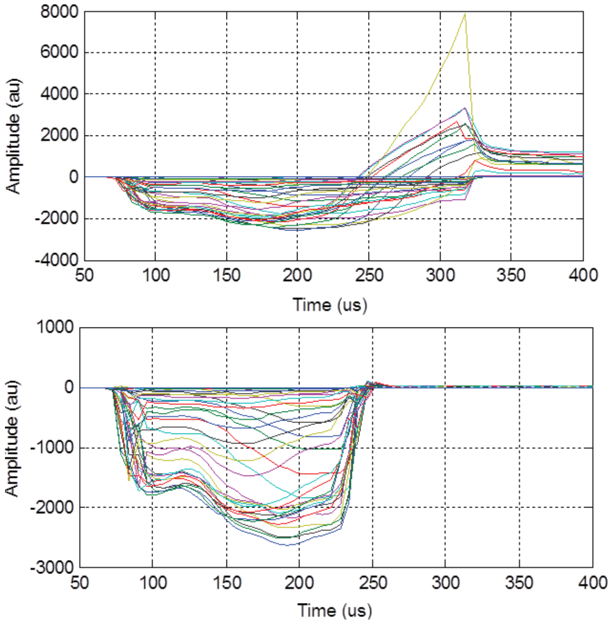

Figure 4: Wire scanner signals for different wire positions, acquired in the beam waist condition, with a pulse length of 250 µs (top) and 150 µs (bottom).

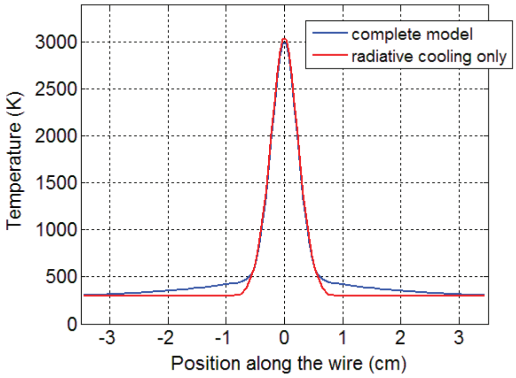

Figure 5: Simulated temperature profile along the wire in the beam waist condition.

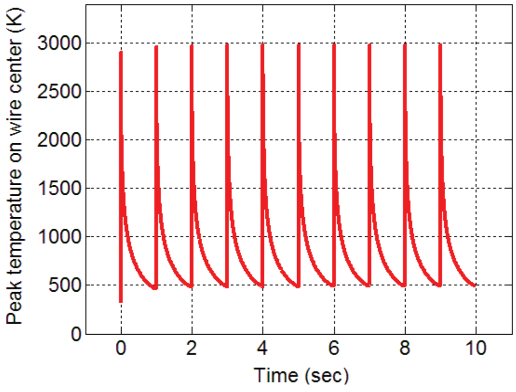

Figure 6: Simulated time evolution of the wire peak temperature after ten consecutive pulses in the beam waist condition.

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the beam size is the most efficient way to limit the wire heating.

WIRE GRIDS

Two wire grids are installed on the 3 MeV movable test bench (see Fig. 2). One of them consists of a horizontal wire plane only and is used for spectrometer measurements. The other grid, which has both a horizontal and a vertical wire plane, is part of the emittance meter described in the next section. The wire signal readout is the same as for the wire scanners described above, so the profiles can be measured with a time resolution of 4 µs. A typical horizontal beam profile acquired by the grid in the spectrometer line is shown in Figure 7. The spectrometer line has been used to adjust the phase and the amplitude of two of the bunchers in the MEBT line with respect to the RFQ and with respect to each other. The used method relies on the fact that for phase values above the nominal bunching phase the average bunch energy increases and therefore the particle curvature radius in the spectrometer magnet is larger, while for phases below the nominal one the curvature radius is smaller. When setting the phase to the nominal bunching phase and increasing the RF amplitude supplied to the buncher, the profile width shrinks but the mean position does not change. The beam width and position at the end of the spectrometer line were measured by the horizontal wire grid. This method allowed the relative phase positions of the bunchers to be precisely determined and was found to be in perfect agreement with a similar method performed using the Bunch Shape Monitor [8].

PROFILE AND EMITTANCE MEASUREMENTS

The emittance meter installed on the movable test bench consists of a slit and grid system for a direct sampling of the transverse phase space from which the emittance can be calculated [9]. The slit selects a narrow slice of the beam at a well defined position. The angular distribution of the particles transmitted through the slit is transformed into a position distribution in the downstream drift space of about 3m and sampled using two wire grids (horizontal and vertical) as profile monitors. By scanning the slit across the beam, the whole phase-space can be reconstructed. The slit consists of two blades mounted with a 15° angle with respect to the beam axis in order to dilute the energy deposition. Each blade consists of a harmonica shaped, water-cooled copper structure covered by a graphite plate. The 200 µm gap separating the blades allows the passage of the beamlet. The slit has been designed to accept particle energies up to 12 MeV and is capable of withstanding the full nominal beam intensity of 65 mA if the beam pulse length does not exceed 100 µs. During this first commissioning period the beam intensity after the RFQ did not exceed 15 mA, and therefore could not damage the slit even with the longer pulse length of 250 µs. The wire grids have 48 wires with a pitch of 750 µm. Each wire has its own readout chain consisting of an amplifier followed by an ADC with a sampling frequency of 250 kHz, thus allowing the time resolution of 4 µs. The slits and the SEM grids are driven by stepping motors with 50 µm resolution. For a typical emittance measurement the start position of the slit, the end position and the step size are defined by the user. The movement of the wire grid is determined by a scaling factor with respect to the slit movement and for each slit and wire grid position a predefined number of measurements are taken. It is also possible to individually define the positions of the slit and of the grid for each scanning step through an input file provided to the control software.

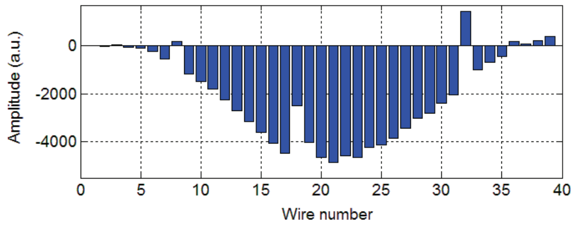

Figure 7: Typical beam profile acquired by the wire grid in the spectrometer line.

In the first commissioning stage the movable test bench was directly connected to the RFQ without the MEBT line being installed. In order to measure the beam profile in the absence of the MEBT wire scanners, the edge of the slit blades was used as a scraper and the beam intensity not cut by the slit was measured by a downstream BCT. Inverting this measured curve, which corresponds to the beam lost on the slit, and differentiating the loss curve, allowed the transverse profile at the position of the slit to be deduced. An example of this kind of measurement is shown in Fig. 8. Even after the installation of the MEBT line the

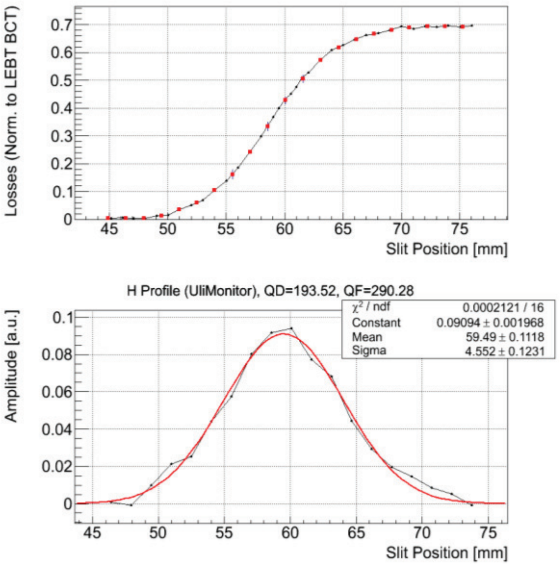

Figure 8: Transverse profile acquired by using the emittance meter slit as a beam scanning scraper.

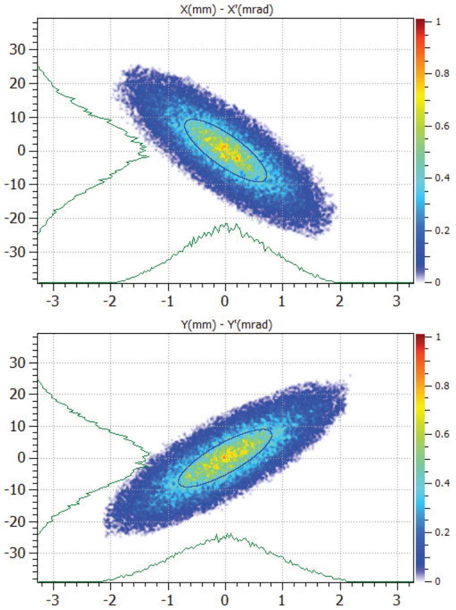

Figure 9: Transverse emittance measurement at the output of the RFQ at the energy of 3 MeV.

scraping method was adopted as a fast method to measure the beam profile at the position of the slit. The same result was obtained with an emittance meter scan while integrating the signals measured by all the wires of the downstream wire grid for a given slit position. The two methods were found to be in perfect agreement. We were also able to reconstruct the beam profile by measuring the intensity of the beamlets passing through the slit aperture during a slit scan using the downstream BCT. The vertical profile was very clean due to the smaller beam size and therefore the higher beam intensity passing through the slit. The horizontal signal-to-noise ratio was poorer, but the profile was still measurable and indicated an intensity resolution of the BCT better than 100 µA.

As far as transverse emittance measurements are concerned, different kinds of measurements have been performed during this first commissioning period. When the test bench was directly connected downstream of the RFQ, without the MEBT line being installed, the emittance at the output of the RFQ was reconstructed by quadrupole scanning and profile measurements using the slit as a beam scraper. The normalized rms emittance values obtained were 0.314 π mm mrad in the horizontal plane and 0.344 π mm mrad in the vertical plane. The emittance plots are shown in Fig. 9. The expected values from simulations were respectively 0.357 π mm mrad and 0.371 π mm mrad. When the MEBT line was connected downstream of the RFQ, the emittance measurement was repeated with the same method, this time using the profile measurements provided by the first wire scanner in the MEBT line. In this case the values obtained were significantly lower, of the order of 0.25 π mm mrad, the reason for which has to be further investigated. When we adopted the emittance meter (slit and grid system) to make a direct measurement of the beam emittance at the slit location (at the output of the MEBT line), we also got values of the order of 0.25-0.30 π mm mrad, lower than the expected 0.35 π mm mrad. This was partially attributed to a low acceptance of the emittance meter in this first period of commissioning, due to the fact that only 32 wires (out of the 48 available wires) were connected to readout electronics. Another explanation comes from beam losses occurring in the 3 m drift space between the slit and the grid. This was in fact confirmed by a BPM positioned upstream of the grids which saw particle losses falsifying its position signal. Since no steering magnet was available upstream of the test bench, it was difficult to try correcting this effect. In the upcoming second commissioning period, after the installation in the LINAC4 tunnel, we will profit from a complete readout of the emittance meter wire grids and from the possibility to use steerers in the MEBT line in order to get more reliable emittance measurements at the output of the chopper line.

CONCLUSIONS AND OUTLOOK

A dedicated test stand was set up for the commissioning of the 3MeV line of the Linac4 accelerator at CERN. The beam instrumentation hosted in the MEBT line and in a movable test bench was commissioned and used to characterize the beam. Wire scanners, wire grids and a slit-and-grid emittance meter capable of standing the 3 MeV beam power were successfully used for profile and emittance measurements. A second commissioning period will start soon after the permanent installation of the 3MeV line in the Linac4 tunnel and will allow the issues encountered during the relatively short first commissioning period to be addressed to better characterize the 3MeV H- beam.

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