TRANSVERSE PROFILE AND EMITTANCE MEASUREMENTS WITH A LASER STRIPPING SYSTEM DURING THE CERN LINAC4 COMMISSIONING AT 3 AND 12 MeV

E. Bravin, T. Hofmann, Uli Raich, F. Roncarolo*, F. Zocca, CERN, Geneva, Switzerland
J. K. Pozimski, Imperial College of Science and Technology, London
G. Boorman, A. Bosco, S. M. Gibson, K. Kruchinin Royal Holloway, University of London, Surrey
C. Gabor, STFC/RAL/ASTeC, Chilton, Didcot, Oxon

Abstract

The CERN LINAC4 beam commissioning at 3 MeV was completed in early 2014 and the one at 12 MeV is ongoing. A novel system for measuring the transverse beam profile and emittance, based on low power laser stripping and H0 detection using a diamond detector, was successfully tested at these two energies. The measurement results agree with the operational slit-grid method within a few percent in terms of both transverse profile and emittance. After describing the general system setup, this remarkable achievement is discussed in detail together with the present limitations, which will be addressed in order to design a laser based emittance monitor for the LINAC4 top energy of 160 MeV.

INTRODUCTION

The CERN LINAC4, that will accelerate H^- ions from 45 keV to 160 MeV, is in the beam commissioning phase at low energy [1]. The transverse profiles will be measured at different energies along the acceleration with wire scanners and wire grids [2]. Presently, wire grids and wire scanners are also foreseen to be used at 160 MeV to reconstruct the transverse emittance via either the *quadrupole scan* or the *three-profile* method.

However, wire scanners and wire grids are interceptive devices which implies: i) partial or complete stripping of the electrons from the H^- ions and subsequently beam losses because of the opposite polarity of the thus created protons and ii) their use will be allowed only for a reduced beam pulse length (e.g. 40 mA, 100 μs beam pulse) in order to avoid wire damage

These issues can be overcome with a modern transverse beam measurement system based on a pulsed laser that strips the H^- outer electron (the binding energy is about 0.75 eV) while selecting tiny slices of the beam (see Fig. 1). The un-stripped H^- ions are bent away by a downstream dipole, while the neutral H^0 drift on a straight path toward a strip-detector. Like in a conventional slit-grid system, the H^0 profile measurement during a laser scan allows the transverse phase space to be reconstructed. The stripped electrons can be extracted at the laser location by a weak dipole field and counted by a Faraday cup-like detector in order to reconstruct the transverse profile.

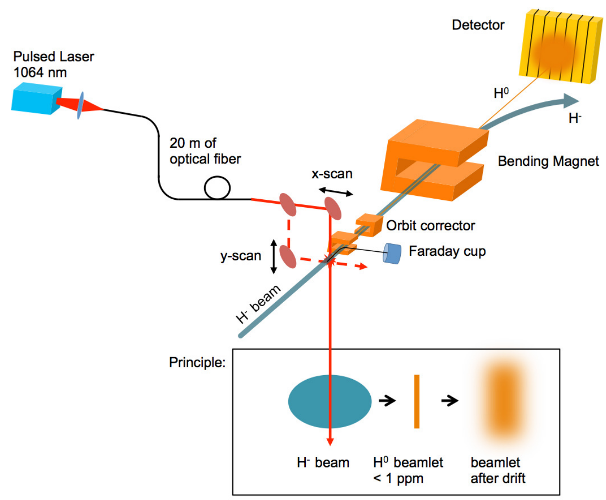

Figure 1: Laser emittance meter concept.

3MeV AND 12MeV SETUP

During the LINAC4 commissioning at 3 and 12 MeV, the transverse emittance of the beam was measured with the classical slit-grid system installed on a temporary diagnostic bench [3] that was placed at first after the MEBT and then after the first DTL tank. In order to advance with the final system design before having the possibility of tests at 160 MeV, the same test bench was equipped with a laser prototype system (see Fig. 2). The system consisted of a rack-mounted laser source (Q-switched, diode pumped [4]) coupled to an optical fiber (5 m and 10 m for the two different locations) delivering the laser beam to a focusing and scanning system. The laser was scanned in the vertical plane through the H^- beam via a view port mounted on the vacuum vessel also hosting the slits of the operational slit-grid emittance meter. A polycrystalline diamond strip detector was installed 3.3 m downstream just before the emittance meter wire grids, after the spectrometer dipole. For this first test, no stripped electrons detection was foreseen. As shown in Table 1, during each H^- pulse, lasting about 300 μs, the laser was pulsing at 60 kHz (i.e. a laser pulse every 16 μs) and amplified to about 0.5 kW peak power.

* federico.roncarolo@cern.ch

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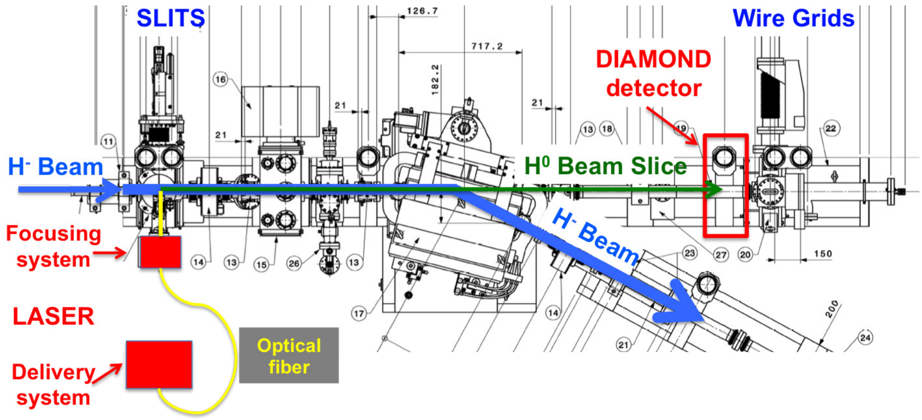

Figure 2: Layout of the 3 MeV diagnostics line as it was installed after the MEBT, including the operational emittance meter (slit and grids) and the prototype laser-diamond system.

LASER POWER MONITORING

Both the laser delivery and focusing systems were equipped with a Photo Diode (PD) detector aimed at monitoring the laser power before and after the optical fiber. With the 10 m long fiber, the PD peak signals were calibrated with respect to the average power measured by a power meter, when setting the laser to 60 kHz repetition rate and 10 ms amplification period. The calibration results are shown in Fig. 3. Both PD exhibit a linear response as expected. The difference in signal amplitude (higher for the PD after the fiber) is dominated by the fact that the first PD is located behind a standard mirror whereas the second is installed after a semitransparent mirror (splitting the light between the PD and a CCD camera). On the other hand, only the first PD can be used for on-line power monitoring during operation, since the second belongs to a calibration line that cannot be used in parallel to beam measurements.

Table 1: Summary of laser parameters for the system used at 3 and 12 MeV.

Parameter	Value
Wavelength	1080 nm
Pulse Peak Power	400 ... 800 W
Pulse Length	FWHM ≈ 80 ns
Beam Quality Factor(M^2)	< 1.8
Repetition Rate	30-60 kHz

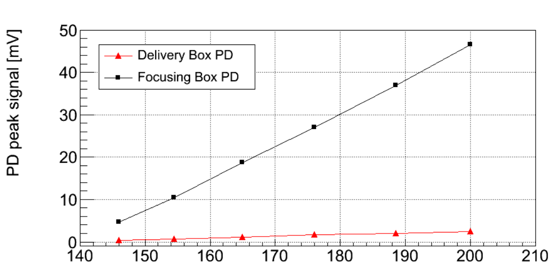

Figure 3: Photo diodes peak signals as a function of average laser power (with 60 kHz repetition rate and 10 ms amplification period).

3MeV MEASUREMENTS

The first set of measurements were aimed at achieving the milestone of proving the laser stripping of H^- ions and the detection of H^0 beam slices with the diamond detector.
During a laser scan, for each laser position the diamond detector was scanned through the H^0 beamlet distribution in order to have every diamond channel sampling the whole beamlet. The signal of a diamond channel during a H^- beam pulse, for one laser position and one diamond position is shown in Fig. 4. The diamond signal is compared to the beam current as measured by a beam current transformer located upstream of the laser station. The diamond pulses reproduce well the beam current shape.
Fig 5 shows a comparison of the diamond signal (blue trace) and the laser pulse as measured by the PD detector inside the laser delivery box. The laser pulse is plotted first as recorded (red solid line) and then shifted in time (dashed red line) to appreciate the shape overlap with the diamond signal. The introduced time shift is about 110 ns, well in agreement with the 114 ns time-of-flight of 3 MeV ions from the laser to the diamond location (the additional 4 ns can be explained by different cable lengths from the detector to the oscilloscope used for these acquisitions). Not only did this first set of measurements provide evidence of stripping, but it also allowed the reconstruction of the H^- vertical phase space to be compared to the slit-grid measurements (see Fig. 6). The phase space data could be used to calculate the RMS normalized emittance. For both the slit-grid and the laser-diamond systems, the result depends on the data thresholding in order to filter out noise from the RMS calculation. A basic method consists in excluding all wire (diamond) signals with an amplitude below a percentage of the maximum amplitude measured during the whole scan. The agreement between the two systems resulted to be almost perfect for small thresholds

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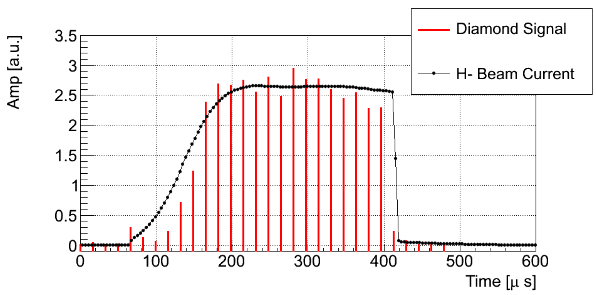

Figure 4: Signal form a single diamond detector channel sampling the H^0 particles for a given laser position, as function of time along the H^- beam pulse. This is compared to the beam current measured with a beam current transformer upstream the laser station.

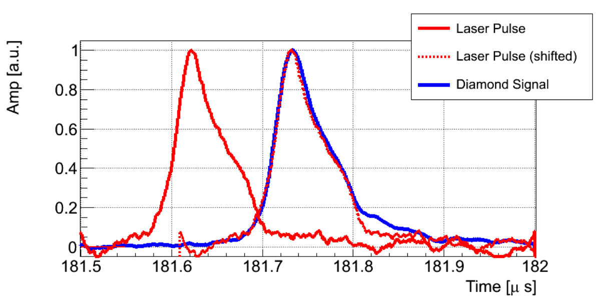

Figure 5: Zoom on one of the diamond signals of Fig. 4, compared to the corresponding laser pulse (as recorded by a scope and shifted in time to see the overlap with the diamond signal).

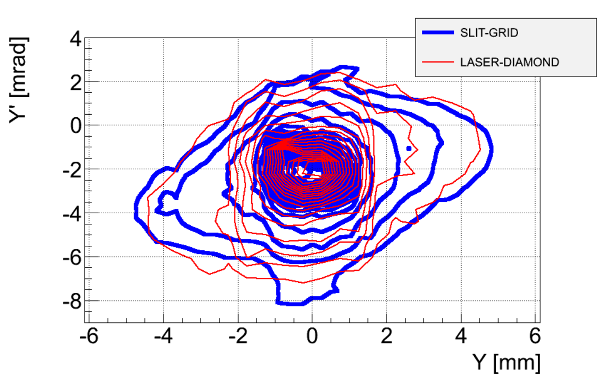

Figure 6: Contour plots resulting from a slit-grid and laser-diamond scans at 3 MeV.

and diverges to about 1.8 % for a 1 % threshold.

Despite these remarkable results, the tests also evidenced the non-uniform response of different diamond channels. In addition, the occasional occurrence of diamond signal droop during the LINAC4 pulse (i.e. diamond peak signals decreasing during the beam current flat top region) compromised the reliability of many measurements.

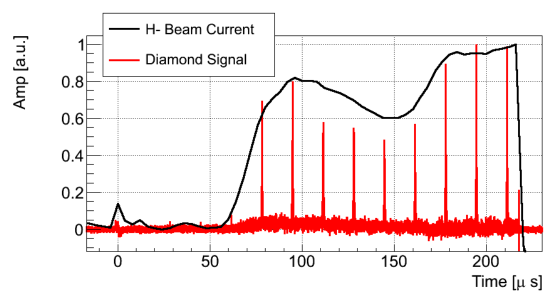

Figure 7: Comparison between the diamond and the beam current transformer upstream of the laser during the very first test at 12 MeV.

The cause of these problems is under investigation with two main effects being considered: i) the non-optimized electronics, in particular the pre-amplifiers response and saturation levels. and ii) the possible implantation of protons in the diamond substrate after the electron stripping in the very first layer. This could change the effective bias of the diamond electrodes.

12MeV MEASUREMENTS

Unfortunately, due to unforeseen delays in the DTL tank fabrication and installation, at the moment of writing only a few measurements could be taken with the laser-diamond system, but the first results are very encouraging. Fig. 7 compares the diamond signal to the measured beam current upstream of the laser, while keeping the laser and the diamond detector at a fixed position. The diamond signal to noise ratio is very high, especially considering that no pre-amplifier was used in this test.

CONCLUSIONS AND OVERVIEW

The milestone of proving the feasibility of laser-stripping H^- profile and emittance measurement with a relatively low power laser source was for the first time achieved during the CERN LINAC4 commissioning at 3 MeV. The measured signal and background levels compare very well with the expected ones from simulations (to be published at the IBIC14 conference [5]). The setup allowed a set of complete emittance scans to be performed, that could be compared to the operational slit-grid system. The agreement in terms of normalized emittance was found to be below 2 %. These encouraging results, to be complemented by more tests at 12 MeV, represent the first step towards the design of one or more systems for the LINAC4 at top energy, for which the main challenge now finding the most adequate H^0 detector type and related electronics.

ACKNOWLEDGMENTS

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