

# STATUS OF AND FUTURE PLANS FOR THE CERN LINAC4 EMITTANCE METER BASED ON LASER ELECTRON-DETACHMENT AND A DIAMOND STRIP-DETECTOR

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## Abstract

LINAC4 has started its staged commissioning at CERN. After completion it will accelerate high brightness  $H^-$  beams to 160 MeV. To measure the transverse profile and emittance of the beam, a non-destructive method based on electron photo-detachment is proposed, using a pulsed, fibre-coupled laser to strip electrons from the  $H^-$  ions. The laser can be focused and scanned through the  $H^-$  beam, acting like a conventional slit. A downstream dipole separates the neutral  $H^0$  beamlet, created by the laser interaction, from the main  $H^-$  beam, so that it can be measured by a diamond strip-detector. Combining the  $H^0$  beamlet profiles with the laser position allows the transverse emittance to be reconstructed. A prototype of this instrument was tested while commissioning the LINAC4 at 3 and 12 MeV. In this paper we shall describe the experimental setup, challenges and results of the measurements, and also address the characteristics and performance of the diamond strip-detector subsystem. In addition, the proposal for a permanent system at 160 MeV, including an electron detector for a direct profile measurement, will be presented.

## INTRODUCTION

In the context of the High-Luminosity upgrade of the LHC (HL-LHC), CERN needs to upgrade its LHC injector chain, to deliver higher brightness beams. LINAC4 will replace the ageing LINAC2, the first injector in the chain, aiming to accelerate  $H^-$  ions from 45 keV at the source front-end to 160 MeV at the injection into the PS-Booster (PSB). Using a  $H^-$  beam makes injection via the charge-exchange scheme into the PSB possible [1]. With the brightness of the PSB proton beam is expected to double with respect to the present configuration based on protons injected at 50 MeV from LINAC2.

The transverse emittance has to be measured precisely at the machine's top-energy of 160 MeV. It is not possible to do so with a conventional slit & grid method as at this energy the  $H^-$  ions will travel through any possible slit material. Other methods, such as three-profile measurement, can be heavily influenced by space-charge effects while the secondary emission monitors typically used for this cannot handle the nominal LINAC4 pulse length of 400  $\mu$ s.

To overcome these problems, a non-destructive method based on laserwire technology was proposed [2]. A pulsed

laser with a peak power of about 1 kW can be focused to a diameter of less than 200  $\mu$ m in the interaction region with the  $H^-$  beam. Since the outer electron of the  $H^-$  is very weakly bounded to the atom, it can easily be stripped by a low energy photon [3]. Having neutralized a slice of the  $H^-$  beam, the  $H^0$  move straight forward to a detector while the  $H^-$  are deflected by a bending magnet between the laser and the  $H^0$  detector. By scanning the laser beam across the  $H^-$  beam, the  $H^0$  profiles measured can be used to reconstruct the transverse emittance. Figure 1 shows the prototype setup that has been developed for tests during the LINAC4 commissioning at 3 and 12 MeV.

## EXPECTED SIGNAL AND BACKGROUND

The  $H^0$  background is expected to be dominated by  $H^-$  stripping upstream due to collisions with residual gas atoms particularly where the laser  $H^-$  interaction region is not preceded by a dipole magnet. This has been simulated in order to estimate the signal to background ratio at the  $H^0$  detector. The simulation results are shown in Table 1 for different beam energies (3 and 12 MeV during commissioning and 160 MeV for the final system). The signal values are calculated assuming a laser pulse with an energy of 67  $\mu$ J when crossing the center of the  $H^-$  beam and a diamond strip detector with an area of 18 mm x 3.5 mm, used to integrate the arriving  $H^0$ . The signal variation for different energies comes from the different time of flight of the  $H^-$  in the laser light (the slower the  $H^-$  the larger the stripping for similar stripping cross-sections) and the varying  $H^-$  beam sizes at different energies. The reduction of the background for increasing energy follows from the lower expected rest gas concentration. More details can be found in [2].

Table 1: Comparison of Simulation Results for Signal and Background in Different Commissioning Stages

| $H^-$ Beam Energy [MeV]      | 3           | 12         | 160         |
|------------------------------|-------------|------------|-------------|
| Laser Stripped [ $H^0$ / ns] | 1549        | 408        | 2400        |
| Background [ $H^0$ / ns]     | 105         | 69         | 67          |
| <b>SNR</b>                   | <b>14.7</b> | <b>5.9</b> | <b>35.8</b> |

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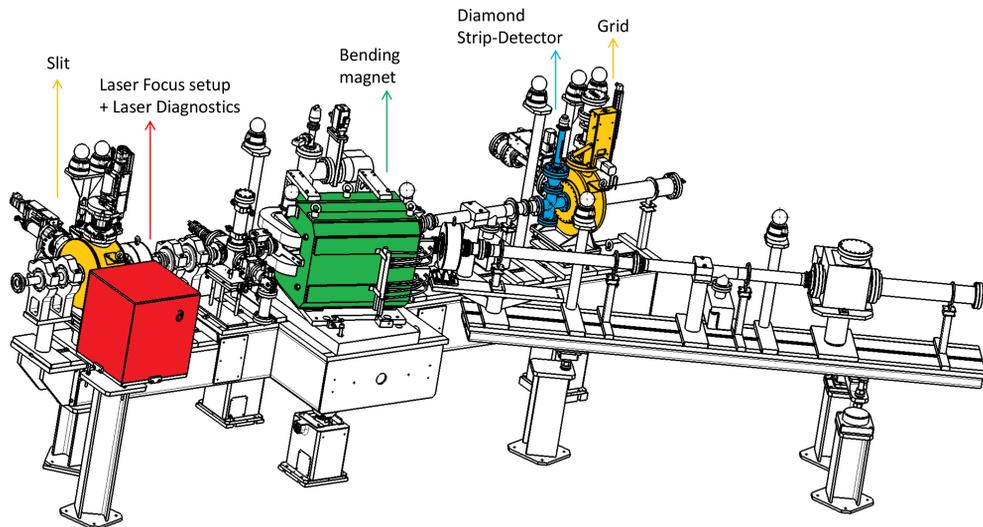


Figure 1: LINAC4 test bench. The laser is transported by an optical fiber to the red box and then focused into the beampipe. The bending magnet separates the  $H^0$  from the  $H^-$ . The  $H^0$  profiles are measured by a diamond strip detector. The laser-diamond measurements can be directly compared to the operational slit-grid system scans.

### PROTOTYPE TEST AT THE LINAC4 3 MeV AND 12 MeV BEAM

A prototype system was developed for tests during the LINAC4 3 MeV and 12 MeV commissioning. The nominal beam parameters are summarized in Table 2. However, during the 3 and 12 MeV tests the  $H^-$  source managed to deliver only up to 8.5 mA.

Table 2: LINAC4 Beam Parameters

| Parameter       | Value       |
|-----------------|-------------|
| Particle type   | $H^-$       |
| Top Energy      | 160 MeV     |
| Pulse Frequency | 0.83 Hz     |
| Pulse Length    | 400 $\mu$ s |
| Nominal current | 40 mA       |
| RF-frequency    | 352 MHz     |

In the measurement setup shown in Fig. 1, the laser source, a diode pumped Master Oscillator Power Amplifier (MOPA) fiber-laser generates 80 ns FWHM pulses [4]. It was operated with a repetition frequency of 30/60 kHz and a pulse energy between 75 and 150  $\mu$ J. The transport of the laser beam to the LINAC4 beam pipe was accomplished by using a Large Mode Area (LMA) optical fiber [5]. This method is on one hand limiting the maximum laser-pulse power but on the other hand a very effective and simple method, when compared to high power, open air lasers. Finally the laser is collimated after the fiber and focused into the beam pipe so that the  $H^-$  beam sees it as a laser wire with an almost constant 150  $\mu$ m diameter. After the interaction of the  $H^-$  ions with the laser, the  $H^0$  atoms created drift for 3.35 m towards the diamond strip-detector shown in Fig. 2. The detector is a 20 x 20 mm, 500  $\mu$ m thick disc of polycrystalline diamond.

The front side is covered by 5 strip-shaped aluminium electrodes while on the back side a 500 V bias is applied to the whole surface. When a  $H^0$  particle hits the detector, the remaining electron is stripped in the first few nanometers with the resulting proton traversing the diamond material, creating carrier and whole pairs. At 3 MeV the proton is absorbed in the diamond after about 50  $\mu$ m, while at 12 MeV it can cross the complete 500  $\mu$ m and exit the detector. The signal produced is proportional to the energy deposited inside the diamond. The detector read out, shown at the bottom of Fig. 2, includes a 1  $\mu$ F capacitor used to rapidly recharge the diamond when electrons are read out. The signal from the diamond is digitized with a 1 GS/s oscilloscope.

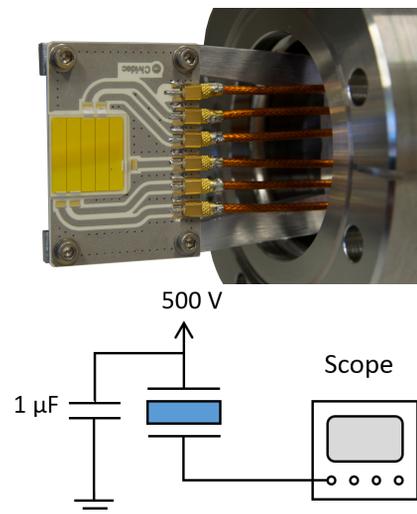


Figure 2: Top: Polycrystalline diamond detector with 5 aluminium electrodes. Bottom: Readout schematic for one diamond channel [6].

### 3 MeV Results

The comparison between the diamond signal and the beam current during a beam pulse is shown in Fig. 3. The signal peaks correspond to the 30 kHz laser pulses. The slight increase of the signal floor can be explained by the  $H^0$  atoms created by residual gas collisions. The ratio between the peak signal and baseline value is fairly constant (between 10 and 11). Given the uncertainties of the simulation input (e.g. gas pressure, detector time response etc...), this value compares well to the simulated value of 14.7 (see Table 1).

Even though in some cases the signal from the diamond detector reproduced well the beam current evolution [7], in most cases, as presented here, the agreement was poor in the second part of the beam pulse. The reason for this is not yet fully understood, but proton implantation in the diamond is likely to play a key role. From simulations, the predicted number of protons implanted by the background for one LINAC-pulse is  $3.7 \times 10^7$ . The variation of the electrostatic field inside the diamond could thus lead to a decreased Charge Collection Efficiency (CCE) during the LINAC pulse. This might also explain the signal amplitude of just a few mV, which is significantly lower than expected by calculations not considering implantation. All measurements at 3 MeV were therefore performed with a 46 dB preamplifier to achieve an acceptable signal level.

Despite the non-optimized diamond detector, it was still possible to complete some emittance scans. Due to the inhomogeneous response of the different diamond channels the

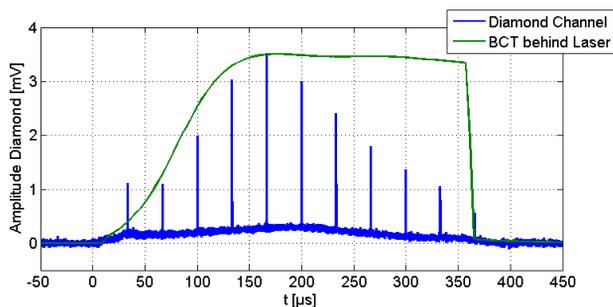


Figure 3: Signal of one diamond detector channel at the 3 MeV test compared to Beam Current Transformer (BCT) signal (normalized to the diamond channel signal).

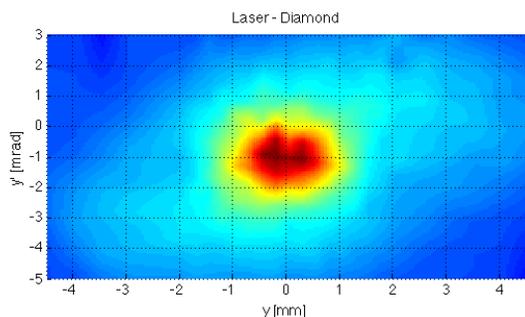


Figure 4: Transverse emittance of the LINAC4 beam at 3 MeV measured with laserwire & diamond detector.

reconstruction of beam profile and emittance was performed with the data of just one channel. Details on the analysis of the acquired data can be found in [8]. An example of the measured phase space distribution is shown in Fig. 4. This result was compared to the operational slit-grid system and the agreement in terms of normalized emittance was found to be within 2% [7].

### 12 MeV Results

At the time of writing just the very first tests at 12 MeV were accomplished. Figure 5 shows the signal from one channel of the diamond detector, compared to a beam current transformer signal, recorded with a similar setup as used for the measurements at 3 MeV. The signal amplitude of the diamond detector is now much higher than at 3 MeV and the shape now follows the beam current measured with the BCT. Since at 12 MeV proton implantation into the diamond is expected to be negligible, this preliminary results would confirm the hypotheses discussed above for the 3 MeV case. The signal to background ratio is also decreased as predicted in Table 1. More measurements at 12 MeV are foreseen in the next few months and will be used for performing emittance scans and to check the homogeneity of the different diamond detector channels.

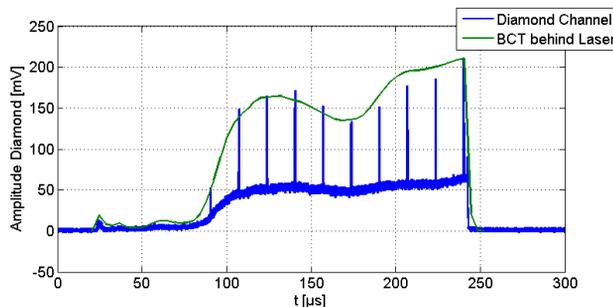


Figure 5: Preliminary result from a 12 MeV beam test. Comparison of one diamond detector channel with a BCT signal (normalized to the diamond channel signal).

## DESIGN OF THE 160 MeV SYSTEM

The final emittance meter will be installed in the 160 MeV section of LINAC4 as shown in Fig. 6. It is foreseen to install two independent systems. Both shall be able to measure the beam emittance in the x and y plane. Due to the high beam energy and proximity to the main dump the radiation level has to be considered when planning the installation, and therefore the laser source will be situated in a cabinet on the surface, about 10 m above the tunnel. The laser beam will again be delivered to the  $H^-$  beam line through a LMA fiber, of about 20 m in length. The design of laser optics and diagnostics can be reused with only minor changes from the 3/12 MeV prototype [4].

### $H^0$ Detector

The first candidate for  $H^0$  monitoring in the final system at 160 MeV is the diamond strip detector tested at 3 and 12 MeV.

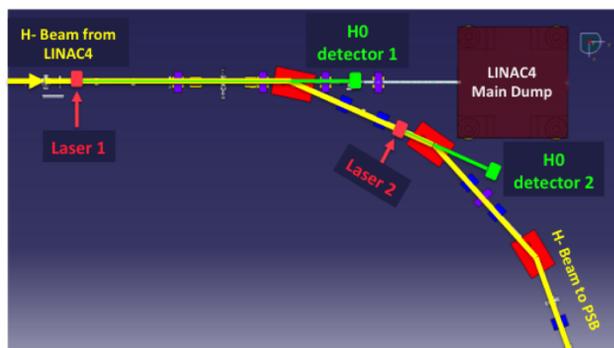


Figure 6: Layout of the 160 MeV section of LINAC4 showing the transfer line towards the PS-Booster and the locations reserved for two laser profile and emittance meter systems.

The number of channels can be increased by changing the design of the front electrodes. Instead of the five existing electrodes with a width of 3.5 mm, it is possible to use a metallisation pattern with up to 35 stripes and a width of 500  $\mu\text{m}$  per channel. Due to the  $H^0$  bombardment and the radiation from the dump, the radiation hardness of the detector has to be carefully examined. When considering 160 MeV protons, diamond detectors are rated about 10 times more radiation hard than silicon detectors [9]. But even this seems to be on the borderline for the LINAC4 requirements. A test carried out with an alpha source in the laboratory after the measurement campaign at the 3 MeV  $H^-$  beam, already showed a degradation of the detector. In order to measure a correct profile despite this ageing due to radiation, a calibration procedure would need to be performed periodically and possibly automatically. Tests to find the most reliable calibration procedure are ongoing.

Alternative  $H^0$  detection concepts such as the use of Gas Electron Multiplier (GEM) [10] are also under investigation.

### *Profile Measurement by Electron Collection*

Measuring the number of stripped electrons during a laser scan allows the transverse beam profile to be reconstructed. This can be achieved by installing a weak bending magnet just after the laser-beam interaction point, so that the electrons are steered to a Faraday cup detector. A system including stripped electron counting has already been implemented at the Oak Ridge Spallation Neutron Source (SNS) [11].

At 160 MeV the stripped electrons have a kinetic energy of just 87 keV. A magnetic field of less than 0.02 T along a 8 cm long gap is therefore sufficient to deflect them by 90°. The unstripped  $H^-$  ions travelling through the same magnet will be deflected by less than 1 mrad, for which an identical corrector magnet with opposite polarity placed just after the electron extraction point will transparently re-steer the main beam to the original orbit.

The challenge for the Faraday cup will be to achieve sufficient time resolution. The Faraday cup as well as its read out electronics will have to be designed to resolve the 80 ns laser-

pulses to distinguish it from the background. The design of the Faraday cup and the magnets is currently ongoing.

## CONCLUSIONS AND OVERVIEW

A laser-based emittance meter prototype was successfully developed and tested in LINAC4 at both 3 and 12 MeV. At 3 MeV the  $H^-$  stripping was found to agree well with prior simulations but the implantation of protons into the detector caused a very weak response of the detector. Nevertheless, a comparison of emittance measurements with the slit and grid system showed very good agreement.

The first tests at 12 MeV, where proton implantation is negligible, show that  $H^0$  detection with a diamond detector can work with high sensitivity. If confirmed by further measurement campaigns at 12 MeV, this would also apply to the final system at 160 MeV.

The next year will be dedicated finalizing this development and producing the final system to measure beam profiles and emittances at the top energy of LINAC4.

## ACKNOWLEDGMENTS

We acknowledge the support of the Marie Curie Network LA<sup>3</sup>NET which is funded by the European Commission under Grant Agreement Number GA-ITN-2011-289191.

In addition, we would like to acknowledge the contribution to this work and to the general development of laser-stripping technologies by Christoph Gabor, who sadly passed away before these results could be published.

## REFERENCES

- [1] W. Weterings et al., "Status of the 160 MeV  $H^-$  injection into the CERN PSB", TUPPR091, Proceedings of IPAC2012, New Orleans, Louisiana, USA
- [2] T. Hofmann et al., "Laser based stripping system for measurements of the transverse emittance of  $H^-$  beam at the CERN LINAC4" MOPME075, Proceedings of IPAC2013, Shanghai, China
- [3] J.T. Broad and W.P. Reinhardt, "One- and two-electron photoejection from  $H^-$ : A multichannel J-matrix calculation", Physics Review A 14, 2159 (1976)
- [4] S. Gibson et al., "Overview of laserwire beam profile and emittance measurements for high power proton accelerators", TUPF15, Proceedings of IBIC2013, Oxford, UK
- [5] Datasheet, "20/130 Passive LMA Double Clad Fiber", www.nuferrn.com
- [6] CIVIDEC Instrumentation GmbH, www.cividec.at
- [7] F. Roncarolo et al., "Transverse profile and emittance measurements with a laser stripping system during the CERN LINAC4 commissioning at 3 and 12 MeV", Proceedings of LINAC2014, Geneva, Switzerland
- [8] S. Gibson et al., "A fibre coupled, lowpower laserwire emittance scanner at CERN LINAC4", Proceedings of IPAC2014, Dresden, Germany
- [9] Wim de Boer et al., "Radiation hardness of diamond and silicon sensors compared", Phys. Stat. Sol. A 204, No. 9, 3004–3010 (2007)

- [10] S. Duarte Pinto et al., "GEM-based beam profile monitors for the antiproton decelerator", J. Instrum., Volume 7, March 2012
- [11] Y. Liu et al., "Laser wire beam profile monitor in the spallation neutron source (SNS) superconducting linac", Nucl. Instr. and Meth. in Phys. Res. section A 612, 241, (2010).