ISBN: 978-3-95450-241-7 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2022-TU3C3

LINAC4 LASER PROFILE AND EMITTANCE METER COMMISSIONING

A. Goldblatt*, F. Roncarolo, J. Tagg, O. Andreassen, CERN, Geneva, Switzerland
T. Hofmann, Bobst Mex SA, Lausanne, Switzerland
G. E. Boorman, A. Bosco, S. M. Gibson, John Adams Institute, Royal Holloway, United Kingdom

Abstract

The CERN LINAC4 is now equipped with two laser profile and emittance meters, a basically non destructive measurement of the transverse beam profile, not limited by the beam power density. The light of a pulsed laser is transported through optical fibers and focused into the 160 MeV/c H^- beam. The interaction of this laser "wire" with the H^- ions detaches electrons that are collected by an electron-multiplier, while the resulting H^0 particles, after being separated from the main H^- beam by a dipole magnet, are recorded by a diamond strip detector, located a few meters away from the interaction point. The transverse beam emittance and profile are reconstructed from the laser by a stepped scan through the H^- beam. After several years of feasibility tests and prototyping, this paper presents the details about the final hardware implementation, operational aspects, and the 2022 experimental results.

INTRODUCTION

Since 2019, when being connected as injector to the Proton Synchrotron Booster (PSB), LINAC4 serves as source of all CERN proton beam formats. While its predecessor LINAC2 was producing 50 MeV/c protons, LINAC4 accelerates H^- ions up to 160 MeV/c which are converted into protons – via a thin stripping foil – during injection into the four rings of the PSB. During the construction and commissioning of the LINAC4, a novel laser-based system was developed to measure the transverse beam profile and emittance in a non destructive way. After several years of design and testing, two systems were installed in strategic locations, both receiving 160 MeV/c H^- beams. The instrument operates on the *photo-detachment* principle, i.e. a laser-based stripping of the weakly coupled, second electron of the H^- ion, described in detail in [1–4]. The light of a pulsed laser is transported through optical fibers and focused to a cross section of about 140 µm diameter into the H^- beam. For each LINAC pulse, approximately 7% of the ions interacting with the laser are fully stripped. As depicted in Fig. 1:

- at the interaction point (IP) the detached free electrons are bent by a short dipole (weakly affecting the main beam) into an electron-multiplier tube (EMT).
- the neutral H^0 particles are measured on a diamond strip detector a few meters downstream, after being separated from the H^- beam by a main linac dipole.

The laser is scanned in well defined increments horizontally (H) or vertically (V) through the H^- beam. Correlating the laser positions at the IP with the EMT and diamond detector signals allows the reconstruction of the beam profile and emittance, respectively, similar to a classical slit-grid emittance-meter.

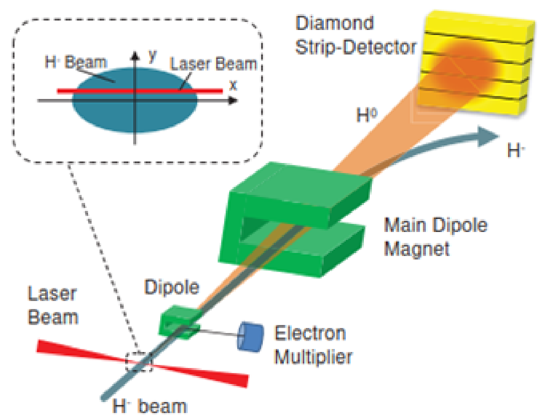

Figure 1: Concept of the laser emittance meter.

HARDWARE IMPLEMENTATION

It was decided to implement two systems to guarantee redundancy, and also to be complementary. The first system was installed at the end of the linac, before the first horizontal bend to the PSB transfer line. Here the beam emittance is dominated by the the beam size wrt. the dispersion. The second system is located between two main dipole magnets in the transfer line, where the H^0 background due to beam gas stripping is low. The distance between the H^0 detectors and the laser IP, 4.5 and 7 m, was chosen to have a convenient phase advance for sampling the angles of the emittance ellipse, like performed in slit-grid emittance-meters. The laser source, located in a dedicated hutch in the LINAC4 klystron hall, consists of an infrared laser with adjustable power, frequency and pulse length, with charateristics detailed in Table 1. The beam quality factor ensures a small beam diameter and long *Rayleigh* range at the interaction point, which is crucial to achieve a good resolution. The laser beam is transported from the surface to the interaction points in the LINAC4 tunnel through large mode area optical fibers with a special end-facet, designed to withstand the laser power density. Each of the two instruments receives two fibers of 30 and 70 m length to reach the two IP locations, for horizontal and vertical laser scans.

The diamond strip detector is composed of two motorized sensors, each having 28 channels with a pitch of 0.34 mm. They were produced by a polycristalline chemical vapor deposition (pCVD) method and are radiation tolerant. Two

* aurelie.goldblatt@cern.ch

ISBN: 978-3-95450-241-7 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2022-TU3C3

sizes are used, 20 20 or 32 10 mm. The diamond detector signals are amplified in the LINAC4 tunnel and transported to the surface where the digital data acquisition system is located. The electron-multiplier tube (Hamamatsu model R2362) has an aperture diameter of 20 mm and a gain of approximately 10^6. The laser hutch and the optical breadboards in the tunnel are equipped with photodiodes, energy meters and digital cameras to setup, tune and periodically control the laser-fiber coupling, transmission and focusing. A PXI system from National Instruments [5] handles the control and acquisition. It contains a PXIe controller (running LabVIEW RT 2017), a timing/synchronisation card, a general purpose DAQ card, and the ADCs for the signals digitization. The sampling frequency of the diamond detector ADC is 50 MHz, while the ADCs for the electron multiplier and photodiodes clock at 120 MHz. The controller include FPGAs for the entire low level control and real time signal processing, and was recently integrated to the CERN control and read-out infrastructure (FESA [6]).

Table 1: Laser Specifications

Model	Spectra Physics VPFL-ISP-POD-50
Wavelength	1064 nm
Power	Average 50 W, max peak 30 kW
Frequency	Single shot to 2 MHz, used 500 kHz
Pulse width	2 to 250 ns, used 100 ns
M^2	1.3

OPERATIONAL ASPECTS

The final beam commissioning of the laser emittance meter started in 2018 with a temporary version of timing architecture, which later in 2020 was upgraded to include the synchronization between LINAC4 and the PSB. The LINAC4 beam consists of RF macro-pulses of up to 650 µs duration every 1.2 s, filled with micro-bunches created by the RF accelarating structures operating at 352 MHz. A fast RF chopper, located in the 3 MeV medium energy beam transport (MEBT) is used to tune the macro-pulse filling factor following the PSB user request, and creates empty buckets required for the LINAC4 beam injection into the four PSB rings[1], and the ones necessary for the multi-turn injection into each ring. Each 1 µs duration PSB turn must have a 300 ns empty gap for beam injection and extraction. The laser is pulsed synchronous with the chopper at a fixed frequency, typically at 500 kHz. Therefore, several timing signals are directly linked between the RF chopper system and the DAQ system of the laser emittance meter: the laser is synchronized to the 1 MHz PSB revolution frequency, while start and end of the data acquisition are triggered by the timing signals of the four PSB rings that define start and end of the beam injection. In that way each laser wire data chunk in a LINAC4 macro-pulse can be automatically associated to the beam for a particular PSB ring. The time delays of both, laser pulse and data acquisition are adjustable in steps of 10 ns, which can be used to sample different parts of the macro-pulse. During a measurement scan, the laser and diamond positions change every 1.2 s. A full scan takes about ten minutes in order to achieve a good resolution of the phase space ellipse. For the reconstruction of the beam profile and emittance from the raw data, the pulse signals of the diamond strip-detector have to be integrated and their channel position have to be correlated to the actual position of the laser beam at the IP. As illustrated in Fig. 2, this is performed in the FPGA "on the fly" during the scan. The EMT pulse data is processed ans included via software at the end of each scan, as discussed in the next section.

[1] The very last part of the LINAC4-PSB transfer line is equipped with a *fast distributor*, based on a combination of pulsed magnets and septas, splitting the macro-pulse into the four PSB rings.

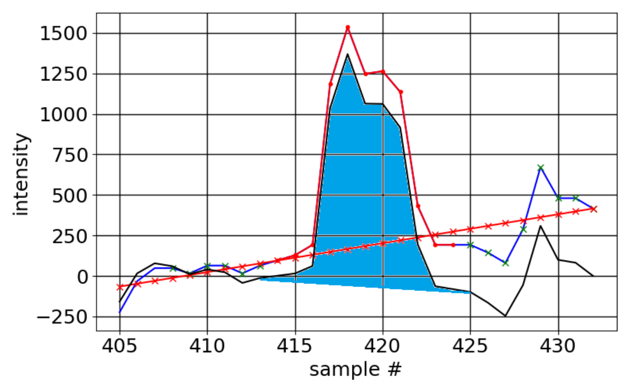

Figure 2: The FPGA process the diamond data by subtracting the background, summing the pulse area (in blue) and saves the resulting value.

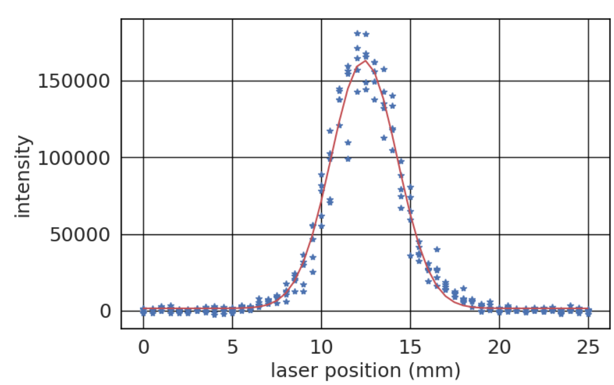

Figure 3: Reconstructed profile from the electron multiplier data.

DATA PROCESSING

Presently, the profile and emittance reconstruction algorithms are performed via Python routines launched at the end of a scan. For each laser sampling point along the beam pulse, e.g. each 2 µs if the laser pulse rate is set to 500 kHz:

ISBN: 978-3-95450-241-7 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2022-TU3C3

- the EMT pulse integral as function of laser position provides a data point according to the beam transverse beam profile and correspondent size (via a Gaussian fit). An example of a complete scan is shown in Fig. 3.
- the correlation of the laser positions and the H^0 beamlet profiles measured by the diamond strip detectors, together with the known distance between laser-H^- beam IP and diamond detector allows inferring the beamlet position and divergence, and thus reconstruct the H^- beam transverse phase space.

The transverse emittance is estimated by calculating the phase space ellipse area after subtraction of the background by applying a data intensity threshold. Determining the optimal threshold to suppress background while not excluding beam tails in the position and angle coordinates is not always trivial and deterministic. It turned out to be reasonable to estimate the correct threshold near the inflection point of the curve. An example of the emittance values obtained as function of the threshold (expressed as percentage of the phase space maximum) is shown in Fig. 4.

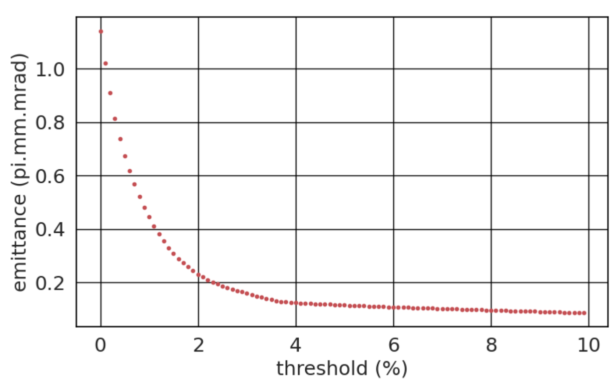

Figure 4: Example of vertical normalized emittance values as calculated for different applied thresholds.

Comparison of EMT and Diamond Profiles

The projection of the emittance phase-space H or V ellipse, measured by the diamond detector, along the position axis gives the corresponding H or V beam profile, and can be compared to the direct profile measurement utilizing the EMT. Both methods use the same laser scan and the resulting photo-detachment, but are based on different, independent detection techniques, counting detached electrons vs. profiling H^0 beamlets. So far, our beam studies show a good the agreement between the two techniques, with the results to be well within a 0.5% difference in the H plane when comparing the measured beam size along the macro-pulse, as Fig. 5 shows.

However, the vertical beam sizes measured by the the EMT appeared to be smaller compared to the measurement from the projection of the phase-space ellipse. The EMT profiles also show evidence of sharply decreasing tails, which may be a hint to the effect of a beam *scraping*. Therefore, we are now investigating the combined effects of

(i) a limited EMT detector acceptance.

(ii) the vertical beam size at this location appears to be larger than the horizontal beam size.

(iii) the field strength of the short magnet used to bend the stripped electrons is set to a single value for the entire laser scan, optimized to get the highest signal with the laser hitting the H^- beam center.

(iv) a possible tilt of the bending magnet introducing H-V coupling, and thus a vertical kick of the detached electron beam.

As the EMT is not movable, the study of these hypothesis will require dedicated machine development time to perform multiple laser scans with different magnet settings[2].

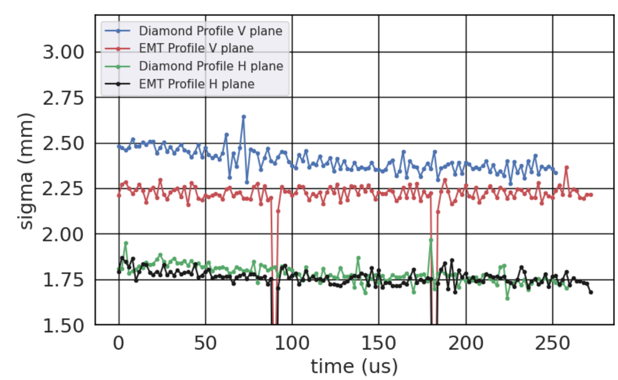

Figure 5: Diamond and EMT profiles along the macropulse.

Diamond Detector Signal Perturbation

The first measurements in 2022 of the beam emittance along the LINAC4 pulse revealed the presence of a perturbation, common to all diamond detector channels. As shown in Fig. 6, without any filtering a strong signal, larger than emittance variation along the macro-pulse, perturbs the emittance measurement.

A *Fourier* analysis of the integrated diamond detector signals, with the detectors in the parking position, confirms an unwanted strong, signal harmonic at ≈ 50 kHz, see Fig. 7. A Fast *Fourier* Transformation (FFT) of the integrated signals of all diamond detector channels exposed to the H^0 beam reveals the beam itself seems to contain frequency components which perturb the diamond signal, see Fig. 8.

During a stop in the 2022 run, it was possible to identify a 2 MHz perturbation signal, taking its source in the individual cables transporting the diamond raw signals before integration from the detectors to the pre-amplifiers few meters away. After integration of the diamond pulse signals, this could explain the observed 50 kHz artifact. During the upcoming

[2] Even if the effect on the main beam is weak, the H^- beam trajectory always has to be re-adjusted for each change of the magnet field.

ISBN: 978-3-95450-241-7 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2022-TU3C3

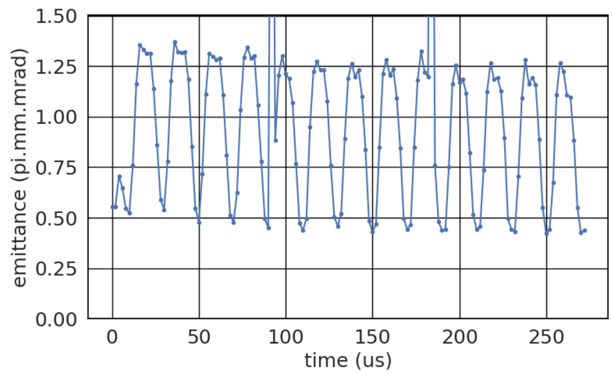

Figure 6: Emittance reconstruction from the integrated the diamond detector raw data along the macro-pulse.

winter stop at the end of 2022 it is foreseen to review the shielding, routing and grounding of all cables. Meanwhile, applying a digital notch filter during the data processing resulted to be very effective in filtering the 50 kHz perturbation. It should be noted, this 50 kHz perturbation signal on the diamond detectors, while perturbing the emittance calculation, does not affect the beam size measurements inferred from the phase space projection, it only adds an offset on the measured beam profiles.

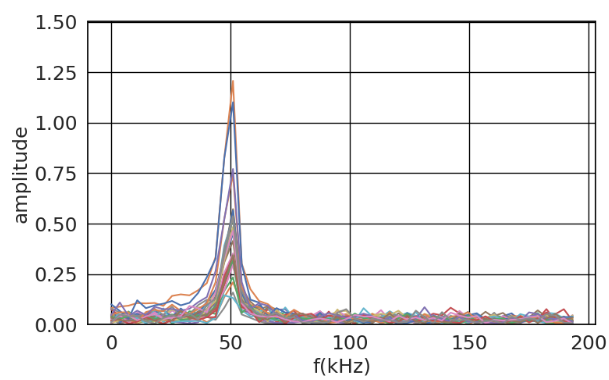

Figure 7: FFT of the integrated data, with diamond detector out of beam. Each line corresponds to a diamond detector channel.

Emittance Measurements

Fig. 9 shows a typical emittance measurement from the laser emittance meter located in the transfer line, as reconstructed phase space ellipse from the diamond data for one pulse along of the LINAC4 macropulse. As shown in Fig. 10, the vertical emittance along the LINAC4 macropulse decresases during the first 150 µs section, until it reaches a similar emittance value (in the 2nd and 3rd 150 µs sections) as the emittance measured in the horizontal plane, which almost matches the emittance measured by the wire scanners, generally used as reference. The notch filter used to suppress the 50 kHz perturbation of the integrated diamond data is suspected adding some unwanted “edge” effects to the calculation of the emittance along the macropulse. More investigations will be made, as well as measurements with the laser emittance meter system located towards the LINAC4 dump line.

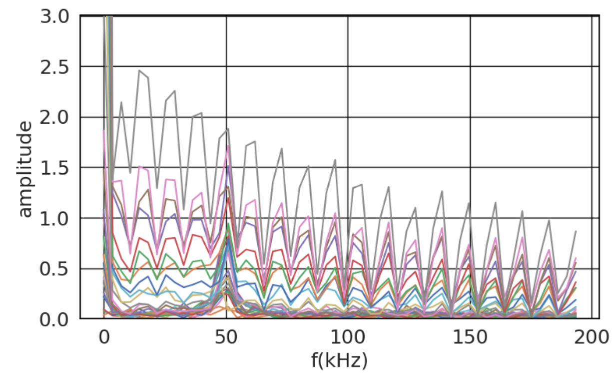

Figure 8: FFT of the raw diamond detector data. Each line corresponds to a diamond channel. The channels exposed to the H^0 beam show multiple harmonics.

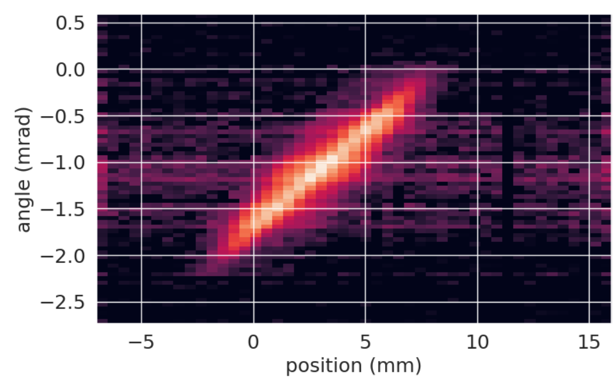

Figure 9: Example of vertical phase space ellipse measured by the laser emittance meter from one laser pulse of the macropulse.

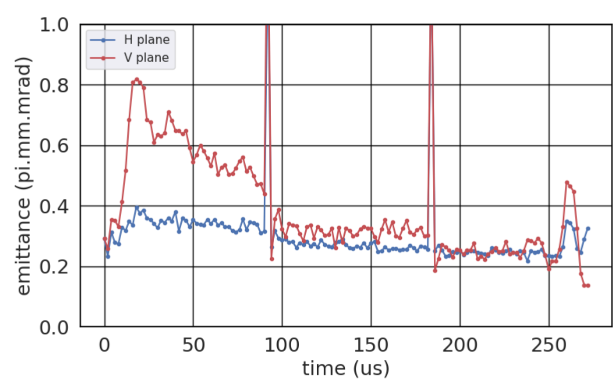

Figure 10: Normalized emittance along the macropulse measured by the laser emittance meter.

ISBN: 978-3-95450-241-7 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2022-TU3C3

CONCLUSION AND OUTLOOK

The completion of the commissioning of the laser emittance meter at the beginning of year 2022 allowed first systematic measurements in view of assessing the performance of the instrument. It appeared the quality of the emittance measurement from the diamond sensors is degraded by the presence of periodic perturbation signal that has an electrical origin, but seems as well transported by the LINAC4 beam. A digital notch filter is used to effectively supress the electrical perturbation signal, but it is planned to improve the shielding of the signal cables during the next winter technical stop.

The emittance measured along the LINAC4 macropulse by the laser emittance meter located in the transfer line shows some unexpected behavior in vertical plane that might have its origin from the filtering. More analysis will be performed to understand this phenomena and other measurements with the laser emittance meter located towards the beam dump line will bring other interesting material to study.

In the near future, different hardware and software strategies will be explored to improve the performance of the laser emittance meter. The comparison with other emittance and profile instruments will be performed as well.

ACKNOWLEDGEMENTS

We would like to thank our colleagues from CERN and Royal Holloway Institute for their strong past and present involvement, work and support on this project.

REFERENCES

[1] T. Hofmann, "Development of a Laser-based Emittance Monitor for Negative Hydrogen Beams", Ph.D. thesis, University of Erlangen-Nuremberg, Germany, 2017.

[2] T. Hofmann, U. Raich, F. Roncarolo, G. E. Boorman, A. Bosco and S. M. Gibson, "Results From the Laserwire Emittance Scanner and Profile Monitor at CERN's Linac4", in *Proc. LINAC'16*, East Lansing, MI, USA, Sep. 2016, pp. 715–719. doi:10.18429/JACoW-LINAC2016-TH2A02

[3] T. Hofmann, G. E. Boorman, A. Bosco, S. M. Gibson and F. Roncarolo, "Commissioning of the Operational Laser Emittance Monitors for LINAC4 at CERN", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 2357–2360. doi:10.18429/JACoW-IPAC2018-WEPAL074

[4] R. E. Shafer, "Laser diagnostic for high current H– beams", *AIP Conference Proceedings*, vol. 451, no. 1, pp. 191–198, 1998. doi:10.1063/1.56999

[5] National Instruments, https://www.ni.com/.

[6] A. Guerrero, J. J. Gras, J-L. Nougaret, M. Ludwig, M. Arruat and S. Jackson, "CERN Front-End Software Architecture for Accelerator Controls", in *Proc. ICALEPCS'03*, Gyeongju, Korea, Oct. 2003, paper WE612, pp. 342–344.