RESULTS FROM THE LASERWIRE EMITTANCE SCANNER AND PROFILE MONITOR AT CERN'S LINAC4

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Abstract

A novel, non-invasive, H^- laserwire scanner has been tested during the beam commissioning of CERN's new Linac4. *Emittance* measurements were performed at beam energies of 3 and 12 MeV with this new device and were found to closely match the results of conventional slit-grid methods. In 2015, the configuration of this laserwire scanner was substantially modified. In the new setup the electrons liberated by the photo-detachment process are deflected away from the main beam and focused onto a single crystal diamond detector that can be moved in order to follow the laser beam scan. The beam *profiles* measured with the new laserwire setup at 50 MeV, 80 MeV and 107 MeV are in good agreement with the measurements of nearby SEM grids and wire-scanners. The design of the final laserwire scanner for the full 160 MeV beam energy will also be presented. In Linac4 two independent laserwire devices will be installed in the transfer line to the BOOSTER ring. Each device will be composed of two parts: one hosting the laserwire and the electron detector and the second hosting the segmented diamond detector used to acquire the transverse profiles of the H^0 beamlets.

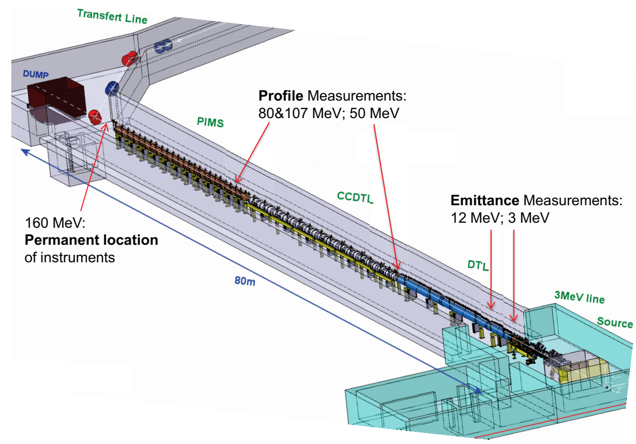

Figure 1: Linac4 facility with beam energies at different commissioning steps. The laserwire instrument has been tested at 3 and 12 MeV for emittance measurements and at 50, 80 and 107 MeV for profile measurements. The final instruments will be installed at Linac4's top energy of 160 MeV.

INTRODUCTION

Laser-based devices offer several diagnostic possibilities for H^- accelerators. Transverse profile measurements are the most commonly used [1] but other measurements as transverse emittance [2], longitudinal bunch profile [3] or energy spread [4] have also been implemented recently. The main advantages are the wide operational ranges in terms of beam energies and intensities and the absence of mechanical parts intercepting the main beam (non-destructive measurements).

In our case the laserwire instruments will be used to measure the transverse profiles and the transverse emittances of the beams at the end of Linac4, at an energy of 160 MeV. These measurements will be used to tune the optics parameters of the accelerator and optimize the matching to the BOOSTER ring, thus maximizing the injection efficiency. Prototypes of the Linac4 laser-scanners have been tested during the commissioning of the machine. Figure 1 illustrates the locations, at the different energies, where the tests have been performed.

The monitor concept is illustrated in Fig. 3: as the thin laser beam crosses the H^- beam, the low energy photo-detached electrons are deflected by a small magnet onto an electron collector, while the neutralized H^0 atoms drift unperturbed to a downstream segmented detector. A dipole magnet, located between the laser and H^0 detector, is then used to separate the H^0 beamlet from the main H^- beam. By scanning the laser through the H^- beam, the beam profile can be obtained from the evolution of the electron signal on the collector and the transverse phase-space can be reconstructed using the H^0 profiles acquired as function of the laser position.

The system is based on a relatively low-power pulsed laser (~kW peak-power), which can be reliably transported to the interaction point (IP) with the H^- beam by an optical fiber.

EMITTANCE MEASUREMENTS

The first prototype was designed to validate the vertical phase-space reconstruction via the H^0 detection and was tested during the 3 and 12 MeV commissioning periods. Figure 2 shows the test setup with a zoom on the laser delivery system situated next to the IP. To detect the profiles of the H^0 beamlets after the bending magnet a polycrystalline (pCVD) diamond strip detector was used (see Fig. 4). This type of detector offers high sensitivity and bandwidth and, most important, an excellent radiation hardness [5].

The Linac4 beam consists of 400 µs long macro-pulses with H^- bunched at 352.2 MHz while the laser generates macro-pulses of 1 ms with 80 ns long pulses repeated at

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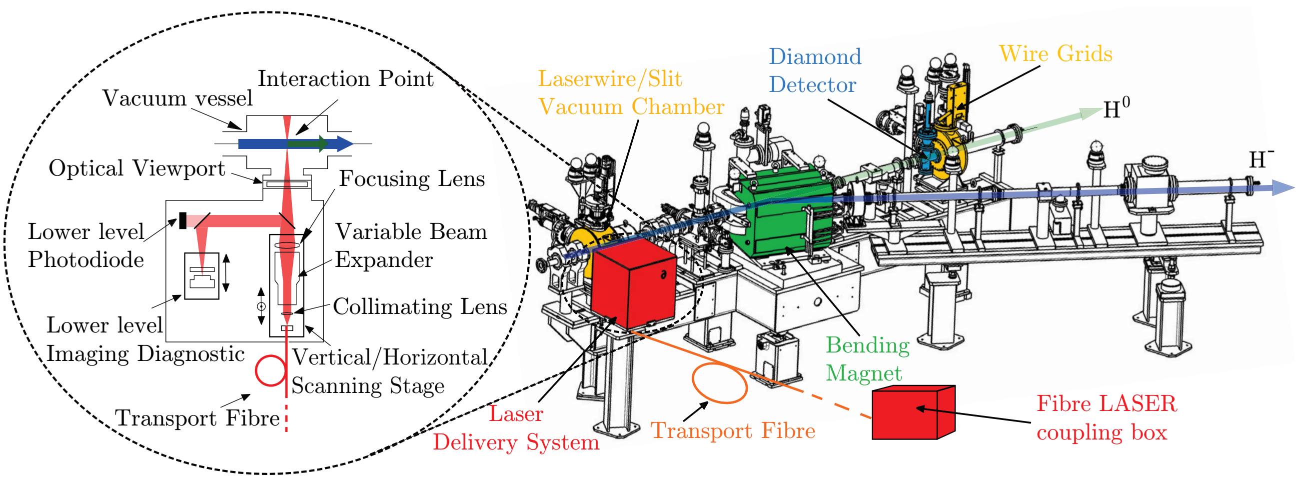

Figure 2: Layout of the 3 and 12 MeV diagnostics test-bench, including the operational emittance meter (slit and grid) and the laserwire emittance scanner prototype [6].

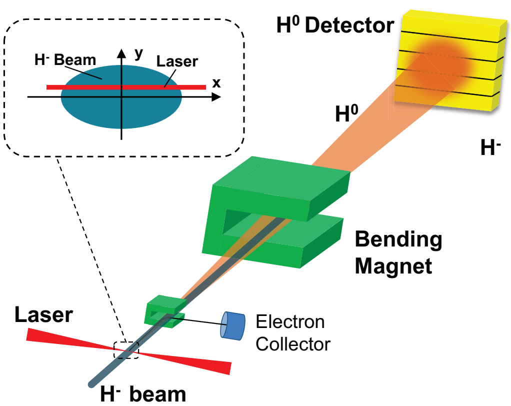

Figure 3: Concept for combined vertical profile and emittance measurement. Measurement in the horizontal plane can be realized by rotating the laser beam and the H^0 strip-detector by 90°.

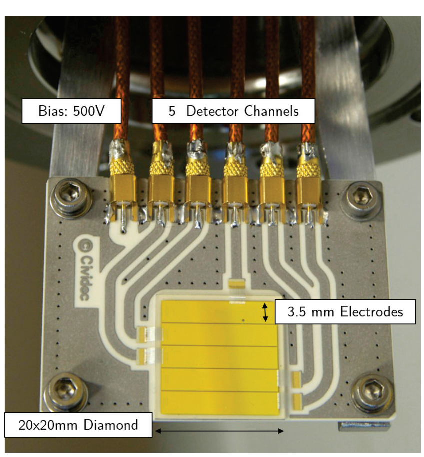

Figure 4: pCVD diamond detector with 5 strip electrodes [6].

60 kHz. One H^- beam macro-pulse is thus hit by several laser pulses and each laser pulse interacts with many H^- bunches (see Fig. 5).

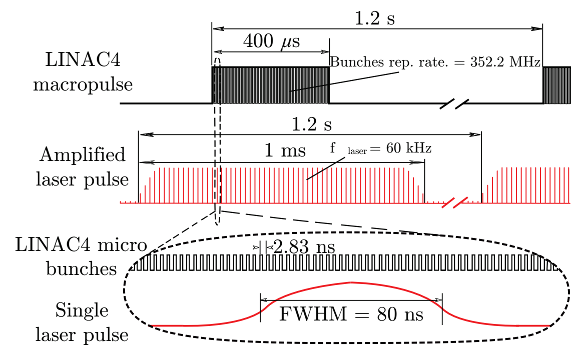

Figure 5: Timing of Linac4 and laserwire compared [6].

The transverse properties of the laser beam have been characterised at the IP location by using the imaging diagnostic setup shown on the left of Fig. 2. The laser waist was found to be approx. 150 µm in diameter with a Rayleigh range of more than 7.5 mm. Considering the small transverse dimensions of the H^- beam the laser beam can thus be considered like a thin wire. The longitudinal properties of the laser pulses have been characterized using a photo-diode.

Figure 6 shows an overlay of the laser pulse at the photodiode and the H^0 pulse on the diamond detector. The clear correlation confirms that the signal on the diamond detector corresponds to H^0 particles originated by the laser interaction.

The response of the diamond detector has been characterised in terms of its linearity, intrinsic bandwidth and homogeneity of the stripes. Further details on these measurements can be found in [7].

The measurement of the vertical phase-space was conducted by scanning the laser across the H^- beam and recording the created H^0 profiles with the diamond detector to measure the beamlet's angular distribution. One point in phase-space corresponds to a signal as shown in Fig. 6. After subtracting the background, the integral is built and plotted for each position. An example of the resulting phase-space plot, recorded at 12 MeV beam energy, can be seen at the bottom of Fig. 7. The agreement with the slit-grid measure-

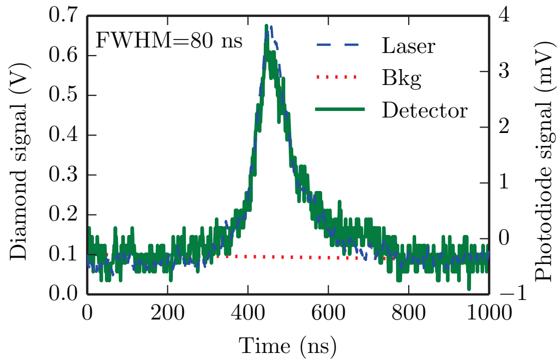

Figure 6: H^0 pulse on the diamond detector (solid - inverted), compared to the corresponding laser pulse (dashed). Dotted trace – linear fit of the background [6].

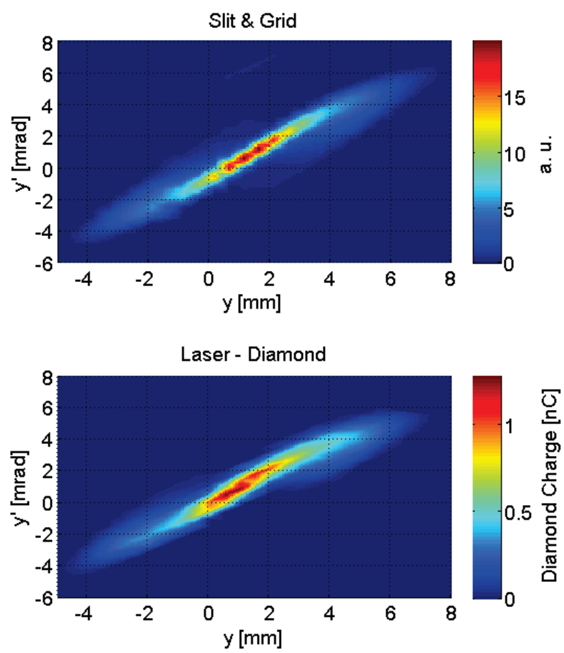

Figure 7: Phase-space sampled with the slit/grid method (top), with the laser/diamond system (bottom) [7].

ments (top of Fig. 7) was found to be within 3 % in terms of emittance, which is a remarkable result. Discrepancies can just be observed in the angular domain (y') as the resolution of the detector prototype was still rather low (see strip-width in Fig. 4) to limit the effort in the DAQ chain. This is going to be re-designed for the final instrument being installed at 160 MeV region. Apart from this, the dominant error sources for the measured emittance value

$$\epsilon_y = \sqrt{\langle y^2\rangle\langle y'^2\rangle - \langle yy'\rangle^2} \tag{1}$$

are shot to shot fluctuations of the H^- -beam and/or laser-pulses and the noise suppression method (see [7]). A more detailed discussion of the emittance measurements can be found in [6, 7].

PROFILE MEASUREMENTS

The commissioning steps at 50, 80 and 107 MeV were conducted with a different diagnostic test bench, shown in Fig. 8. Due to the lack of a main dipole, the H^0 beamlets could not be separated from the H^- beam. This period was therefore used to monitor the detached electrons and reconstruct the vertical beam profile of the H^- beam.

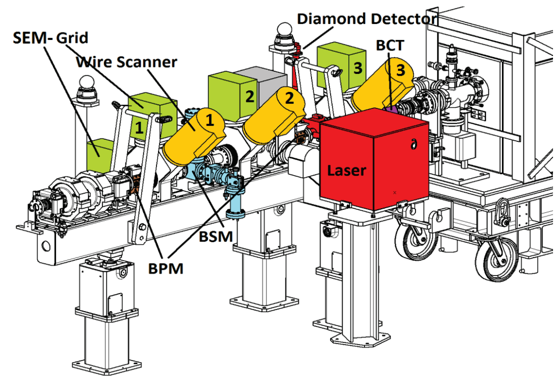

Figure 8: Diagnostic test-bench used for beam commissioning at 50, 80 and 107 MeV H^- beam [8].

The conceptual design of the profile station, consisting of a laser interaction chamber, a dipole magnet and a single crystal (sCVD) diamond detector to record the liberated electrons, is shown Fig. 9. Prior to the beam measurements, the new laser source and the transmission of light to the beam-pipe were characterised and the trajectory of the electrons across the magnetic field was simulated. An in-depth discussion on the whole setup can be found in [9]. The

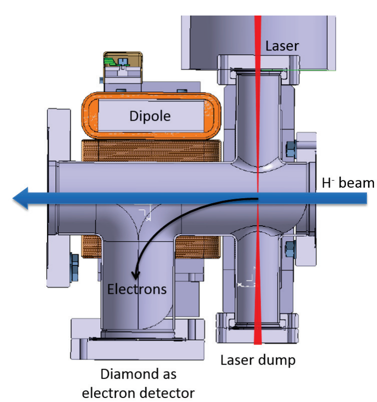

Figure 9: Setup for profile measurement. Detached electrons are deflected by a weak dipole field and recorded by a sCVD diamond detector [9].

pre-amplified signal on the diamond detector for one laser position can be seen in Fig. 10. A clear signal of laser-detached electrons corresponding to the yellow surface is obtained for each laser position. After a scan of the laser across the H^- beam, the vertical beam profile was reconstructed by plotting the integrated charge versus the laser position. The result is compared to the other profile monitors installed on the test-bench in Fig. 11. Due to their different

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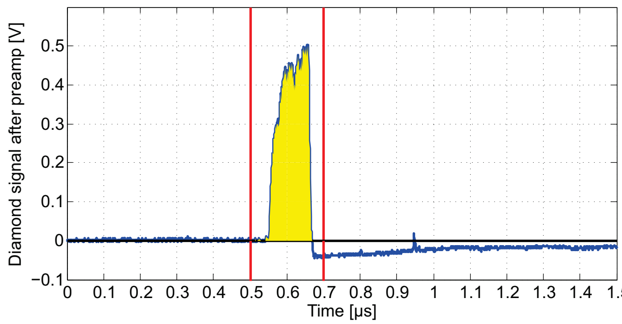

Figure 10: Signal of liberated electrons as measured by the diamond detector with integration limits in red and integrated charge in yellow.

longitudinal position, the profiles have been scaled linearly as no quadrupole magnet is located in between. An excellent agreement was found for all 5 instruments. The discrepancy between the profile recorded with the laserwire instrument and the linear interpolation between the SEM/WS profiles have been monitored for multiple measurements at different beam energies and different beam settings. The error has been consistently below ±2% in terms of beam size. A more

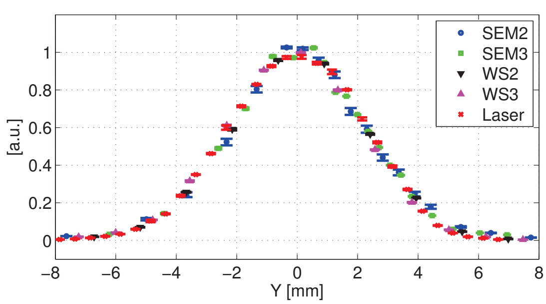

Figure 11: Overlay of profiles recorded at 107 MeV energy with different devices (WS = wirescanner; SEM = Secondary Emission Grid).

detailed characterisation of the profile-monitor including the electron trajectory, the detector linearity as function of number of impinging electrons and the detector homogeneity can be found in [9, 10].

DESIGN OF FINAL INSTRUMENT

A design for combined profile and emittance measurements by sensing electrons and H^0 atoms in both planes (X and Y) has been developed, based on the experience gained with the prototypes described previously. Figure 12 shows the Linac4 layout including the location of two laser interaction stations (each with X and Y laserwire axes, steerer and electron detector, all evidenced in red) and H^0 monitor systems (light blue), separated by a dipole (green).

Laser System

The laser system has been designed in order to perform measurements in the horizontal and vertical planes simultaneously. As illustrated in Fig. 13, the laser beams are

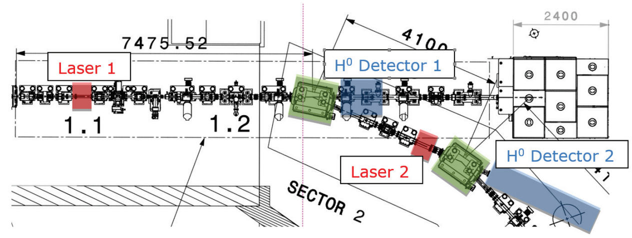

Figure 12: Setting for 2 laserwire instruments, which will be installed at the 160 MeV region at Linac4.

delivered to the IP by optical fibers and are focussed (L1/L2) into the vacuum vessel horizontally and vertically simultaneously. To distinguish the interaction products with the H^- beam, the laser pulses are separated in time by $\sim 250\,ns$. The stages Sg1 and Sg2 can be used to either scan the laser beams across the H^- beam or to re-direct the laser beams via mirrors (M1/M2) to a CCD for its characterisation.

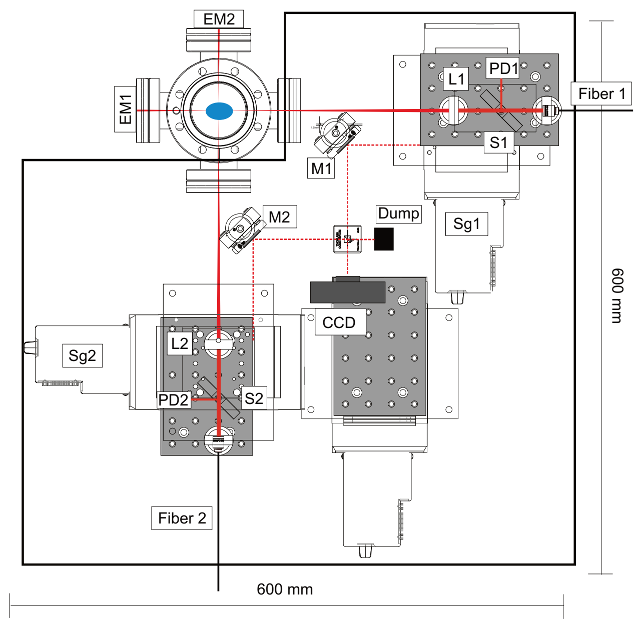

Figure 13: Laser injector with beam-pipe.

Electron Detector

Based on the experience during the 50/80/107 MeV run, the detector design for electron detection was reviewed. Although the sCVD diamond detector provided very clear and linear signal response in most beam conditions, in certain settings a background of scattered protons, H^- or H^0 was worsening the signal quality. Due to the high proton restmass, even single protons could cause a perturbing spike in the detector signal. It was thus decided to change to a Electron Multiplier Tube (EMT), of which the response is independent of the rest-mass of the impinging particle and it is thus able to suppress the proton background. The principle of this detector is shown in Fig. 14. It is based on secondary electron emission of the staged dynodes. In this way an amplification of up to 10^7 can be reached.

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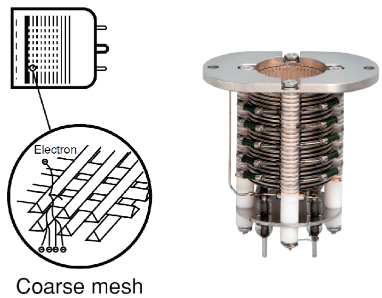

Figure 14: Electron Multiplier Tube (EMT). Left: Principle of coarse mesh type EMT; Right: Photo of EMT selected for 160 MeV electron detection [11, 12].

H^0 Detector

For the detection of the H^0 atoms the design of the pCVD diamond detector has been revised in order to achieve higher resolution by using a finer strip pattern (0.33 mm compared to 3.5 mm at the detector in Fig. 4). Figure 15 shows the new design of one H^0 detector where the yellow area on the bottom corresponds to a 32 x 10 x 0.5 mm pCVD diamond disc with 28 strip electrodes. The detector will be mounted on a vertical actuator to cover the range of arriving H^0 beamlets. For simultaneous measurement of both planes a similar detector will be placed 10 mm downstream on a horizontal actuator. Due to the kinetic energy of the H^0 atoms, they can cross both detectors with negligible scattering and thus horizontal and vertical profiles can be acquired simultaneously.

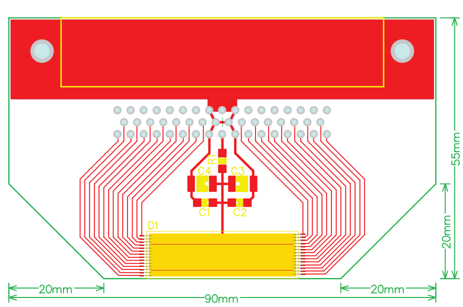

Figure 15: Design of diamond detector used for H^0 detection at 160 MeV.

SUMMARY

Two prototypes of the laserwire emittance scanner have been tested during Linac4 commissioning. The first instrument was tested at 3 and 12 MeV with main focus on the vertical *emittance* measurement with a low-power fiber-laser and a pCVD diamond detector. The second prototype measured the vertical beam *profile* at the 50, 80 and 107 MeV by using a steerer magnet to deflect the liberated electrons into a sCVD diamond detector. Both instruments were compared with operational instruments and in all cases a very good agreement was found.

Based on the experience with both prototypes, the design for a permanent installation of 2 instruments at Linac4's top energy of 160 MeV was completed. It combines both the emittance and profile monitors and will allow measuring both planes (X & Y) simultaneously. Furthermore, the electron detector will be replaced by an electron multiplier which is insensitive to the experienced proton background and the H^0 detector will be significantly enhanced regarding its resolution.

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