EXPERIMENTAL RESULTS OF A COMPACT LASERWIRE SYSTEM FOR NON-INVASIVE H⁻ BEAM PROFILE MEASUREMENTS AT CERN'S LINAC4

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Abstract

A non-invasive laserwire system is being developed for quasi-continuous monitoring of the transverse profile and emittance of the final 160 MeV beam at CERN's LINAC4. As part of these developments, a compact laser-based profile monitor was recently tested during LINAC4 commissioning at beam energies of 50 MeV, 80 MeV and 107 MeV. A laser with a tunable pulse width (1-300 ns) and ~200 W peak power in a surface hutch delivers light via a 75 m LMA transport fibre to the accelerator. Automated scanning optics deliver a free space < 150 micron width laserwire to the interaction chamber, where a transverse slice of the hydrogen ion beam is neutralised via photo-detachment. The liberated electrons are deflected by a low field dipole and captured by a sCVD diamond detector, that can be scanned in synchronisation with the laserwire position. The laserwire profile of the LINAC4 beam has been measured at all commissioning energies and is found in very good agreement with interpolated profiles from conventional SEM-grid and wire scanner measurements, positioned up and downstream of the laserwire setup. Improvements based on these prototype tests for the design of the final system are presented.

MOTIVATION

Non-invasive Beam Diagnostics at LINAC4

Conventional beam diagnostics such as SEM-grids and wire scanners inherently obstruct a significant fraction of the particle beam during measurements. To enable quasi-continuous monitoring of CERN's new LINAC4 160 MeV H^- accelerator, a laserwire system is being developed that probes the particle beam properties via photo-detachment interactions as the H^- ions traverse a narrow beam of light. As only 10^8 of the 10^{14} H^- ions in each LINAC4 pulse are typically neutralised by this laserwire, the technique is essentially non-invasive.

The ultimate aim of these developments is to install a permanent dual-laserwire system for use at LINAC4 top energy of 160 MeV, to measure the transverse emittance and beam profile. In our previous studies, a prototype laserwire emittance scanner was successfully demonstrated at the 3 MeV and 12 MeV commissioning phases of LINAC4 [1–3]. By scanning the vertical position of the laserwire with respect to the beam, the transverse emittance was reconstructed from the spatial distribution of neutralised H^0 atoms recorded by a downstream segmented diamond detector. The main H^- beam was deflected by a dipole magnet, which for those measurements formed part of the diagnostics test bench at LINAC4.

The main dipole was not present for LINAC4 commissioning at 50 MeV through to 107 MeV beam energies, instead, the opportunity was taken to develop a new setup to measure the transverse beam profile, based on the electrons liberated by the photo-detachment process.

Beam Profile Monitor Design

The design of the beam profile monitor was presented previously [4] and is shown here for completeness in Figure 1. The laser beam delivery optics from the prototype were adapted and reused to direct light into a new, compact interaction chamber, in which the laserwire is orthogonal to the incoming H^- beam. A transverse slice of the H^- beam is neutralised as the H^- beam passes through the laserwire focus, liberating low energy (27 keV for 50 MeV H^-) electrons that are readily deflected through 90° by a 0.9 mTm integrated field of a weak dipole magnet. The main H^- beam remains almost undeflected by the weak dipole. The electrons are collected by a fast 4 mm × 4 mm, sCVD diamond detector, that can be moved vertically in synchronisation with the laserwire position, allowing the beam profile to be reconstructed.

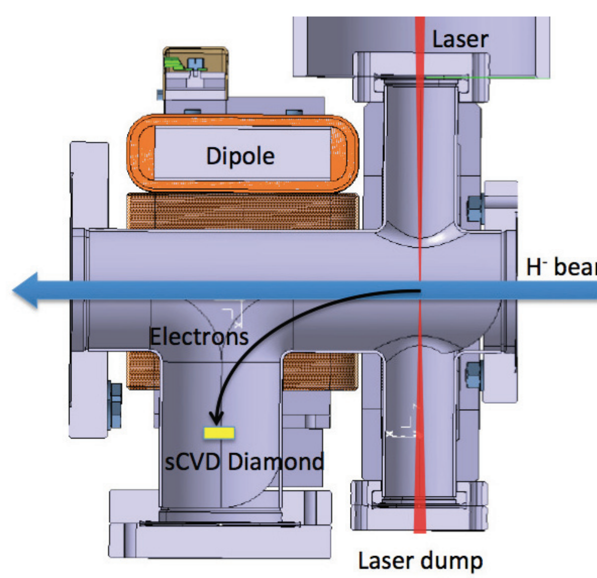

Figure 1: Conceptual design of the H^- beam profile monitor [4].

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EXPERIMENTAL SETUP

Laser and Fibre Transport

A V-GEN (VPFL-ISP-1-40-50) λ = 1064 nm fibre-laser with pulse widths tunable between 1–300 ns is housed in a dedicated hutch in the surface level klystron gallery above LINAC4. Due to the low (kW) peak power and favourably large linewidth $\lambda_L > 1$ nm, the light can be transported 75 m to the tunnel in a Large Mode Area optical fibre, without significant perturbation in the pulse shape from non-linear Stimulated Brillouin Scattering inside the fibre, as proven in earlier studies [4].

Diagnostic Test Bench

The temporary diagnostics test bench illustrated in Figure 2 was positioned at the end of the DTL cavities and later after the first PIMS cavity, to characterise the beam at energies of 50 MeV and up to 107 MeV respectively.

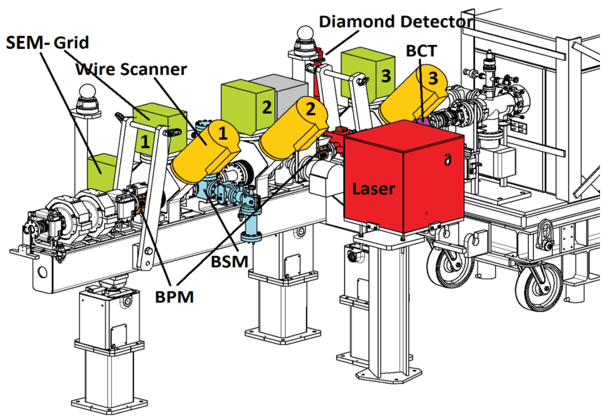

Figure 2: Diagnostics test bench used for LINAC4 commissioning of 50 MeV, 80 MeV and 107 MeV H$^-$ beam [5].

The setup includes wire scanners and SEM-grids for transverse profile and emittance measurements; two beam positions monitors to determine the mean transverse position and beam energy from time of flight measurements between both BPMs. The beam current was measured with the BCT and the longitudinal bunch profile was assessed with the bunch shape monitor (BSM). The laser beam delivery optics box is shown in red, which focuses light into the vacuum chamber of the laser beam profile monitor, pictured in Figure 3.

Focusing Optics, Photodiode and Energy Meter

An internal view of the focusing optics in the beam delivery system is shown in Figure 4 revealing the single sided AR-coated beam sampler, S, that diverts a 4% reflection to the photodiode for normalisation of pulse-to-pulse fluctuations. The fine vertical position of the focusing optics assembly is remotely-controlled to scan the laserwire position. In the lowest position, light is diverted to a moveable camera for in-situ laser beam characterisation. A 50 mm × 50 mm active area pyroelectric energy meter is attached on the far side of the IP in Figure 3 and doubles as the laser dump. This integrates the absolute energy of the train of amplified laser pulses that intercept each LINAC4 macropulse.

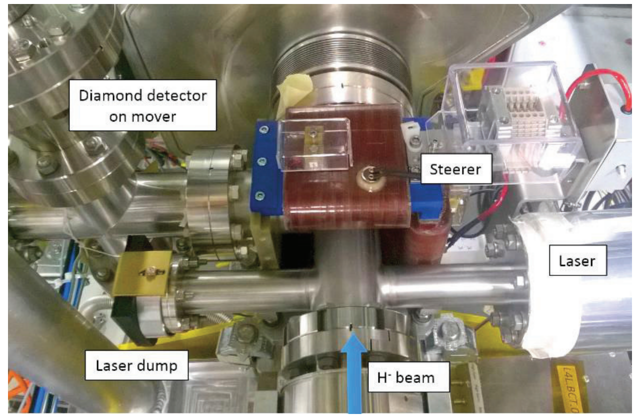

Figure 3: Vacuum-chamber for laser interaction and steerer magnet to deflect electrons towards the diamond detector [4].

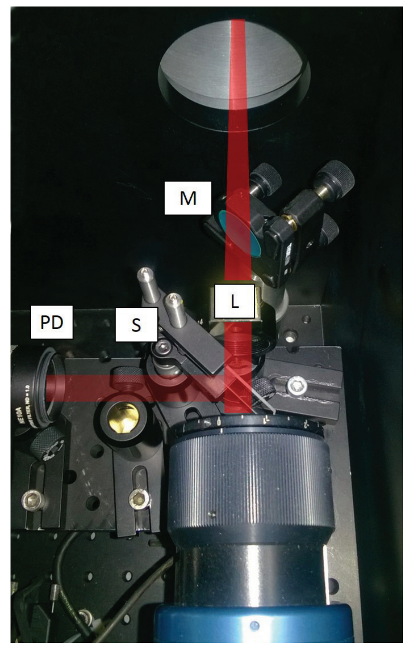

Figure 4: Controllable optics overlaid by the expanded laser beam that is focused by a 500 m lens (L) towards the IP with the H$^-$ beam. An AR-coated beam sampler (S) diverts a 4% reflection to the photodiode.

SYSTEM CHARACTERISATION

Laserwire Spatial and Temporal Properties

The narrow beam of light is generated by fibre-coupled collimation and focusing optics in the beam delivery system. This also incorporates mirrors to divert the laserwire to a camera that can be translated over a range surrounding the equivalent focus of the interaction point (IP). Therefore the spatial characteristics of the laserwire can be measured in-situ using techniques described previously [2, 3]. The result shown in Figure 5 for the 50 MeV setup indicates an improved performance of the laserwire focus, compared to the previous 3/12 MeV measurement campaigns. Due to the lower M^2, the Rayleigh range is longer in both planes and

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the waist is slightly thinner. The small optical astigmatism does not influence the measurement, which is in the vertical plane only.

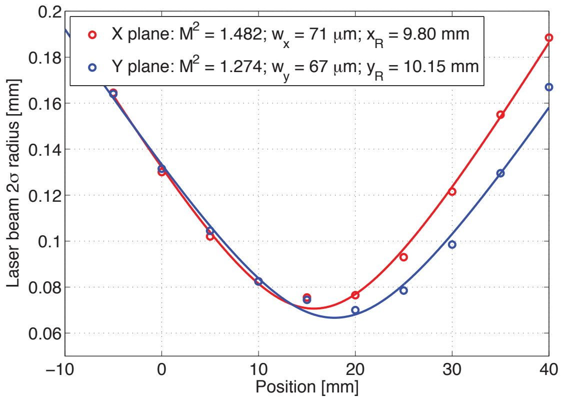

Figure 5: Spatial characteristics of the laser beam at the interaction point with H^-.

Pulse-to-pulse fluctuations in the laser power can be a significant source of error. Pulses from the V-GEN laser were measured to have a 3% RMS peak power stability after propagation through the 75 m fibre. To mitigate this error, the diamond detector signal is normalised per pulse by the photodiode signal recorded just before the IP.

Diamond Detector Response

Electrons liberated by each laser pulse are recorded by the single-crystal chemical vapour deposition (sCVD) diamond detector [4]. Initial laboratory tests with an α-source verified that the diamond sensor, with a 500 V bias applied and scaled by a 40 dB amplifier gain, gave close to the expected 6.7 pC charge for 100% CCE.

The response of the diamond detector was assessed by a scan of the laser pulse energy. The integrated charge of the diamond signal per laser pulse is plotted versus the integrated photodiode signal, for a range of pulse energies in Figure 6. The diamond detector response is found to linearly follow the photodiode signal, with a small offset thought to be due to a background of stray protons, H^0 or H^- directly impacting the diamond sensor in the 50 MeV setup.

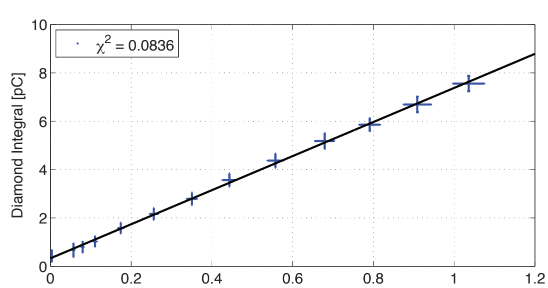

Figure 6: Integral of pulse signals recorded with the diamond detector versus the photodiode before the IP with the 50 MeV H^- beam.

Beamlet Measurements

Each transverse slice of H^- beam neutralised by the laserwire liberates a thin beamlet of electrons, that is magnetically steered towards the diamond sensor. The field was adjusted to compensate for the different electron momenta at each H^- beam energy, and ensure the beamlet strikes the target 4 mm × 4 mm sensor, which is placed in the focal plane of the dipole, optimised by tracking simulations [4]. The photodetachment cross-section, σ_{PD}, also varies with beam energy due to the relativistic Doppler-effect: σ_{PD} = 3.86, 3.94 and 3.98 $.10^{-17}$ cm^2 for E_{kin} 50, 80 and 107 MeV respectively.

The beamlet size was determined at 80 MeV by keeping the laserwire stationary and performing a two dimensional scan of the vertical (Y) position of the diamond detector, and the horizontal beamlet position (Z) by varying the magnetic field. The recorded diamond signal is shown in Figure 7. In Figure 8 the beamlet size is obtained by a projection along the Y-axis as $\sigma_Y = 0.45 \pm 0.1$ mm, and a similar analysis gives $\sigma_Z = 0.4 \pm 0.1$ mm. While the results match the horizontal beamlet size expected from tracking simulations, the beamlet is broader than the expected $\sigma_Y = 0.1$ mm in the vertical plane, which is attributed to stray fields in X and Z that deflect electrons slightly in the Y-plane. Crucially, the result shows that the beamlet is small enough to be captured entirely by the active surface of the diamond detector.

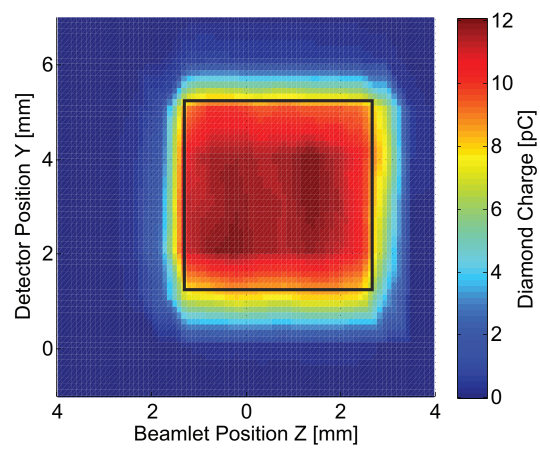

Figure 7: Integrated charge recorded during a two-dimensional scan of the diamond detector and inferred horizontal position of the beamlet. The black frame indicates the 4 mm × 4 mm surface of the diamond sensor.

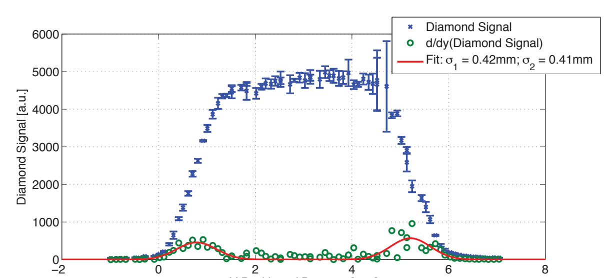

Figure 8: A fine scan of vertical detector position. The vertical beamlet size is extracted from the signal derivative.

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BEAM PROFILE MEASUREMENTS

The vertical size of the H^- beam was measured by laserwire and diamond detector scans at the three beam energies of 50, 80 and 107 MeV, corresponding to Figures 9, 10 and 11. For all results, the diamond charge at each 2D position of the laserwire and diamond detector was determined by averaging the diamond pulse signals over the laser pulse train corresponding to at least one LINAC4 macropulse. At each laserwire position the maximum charge value in the range of diamond detector positions is obtained to plot the beam profile.

The laserwire profile is compared with those from SEM-grids and wire scanners positioned close to the laserwire. Accounting for H^- beam drift, the σ_Y recorded with the laserwire is found to lie extremely close to the interpolated value between SEM-grid measurements, as in the upper plot of Figure 9. In the lower plot of Figure 9 and in Figures 10 and 11, the SEM-grid and wire scanner results have been scaled to the position of the laserwire and show good agreement. Any discrepancies between the laserwire and linear interpolation of the SEM / WS profiles were monitored for multiple measurements and at different beam energies and found to be consistently below an error on the beam σ of $< \pm 2\%$. This is at a level similar to the difference between SEM / WS devices placed at the same measurement plane, indicating the laserwire has a similar performance.

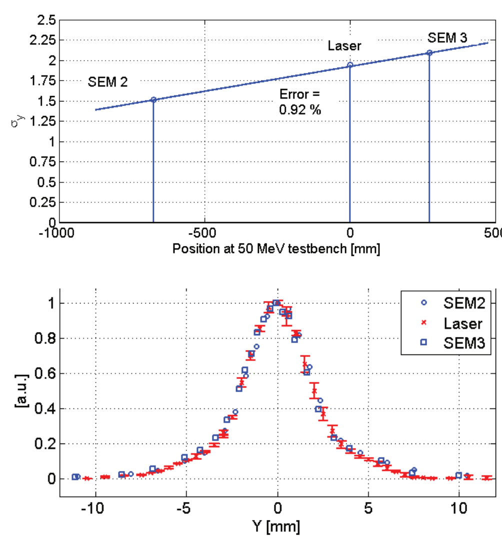

Figure 9: The vertical size of the 50 MeV H^- beam was measured using SEM grids and the laserwire. The laserwire profile is overlaid with profiles from the SEM grids scaled to the laserwire position.

SUMMARY AND OUTLOOK

A compact, non-invasive laserwire to measure H^- beam profiles based on detection of photo-detached electrons has been demonstrated at LINAC4 commissioning energies of 50, 80 and 107 MeV. The electron beamlet size was small enough to be entirely captured by the diamond sensor, which responds linearly with laser pulse energy. The beam profiles

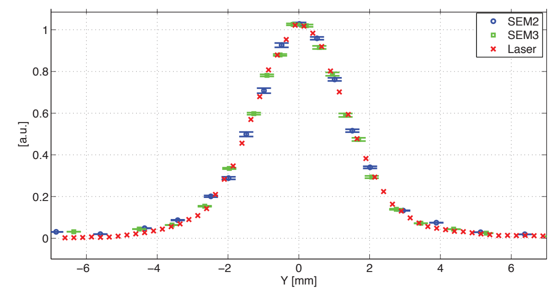

Figure 10: Comparison of SEM-grid σ-scaled profiles with the laserwire profile for the 80 MeV H^- beam.

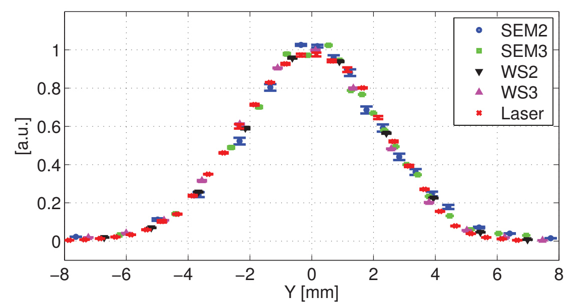

Figure 11: Overlay of 107 MeV H^- beam σ-scaled profiles recorded with different devices.

are in good agreement, $< \pm 2\%$, with nearby SEM-grids and wire scanners. Based on these and our earlier results, a permanent laserwire at 160 MeV will be installed to measure the transverse emittance in both planes, and will include beam profile monitors that measure the photo-detached electrons.

ACKNOWLEDGEMENT

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