OVERVIEW OF LASERWIRE BEAM PROFILE AND EMITTANCE MEASUREMENTS FOR HIGH POWER PROTON ACCELERATORS

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Abstract

Laserwires were originally developed to measure micron-sized electron beams via Compton scattering, where traditional wire scanners are at the limit of their resolution. Laserwires have since been applied to larger beam-size, high power H^- ion beams, where the non-invasive method can probe beam densities that would damage traditional diagnostics. While photo-detachment of H^- ions is now routine to measure beam profiles, extending the technique to transverse and longitudinal emittance measurements is a key aim of the laserwire emittance scanner under construction at the Front End Test Stand (FETS) at the RAL. A pulsed, 30 kHz, 8 kW peak power laser is fibre-coupled to motorized collimating optics, which controls the position and thickness of the laserwire delivered to the H- interaction chamber. The laserwire slices out a beamlet of neutralized particles, which propagate to a downstream scintillator and camera. The emittance is reconstructed from 2D images as the laserwire position is scanned. Results from the delivery optics, scintillator tests and particle tracking simulations of the full system are reviewed. Plans to deploy the FETS laser system at the LINAC4 at CERN are outlined.

INTRODUCTION

Over the past decade, advanced designs of high power proton (H^- ion) accelerators have emerged for numerous applications including: next generation Spallation Neutron Sources, a Neutrino Factory, a Muon Collider and Accelerator-Driven Systems for sub-critical reactors enabling the transmutation of nuclear waste. Some example of existing and future facilities include: the Spallation Neutron Sources at Oak Ridge (SNS), J-PARC, and ISIS at RAL, the European Spallation Source (ESS) under construction at Lund, Project-X at Fermilab, the CERN Superconducting Proton Linac (SPL), and ADS projects in China and India. Such accelerators inherently require precise beam diagnostics to carefully monitor the transverse profile and emittance of the delivered beam. However, as the beam powers generated are in the megawatt regime and beam currents typically exceed 10 mA, the beam intensties are above the damage threshold for traditional interceptive beam instrumentation such as wire scanners.

An alternative is laser-based wire scanners (laserwires) that offer a non-invasive method to probe high intensity beams. Laserwires were originally developed to measure micron-sized electron beams via Compton scattering [1], though have since been applied to larger beam-size, high power H^- ion beams to routinely monitor beam profiles[2].

In this paper we focus on recent developments for a generic laserwire emittance scanner that is suited to non-invasive beam profile and emittance measurements at high-power H^- linacs. A fibre-coupled laser delivery system with motorized collimation optics has been designed to offer ease of installation and flexible operation modes. Whilst originally developed in the context of the Front End Test Stand (FETS) [3, 4] at RAL, the optical system is portable and will first be deployed for tests this Autumn 2013 in the new LINAC4 beamline at CERN, as the first stage of a planned collaborative study [5].

FETS

FETS is a demonstrator for technologies at the front end of a high power proton driver, currently being installed and commissioned at RAL [3]. Essentially, FETS consists of a H^- ion source, a magnetic low energy beam transport (LEBT), 324 MHz Radio Frequency Quadrupole accelerator (RFQ), medium energy transport line (MEBT), high speed beam chopper and comprehensive diagnostics, as sketched in Figure 1. The ion source and LEBT are operational and routinely deliver 60 mA beam current at a 50 Hz repetition rate with up to 2 ms pulse duration. When the RFQ installation is completed in 2014, it will ramp the beam energy to 3 MeV. The chopped beam will then enter the laserwire diagnostics chamber, as in the next section.

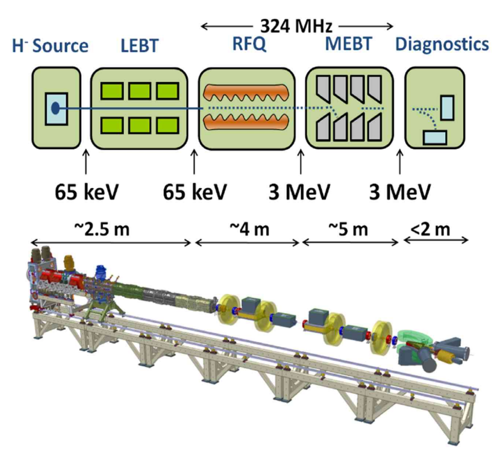

Figure 1: Overview of the FETS beamline components.

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LINAC-4

The new Linac-4 under construction at CERN will accelerate H^- ions to 160 MeV and will ultimately replace the existing 50 MeV proton linac, as part of the CERN SPL [6]. The switch over to Linac-4 as the main proton source for LHC is envisaged during the 2017/2018 long shutdown, as the first step towards the High Luminosity LHC. The Linac-4 ion source, 3 MeV RFQ and MEBT which includes a chopper, have been commissioned on the surface and beam diagnostic results obtained [7]. The system is currently being moved to the tunnel in readiness for commissioning initially at 3 MeV and later with the full Linac-4 chain at 160 MeV.

Collaborative Effort

In future after Linac-4 installation in the tunnel, a non-invasive laserwire system is planned to measure the transverse emittance [5] and the fruitful beginnings of a collaborative effort to develop the laserwire delivery system is described here. As a first step, the laserwire delivery system will be tested during the commissioning of the 3 MeV front end of Linac-4. Although the beam energy is therefore the same as at FETS, the layout and timing of the accelerators is different, especially in terms of the arrangement of the dipoles so the measurement priniciple at the two accelerators is first reviewed in the subsequent sections of this paper. The optical fibre-based laser beam delivery system is then described and optimisation of the laser parameters discussed in the context of maximising signal to background in the detector.

MEASUREMENT PRINCIPLE

The basic principle of the laserwire emittance scanner is to neutralise H^- ions in the narrow slice of the particle beam that traverses the path of the laser. The interaction with a photon energy of 1.16 eV is sufficient to liberate a weakly bound (0.75eV) electron from the H^- ion. The photodetached electrons can be collected directly in a Faraday cup to determine the beam intensity of the slice, so that the transverse beam profile can be measured as the transverse laserwire position is scanned. Alternatively, a dipole magnet can be used to separate the main charged H^- ions from the neutralised particles. The beamlet of neutralised particles then drifts downstream where the spatial profile is recorded by a suitable detector. This spatial profile contains angular information related to the propagation of the beamlet, from which the transverse emittance in one plane can be reconstructed. In principle, the transverse emittance in the orthoganol plane can also be accessed by adjustment of the MEBT quadrupoles before the laser interaction to suitably vary the twiss parameters [8].

Background and Timing

A complication occurs from stripping of H^- ions via interactions with the residual gas in the beam pipe upstream of the laser diagnostic instrument. This can generate a background of neutral particles on top of the signal from the photodetachment process, and this background must be combated.

In FETS layout the background is avoided by arranging the laser interaction point one third into the dipole field, such that the neutral background particles are first separated from the H^- ion beam, before the second separation of the photodetached neutral particles and ions, as shown in Figure 2. The neutralised particles emerge through the central of the three exit ports from the chamber, where the signal is recorded using a scintillator and camera, as shown in Figure 3. At the 3 MeV front end of Linac-4, the laser

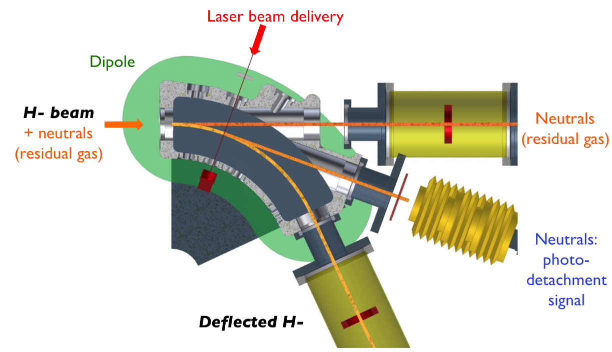

Figure 2: Photodetachment principle in the interaction chamber of the FETS laserwire emittance scanner.

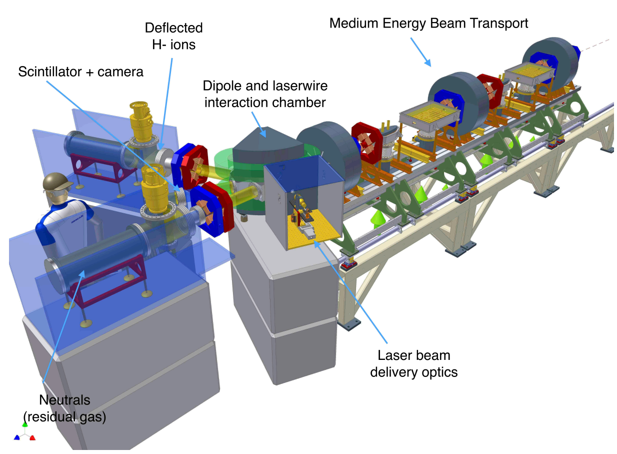

Figure 3: External view of the FETS MEBT and laserwire diagnostic chamber within the dipole magnet.

interaction region is before the dipole, so the neutrals from the residual gas interactions will pass directly through the dipole and will strike the same detector as collects the photodetachment signal. However, detailed studies [5] have shown that background level is roughly constant throughout the 400 μs Linac-4 pulse, whereas the signal from the laser is matched with the timing of the laser pulses. In principle a fast enough detector and DAQ could therefore reduce the integrated background, detailed investigations are ongoing.

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LASER, TIMING AND BEAM DELIVERY

Fibre-Laser System

The laser is a Q-switched, diode pumped, all-fibre Master Oscillator and Power Amplifier (MOPA) laser, model ML-30-PL-R-TKS manufactured by Manligh S.A.S. (Lanion, France). The oscillator generates 110 ns pulses at a repetition rate selectable between 30 and 100 kHz, at a wavelength of 1080 nm, with a pulse peak power of 8.5 kW and a measured average power of 28 W in CW mode. Further details and measurements characterizing the laser system are given elsewhere [4, 9].

Accelerator Synchronization

The laser pulse duration of 110 ns is much longer than the time between micro-bunches (3.1 ns for FETS and 2.84 ns for Linac-4), enabling the each laser pulse to interact with multiple micro-bunches. The chopped accelerator beams will operate at low duty cycles (<%), so the amplified envelope of the laser pulses can be matched to that of the accelerator. This alleviates the need to handle higher than necessary average laser power in the transport fibre, and greatly reduces the risk of surface damage to the fibre.

Laser Beam Delivery System

The laser has an output collimator and Faraday isolator after 2m length of fibre. To have the option to avoid operating the laser within the radiation environment very close to the accelerator, a long transport fibre has been made that allows the laser to be operated remotely. The transport fibre is Nufern PLMA-GDF-20/130, which has a core size of 20 μm and a numerical aperture of 0.08. A portable fibre coupling box has been designed to easily couple light from the laser and a coupling efficiency of 65 % has been achieved in recent measurements. After the coupling optics, the fibre is protected in a custom made 100 m armoured and safety interlocked cable which conveys light from the MOPA laser source to beam delivery collimation optics, as laid out in Figure 4.

The collimation optics are designed to enable fine control of the position and thickness of the laserwire that is delivered into the interaction chamber. A pair of translation stages control the vertical and longitudinal position of the laser beam, with micron-level resolution. Additionally a motorized beam expander (Sill Optics S6EZN5976/126) enables various laser spot sizes to be obtained in eight magnification steps. Further adjustment can be made by careful selection of the collimating lens at the output of the fibre and the focusing lens after the beam expander. The set up is flexible and offers the possiblity to generate a range of different beam sizes, as detailed in [9]. In the system planned for Linac-4, the light will be brought to a focus at the centre of the particle beam position, with a beam size small enough to ensure adequate photon density, while retaining a Rayleigh length ($Z_R = \frac{\pi w_0^2}{\lambda M^2}$) that exceeds the transverse dimension of the particle beam. From initial studies, a collimating lens of 6.4mm, a BE magnification of x3 and a

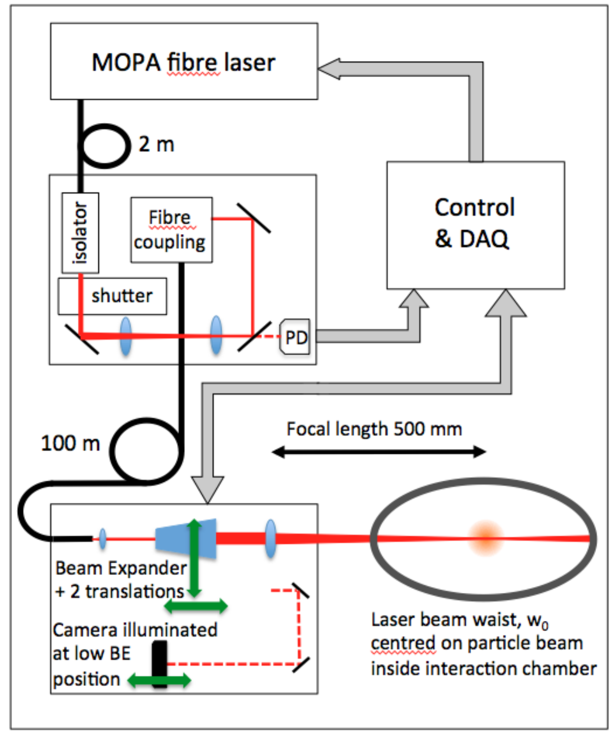

Figure 4: Optical layout of laser transport and beam delivery system.

focusing lens of $f = 500$ mm is selected as the baseline design. This will create a laser beam waist $w_0 = 0.18$ mm with a Rayleigh length $Z_R = 61$ mm.

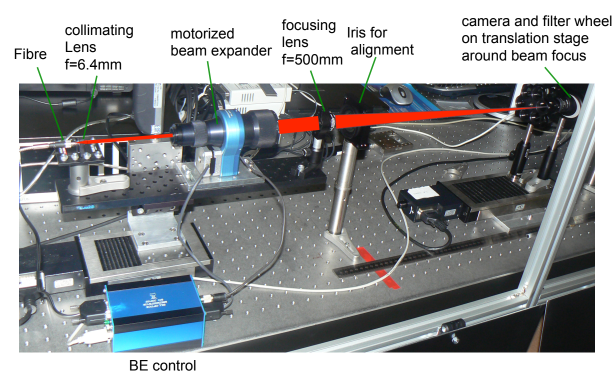

Figure 5: Beam delivery system set up for M^2 measurements.

Using the above parameters for the collimation optics, the system was set up as shown in Figure 5, with the beam directed at a camera on a longituinal stage. The size of the beam was recorded as the stage was translated and the output after the fibre collimation was measured to have a Gaussian beam quality of $M^2 < 1.76$. This is marginally better than the raw quality from the laser output, most likely due to mode cleaning qualities of the long fibre [9]. The beam profile directly out of the fibre and after the collimating and focusing optics are shown in Figures 6 and 7 respectively.

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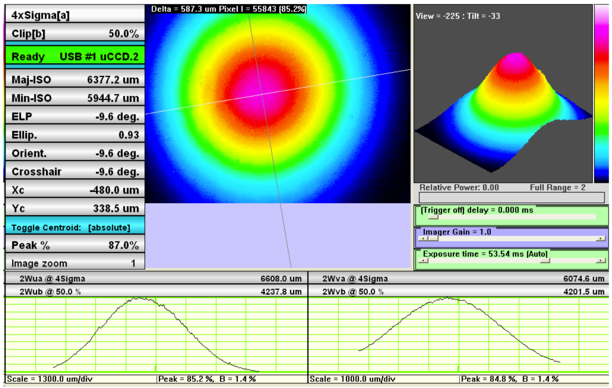

Figure 6: Beam profile directly out of the 100m long transport fibre, with no collimation optics.

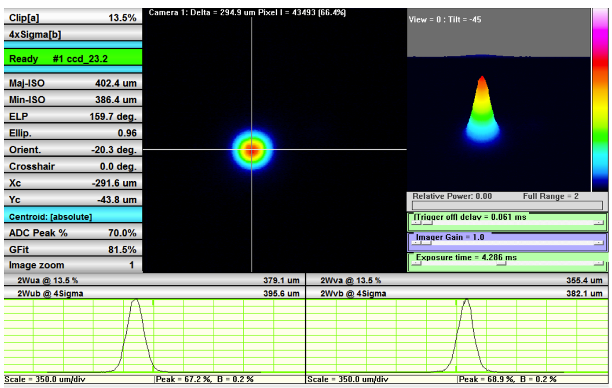

Figure 7: Beam profile close to the focus, after collimating optics, beam expander and $f = 500\,\mathrm{mm}$ focusing lens.

SIGNAL DETECTION & OPTIMISATION

The exact optimisation of the beam delivery optics parameters will depend on the signal levels obtained during the tests at CERN. The system is therefore designed with flexibility, and an optional camera from a fold back mirror has been proposed to measure the beam profile (and M^2) in situ should it be required. Detailed particle tracking studies for FETS and Linac-4 are underway to estimate the signal yield at the detector plane and initial results of the FETS particle tracking studies are in these proceedings [10].

The detection system planned for FETS is a scintillator which is viewed by a camera located off the central of the three exit ports in the interaction chamber. The intergration time of the detector is not critical, because the residual gas background exits the interaction chamber from the straight through port. At Linac-4 a faster detector is planned to aid reduction of the background through the timing cuts around the laser pulses, as described above. A 5 strip, poly-crystalline diamond detector is under consideration [5], which offers the advantage of radiation hardness to fluences beyond that readily achievable with silicon detectors. The timing and DAQ requirements of these system are described in [11].

CONCLUSION

The development of a laserwire emittance scanner has been described that enables non-invasive beam diagnostics at high power proton accelerators. The beam delivery system developed for FETS has been optically tested and found to meet the specified beam quality after the transport fibre. The system is planned to be tested in the Linac-4 beamline at CERN in late 2013 as part of a collaborative effort to develop an laserwire emittance scanner for the next generation LHC injector.

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