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Experimental results of the laserwire emittance scanner for LINAC4 at CERN☆

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ABSTRACT

Within the framework of the LHC Injector Upgrade (LIU), the new LINAC4 is currently being commissioned to replace the existing LINAC2 proton source at CERN. After the expected completion at the end of 2016, the LINAC4 will accelerate H^- ions to 160 MeV. To measure the transverse emittance of the H^- beam, a method based on photo-detachment is proposed. This system will operate using a pulsed laser with light delivered via an optical fibre and subsequently focused onto the H^- beam. The laser photons have sufficient energy to detach the outer electron and create H^0/e^- pairs. In a downstream dipole, the created H^0 particles are separated from the unstripped H^- ions and their distribution is measured with a dedicated detector. By scanning the focused laser beam across the H^- beam, the transverse emittance of the H^- beam can be reconstructed. This paper will first discuss the concept, design and simulations of the laser emittance scanner and then present results from a prototype system used during the 12 MeV commissioning of the LINAC4.

1. Introduction

The photo-detachment process for hydrogen ions has been known since 1959 [1]. The advent of H^- ion based linear accelerators (linacs) made possible to apply this process in order to measure parameters of the H^- beam [2]. For today's modern high current linacs this technique offers numerous benefits. Due to its non-invasive nature, beam parameters can be measured parasitically and since no mechanical parts are needed to intercept the particle beam, the risk of overheated and damaged components is eliminated. Since the reduction of downtimes is a major aim for any accelerator, this non-destructive instrument can contribute to maximise the efficiency.

The advantages are particularly relevant for the LINAC4 which is due to deliver high brightness beams reliably to the LHC injector complex. The declared aim of the HL-LHC, to increase the integrated luminosity by a factor of ten [3], is directly dependent on the LINAC4 performance and reliability. The increased final energy of 160 MeV creates further challenges for the beam instrumentation. Due to the long range of protons at this energy (e.g. >20 cm in graphite) conventional methods such as slits or scrapers cannot be used. By using a laser as a 'slit', firstly the range problem is solved and secondly the laser can be adjusted such that just a tiny fraction of H^- ions become neutralised H°. This makes the laserwire principle truly non-invasive. A comprehensive overview of the laserwire system and the integration at LINAC4 can be found at [4,5].

In this paper the emphasis is put on measurement results obtained while commissioning such a laserwire system on a 12 MeV H^- beam. Since the principle of this technique has been already demonstrated in other facilities [6–8], the focus was on making advances in key parameters of the system. In this regard a low-power laser was used which made it possible to design a simple fibre-based system, which runs very reliably and has imperceptible impact on the ion beam.

2. Instrument design

2.1. LINAC4

LINAC4 is the first step in the LHC Injector Upgrade (LIU) program which is essential for delivering the high brightness beams for the HL-LHC upgrade. After determining the principal machine

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Table 1
Principal LINAC4 parameters.

Parameter	Value
Overall linac length	90 m
Output energy	160 MeV
Bunch frequency	352 MHz
Beam pulse length	400 μs
Beam pulse repetition rate	0.83 Hz
Average pulse current	40 mA
Nominal transverse emittance	0.4π mm mrad

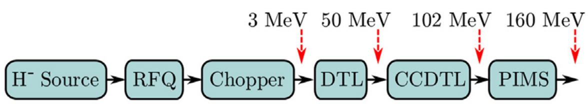

Fig. 1. LINAC4 block diagram. After generating the ion beam in a caesiated surface source the radiofrequency quadrupole (RFQ) first accelerates and then generates a bunched beam at an energy of 3 MeV. The chopper selects a temporal slice of the beam for further acceleration. DTL, CCDTL (Cell-Coupled) and PIMS (Pi-Mode-Structure) are the drift tubes linacs (DTL) required to accelerate the beam to the final energy of 160 MeV.

parameters in a technical design report in 2006 [9], the civil engineering was completed and the machine is currently in the commissioning phase. Table 1 and Fig. 1 provide an overview on the machine's essential parameters.

The determination of the transverse emittance at the end of the linac is essential in order to avoid high losses when the beam is injected into the PS-Booster [10]. Therefore the 160 MeV region is the envisaged final location for the proposed laserwire instrument. To advance with the instrument's design while the commissioning of LINAC4 is still underway, the phases at 3 MeV and 12 MeV (after the first DTL tank) were used to test the laserwire prototype.

2.2. Instrument concept

Due to the small binding energy of the outer electron of 0.75 eV, the H^- ion can be neutralised rather easily. Collisions with residual gas atoms [4] or strong magnetic fields in the Tesla range can detach one electron. The principle of our instrument is based on electron detachment due to collisions with photons. This process has a large cross-section of $>3\times10^{-17}\,\mathrm{cm}^2$ in the range between 500 nm and 1200 nm photon wavelength [1].

To sample the transverse phase space of an ion beam, a common method is to select thin slices of the beam and measure its angular distribution, known as the slit/grid method [11]. In analogy to this principle, Fig. 2 shows a schematic of the laserwire, which in contrast to the slit/grid method, is non-destructive.

2.3. Laser system

Since the laser system was described in detail in previous publications [4,5] it will be summarised here. The general parameters of the chosen working point of the laser source are listed in Table 2. The low pulse energy in comparison to other laserwire systems makes it possible to deliver the laser light to the particle beam via a long optical fibre (10 m was already achieved during the experiments completed at 3 and 12 MeV and a longer fibre will be used for the final system). This greatly reduces the complexity of the overall laser light delivery system.

The laser beam is kept at a fixed position and focused into the vacuum vessel with a diameter of approximately 150 μm. Due to the quasi-monomode beam quality ($M^2=1.8$), the laser beam diameter remains almost constant when colliding with the millimetre-size particle beam. The vertical scanning of the laser beam is performed by a remote controlled stage. A CCD camera and a fast photodiode are used to monitor the laser beam quality.

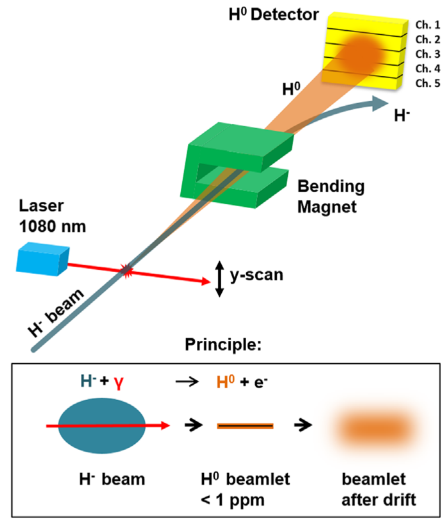

Fig. 2. Concept of the laserwire emittance measurement. A focused laser beam crosses the H^- beam and detaches electrons from the ions. The resulting neutral H^0 atoms drift unperturbed towards a detector while the H^- ions are deflected in a downstream bending magnet. By measuring the H^0 profiles in the detection plane, the angular distribution of the beam is gained. A scan of the laser through the H^- beam allows sampling the transverse phase space [12].

Table 2
Laser parameters.

Parameter	Value
Wavelength	1080 nm
Pulse energy	154 μJ
Pulse length (FWHM)	80 ns
Pulse frequency	60 kHz
M^2	1.8

2.4. H^0 detection system

For the measurements at 12 MeV, the 20 mm × 20 mm polycrystalline diamond detector with 5 strip channels already exploited during the 3 MeV experiments [13] was used to detect the neutralised H^0 atoms. Contrary to the 3 MeV case, the 12 MeV H^0 atoms fully traverse the 500 μm thick diamond substrate. This eliminates problems with piled up charge inside the diamond and greatly increases the signal level. A simulation of the ionisation inside the diamond was performed using the software package SRIM [14]. It was found that one H^0 loses 9.3 MeV when traversing the diamond. The charge collected by the detector can be calculated as:

$$Q_{Diamond} = n_{H^0}\cdot e\cdot\frac{E_{ionize}}{E_{Gen}}\cdot CCE \tag{1}$$

where n_{H^0} is the number of H^0 hitting the diamond, E_{ionize} the energy that one H^0 loses in the diamond and E_{Gen} the average energy to generate an electron–hole pair, which is 13.1 eV for diamond [15]. Depending on the diamond material quality the Charge Collection Efficiency (CCE) can vary significantly. For the detector used in the measurements a CCE between 10% and 20% was assumed [16]. Using this value, a simulation was executed to estimate the collected charge taking into account the power of the laser as presented in Table 2, the beam dynamics and the size of a detector strip channel (3.5 mm × 18 mm). The simulation result

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