LASER BASED STRIPPING SYSTEM FOR MEASUREMENT OF THE TRANSVERSE EMITTANCE OF H⁻ BEAMS AT THE CERN LINAC4*

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Abstract

The new LINAC4 at CERN will accelerate H^- particles to 160 MeV and allow high brightness proton beam transfers to the Proton Synchrotron Booster, via a charge-exchange injection scheme. This paper describes the conceptual design of a laser system proposed for transverse profile and emittance measurements based on photon detachment of electrons from the H^- ions. The binding energy of the outer electron is only 0.75 eV and can easily be stripped with a laser beam. Measuring the electron signal as function of the laser position allows the transverse beam profile to be reconstructed. A downstream dipole can also be used to separate the laser neutralized H^0 atoms from the main H^- beam. By imaging these H^0 atoms as a function of laser position the transverse emittance can be reconstructed in the same way as in traditional slit-and-grid systems. By properly dimensioning the laser power and spot size, this method results in negligible beam losses and is therefore non-destructive. In addition, the absence of material intercepting the H^- beam allows the measurement of a full power H^- beam. This paper will focus on the general design and integration of both the laser and H^0 detector systems.

INTRODUCTION

The first step of the High Luminosity upgrade of the LHC is the development of LINAC4 which accelerates an H^- beam up to 160 MeV. By operating the machine with H^- ions a charge exchange system can be used to inject high brightness beams in the PS-BOOSTER. For the commissioning and operation of the LINAC4 the measurement of the transverse emittance is a key factor. Up to 50 MeV the slit-and-grid method can be used. For higher energies the range of the ions is too high to stop them with a slit and therefore a novel technology is needed. This laser based measurement system is the subject of this paper.

CONCEPT & MODELLING

We propose a laser system for transverse profile measurements in a non-destructive manner, based on photon detachment of electrons from the H^- ions. The basic concept is shown in Fig. 1. A pulsed laser crosses the particle beam. Since the binding energy of one electron is only 0.75 eV the detachment cross-section exceeds $3.5 \cdot 10^{-17}$ cm^2 in the wavelength range of 800 nm ... 1100 nm as shown in Fig. 2. A H^0 beamlet and free electrons are created in the process. By using a bending magnet and a Faraday cup the electrons can be measured,

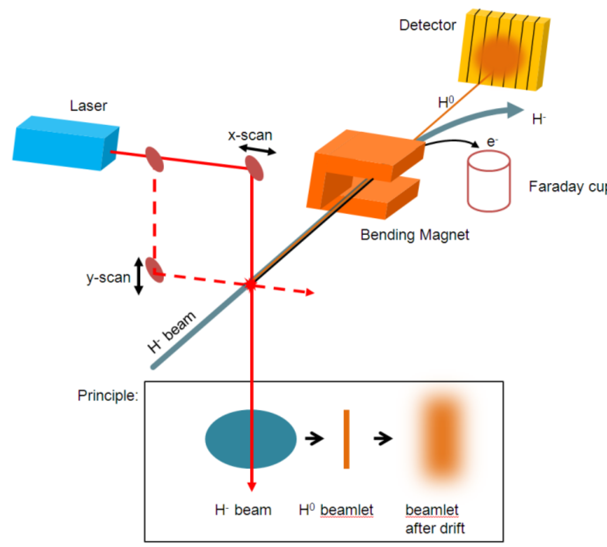

Figure 1: Concept of the laser emittance meter.

providing a signal proportional to the number of H^- ions intercepted by the laser. The H^0 beamlet drifts unperturbed trough the accelerator section downstream the laser towards a position sensitive detector. The detector signals can be used to reconstruct the divergence of the H^0 beamlet. By scanning the laser across the beam the transverse emittance of the H^- beam can be measured.

Laser-Particle Interaction

To simulate the interaction of the laser with the H^- ions the photon flux of the laser must be modelled with respect to the distance from the laser axis r and the position along the laser z. We used a Gaussian model taking into account a quality factor M^2. For the model of the particle beam we could use data from beam dynamics simulations summarized in Table 1.

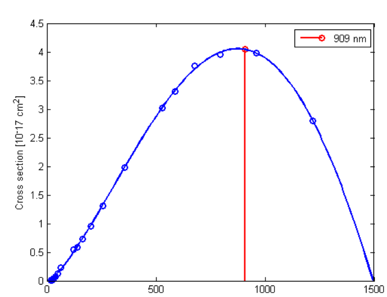

Figure 2: Photo neutralization cross-section [1]; in red: Lorentz shifted 1064 nm laser at beam with 160 MeV.

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Table 1: Beam Emittance (1σ) at the end of LINAC4

	Divergence	Size
x	0.9 mrad	2.7 mm
y	1.0 mrad	3.7 mm

The probability of stripping is given by

$$p_{Strip} = 1 - e^{-\sigma(E) \cdot F_{pho} \cdot t} \quad (1)$$

with $\sigma(E)$ the cross-section, F_{pho} the photon flux and t the time of flight of the particle through the laser. Since the photon flux is not constant along the path of the particle which can be seen in Fig. 3 the stripping probability p_{Strip} must be calculated gradually like shown in Eq. (2).

$$p_{strip} = 1 - \prod_{i=1}^{n} \overline{p_{strip_i}} \quad (2)$$

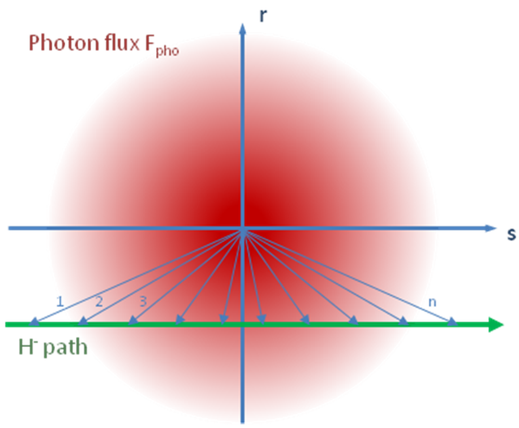

Figure 3: Laser particle interaction.

Each particle is weighted with its stripping probability. After a drift space the weighted particles are integrated. The resulting signal at the detector is shown in Fig. 4.

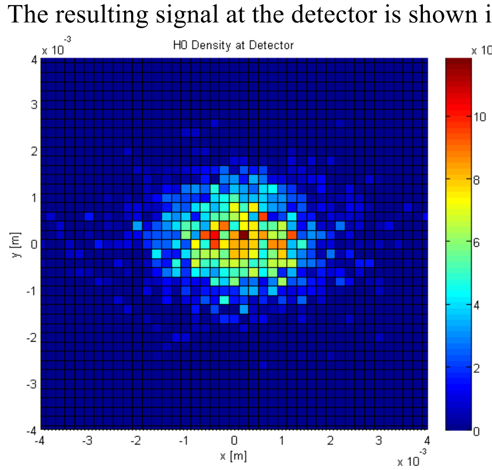

Figure 4: H^0 distribution at the detector 3.5 m downstream the laser.

Residual Gas Stripping

One challenge of this measuring principle is the background created by residual gas stripping. All along the beam path, the residual gas can strip one electron from the H^- ion. Especially in the LEBT and the RFQ the stripping probability is increased by the high gas pressure (10^{-5} mbar in the LEBT) and the low beam energy. The stripping probability is given by

$$p_{Gas\ Strip} = 1 - e^{-l/\lambda(P,\beta)} \quad (3)$$

where l is the length of the path and λ the mean free path. The value of λ depends on gas pressure P and $\beta = {}^{v}/_{c}$.

To evaluate the amount of background arriving at the detector we used again the data from the beam dynamics simulations. Using the RMS divergence of the beam in every accelerator section (LEBT, RFQ, MEBT, DTL, CCDTL, PIMS) we can calculate the distribution of impacts on the H^0 detector at the end of LINAC4. The sum of the background from the different sections gives a cumulated background level of $8.0 \cdot 10^2\ ns^{-1}$.

Since the background H^0's are generated all over the accelerator, they will have a broad range of momentum. This means also that the background is expected to be nearly constant during the 400 µs LINAC4 pulse due to the superposition of particles with different delays.

SUBSYSTEMS

The central components of the system are the laser and the H^0 detector. Q-switched lasers [2] and fiber laser are suitable options. Table 2 shows the main differences.

Table 2: Laser Alternatives

Laser type	Fiber laser	Q-switched
Pulse energy	< 1 mJ	> 20 mJ
t_{pulse}	10…100 ns	5…10 ns
Repetition rate	> 30kHz	< 15 Hz
Beam quality (M^2)	< 1.5	< 1.5
Beam transport	Fiber	Free Space
p_{strip} @ 160 MeV	< 3 %	100 %
Stripped H^- [ns^{-1}] @ 160 MeV	~10^5...10^6	~$8 \cdot 10^6$

The main advantage of a q-switched laser is the high pulse power, which can provide 100% stripping of the H^- ions. However the laser is limited in the repetition rate and also the pulse duration which is defined by the resonator length.

For a fiber laser the pulse energy is restricted by the limit a small fiber diameter can handle. This is usually not more than 1 mJ. The advantage of a fiber based laser is the flexibility in the pulse duration and rate, as well as the possibility to transport the laser simply in a fiber to the beam pipe.

The laser choice is closely connected with the selection of the detector. The variety of possible types is here even bigger.

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The key criteria are:

- Size and spatial resolution
- Sensitivity
- Radiation hardness
- Bandwidth
- Homogeneity

A SEM-grid is a very common detector for emittance measurements. However in our application it will very likely not be suitable because of its low sensitivity. Since the H^0 will deposit an electron at the wire and the exiting proton causes secondary emission, the effects cancel and give a very weak signal. The sensitivity is less than 1 electron per H^0 hitting the wire. After first investigations, solid state detectors seem to be the best alternative. Concerning sensitivity, they are with $\sim 10^4$ electrons/H^0 far ahead. As an example, poly-crystalline diamond detectors (Fig. 5) can be produced in a reasonable size. The spacial resolution can be defined by the metallization. Furthermore, the electron collection time is just 1.5 ns for a 200 µm ideal diamond detector [3] which means an adequate bandwidth. The challenge for solid-state detectors is the radiation hardness. For silicon detectors the typical values of equivalent fluencies are $10^{12}\ldots10^{15}\,\mathrm{cm}^{-2}$ [3]. Diamonds can go beyond this, but radiation can compromise the homogeneity of the detector. Therefore a calibration mechanism must be foreseen in the final system.

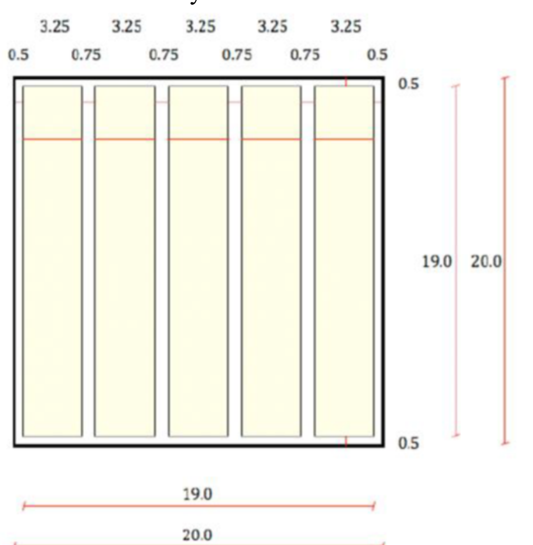

Figure 5: Polycrystalline diamond detector with 5 strips (sizes in mm) [4].

PRELIMINARY RESULTS

Concerning the background level, Fig. 6 shows preliminary results of a test performed at the LINAC4 3 MeV test stand [5]. A slit (where it is foreseen to test also a laser stripping system) and grid system was used to record two profiles with the slit sampling the beam core (red curve) and tail (green curve). These signals have been scaled down to 6 %, to simulate the expected stripping efficiency at 3 MeV. The blue data points are the grid signal taken with a bending magnet powered (between the slit and the grid) and therefore results from only background H^0 particles. The presence of a significant H^0 background level can be confirmed. Quantitative analysis of this data is currently ongoing.

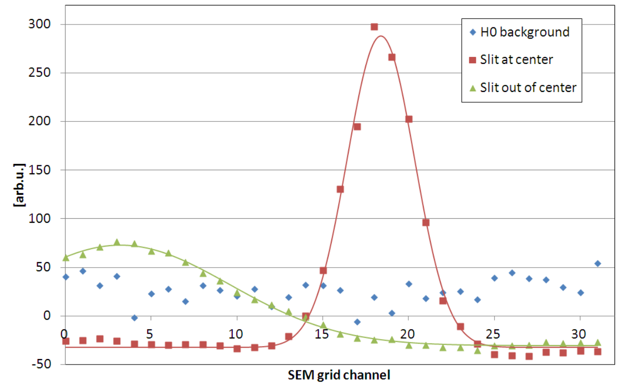

Figure 6: First results from 3 MeV test stand with 200 µm slit.

SUMMARY

In the context of the development of a laser based transverse emittance measurement, the parameters of the main components, the laser and the H^0 detector were studied and the choices of suitable components were narrowed.

The interactions of the particles with the laser were modelled. Furthermore the background level due to residual gas stripping was calculated and first measurements in this regard were accomplished at the 3 MeV test stand.

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