LASER-BASED BEAM DIAGNOSTIC FOR THE FRONT END TEST STAND (FETS) AT RAL*

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Abstract

High power proton accelerators (HPPA) are required for several future projects like spallation neutron sources or a neutrino factory [1]. Compared with existing machines [2] the beam power therefore has to be increased by a factor of 30. The Front End Test Stand at RAL is being built to demonstrate that a chopped H^- beam of 60 mA at 3 MeV with 50 pps and sufficiently high beam quality, as required for all proposed proton drivers, can be built. A detailed description of the project and the current status is given in [3]. For the test stand a comprehensive set of beam diagnostics is also required. Due to the high beam energy and power, non-destructive diagnostic methods are favourable. H^- beams offer the possibility to use intense laser light to detach the additional electron and use the produced particles for beam diagnostics. The principle is appropriate to determine the transversal beam density distribution as well as the transversal and longitudinal beam emittance in front and behind the RFQ. A detailed layout of the beam diagnostics including a discussion of the predicted spatial and temporal resolution and the dynamic range of the proposed devices will be presented.

INTRODUCTION

To increase the intensity and brightness of particle beams, a detailed knowledge of the transverse and longitudinal phase-space distribution (emittance) is of most importance. Several well-known devices to measure the spatial particle density distribution, such as wire scanners and harps, or the emittance of a particle beam, like electric-sweep (Allison) scanners and the slit-grid instrument, are widely used. However, these conventional destructive methods suffer for such high power beams because of the power density deposited on the surfaces like slits or pinhole plates. Additionally, in the case of the emittance scanners the beam is lost during the measurement and therefore online monitoring of the beam is impossible. Furthermore, for space charge compensated beam transport, often used in magnetic low energy beam transport (LEBT) sections, the degree of space charge compensation can change during the measurement due to the production of secondary particles on the surfaces of the device. Therefore the development of a non-destructive measurement method, with a marginal influence on the beam, is desirable. For negatively charged particle beams (e.g. H^-) the photo dissociation technique (also called photo detachment) offers an elegant solution: photons with an energy above the threshold for photo dissociation of H^-, ~0.75 eV, can be used to partially neutralize an H^- beam. For a photon with an energy of 1.5 eV the maximum cross section for photo neutralization is approximately 4.0×10^{17} cm^2. Calculations of the particle yield and previous experiments [4, 5, 6] have demonstrated that a Nd:YAG laser can be used as an effective light source.

Behind the laser neutralisation section the number and distribution of either the detached electrons or the neutrals produced in the interaction region can be analysed while the ion beam is still in use. Therefore charge separation, usually achieved using a magnetic dipole field, and a particle detector system are required. As neither the laser photons nor the recoiling photo detached electrons transfer a significant momentum to the H^0 atoms, the beam of neutralized ions has the same distribution in the six dimensional phase space as the primary beam. It is therefore appropriate to measure the H^0 beam distribution by a detector system with spatial resolution. The electrons are often only used when the total amount of neutralisation, such as for the laser wire profile measurement technique, or fast detection, like for energy spread measurements using a TOF method, is required.

For the FETS two different diagnostic devices using the laser detachment technique are being designed. One is using a laser wire technique and the detection of the electrons to determine the transversal and longitudinal density distribution of the ion beam, similar to [7, 8]. The main difference to the systems already in use is the ability to investigate the full three dimensional density distribution by applying tomographic techniques. Additionally, it will be possible to use the system for the diagnosis of low energy beams, by means of a post acceleration of the electrons into the charge separation area to reduce errors arising from external fields and improving the transmission into the detector.

By using the neutralized particles the phase space distribution (emittance) of the beam can be reconstructed for a given distance between the neutralization region and the detector. The proof of principle has already been demonstrated in [9, 10, 11]. For the FETS a scintillator detector will deliver the transversal phase space information and a TOF system, using the detached electrons, will provide the longitudinal information.

For both experimental setups a laser diode light source at ~650 nm, that will also be used for the alignment of the optical system, will allow initial tests, while a short pulsed Nd:YAG system (10 ns) available at RAL and a new very short pulsed system (30 ps) will be used later.

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MEASUREMENTS OF THE TRANSVERSE AND LONGITUDINAL BEAM DENSITY DISTRIBUTION

To measure the ion beam density tomographic methods will be utilised. The photo dissociated electrons will be use to construct projections of the beam onto planes at varying angles. As the number of electrons collected is proportional to the beam density along the path of the laser the density distribution can be reconstructed from the projection data. It is necessary to use tomography to get a true picture of the three dimensional density distribution as the FETS ion beam has no rotational symmetry to simplify the analysis. Measurements of the longitudinal distribution can be made by introducing a delay between the laser pulse and the beam pulse.

The resolution of the system is limited by how well the laser can be focussed without severe waisting. It is anticipated that it will be possible to image sub-millimetre scale features of the H^- beam.

Optical Setup

The discrepancy between the reconstructed density distribution and the true distribution will decrease as the number of projections taken increases. It is estimated that at least 20 projections, spread as evenly as possible over 180°, are required for a satisfactory reconstruction.

To make the projections it will be necessary for the laser to pass though the ion beam at various angles and locations. The adjustment of the laser's path through the ion beam will be achieved using 4 mirrors on mounts that can be moved and rotated within the vacuum vessel. Vacuum compatible motors will be used to eliminate the need for complicated mechanical feedthroughs. Synchronised movement of the mirrors will allow the required projection data to be taken. The laser beam will be coupled out of the vacuum vessel with a beam dump to avoid additional photo dissociation due to laser reflection. A schematic of the optics is shown in Figure 1.

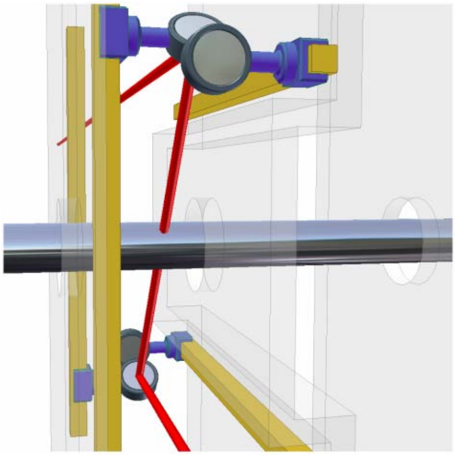

Figure 1: A CAD impression of the optical setup. The ion beam is shown in silver and the path of the laser, in red. The mirrors will be able to rotate about their centreline and move along the yellow rods.

Detector System

The photo dissociated electrons will be deflected by a dipole magnet into a detector, presumably a Faraday cup. The particle yield is expected to be of order 10^5 electrons per laser pulse, so a low-noise, charge-sensitive amplifier will be necessary to process the signal. The amplified signal will be digitised using an ADC and this result passed to a computer for the analysis.

The H^- ions from the FETS ion source have an energy of 65 keV. Following photo dissociation the maximum kinetic energy of the electrons is about 35 eV. The magnetic field required to deflect the electrons at this energy is ~ 0.4 mT, which is comparable to the stray fields that will be present. To prevent the electrons being affected by the stray fields, which would have an adverse effect on the collection efficiency, it is proposed to accelerate the dissociated electrons. By placing the magnet and electron collection in a box held at ~ 2 kV, the electrons will be accelerated such that the field required to deflect them is ~3 mT and the effect of the stray fields will be significantly reduced. Importantly, this acceleration will not damage the quality of the ion beam. A second magnet of the opposite polarity will be used to correct the path of the un-neutralised ions such that the ion beam will have a small displacement from the initial beam axis (< 1mm), rather than an angular deflection. A schematic of the detector system is shown in figure 2. Further optimisation studies of the electron collection are ongoing.

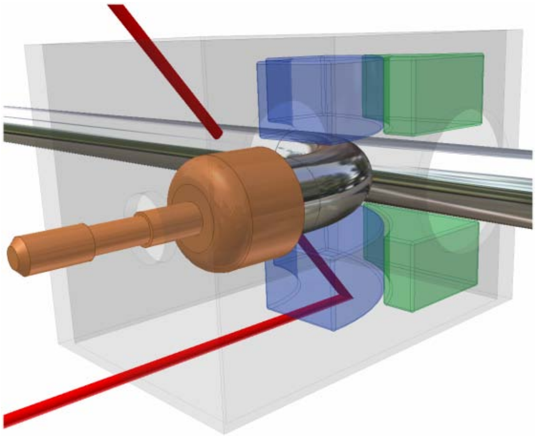

Figure 2: Schematic layout of the detector system. The ion beam and dissociated electrons are shown in silver, with the electrons being deflected into the (copper-coloured) detector. The bending dipole is shown in blue; the magnet for correcting the ions' path, in green. The path of the laser is shown in red.

MEASUREMENTS OF THE 6-DIMENSIONAL PHASE SPACE DISTRIBUTION

To measure the beam density distribution in the six dimensional phase space behind the RFQ and the chopper, an additional diagnostic device is being designed. The setup under considerations is shown in Figure 3. It consists of a large magnetic dipole (already available) intended for the determination of the transverse emittance and a further detector system in front of the bending magnet for the longitudinal emittance measurements.

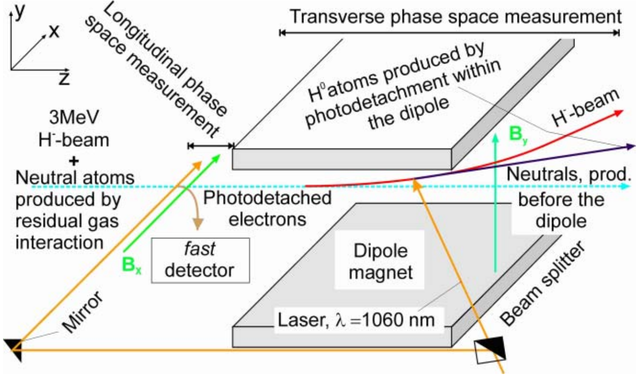

Figure 3: Schematic layout of the emittance measurement device. The fast (electron) detector in front of the dipole will be used for longitudinal emittance measurements and the neutrals, produced within the dipole, deliver the transverse emittances xx', yy'.

A very fast detector system (typ. 10 ps) will be used (in conjunction with the very fast pulsed laser system) to measure the longitudinal emittance, using a time of flight method for the detached electrons. In addition to the high time resolution, a precise synchronization of the laser pulse in respect to the RF phase is required. The longitudinal emittance will be measured by introducing a delay to the laser pulse with respect to the RF phase.

A second, slower detector (typ. some 100 ns) with spatial resolution will be used to measure the transverse emittance. It is intended to detect the produced neutrals using a scintillator screen and the readout will be performed by a fast CCD camera. A computation of the penetration depth with the SRIM [12] code gives a projected range of approximately 50 µm in a P46 target for 3 MeV protons. Similar values are expected for other solid scintillators. Therefore it is possible to stop the whole beam within the detector. The detection of the photo neutralised H^- ions necessitates a careful separation of the neutrals produced by residual gas interaction in order to improve the signal to noise ratio. Therefore the interaction region is within the dipole after bending the beam out of the straight direction. Furthermore, it is intended to measure the phase space distribution in both transverse planes. This makes the layout of the laser optics more complicated as at least two mirrors have to be installed inside the vacuum chamber of the dipole: one for the horizontal plane and one for the vertical plane. To avoid damaging the vacuum chamber and to prevent stray light, it is necessary to dump the laser light in a controlled manner. This will require two additional mirrors inside the chamber. The main requirements of this system are a sub-nanosecond time resolution (defined by the laser pulse length), triggering relative to the RF phase and a low dark current & noise level. Several important parameters of the experimental set up are listed in Table 1.

Table 1: Summary of several experimental parameters of the phases space measurements behind the RFQ.

Ion Beam	
Current	60 mA
Repetition rate	50 Hz
Pulse length	2 ms
Duty cycle	10 %
Micropulse length	~ 1 ns
Dipole Magnet	
gap high of the pole shoes	100 mm
Bending Radius	1.12 m
Reference path length	0.88 m
Field gradient	n = 0
B—field at 3 MeV, H^-	240 mT
Photo detachment	
Laser pulse energy	1...2 mJ
Energy of detached electron	1.6 keV
Neutralisation fraction	≤ 1 % of the beam pulse
Particle yield (pp)	10^7
Resolution & Range	
X, Y – range	± 25 mm
X, Y – resolution	0.5 mm
X', Y' – range	± 100 mrad
X', Y' – resolution	1 mrad
$\Delta W/W$	1 %

OUTLOOK

In the near future simulations of the beam envelope in both devices are planned as well as detailed studies of the individual detector systems. The construction of the transversal profile measurement is planned for the end of the year and first beam tests are scheduled for summer next year. The time schedule for the emittance measurement is somewhat more relaxed as first beam is not expected behind the RFQ before the end of 2008.

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