# A NON DESTRUCTIVE LASER WIRE FOR $H^-$ ION BEAMS*

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## *Abstract*

The Front End Test Stand (FETS) is an R&D project hosted at Rutherford Appleton Laboratory (RAL) with its aim to demonstrate a high power, fast chopped H- ion beam. Possible candidates of applications are Isis upgrade (RAL neutron source), future spallation sources or the Neutrino factory. The high beam power may cause problems due to its thermal power deposition on diagnostics parts introduced into the beam so non-invasive beam instruments are highly preferred to avoid those problems. Diagnostics for H- beams can benefit of laser light where photons with suitable energy are able to detach the additional electron. This method is applied to a beam profile monitor close to the ion source of the FETS beam line. The paper gives a status report of the ongoing process of experimental set-up and provides a detailed discussion of problems and recent changes.

## INTRODUCTION

High Power Proton Accelerators (HPPA), capable of producing beams in the megawatt range, have many applications, including drivers for spallation neutron sources, production of radioactive beams for nuclear physics, hybrid reactors, transmutation of nuclear waste, and neutrino factories for particle physics [1,2]. These applications require high quality beams and call for significant technical development, especially at the front end of the accelerator, where beam chopping at an energy of a few MeV and high duty cycle (1…10%) are required in order to minimise beam loss and induced radioactivity at injection into downstream circular accelerators.

The Front End Test Stand (FETS) [3] project, a UK based collaboration involving RAL, ASTeC, Imperial College London, University of Warwick, Physical Department of Universidad del Pais Vasco, and Bilbao, Spain, will test a fast chopper in a high duty factor MEBT line. More recently the project is also supported by Royal Holloway, University of London. The key components of the beamline are an upgraded Isis Penning ion source with 65keV beam energy, a three solenoid Low Energy Beam Transport (LEBT) line, a high duty factor 324 MHz Radio–Frequency Quadrupole (RFQ), a MEBT section including a novel Fast–Slow beam chopper and a comprehensive set of beam diagnostics. The ion source and LEBT are currently being commissioned; the status is described in [4,5,6].

## *Photo detachment used for beam diagnostics*

For negatively charged particle beams the photo dissociation technique (also called photo detachment) offers an elegant solution to do non destructive diagnosis. Photons with an energy above the threshold for photo dissociation (H- binding energy ~0.75eV) can be used to partially neutralize the beam. For H-, and a photon with an energy of 1.5eV, the maximum cross section for photo neutralization $H^- + \gamma \rightarrow H^0 + e^-$ is about 4.0* $10^{17}$ $cm^2$. Calculations of the cross section [7,8,9] and the particle yield [10] respectively in previous experiments [11] have demonstrated that a Nd:YAG laser (2nd harmonic Nd:YAG as well diode pumped solid state (DPSS) Lasers are also possible) can be used as an effective light source.

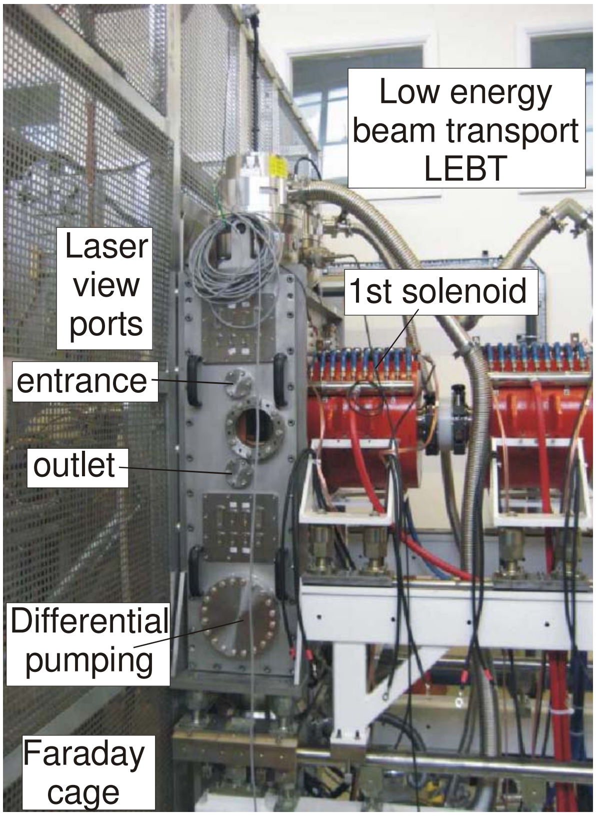

Fig 1: The differential pumping tank housing the detector with the laser mirrors. The first solenoid is as close as possible due to beam transport restrictions.

Behind the laser neutralization 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 photodetached electrons transfer a

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significant momentum to the $H^o$ 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 with a detector system with spatial resolution [12].

The electrons are more suitable when the total amount of neutralization, such as for the laser wire profile measurement technique, or fast detection, as for energy spread measurements using a Time of Flight (TOF) method, is required. Because of the low velocity and therefore magnetic rigidity of the electrons detached of a 65 keV $H^-$ beam, the electrons will be (post)accelerated to 2 keV as they enter the dipole magnet to reduce any deflections by stray fields.

The final aim is to combine measurements with some computational tomographic method like the Algebraic Reconstruction Technique ART [13,14] to get the correlated transverse beam distribution of the ion beam.

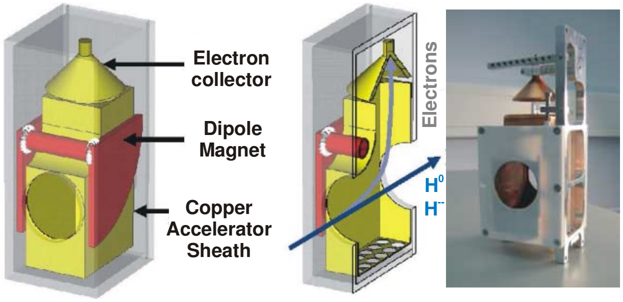
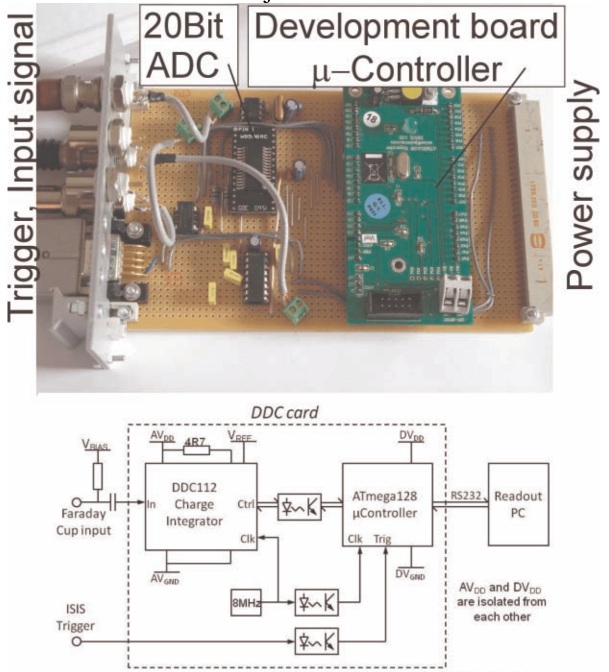


Figure 2: The detector consists of an accelerator sheath to bring the detached electrons up to speed, a magnet to separate and the Faraday cup, also biased. Not shown a suppression ring at the entrance to shield the detector of $e^-$ produced by gas stripping in front of the detector.

## EXPERIMENTAL SET-UP

The detector design for the detached electrons has been carried out by D.A. Lee [16,17]. The whole experiment is integrated in a pumping vessel, shown in Fig.1. Longitudinal space is very limited thus the first solenoid is mounted as close as possible onto the back wall of the vessel. The detector utilizes a small dipole to bend the detached electrons into the Faraday cup. Due to the low energy an acceleration sheath has been implemented to bring the particles up to +2000 V; see Figure 2. The performance of the detector is given by the voltage settings for acceleration sheath, suppression ring and bias of the Faraday cup and the magnet current of the dipole. A more detailed description of the basis of the instruments see [12,15]. The laser used for the measurements is a 500 mW, frequency doubled, diode pumped Nd:$YVO_4$ laser, operation at 671 nm achieving approximately 90% of the maximum photo-detachment cross section.

To compute a correlated 2D distribution (with a tomographic method, e.g., ART) two pairs of mirrors were prepared to be moved on linear and rotatable vacuum suitable piezo-driven stages to scan the laser at a variety of angles through the ion beam. Due to tight space, small mirrors were used mounted on custom-made mirror holders without adjuster screws.



Design by Gary Boorman, RHUL

Figure 3: *Top*: The strip-board built for test purposes. The readout of the ADC is controlled by an ATMega microprocessor sitting on a development board. *Bottom*: the new circuit to avoid ground loop problems.

### *Initial test results*

A first phase of commissioning the beam profile monitor took place in summer 2009 using the described set-up. The results are presented in detail in [17]. Here, only a brief summary should motivate further developments.

The experiments were a success insofar as functionality of the detector has been shown. But it appeared that the beam size is much bigger than assumed in simulations, so the detector hole acts as a collimator. This produces a large background signal exceeding the maximum possible charge which can be accumulated with the integrator chip DDC112. Therefore, detector settings were chosen to minimise the total average charge enabling the most sensitive measurement range of the ADC. Integrated over several thousand pulses the accumulated charge gave a mean of about 290 pC with a variance of 5 pC. This width is mainly caused by the pulse-to-pulse stability of the source and is more than you can achieve with the present DPSS laser.

## CURRENT INSTALLATION STATUS

Different possibilities seem feasibly to improve the system to measure photo detached electrons. Since the closed marriage between vacuum vessel and detector it would be rather difficult to change the design fundamentally, hence a more evolutionary solution was preferred. The key to addressing the discovered problem with the background is to go up in laser power and also to simplify the whole set-up as much as possible. Simplicity lets us prove the principle with special focus on the mirror arrangement inside the vacuum, i.e., a fixed, central position. After this basic demonstration, the aim of measuring correlated 2D beam profiles would be approached in a more empirical step by step process.

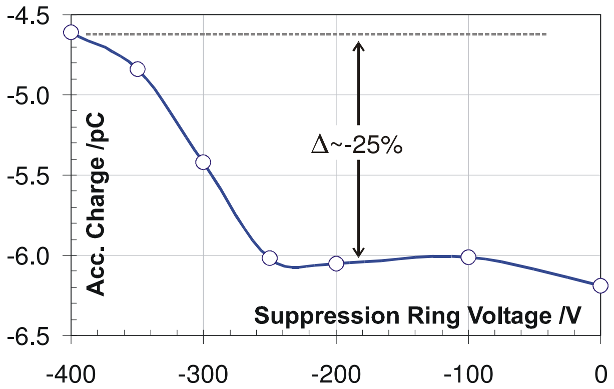


Figure 4: Variation of the suppression ring voltage. The data were taken without Faraday cup bias but an acceleration sheath potential of +1.8kV and a magnet current of 0.8A.

### *Laser and optics*

The Institute of Applied Physics IAP, Goethe-University Frankfurt kindly loaned us a more powerful laser to carry out the photodetachment experiments. This device has a thin-disk Yb:YAG crystal emitting at 1030 nm and providing very small radius and divergence angle, and an $M^2$ close to theoretical possible minimum. The device has been used already for photodetachment experiments at a different set-up in Frankfurt [18].

Various other changes have been introduced as well. First of all, the optics elements (mirrors and holders; vacuum windows) have been adapted to the change in wavelength. A lot of effort was spent to improve the rigidity of all the opto-mechanical mounts inside and outside of the vacuum.

A new optical breadboard was designed and built which can be securely mounted on the outside of the drawer of the differential pumping vessel (Fig. 1), providing space for additional alignment measures. This extended breadboard is necessary due to the difference in position of the drawer unit between open and closed.

### *Readout electronics*

The electronics mean here the current amplifier from Texas Instruments DDC112 controlled and readout by an Atmel ATMega microprocessor [15]. This concept has been migrated to a temporarily strip-board solution, Fig.3, for development purposes only. Tests with a TGA1244 pulse generator have been carried out demonstrating problems to measure charges down to sub-nano Coulomb due to a ground loop issue. This should be fixed with a new layout, also shown in Fig.3. In near future the complete electronics will be build with a PCB which will reduce problems with noise or ground loop issues further.

Another important aspect is the software to control the microprocessor and store date on a computer. So far, it was not possible to run the ADC in a so called non-continuous mode. In continuous mode the integration time is fixed given by the main trigger but in non-continuous operation it is possible to delay the integration respectively to the trigger (this is equivalent with integration across the full ion source pulse) as well as changing the integration time.

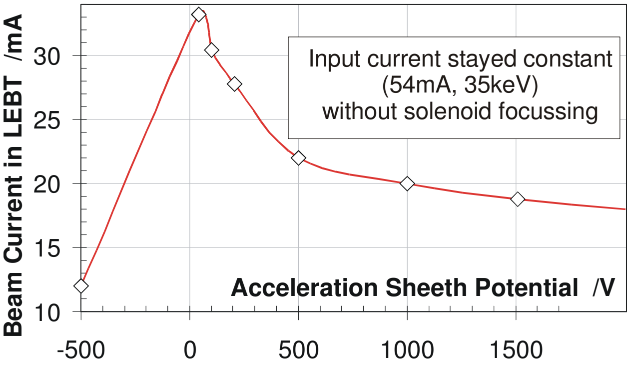


Figure 5: Variation of the jacket voltage, everything else were off. The potential of the acceleration sheath influences significantly the ion beam.

## BACKGROUND MEASUREMENTS

To understand the background behaviour, several parameters of the detector were varied, and the Faraday cup signal was monitored with a scope. If not stated differently, the source produced a 54 mA beam at 35 keV beam energy. Compared with previous measurements, the behaviour is similar, but only qualitatively. The absolute numbers show a different picture, i.e., these background measurements can vary from day to day, and even if the source settings are identical the background behaviour can be quite different.

In Fig. 4 the voltage of suppression ring was varied but the sheath potential was kept constant at +1.8kV as well as the dipole (0.8A), and the Faraday cup bias was off. In the best case, a reduction of 25% could be achieved. It might be possible that the remaining signal comes from electrons produced within the detector. The suppression ring is only supposed to shield electrons due to residual gas stripping further upstream of the profile detector.

The various potentials influence not only the Faraday signal but also the beam transport through the detector. Figure 5 shows the variation of the acceleration sheath potential but everything else off. The voltage has the strongest impact on beam transportation because it has the highest potential and geometrically, the jacket shows similarities to an einzel lens. The beam current was monitored with current transformers upstream and downstream of the detector (between the second and third solenoid of the low energy beam transport, all solenoids off).

As shown in Figure 5, the drop is significant and can be interpreted as part of the background problem since the beam widens due to the external potential by influencing the space charge compensation; a more detailed discussion is provided in [19].

Having that in mind, the variation of the beam energy should also have an influence on the background because the strength of the transverse focusing changes by varying the post acceleration, i.e., beam energy [19]. To check this aspect the source settings were not changed but the post acceleration was varied between 25 and 60 keV, shown in Figure 6. As a starting point, a 35 keV beam was used, where the signal minimized as good as possible (+1800 V acceleration sheath, +300 V cup bias, 800V grid potential, magnet 0.8A).

Keeping the detector constant, the background signal depends on the post-acceleration, but only low energies show a clear result where a mismatched beam produces a huge positive signal, an indication of positive residual gas ion created by beam losses. Higher beam energies show a change more at the beginning; towards the end of the ion source pulse, the influence is very small. The two peaks within the first 100 µs may have to do with the rise time of the ion source extraction power supply, [19] but that need more quantified investigations.

Note the smaller signal towards the end of the ion source pulse compared to the ringing during the first 80-100µs. Regarding the photodetached electrons, the non-continuous operation mode of the ADC helps to avoid overloading the input capacitance of the charge integrator.

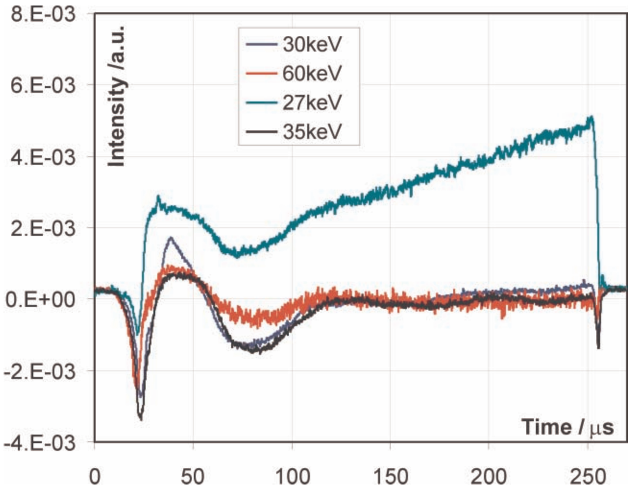


Fig. 6: The background signal was minimised for 35keV beam keeping the detector settings constant. Then, the beam energy was varied:

## SUMMARY AND OUTLOOK

First tests of the detector, laser and optics took place in late summer 2009 (summarized in [16,17]) and demonstrated functionality of the detector, but also identified several problems, which need to be addressed.

One outcome of this work is a need for increased laser power to prove the principle of photodetachment with this experiment. Thankfully, the Goethe-University Frankfurt, IAP, supports this project with a suitable cw laser. Several changes in the electronics, optics and mechanical set-up have been performed to adapt the new laser and to simplify the experiment.

At the moment the focus is on principle demonstration experiments without scanning the laser through the ion beam. This demonstration of photo detachment should be achieved in the very near future. Further steps, with better alignment feedback, beam profile measurements should be possible in horizontal direction.

Still, the final aim is to integrate rotatable mirrors to make accessible the full 2D beam distribution. Measurements will be combined with computational algorithms like the Algebraic Reconstruction Method (ART) or possibly Maximum Entropy (MaxEn)t [20].

A strong argument for photodetachment is the renunciation of mechanical parts inside the beam, i.e., having a non-invasive technique to minimize the influence on beam transportation. In the long term the beam losses shown in Figure 5 caused, by the acceleration potential of the detector, are not acceptable and need to be addressed as well.

One solution could be to move the detector to a more suitable position at the beamline with a smaller beam radius. That may imply a higher beam energy further downstream of the RFQ. Radius and divergence angles are typically smaller than at the ion source energy but the photodetached electrons also have higher energy. The latter means that the potential of the acceleration sheath can be reduced, since the detached electrons of a 3 MeV H- beam are at 1.6 keV, compared to the ~40 eV of photodetached electrons from a 65 keV ion beam.

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