Beam diagnostics based on Photo–Detachment for the Front End Test Stand FETS

C. Gabor[1], J.K. Pozimski[1+2], A. Letchford[1+3], C. Prior[1]

1) STFC/ RAL/ ASTeC, Intense Beam Group, Chilton, Didcot, Oxfordshire, UK
2) Imperial College London, UK
3) STFC/ RAL, ISIS Injector Group, Chilton, Didcot, Oxfordshire, UK

Abstract

For diagnostic study of high power particle beams, non-destructive measurement devices provide minimum influence on the beam and avoid various problems in connection with the high power density on surfaces. An H- ion beam offers the opportunity of non destructive beam diagnostics based on the effect of photo detachment. By the interaction of light with H-ions, the additional electron can be detached and a small number of neutrals will be produced. An additional magnetic dipole field can then be used to separate the detached electrons and neutrals from the ions. Using an integral detector the spatial distribution of the beam ion density can be derived, while the use of a spatial resolving detector enables the phase space distribution to be determined.
This measurement principle will be used to determine emittance and beam profile of the FETS project at STFC/ RAL. The aim of FETS is to demonstrate a chopped H- beam of up to 60mA at 3MeV and 50pps with sufficiently high beam quality. The paper will present a detailed description of the proposed set-up at RAL and discuss several results of simulations and data gained as a "proof–of–principle" experiment in Frankfurt.

1 Introduction: The FETS Project

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%) is required 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, the University of Warwick and the Physical Department of Universidad del Pais Vasco, Bilbao, Spain, will test a fast chopper in a high duty factor MEBT line. The key components, as shown in Figure 1, are an upgraded ISIS Penning ion source, a three solenoid Low Energy Beam Transport (LEBT) line, a high duty factor 324MHz Radio–Frequency Quadrupole (RFQ), a MEBT section including a novel Fast–Slow beam chopper and a comprehensive set of beam diagnostics.

The main specifications of the FETS are summarized in Table 1 addressing all generic and specific requirements for the next generation proton driver, including an upgrade for ISIS (`http:www.isis.rl.ac.uk`), respectively.

Parameter	Design value
Ion species	H^-
RFQ input energy	60–70keV
RFQ output energy	3.0MeV
Beam current	50–60mA
Pulse duration	0.3….2ms
RF–frequency	324MHz
Pulse repetition frequency	50Hz
MEBT chopper field transition time	2ns
Chopped beam duration	0.1…100μs
Chopper pulse repetition frequency	1.3MHz
Micro pulse structure	~ 0.5ns

Table 1: *Some key parameters of the Front End Test Stand FETS.*

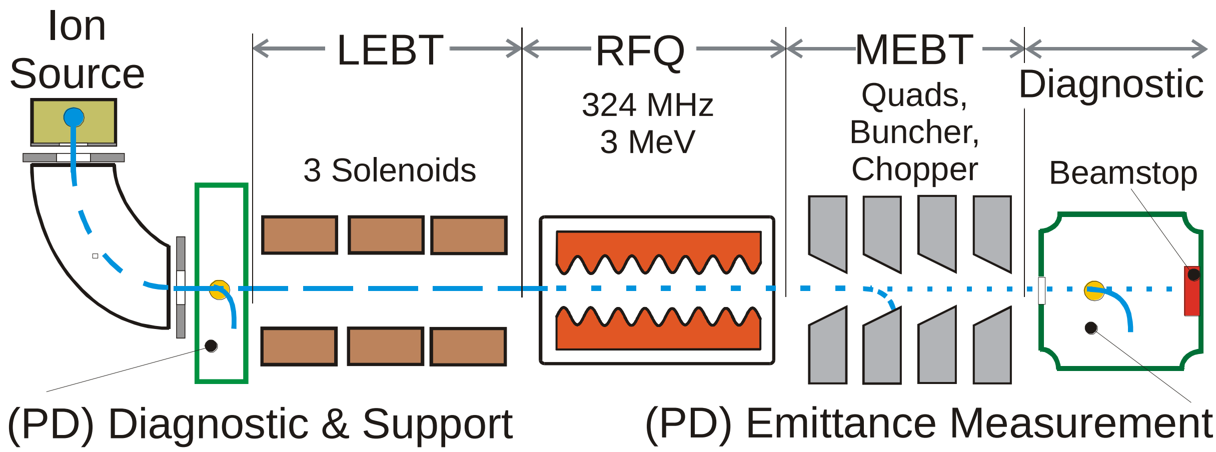

***Figure 1**: Schematic overview of Front End Test Stand (FETS) beam line. Only the non-destructive photo detachment beam tomography in front of the Low Energy Beam Transport (LEBT) and the laser based emittance measurement device behind the MEBT/ chopper are shown. Additionally well–known diagnostics like FDC, toroids and destructive emittance scanners will be, permanently or in commission phase, installed along the beam line.*

2 Non–destructive laser diagnostics based on photo detachment

A detailed knowledge of the transverse and longitudinal phase–space distribution (emittance) is of importance in order to increase the intensity and brightness of particle beams, as required for HPPA.

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 electrostatic–sweep (Allison) scanners, slit-grid or slit–slit with FDC instruments, are widely used. Due to the power density deposited on surfaces like slits or pinhole plates these conventional destructive methods suffer under the high power beams required.

Additionally, in the case of emittance scanners, the beam is lost during the measurement and therefore on line monitoring while beam is at target, 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 (here H-) the photo dissociation technique (also called photo detachment) offers an elegant solution: 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 is approximately 4.0* 10^{17} cm^2. Calculations of the cross section [4, 5, 6] and the particle yield [7] respectively in previous experiments [8] have demonstrated that a Nd:YAG laser (2^{nd} harmonic Nd:YAG as well diode pumped solid state (DPSS) Lasers are also possible) can be used as an effective light source.

Behind the laser neutralization 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 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. Due to different energies, i.e. different velocities, the particles will be separated along a certain drift length.

2.1 FETS–principle of ion beam density measurements

For FETS two different diagnostic devices using the laser detachment technique are being designed. One uses a laser wire technique and the detection of electrons to determine the transversal and longitudinal density distribution of the ion beam, similar to [9, 10]. The main difference to the systems already in use is the ability to investigate the full three dimensional density distribution by applying tomography techniques.

To measure the ion beam density the tomography method will be utilized. 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 real picture of the three dimensional density distribution (using a pulsed laser) 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 with an expected time resolution of approximately 6μs.

The photo dissociated electrons will be deflected by a dipole magnet into a detector (Faraday cup). The particle yield is expected to be of the order of 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 digitized using an ADC and this result passed to a computer for the analysis. Recently the design and optimization of detector system, magnetic field distribution to separate detached electrons and negative ions and post acceleration (in order to reduce stray field influence on electrons, have been brought to completion [11].

The position of this beam profile monitoring will be along the Low Energy Beam Transport (LEBT, see also Figure 1). The actually work for this diagnostic tool is being carried out by David Lee, Imperial College, London.

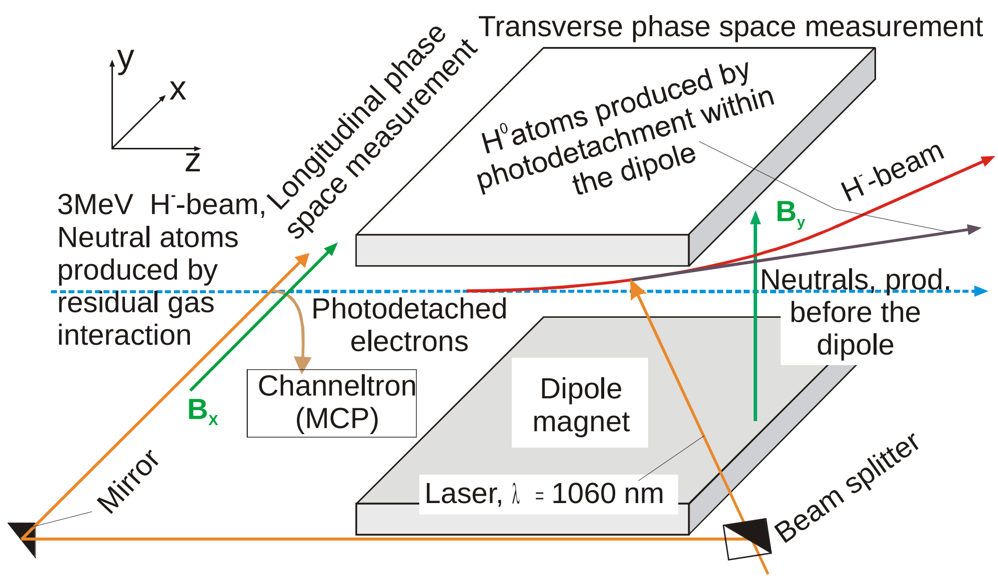

***Figure 2**: Schematic layout of the emittance measurement device. The electron detector in front of the dipole will be used for longitudinal emittance measurements and the neutrals, produced within the dipole, deliver the transverse emittance.*

2.2 FETS - principle of measurement of the 6–dimensional phase space distribution

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 [12, 13, 14]. 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 and should be placed behind the RFQ and MEBT.

The set-up under consideration is shown in Figure 2. It consists of a large magnetic dipole intended for the determination of the transverse emittance and, in front of the bending magnet, a further detector system for the longitudinal emittance measurements. A fast detector system (typically 10ps) will be used in conjunction with a very fast pulsed laser system to measure the longitudinal emittance, using a time of flight method for the detached electrons. The longitudinal emittance will be measured by introducing a variable delay to the laser pulse with respect to the RF phase whereas the actual measurement will be added up over several pulses.

In addition to the high time resolution, a precise synchronization of the laser pulse with respect to the RF phase is required. In addition too the fast particle detector, a (short-pulsed) q–switched Laser system such as a Nd:YAG laser from Lot Oriel (`http://www.lot-oriel.com`), with a high time reliability (low jitter), is also important to reach this time resolution. The decision over which particle detector to use is still under discussion, however. The particle detector has to be a low dark current with an adequate amplification of signal and a time resolution of few ps.

A second, slower detector, typically several 100ns with spatial resolution, will be used to measure the transverse emittance. It is intended to detect the neutrals using a scintillator screen like P46 or YAG (Rubin)–crystal and the readout will be performed with a fast CCD camera. A computation of the penetration depth with the SRIM (http://www.srim.org) code gives a projected range of $\approx 50\mu$m in a P46 target for 3 MeV protons and should deliver enough photons to use a CCD-camera.

3 Simulation and Measurements of transverse emittance

The concept of transverse phase space measurement using a laser was investigated in Frankfurt, Institute of Applied Physics (IAP), in order to demonstrate the principle for low energy beams, and is described in [15]. Measurement results and simulations are shown below.

Because the same principles were employed at IAP and FETS the results are comparable. Recent simulations have improved the agreement between theoretical data and measurements and provide additional information about the phase space.

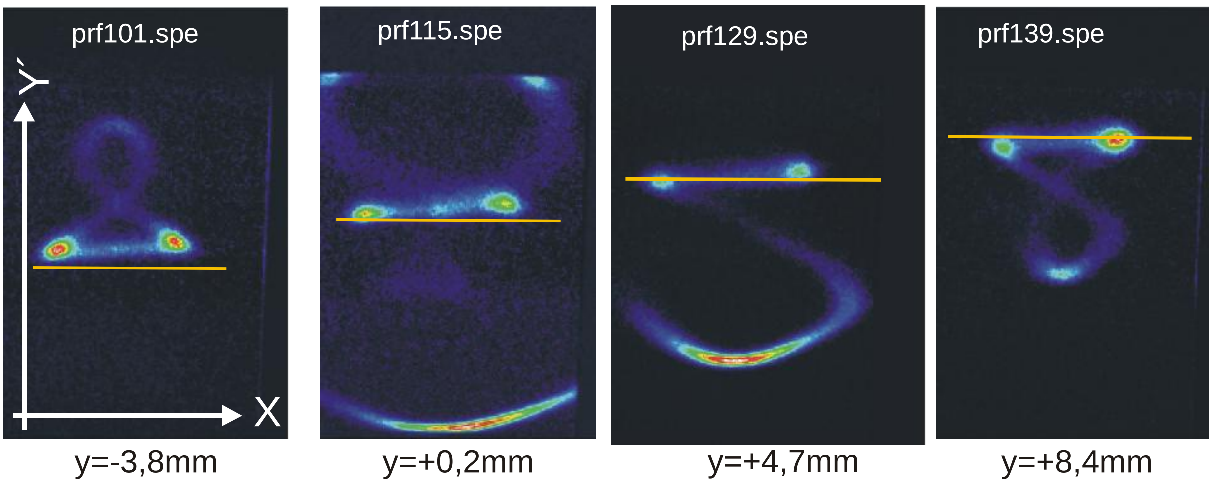

Figure 3: *Measurement results of the Frankfurt photo detachment experiment. The scintillator signal is shown in false colour at several laser positions. The drift of neutralized particles is 310mm; for each picture the position of the laser is marked. The vertical direction y corresponds as well with the angle y' /mrad. Due to a low magnetic dipole gap, the ion beam is on top as well as bottom and is partly collimated by the vessel.*

The diagnostic experiments were carried out at an ion beam current of $I_{H^-} \approx 1.5\text{mA}$. Reference emittance measurements were performed with a slit–grid emittance scanner just behind the ion source and behind the LEBT to compare these phase space distributions with photo detachment measurements. The produced neutrals and the H- beam were separated with a dipole magnet. A scintillator, together with a CCD camera, detected the neutralized particles and acts as an angle detector of the emittance measurement device, whereas the front slit of (e.g.) a slit–grid emittance scanner is replaced by the laser and determines the position of measurement. The measurements of photo detachment have been performed at different y-positions, and several examples of raw data give Figure 3.

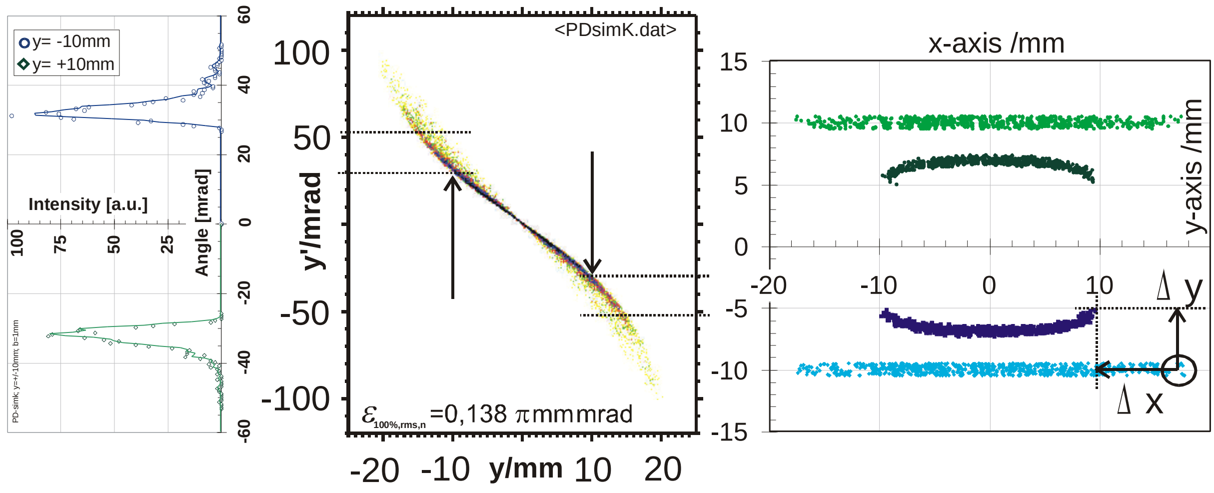

***Figure 4**: (from left to right) Integrated beam profile I(y') of the emittance pattern (solid line) and integration of the neutralized particles after 100mm of drift (dotted curve). The centre picture shows the emittance; and the "neutralized particles" (cut out in xy-space) at +/- 10mm are shown on the right, with particles after the drift enclosed by the neutralized patterns.*

In order to compare the raw data with an emittance pattern in phase space yy', the pictures have to be integrated along the (horizontal) x-axis. That means a transformation

$$I(x,y)_{scint} \;:\; \int I(x,y)_{scint}\,\mathrm{dx} \;\mapsto\; I(y)$$

The vertical y-axis corresponds with the angle of the ion beam, and can be obtained by the offset Δy between the position of the laser and the pattern of the CCD image – with l as the distance between laser and scintillator, the divergence angle can be calculated as $y' = \tan(\Delta y/l) \approx \Delta y/l$ [mrad].

Compared to slit-slit emittance measurements the scintillator images demonstrate an intermediate step where –instead of a spatial distribution– the integration $\int \mathrm{dx}\,\mathrm{dx}'$ over position and angle causes loss of information about the phase space. A slit–slit scanner delivers directly the angle profiles shown on the left in Figure 4 without any reverse function to the particle pattern on the right.

In consideration of several technical problems, like adjustment and possible influence of the (low) gap of the dipole, comparison between both profiles gained by photo detachment and a slit-grid emittance scanner shows good agreement in divergence angle [12].

Related to the measured curved pattern, a further point of interest was understood the image function of the angle detector. Several simulations have been carried out and, first, the process of photo detachment and their transfer function were discussed for an ion beam with almost no aberrations.

An example is presented in Figure 4 where the xy-space (right) shows the particles at the laser position (process of neutralization) and enclosed the particles after the drift. The difference of position of the neutralized part of ions and the pattern after the drift and the known length of drift deliver the angle in both directions x and y. The angle profiles y' of the emittance and the curved pattern of the neutrals are compared in the left graph.

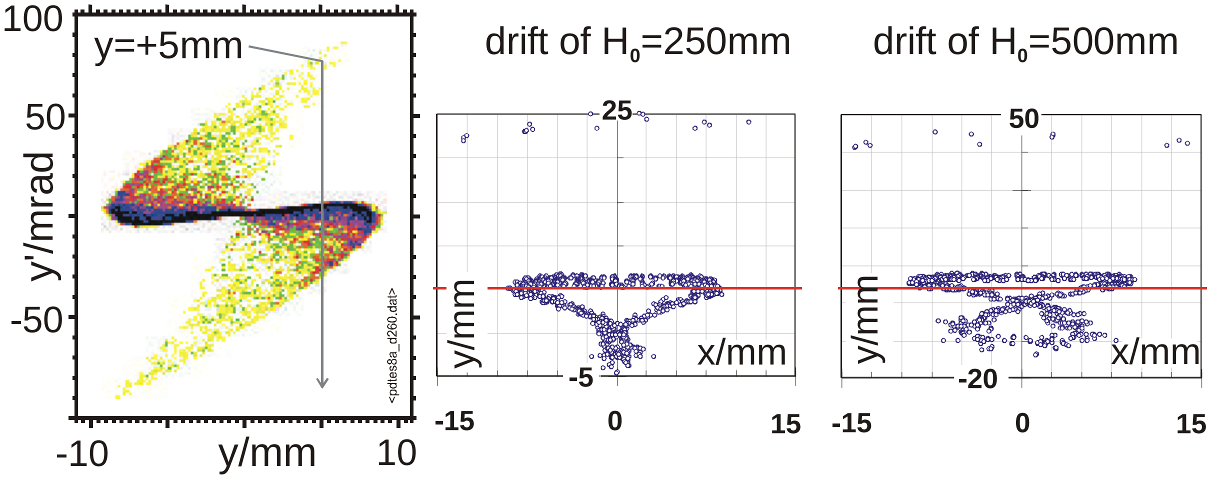

Figure 5: *(left to right): the Figure shows a cylindrically symmetric emittance with large filamentation. At +5mm, the laser crosses the ion beam, i.e. all particles were cut out in xy-space. The patterns at the scintillator are shown after two different drift lengths. Both cases show separate parts of neutralized particles, some with larger positive ngles, others with smaller positive as well as negative angles, with curved \& closed patterns. In general the shape of the curves depends on the drift length, aberrations and symmetry of the ion beam.*

Furthermore, the convergent beam causes a symmetrically smaller pattern after the drift along both the x-and y-axis, i.e. the simulation is based on a cylinder symmetric ion beam distribution. The extracted profiles of the emittance in phase space show, at the marked (positive) position, smaller intensities at larger angles, which is characteristic of *S–shaped* aberrations. For a shaped emittance pattern, the orientation of the neutralized particle patterns on screen is always bent from the centre line as shown in Figure 4, and is independent of convergence or divergence of the beam.

The measurement results of Figure 3 show more detail than the simulations presented in Figure 4: considering the limitation of detector signal, the distorted curves show an almost closed pattern; further parts are collimated by the vessel of the dipole magnet. Initially, the shape of these signals were attributed to a non–cylindrically symmetric ion beam and influenced by the small gap height of the dipole magnet, but recent investigations into the transfer function are in much better agreement with the experimental data. The closed curves are produced by a large aberration in the emittance (Figure 5), which is also measured with a traditional slit–grid emittance scanner in front of the dipole [12]. The left graph of Figure 4 shows a simulated emittance distribution representing the measured phase space; on the right are shown the results of the photo detachment simulation.

The emittance shown is very close to the measurements. For that comparison, it is not possible to use the experimental yy' emittance because of the loss of information of the whole xy–space during the data acquisition along the slit.

The laser cut in Figure 4 was carried out at +5mm and (right) particle distributions on the scintillator were shown after two different drift lengths, on which the radii of curvature depend. The right simulation with a drift length of 500mm is comparable with the right picture of Figure 3.

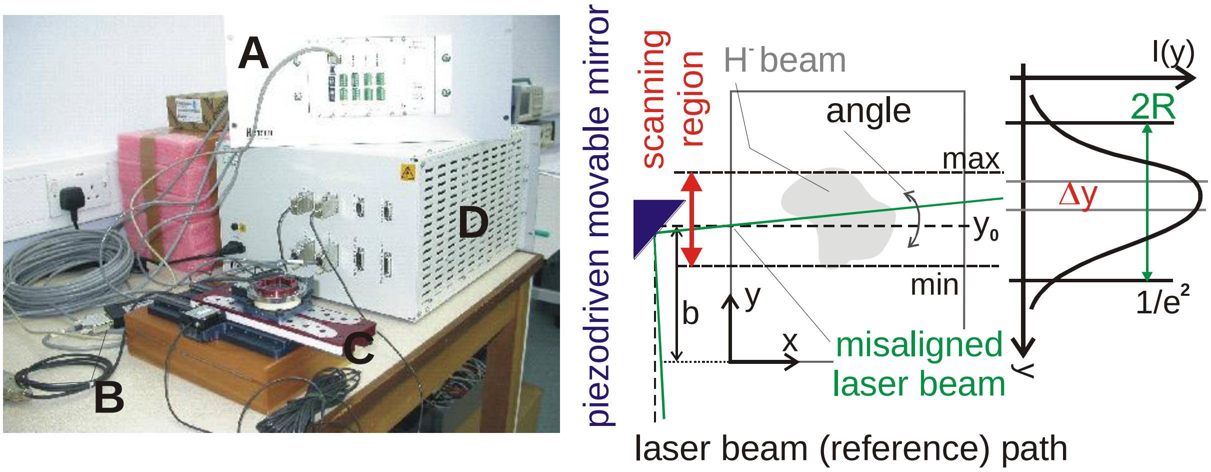

Figure 6: *Left: A Motion control; B Encoders; C Piezo-driven linear stage, in combination with a rotary stage; D Amplifiers and power supplies. The movable stages must be vacuum suitable to operate inside the vessel and guide the laser through the ion beam.*
Right: Schematic drawing of a misaligned laser. Different slopes with respect to the reference path cause problems during computation of the phase space. In addition, the spatial resolution can be enhanced beyond the laser beam radius by considering the exact gaussian distribution of the photon density.

The second part of the simulated distribution with large angle of $y' = 40\ldots45\mathrm{mm}/0.5\mathrm{m} = 80\mathrm{mrad}$ was cut by the vessel of the dipole, and is shown in right picture of Figure 3.

Apart from the influence of drift length, further parameters are involved in determining the pattern of the curved distribution: beam radius, coupling of transverse planes, laser position and angle, i.e. the convergence or divergence of the whole beam. A more detailed discussion is given in [15].

4 Status of recent work

Sufficient spatial resolution means high demands, in particular with regard to laser beam alignment, i.e. a constant perpendicular angle between photons and H- ions over the whole scanning range. Besides a slanting laser beam with respect to an assumed centre for the H-beam (reference path), the real photon distribution affects the spatial resolution as well. Both are shown in Figure 6.

In general, an angle between the laser and ion beams leads to a more complicated integration. Instead of an integration $\int I(x,y)\,\mathrm{dx}$ of the neutrals, it is necessary to introduce a linear equation of the form $L(x) = a \cdot x + b$ with $a = \frac{\mathrm{dy}}{\mathrm{dx}}$.

In the ideal case, this linear equation simplifies to $L(x) = b = y_n$ where the index n (=0 at the origin) stand for a certain transverse position between the maximum and minimum positions within the scanning region.

But assuming a slope of the laser leads to an integral like $\int I(x,y)\,\mathrm{dL}$, this leads to more complicated error handling for the emittance computation. Additionally, the movable mirrors can cause various slopes at different positions, i.e. $(dy/dx)_i$ varies along the scanning region (with $i = \mathrm{MIN}\ldots n\ldots\mathrm{MAX}$).

The other aspect –spatial resolution– was mentioned earlier and relates to the transverse photon density distribution. In the interaction region of H- and photons, a well-collimated, pencil-like laser beam is preferable to prevent a waist. Therefore a laser source with good beam parameters (small radius and divergence angle) and optics with long focal length must be used. The best results can be achieved in the lowest mode, i.e. the gaussian TEM_{00} mode.

In contrast to misalignment, it is possible to consider the density distribution rather more easily during the emittance computation. But this requires a good knowledge of the beam propagation where important parameters like radius, divergence angle and M^2 are determined experimentally. The latter parameter is the ratio between the real, measured beam and an assumed TEM_{00} beam with the same radius and angle. It is similar to an emittance invariant of the system and is useful to calculate envelopes and waist spot-size. With appropriate focusing, it is possible to gain spatial resolution beyond the actual radius as long as the peak is broad and the difference between maximum and tails is big enough.

All of the aspects discussed above must be investigated experimentally, and more technical problems (like mirror mounting, e.g. within a limited space) need to be considered. Therefore the work concentrates on building up a laser lab with all the necessary equipment (breadboard, optics, opto–mechanics and laser diagnostics).

5 Conclusion and Outlook

The measurements on an H- ion beam in Frankfurt have demonstrated the principle of photo detachment as a beam diagnostic for a low energy ion beam. No mechanical part is within the ion beam, but there are high demands on laser power, beam "quality" and noise reduction of the CCD camera, depending on the yield of neutrals and the detector system. Both the laser system and the detector should be easy to adapt to higher beam energy and beam current, and these advantages can be used to reach better time resolution.

SRIM—simulations have shown that the deposited energy projected into the range of a 3MeV H- beam allows use of (similar) scintillator materials with a CCD-camera as an angle detector system.

At the moment the R & D progress of the FETS main components such as ion source [16], RFQ [17] and MEBT/ chopper [18] is still going on. Beginning next year (2008), it is planned to install the first parts of the set-up, i.e. the ion source with high voltage platform and support, and carry out (first) beam measurements, mainly ion source tests.

Relating to the photo detachment emittance instrument, studies have started to improve reconstruction of the emittance. With the additional phase space information extracted from the spatial distribution of the neutrals, it should be possible to compute more than a two-dimensional emittance but the work is still in progress. One aspect is to investigate the advantage of a movable particle detector. Furthermore the work to design the magnet needs to be stepped up next year, along with the detector design for the longitudinal measurements.

Assembling the laser beam path and adjustment of the laser mirrors will be finished by early 2008. It is intended to use a laser diode in the visible range of laser light at a reduced power level suitable for both photo-detachment experiments at low level (particularly the beam profile monitoring mentioned above, using a tomography method by David Lee) and testing the optical set-up experimentally.

The final construction of the tomography is planned for the second half of 2008, while the time schedule for the emittance measurement is more relaxed since because first beam to the RFQ is not expected until 2009.

Acknowledgements

We acknowledge the support of the European Community-Research Infrastructure Activity under the FP6 “Structuring the European Research Area” programme (CARE, contract number RII3-CT-2003-506395).

The author would like to thank U. Ratzinger and H. Klein for their continued support and helpful comments on the H- experiment at Goethe—Universität Frankfurt, Institut für Angewandte Physik IAP, Germany.

References

[1] T.R. Edgecock, 6th Int. Workshop on Neutrino Factories and Superbeams (NuFact 2004), July/ August 2004, Osaka
[2] R. Maier, High power proton LINACs: Application and design concepts, Proc. of EPAC, 2002, pp.174–178, Paris, France
[3] D.J.S. Findlay, M.A. Clarke–Gayther, D.C. Faircloth, et al., The RAL Front End Test Stand, Proc. of NuFact 2004, Osaka University, Japan, pp.323–325
[4] J.T. Broad, W.P. Reinhardt, One and two photoejection from H-: A multichannel J-matrix calculation, Phys. Rev., 14, 6(A), 1976
[5] M. Daskhan, Photo-detachment cross section of the negative hydrogen ion, Phys. Rev., 28, 5(A), 1983
[6] M.P. Ajmera, K.T. Chung, Photodetachment of negative hydrogen ions, Phys. Rev., 12, 2(A), 1975
[7] C. Gabor, O. Meusel, J.K. Pozimski, Status report of the Frankfurt H- LEBT including a non-destructive emittance measurement device, Proc. of 9th Internat. Sym. of PNNIB, 2002, CEA/ Saclay, Paris, France
[8] W.B. Cottingame, G.P. Boicourt, J.H. Cortez, W.W. Higgings, O.R. Sander, D.P. Sandoval, Non-interceptive Techniques for the Measurement of Longitudinal Parameters for Intense H-, IEEE Trans. Nucl. Sci., NS-32, 1985, p.1871, Proc. Particle Accelerator Conference, PAC 1985
[9] S. Lee, Z. Igarashi, T. Toyama, M. Ikegami, T. Tomisawa, H. Akikawa, S. Sato, A. Ueno, Y. Kondo, K. Hasegawa, Direct measurements of space charge-potential in high intensity H-

beams with laser based photo neutralization method, DIPAC 2005, www://accelconf.web.cern.ch/accelconf
[10] M.A. Plum, T. Shea, S. Assadi, L. Doolittle, P. Cameron and R. Connolly, Diagnostic challenges at SNS, Proc. of DIPAC 2003 JACoW Conference Proceedings, www://accelconf.web.cern.ch/accelconf
[11] D.A. Lee, J.K. Pozimski, C. Gabor, P. Savage, A laserwire beam profile measuring device for the RAL Front End Test Stand, Proc. of DIPAC 2007 Venice, Italy, JACoW Conference Proceedings
[12] C. Gabor, H. Klein, U. Ratzinger, J.K. Pozimski, Experimental results of a non-destructive emittance measurement device for H- beams, Proc. of the Particle Accelerator Conference, PAC 2005, Knoxville, Tennessee, USA
[13] R.C. Conolly, K.F. Johnson, D.P. Sandoval, V.W. Yuan, A transverse phase-space measurement technique for high-brightness H- beams, Nucl. Instr. and Meth., A313, 1992, pages 414—419
[14] V.W. Yuan, R.C. Connolly, R.C. Garcia, K.F. Johnson, K. Saadatmand, O.R. Sander, D.P. Sandoval, M.A. Shinas, Measurement of longitudinal phase space in an accelerated H-bam using a laser-induced neutralization method, Nuclear Instruments and Methods, A 329, 1993, p.381–392
[15] C.Gabor, Untersuchungen zur zerstörungsfreien Emittanzmessung an einem Testaufbau für negative Ionen, Goethe-Universität Frankfurt, IAP, 2007
[16] D.C. Faircloth, J.W.G. Thomason, Energy distribution of H- ions from the ISIS ion source, Proc. of EPAC 2006, Edinburgh, Scotland, p.1708
[17] A. Kurup, A.P. Letchford, Electromagnetic design of a radio frequency quadrupole for the Front End Test Stand at RAL, Proc. of EPAC 2006, Edinburgh, Scotland
[18] D.C. Plostinar, M.A. Clarke-Gather, C. Thomas, Design progress of the re-bunching RF cavities and hybrid quadrupoles for the RAL Front End Test Stand FETS, Proc. of LINAC 2006, Knoxville, Tennessee, USA