Laser based beam diagnostic for the RAL Front End Test Stand (FETS) [1]

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Abstract. For the diagnostic 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 to determine the phase space distribution. To investigate the measurement principle of the latter, a test stand was set up at the IAP in Frankfurt [1]. This system will now be adopted to the requirements of the Front End Test Stand at CCLRC/ RAL. The aim of this FETS is to demonstrate a chopped H^- beam of 60 mA at 3 MeV and 50 pps 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 experimental data gained in Frankfurt.

Keywords: H^-, photo detachment, non–destructive diagnostic, longitudinal & transversal emittance measurement device, tomography
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THE FETS PROJECT

High power proton accelerators (HHPPAs), 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 [2, 3]. These applications require high beam quality beams and call for significant technical development, especially at the front end of the accelerator where beam chopping at low energy (2–3 MeV) and high duty cycle (1–10%) required to minimise beam loss and induced radioactivity at injection into downstream circular accelerators.

The Front End Test Stand (FETS) [4] project, a UK based collaboration involving RAL, ASTeC, Imperial College London, and the University of Warwick, will test a fast chopper in a high duty factor MEBT line. The key components, as shown in figure 1

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TABLE 1. Some Key Front End Test Stand parameters of the ion beam

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

are an upgraded ISIS Penning ion source, 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 diagnostic.

The main specifications of the FETS are summarized in Table 1 adressing all generic and specific requirements for the next generation proton driver, including an upgrade for ISIS[2], respectively.

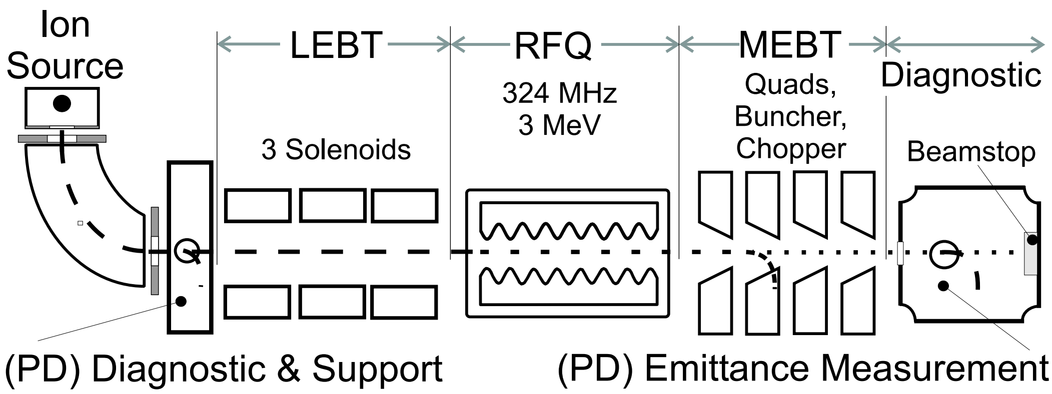

FIGURE 1. Schematic overview of Front End Test Stand (FETS) beam line. Only the non–destructive photo detachment beam tomography in front of the Low energy beam transport and the laser based emittance measurement device behind the MEBT/ chopper are shown. Additional well–known other diagnostics like FDC, toroids and destructive emittance scanners will be, permanently or in commission phase, installed along the beam line.

NON–DESTRUCTIVE LASER DIAGNOSTIC BASED ON PHOTO DETACHMENT

A detailed knowledge of the transverse and longitudinal phase–space distribution (emittance) is of most importance in order to increase the intensity and brightness of particle beams as required for HPPAs. Several well–known devices to measure the spatial particle density distribution, such as wire scanners and harps, or the emittance

[2] `http:www.isis.rl.ac.uk`

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 the surfaces like slits or pinhole plates these conventional destructive methods suffer for the required high power beams.

Additionally, in 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 ($H^- \approx 0.75\,\mathrm{eV}$) can be used to partially neutralize the beam. For H^-, and a photon with an energy of $1.5\,\mathrm{eV}$, the maximum cross section for photo neutralization is approximately $4.0\times10^{17}\,\mathrm{cm}^2$. Calculations of the cross section [5, 6, 7] and the particle yield [8] respectively previous experiments [9] have demonstrated that a Nd:YAG laser can be used as an effective light source.

Behind the laser neutralization 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 neutralization, such as for the laser wire profile measurement technique, or fast detection, like for energy spread measurements using a Time of Flight (TOF) method, is required.[3]

FETS–principle of ion beam density measurements

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 [10, 11]. The main difference to the systems already in use is the ability to investigate the full three dimensional density distribution by applying tomographic techniques. 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

[3] Due to different energies, i.e. different velocities, the particles will be separated along a certain drift length.

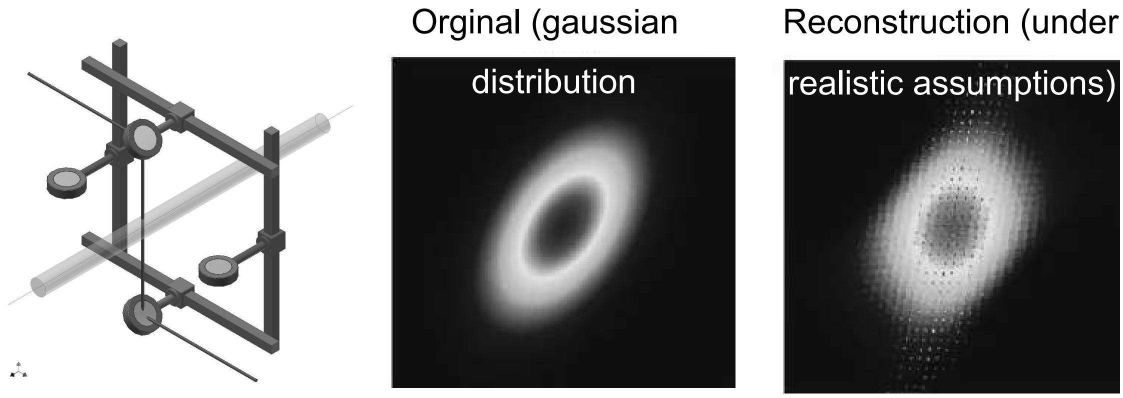

FIGURE 2. (from left to right) Laser beam path through the ion beam. The four mirrors allow the required projection data to be taken. The central image shows a gaussian xy–distribution of an ion beam. The reconstruction of the distribution shows the right image with 20 profiles per angle: due to technical reasons of the mirrors it is not possible to scan the whole range of 100°.

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 pulse 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.

The resolution of the system is limited systematically by the beam quality of the laser or by how well the laser can be focused without severe waisting. Furthermore, the correspondence between the reconstructed distribution and the true distribution will increase as the number of projections and profile sample points taken, increase. The arrangement of the mirror for the laser in the diagnostic chamber is shown in Figure 2, together with a result of a simulation of the beam profile determination. The central plot shows the gaussian beam distribution that was originally assumed. The reconstructed distribution, using 20 data points for the profile and 9° step width (and a reduced coverages of 100° instead of 180°) due to the available mirror positions is shown on the right.

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 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, has been brought to completion.

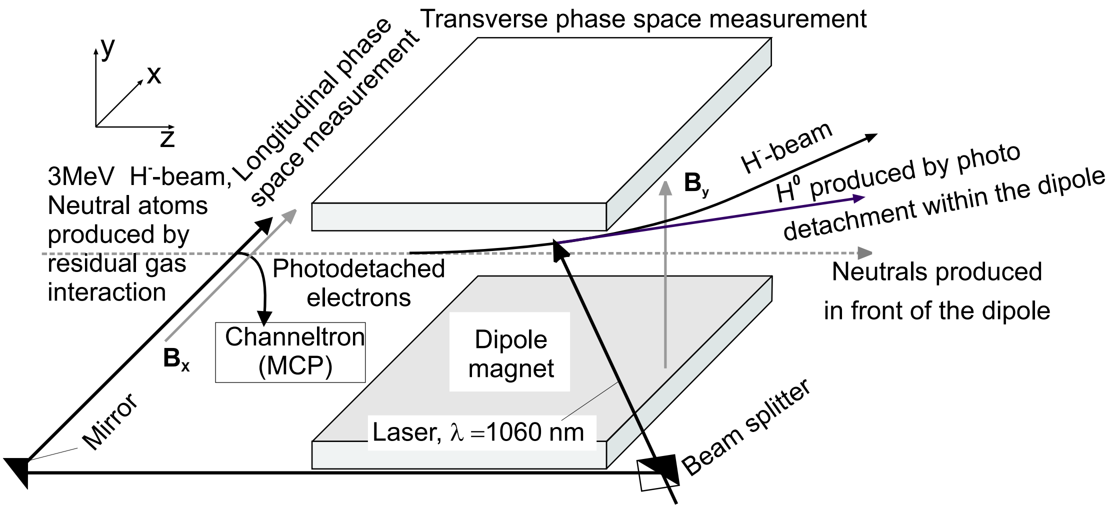

FIGURE 3. Schematic layout of the emittance measurement device. The electron detector in front of the dipole will be used for longitudinal emittance measurements and the neutrals, produced within the dipole, deliver the transverse emittance.

FETS–principle of measurements 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 [1, 12, 13]. 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 setup under considerations is shown in Figure 3. 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 very fast detector system (typically 10 ps) will be used in conjunction with also 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 of several pulses.

In addition to the high time resolution, a precise synchronization of the laser pulse in respect to the RF phase is required. Beside the fast particle detector a (short–pulsed) q–switched Laser system like a Nd:YAG laser of Lot Oriel[4], with a high time reliability (low jitter) are also important parameter to reach this time resolution. The decision of which particle detector will be used is still under discussion, however, the particle detector has to be a low dark current with an adequate amplification of signal and a time

[4] http://www.lot-oriel.com

resolution of few ps.

A second, slower detector with typically several 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 like P46 or YAG (Rubin)–crystal and the readout will be performed by a fast CCD camera. A computation of the penetration depth with the SRIM[5] 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.

SIMULATION AND MEASUREMENTS ABOUT TRANSVERSE EMITTANCE MEASUREMENTS

The concept of transverse phase space measurement by using a laser was investigated in Frankfurt, Insitut of Applied Physics (IAP) in order to demonstrate the principle suitable for low energy beams and is described anywhere. Below, several measurement results and simulations were shown. Due to same principles at IAP and FETS the gained results are comparable. Recent simulations have been improved the agreement between theoretical data and measurements and demonstrate additional information about the phase space.

The diagnostic experiments were carried out at an ion beam of $I_{H^-} \approx 1.5\,$mA. Reference emittance measurements with a well–known slit–grid emittance scanner were performed just behind the ion source and behind the LEBT to compare these phase space

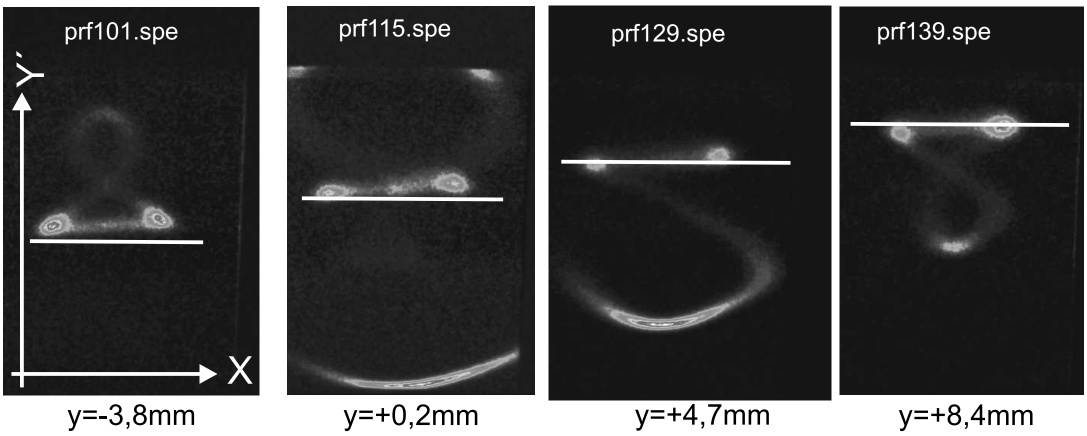

FIGURE 4. Measurement results of the Frankfurt photo detachment experiment. It is shown the scintillator signal in false colour at several positions of the laser. The drift of neutralized particles is 310 mm, for each picture the position of the laser is marked. The vertical direction y corresponds as well with angle y' / mrad. Due to a low magnetic dipole gap the ion beam is on top as well as bottom partly collimated by the vessel.

[5] `http://www.srim.org`

distributions with photo detachment measurements. The produced neutrals and H^- beam were separated with a dipole magnet. A scintillator and 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, several examples of raw data give Figure 4. In order to compare the raw data with an emittance pattern in phase space $y\,y'$, the shown pictures have to be integrate along the (horizontal) x–axis. That means a transformation

$$I(x,y)_{scint} \; : \; \int I(x,y)_{scint} dx \longmapsto I(y) \quad . \tag{1}$$

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 the distance l between laser and scintillator the divergence angle can be calculated as $y' = \tan(\Delta y/l) \approx \Delta y/l$ [mrad]. More or less, the shown scintillator images demonstrate an *intermediate* step comparable to a slit–slit emittance measurement where the integration $\int dx$ causes loss of information about the xy–distribution. Consideration several technical problems like adjustment and possible influence (of the low) gap of dipole comparison between both profiles gained by photo detachment and a slit–grid emittance scanner shows good agreement in divergence angle [1].

Related the measured curved pattern a further point of interest was understanding the image function of the angle detector. Several simulations have been carried out and in the first place the process of photo detachment and their transfer function were discussed on an ion beam with almost no aberrations. An example presents Figure 5 where right the xy–space shows the particles at laser position (process of neutralization) and, enclosed, the drifted particles as well. The difference of position of the neutralized part of ions and the drifted pattern and the known length of drift delivers the angle, namely in both directions x and y. The angle profiles $I(y')$ of the emittance and the curved pattern of the neutrals are compared in the left graph. Furthermore the convergent beam causes a symmetrically smaller pattern of the drifted particles along both x–and y–axis, i.e. the simulation is based on a cylinder symmetric ion beam distribution. The profile, extracted 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 bend from the center line like shown in Figure 5 and independent of convergence or divergence of the beam.

The measurement results of Figure 4 show much more details than simulations present in Figure 5: considering a limitation of detector signal the bended curves show almost closed pattern, further parts are collimated by the vessel of the dipole magnet. Initially, the shape of theses signals were attributed to a non cylinder symmetric ion beam and influence of the small gap high of dipole magnet but recent investigations about the transfer function are being in much better agreement with the experimental data. The closed curves are produced by a large aberration of the emittance (Figure 6) what is also measured with a traditional slit–grid emittance scanner *in front of* the dipole [1]. The

left picture shows the emittance of the simulation and based on a cylinder symmetric beam. This simulation is comparable with the measured yy′ emittance because the integration during the data aquisition you have not a complete xy–space to carry out photo detachment simulation at the measured ion beam emittance. The laser cut were carried out at +5 mm and right, particle distributions on the scintillator were shown after two different drift length and means the radius of curvature depending at least of the drift length. The right simulation with a drift length of 500 mm is comparable with right measurement of Figure 4. The second part of the simulation with large angle of almost $y' = 40\ldots45\text{mm}/0.5\text{m} = 80\text{mrad}$ were cut by the vessel of the dipole in right picture at Figure 4.
Beside the influence of drift length the curvature further parameters are involved to determine the radius of curvature: beam radius, coupling of transverse planes, laser position and angle, i.e. the convergence or divergence of the whole beam. A more detailed discussion will be given in [14].

CONCLUSION & OUTLOOK

The measurements at an H^- ion beam current of approx. $1.5\ldots2$ mA in Frankfurt have been demonstrated the principle of photo detachment beam diagnostic on a low energy ion beam without any mechanical part within the ion beam but make high demands on the laser (power and beam space width product) and noise reduction of the CCD camera, depending of the yield neutrals and the detector system. Both should be easier to adopt emittance measurement equipment to higher beam energy level as well as beam current. SRIM–simulations have been shown that the deposited energy as well the projected range of a 3 MeV H^- beam allow to use (similar) scintillator materials with a

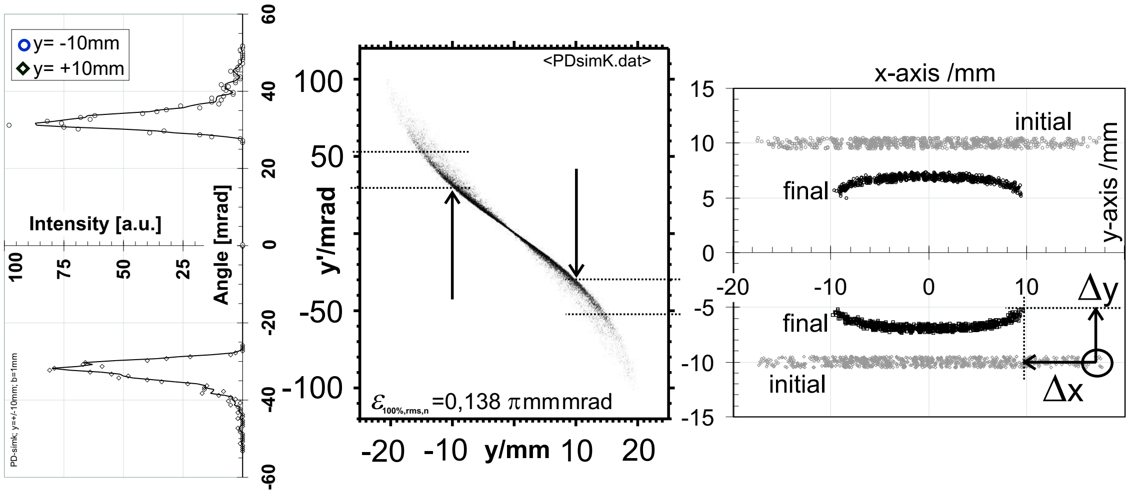

FIGURE 5. (from left to right) Beam profile $I(y')$ integrated of the emittance pattern (solid line) and integration of drifted (100 mm) neutralized particles (doted curve). Centered picture shows the emittance and right, the "neutralized particles" (cut out in xy–space) at ± 10 mm and the drifted particles are enclosed by the neutralized patterns.

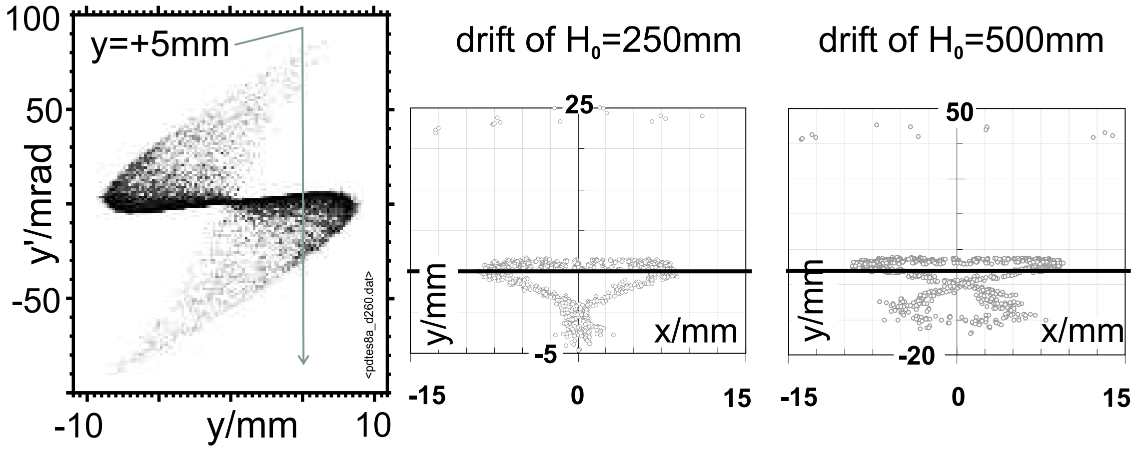

FIGURE 6. (from left to right) It is shown an cylinder symmetric emittance with large filamentation. At +5 mm, the laser crosses the ion beam, i.e. all particles were cut out in xy–space. The patterns at the scintillator are shown after two different drift length. Both cases show separate parts of neutralized particles, once with larger positive angles, once with smaller positive as well as negative angles curved & closed pattern. In general the shape of the curves depends of drift–length, aberrations and symmetry of the ion beam.

CCD–camera as an angle detector system and, furthermore, the additional phase space information can be taken advantage.

At the moment the R & D progress of FETS main components like ion source [15], RFQ [16] and MEBT/ chopper [17] is still going on. Beginning next year it is planned to install first parts of the setup, i.e. ion source with high voltage platform & support and carry out (first) beam measurements, mainly ion source tests.

Relating the photo detachment diagnostic, in the near future simulations of the beam envelope for tomography as well as emittance measurement are planned. Latter simulations will show if the intended dipole is suitable for emittance measurements or not.

Also in the near future first tests of the laser beam path and the adjustment of the laser mirrors have to assemble with a laser diode in the visible range of laser light at reduced power level, usable for both photo detachment experiments at low level and for testing experimental set up.

The final construction of the transverse profile measurement is planned for the end of the year while the time schedule for the emittance measurement is more relaxed because first beam behind RFQ is not expected before end of 2008.

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