The new Muon Beam Camera

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Introduction

For a muon spin relaxation experiment it is important to ensure that the beam is stopped in the sample, and not in the surrounding sample holder or cryostat walls due to steering or focusing errors. In particular it is important that the spot does not move (or such movement can be allowed for) as the experimental conditions such as magnetic field applied to the sample are varied.

For the low intensities of “secondary” muon beams, direct electrical measurement of the beam with capacitive coupling, wire grids or current transformers is not practical. Most methods rely on the energy carried by the muons and so must stop the beam in some sort of imaging system.

Photographic emulsions have been used, but require the film to be removed and developed after each exposure.

Microchannel plates have been used in many experiments, and are relatively field-insensitive. These can either run in particle-counting mode, with the charge division across a resistive anode used to locate each muon, or with an anode divided into segments and total charge measured. Particle-counting will not work with the high instantaneous rates at a pulsed source – typically 1000 muons in a 100ns pulse. A segmented anode has limited resolution.

Scintillating fibre grids are relatively simple to construct, if using avalanche photodiodes, and are insensitive to magnetic fields. Such a detector is in use at PSI [1]. However they only give two profiles in different directions. Real beams which do not have a simple Gaussian profile may not be represented well.

A scintillator sheet and imaging camera will give a true 2D image, comparable to the photographic emulsion. The time structure of the beam is not relevant if the exposure time is greater than the pulse repetition time. Since the camera will only capture a small fraction of the total scintillator light, it requires a large aperture lens, sensitive camera sensor, and absence of any background light which would contribute noise. A beam camera on this principle was constructed at ISIS using an image-intensified CCD camera, and can give a real-time image of the beam – though due to counting statistics the image is usually integrated in order to measure a spot size. However the image intensifier stage is very field-sensitive, relying on transporting electrons in vacuum from a photocathode. That camera is an integrated unit with scintillator, image intensifier and CCD all in one light-tight housing which makes operation simple provided there is room to position it at the beam focus and align it with respect to a typical sample. The beam may have to travel in air between the beam window and the scintillator, causing a slight increase of spot size due to scattering.

Camera design

The new camera uses a cooled CCD sensor, assembled with a Peltier cooler and readout electronics in a commercially available module (Starlight Xpress SXVF-H9), mainly sold for astronomical imaging. The lens (Navitar DO-5095) is chosen to have a wide aperture for maximum light capture, and focal length suitable to image the full size of the beam scintillator (60mm high) at a distance of 450mm. Image readout (raw monochrome data at 16 bits grey scale) is via USB to a laptop computer situated nearby, either operated directly when setting up or accessed over the network when the instrument area is locked up and the beam turned on.

The camera and lens are mounted in air, and view the scintillator through a vacuum window. The scintillator itself is mounted on the sample stage for the CCR, with the downstream radiation shield window removed. The instrument's sample space vacuum chamber therefore provides the light-tight enclosure and the muon beam path can be in vacuum and identical to that used in a muon spin relaxation experiment.

Figure 1: The beam camera and lens

To set up and focus the camera, with the beam off an alignment grid is mounted in place of the scintillator, and some light is admitted to the sample space. The camera can be focused for the sharpest image, with the lens aperture fully open to give the same depth of field, and the scale factor and position of the sample centre on the image are noted.

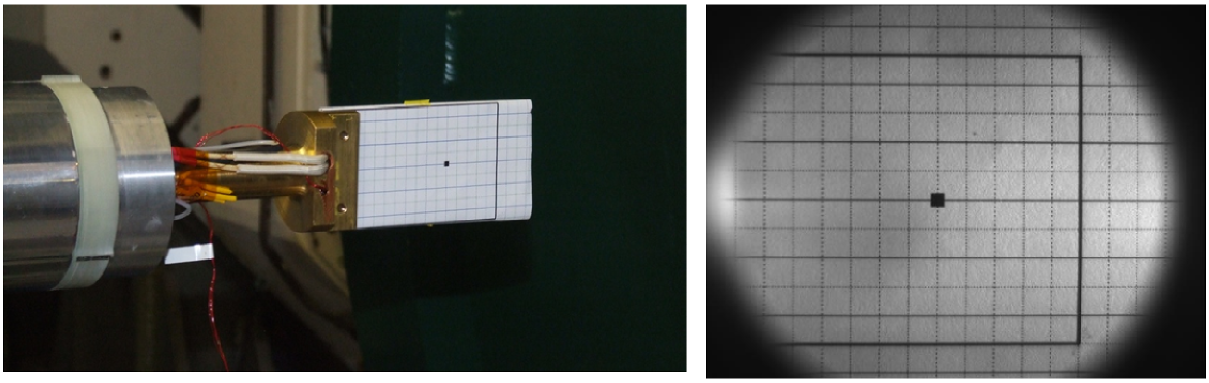

Figure 2: Alignment grid on the CCR head (5mm squares), and the camera's view of it. The circular aperture framing the picture is the hole in the downstream detector bank of the HiFi instrument.

For beam measurements a thin (0.5mm) sheet of plastic scintillator is used, with an aluminium degrader (0.25mm) in front to optimise the muon range. Ideally the muons should stop just inside the back surface of the scintillator having deposited the maximum energy in it. The aluminium sheet also acts as a reflector to improve the light output and blocks line of sight through to the beam window. A thick scintillator block (10mm) was also tried. Although this gives a brighter image this is mainly the contribution from positrons from the decay of stopped muons: those travelling roughly at 90 degrees to the beam can have a path of several cm within the scintillator block, producing more light and increasing the apparent spot size. Exposure times are typically 20 seconds to 2 minutes corresponding to around $10^6 – 10^7$ muons; this still does not overflow the 16 bit intensity range. (There is presently no link between the ISIS accelerator status/beam current and the camera's "shutter" timing, so care must be taken not to record an image while the beam is off, or at lower than the usual repetition rate.)

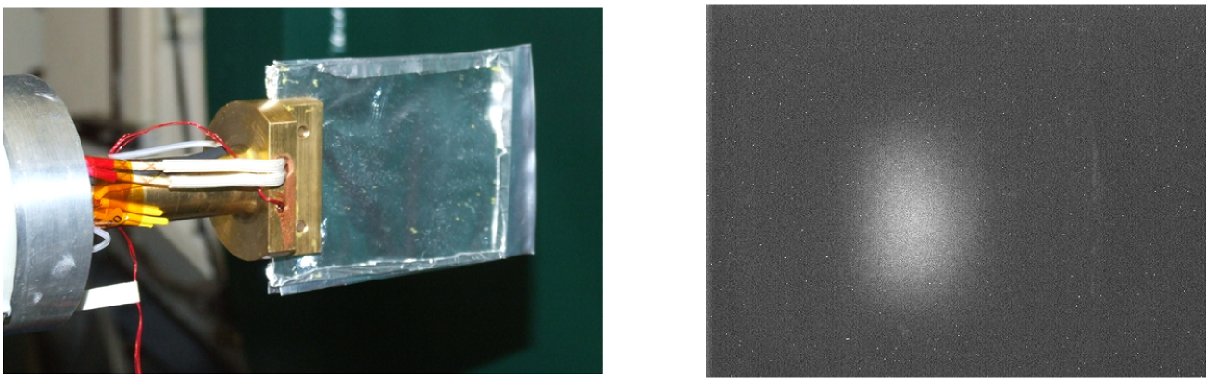

Figure 3: Scintillator with aluminium degrader, and an image of the beam spot (zero field). The edge of the scintillator sheet can be seen to the right, where light that is internally reflected within the sheet can escape.

Measurements

The camera has been used to measure the muon spot in the new HiFi instrument at ISIS, with magnetic fields applied to the sample region, parallel to the beam axis. Initially the camera was used to help focus the beam for the best spot with zero applied field, using the final quadrupole triplet.

Beam pictures were then taken at intervals of 0.25T over the field range of the magnet, showing the variation of spot size and also the movement of the centre of the spot.

The beam image can be fitted to a Gaussian elliptical profile to obtain a centre position, width/height/rotation and intensity:

$$I(x,y) = I_0 \exp(-((x-x_c)/\sigma_x)^2-((y-y_c)/\sigma_y)^2-e((x-x_c)(y-y_c)/\sigma_x\sigma_y)) + I_{bg}$$

We find that the integrated intensity (approximately $\pi I_0\sigma_x\sigma_y$ for small e)remains essentially constant over the whole field range, showing that all the muons hit the scintillator whatever the field (there is no beam loss in the fringing fields or beam window), the camera's response is linear and the camera sensitivity is unaffected by the stray field it experiences.

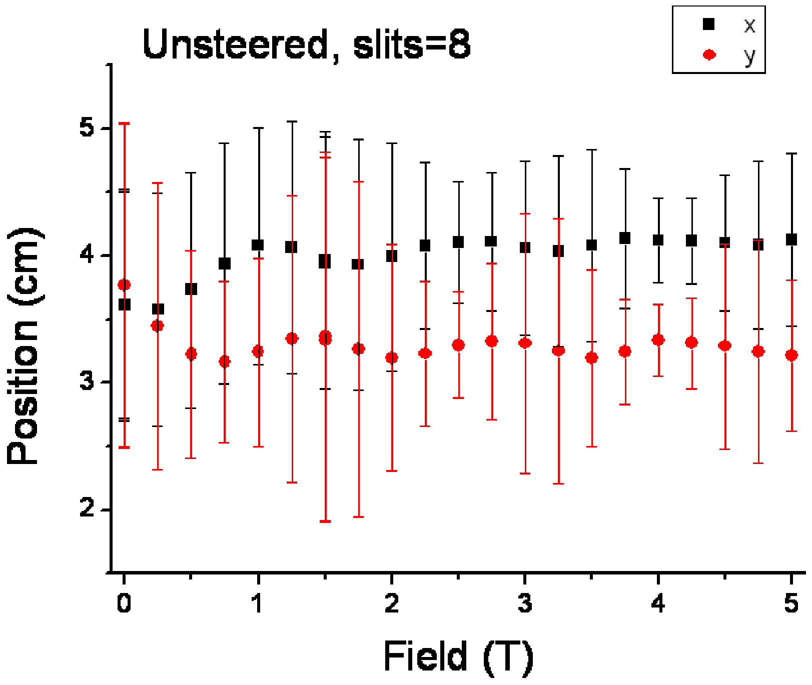

Figure 4: Spot position versus field, with no beam steering. (Error bars show the width/height of the spot)

The ISIS beams have remote collimation, with beam slits located at an intermediate x-focus upstream of the final quadrupole triplet. With zero field at the sample varying the slit changes the x-size as well as the overall intensity. Taking beam pictures for different slit settings shows that in higher fields the spot size is less dependent on slits.

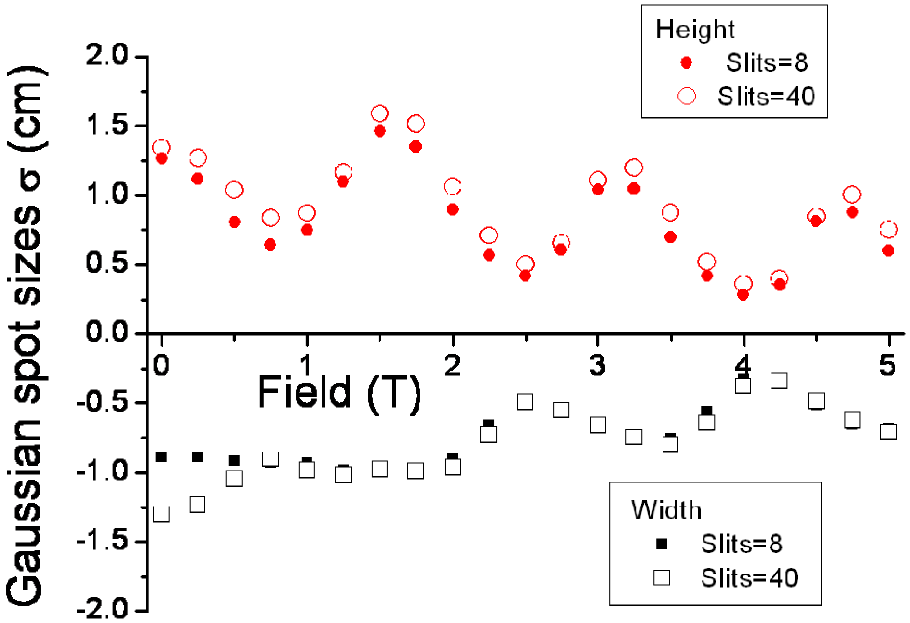

Figure 5: Spot size (x and y profiles) versus field, for two beam slit settings

The effect of the steering magnets on beam position can be checked, by taking beam pictures for different steering magnet currents, at several different fields. These are located just upstream of the final quadrupole triplet, and allow full adjustment of position and angle in both x and y directions. Due to beam spiralling the x and y directions interact. An optimum steering setting can then be chosen, to minimise the spot movement across the whole field range.

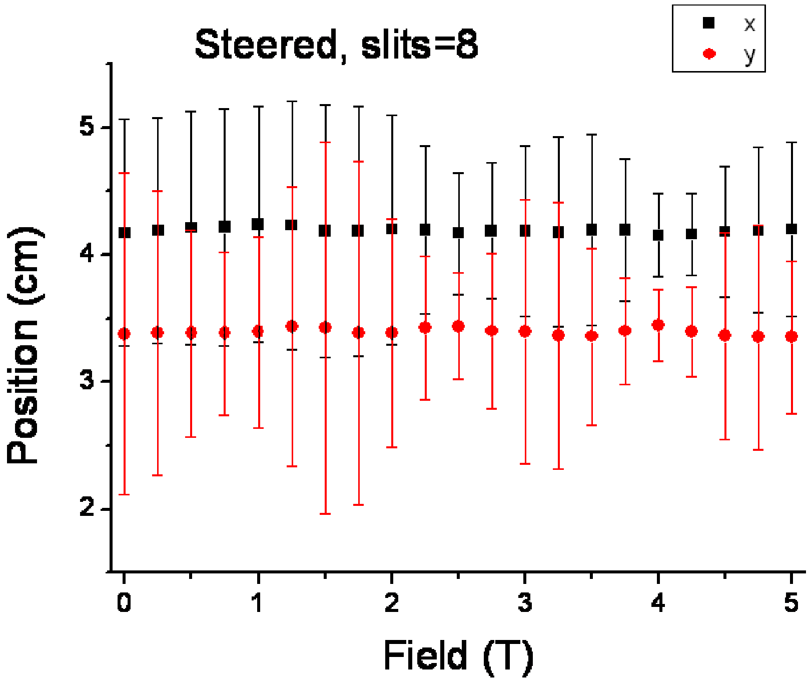

Figure 6: Beam position versus field once steered

The ISIS muon beamline is comprised of quadrupole magnets with vertical or horizontal focusing and bending magnets in the horizontal plane, so the x and y directions do not interact and the beam profile (in zero field at the sample position) is usually an upright ellipse. At moderate fields when the rotation of the beam is of order 45 degrees, the beam profile is approximately a tilted ellipse. At higher fields the spot shape is more complex, since the finite momentum spread of the beam means some muons spiral further than others. These complex shapes clearly cannot be fully described by x- and y-profiles alone.

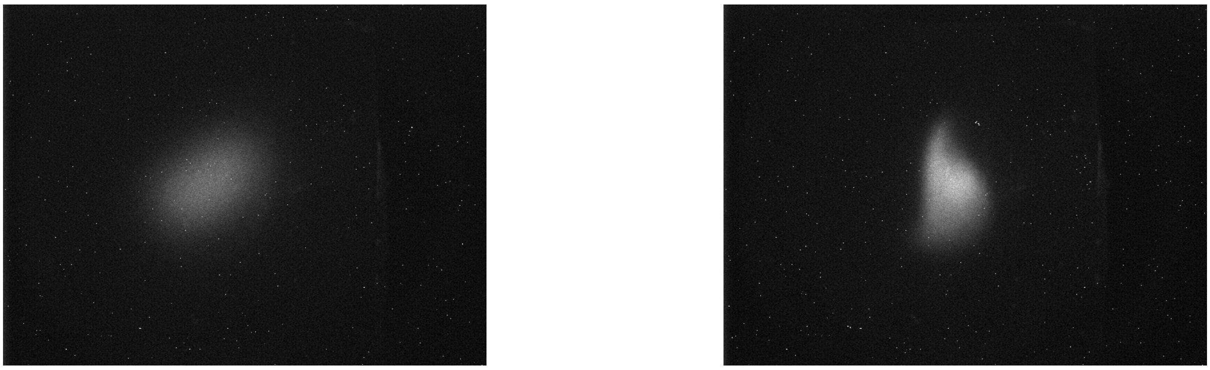

Figure 7: Beam pictures for fields of 0.5T (rotated ellipse) and 4.5T (clearly not a Gaussian profile!)

References

1. A. Stoykov et al, *Nuclear Instruments and Methods in Physics Research* A **550** (2005) 212-216