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An automatic beam focusing system for MeV protons

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Abstract

An automatic focusing system for MeV protons has been developed. The focusing system utilises rapid real time proton induced secondary electron imaging of a calibration grid coupled with a modified Gaussian fit in order to take into account the enhanced secondary electron signal from the calibration grid edge. The focusing system has been successfully applied to MeV protons focused using a coupled triplet configuration of magnetic quadrupole lenses (Oxford triplet). Automatic beam focusing of a coarse beamspot of approximately (5×3.5) micrometres in the X and Y directions to a sub-micrometre beamspot of approximately (0.7×0.6) micrometers was achieved at a beam current of about 50 pA.

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1. Introduction

The Proton Beam Writing (PBW) facility at the Centre for Ion Beam Applications (CIBA) is used for multidisciplinary research in photonics, microfluidics, bio-physics and semiconductor micromachining [1–4]. Unlike e-beam writing technology and electron microscopy, MeV proton focusing technology is still in its development phase and is necessarily more complex because of the high momentum of the proton beam. Focusing is usually achieved using a combination of magnetic quadrupole lenses, and carried out by manually adjusting lens current power supplies whilst minimizing the dimensions of a proton induced fluorescence image from a suitable target. Alternatively,

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for sub micron focusing, the beam spot can be manually minimized by mapping proton induced signals (e.g. from characteristic X-rays (PIXE), backscattered protons (RBS), ionoluminescence (IBIL), transmitted ions (STIM), proton induced secondary electrons etc.) whilst scanning the proton beam across a resolution standard. Since these manual modes of proton beam focusing are inherently slow and dependent on user perception, training and experience, there is a need for an expeditious, rapid, reproducible and accurate way of beam focusing and beamspot size determination.

We have developed a system that maps secondary electron emission of a proton beam scanning across a calibration grid and produces X and Y line scans as the proton beam traverses horizontal and vertical edges. A modified Gaussian function is fitted to the edge profiles and the FWHMs of the modified Gaussian functions in both the X and Y directions are minimised by computer control of the quadrupole lens currents. With this procedure, an MeV proton beam can be focused to submicron spot sizes in 2–10 min, depending on the starting conditions. Due to the copious number of secondary electrons generated, the focusing procedure can be carried out in real time and allows for automatic, rapid and accurate focusing.

2. Description of hardware and software

An automated beam focusing system requires rapid monitoring of the variation of the FWHM of the beam spot in both X and Y directions, in response to the changes made to the magnetic quadrupole lens currents. This has been achieved in our system by using a combination of software developed in-house along with data acquisition computer cards from National Instruments® for data acquisition and computer cards from Oxford Microbeams® for the remote control of their OM52E quadrupole power supplies. The software written in the C++ programming language in the .Net environment, utilizes the National Instruments® NIDAQ and IMAQ libraries for data acquisition, beam control and data presentation while using the libraries from Numerical recipes in C++ [5] for some of the mathematical routines.

Since our approach utilises rapid imaging, we have had to develop our own fast imaging system which uses proton induced secondary electrons. The process of the detection of the proton induced secondary electrons is via a scintillator which is connected to a voltage output based photomultiplier tube. The electron collection efficiency is bolstered by the application of a positive bias voltage ($\sim$2.5–3 kV) around the scintillator. Further details of this system will be described in a future publication, but essentially follows the system described by Teo et al. [6].

At CIBA, three magnetic quadrupole lenses operating in the Oxford triplet configuration are used for beam focusing. Here the lens arrangement follows a CDC (converge–diverge–converge) lens configuration, where the first 2 lenses are coupled, i.e. fed in series with the same current via one power supply. In this system, the demagnifications in the X and Y plane (horizontal and vertical) are unbalanced and for the Singapore proton beam writing line are 228 and 60 respectively. However, this configuration lends itself to automatic focusing because the focus in the two orthogonal beam directions are decoupled to a first approximation. In particular it is possible to optimize the beam spot in the vertical direction with minimal disruption to the horizontal focus, although the decoupling is not so pronounced when the procedure is reversed. More details on the Oxford Triplet beam optics may be found in [7], and, details of the Singapore proton beam line optics may be found in [8,9].

Fitting function: For focusing MeV protons, the beam is scanned across a calibration grid which exhibits pronounced sharp edges, and line scans extracted in both the horizontal (X) and vertical (Y) directions. A mathematical fit can then be used to extract the FWHM of the beamspot in both the X and Y directions. Previously, when using PIXE, STIM or RBS signals, the FWHM has been extracted using a complementary error function [8,10]. However, for proton induced electron emission there is an enhanced electron emission at the edge, and therefore this function needs to be modified. For electron emission therefore we have added another Gaussian function to represent this edge effect. Given below is the mathematical treatment of the 'modified' error function used in our fit.

Adopting a Gaussian shape, the normalized beam function that represents the particle distribution of a beam with a given FWHM f, centred around $x = X_0$ is given by

$$\mathrm{Beam}(x) = \frac{2}{f}\sqrt{\frac{\ln 2}{\pi}}\exp\left[-\frac{\ln 16}{f^2}(x - X_0)^2\right].$$

If this beam is scanned over a sharp edge the collected yield will be obtained by integrating the above function over all x after been multiplied by a step function. The step function represents the sample edge and causes the beam function to return a yield only in the region where there are primary particle interactions with the resolution standard.

Let the sample edge be at $x = a$ so that the step function may be expressed as:

$$\mathrm{STEP}(x) = \begin{cases} 1 & x \in [-\infty, a] \\ 0 & x \in (a, \infty]. \end{cases}$$

The yield collected by the detector will be given by

$$\begin{aligned}\mathrm{Yield}(X_0, f, a) &= \int_{x=-\infty}^{x=+\infty} \mathrm{STEP}(x)\mathrm{Beam}(x)\mathrm{d}x \\ &= \int_{x=-\infty}^{x=a} \mathrm{Beam}(x)\mathrm{d}x \\ &= \left[\frac{1}{2}Erf\left(\frac{2\sqrt{\ln 2}}{f}(x - X_0)\right)\right]_{x=-\infty}^{x=a} \\ &= \frac{1}{2}\left[1 + Erf\left(\frac{2\sqrt{\ln 2}}{f}(a - X_0)\right)\right].\end{aligned}$$

If we now incorporate the enhanced electron emission by the augmentation of a Gaussian function, the complete function that represents the linescan due to an electron signal is given by

$$F(X_0, f, a) = \frac{1}{2}\left[1 + Erf\left(\frac{2\sqrt{\ln 2}}{f}(a - X_0)\right)\right] + \mathrm{Beam}(a).$$

Mathematical fitting: The mathematical fitting of the above function to the linescan data was by means of the non-linear Levenberg–Marquradt method. More details of this may be obtained from [5]. The actual formula used in the fit is given below. The five fitted parameters are a, *Herr*, *Hgau*, *Hlow* and f.

$$\begin{aligned}F(X_0, f, a) = \mathrm{Herr}\left[1 + Erf\left(\frac{2\sqrt{\ln 2}}{f}(a - X_0)\right)\right] \\ + \mathrm{Hgau}\exp\left[-\frac{\ln 16}{f^2}(a - X_0)^2\right] \\ + \mathrm{Hlow}.\end{aligned}$$

3. Results

The beam resolution standard used was a 10 micron thick mesh standard fabricated using proton beam writing and nickel electroplating, which features ~15 μm holes and ~15 μm grid bars [10]. In our preliminary investigations, we have used the simplest beam spot minimisation algorithm possible, that of incrementally stepping through each quadrupole lens current until a minimum FWHM is found in each direction. Due to the decoupled nature of the X and Y focus in the triplet configuration, only 2 successive iterations in the X and Y directions were needed, taking around 2–10 min, depending on the initial focus conditions.

In the case described here, we focused a 1 MeV proton beam to around 5 μm spot size (at around 50 pA current) and scanned the beam across the grid. These start conditions were chosen to reflect the typical beam spot dimensions that can be achieved by reproducing the quadrupole lens currents at the best focus conditions, the reproducibility in the focus being limited by hysteresis. The 2D secondary electron map of the grid, and the corresponding X and Y line scans are shown in Fig. 1(a), (b) and (e). Fig. 1(c), (d) and (f) shows the results of the automatic focusing, and indicates a spot size of 0.73×0.58 μm. It should be mentioned at this stage that RBS and PIXE scanning over a

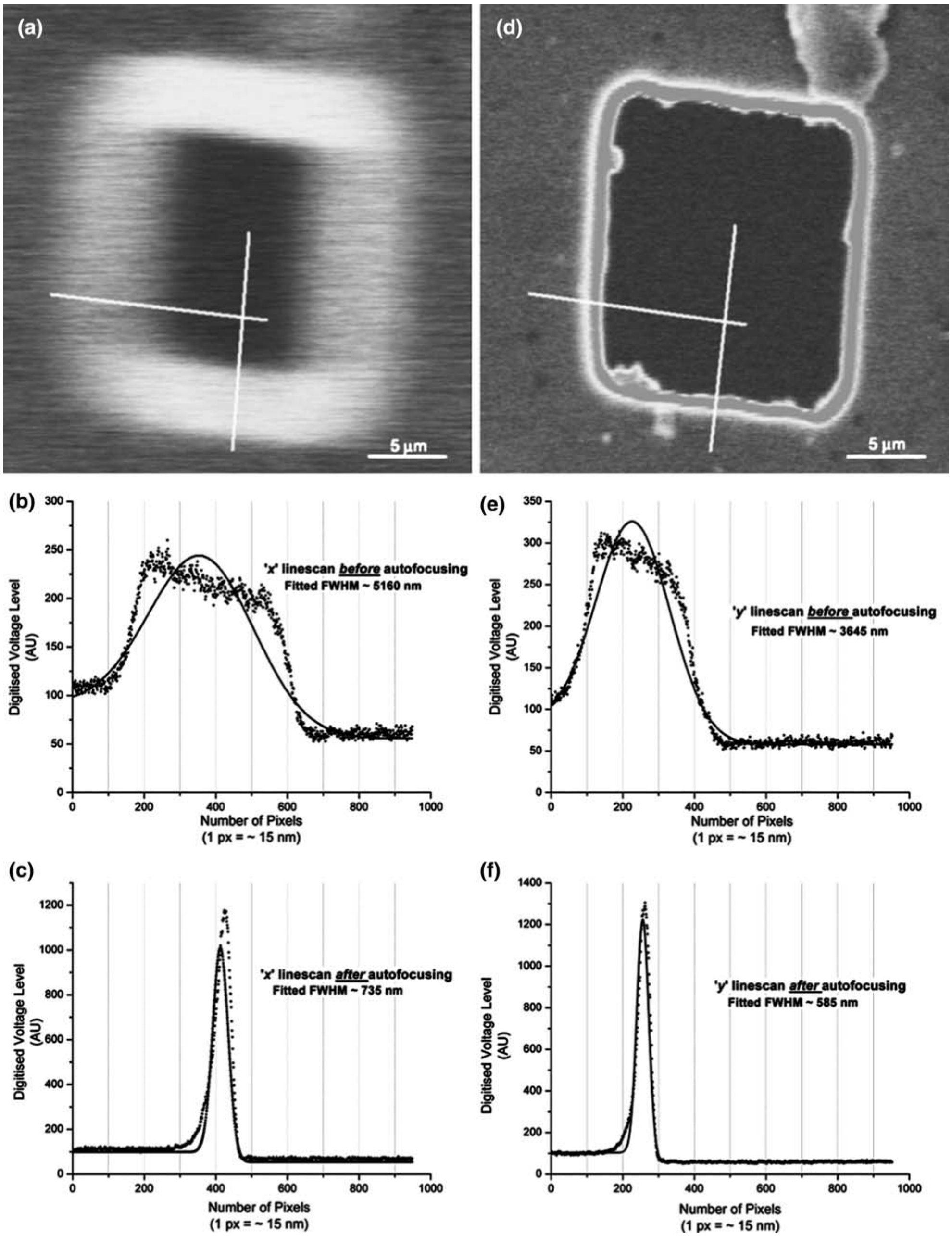

Fig. 1. (a) 2D proton induced secondary electron scan across a calibration grid, showing a beam spot resolution of around 5×3.5 µm, (b) corresponding X line scan + fit before focusing and (c) corresponding X scan + fit, after automatic focusing. (d) 2D proton induced secondary electron scan across the same calibration grid following automatic focusing, showing a beam spot resolution of around 0.7×0.6 µm, (e) Y line scan + fit before focusing and (f) corresponding Y scan + fit after auto focusing.

straight edge results in a more accurate determination of the spot size, but since these processes produce a much reduced signal compared with secondary electron emission, they cannot be efficiently used in the automatic focussing process to sub-micron spot sizes.

4. Conclusions

We have successfully demonstrated the possibility of automatic beam focusing using the Oxford triplet. Starting with a 5 μm coarse focus, consistent with using preset quadrupole lens current for best focus conditions, the automatic focusing system was able to arrive at a sub-micrometer beam-spot size within minutes. The crucial aspects of this work are the use of real time secondary electron imaging to increase data rates thereby reducing focusing time, coupled with a modified Gaussian fit in order to take into account the enhanced secondary electron signal from the calibration grid edge. Further work will involve the use of more robust fitting algorithms, intelligent iterative focusing algorithms and specially constructed calibration standards exhibiting sharper edges by van Kan et al. [these proceedings].

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