ACTA PHYSICA DEBRECINA XLVIII, 1 (2014)

CHANGE OF THE DIVERGENCE OF THE PROTON MICROBEAM AS THE FUNCTION OF SCANNING

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Abstract

Computer simulations have been performed in order to investigate the change of the beam divergence of the MTA Atomki scanning nuclear microprobe as the function of the beam scanning. Typical beam and beam line element settings were used in the simulations: 2 MeV H^+ ions, 200 × 50 object slit and „400 each" collimator slit positions. The results show that the beam divergence in the x- and y- planes are independent of each other, and that the x-direction divergence increases linearly with the x-direction scan; the y-direction divergence increases linearly with the y-direction scan.

I. Introduction

Ion microprobe systems attached to various particle accelerators are widely used for the analysis of environmental, geological, archaeometrical or medical samples [1,2,3,4] and for microlithographic purposes [5]. Probing a microfocused beam of high (few MeV) energy ions on different samples and then collecting certain signals from the interaction of the incident beam and the sample [6,7] allows the production of 2 dimensional elemental maps of the composition of the sample, while scanning the well-focused beam on the surface of suitable resist materials along a pre-defined path allows the production of 3-D microstructues.

The most common way to produce microfocused beams of MeV energy ions is the use of magnetic quadrupole lens systems [8]. Such systems consist of at least two quadrupole lenses which forms a demagnified image of an object aperture placed in front of them. The distance of the object aperture and the focusing part is a few meters. In order to reduce lens aberrations, the divergence of the beam has to be reduced. For this purpose a collimator slit system is placed in front of the focusing quadrupole lenses. The beam scanning is carried out by two independent magnetic dipoles (x- and y-plane scanning) between the focusing quadrupoles and the collimator slits.

In Atomki an Oxford-type coupled triplet system has been working since 1994. Originally it was a quadrupole doublet configuration, then in 2004 it was upgraded to a triplet. This type of microprobe system consists of three quadrupole lenses. The first two lenses are excited equally but with opposite polarity, the third lens is excited differently. The x- and y- demagnifications of this system is 66 and 15, respectively. The typical beam intensity for $1 \times 1\ \mu m^2$ beam size for 2 MeV protons is ≈80 pA [9,10,11].

The divergence of our set-up has already been simulated and measured in the case when the beam passes through the optical axis of the system; the theoretical and experimental results showed a good agreement [12]. The beam divergence values (half opening angles) for the most commonly used „50 each” (low current mode) and „400 each” (high current mode) collimator slit settings are summarized in Table 1.

	β_x (deg)	β_y (deg)
50 μm	0,0319	0,0103
400 μm	0,2893	0,0886

Table 1. Half opening angle (divergence) of the 2 MeV proton microbeam of the Atomki scanning nuclear microprobe for the two most commonly used collimator slit positions.

The motivation of this work was to investigate the change of the divergence due to the scanning. Lage-area ion beam micromachining irradiations showed, that microstructures close to the edge of the maximum scannable area can significantly differ from the same microstrucures close to the centre of the scanned region (see Figure 1.). This is caused by the change of the beam spot size, and if the sample is not positioned precisely to the image plane, the change of the beam divergence can also affect it. The exact knowledge of the change of these beam parameters could lead to a more precise way of planning ion beam micromachining experiments.

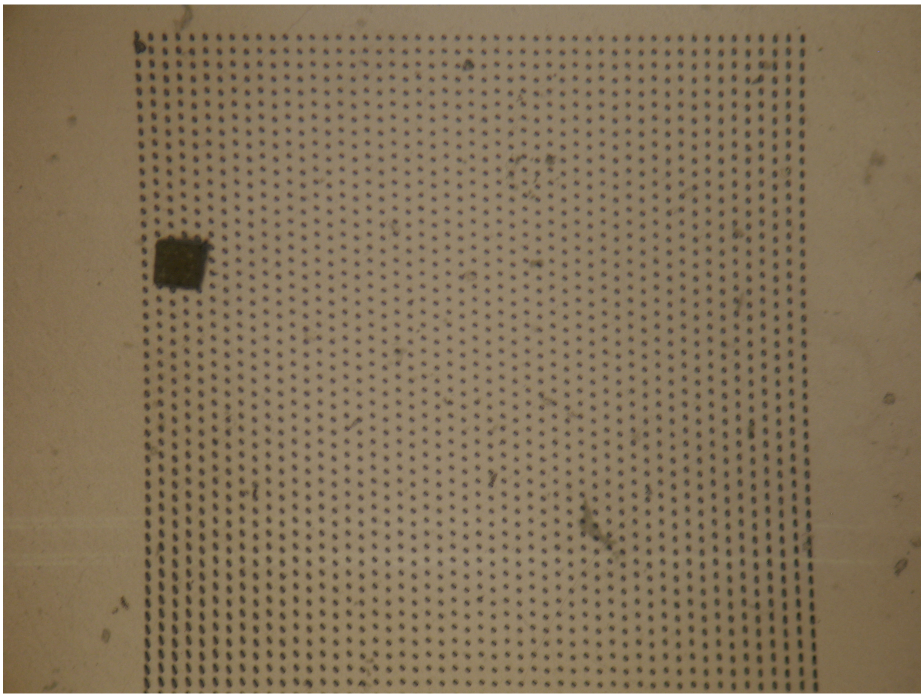

Figure 1. Matrix of microcapillaries made in PMMA by 2 MeV proton microbeam. The scanned area is 2 × 2 mm^2. The capillaries in the central region (i.e. close to the optical axis of the system) are circular shaped as planned. The ones close to the edge of the scanned area (especially in the corners) are distorted due to the beam broadening.

II. Simulations

The computer simulations were carried out by the PRAM (Propagate Rays and Aberrations by Matricies) ion optics computer code [13]. We chose 2 MeV H^+ beam for the simulations since this is most frequently used for both analytical and lithographic works at Atomki. For the sake of simplicity we assumed an ideal beam, i.e the beam does not have any momentum spread and it is homogeneous across the whole object aperture.

The maximum scan size of our set-up for 2 MeV H^+ ions is nominally 2.5 × 2.5 mm^2. This means, that the maximum deflection of the beam from the axis of the optical system is 1.25 mm in x and in y directions, too, because the beam can be deflected both to left or right and up or down. We calculated the divergences at 0, 0.2, 0.3125, 0.4167, 0.625, 0.8265, 0.9375 and 1.25 mm beam-optical axis distances which correspond to 0, 0.4, 0.625, 0.8334, 1.25, 1.653, 1.875 and 2.5 mm scan size, respectively.

During the calculations several beam trajectories were simulated. Most typical ones start from the centre and the corners of the object slit, and have maximum acceptance angle that can pass through the collimator slits. The beam trajectories are drawn on the computer screen (and can be saved as postscript images), and after the calibration of the image the beam parameters can be read: the angle between the ray and the optical axis behind the image plane gives the beam divergence. One such image can be seen on Figure 2, where the beam ray starts from the centre of the object slit (i.e. the object has 0, 0 extension), has maximum acceptance angle of the collimators and is not steered by the scanning dipoles.

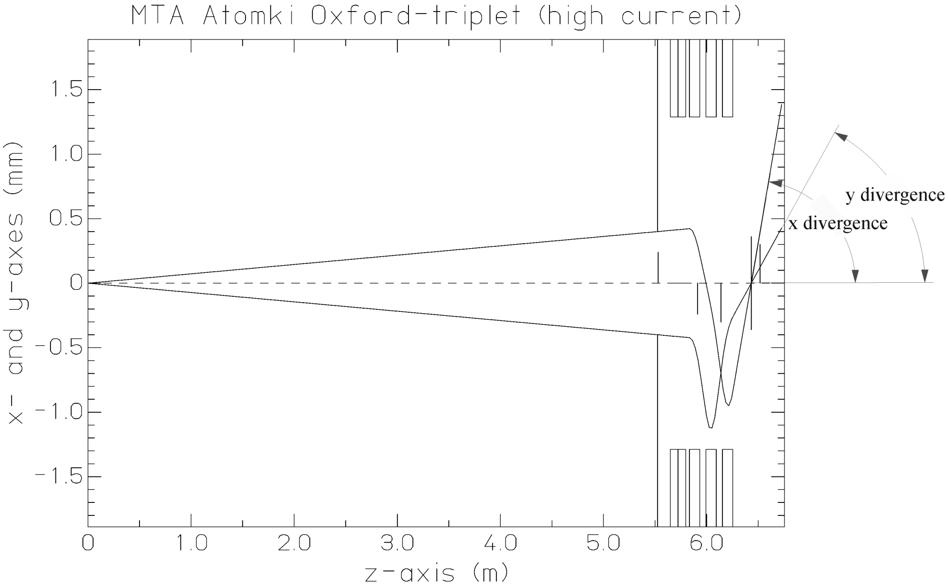

Figure 2. Trajectory for one beam ray (zx and zy plane) from the object slit centre with maximum acceptance angle of the collimator slits.

The simulations revealed that the divergence of the beam in the x- and y-plane are independent of each other. The x-plane scan affects only the x-divergence while the y-plane scanning affects only the y-plane divergence. Obviously, the xy-direction scan affects both x and y divergences, but not more than in case of x-only or y-only scanning. The exact divergence values in the function of the beam distance from the optical axis are drawn in Figure 3. In case of the x divergence the x-axis of the graph shows the distance of the beam at the image plane in the x direction, while in case of the y divergence the x axis of the graph shows the distance of the beam in the y direction. The simulated data show that the beam divergence linearly increases with the distance of the beam from the optical axis.

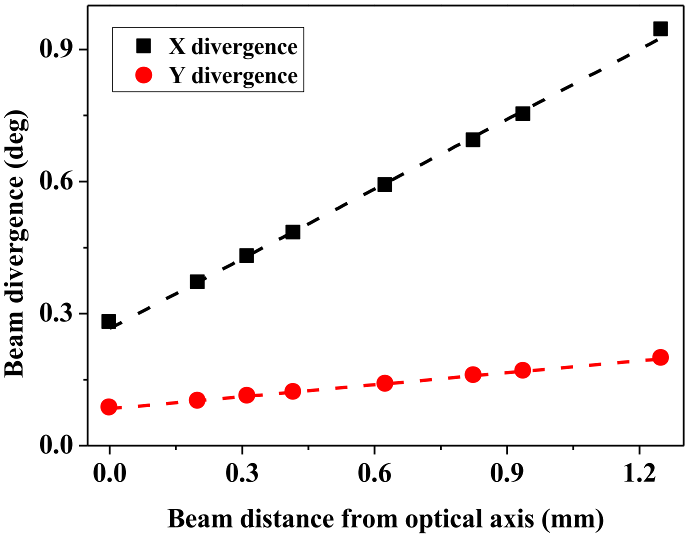

Figure 3: Divergences (x and y) as the function of the beam distance from the optical axis in the x- and y-plane, respectively. The dashed lines are the linear fits of the simulated data.

III. Conclusions

Computer simulations have been performed to investigate the change of the beam divergence of the MTA Atomki nuclear scanning microprobe as the function of the scanning. We found that divergence linearly increases with the beam distance from the optical axis and that the x- and y-plane divergences are independent of each other. The effect has to be taken into account at the planning stage of certain experiments, especially large area proton beam micromachining irradiations.

As the continuation of this work we plan to confirm these simulations with experimental results and then a detailed investigation of the change of the beam spot size is also planned.

Acknowledgements

This work was supported by the TAMOP 4.2.2.A-11/1/KONV-2012-0036 project, which is co-financed by the European Union and European Social Fund.

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