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Proton beam writing nanoprobe facility design and first test results

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ABSTRACT

A second generation proton beam writing line has been installed at the Centre for Ion Beam Applications at the National University of Singapore. This system features a high demagnification lens system based on compact OM52 lenses with reduced working distance. The system can operate in a variety of high demagnification configurations, including the spaced Oxford triplet and the double-crossover Russian quadruplet. It features an electrostatic scanning system and a new collimator slit aperture design. Here we present the first results with this system operating in a spaced Oxford triplet configuration with a beam focus in one direction down to 20 nm. One of the limitations of the current system is the inferior quality of the high-voltage supply driving the electrostatic scanning system. The second focus of this paper is the performance of the new collimator slit aperture design for MeV nanoprobe forming systems. Cylindrically strained electroplated Ni surfaces with a bending radius of 50 mm are used as slit edges. An incident molecular beam of 2 MeV H_2^+ ions was used for the slit scattering measurements. Any scattering by the slits resulting in dissociation of the incident molecular beam into 1 MeV protons facilitated the measurements of scattered and non-scattered components by the passivated implanted planar silicon (PIPS) detector. The studies showed the expected correlation between the aperture size and scattering. The quality of the beam was satisfactory even for small aperture dimensions with a very small percentage of the beam showing energy loss.

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1. Introduction

Focusing of the MeV ion beams in the nuclear micro/nanoprobe systems has been affected by various parameters such as intrinsic aberrations, poor construction and misalignment of magnetic focusing lenses, collimator slit scattering, etc. [1–3]. These parameters pose significant threats to the quality of the focused beam and demand investigations on the effect of these individual parameters for improved nanoprobe systems.

At the Centre for Ion Beam Applications, National University of Singapore, focused MeV proton beam has been utilized in different areas of research such as Proton beam writing (PBW), Imaging of bio medical samples, silicon micromachining and photonics [4]. PBW is a new direct-writing technique that uses a focused beam of MeV protons to pattern resist material at nanodimensions [5]. PBW has two fundamental advantages over electron-beam writing: Firstly the greatly reduced proximity effects [6,7] allow the fabrication of high-density high aspect-ratio nano-structures and secondly PBW has typically a 100-fold higher sensitivity compared with E-beam writing in the same resist material [8]. CIBA holds the world record for focusing protons down to $35 \times 75 \text{ nm}^2$ [9] and have produced 3D high aspect-ratio walls down to 22 nm in hydrogen silsesquioxane HSQ [10]. The rapid growth in nanotechnology coupled with the difficulties in fabrication has fueled the quest for further downsize in beam spot

size. This requires improvement in the focusing capabilities of the existing system and places stringent conditions on the control of aberrations and other parameters. For this purpose a new dedicated PBW test line has been constructed at CIBA to study the effectiveness of several factors like sensitivity of the focusing system to external stray fields, quadrupole lens power supplies with improved stability and slit design. In this paper, we discuss the basic design of the new beam line, preliminary results on beam focusing and results on slit scattering measurements. A more detailed paper on the construction and performance of the improved PBW beam line will be presented later.

2. Design of the 2nd generation proton beam writing facility

The new PBW line is designed for low proton current featuring a high demagnification lens system with short working distance. The lens system has the flexibility to quickly reposition the lenses in order to test other lens configurations (see Fig. 1). In the current tests a spaced Oxford triplet has been tested (using lens 1, 3 and 4). In these tests the spacing between lens 1 and 3 is 190 mm, each lens is 55 mm wide. In future we will also test the Russian quadruplet in spaced double-crossover mode, which has greatly increased demagnifications in both the X and Y directions [11]. The quadrupoles are powered using Bruker power supplies that have a stability of 1 ppm/°C.

The endstation is equipped with a channeltron to collect secondary electrons, a PIPS detector to measure forward scattered beam a simple optical zoom lens to set up PBW experiments and a precision controlled XYZ stage with nm positioning capabilities and

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4 nm closed loop in X and Y directions. The endstation is supported by an optical table to reduce vibrations.

To scan the beam across the sample an electrostatic scanning system is installed. Two sets of deflectors (X, Y) are positioned before the lens system and are driven by either a high (+/− 4 kV Trek High-voltage amplifiers model 609E6) or low voltage (+/− 440 V Fisher) amplifier.

The relatively large penetration depth of protons compared to electrons (of the order 20–50 μm for MeV ions compared with 1–3 μm for keV electrons) is the major concern in slit designing. In addition to angular scattering from the slit surfaces that increases the spot size through spherical aberration, the relatively large penetration depth allows a fraction of the incident ions to pass through the extremities of the slit edges with a corresponding loss of energy. The loss of energy introduces beam spot broadening through chromatic aberration. In addition, significant number of protons can still be transmitted even when the slits are geometrically closed [3]. This region of the slit edge is called transparency zone [3,12–14]. These effects are expected to be more pronounced for high resolution, low current operation (e.g. PBW at the nano level, scanning transmission ion microscopy and ion beam induced current) in which the aperture dimensions are significantly reduced. Earlier studies have shown that the cylindrical shape for the slit edge is useful in minimizing the transparency zone [13] and to suppress the particles scattered at the slit edge [15].

The above aspects have been considered in designing the collimator slits of the new PBW test line. For this, the custom used OM10 beam defining slits in CIBA have been replaced with the cylindrical slit edges. In the custom used slits each aperture is made up of two sets of slits, positioned vertically and horizontally, with the slit edges made from staggered tungsten carbide rods diamond polished to a micrometer finish. These stainless tungsten carbide

slit edges are replaced by the 100 μm electroplated Ni foil. The Ni foil is bent onto the copper block frame with a bending radius of 50 mm. The construction is similar to the one presented by Schmelmer et al. [12]. The copper block with Ni foil clamped on the top is mounted to a linear transporter having 1 μm resolution.

3. Preliminary focusing test with the new PBW facility

A 2 μm -thick Ni grid produced using proton beam writing [16] was used to determine the beam size through energy loss measurements of forward scattered 2 MeV H_2^+ . As can be seen in Fig. 2 this system is able to support and visualize a beam focus down to 20 nm. While reducing the amplification settings on the Fisher power supplies by half the beam size doubled in size to more than 40 nm in X, the other channel in the amplifier was not stable enough to support fine beam focusing in 2 directions. In future focusing tests using more stable high-voltage amplifiers we expect to improve the current performance.

4. Slit scattering measurements

A qualitative study of two aperture effects was performed. First, the relative effect on ion scattering as the horizontal collimator aperture dimensions are reduced and secondly, the proportion of ions, which suffers energy loss as a result of reduced aperture dimensions. A 2 MeV H_2^+ beam was brought into the system, and the beam was detected by the 20 mm² PIPS detector positioned in the forward direction. The object defining slits were fixed at 30 \times 30 μm^2 closely matching normal operating conditions. The vertical aperture opening was kept constant at 50 μm after adjusting symmetrically around the beam axis, also closely matching the normal operating conditions. The horizontal aperture opening was reduced from 67 to 15 μm . Any interaction of the 2 MeV H_2^+ beam with the slit edge would result in the dissociation of the incident molecular beam into 1 MeV scattered protons. Since there is a magnet in between the object defining slits and the collimator aperture slits any scattered beam will be filtered out by the magnet. In this measurement we will only consider collimator slit scattering; the scattered and non-scattered components are well resolved and are expected to exhibit two peaks at 1 (scattered beam) and 2 MeV (non-scattered beam), respectively. The normal working distance between the slit assembly and the end chamber is about 1.5 m. In these measurements the standard PIPS detector available in the PBW chamber and a second PIPS detector at about 3 m behind the collimator slits were used in the measurements presented here. Both detectors were positioned using a linear translator. The detector positioned in the chamber was used to measure the number of protons entering the chamber (scattered and non-scattered beam). The extended working distance for scattering measurement was used to resolve effectively the scattered and non-scattered beams. To measure the effect of aperture

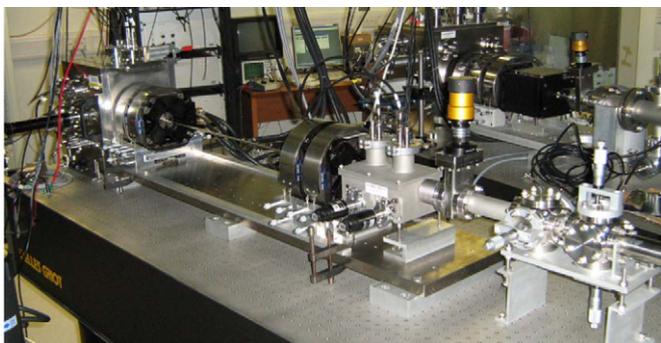


Fig. 1. Layout of the new proton beam writing facility. Coming from the right we see the new scattering slit house with Ni foils acting as slit surfaces, an electrostatic scanning system, four quadrupole lenses that can easily be repositioned (this configuration was not the actual configuration used for the experiments presented in this paper). On the far left we can see the new proton beam writing endstation.

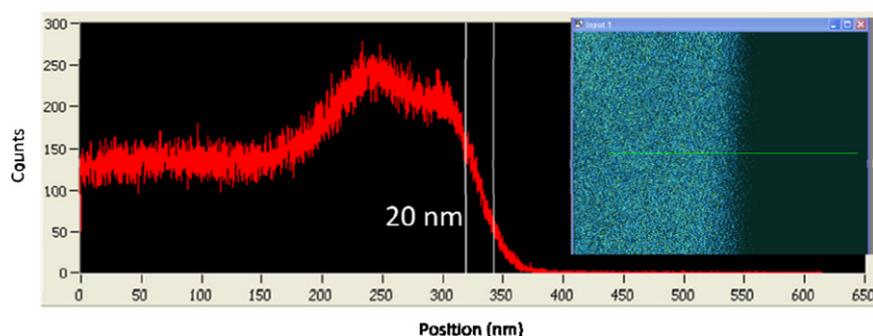


Fig. 2. 2D map and line scan of a focused 2 MeV H_2^+ beam scanned across a 2 μm -thick Ni grid. The PIPS detector is positioned in forward direction off axis with respect to the incoming beam.

size on scattering the detector was positioned to capture the scattered beam alone. Fig. 3 shows a graph of scattered protons per nC against the horizontal collimator slits are reduced from 67 to $-15 \mu\text{m}$. The smooth line passing through the data points is an exponential trend line drawn to guide the eye. It is seen from the graph that the scattered beam as a fraction of the total beam increases with decrease in aperture dimensions. This trend is as expected and comparable to the slit scattering measurements done with OM10 staggered stainless steel apertures on the other microprobe beam line at CIBA [3]. It is worth noting that for aperture openings that indicate geometrically closed values, significant number of scattered protons have been transmitted through the transparency zone.

In order to observe the energy loss as a function of aperture dimension the detector was positioned on the beam axis. Fig. 4 shows the effect of opening the horizontal collimator slits from a

closed to open position. The graph shows that the protons without energy loss, decreased significantly as the aperture size is reduced to values below $27 \mu\text{m}$. The scattered or the beam with energy loss was significant for aperture opening values below $27 \mu\text{m}$. At an opening size of $26 \mu\text{m}$ less than 0.2% of the beam has a significant energy loss corresponding to a projected range in Ni of $1 \mu\text{m}$. At an opening size of $16 \mu\text{m}$ less than 12% of the beam has an energy loss corresponding to a projected range in Ni of $1 \mu\text{m}$. This data suggest that the top-most layer of the slit is crucial in the scattering of beam. Therefore the smoothness of the slits is an important factor determining the slit quality. The wide opening for which the beam undergoes significantly less scattering or energy loss could be attributed to the usage of molecular ion beam. The interaction of the molecular beam is more sensitive to the aperture opening than in the case of using proton beams. Using molecular beams in PBW has the advantage that any scattered beam will be broken-up into individual protons that will not be focused onto the sample plan.

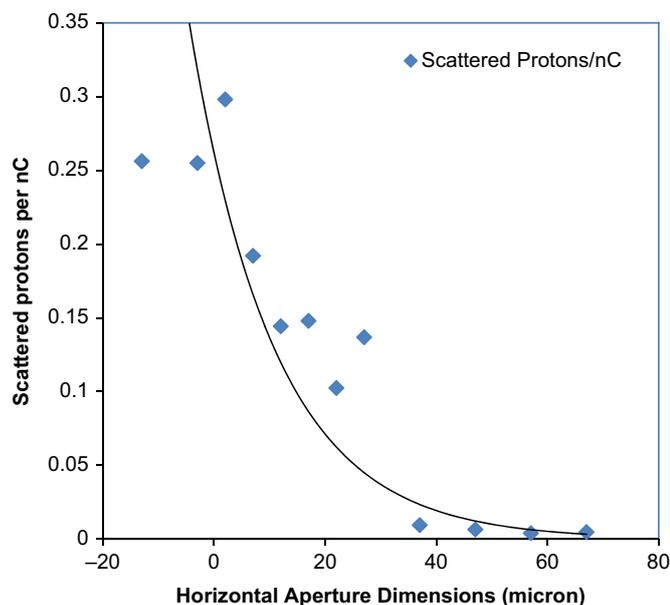


Fig. 3. Graph of scattered protons against horizontal collimator aperture dimensions.

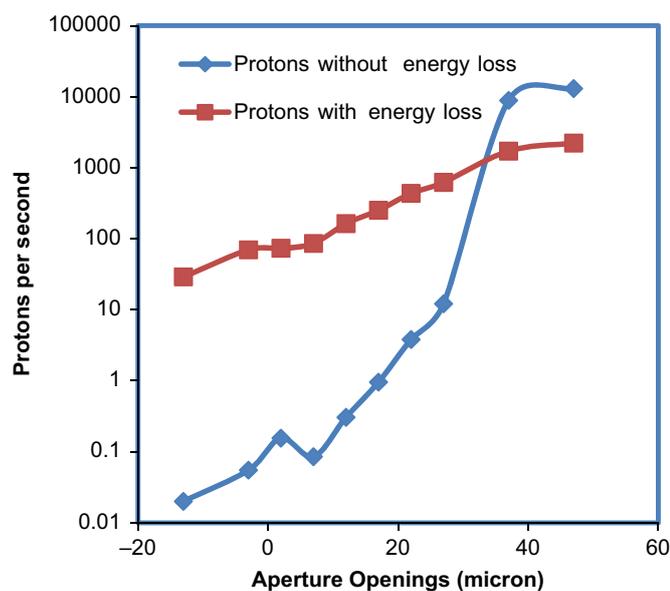


Fig. 4. Graph of the number of transmitted protons against horizontal collimator slit opening.

5. Conclusion

A PBW facility has been set up, which is capable of supporting spot sizes down to 20 nm. Initial tests in this system have been performed using a spaced Oxford triplet configuration. In future experiments we expect to improve the system performance through higher system demagnifications in both X and Y (Spaced Russian quadruplet) and through improved high-voltage amplifiers.

A new slit system made of cylindrically strained Ni foil has been tested on the new PBW beam line at CIBA. The results of slit scattering measurements show that the scattering increases as the aperture dimensions are reduced. Initial results on beam focusing demonstrate that this new slit design can achieve beam spot sizes down to 20 nm. In future experiments higher density materials like Au will be tested in thin layers ($\sim 10 \mu\text{m}$) on their effectiveness as slit surfaces.

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