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Fast resolution change in neutral helium atom microscopy

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In neutral helium atom microscopy, a beam of atoms is scanned across a surface. Though still in its infancy, neutral helium microscopy has seen a rapid development over the last few years. The inertness and low energy of the helium atoms (less than 0.1 eV) combined with a very large depth of field and the fact that the helium atoms do not penetrate any solid material at low energies open the possibility for a non-destructive instrument that can measure topology on the nanoscale even on fragile and insulating surfaces. The resolution is determined by the beam spot size on the sample. Fast resolution change is an attractive property of a microscope because it allows different aspects of a sample to be investigated and makes it easier to identify specific features. However up till now it has not been possible to change the resolution of a helium microscope without breaking the vacuum and changing parts of the atom source. Here we present a modified source design, which allows fast, step wise resolution change. The basic design idea is to insert a moveable holder with a series of collimating apertures in front of the source, thus changing the effective source size of the beam and thereby the spot size on the surface and thus the microscope resolution. We demonstrate a design with 3 resolution steps. The number of resolution steps can easily be extended. *Published by AIP Publishing.*
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I. INTRODUCTION

Thermal de Broglie matter wave beams created by supersonic expansions (free-jet expansions) have been used as a tool for surface science for several decades. Particularly helium has been used extensively in studies of surface diffraction and dynamics.[1–5] Due to helium's excellent properties, inertness and low energy (typically less than 0.1 eV) research has been ongoing in developing a new microscope using neutral helium atoms for imaging.[6–16] Currently the helium microscope exists in two configurations: In the pinhole microscope, the beam is collimated using a small pinhole and is scanned across the surface.[10] A theoretical treatment can be found in Ref. 17. In the second configuration, a zone plate is used to focus a helium beam. A theoretical treatment can be found in Ref. 18. The experiments presented here were all carried out using a zone plate helium microscope (Fig. 1).

For both helium microscope configurations, it has up till now not been possible to change the resolution without breaking the vacuum to exchange the collimating aperture (in the case of the pinhole microscope) or the skimmer (in the case of the zone plate microscope, see Fig. 1).

For the zone plate microscope, it is in principle possible to change the beam size on the sample by heating or cooling the beam. This changes the wavelength of the beam and hence the focal length of the zone plate.[19,20] Keeping the sample plane position fixed, this would result in a defocus and hence a larger spot size on the sample. The temperature of the source used in the experiments presented here can be changed from 110 K to 320 K,[21] corresponding to a wavelength change of around 0.4 Å and thereby a change in focal length of around 70 mm. However, by changing the wavelength, we also change the properties of the beam interacting with the surface and thereby potentially the imaging contrast. Furthermore it will typically take a minimum of several minutes to stabilize the beam at a new temperature. Therefore this is not a recommendable method.

II. THE DESIGN FOR FAST RESOLUTION CHANGE

In order to redesign our helium microscope for fast resolution change, we made an addition to the molecular beam source design described in detail in Ref. 21. The helium beam is created in a supersonic expansion from a reservoir through a nozzle into a vacuum. The central part of the beam is selected by a skimmer. For the experiments presented here, a reservoir pressure of $p_o = 61$ bars was used with a 5 ± 1 μm diameter nozzle and a 120 μm diameter skimmer, placed at 11.5 ± 0.5 mm from the nozzle. The beam was kept at a temperature of 310 K for all experiments. The beam is focused by a zone plate 192 μm in diameter with a 20 μm diameter central stop.[22] The zone plate is combined with an order-sorting aperture (20 μm diameter) as described in Ref. 23. The modified source design can be seen in Figs. 2 and 3. Instead of using a microskimmer which was used in previous focusing experiments,[23] a standard skimmer of 120 μm diameter (BEAM DYNAMICS, INC.) is used. This ensures that we get the beam flow expected from theoretical predictions for large skimmers, which is important as it was recently reported that the flow

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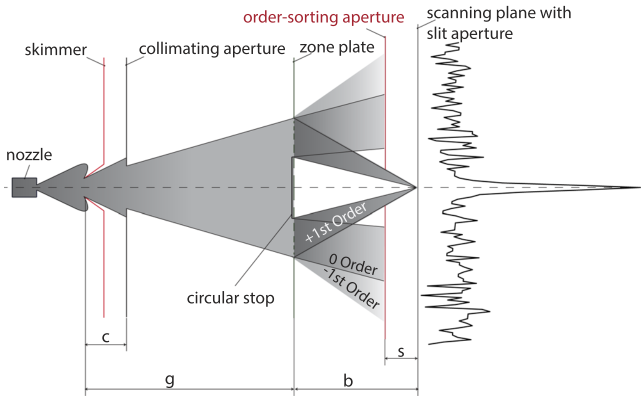

FIG. 1. Experimental setup: Following the free-jet beam expansion through a 5 μm diameter nozzle, the central part of the beam is selected by a 120 μm diameter skimmer. A movable collimating aperture holder located closely behind the skimmer collimates the beam further. With the *in situ* option of variable collimating aperture diameters (10 μm, 20 μm, and 50 μm), the effective source size of the beam can be adjusted without breaking the vacuum. The collimated beam is focused onto the sample by the zone plate (Fresnel type). An order-sorting aperture ensures that the zero-order part (and most of the higher orders) of the focused beam is filtered out. The focal spot size is determined by scanning a 10 μm slit aperture along the focal plane.

through microskimmers is reduced.[24] The source has been modified as follows: In front of the skimmer, two piezo electrical tables (Attocube, ANPx101/NUM/UHV) are placed on top of each other to provide x and y movements. On the top table, a 8 × 14 mm home made chip (see Fig. 2) with 3 collimating apertures in the sizes of 50.6 μm, 20.3 μm, and 10.2 μm is mounted. The apertures are placed as close to the skimmer as possible to maximize the flow without getting any reduction in intensity due to backscattering (distance from collimating aperture to skimmer opening is 28 ± 1 mm); see Figs. 2 and 3. Note how the mount for the collimating apertures is raised from the piezotable on a light construction (made of aluminium 6082-T6). This ensures a minimum heat transfer from the piezo tables which have an elevated temperature during operation (increased by the vacuum conditions) as well as a free expansion of the beam after it has passed through the collimating apertures. Figure 3 shows how the piezo tables are mounted in the chamber. The collimated beam is focused by the zone plate (see Fig. 1) onto the sample plane. For the experiments presented here, the beam was characterized by scanning a 10 ± 1 μm wide slit across the focused beam in 0.3 μm steps. The distance from the collimating aperture to the zone plate is 0.885 m [length (g)–(c) in Fig. 1] and the distance between the zone plate and the scanning plane is b = 0.207 m, giving a demagnification factor of M = 0.235 (see Fig. 1). The signal through the slit is measured using a so-called Pitot detector. In this type of accumulation detector, the pressure increase in a small volume is recorded with a sensitive cold cathode pressure measurement gauge (IKR-060 Pfeiffer). When the He-beam flow through a 1 mm diameter aperture into the detector accumulation volume is equal to the effusive flow back out of the accumulation volume, through the same entrance aperture, an equilibrium pressure can be measured. This equilibrium pressure can be directly related to the beam intensity.[21,23] The collimating apertures used here are between ca. 50 and 10 μm in diameter. These sizes were chosen to ensure that there is always enough signal in the Pitot detector to characterize the beam. With a more sensitive detector, smaller apertures can be used to obtain higher resolutions. We recently demonstrated that circular apertures down to 15 nm diameter can be made using electron beam lithography.[16] Apertures down to 1 nm have been made using helium ion lithography.[25] For the resolution limitation of helium microscopy see Refs. 17 and 18.

The apertures (holes) were fabricated on 200 nm thick silicon nitride membranes using electron beam lithography and reactive ion etching. The fabrication procedure is described in detail in Ref. 26. It is worth mentioning that the process was optimized slightly to ensure that the holes were etched through the SiN_x completely, using 15 SCCM CF_4 for 21 min at 10 mTorr and 100 W for the final etch step. The measured dimensions [scanning electron microscope (SEM)] were 50.6 μm, 20.3 μm, and 10.2 μm.

III. RESULTS

Figure 4 shows measurements of the focused beam for the 3 different collimating apertures. Note that the experimental

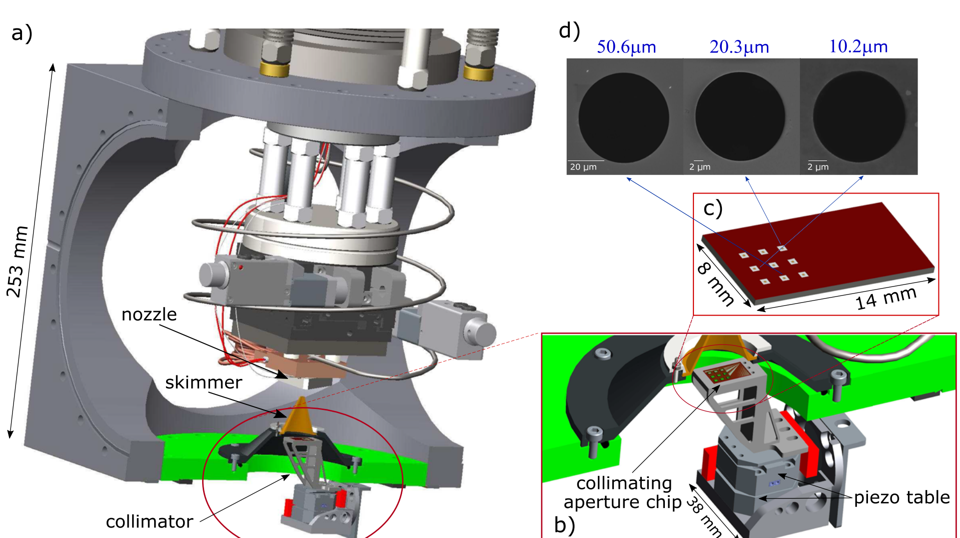

FIG. 2. CAD illustrations of the source setup with the variable collimating aperture element. (a) Overview showing the nozzle, skimmer, and collimating aperture arrangement. (b) Close up view illustrating the collimating aperture alignment: The two piezo tables placed on top of each other allow for x/y positioning of the collimating aperture chip. (c) 3D illustration of the collimating aperture chip. The chip has 9 different SiN_x membrane windows, each of them holding a different diameter collimating aperture. For this experiment, just three collimating apertures were used. (d) SEM images of the collimating apertures.

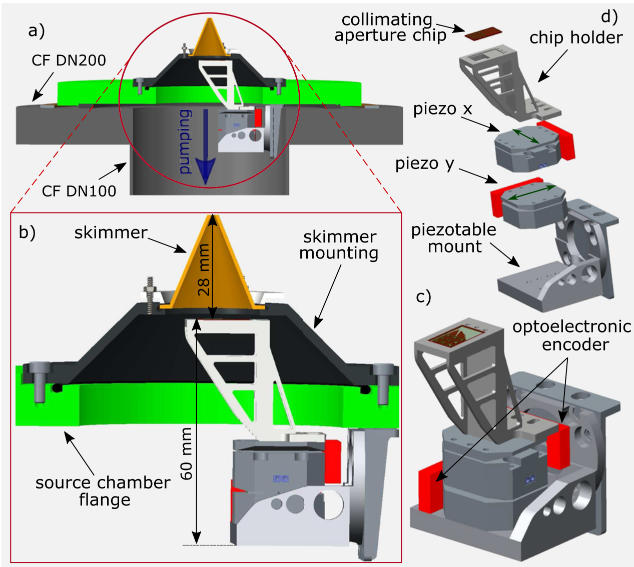

FIG. 3. CAD illustration of the collimating aperture mount. (a) Overview. (b) Close up view. The collimating aperture chip is mounted in a raised position. (c) 3D illustration of the collimating aperture chip arrangement showing the piezotable mount which holds the two piezo tables for x/y alignment of the collimating apertures as well as the mounting of the collimating aperture chip. (d) Explosion sketch of the collimating aperture chip arrangement.

data were recorded by scanning a 10 ± 1 μm slit aperture over the focus spot in the focal plane, and hence the measurements are a convolution of the real focus spot size with the 10 μm slit. To determine the measured focus spot diameters, an error function fit was performed.[12] The focus spot diameters are d_{c10} = 2.3 ± 0.5 μm, d_{c20} = 4.7 ± 0.5 μm and d_{c50} = 10.2 ± 0.5 μm. These values correspond to the expected focal spot diameters, given the demagnification factor of the instrument M = 0.235, and present a successful resolution change by a factor 4.4. There is a slight deviation for the 50 μm aperture where, according to the demagnification factor, one would expect 11.7 μm. This is due to the fact that the supersonic expansion gives an intensity distribution that does not illuminate the 50 μm aperture uniformly. The intensity profiles in supersonic expansions have been investigated in a range of measurements; see for example, Refs. 27 and 28. Note that all measured curves have been background corrected. A final point to note is that the intensity in the focus from the 20 μm collimating aperture is exactly 4 times as high as for the focus from the 10 μm collimating aperture. This was measured in a separate experiment where the total transmitted focus intensity was recorded without a slit aperture. This indicates that for the beam parameters used here there is no beam attenuation due to backscattering from the collimator plate.

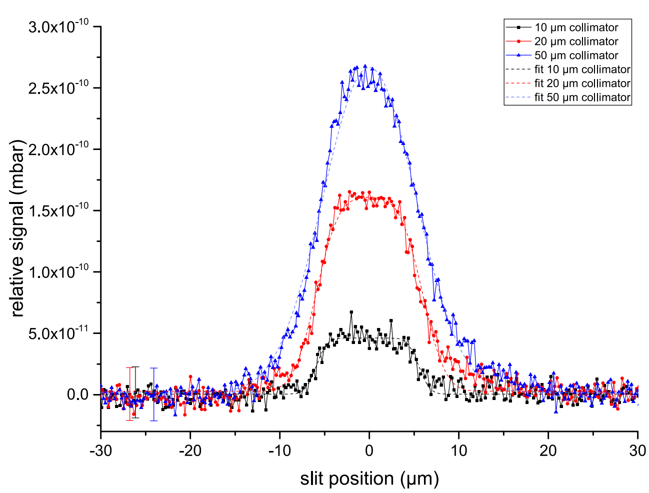

FIG. 4. Experimental scan results presenting line scans of a 10 μm slit aperture over the varying focal spot diameters from different collimating aperture sizes. Note: the focal spot diameter is convoluted with the 10 μm slit due to the measurement procedure. Error function fits to determine the real focus diameters from the measurements are presented as dashed lines. The focal spot diameters are d_{c10} = 2.3 ± 0.5 μm, d_{c20} = 4.7 ± 0.5 μm, and d_{c50} = 10.2 ± 0.5 μm in excellent agreement with a demagnification factor of 0.235.

IV. SUMMARY AND CONCLUSION

In this paper we present a modified design of a supersonic helium source, which can be used in helium microscopes to provide fast, stepwise resolution change in analogy to the turret used for optical microscopy. We demonstrate three resolution steps with a factor 4.4 resolution change and with focused spot sizes ranging from 10.2 down to 2.3 μm. The design can easily be extended to include more resolution steps and yield smaller foci. In principle, foci (resolutions) down to the nanometer range are possible. In practice, the possible focus sizes will depend on factors such as the beam intensity, chromatic aberration, and detector efficiency.

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