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Abstract. Manipulation of atomic and molecular beams is essential to atom optics applications including atom lasers, atom lithography, atom interferometry and neutral atom microscopy. The manipulation of charge-neutral beams of limited polarizability, spin or excitation states remains problematic, but may be overcome by the development of novel diffractive or reflective optical elements. In this paper, we present the first experimental demonstration of atom focusing using an ellipsoidal mirror. The ellipsoidal mirror enables stigmatic off-axis focusing for the first time and we demonstrate focusing of a beam of neutral, ground-state helium atoms down to an approximately circular spot, $(26.8 \pm 0.5)\,\mu\text{m} \times (31.4 \pm 0.8)\,\mu\text{m}$ in size. The spot area is two orders of magnitude smaller than previous reflective focusing of atomic beams and is a critical milestone towards the construction of a high-intensity scanning helium microscope.

Contents

1. Introduction

The field of atom optics has developed rapidly in recent years [1–4]. A general challenge is the controlled manipulation of beams of atoms and molecules, which is typically approached using techniques related to photonics or magnetic fields [5]. For example, lasers are applied in cooling experiments and static light fields or magnetic fields are used to focus or diffract atomic and molecular beams [6]. Thus, even for inert species such as helium, hexapole magnets have been successful in weakly focusing atomic beams of ^{3}He [7] and metastable ^{4}He [8]. Common to all these techniques is that they exploit 'internal properties' of the atoms or molecules, such as their polarizability, spin, charge or atomic excitations. However, for charge-neutral, ground-state particles with very weak polarizability and no spin, such as ground-state helium-4, alternative methods must be found. A method that can be applied in such cases is to use nanostructured optical elements, conceptually similar to those used in classical optics, to manipulate the atoms via diffraction and/or reflection. A number of such experiments have been presented over the years. One of the earliest was Keith *et al* [9], who used a nanostructured transmission grating in a gold foil to diffract a beam of atomic sodium. In [10] a nano-fabricated grating was applied to show the existence of helium dimers and in [11] to demonstrate the quantum behaviour of C_{60}. Most recently, a classical Poisson spot experiment was performed for the first time with neutral matter waves, using a beam of deuterium molecules and a nano-fabricated circular stop of silicon nitride [12].

When it comes to neutral atom focusing, as in classical optics, we may consider two main classes of optical element: transmission and reflection elements. The former are experimentally complicated, because they must be made as relatively large scale, but free-standing nanostructures. Fresnel zone plates with free-standing rings have been used to focus a beam of neutral helium atoms down to a spot size of less than 2 μm [13, 14] and have also been applied to focusing deuterium molecules [15] and metastable helium [16]. The focused helium beam in [13] was subsequently used to obtain the first microscopy image using neutral atoms as an imaging probe. Two main advantages of using helium as an imaging probe are (i) that the energy of thermal helium atoms is low, typically 15–100 meV, compared to hundreds of eV for electrons of comparable de Broglie wavelength and wavevector, and (ii) that helium atoms are uncharged and chemically inert. Consequently, fragile samples can be looked at without damage and insulating materials can be investigated without the need for a conductive coating. Helium atom scattering has been a well-established surface characterization tool for the last 30 years, providing information on solid surface structures as well as dynamic phenomena such as adsorbate kinetics and surface phonons [17–20].

There are two main disadvantages of applying amplitude Fresnel zone plates in atom optics. Firstly, no more than 12.5% of the incident beam illuminating the Fresnel zone plate goes into the first-order focus [21], which sits on a broad, zeroth-order background, reducing the effective signal-to-noise ratio in subsequent applications. Secondly, the numerical aperture of a zone plate suitable for focusing angstrom de Broglie wavelengths is limited by technical restrictions to at the most a few hundred microns in diameter, thereby strongly collimating the beam produced by conventional atom beam sources, which is typically several millimetres in diameter. Consequently, only a fraction of the incident beam illuminates the Fresnel zone plate and the focus intensity is reduced accordingly. Thirdly, zone plates suffer from chromatic aberrations. This is a problem in atom optics because it is generally not possible to make high-intensity beams with a narrow velocity distribution. A recent paper [15] shows that with the beam techniques presently available, the highest resolution possible for a helium microscope employing a zone plate is around 500 nm. These disadvantages can, in principle, be overcome using a focusing mirror. A focusing mirror does not suffer chromatic aberrations and the mirror surface can be made to subtend a far larger fraction of a broad incident beam. For example, a hydrogen beam has been focused using a rotating liquid-helium-covered hemispherical quartz mirror [22]. So far, two experiments on neutral helium atom focusing using reflection from solid mirrors have also been reported [23, 24]. The first demonstrated one-dimensional focusing, whereas the second achieved two-dimensional focusing, with a focused beam diameter of (210 ± 50) μm. A limitation of the latter experiment was its use of a centro-symmetric mirror design within an off-axis scattering configuration, causing astigmatism and limiting the minimum focused beam diameter. As we will show below, substantial improvements can be achieved with the introduction of a stigmatic, ellipsoidal mirror.

2. Experimental setup

The experiments presented here were all carried out in the molecular beam apparatus MAGIE. For a detailed description of the apparatus see [25]. Figure 1 shows a sketch of the experimental setup. A neutral, ground-state helium beam was created by supersonic expansion from a 10 μm nozzle. Measurements were made at a source pressure of (100 ± 1) bar. The nozzle temperature was kept at (120.0 ± 0.2) K for all experiments, corresponding to a beam energy of (26.7 ± 0.3) meV with a velocity spread of about 1%. The central part of the supersonic beam expansion region was selected using a micro-skimmer of (46 ± 1.5) μm in diameter.

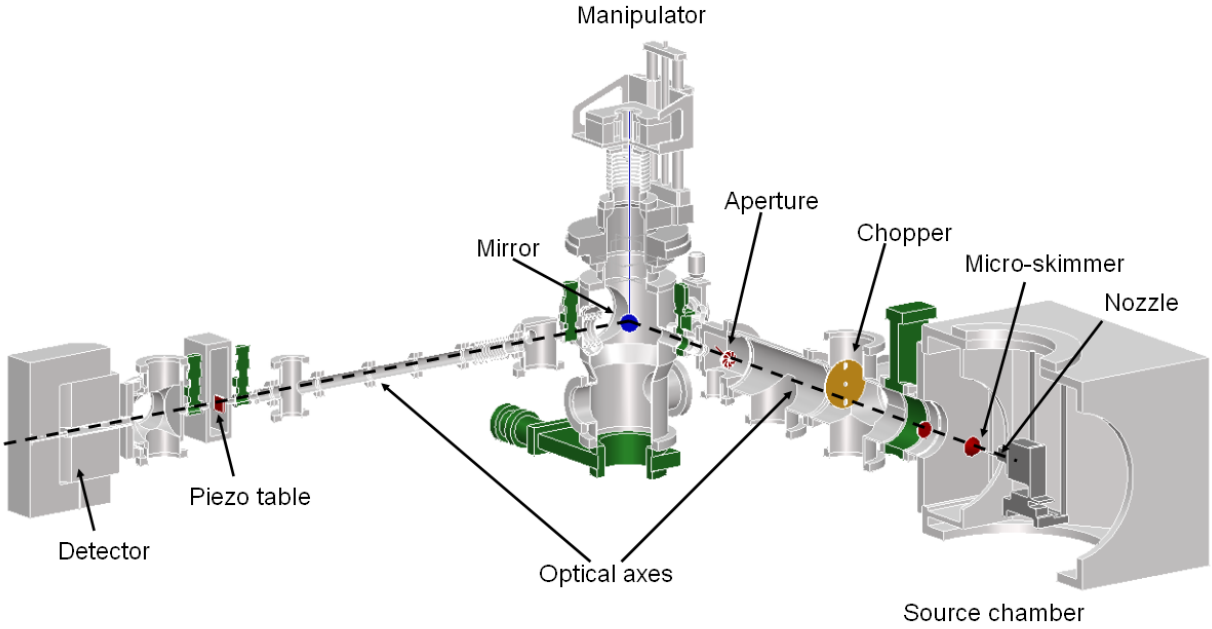

Figure 1. Section view of the beam apparatus MAGIE. The helium beam is generated by selecting the central part of a supersonic expansion from the nozzle with a micro-skimmer. The beam propagates along the optical axis to the mirror and illuminates an area limited by a collimating aperture. The beam is focused to a spot that can be profiled using a two-dimensional piezo table and detected by an electron impact ionizer detector. The angle between the source chamber and the detector is 90°. The chopper can be used to chop the beam for energy resolved surface scattering experiments but is not used in this paper.

The micro-skimmer was produced by pulling a glass capillary tube using a commercial puller [26]. According to Reisinger *et al* [27], the effective size of the beam source for subsequent optical calculations can be taken to be the micro-skimmer diameter. At the mirror, the atoms are in the molecular flow regime, travelling along non-interacting, divergent trajectories. The beam was incident at an angle of $(45.0 \pm 0.2)^\circ$ on the mirror and the spot size on the mirror, limited by an upstream 300 μm aperture, was 656 μm in the x-direction × 464 μm in the y-direction (for the mirror coordinate system see figure 2(b)). The distance between the mirror and the source was 1500 mm. The beam was focused by the mirror onto an image plane at a distance of 670 mm, where it hit a cross-piece aperture consisting of a vertical and a horizontal slit (5 μm × 3 mm) mounted on a piezo table. The slits were scanned over the focus with sub-micrometre resolution to determine the corresponding focus size in two dimensions. The beam was detected using an electron impact ionizer mounted with a magnetic mass selector and a channeltron electron multiplier.

The desired macroscopic shape of the mirror is determined by applying geometrical optics. The optimum shape is simply a segment of the appropriate 'Cartesian surface', a surface where all rays emerging from one focal point are reflected into the other focal point [28], as illustrated in figure 2(a). In practice, an ellipsoidal mirror was created by electrostatic bending of a single-crystal silicon wafer through a carefully defined aperture. It was necessary to use a single crystal to ensure that the surface was smooth relative to the wavelength of the incident beam.

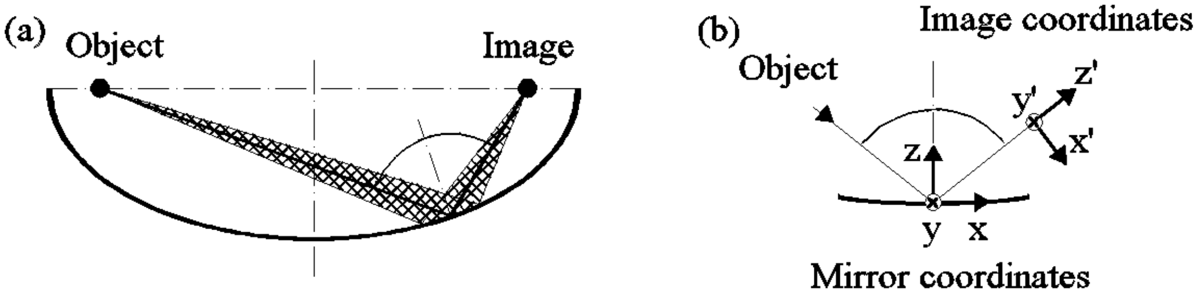

Figure 2. (a) An ellipsoidal Cartesian surface focuses each ray coming from the object point into an image point. (b) The coordinate system for the ellipsoidal mirror (x, y, z) and for the image plane (x', y', z'). The origin of the mirror coordinate system is the point of reflection of the central ray on the mirror surface.

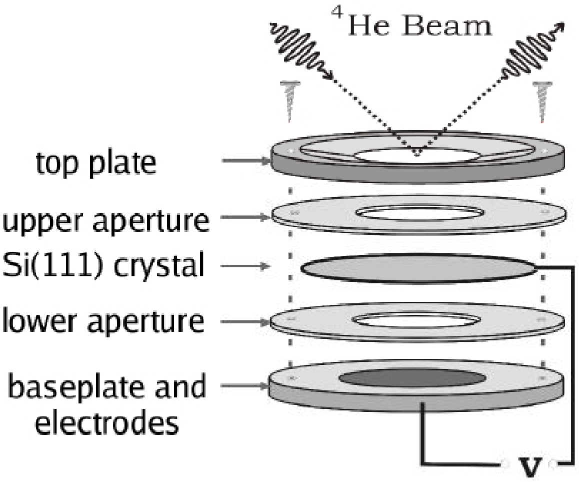

Figure 3. Schematic diagram of the ellipsoidal mirror. A silicon single-crystal wafer is grounded and a positive voltage is applied to the electrode structure. The silicon wafer is clamped between two sapphire apertures, each of 0.25 mm thickness. An additional sapphire plate of 0.25 mm thickness (not shown) is placed on top of the electrode structure, so that the distance between the undeflected silicon wafer and the electrodes is 0.5 mm. To provide the desired Cartesian surface, the lower and upper apertures are elliptical.

Additionally, the single-crystal wafer had to be very thin, about 50 μm thick, to provide the necessary elastic properties for repeated bending. For a more detailed discussion of this issue, see [29, 30].

Figure 3 shows a sketch of the mirror assembly. The assembly is essentially a parallel plate capacitor [29, 30]. A 50 mm diameter silicon single-crystal wafer, electrically grounded, was clamped between two sapphire apertures with elliptical holes, and held above an electrode array. The aperture dimensions depend on the scattering geometry and stigmatic imaging requires the ratio of aperture principal radii to be given by $\cos\theta$, for a beam incident at angle θ on the mirror [28]. For this setup, the axes had dimensions of 30 and 21.2 mm. The electrode structure

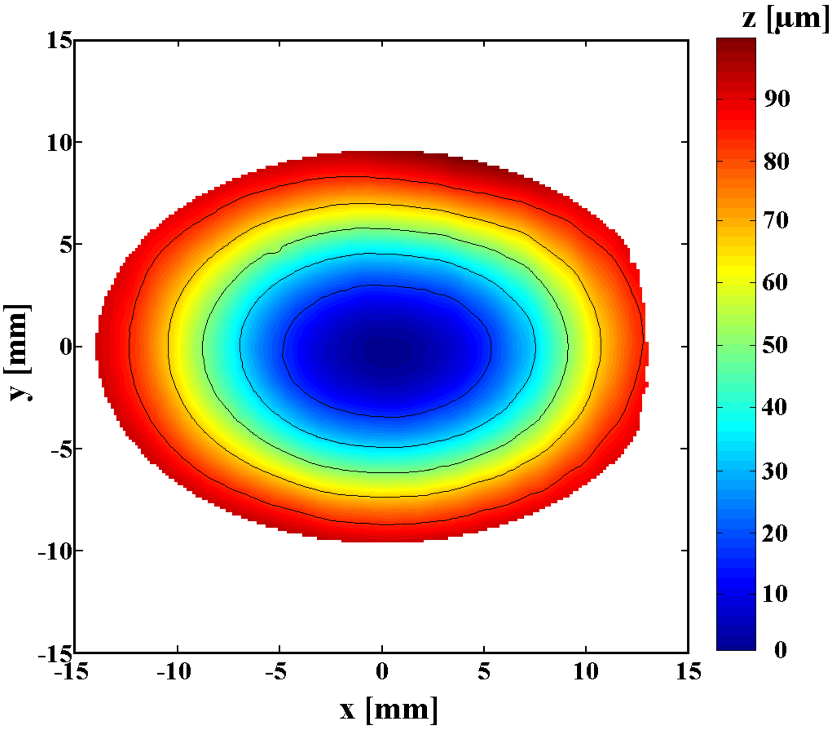

Figure 4. Mirror profile measured in the profilometer [32] for a uniform applied voltage of 2700 V at the five electrodes. The *x*-axis is along the major axis of the sapphire clamping aperture (see figure 3), the *y*-axis is along the minor axis and the wafer deflection is displayed in the *z*-axis. (*x*, *y*, *z*) are the mirror coordinates of figure 2(b).

had an overall ellipsoidal shape similar to the holes in the sapphire apertures, but were slightly smaller: 20.1 and 15.54 mm, respectively. Calculations presented in [28] show that this gives the most favourable bending. To be able to compensate for wafer imperfections, the electrode structure in the mirror holder (figure 3) actually consists of five separated electrodes, see [31]. Prior to operation, the bending behaviour of the crystal wafer was checked with a specially constructed profilometer that allows in-vacuum measurements of the macroscopic shape with micrometer precision [32]. Figure 4 indicates the profile of the mirror under similar conditions to those used in the focusing experiment, showing the ellipsoidal deflection of the silicon wafer given by the ellipsoidal boundary conditions of the sapphire apertures.

To obtain a stable surface in vacuum, the wafer was hydrogen passivated at the University of Cambridge as described in [33, 34]. It was then clamped in the mirror holder (figure 3) under an argon atmosphere. The whole mirror assembly was placed in an argon-filled transport container similar to that described in [35] and was shipped to the Institute of Experimental Physics in Graz, Austria. Here the atom mirror was mounted again under argon in MAGIE on a special holder made of PEEK (polyetheretherketone; from Allectra GmbH) to electrically insulate the atom mirror from the apparatus.

A limitation of the present mirror that has not been discussed so far is that the specular reflectivity of the hydrogen-passivated silicon surface at room temperature turned out to be rather low, 0.4%. The best value reported for helium and for molecular hydrogen is about 3%

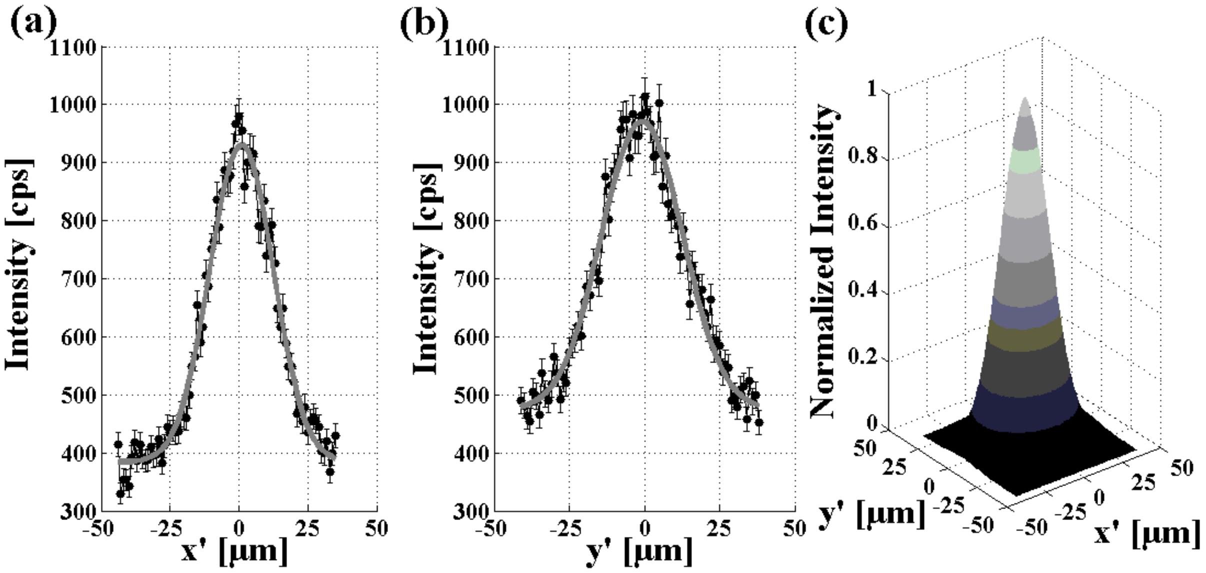

Figure 5. In (a) and (b) the measured He intensities are presented (black dots) with a fit (grey line) to determine the actual best full-width at half-maximum. These scans were done with slits in the piezo table along the axes x' and y'. In (c) the best helium beam focus is shown in three-dimensional representation. The voltage applied to all electrodes was 2760 V.

at a surface temperature of 120 K [33]. The low reflectivity is also the reason why we could not apply a smaller source diameter in these experiments. However, a recent result [36] reports a novel Si(111) coating of quantum-stabilized lead of magic height, which increases the specular reflectivity to 20%, promising high-intensity atomic and molecular beam focusing in the near future.

3. Results and discussion

Figure 5 shows the best focus obtained. The focus has a full-width at half-maximum of $(26.8 \pm 0.5)\ \mu$m $\times$ $(31.4 \pm 0.8)\ \mu$m along the main axes x' and y' (for the coordinate system, see figure 2(b)). A constant voltage V was applied to the electrode structure. To experimentally determine the focal size, the beam was scanned in the horizontal and vertical directions with slits ($5\ \mu$m $\times$ 3 mm) in steps of $1\ \mu$m. The measured signal was then de-convoluted with the slit function and the horizontal and vertical scans were combined to show a three-dimensional image of the focus. The best focus was obtained with a voltage of 2760 V. This is less than theoretically predicted [28] but was later attributed to insufficient clamping of the silicon crystal, leading to an initial, irreversible slip of the crystal in the mirror holder.

Given an ideal Cartesian surface for the setup, the expected magnification, given by the ratio of object–mirror and mirror–image distances, is –0.45. Consequently, the ideal focus would have a diameter of $(20.6 \pm 0.7)\ \mu$m. This is a little smaller than what we actually achieve, but compared to the best focus that could be obtained under similar conditions with a parabolic mirror: ‘a disc of least confusion’ of about $230\ \mu$m in diameter, the improvement is very significant. The value for the ‘disc of least confusion’ was calculated using the ray-tracing

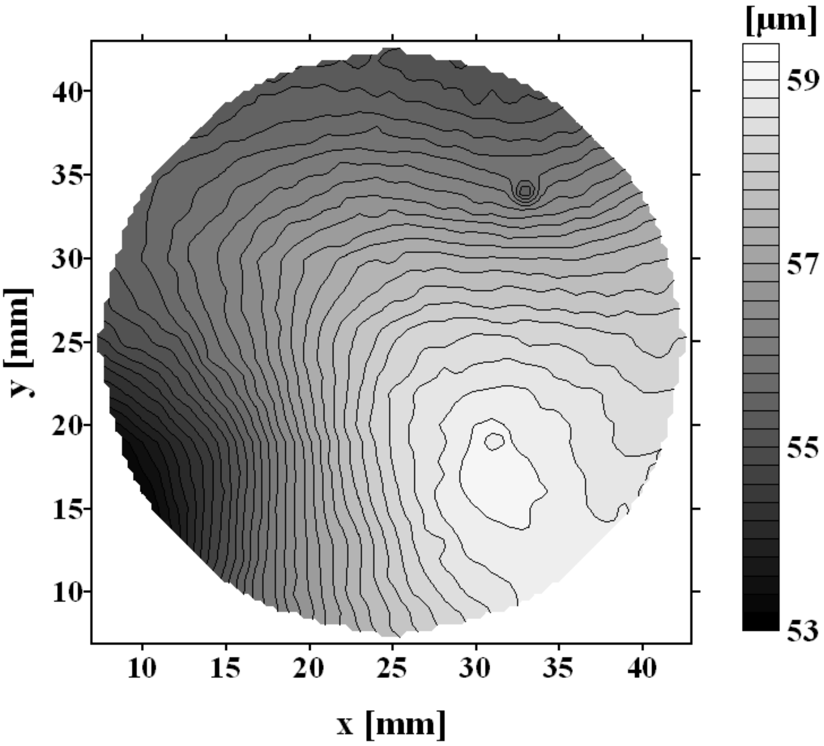

Figure 6. Thickness map of the Si(111) wafer used in this experiment. The thickness map was recorded using the instrument described in [38].

formalism of [37]. It should also be noted that the ideal Cartesian surface is not completely symmetrical along the x-axis (see figure 2(a)). Because the electrode structure in this experiment is completely symmetrical, this is not something that is compensated for in these experiments. It is also possible that the applied voltage was not the absolute optimum. The deviation from the ideal focus of the smallest measured focus can also be attributed to the inhomogenities in flatness of the Si(111) wafer. As shown in figure 6, the Si(111) wafer exhibits thickness variations of 3 μm.

4. Conclusions and outlook

In this paper, we have presented the first focus of a beam of neutral helium atoms achieved with an ellipsoidal mirror. The focus has a size of $(26.8 \pm 0.5)\,\mu$m × $(31.4 \pm 0.8)\,\mu$m along the main elliptic axis. Taking into account the experimental setup magnification of –0.45, the best obtainable focus would be $(20.6 \pm 0.7)\,\mu$m. We attribute the difference between these two values to the fact that the ideal Cartesian surface is not completely symmetrical and to imperfections such as thickness variations and warp in the silicon wafer used in the experiments; both effects can be compensated for in future experiments: concerning the silicon wafer, the Institute of Electronic Materials Technology (ITME) is now able to produce 50 μm-thick silicon wafers with a thickness deviation of less than 0.5 μm. With the new coating of the silicon surface, the helium reflectivity can be increased to 20%. An improvement of the thermal properties of the mirror assembly will further stabilize the Cartesian surface in the course of time. Finally, the silicon wafer clamping mechanism in the mirror assembly will be redesigned to improve the performance in vacuum.

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