Quasi-Bessel hollow beam as optical guide for micro-particles

Li Li^{1,2}, Niko Eckerskorn¹, Richard A. Kirian³, Jochen Küpper^{3,4,5}, Daniel P. DePonte³,
Wieslaw Krolikowski¹, W. M. Lee⁶, Henry N. Chapman^{3,4,5} and Andrei V. Rode^{1*}

¹*Laser Physics Centre,
Research School of Physics and Engineering,
Australian National University, Canberra ACT 0200, Australia*

²*The State Key Laboratory of Optoelectronic Materials and Technologies, Sun Yat-sen University,
Guangzhou 510275, China*

³*Center for Free-Electron Laser Science, DESY, Notkestrasse 85, 22607 Hamburg, Germany*

⁴*Department of Physics, University of Hamburg, and* ⁵*The Hamburg Centre for Ultrafast Imaging,
Luruper Chaussee 149, 22761 Hamburg, Germany*

⁶*Research School of Engineering, Australian National University, Canberra ACT 0200, Australia*

**e-mail: avr111@physics.anu.edu.au*

ABSTRACT

We have developed a high-aspect ratio optical pipeline aiming to produce a highly collimated stream of micron-size particles in either gaseous or vacuum environments. A hollow, first-order quasi-Bessel beam with variable divergence was generated with a phase-only spatial light modulator (SLM), by superimposing the quadratic phase of a lens and an axicon with a 0.5° base angle. The beam was further re-imaged to form a centimetre-long funnel beam with ~5 μm diameter and up to 2000 length-to-diameter aspect ratio. The divergence of the central core of the Bessel beam was controlled by varying the effective lens in the hologram. The SLM-based optical beam was compared to a similar beam composed using a physical axicon. The experimental tests were conducted with 2-μm size polystyrene spherical particles to evaluate the optical force. We present estimated optical forces exerted on the particles in the transverse plane, both depending on the particle size, laser power, and background-gas pressure.

Keywords: optical pipeline; optical vortex; quasi-Bessel beam; optical trapping in air and in vacuum

1. INTRODUCTION

Studying membrane proteins remains a major challenge for structural biologists. These proteins contain hydrophobic and hydrophilic surfaces, are typically scarce and highly flexible, frequently become unstable when removed from their natural membrane environment and are usually difficult to grow into large, well-ordered crystals suitable for conventional crystallography. Structural biology is in urgent need of high throughput methods for structure determination of proteins, particularly those that are large, very complex, and difficult to crystallise. X-ray free electron laser (X-FEL)-based serial femtosecond crystallography is an emerging method with potential to rapidly advance the challenging field of membrane protein structural biology [1,2]. The atomic-scale imaging afforded by x-ray scattering provides a ‘seeing is believing’ route that powerfully addresses questions in disciplines ranging from physics and chemistry through materials science to geophysics and structural biology. Coherent x-ray radiation of new generation of Free Electron Lasers (FEL) reaching into the soft x-ray regime in the FLASH facility at the DESY synchrotron in Hamburg, Germany, [3] while The Linac Coherent Light Source (LCLS) in Stanford, USA, offers new unprecedented capabilities for structural characterisation of crystalline proteins and biological macromolecules with

atomic-scale resolution [1,2,4,5]. Intended applications in near future include the imaging of complex, single biological molecules with ~ 10 fs time resolution.

Coherent diffractive x-ray imaging of individual biological macromolecules with Free Electron Lasers (FEL) requires a “touch-free”, high-precision particle injection method to deliver individual biological molecules or nanoparticles to the micron-sized focus of the x-ray beam. This method must function both in vacuum and in a gas environment, and operate collinearly with a particle laden gas stream produced by an aerodynamic lens. The currently existing aerodynamic lens with random injection of aerosols has an average imaging efficiency of $\sim 10^{-5} - 10^{-6}$ samples, which is far from satisfactory. New methods should provide precise delivery of biological macromolecules and droplets of 1 μm diameter or less, preferably as an exactly periodic, single-file, mono-disperse stream that is phase-locked to an external timing signal.

To address this challenge we are developing an optical quasi-Bessel beam as an optical pipeline with a hollow core featuring a axial-to-lateral aspect ratio up to ~ 2000 and variable beam diameter to guide particles with a spatial precision of less than $3\mu\text{m}$ over centimetre-long distances. We show here the ways to control the beam divergence aiming to focus the stream of particles by radiation pressure, analyse the forces acting on the particle in the beam and present preliminary results on diverging a stream of particles by a counter-propagating hollow Bessel beam collinearly aligned with the axis of the stream.

2. GUIDING PARTICLES WITH OPTICALLY INDUCED FORCES

2.1. Radiation pressure

The concept of guiding particles with an optical pipeline in vacuum is based on the macroscopic force applied due to radiation pressure $P_{\text{rad}} = (1 + R)I/c$, where R is the reflection coefficient, I is the laser intensity and c is a speed of light. This implies that under radiation pressure the particles tend to move along the intensity gradient to areas of lower irradiation. For simplicity, and at the same time for evaluation of the minimum amount of optical force, we further assume highly absorbing particles, $R = 0$; any reflection from the surface increases the radiation pressure up to the pressure on totally reflecting surface $2I/c$. The force F_{rad} exerted by the beam on a particle is $F_{\text{rad}} = P_{\text{rad}}S$, where S is the projected surface area of the particle. The effect of polarisation of light on transport and levitation of spherical particles for the cases of linear, circular and spatially variant (azimuthally or radially oriented) polarisation states were considered in detail using Fresnel formulas in [6,7]. Typical magnitude of the radiation pressure forces used to manipulate and guide micron size particles with a 1-W vortex beam is from femto-Newtons to pico-Newtons, depending on the beam to particle size ratio.

2.2. Photophoretic force

An additional thermal force emerges in a gaseous media due to a possible non-uniform temperature distribution within the irradiated particle. Surrounding gas molecules interacting with the ‘hot’ side of the particles acquire more energy and higher speed than those reflected from the colder side; as a result the particle gains a net momentum directed towards lower irradiation intensity. This force, named photophoretic force [8,9], depends on the particle size relative to the mean-free path of gas molecules, optical properties and thermal conductivity of the particle.

Photophoresis converts light to mechanical energy via a chain of events: (i) – Absorbed light heats part of a particle’s surface inducing a temperature gradient across the particle, (ii) – the molecules of a surrounding gas bounce off the heated part with increased kinetic energy, and (iii) – the resulting imbalance in momentum exchange propels the particle away from regions of high light intensity. Simple estimates show that even moderate light absorption can produce photophoretic force several orders of magnitude larger than the radiation–pressure force [10,11].

The interaction of light with particles in gases at different pressures is characterised by a Knudsen number Kn , which is the ratio of the mean-free path of the gas molecules (~ 100 nm at normal conditions in air) to the size of the particle. For small particles and low pressure ($Kn > 10$ range) the photophoretic forces can be estimated by kinetic theory [9]. This force is comparable to the radiation pressure for both weakly and strongly absorbing particles. For low $Kn \ll 1$ (larger particles) the nature of the interaction has a very different mechanism: the particle’s motion is due to the thermal creep phenomenon. Gas molecules slide over the particle surface and the corresponding tangential stress tends to move

the gas from colder to hotter parts of the surface. The available experimental literature data suggest that the thermal force peaks when the particle size is equal to the Knudsen number Kn . Up to date, *no complete theory* has been developed unifying laser trapping by radiation force and photophoretic force, and there is no united approach which would cover the difficult range $0.1 \leq Kn \leq 10$ of particular interest for macromolecules trapping and transport.

Optical guiding of absorbing particles by photophoretic force over large distances in open air was recently realised by an optical pipeline [12]. It was performed using a Laguerre–Gaussian beam, a donut-like intensity structure with a high-intensity ring of light that surrounds a dark core, and a phase structure of intertwined phase fronts [13]. Optical vortices create a ring-shaped transverse intensity distribution and the particles are trapped at the intensity minima. Consequently, the heating of trapped particles is minimal which is important for *in situ* studies of particle properties. Small particles – roughly, those smaller than the beam width – can then be confined in the dark core and propelled away from the beam source by the pressure of photophoretic forces. By tilting the beam, trapped particles could be delivered to the desired remote spatial location with accuracy ± 10 microns over a half-a-meter distance, demonstrating the delivery precision within the angle of the order 10^{-4} rad.

Both radiation pressure and photophoretic forces are linearly dependent on light intensity, and both forces are collinear to the intensity gradient pushing particles in the direction towards minimum intensity. For this reason the most appropriate shape of the beam compressing a stream of particles is an optical ‘funnel’ with a variable angle of divergence. Optimally the beam intensity and geometry – the size and the angle of divergence, could be precisely adjusted to impose the force required to compress a stream of particles with particular particle size, speed of flow, and the jet dimensions. Below we present the results of our first attempts to construct such an optical funnel to compress a jet of particles directed to the focus of the x-ray FEL laser.

3. FORMATION OF AN OPTICAL FUNNEL WITH CONTROLLED DIVERGENCE

3.1. First-order quasi-Bessel beam

The ideal Bessel beam derives from a class of exact solutions to the free scalar wave equation, expressed in the form of zero-order Bessel functions of the first kind, J_0 [14,15]:

$$E(r, \varphi, z) = E_0 \exp(ik_z z) J_0(k_r, r); \quad (1)$$

where r and φ are transverse and polar coordinates, k_r and k_z are the wave vectors in longitudinal and transfer directions, and z is the coordinate in propagation direction. The beam shape has a central core with a series of concentric rings, much like a ‘bulls-eye’ pattern. A salient feature of the Bessel beams is that the intensity profile of the central core $I(r, \varphi, z)$ is independent on z , propagating without a diffractive, transverse spread:

$$I(r, \varphi, z) \propto |E(r, \varphi, z)|^2; \quad I(r, \varphi, z) \Big|_{z \geq 0} = I(r, \varphi). \quad (2)$$

Finite apertures of optical elements form Bessel beams with finite dimensions. The experimentally close approximation to the ideal Bessel beams, the quasi-Bessel or Bessel-Gauss beams formed in laboratory experiments, have the central non-diffracting maximum over a limited propagation distance. The intensity in the central axis decreases with distance and eventually goes to zero converting into a ring-shaped beam. The Rayleigh range for a focused Bessel beam can be approximated as [14]:

$$z_R^{Bessel} \cong \frac{\pi D d_f}{4 \lambda}; \quad (3)$$

where $d_f = 2\lambda / \pi NA$ is the beam diameter at the focus f of a lens with a numerical aperture $NA \cong nD/2f$, n is the refractive index of the media, λ is the wavelength and D is the lens aperture. In comparison with the Gaussian beam where the Rayleigh length $z_R^{Gauss} = \pi w_0^2 / \lambda$, the Bessel beams exhibit much longer Rayleigh length as $D \gg d_f$.

When a Gaussian beam with intensity I_0 and beam waist w_0 illuminates an axicon with angle α , the resulted intensity distribution has a form [16,17]:

$$I(r, z) = 2\pi k z (\tan^2 \alpha) (n-1)^2 I_0 \exp\left(-\frac{2z^2 (n-1)^2 \tan^2 \alpha}{w_0^2}\right) J_0^2(k r (n-1) \tan \alpha); \quad (4)$$

where $k_r \cong k(n-1) \tan \alpha$; $k = \sqrt{k_r^2 + k_z^2} = 2\pi/\lambda$. With the help of Eq.(4), the central core can be expressed as:

$$d_f = \frac{2.405}{k(n-1) \tan \alpha} \cong \frac{2.405}{k_r}. \quad (5)$$

Substituting Eq.(5) into Eq.(3) one obtains the Rayleigh length in the form [15]:

$$z_R^{Bessel} \approx \frac{D}{2(n-1) \tan \alpha}. \quad (6)$$

In practice, the quasi-Bessel beams can be formed by a number of techniques generating a cone-like propagation of wave vectors: with a circular slit [14,15], with a conically shaped axicon [19], or by computer-generated hologram techniques using spatial light modulators (SLMs) [20]. In particular, variable spatial shaping with SLM adds the flexibility of a constant or tunable intensity distribution over the propagation of Bessel-Gaussian beam in the media with specific refractive index [21].

High-order Bessel beams have a phase singularity on the beam axis and hence have a dark rather than bright core. A hollow-core Bessel beam can be formed by focusing a doughnut-shaped Laguerre-Gaussian beam with an axicon. In case of the first topological charge $l = 1$ of the Laguerre-Gaussian beam the intensity proportional to [18,22-24]:

$$I_1(r, \varphi, z) = 2\pi k_r w_0 I_0 \left(\frac{z(n-1) \tan \alpha}{w_0}\right)^3 \exp\left(-\frac{2z^2 (n-1)^2 \tan^2 \alpha}{w_0^2}\right) \exp\left(i\left(\varphi - \frac{\pi}{2}\right)\right) J_1^2(k_r r); \quad (7)$$

where J_l is a first order Bessel function.

We applied the concept of the optical pipeline to design an appropriate beam to compress the stream of particles ejected by an aerodynamic lens into the vacuum chamber. The geometry of the FEL experiments imposes a number of limitations on the way the optical guiding can be constructed. First, the laser beam should counter-propagate the jet of particles with its axis precisely aligned to the axis of the particle jet and with micron-scale precision passing the focal spot of the FEL x-ray beam. Second, the beam should have a controlled divergence to be able to funnel the particle jet coming from the aerodynamic lens and to guide them into the x-ray focus. The jet diameter is of the order $50 \mu\text{m} - 100 \mu\text{m}$, ideally it should be compressed to $3 \mu\text{m}$ (the size of the x-ray focal spot). Third, the wide angle of scattered x-ray captured in coherent diffractive imaging implies that the distance from the aerodynamic lens nozzle to the x-ray focus should be no smaller than 20 mm. And finally, the intensity of the beam should be high enough to provide optical forces sufficient to divert the particles exiting the aerodynamic lens nozzle at speeds of the order of 50 m/s – 100 m/s to the desired focal point.

Summing up, the experimental conditions of optical compression of a jet of particles in FEL experiments imply that the doughnut-shaped funnel beam should have a waist of the order of $5 \mu\text{m}$, should expand to $\sim 50-100 \mu\text{m}$ over a distance of 20 mm (the length-to-diameter aspect ratio $\sim 1,000$, beam divergence 3.5 mrad), and that the intensity of the beam should divert the one-micron particles moving with the speed of $\sim 50-100 \text{ m/s}$ to the x-ray focus of the FEL – see Fig.1. The doughnut-shaped profile of a first order quasi-Bessel beam seems to be the most plausible option to satisfy all these requirements simultaneously.

We used two different approaches to form such a beam, one is by a combination of an optical phase plate with an axicon, and another one by a computer-controlled Spatial Light Modulator (SLM). Both methods are presented below.

Figure 1. Conceptual scheme illustrating the compression of a particle stream injected into the interaction chamber with an aerodynamic lens, using a counter-propagating first-order quasi-Bessel beam – the ‘funnel’. This figure is adapted from [25].

3.2. Beam formed by an axicon

Building structural beams with optical elements offers high laser power, which is critical for applications using forces of radiation pressure at the sub-picoNewton range. The experimental setup, which accommodated both SLM and an axicon/phase plate combination to generate a slowly diverging quasi-Bessel beam with diameter ranging from 5 μm to 50 μm over a propagation distance of 20 mm, is shown in Fig.2. The beams resulting from both the axicon and the SLM were analysed with an imaging system consisting of a de-magnifying telescope projecting onto a CCD camera for comparison.

Figure 2. The experimental setup generating and characterizing a first-order Bessel beam with a combination of a spiral phase plate and an axicon in one arm (black path) and an SLM (red path) in the other arm.

A vortex beam with a single topological charge was formed by propagating the expanded linearly polarized output beam of a 532 nm 100-mW cw laser through a 16-step phase plate from Holo/Or Ltd. A Galilean telescope constructed from a pair of 150 mm lenses was used to control the divergence of the beam entering the axicon with a base angle 0.5° : increasing the incident beam divergence caused an increase in the divergence of output beam. The beam was then demagnified with a telescope comprising a lens ($f_3 = 600$ mm) and a microscope objective (WD = 10.6 mm). The imaging system consists of a $20\times$ microscope objective and CCD camera placed on a translation stage. It was designed to characterize the resulting field after the last telescope in three dimensions, both for the optical axicon and SLM-constructed beams. The dependence of the central core diameter on the distance from the axicon and the resulted beam divergence is shown in Fig.3a,b.

Figure 3. a) – dependence of beam diameter on the propagating distance for the beams generated by a combination of a spiral phase plate with an axicon at different divergence of the entrance beams (shown in the graph); b) – dependence of the Bessel beam divergence (circles) and the Rayleigh length (triangles) on the divergence of the incoming beam.

The increase in divergence of the central core of the beam resulted in corresponding shortening of the Rayleigh range of the beam, which is clearly seen in Fig.3. To obtain the desired beam size, the magnification of last telescope has to be large, which results in a short Rayleigh range of the demagnified Bessel beam. With the desired beam size and divergence, the propagation distance of the beam is even shorter, typically less than 0.5 mm, which is impractical for our applications. For this reason, we switched to forming the beam by computer-controlled SLM.

3.3. Experiments on diverting a jet of particles

We performed preliminary experiments aiming to divert a jet of particles exiting the aerodynamic lens into a vacuum chamber with a counter-propagating quasi-Bessel beam collinearly aligned with against the jet. The experiments were performed with $1.9\text{-}\mu\text{m}$ polystyrene spheres injected with an estimated speed of 50 m/s – 100 m/s and collected onto a microscope slide covered by a sticky gel-pack located at a distance 66 mm from the nozzle. The jet cross-section was estimated by measuring the particle distribution on a gel-pack under a microscope as $\sim 70 \pm 5$ μm in diameter. A 5-W cw Bessel beam with diameter of ~ 75 μm was formed by a helical phase plate and an axicon with a base angle of 0.5° , directed opposite to the jet propagation through the microscope slide and aligned collinearly with the jet.

By shifting the jet in the transverse plane by 25 μm , 50 μm , 75 μm and 100 μm relative to the Bessel beam we were able to repeatedly and reliably shift the position of the particles arriving on the slide by up to 80 μm when the laser beam was “ON” and return the jet to the original path when the laser was “OFF” – see Fig.4. However, in these preliminary experiments we did not observe the effect of ‘focusing’ of the particle jet. One of the reasons was possible misalignment of the beam, as it was difficult to guarantee that the jet shift was purely in the transverse direction.

From the measured shift of the beam and reasonably assuming a particle velocity of 50 m/s we can roughly estimate the light pressure imposed by the beam on a $2\text{-}\mu\text{m}$ particle. A back-of-the envelope estimates yields $\sim (0.1\text{--}0.3)$ pN force to

be deflected from the original path by the observed distance on the slide. However, more accurate measurements of the particle speed, beam alignment, and particle size are required to predict accurately the particle path and the required laser beam parameters. In particular, in-situ diagnostics of the particle jet are needed. Nevertheless, this proof-of-principle demonstration shows a hollow-core Bessel beam from a cw laser source does apply sufficient radiation pressure to divert the particle jet in FEL experiments.

Figure 4. Concept for the ‘dusting’ experiments with a 5W coaxial Bessel beam counter-propagating the jet of particles. On the right is an image of the particles deposited on a sticky gel-pack microscope slide. The laser beam is misaligned by 75 μm transversally, relative to the jet axis. The top spot was deposited on the slide while the beam was in the ‘off’ state. The lower spot corresponds to the beam turned ‘on’, demonstrating the shift of particle path by radiation pressure imposed by the 5W cw beam. The image shows the beam in ‘off’ position. The ‘on’ spot has a strip-like structure because it is illuminated by the rings of the Bessel beam in ‘off’ state with a minimal power needed only for illuminating the deposited particles.

4. FIRST-ORDER BESSEL BEAM FORMED BY AN SLM

4.1. Beam divergence

Spatial light modulators offer great flexibility to construct beams with virtually any desired architecture and to change the structure of the beam with time. One of the limitations however is the incident laser fluence, which is bounded at $\sim 1 \text{ W/cm}^2$ by the cw-laser damage threshold of the SLM.

A linearly polarized Gaussian beam operating at 532nm was transformed into a vortex with single topological charge by a spiral phase plate, and then expanded by a $5\times$ telescope ($f_1 = 50 \text{ mm}$, $f_2 = 250\text{mm}$) – see Fig. 2. A polarizer was used to control the polarization of the incident beam. The resulting field was projected onto the SLM (Holoeye Pluto) chip with the angle of incidence smaller than 3° to normal incidence. The Pluto SLM is a reflective phase only device with 1920×1080 pixels of $8\mu\text{m}$ pitch. The 256 grey levels of the SLM are calibrated to a linear phase modulation ranging up to 2π at 532nm. Computer generated holograms addressed to the SLM were designed to cover a negative lens (L) and an axicon with internal angle $\gamma = 0.5^\circ$, which can be respectively expressed as $\phi_L = -ik r^2/2f$ and $\phi_A = -ikr(n-1)\alpha$, where k is wave vector, r is polar coordinates, f is focal length of L , n and α are refractive index and base angle of axicon correspondingly. The phase hologram is obtained by simply superposing ϕ_L and ϕ_A . By taking the phase value of hologram modulo 2π , the phase excursions are well coincident with the phase range of the SLM. A first order quasi Bessel beam was formed right after the SLM, and the divergence of the beam can be varied by changing the phase factor of L . The beam was then demagnified by a telescope comprising a lens ($f_3 = 600 \text{ mm}$) and a microscope objective (working distance 10.6 mm). The same imaging system as in the case of physical axicon was

used to characterize the resulting field in three dimensions. We used fast Fourier transform Beam Propagation Method (FFT-BPM) to simulate the propagation of quasi Bessel beam [26]. The algorithm for calculating the field at an arbitrary plane perpendicular to the z -axis can be expressed as $E(x, y, z) = F^{-1}\{F[E(x, y, 0)]e^{-ik_z z}\}$, where F represents the Fourier transform operation, F^{-1} represents the inverse Fourier transform, $E(x, y, 0)$ is the field distribution right after the axicon/SLM.

A diverging quasi-Bessel beam with diameter changing from $4.0\ \mu\text{m}$ at the waist to $39.0\ \mu\text{m}$ over a distance of 20 mm was obtained when the focal length of L was set to $f = -0.53\ \text{m}$; the quasi-Bessel beam divergence was $\sim 4.4 \times 10^{-4}$ rad, which results in aspect ratio in the Rayleigh range ~ 1100 . The beam diameter vs propagation distance is presented in Fig.5. Power of the inner ring was measured using a power meter with an entry iris pinhole to choose the central ring only. The power of the beam in each beam cross-section relative to the incident power on the SLM surface is shown as a function of the propagation distance in Fig.5.

Figure 5. The blue dots depict the diameter of the inner ring of the quasi-Bessel beam versus the propagation distance. The squares are the power in the central core of the Bessel beam at each cross-section relative to the power entering the SLM.

4.2. Intensity distribution in the diverging first-order Bessel beam

The results on power distribution along the central core and the size of the inner ring provide the means to recover intensity distribution in the beam. The intensity distribution, in turn, is a template for calculating the radiation pressure imposed by the beam onto a particle of particular size, and thus to predict the particle track depending on the entering point, speed, angle, and such particle characteristics as optical properties and its mass.

The intensity distribution, as shown in Figure 6, was measured by imaging the beam onto a calibrated CCD and correlating power measurements. The beam has the desired spatial characteristics, i.e. an aspect ratio of ~ 1000 and shows linear growth in size over its propagation distance. The intensity of the inner, confining ring of the Bessel beam falls over three orders of magnitude over its propagation distance. This results in relatively much weaker forces at the 'opening end' of the optical funnel, as the funnel seems not be 'solid' enough to collimate a particle stream with a large diameter. A more ideal solution would have the intensity along the axis of the funnel be constant, which has been shown to be possible for a zero-order Bessel beam using an iterative algorithm for hologram generation [21]. This would allow the funnel to pick up and collimate particles entering it at speeds, angles and wider spatial distribution away from the axis.

Working forward from the intensity map shown in Figure 6c, it is possible to recover the optical forces exerted by light pressure on sample particles. This will allow us to model the acceptance of the trap by calculating trajectories for particles entering the funnel with different parameters, i.e. nontrivial spatial and velocity distributions, and the required level of power to guide particles to the x-ray focus, which will be presented elsewhere.

Figure 6. Experimentally measured spatial intensity distribution of a funnel-like slowly diverging first order Bessel beam (only the inner ring shown) over the 20-mm distance, the total power on SLM was 7.67 mW, and the power of the total cross-section of the Bessel beam was 1.87 mW. a) The radius of the inner confining ring is expanding from $2\mu\text{m}$ to $40\mu\text{m}$ over 20mm; the width of the line reflects the experimental error bars. b) The maximum intensity in the confining ring drops more than three orders of magnitude over the propagation distance of 20mm; the minimum intensity on the beam is about an order of magnitude lower than the maximum in the same cross-section. c) The two-dimensional intensity map recovered from experiments provides a template to predict particle tracks entering the beam.

5. CONCLUSIONS AND FUTURE DIRECTIONS

We constructed a highly-collimated optical micro-pipeline, or funnel, a hollow core quasi-Bessel beam with waist diameter $\sim 4\mu\text{m}$ and aspect ratio up to 1000 with controlled level of divergence, aiming to guide micron-size particles to a precise position in a 3- μm focus of x-ray free electron laser. The control over the divergence of the Bessel beam was performed by varying the incoming beam divergence when used an optical axicon, and by varying the effective lens in the hologram formed by an SLM.

We measured laser power in a series of cross-sections of the beam relative to the incident power, and reconstructed an intensity map of the beam, which will be further used to calculate the optically guided particles trajectories in this beam. The experimental tests were conducted with $2\text{-}\mu\text{m}$ size polystyrene spherical particles to demonstrate, as a proof-of-principal, the ability to change the particle jet trajectory under the optical pressure and to evaluate the optical force. The estimated optical forces exerted on a 2-micron particle in the transverse plane by a 5-W hollow-core Bessel beam is of the order of $\sim(0.1\text{--}0.3)\text{ pN}$, this corresponds to the laser intensity on the particle surface of $\sim 10^5\text{ W/cm}^2$.

There are several important problems to be resolved before the micro-pipeline developed here can be applied as a reliable means to compress the jet of particles by at least an order of magnitude to significantly improve the precision of particle injection method, as required by FEL conditions. First, it would be advantageous to have better control over the intensity distribution in the funnel, aiming to increase the intensity at the entrance of the jet into the optical funnel. Second, calculations of particle trajectories guided by the pipeline depend on a number of unknown parameters such as particle optical properties, size distribution and the flow rate from the aerodynamic lens. In particular, in-situ diagnostics of the particle path in the funnel still has to be developed. In addition, knowledge of local gas pressure at the nozzle of the aerodynamic lens and thermal properties of the particles would allow evaluating the contribution of

thermal force. Furthermore, other potentially valuable architectures for optical trap should also be considered and studied. Fast (relative to particle speed) scanning of a zero-order Bessel beam with engineered intensity [21] would mimic a constant trapping potential matching particular particle properties. Another possible option is constructing a series of concentric optical vortices. Summing up, rapid development of SLMs with improved efficiency and speed offers a wide range of new opportunities to optically guide micro- and nanoparticles with unprecedented precision in vacuum and in gaseous media.

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