Vortex mode stability in mode conversion experiments and a possible practical manifestation of free-electron Landau states

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Recent progress in transferring the astigmatic mode conversion (MC) principle from light optics [1] to electron optics has provided an interesting alternative for the production of high-brightness and high-purity electron vortex beams (EVBs) [2]. EVBs carry quantized orbital angular momentum (OAM) $m\hbar$ and have already been applied in a multitude of experiments [3], with potential applications in nanoscale magnetic measurements using the electron magnetic circular dichroism technique [4,5].

The mode stability, *i.e.*, its transverse dispersion along the electron trajectory, is the basis for reliable and controllable experiments.

For a single quadrupole (QP) MC setup [6] (Fig. 1(a)), image simulations (Fig. 1(b)) show that a dual QP setup (Fig. 1Fig. 1(c)) results in enhanced vortex mode stability up to one Rayleigh range z_R (Fig. 1(d)), when compared to a single QP MC setup.

However, experiments on the dual QP MC setup reveal several unexpected observations: (i) For defocus (d_f) values larger than z_R, the vortex mode begins to disperse (Fig. 2 lower right panel), in contrast to predictions based on wave optical simulations (Fig. 2, inset in the lower right panel); (ii) When switching the polarity of the EVB by a π/2 QP rotation, the observation planes are apparently interchanged, *i.e.*, the far-field pattern appears in the front-focal plane, whereas the focused EVB appears in the back-focal plane and *vice versa* for the opposite vortex mode (Fig. 2).

In order to shed some light on these anomalies, ray tracing simulations have been performed using realistic magnetic field distributions. The MC optics are optimized for non-vortex beams (black lines), yielding a well-focused stigmatic beam at the MC output (Fig. 3(a) inset). By assigning OAM to the electrons, the $m\neq0$ beams are no longer mode-matched/stigmatic (Fig. 3(a) inset).

Analysis of the azimuthal rotation of the electrons shows a slight angular dispersion of ~1.5° between $m=\pm1$ electrons after passing the adapter lens (ADL). The influence of such a slight angular misalignment has been tested (Fig. 3(b)). The focal planes of $m=\pm1$ electrons are now separated from one another (Fig. 3(b) inset), possibly explaining the observation (Fig. 2).

The beam waist inside the ADL is comparable to the magnetic length parameter in the ADL field [7]. The angular dispersion could therefore be caused by peculiar Landau state rotations inside the ADL. This would be the first practical implication of free-electron Landau states. These findings could also help to provide optimized experimental parameters to enhance vortex mode stability in electron optical MC experiments.

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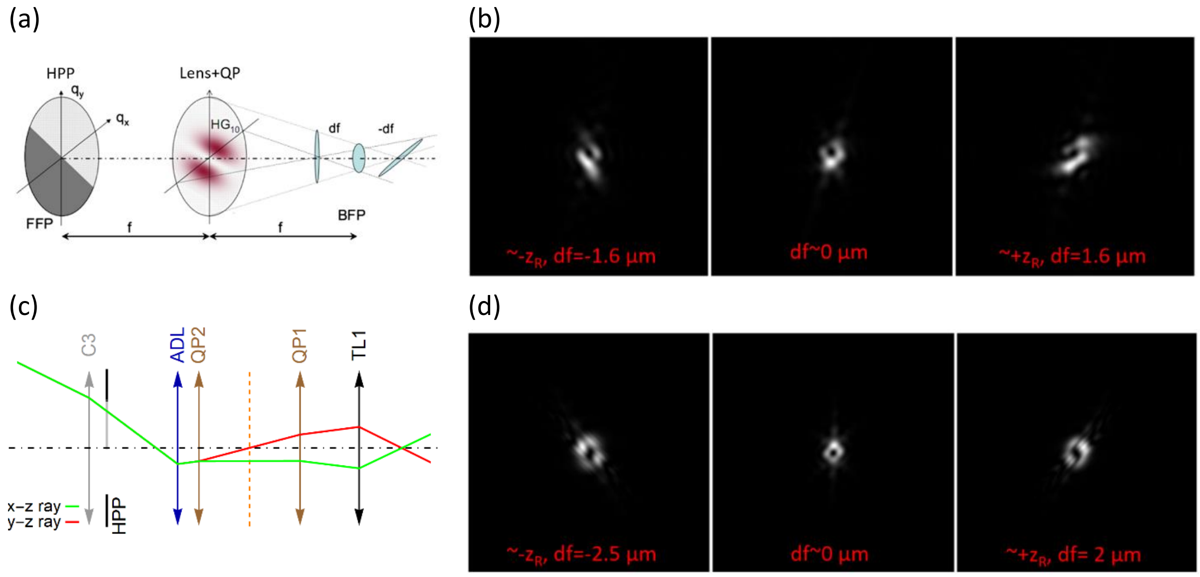

Fig. 1: (a) Experimental setup for single QP mode conversion (MC), adopted from [6]. (c) Ray path diagram for the dual QP MC setup. A Hilbert-phase-plate (HPP) produces a Hermite-Gaussian (HG) mode, which is converted to a vortex mode and stabilized inside the QP doublet QP1 and QP2. (b,d) Wave optical simulation results comparing the vortex mode stability of the two methods. In (b) the single QP MC ansatz resembling the experiment in [6] and in (d) the dual MC approach realized in a Cs-corrector [2] were simulated within the defocus range of plus/minus one Rayleigh range (±z_R). The closed donut like EVB structure is better conserved in the latter case.

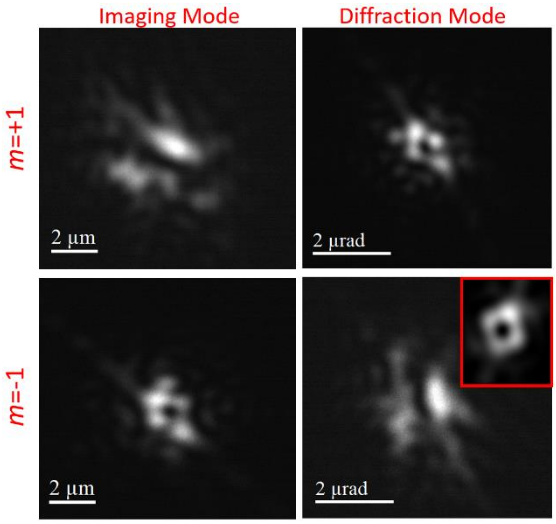

Fig. 2: Vortex mode instability for df>>z_R and vortex mode switching anomaly in the dual QP setup. The far-field pattern (df>>z_R) of the EVB in the lower right panel is strongly dispersed when compared to simulations (inset in the lower right panel). By switching the modes' polarity, the observation planes are seemingly interchanged.

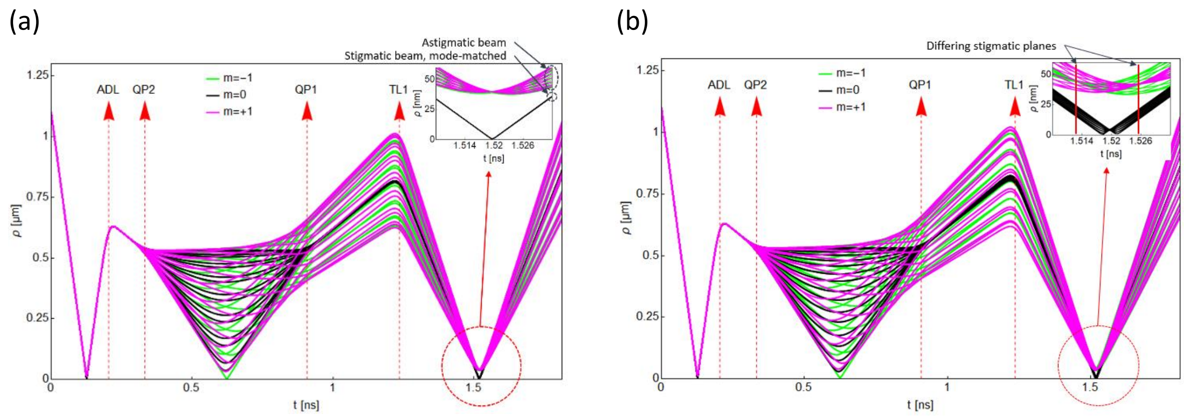

Fig. 3: (a,b) Ray tracing simulations of the dual MC setup, showing bundles of 200 kV electron rays, providing a possible explanation for the observed vortex mode instability by the introduction of OAM and for the axial separation of stigmatic planes by slightly adjusting the QP2 azimuthal rotation angle to compensate for a Landau-level-induced angular shift of vortex electrons.