

Orbital-angular-momentum-enhanced laser absorption and neutron generation

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We experimentally demonstrate enhanced absorption of near-relativistic optical vortex beams in D₂O plasmas to generate a record fast-neutron yield of 1.45×10^6 n/s/sr. Beams with a topological charge of 5 were shown to deliver up to a 3.3 times enhancement of fast-neutron yield over a Gaussian focus of the same energy and an order of magnitude higher intensity. This result was achieved via mJ-class, high-repetition-rate (480 Hz) laser of 16 mJ and a pulse duration of 67 fs striking a free-flowing, 15-  m diameter heavy-water stream. Three-dimensional Particle-in-Cell simulations show unique vortex pulse filamentation and subsequent laser absorption. The orbital angular momentum beam evolution within the nonuniform plasma column leads to the excitation of sheared plasma waves, resulting in net transfer of angular momentum, enhanced volumetric heating, and subsequently increased D-D reactions.

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Vortices are often associated with the natural motion of fluid systems; examples include hurricanes, tornadoes, and whirlpools. Like fluids, electromagnetic waves can exhibit vortex motion and carry orbital angular momentum (OAM) [1,2]. The concept of an optical vortex was first described by Nye and Berry [3], but it was the seminal work by Allen *et al.* [4] that showed paraxial Laguerre-Gaussian (LG) modes carry a well-defined OAM [5,6]. LG modes mathematically characterize symmetric laser profiles through cylindrical paraxial solution of the Helmholtz equation [7–9]. One of the most unique characteristics is the twisting helical phase structure that creates a phase singularity. This singularity manifests as an on-axis null or a "doughnut-shaped" intensity pattern in the far field [10,11]. Recently, there has been considerable interest in extending the application of optical vortices to the realm of ultrashort high-intensity lasers and their role in modulating laser-plasma interactions via the transfer of angular momentum and magnetic field generation [12–18]. Until now, it has been unclear if this structured light can benefit laser-driven neutron generation. Although rapid progress has been made in the field [19–32], many of the setups are restricted to single-shot cryogenic systems, pitcher-catcher arrangements, and facility-scale high-intensity lasers. As such, there is motivation to find enhanced laser absorption mechanisms and debris-free targets scalable to high-repetition-rate systems (>1 kHz).

In this work, we experimentally demonstrate the use of tightly focused (f/1.5) LG₀₁ and LG₀₅ ultrashort pulses inci-

dent on a microscale free-flowing D₂O liquid jet for deuteron heating and fast-neutron generation at unprecedented low intensity [33]. The high-order LG modes propagating at grazing incidence with respect to an overdense target result in an order of magnitude enhancement in sustained fast-neutron generation over previously reported normal incidence interactions using relativistic Gaussian pulses, but up to two orders of magnitude lower intensity [34–38]. Using fully kinetic particle-in-cell methods, we corroborate these findings and confirm evidence of LG beam self-focusing due to nonlinear plasma effects resulting in sheared plasma currents, the net transfer of angular momentum to electrons, and enhanced laser absorption, subsequently leading to volumetric heating and D(d, n)³He fusion as energy is relayed to target ions. Polarization effects on neutron production are also investigated, showing a decoupling of absorption dependence compared with a Gaussian driver.

The experiment was conducted on the λ^3 laser system at the University of Michigan. In the experiment, two separate spiral phase plates (SPPs) of topological charge $l = 1$ and $l = 5$ were used to mode convert a normally Gaussian driver (LG₀₀) of $\lambda = 800$ nm into an OAM carrying LG pulse [1]. A schematic of the target chamber, optical diagnostics, and secondary radiation detectors is shown in Fig. 1. The laser delivered 16 mJ in $\tau_p = 67$ fs (FWHM) to the target center via a 60   f/1.5 off-axis parabolic mirror (OAP). The beam was chirped to a non-Fourier-transform-limited pulse duration to minimize the risk of catastrophic self-focusing in the SPPs. Following iterative beam optimization [39,40], the laser was focused to a $2.86 \mu\text{m } 1/e^2$ spot, resulting in a theoretical maximum on-target intensity of 7.5×10^{18} W/cm². Mode conversion to the LG₀₅ resulted in an estimated peak intensity of 7.9×10^{17} W/cm² in a $\sim 6 \mu\text{m}$ peak-to-peak ring, as shown in the inset of Fig. 2. All pulses were linearly p-polarized light, except as noted in the polarization study.

Similar to work performed by Hah *et al.* [37], a free-flowing liquid microjet was used as a high-repetition-rate target. Heavy-water (D₂O) was pumped at a constant rate

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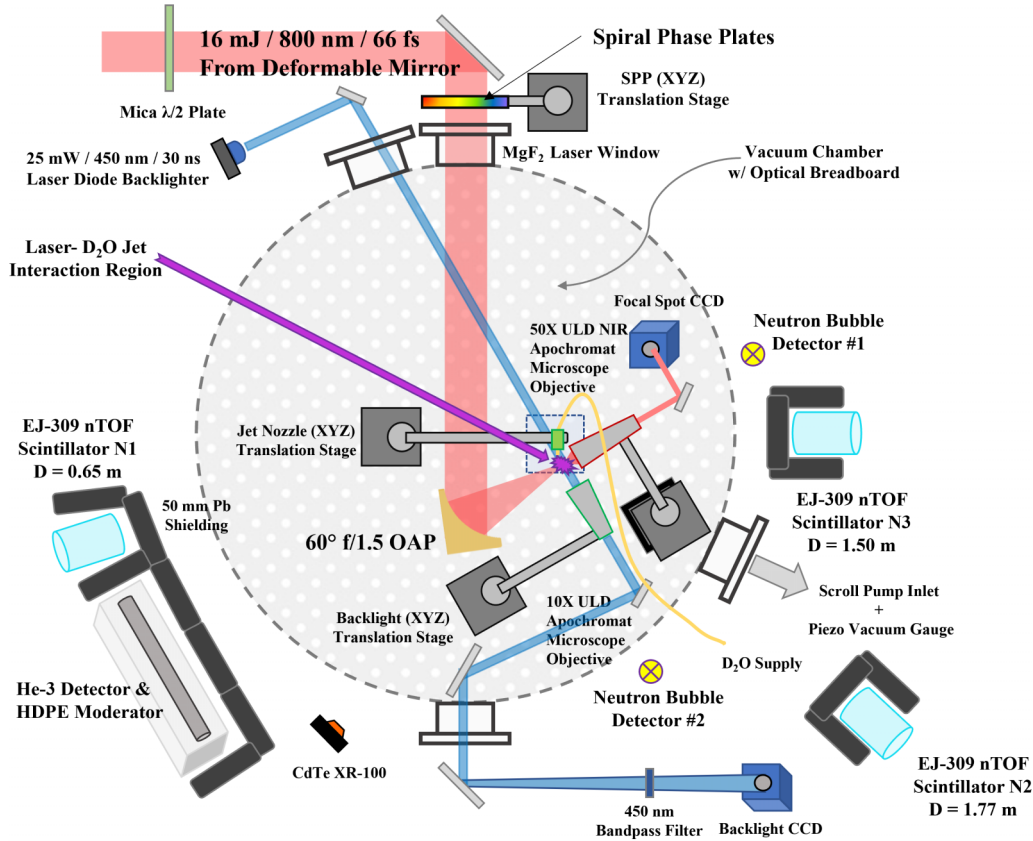


FIG. 1. Target chamber configuration. The placement of detectors and beam optics is not to scale.

of 185 $\mu\text{L}/\text{min}$ to create a stable, laminar flow resulting in a 15–20 μm diameter jet with ambient background vapor pressure at 12 Torr. The laser was focused $\sim 300 \mu\text{m}$ below the capillary and the interaction imaged by transverse optical probing. Placement of the jet relative to peak focus was obtained by moving the jet to maximize the hard x-ray dose at reduced laser energy and recollimating back-reflected second harmonic light via the OAP at high energy, indicating normal incidence. Previous work [37] observed up to $2.2 \times 10^5 \text{ n/s/sr}$ D-D fusion neutron yield from a relativistic Gaussian beam of $3 \times 10^{19} \text{ W}/\text{cm}^2$ interacting with a free-flowing D_2O liquid microjet at near normal incidence with a tunable scale-length from prepulse generation. Recreation of the preplasma enhancement, here done with a transverse offset instead of a prepulse, found a grazing incidence laser-target interaction with p-polarized light ultimately corresponds to the highest isotropic yield found while translating the jet perpendicular to focus. We extend the investigation of grazing incidence to the subrelativistic optical vortices for enhanced laser absorption.

Isotropic D-D neutron flux was characterized using absolute dosimetry provided by neutron bubble detectors (BDs) and relative counts measured by three calibrated EJ-309 proton-recoil liquid scintillation detectors. During each run, BDs were placed at a distance of $d = 30.5 \pm 0.5 \text{ cm}$ and $d = 34.2 \pm 0.5 \text{ cm}$ from the target center. The scintillation detectors (N1–N3), operating in a pulse shape discrimination mode, were located at distances of $d = 65.0 \pm 0.5 \text{ cm}$, $177.0 \pm 0.5 \text{ cm}$, and $150.0 \pm 0.5 \text{ cm}$, and relative angles to the driver of 180° , 90° , and 355° , respectively. The accumulation

time for a series of shots at full power was 300 seconds. The average isotropic flux measured for Gaussian beams striking at optimal transverse offset over 7.78×10^5 shots was $2.56(0.55) \times 10^5 \text{ n/s/sr}$. Inserting the SPPs, the pulse was mode-converted into an OAM-carrying vortex beam, and an identical alignment process followed. Similar to the Gaussian case, maximum yields were found at grazing incidence, with the average isotropic flux measured for topological charge $l = 5$ over 2.63×10^6 laser shots was $8.43(0.17) \times 10^5 \text{ n/s/sr}$, and the maximum recorded dose during any single run was logged at $1.45(0.34) \times 10^6 \text{ n/s/sr}$. This led to a relative signal enhancement of $3.29 \pm 0.71\times$ for the OAM to PG case as measured by BDs. Postprocessing of the parsed scintillation events corroborated this relative signal enhancement and calculated for each detector as N1: $3.29 \pm 0.69\times$, N2: $3.18 \pm 0.67\times$, and N3: $3.41 \pm 0.72\times$. Figure 2 provides a representative visualization of the fast neutron signal enhancement as recorded by binned scintillation events for LG_{00} and LG_{05} cases for optimal offsets of 12 μm and 32 μm , respectively.

Aside from relative signal enhancement, the nTOF measurement elucidates no fundamental difference in the fast-neutron population. As seen in Fig. 2, the maximum ion energy cutoff was $\sim 1 \text{ MeV}$, and the bulk of the characteristic $E_N = 2.45 \text{ MeV}$ D-D neutrons arrived at the detector plane with down-scattered energy. These results are consistent with similar laser-driven neutron source experiments performed in the presence of a low-pressure background of deuterated vapor [30,37]. A lack of extension to the high-energy tail of the LG_{05} measured fast-neutron spectra suggests the bulk ion

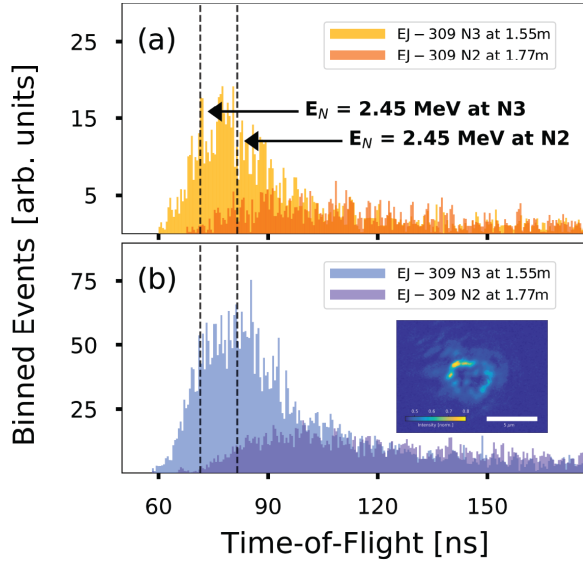


FIG. 2. Fast-neutron time-of-flight measurements performed with $\tau_{\text{coinc}} = 512$ ns coincidence for the (a) Gaussian and (b) LG₀₅. Liquid scintillation events with proper fast neutron PSP and light output characteristics are shown in 500 ps bins for detectors N2 and N3. Nearly identical signals are recorded for the Gaussian case, with $\sim 30\%$ the number of observed events. The inset demonstrates the LG₀₅ focal spot taken at reduced power.

temperatures vary little from the Gaussian case. To explore the dynamics of OAM enhancement and the role of grazing incidence on laser coupling, a series of transverse scans was conducted. First, we consider higher peak intensity and reduced OAM by introducing an SPP with a topological charge of $l = 1$. Second, we explore the role of polarization by inserting a half-wave plate to rotate the incoming linearly polarized driver beam to the s-polarized state [41,42]. Third, using the LG₀₅ optimal longitudinal positions, we scanned the spatial position of the target across the focused beam to quantify the effective absorption range at grazing incidence. During each scan, a series of $4.00 \mu\text{m}$ closed-loop steps was made starting from the farthest transverse position of the $l = 5$ OAM beam that coincided with x-ray yield above background. At each position, the total PSD filtered counts within the fast neutron region of interest from the N1 EJ-309 detector were used as the detection figure of merit. For a dwell time of $t = 40.0$ seconds, coincidence neutron events were recorded.

As seen in Fig. 3, the LG₀₅ beam interacts on a spatial scale that extends over nearly 20 beam diameters ($D_{\text{LG}_{05}} \approx 6 \mu\text{m}$) and 6–7 liquid jet diameters. A similar interaction scale length is also evident for the LG₀₁ beam, even with the measured intensity profile approximately $0.44\times$ the diameter of the LG₀₅ mode. The asymmetry shown in the amplitude of relative neutron yield at either edge of the jet for the OAM modes is attributed to the distortion of the annular mode profile, as observed in focal spot imaging in Fig. 2. All three beams show a pronounced reduction in neutron yield at target-normal, independent of polarization state. This is expected due to plasma mirroring. All three scans performed with p-polarized beams show a bimodal distribution of peak counts across the transverse scan profile, but only the spatial rise and fall distances of

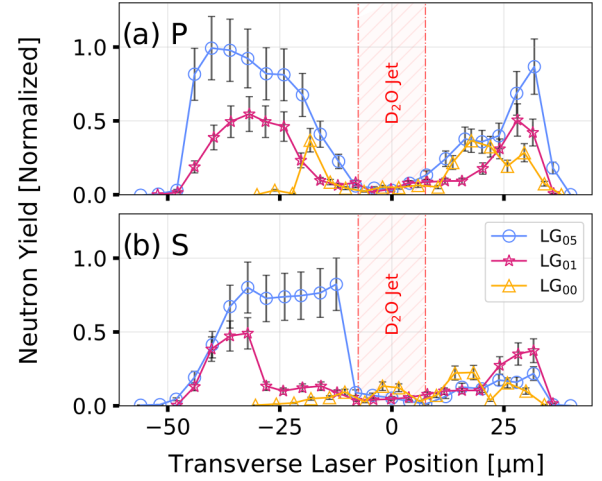


FIG. 3. Neutron signal normalized to the maximum count recorded for the case of p-polarized light with topological charge $l = 5$. (a) and (b) plots correspond with the p-polarization and s-polarization of the driver beam, respectively. Hatched red area denotes the approximate bulk water jet position. Error is representative of the percent deviation found between detectors.

the LG₀₀ case are of the order of the $1/e^2$ beam diameter. The broad spatial range over which the OAM beams efficiently couple energy into the plasma surrounding the liquid jet suggests the presence of an extended region of critical density vapor at the microjet edge. This is unsurprising, as the local density changes 5 decades in magnitude from $n_e = 3.8 \times 10^{18} \text{ cm}^{-3}$ to $n_e = 3.3 \times 10^{23} \text{ cm}^{-3}$ in this region. Following normalization of the binned fast neutron scintillation events to the maximum count measured for the LG₀₅, we report the accumulated transverse scan results in Fig. 3. In the LG₀₀ case, the p-polarized light effectively couples into the target through resonance absorption [43] at oblique incidence, but s-polarized light results in negligible heating across the transverse profile. In sharp contrast, efficient laser-plasma energy coupling of an OAM beam having s-polarization is observed for both LG₀₁ and LG₀₅, with a likely explanation arising from the advancing helical phase that drives skewed propagation of the Poynting vector [44]. While striking the jet, azimuthal density gradients cause the LG beam to undergo asymmetric filamentation, exciting sheared plasma waves, which lead to efficient laser absorption and the transfer of angular momentum into the jet. This filamentation occurs regardless of laser polarization and demonstrates a decoupling for OAM carrying LG pulses compared with classical polarization-dependent resonant absorption.

To study this interaction, we use the three-dimensional electromagnetic PIC code OSIRIS 4.0 [45]. The simulation uses a spatial interaction volume of $76.4 \times 40.2 \times 40.2 (\mu\text{m})$ with $908 \times 508 \times 508$ (X1, X2, X3) cells, correlating to a grid resolution of $\lambda/10$ in each dimension. The time step was set to the CFL condition and demonstrated negligible grid heating with cubic particle weighting through the duration of interest. The laser was injected from the wall in the X1 direction. The free-flowing jet was initialized as a cylindrically uniform cold plasma with a diameter $D = 15 \mu\text{m}$. Jet density was set at $n_0 = 10 \times n_{cr}$ to minimize numerical artifacts. The

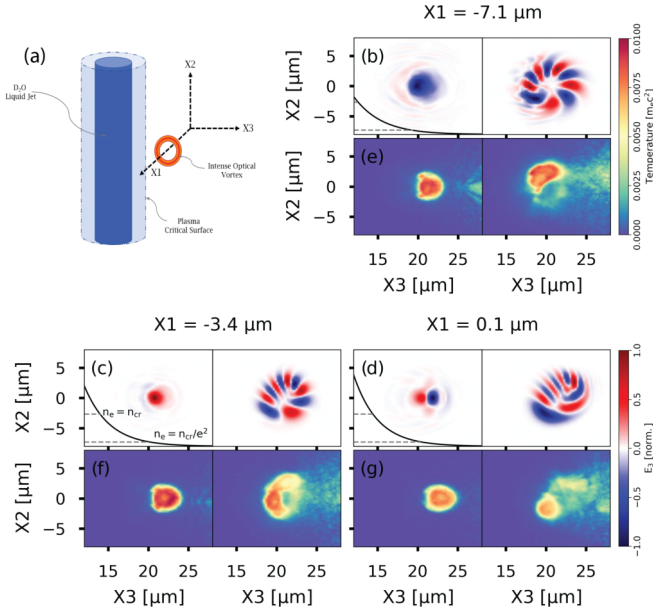


FIG. 4. (a) Graphical representation of the simulation and relevant axes. (b)–(d) Electric-field, X2-X3, slices of the Gaussian (left) and LG₀₅ (right) taken at the halfway point of the interaction ($t \approx 330$ fs) at various X1 longitudinal positions. Fields are normalized to the maximum of each frame. Jet center is located at (0,0) with incident beams at an offset $r_0 = 20.0$ μm from the center. The black line represents the density profile of the transverse slice. Corresponding plasma temperatures 140 fs after the passage of the fields from (b)–(d) are shown in (e)–(g) with the same colorbar.

effect of finite laser prepulse contrast ($\leq 10^{-7}$) in tandem with a D₂O vapor induces a preplasma and associated density scale-length at the liquid jet's boundary. To model the density inhomogeneity, a 3- μm scale-length exponential was applied to the jet edge. Macroparticles representing deuterium and oxygen ions were initialized as immobile particles on the grid and assumed to be fully preionized at 18 particles per cell. Collisional effects were turned off to emphasize collisionless laser absorption differences between a Gaussian and vortex driver.

In the simulation, a LG₀₀ laser pulse with $E_p = 16$ mJ, $\tau_p = 67$ fs (FWHM), and waist of $2\omega_0 = 3.0$ μm was used as a relativistic ($a_0 = 1.5$) reference case. Using a built-in suite for vortex beam generation, an LG₀₅ beam was launched with equivalent pulse energy, duration, and a properly scaled waist of ~ 5.5 μm peak-to-peak. As modeled and in good agreement with theory [1], the focused LG₀₅ mode corresponds to an initial normalized peak vacuum intensity of $a_0 = 0.67$. All fields were launched as linear p-polarized. Figure 4(a) shows a basic diagram of the particle-in-cell model. Figures 4(b)–4(d) shows a comparison of transverse X2-X3 electric field slices of both pulses at $t = 0.33$ ps, demonstrating the longitudinal pulse evolution during propagation through the radially dependent plasma profile. Striking the jet off-axis leads to both a longitudinal and azimuthally asymmetric plasma gradient. As expected, in the pure Gaussian case, the driving pulse undergoes whole-beam self-focusing, reaching peak intensities of $a_0 = 2.34$. In doing so, the pulse ponderomotively heats a central on-axis electron filament with the hottest

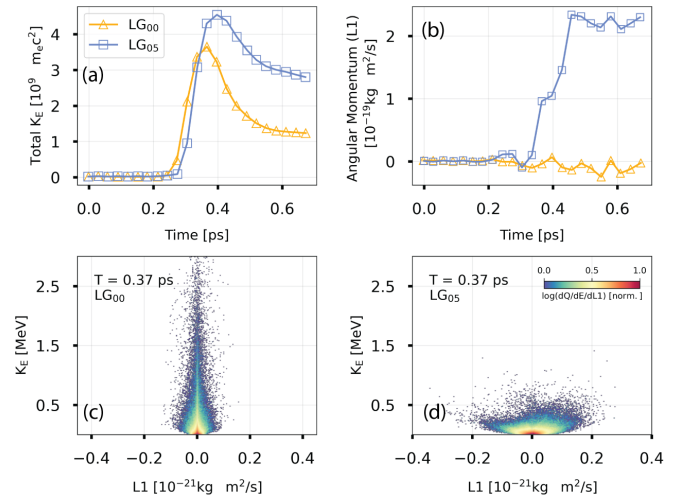


FIG. 5. (a) Total kinetic energy contained within the water jet over the duration of the simulation. As shown, the use of the LG₀₅ can lead to nearly double the energy absorption compared with higher intensity LG₀₀ modes. (b) The evolution of total L1 angular momentum in the bulk jet for 10% of tracked electrons. (c), (d) The E_k -L1 phase-space, which shows the formation of an asymmetric distribution and net L1 transfer for the LG₀₅ case.

electron energies on the order of the ponderomotive energy; $U_{\text{pond}} = m_e c^2 (\sqrt{1 + a_0^2/2} - 1) \sim 1$ MeV. This rapid heating leads to a radially symmetric outward electron expansion, which is quickly slowed by the surrounding column. The pulse is deflected, leading to an elliptic exit focal profile while expelling hot electrons away from the bulk.

In contrast, the LG₀₅ pulse experiences more complex evolution, resulting in filamentation and penetration to higher densities. The plasma gradients lead to variation in the phase velocity across the beam azimuth in addition to radial deflection evident in the ellipticity of the exiting pulse. This mismatch in phase velocity creates a nonperiodic phase and longitudinal shearing of the LG phase fronts as visualized in Fig. 4. Coupled with the skewed propagation of the Poynting vector [44], this acts as a seed for filamentation and driving of sheared plasma waves, which lead to a coupling of angular momentum into jet and efficient laser absorption. The result of this process can be seen in Figs. 4(e)–4(g), which depicts the helical evolution of the plasma temperature profile in X1, 140 fs after the pulse has passed. The coinciding transfer of OAM is demonstrated in Fig. 5, where the asymmetric E_k -L1 phase space of the LG case corresponds to a net transfer of angular momentum in the X1 direction (L1). Comparing the evolution of the total angular momentum within the bulk for both cases demonstrates significant OAM present in the LG, not apparent in the pure Gaussian interaction. From this, we attribute the energy transfer to be caused by the decay of angular-momentum-carrying plasma waves, lending to more efficient laser absorption and higher kinetic energy than the high-intensity Gaussian driver. The shearing of the phase-fronts is largely polarization independent and is expected to contribute to the polarization insensitivity of the OAM modes observed within the experiment, in addition to the filament-induced rippling and structuring, which can override the role

of the incident polarization state [42,46]. Given the extended region of water vapor present in the experiment, the azimuthal density gradients may allow for similar filamentation and coupling across a much larger interaction region compared with the Gaussian case.

In conclusion, we demonstrate the application of self-focusing with near-relativistic optical vortex beams to generate a record isotropic fast-neutron yield of 1.45×10^6 n/s/sr. Beams with a topological charge of $l = 5$ were shown to deliver up to a $3.3\times$ enhancement of fast-neutron yield over an optimally tight-focused Gaussian beam. This completely unexpected result was achieved with modest laser energies of 16 mJ and a relaxed compressed pulse duration of $\tau_p = 67$ fs. The enhancement in laser absorption is attributed to LG beam filamentation from azimuthally varying phase-fronts that drive sheared plasma waves, leading to OAM transfer and efficient laser-plasma coupling. We demonstrated the first experimental observation and application of this effect. The pulse parameters are well suited for emerging ultrashort

pulsed fiber-architecture lasers capable of sustained multi-kHz operation [47–50]. Tabletop neutron flux of this level is comparable to that characteristic of commercial sealed-tube D-D generators [51] but with pulse durations of 20 ns. Further repetition rate scaling (1–10 kHz) could easily generate of-order $\sim 10^7$, $\sim 10^8$ n/s, and would be well suited for time-resolved prompt gamma neutron activation analysis studies [52].

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