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Spatiotemporal optical vortices (STOVs) and relativistic optical guiding

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We study the generation of spatiotemporal optical vortices (STOVs) from self-focusing processes in plasma and their role in mediating intrapulse energy transport in intense, self-guided laser pulses using fully three-dimensional, particle-in-cell simulations.
In previous work, STOVs were observed both in experiment and in simulation to emerge from self-focusing collapse arrest from filamentation in air using lower-intensity femtosecond pulses (~10^13-10^14 W/cm^2), and they have been generated linearly using a pulse shaper [1-2]. In the case of atmospheric filamentation, n2 of air induces an intensity-dependent refractive index within the laser pulse that leads to runaway self-focusing until collapse arrest via plasma generation [3]; phase shear between the higher-intensity, self-focusing core and the lower-intensity periphery of the laser was found to spawn these vortices [1]. These STOVs then proceed to mediate intrapulse electromagnetic energy flow during filamentation [1].
In plasmas, analogous though distinct mechanisms such as from relativistic and ponderomotive effects that are relevant for high-intensity, self-guided pulses (>10^18 W/cm^2) impose a similar intensity-dependent refractive index and induce self-focusing. Understanding the interaction of relativistically intense laser pulses with plasma would be of use for laser wakefield acceleration experiments, which tend to operate in this regime.
In this work, we simulate relativistic self-guiding of an intense laser pulse and show, for the first time, the generation of STOVs in plasma by nonlinear phase shear from relativistic and ponderomotive effects. We observe, in three dimensions, the nucleation of STOVs at points around the pulse, their expansion, reconnection, and evolution into a pair of vortex rings. Finally, we find that these vortices mediate the flow of electromagnetic energy within the pulse and illustrate how this influences the broader propagation of the laser.

[1] N. Jhajj et al. Spatiotemporal optical vortices Phys. Rev. X 6, 031037 (2016)
[2] S. W. Hancock et al. Free-space propagation of spatiotemporal optical vortices, Optica 6, 1547 (2019)
[3] A. Couairon and A. Mysyrowicz, Femtosecond Filamentation in Transparent Media, Phys. Rep. 441, 47 (2007).

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