# Long-lived density spikes in laser-driven Coulomb explosion flows

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A relativistically intense femtosecond laser pulse passing through a subcritical gas plows away all electrons in its path and creates multi-stream flows in the electron distribution. These flows form folds and cusp singularities [1] that were proposed as directional nano-scale sources of bright, coherent x-ray radiation [2, 3].

PIC simulations in a simplified 2D setting [4] (initialized with an artificial electron cavity) indicated that the ensuing Coulomb explosion of the trailing ions also produces multi-stream flows with singular "shock" fronts appearing as spikes in the ion distribution (see Suppl. Fig.9(f-1) of [4]). Using the code REMP [5], this has now been confirmed by self-consistent 3D PIC simulations of a near-relativistic picosecond infrared laser pulse shot through a subcritical hydrogen plasma (neutral mix of cold unbound $H^+$ and $e^-$).

Coulomb explosion shocks are a known phenomenon [6] that is relevant for various applications, such as electron bunch acceleration and ionized nanocluster dynamics.

Here, we study radially converging ion fronts produced by laser pulses plowing through H plasma. As an example, Fig.1 shows results from two simulations of cold subcritical H plasma ($n_e = 10^{16}\,\mathrm{cm}^{-3}$) perturbed by 10 ps long infrared ($\lambda = 10\,\mu$m, $n_{crit} = 10^{19}\,\mathrm{cm}^{-3}$) near-relativistic ($a_0 = 0.56$) laser pulses with different radial profiles. The snapshots were taken 18 ps after the laser's peak passed through its focus ($1/e^2$ width $w_{foc} = 70\,\mu$m, at $X = x - x_{foc} = 0$).

In panels **(a-c)**, the Coulomb explosion in the wake of a Gaussian pulse yields ring-shaped off-axis density spikes that are largest at the point where the Coulomb explosion "shock" front turns singular (red arrows). Panels **(d-e)** on the right show that a donut-shaped Laguerre-Gaussian pulse yields additional on-axis spikes (pink arrows) that are enhanced by an order of magnitude. In this example, they reach 0.2 $n_{crit}$ on the ~0.01 mm scale, and potentially exceed $n_{crit}$ on the micron scale (not resolved here).

These large on-axis spikes form because the radially converging "shock" front becomes singular at the instant it arrives at the axis. Interestingly, instead of merely turning into a pair of diverging folds, the primary singular shock develops dynamic caustic substructures that stay near the axis. On the cavity scale, they have the appearance of a persistent on-axis singularity, which is seen as a long-lived on-axis spike in the region $|X| < 0.3$ mm in Fig.1(d-f).

We will study the underlying mechanisms numerically and seek possible practical applications.

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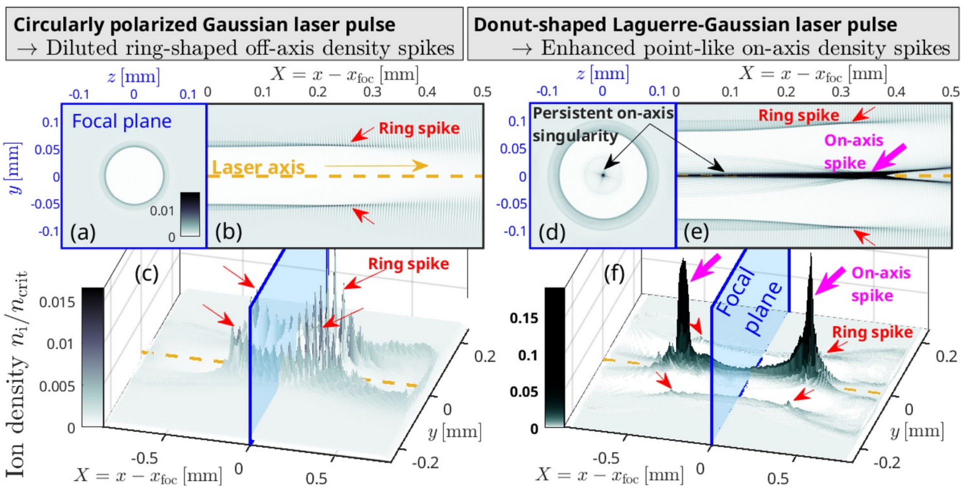


**Figure 1.** PIC simulation results showing the structure of the ion density landscape shaped by the Coulomb explosion after a laser pulse has passed through a cold uniform unmagnetized hydrogen plasma. Panels **(a-c)** on the left show results obtained with a circularly polarized Gaussian pulse, and panels (**d-f**) for a donut-shaped Laguerre-Gaussian pulse. Gray-scale contours represent the ion density $n_i$ ($\approx n_e$) normalized by the critical density $n_{crit}$. The laser has propagated along the $x$ axis and its focal plane (blue) is located at $X = x - x_{foc} = 0$. Panels (**a**,**d**) show the $n_i(y,z)$ contours in a 0.26 mm wide transverse cross-section at the focal plane ($X = 0$). Panels (**b**,**e**) show the $n_i(X,y)$ contours in the longitudinal cross-section at the height of the midplane ($z = 0$) behind the focal plane ($X > 0$). The same $n_i(X,y)$ data as in (**b**,**e**) are shown in (**c**,**f**) for a 1.7 mm long portion of the cavity centered around the focal plane (-0.87 mm < $X$ < 0.83 mm). All panels use a similar color scale for $0 \le n_i/n_{crit} \le 0.017$, but the contours in panels (**d-f**) on the right are extended up to $n_i/n_{crit} \le 0.19$.