Enhanced intensity of betatron radiation from few-TW LWFA with an asymmetric density profile in a sub-mm gas jet

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Betatron radiation, generated by relativistic electrons oscillating transversely in plasma wakefields, is a key feature of laser wakefield acceleration (LWFA) and a promising ultrafast x-ray source. The intensity of the emitted radiation is proportional to the radiative energy loss [1] $W_{loss} = n_e^2\gamma^2 r_\beta^2$, where n_e is the plasma density, γ is the relativistic Lorentz factor of electron and $r_\beta \propto \frac{p_\perp}{m_e\omega_p^2}$ [2] is the oscillation radius determined by the transverse momentum $p_\perp$, the electron mass m_e and the oscillation frequency ω_β. As illustrated in Fig. 1(a), our study shows that utilizing an asymmetric plasma density profile with a shortened density down-ramp [3] facilitates rapid plasma bubble expansion, resulting in an increased oscillation radius of accelerated electrons with greater transverse momenta, thereby boosting the radiation intensity.

This study conducted particle-in-cell simulations using OSIRIS [4] with a quasi-3D framework to investigate the betatron radiation when a 3-TW laser pulse is focused into either an unshaped or a shaped nitrogen jet. As illustrated in Fig. 1(b), the unshaped target features a Gaussian electron density distribution with a full width at half maximum (FWHM) of 670 μm, while the shaped gas jet exhibits an asymmetric plasma density profile with a reduced FWHM length of 605 μm, fitted by two distinct Gaussian components, with FWHMs of 405 μm on the front side and 200 μm on the rear side, respectively. As shown in Figs. 1(c) and 1(d) for the trajectories and energy spectra of accelerated electrons, the shaped target with a steeper density gradient in the down-ramp region enables accelerated electrons to maintain higher energy and accumulate greater beam charge, compared to electrons experiencing significant dephasing in the unshaped target. Note that Fig. 1(c) also shows that accelerated electrons exhibit a greater oscillation radius in the down-ramp of the shaped target, accompanied by enhanced transverse momentum as indicated in Fig. 1(e). Consequently, as illustrated in Fig. 1(f) for the spectrum of x-rays calculated by JRAD [4], the shaped target helps increase the overall radiation yield—by approximately a factor of two—particularly in the high photon energy range (> 6 keV), compared to the unshaped target. These results represent a promising approach to effectively enhance betatron emission from few-TW LWFA for advanced compact X-ray sources in future applications.

References
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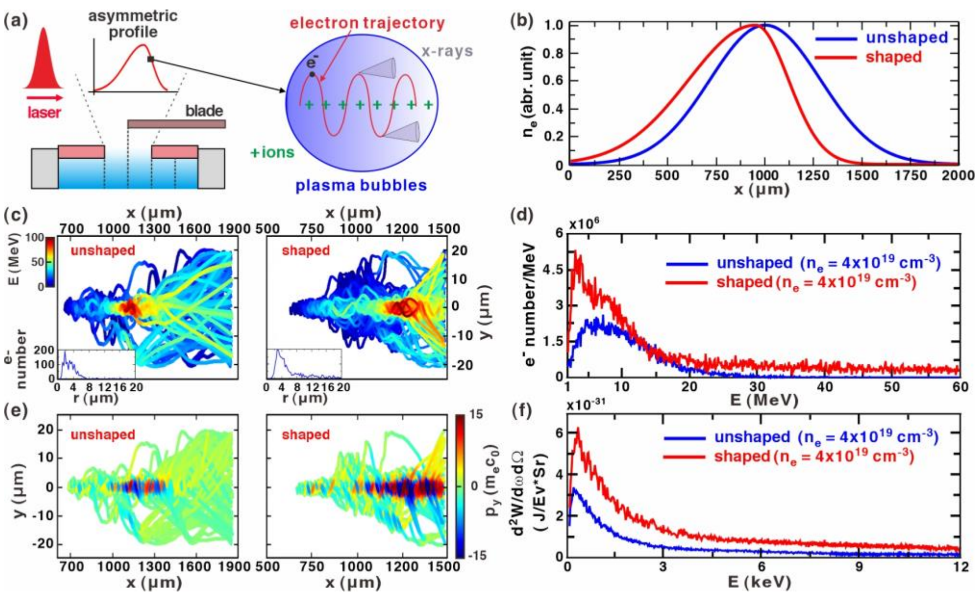

Figure 1. (a) Schematic for creating the shaped gas jet with a asymmetric density profile by using a blade to impede part of gas flow out of the nozzle. (b) Illustration of the unshaped (blue) and shaped (red) density profiles defined in the simulations. (c) Trajectories of accelerated electrons with the inset showing the histogram of betatron amplitudes and (d) electron spectra obtained with the unshaped and shaped target. (e) Comparison of the transverse momentum P_y distributions of the accelerated electrons and (f) the x-ray spectra of betatron radiation with the unshaped and shaped target.