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High energy electron acceleration and mid-infrared radiation in curved plasma channel

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This work presents a comprehensive study on laser-driven electron acceleration[1] and mid-infrared (MIR) radiation generation[2] in curved plasma channels, integrating experimental validation and theoretical innovation to address critical challenges in compact accelerator design and ultrafast optical science.

In experiment, we have demonstrated stable guidance of intense laser pulses (200 TW, 30 fs, 800 nm) in a 3 centimeters curved plasma channel with a curvature radius gradually increasing from 6 cm to ∞ and a 10.4° deflection angle (Figure 1(a)). The curved plasma channel is created by discharging helium in a capillary formed by a pair of etched sapphire substrates[3]. In this curved plasma channel, the laser propagation trajectory is modulated by the laser off-axis incidence (0-150 μm). At the optimum off-axis incidence position (~100 μm), laser guiding results show the transverse oscillations are suppressed and the transmitted laser reaches the highest energy concentration of 43% (Figure 1 (b)), the electron acceleration results demonstrate that the maximum electron energy reaches 0.7 GeV with energy spread ~12% (Figure 1 (c)). The curved plasma channel paves the way for seamless multistage laser wakefield accelerators, offering potential for future TeV level electron-positron colliders.

We further explore the plasma optics function of curved plasma channels as "plasma prisms" for relativistic laser separation and frequency conversion (Figure 2(a)). Under the photon deceleration scheme, we theoretically demonstrate that the curved plasma channel can convert a 20 TW near-infrared (NIR) pulses into few-cycle MIR pulses with 37 mJ energy and $\sim 10^{16}\ \mathrm{W/cm^2}$ intensity. The plasma prism achieves spatial separation of NIR and MIR components via curvature-induced angular dispersion, enhancing the spectral purity of the MIR pulse by two orders of magnitude compared to straight photon deceleration schemes. By adjusting the size (1–6 mm) and curvature radius (10–50 mm) of the curved channel, the plasma structure enables flexible frequency conversion of produced MIR pulses and exhibits tunable angular dispersion properties (Figure 2(b-c)), ranging from normal dispersion, anomalous dispersion, and dispersion-free "grism" behavior. The distinctive dispersion properties of plasma prisms make them valuable for various frontier technologies, including plasma stretchers, plasma spectrometers, and high-purity MIR sources for strong-field physics and ultrafast spectroscopy.

References
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[2] X.Z. Zhu *et al*, (submitted).
[3] J. Li *et al*, High Power Laser Sci. Eng. **11**, 05000e58 (2023).

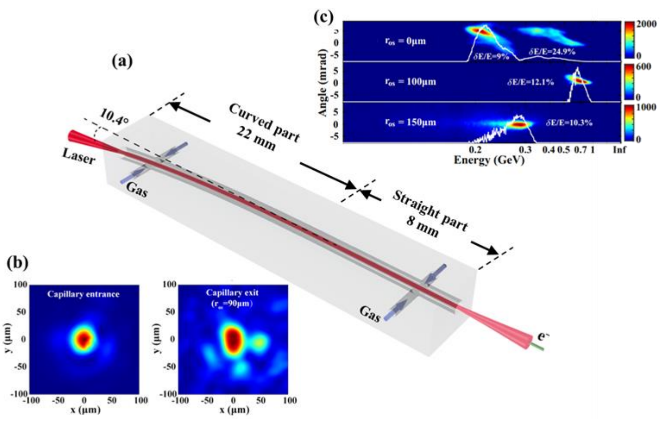

Figure 1. (a) Structure of the curved and straight plasma channel. (b) Electron bunches obtained by laser wakefield acceleration with different laser incidence offsets. (c) Experimental setup for the measurements of laser guiding and electron acceleration.

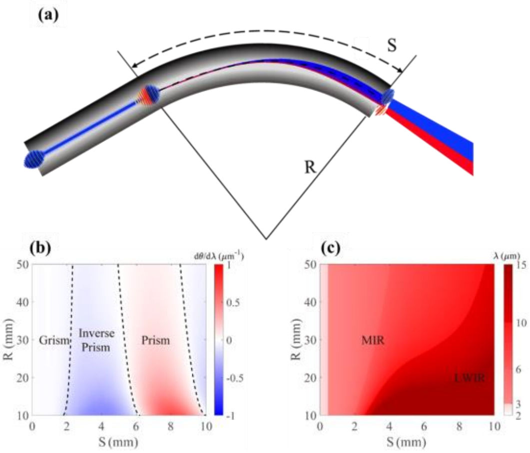

Figure 2. (a) Concept of plasma prism for polychromatic pulse dispersion. A curved plasma channel with length S and radius R was used to spatially disperse the laser pulse. (b-c) Transition diagram of angular dispersion and wavelength conversion of plasma prism under variation of S and R.