Electron acceleration by Laguerre-Gaussian beams from a high-density dual-staged plasma nozzle

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Introduction

Overview:

- Laser wakefield acceleration (LWFA) of electrons is predominantly achieved using gas targets. In recent years, the development of high-repetition-rate, high-intensity lasers has driven research into employing high-density gas targets to generate very high-energy electrons (VHEE) beams, which hold potential for medical applications [1].
- Laguerre-Gaussian (LG) laser beams differ from Gaussian beams by their azimuthal phase structure, imparting orbital angular momentum (OAM), and a donut-shaped intensity profile with a central minimum. These features, combined with advanced gas nozzle setups, enable new possibilities for optimising electron acceleration [2,3].
- Among the various injection techniques that have been carried out to control the electron injection to overcome the non-linear effects of pump depletion, dephasing length, and diffraction, the ionisation injection is the most effective technique for injecting electrons in the wakefield [4].
- A key aspect of LWFA is its ability to generate an appropriate gas density profile within the ionization injection technique, allowing for controlled electron injection into the accelerator phase while preserving the ideal plasma density for acceleration. A widely used approach for achieving the desired density profiles is the application of a two-stage supersonic gas nozzle [5].
- The first stage of the gas nozzle is responsible for ionizing electrons and adjusting their position within the rear portion of the plasma bubble during the injection. The second stage focuses on accelerating the electrons via LWFA, ensuring maximum acceleration distance and minimizing the energy spread of the electrons [6].

Simulation setup and parameters

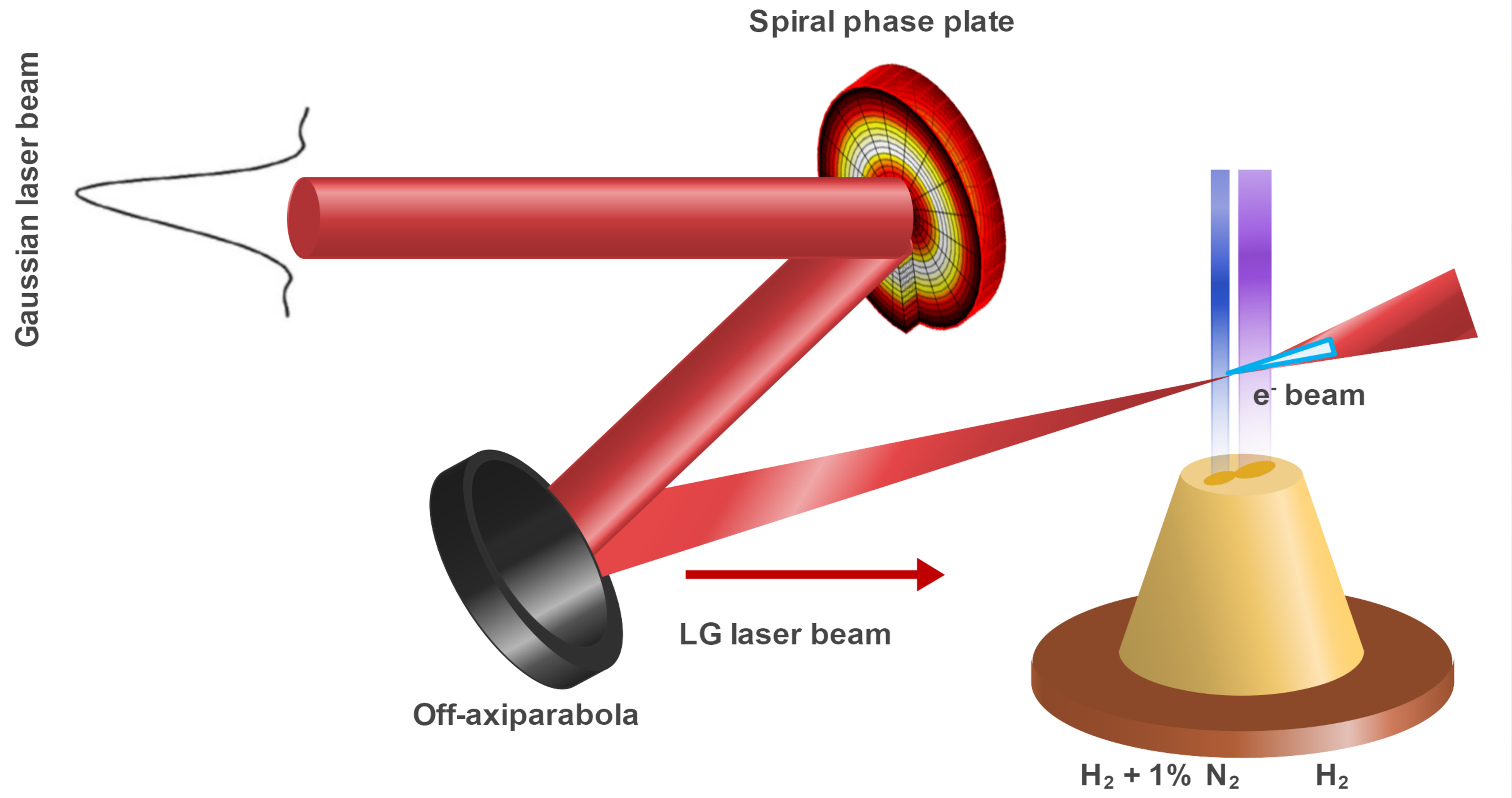

Figure 1. Schematic view of the two-stage LWFA configuration examined in this study. The first stage, designated as the injection stage, utilizes a mixture of nitrogen (N_2) and hydrogen (H_2) gases. The second stage, known as the acceleration stage, uses only pure hydrogen (H_2).

Pulse duration (FWHM), τ_0 (fs)	Pulse length (FWHM), $L_0=c\tau_0$ (μm)	Laser strength parameter, a_{LG}	Laser wavelength, λ (μm)	Laser peak power, (TW)	Laser pulse energy, (J)
15	4.5	4.5	0.8	67	~1
Beam waist, w_{LG} (μm)	Hydrogen concentration, n_{atoms} (10^{19} cm^{-3})	Nitrogen concentration	Plasma wavelength, λ_{LG} (μm)	Length of the first nozzle (μm)	Length of the second nozzle (μm)
10	1	1%	10.5	2400	200

Table 1. Simulation parameters for laser and plasma.

FBPIC simulation results

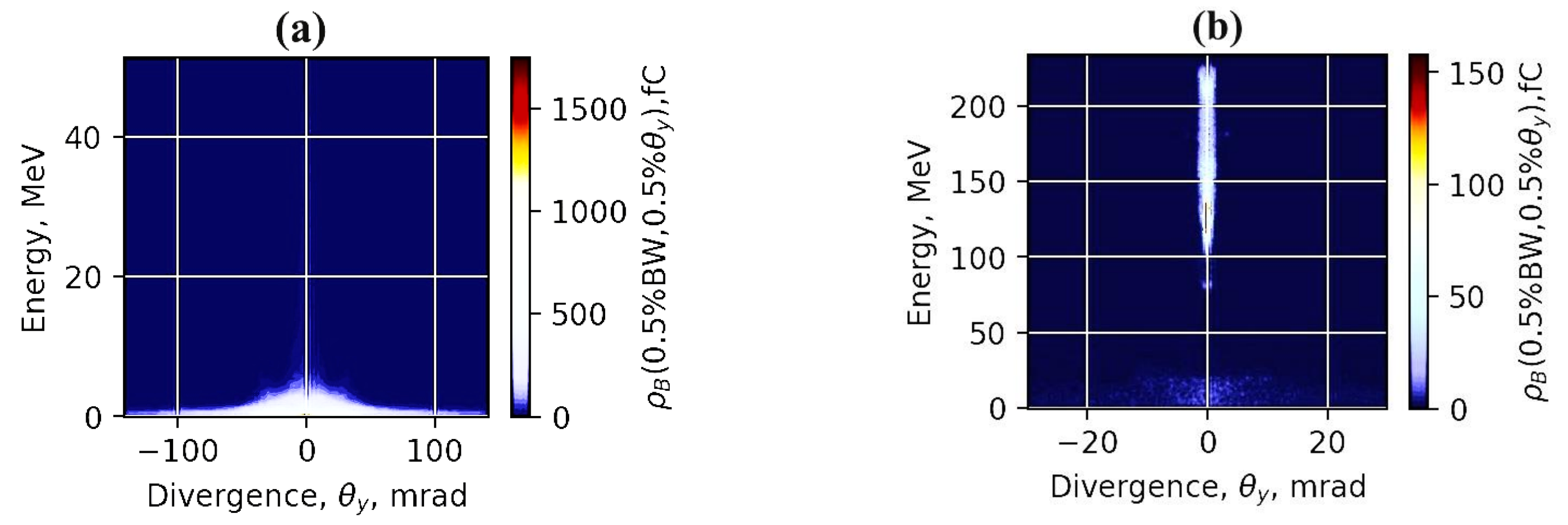

Figure 2. The energy spectra of the electron beam accelerated by the LG00 laser beam at distances (a) 180-240 μm and (b) 990-1020 μm when 1% nitrogen was mixed with 99% hydrogen in the first gas nozzle.

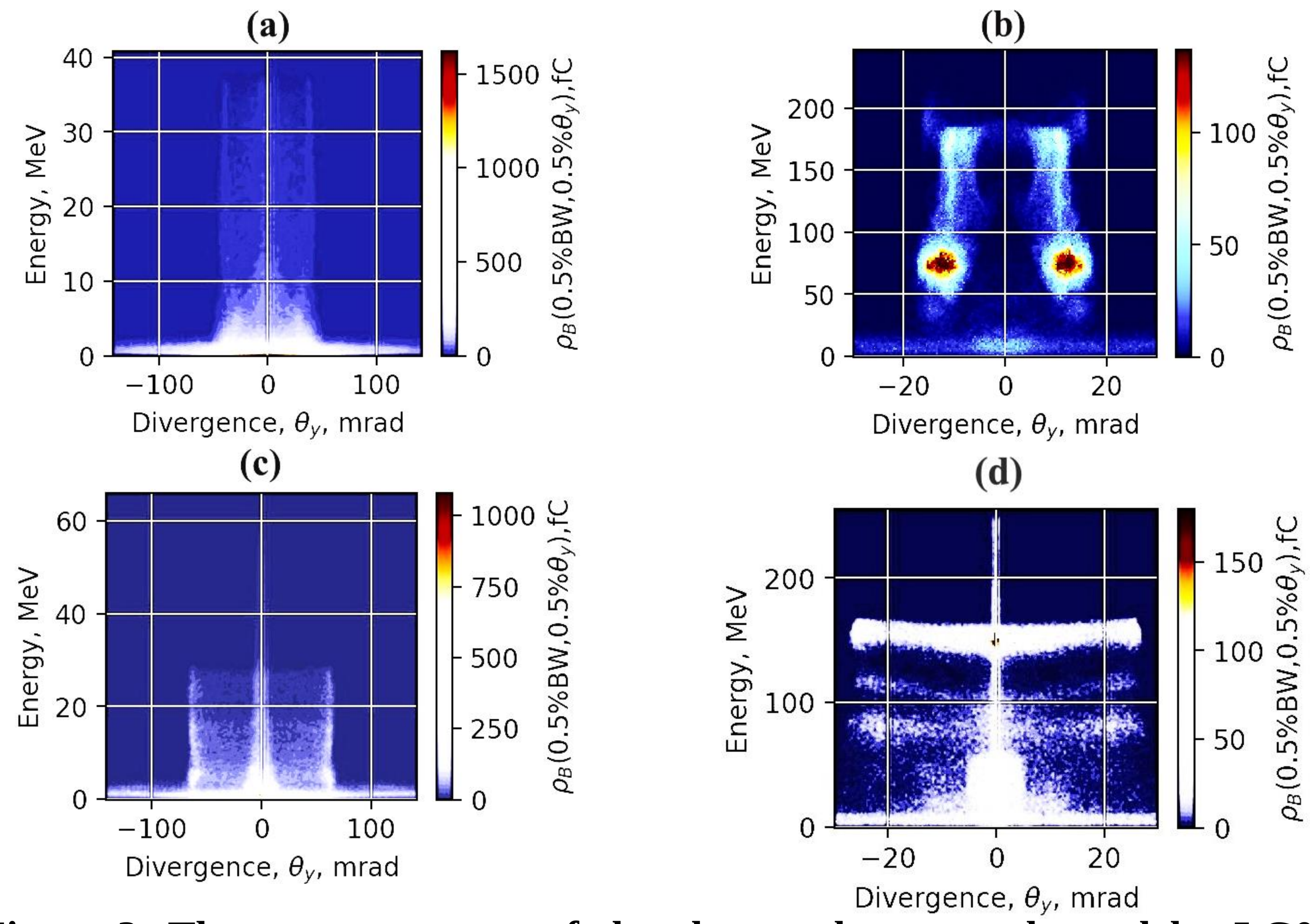

Figure 3. The energy spectra of the electron beam accelerated by LG01 or LG10 laser beams at distances (a, c) 180-240 μm and (b, d) 990-1020 μm when 1% nitrogen was mixed with 99% hydrogen in the first gas nozzle.

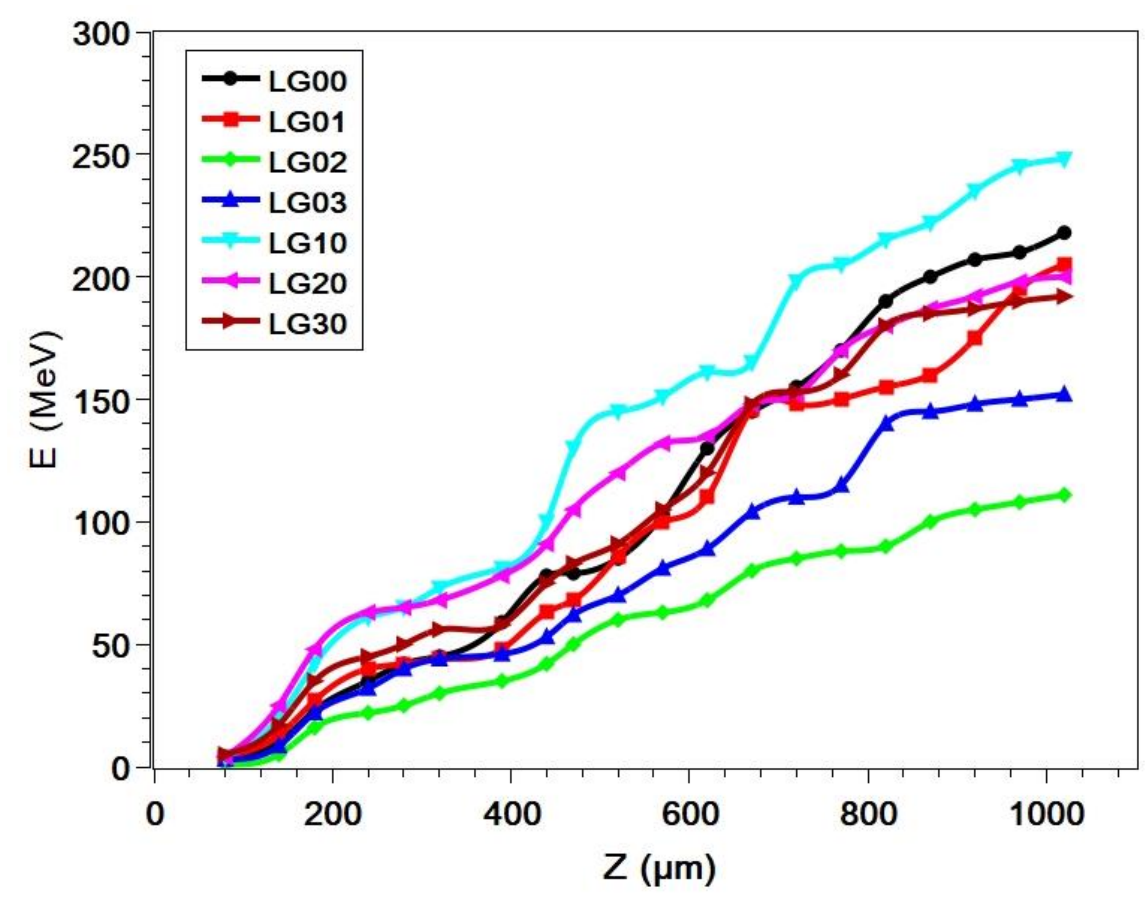

Figure 4. Simulation results for electron energy as a function of the laser propagation distance for different modes of LG laser beam from LWFA in plasmas of H_2-N_2 gas mixture in the first nozzle and pure H_2 in the second gas nozzle.

CONCLUSIONS

- The highest electron energy is obtained when we employed LG10 laser beam, in this case the electron energy reaches around 250 MeV.
- Compared to LG00, LG01 has a ring-shaped intensity profile with a dark core, allowing precise targeting and dose shaping in medical applications. This spatial structure allows better control over where energy is deposited in tissue.

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