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Development of laser wakefield electron acceleration driven by high-repetition rate ultrafast lasers

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Raising the repetition rate of driving laser pulses can straightforwardly increase the average current of accelerated electrons from laser wakefield acceleration (LWFA), such that a high radiation yield can be achieved for developing advanced X-ray radiography and radiation therapy. To date, 200-mJ, 1030-nm pulses with a duration of 1.1 ps can be produced from a thin-disc Yb:YAG system at a repetition rate of 5 kHz [1]. By introducing these 1030-nm, ps-level pulses with a technique of post spectral broadening and pulse compression, such as the gas-filled multipass cell [2] or the multiple-plates continuum [3], pulses with a peak power < 4 TW can be acquired to drive LWFA at kHz frequencies with the goal to increase the average electron current by 2-3 orders of magnitude higher than conventional LWFA ≤ 10 Hz.

In principle, a normalized vector potential $a_0 \simeq 2$ or a laser intensity $I_L \gg 10^{18}$ W/cm^2 is required to drive LWFA in the 3D nonlinear regime [4]. In order for the few-TW LWFA to be successful, a gas target capable of providing a plasma density $n_{ep} \gg 10^{19}$ cm^{-3} and inducing a strong self-focusing of the pump pulse has to be invented. This self-focusing effect is characterized by the critical power $P_{cr} \approx 17(n_{cr}/n_{ep})\, GW$, depending o the plasma critical density $n_{cr} = \epsilon_0 m_e \omega_L^2/q_e^2$ and the laser frequency ω_L. Our experiences indicate that $P_L \sim 3\, P_{cr}$ is favorable for conducting the few-TW LWAF. As the transverse radius w of the self-focused pump pulse gradually reduces to $2w \sim \lambda_p$ (typically 3 - 5 µm in operation), a greatly increased laser intensity is realized for driving plasma waves.

One of our approaches for realizing a stable source of tens-of-MeV electrons from LWFA is based on the recent experimental result achieved when ~ 3 TW laser pulses are focused onto a pulsed thin gas jet of dense nitrogen. As shown in Fig. 1(a), the thin, high-density nitrogen gas jet was produced from the gas flow out of a 152-µm diameter orifice under a high backing pressure. The nozzle consists of an orifice module mounted on a gas tube with the gas flow controlled by a pulsed valve underneath. Density of the gas atoms/plasma in the target region is varied by adjusting the backing pressure. The produced plasmas are measured by the probe of shadowgraphic images with a wavefront sensor, from which the plasma electron density distributions of the nitrogen target can be retrieved as shown in Fig. 1(b). When a 3.2-TW pulse is introduced with a backing pressure of 600 psi, the produced plasma density is fitted into a Gaussian profile with a width ~ 860 µm (in full width at half maximum, FWHM) and a peak density ~ 2.8×10^{19} cm^{-3}. The generated electron beam exhibited relatively small divergence properties for θx ~ 20 mrad and θy ~ 10 mrad in FWHM as shown in Fig. 1(c). Under this condition, electrons were obtained with quasi-monoenergetic spectrum peaked at ~ 11 MeV with an energy spread ~ 17 MeV in FWHM and a bunch charge ~ 22 pC (>5 MeV) as shown in Fig. 1(d); more importantly, they are produced with satisfactory reproducibility under ~17% energy and ~15% charge stability. The experiments verified that such a scheme is a viable choice for generating stable tens-of-MeV electrons with few-TW laser pulses at a high-repetition rate.

References

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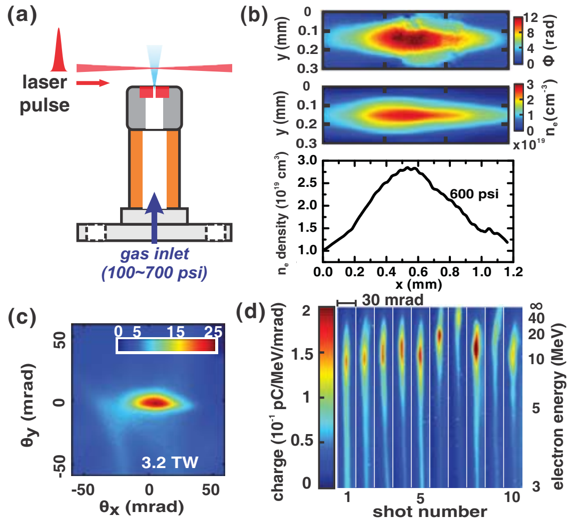

Figure 1 (a) Structure of the gas nozzle and the pump beam path. (b) The spatial phase shift of a shadowgraphic image, the retrieved plasma electron density distribution, and the density line profile of a nitrogen plasma produced by 3.2-TW laser power and 600-psi backing pressure. (c) Spatial profiles of accelerated electrons and (d) 10 consecutive images for the dispersed electrons generated with 3.2-TW pulses.