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Simulation of a Laser Wakefield Accelerator in Downramp Injection Regime Suitable for High Repetition Rates

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Abstract: We discuss the results of simulating a laser wakefield accelerator in the 50 MeV range suitable for repetition rates > 10 Hz using commercial lasers and compare with other approaches for this purpose. © 2022 The Author(s)

1. Introduction and methods

Bunched beams of accelerated electrons with sub-picosecond duration and peak energy in the multi-MeV range (up to a few GeV) can be generated by room-sized machines using the technique *laser wakefield acceleration* (LWFA) [1]. If the bunches are quasi-monoenergetic (QME), LWFA allows new tunable radiation sources and, if operating at repetition rates in the scale of kHz, applications that require scanning, matter probing or isotope production become possible, among others [2]. In this case, the generation of QME electrons by LWFA usually requires operation in one of the following techniques: 1) the so-called *blowout* regime applied to a high-density plasma wave [3], using laser pulses of a few cycles (~fs) and peak power around 1 TW obtained from complex laser systems [4, 5]; 2) the self-modulated LWFA (SM-LWFA) [6], using simpler tabletop laser amplifiers that provide pulses of around 100 fs and peak power of a few TW, in which the laser interacts with a high density plasma wave through the phenomenon of self-modulation, and QME electrons being obtainable as a smaller part (1%) of the accelerated beam in some configurations [7]. In both cases, thin targets (a few hundred μm thick) are typically used, due to the short dephasing length. SM-LWFA is being theoretically and experimentally revised [8], in search of QME with energies of several tens of MeV, which are needed, for example, to produce ^{99}Mo from ^{100}Mo by a gamma-induced nuclear photoreaction that may be a viable technique for modern nuclear medicine [9].

A third technique is the generation of QME electrons in a resonant (*non-blowout*) LWFA using lower gas densities, mm-thick target, and tabletop laser systems, a convenient approach given the current availability of commercial lasers with peak power of several TW and duration around 30 fs. Among the known ways to cause electron trapping in LWFA, ionization injection triggered by self-focusing can generate extra electrons early in the acceleration process, leading to higher final energies. A recent experimental and simulation study used a mixture of helium and nitrogen as target, with a repetition rate of 2.5 Hz, and QME electrons of (80±30) MeV were stably generated over eight hours, using laser parameters that could allow operation at many Hz [10].

In this work, we show simulation results for the resonant LWFA using a pure helium target, a simple setup in which no special gas mixture or mix regulator is required. In the processes studied, significant injections of electrons are observed in regions with changes in plasma wave velocity, mainly in the exit ramp of densities (downramp). The simulations followed the procedure described in [10], also using the algorithm FBPIC [11]. Three configurations were considered, the zero variation (v0) being composed of a He jet target with two 500 μm density ramps and a 500 μm density plateau. The incident laser pulse has a duration of 35 fs FWHM and a beamwaist $w_0 = 8$ μm in a focal position (with the jet off) coinciding with the top of the first ramp. There, the electric field amplitude is $a_0 = 1.4$, which, considering an encircled energy factor of 0.7 [10], corresponds in this case to an incident laser pulse of 5.7 TW. In variation #1 (v1), the target has two 400 μm ramps and a 400 μm plateau. In variation #2 (v2), the target has two 300 μm ramps and a 300 μm plateau. The density of helium on the plateau is 7.10^{18} atoms/cm^3.

2. Results

In all three simulations, the laser envelope indicates a strong self-focusing as the pulse reaches the end of the first ramp, with a slight shortening of the pulse duration, followed by self-collimation along the plateau. At the focus position, the new laser amplitude in all three cases is $a_0 \approx 3$, below the wave-breaking value calculated at that position, $a_{0,wb} \approx 11$, and no injection is observed there. The new beamwaist ($w_0 \approx 5$ μm) is suitable for the blowout operation but the new peak power, $P_0 \approx 8.7$ TW, is much lower than the required critical power $P_{c,bubble} \gtrsim 40$ TW [1]. In all cases, an intense wakefield is formed at the self-focusing position and lasts up to the end of the target (see Fig. 1-a). A significant injection is always observed in the last part of the plateau and at the beginning of the downramp. The extent to which these electrons are accelerated and the amount of dephasing they undergo at the end of the target produce the differences obtained between the simulation results shown below.

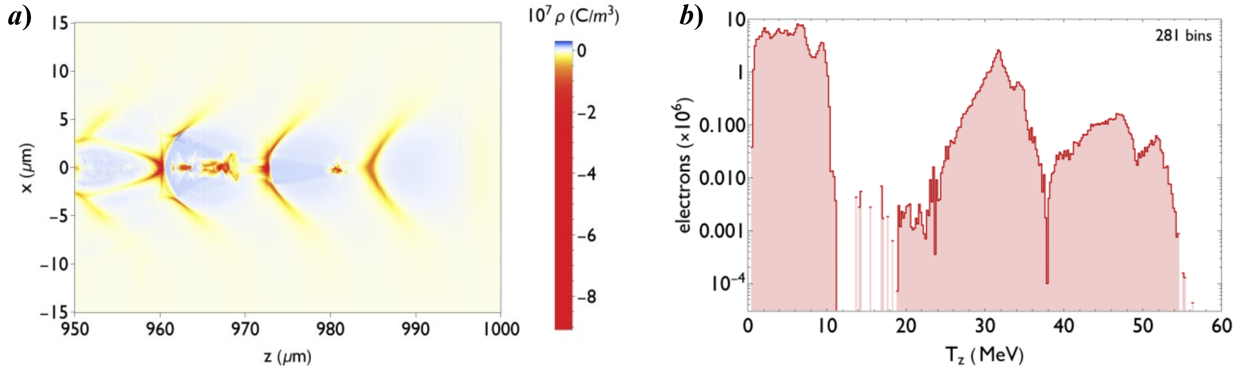

Fig. 1. Results from variation #1: (a) wakefield and entrapped electrons; (b) accelerated beam spectra.

The maximum recorded energy of the electrons is 60 MeV in v0, 56 MeV in v1 and 38 MeV in v2. The total accelerated charge of the electrons is around 40 pC in all cases, but the high energy QME part of those beams presented much less charge. Fig. 1-a shows the wakefield in variation #1 along the downramp. Fig. 1-b shows the spectra of the accelerated electrons (after leaving the plasma, propagating in the vacuum chamber), in variation #1. Three energy partitions can be clearly seen: one centered at 5 MeV, with a charge of 36 pC, another centered at 31 MeV, with a charge of 4.5 pC, and a third centered at 45 MeV, with a charge of 0.6 pC.

3. Discussion and conclusion

Blowout systems using few-cycle laser pulses usually generate QME bunches with energy centered around 5 MeV, 10%-50% spread, charge around 4 pC, and similar values can be obtained from QME bunches in the SM-LWFA regime [8]. The system simulated here shows QME bunches with a charge similar as mentioned above, but QME peak energy an order of magnitude higher. As it can be operated at repetition rates of 10 Hz or higher using commercial lasers, it is now an interesting alternative for applications such as the production of radioisotopes.

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