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SUB-MeV ION GENERATION BY STANDING WAVE EXCITATION OF IONIZED GASES

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Abstract

Ripping off electrons in gas plasma by standing waves of single- or few-cycle EM pulses is investigated by the EPOCH PIC code simulations. Since, contrary to the common laser-plasma acceleration by using single laser beam, the driving EM pulses have no resultant momentum, the total momentum of the electrons and ions is created entirely by the electric field of the EM pulses. Laser and terahertz (THz) pulses with experimentally available parameters are used as EM pulses. Calculations predict generation of relativistic electron bunches with few-hundred fs duration by using two THz pulses with 0.3 THz frequency and 20 MV/cm peak electric field, respectively. After ripping off the electrons, the Coulomb explosion of the remaining ions results in 0.1 MeV average ion energy with energy distribution suitable for very efficient use of accelerated ions in ultrashort-pulse neutron sources.

INTRODUCTION

In the last two decades several ion acceleration mechanisms have been suggested and extensively studied: the target normal sheath acceleration (TNSA), the radiation pressure acceleration (RPA), the collisionless electrostatic shock acceleration (CESA), and the Coulomb explosion acceleration (CEA) [1]. Despite the fact that in most laser-ion acceleration experiments thin metal or plastic foil targets are used, CESA acceleration of ions in gas plasma has also been demonstrated successfully [2]. In this respect, beside the CESA, the other exception is the CEA mechanism. This was most extensively investigated in cluster plasmas [3, 4].

In the last few decades, the energy of the THz pulses has increased by many (7) orders of magnitude [5, 6], now approaching 1 mJ, with up to 100 MV/cm peak electric field which is more than enough to accelerate particles efficiently. The THz generation techniques have been developing continuously and recently 11 mJ THz pulse energy with up to 40 MV/cm peak electric field has been predicted [7]. Our calculations are based on these high intensity THz pulses.

We have been working on a new scalable and controllable particle accelerator setup by CEA in gas plasma instead of cluster one [8]. Here we propose and numerically investigate a not yet explored laser driven particle acceleration scheme: using counter-propagating driving pulse pairs in order to accelerate electrons and ions in low density gas plasma.

ACCELERATION SCHEME POWERED BY INTENSE THZ PULSES

We have investigated the particle acceleration using single- and few cycle THz pulses. The schematic view of our proposed setup, which can work as an electron gun and as a positive ion accelerator, is shown in Fig. 1. In our proposed setup two counter-propagating THz pulses propagate perpendicular to the z direction with electric field vectors along the z-axis. The magnetic fields of the counter-propagating THz pulses have opposite signs, which minimize the deflection effects of the bunches. The laser parameters are shown in Table 1. We numerically investigated the ion acceleration by Coulomb explosion following the ripping of the electrons from gas plasmas by high energy ultrafast standing waves. For the numerical simulation of the particle acceleration, EPOCH and GPT [9] softwares were used. Because of the three orders of magnitude ratio of the masses of the ions and electrons, in the proposed scheme the acceleration process is well separated into two stages. After the charge separation (which is investigated by EPOCH), the electron and ion dynamics are followed by the GPT software up to 1000 ps.

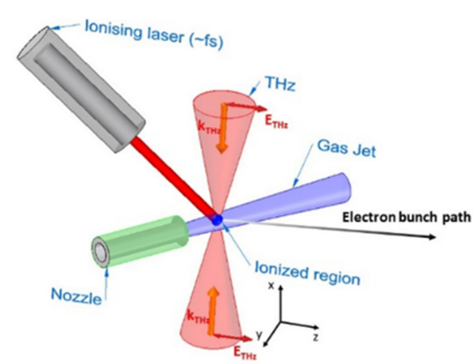

Figure 1: The schematic view of the proposed accelerator setup.

Table 1: Accelerator THz Pulse Parameters

Parameter	Value
Frequency	0.3 THz
Beam waist	1000 µm
Energy	33.55 mJ
Peak electric field	20 MV/cm
FWHM	2.025 ps

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In the simulations we examined the effects of both the initial bunch charge and the spatial distribution of the plasma to the final energy spectra and the final spatial distributions. The parameters of the different initial bunch shapes are shown in Table 2.

Table 2: Initial Bunch Parameters

Parameter	"Disk"	Long cylinder	Short cylinder
Beam mean energy	0-4 eV	0-4 eV	0-4 eV
Length	12.5 µm	250 µm	75 µm
Diameter	250 µm	25 µm	46 µm
Charge (total pulse)	1.1 nC	0.7 nC	10-300 pC

Dependence of the Acceleration Efficiency on the Number of Cycles

Using long wavelength (>100 µm) and oscillation period make possible acceleration of electron bunches with larger size and charge and relax the needed timing accuracy between the ionizing laser and accelerator driving field [10]. Using single cycle THz pulses and the proper synchronization (the ion bunch is generated at the same time with the arriving time of the zero-crossing point of the electric field to the interaction point), we can achieve that the particles perceive only the accelerating, but not the decelerating temporal part of the THz pulses. In this case the electrons can be ripped off from the ionized region and accelerate along the -z direction. For protons that are 1836 times heavier than electrons, the accelerating effect of the electric field strength components pointing in the z-direction is much smaller. However, because of the space charge effect the positive ion bunch, while it accelerates in the opposed direction, is going to explode. Simulated one, two, and three cycle THz pulses the huge percent of the electrons cannot accelerate efficiently and remain close to the positive ions. The energy spectra of the electrons which were remained in the investigated volume are shown in Fig. 2.

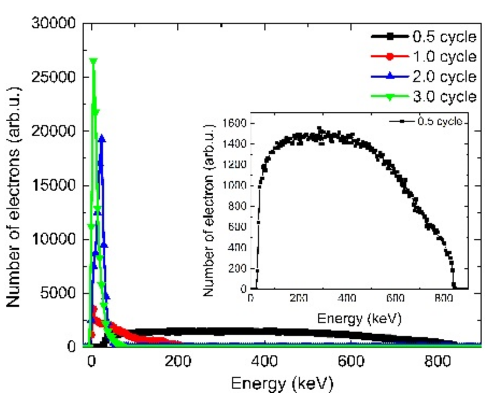

Figure 2: Energy spectra of the electrons (inset: Energy spectra of the electrons using "half" cycle THz pulses).

ION ACCELERATION

Half-cycle Simulations

We have optimized the initial bunch shapes and initial bunch charges based on the efficient charge separation. Considering the charge threshold, the bunch parameters are shown in the Table 2. In case of the positive ion acceleration, we examined two types of the initial bunch shape: the "disk" and the long cylinder. We performed simulations for three different cases: i) hydrogen gas is ionized (the plasma consists of only electrons and protons), ii) water vapour is, iii) heavy water is ionized.

We compared the energy spectra of protons in the i) and ii) cases based on the optimized bunch shapes as shown in Fig. 3. The bunch with the long cylinder initial bunch shape has higher charge density than the initial bunch with the disk shape, thereby both the maximum and mean kinetic energy of the positive ions is higher in that case. On the other hand, in case of the long cylinder as initial bunch shape, although the polarization direction of the THz pulses is in the z direction, most of the positive ions explode in the x-y plane due to the Coulomb effect (as it has 10 times shorter length in these directions than in the z direction). The disadvantage of this effect is that we cannot control the directions of the effectively accelerated ions and they collide with the THz sources. Using tilted THz pulses, we can eliminate this problem to apply the accelerated positive ions in many experimental applications. Using our proposed setup, generating with 0.7% efficiency of sub-MeV energy protons and ~ 0.4 MeV electrons, both with 1.1 nC bunch charge is predicted.

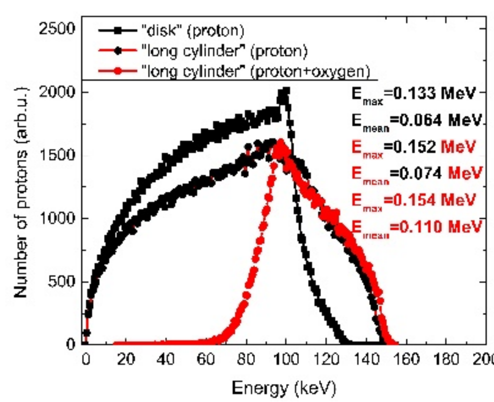

Figure 3: Comparison of the energy spectra of protons based on the two optimized setups.

ELECTRON ACCELERATION

Half-cycle Simulations

After the optimization of the ion acceleration by CEA, we have analysed the setup as an electron gun. In these cases, we simulated two counter-propagating single-cycle THz pulses as well, which create a transient standing wave and accelerate the electrons. The birth time of the ion bunch is also synchronized to the zero-crossing of the THz field. The parameters of the short cylinder as an initial bunch shape are shown in Table 2. Since we do not want to

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exploit the Coulomb effect to achieve effective acceleration of positive ions, we supposed much less initial bunch charges and different bunch shape in comparison to the ones supposed for ion acceleration. Due to the 2-3 orders of magnitude smaller bunch charges, we can achieve the charge separation easily and using the initial parameters mentioned above the simulations predict about 600 keV electron energy from the gun. Without any longitudinal bunch compression method such as velocity bunching for 10 pC initial bunch charge the energy spread of the electron bunch is 12.0% and the bunch duration is 3.1 ps, detected both after 200 ps from the interaction (at a position of ~ -51 mm from the gun). If we use smaller bunch charges such as a few fC, these values can be even more promising.

Motivated by these promising results, we will investigate the possibility of developing a THz pulse driven semi-relativistic electron gun emitting bunches with 10 pC and around 100 fs duration.

We also examined the energy spectra of the accelerated bunch for larger initial bunch charges with the same initial bunch dimensions. The corresponding energy spectra are shown in Fig. 4. Because of the coulomb effect the higher initial charge of the ion bunch is, the more significant the space charge effect is and its causes broader energy spreads.

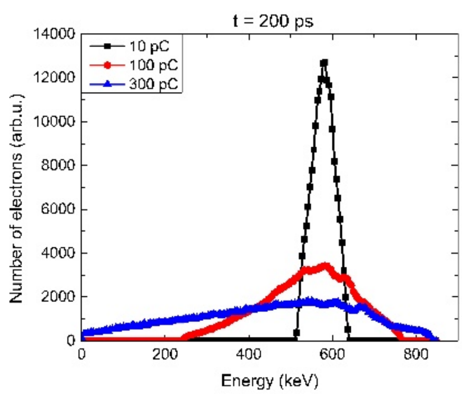

Figure 4: The energy spectra of the electron bunches after they ripped off from the ionized region (short cylinder).

CONCLUSION

We present a scalable technique from few μm to few thousands of μm driving wavelengths, thereby also could be possible to generate ultrashort (few ps) neutron bunches as far as relativistic electron bunches. The required THz pulse parameters can be provided by presently suggested THz technology. The here suggested setup is a new controllable ion source which enables to use gas plasmas instead of the nanoscaled solid-state as an initial particle source. We examined the effects of standing waves concerning the efficiency of the particle acceleration. On the other hand, we investigated the effects of the different initial bunch charges, initial bunch shapes (different dimensions), and the number of THz beams with respect to the final kinetic energies and final dimensions of the separated ion bunches. After the acceleration stage around 0.1 MeV peak ion - and higher than 0.6 MeV electron energy can be achieved using the optimized setups.

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