TJ cm$^{-3}$ high energy density plasma formation from intense laser-irradiated foam targets composed of disordered carbon nanowires

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Abstract

High energy density plasma formation from intense laser-irradiated foam targets composed of disordered carbon nanowires is investigated using three-dimensional particle-in-cell simulations. It is shown that due to the unprecedentedly high laser energy absorption rate of the foam target, approximately three times larger as compared with simple solid targets, the plasma energy density reaches an unexplored TJ cm$^{-3}$ regime at 10$^{23}$ W cm$^{-2}$ laser irradiation. In addition, nanowire thermal expansion caused by prepulse heating is considered. We find that after expansion, the target becomes relativistically transparent to the main pulse. The average value of particle energy density decreases slightly and its distribution tends to resemble that of solid targets. Furthermore, energy density scaling with laser intensities is given. It suggests that an even more extreme plasma state is reachable using ultraintense lasers, as the energy loss to photons caused by quantum electrodynamics effects is rather negligible.

Keywords: high energy physics, particle-in-cell simulations, laser plasma

(Some figures may appear in colour only in the online journal)

1. Introduction

High energy density (HED) physics studies matter and radiation at energy density exceeding 10$^5$ J cm$^{-3}$ [1]. This extreme state of matter exists in the deep interior of giant planets and stars in the Universe [2] as well as in the center spot in inertial confinement fusion in terrestrial laboratories [3, 4]. The investigation of the collective properties of matter in exotic states as well as its interaction with radiation and particle beams paves the way for elucidating a number of astrophysical observations as well as understanding and ultimately controlling the thermonuclear fusion.

Due to the complexity and non-linearity of the collective interaction, a full understanding of HED physics requires vast repeatable experiments, sophisticated diagnostic instruments, together with massively parallel computing. New facilities, such as high power lasers [5], linear accelerators [6], and Z-machines [7], are capable to deliver the energy required in HED laboratory experiments. Other complementary methods, such as gas guns, explosively driven experiments, and diamond anvils, can also produce HED conditions [2]. Here, we
focus on the scheme of laser-driven HED conditions due to its close relation to astrophysics [8–10], nuclear fusion [11, 12], x-ray generation [13], etc.

The inertial confinement fusion experiments on the National Ignition Facility (NIF) are excellent examples of how HED conditions can be produced using MJ-scale high-terawatt (100 s TW) lasers. The energy density achieved at the center of highly compressed capsule is predicted as high as 10 GJ cm

−3 [14]. With the development of chirped pulse amplification technology [15], compressing hundreds of Joule energy into tens of femtosecond (fs) becomes possible, leading to the era of petawatt (PW) lasers. For instance, Extreme Light Infrastructure (ELI) can readily operate at 10 PW [16], and the 100 PW Station of Extreme Light at Shanghai Institute of Optics and Fine Mechanics (SIOM) is currently under construction [17]. The parameter range of HED conditions to be produced will expand significantly.

So far, some short-pulse intense laser-solid experiments have been conducted with promising results on the production of HED conditions [18–23]. However, one crucial issue for laser interaction with solids is that the latter is highly opaque, the interaction region is thus limited within skin layers of the target surface. A significant part of the laser energy is reflected, resulting in a rather low energy absorption rate. Alternatively, foam targets [24], with large specific surface area, show capabilities of unprecedentedly high laser energy absorption rate. It is evidenced by the enhancements of x-ray emission [25–30], THz pulse energy [31], particle temperature [32, 33], and laser-accelerated proton energy [34]. HED plasma production from vertically aligned nanowires was first demonstrated by Purvis et al [35]. Plasmas with energy density about 2 GJ cm

−3 were produced at only 0.5 J laser irradiation. More recent studies have shown that vertically aligned nanowires are advantageous over solid targets in terms of deep laser energy penetration [36], high ionization state generation [37], peak local energy density [38, 39], low required laser energy [40], etc. Moreover, by carefully controlling growth conditions, one can also obtain disordered nanowires. It is shown that foams composed of disordered nanowires are more robust to laser field polarization as compared with aligned ones in the case of nonrelativistic interactions [41]. It also relaxes requirements on the calibration of laser systems. For relativistic lasers at 100 s TW to PW scale, the previous works by Fedeli et al [42, 43] and Passoni et al [44] focus on the impact of target morphology on the laser absorption rate as well as associated electron acceleration, and demonstrate the enhancement of the quality of secondary particle and radiation sources using solid targets coated with disordered nanowires. However, in the scope of HED plasma production, the influence of using foam targets composed of disordered nanowires needs further investigation. In particular, to which parameter regime can be achieved from multi-PW laser interaction with such targets and how it scales with laser parameters remain a question. In addition, quantum electrodynamics (QED) effects become important at ultrahigh laser intensities, how QED effects alter the result is still unclear.

In this Article, we investigate HED plasma formation from intense laser-irradiated foam targets composed of disordered carbon nanowires. Three-dimensional (3D) particle-in-cell (PIC) simulations show that plasma with an average energy density approaching TJ cm

−3 is produced at 1023 W cm

−2 laser irradiation, resulting from the energy absorption rate being enhanced by approximately three times as compared with simple solid targets. The thermal expansion of nanowires caused by prepulse heating is also considered, and it has slight detriment on the quantity of obtained energy density. In addition, the energy conversion efficiencies as well as plasma energy density scaling with laser intensities are given, where QED effects are self-consistently calculated, suggesting an even more extreme state is potentially reachable at ultraintense laser irradiation.

2. Proposed scheme and simulation setups

As illustrated in figure 1, we focus on a scenario where a 85 J energy, 18 fs-FWHM duration (Gaussian temporal profile in fields), 1 × 1023 W cm

−2 peak intensity, 1.7 µm 1/e spotsize (Gaussian spatial profile in fields), y-polarized laser pulse at λ = 0.8 µm wavelength impinges on a foam target, placed at x > 0, composed of nanowires with random orientations and locations. The nanowires are fully ionized carbon cuboids with an ion density of 80n_c. Here n_c = m_eω_e^2ε_0/e^2 is the critical plasma density, where m_e is the electron rest mass, ω_e is the laser frequency, e is the elementary charge and ε_0 is the vacuum permittivity. The nanowires are allowed to overlap. The ion density at the overlapped region is kept as 80n_c. The same initial nanowire distribution is used in all our simulations. The carbon density here represents graphite at room conditions, and the laser parameters resemble that of the 10 PW beamline at ELI-NP [16]. The edge lengths of nanowires are 0.2 µm, 0.2 µm and 1 µm. The filling factor is 18%. That is, the average electron and ion densities of the foam are roughly 85n_c and 14n_c, respectively. Such a target
possesses high local density, but the average density lies in the relativistic transparency regime \([45]\). The initial electron and ion macroparticle temperatures are 100 eV and 10 eV, respectively. Simulations are carried out using 3D PIC code EPOCH \([46]\), which incorporates quantum photon emission process via a Monte Carlo method. Radiation reaction on the electron dynamics is self-consistently calculated. The simulation box is of size \(7 \times 7 \times 7 \, \mu m^3\), with \(1200 \times 600 \times 600\) grid cells and 4 macroparticles per cell for both electrons and ions. Simulations with 8 macroparticles per cell have been conducted, which present almost identical results. The total simulation time is \(70T_0\). Here \(T_0 = \lambda / c\) is the laser cycle, where \(c\) is the speed of light in vacuum. Periodic lateral boundaries are used, representing similar behavior of adjacent nanowires located outside the simulation box. simple_laser and simple_outflow are used for the left and right boundaries, respectively.

### 3. Physical process

As shown in figures 2(a) and (b), as the laser impinges on the foam target, electrons on the nanowire surfaces are immediately heated. The heating mechanisms, invoking Brunel-type absorption \([47]\) and \(j \times B\) acceleration \([48]\), depend on the nanowire orientations with respect to the laser pulse. When the laser electric field perpendicular to the interaction surface is larger than the \(j \times B\) term, that is when \(\sin \theta > v_{osc} B_l / 2E_l\), the Brunel-type absorption becomes more significant than the \(j \times B\) heating. Here \(\theta\) is the angle between laser propagation direction and the interaction surface, \(v_{osc}\) is the electron oscillating velocity under the laser electric field \(E_l\), and \(B_l\) is the laser magnetic field. Since the laser amplitude here \(a_0 = 216\) is large and the spatial scale of the nanowires is comparable with the laser wavelength, a large part of electrons is ripped off the nanowires. The remaining positive charge causes the coulomb explosion \([49]\) of the nanowires. We see in figure 2(b), the nanowires start to expand and fill up the vacuum gaps between \(0 \, \mu m < x < 3 \, \mu m\) inside the foam. One special case here is that the nanowires are orientated quasi-parallel to the laser propagation direction. As shown in figures 2(b1) and (b2), the strong return current inside the nanowire induces gigagauss-scale azimuthal magnetic field, which in turn compresses the former. Such a micro Z-pinch \([38]\) leads to the formation of extremely dense plasma with densities up to \(3000n_c\) before the coulomb explosion occurs. Due to the porous structure and high local density of the target, the laser pulse can penetrate deeply reaching \(x = 3 \, \mu m\) before the vacuum gaps are filled up by the expanding nanowires. Moreover, the light scattered by the surfaces of nanowires can go even further up to \(x = 4 \, \mu m\). The laser reflection rate is only about 14% at this moment, whereas in the solid target case (to be discussed later) it is up to 47%.

Figure 3(a) for the diagram of electron phase space shows that high energy electrons moving in the positive \(x\) direction are separated by half the laser wavelength, which is indicative of \(j \times B\) acceleration. On the other hand, it is shown in figure 3(b) that electrons are oscillating with the laser electric field with a \(\pi/2\) phase difference, which is essential for Brunel-type absorption. Figures 3(c) and (d) for ion phase space show coulomb explosion. The transverse momentum phase space, figure 3(d), is symmetric. The longitudinal one, figure 3(c), shows preferential ion acceleration into positive direction. It
can be interpreted in terms of electron $j \times B$ heating mentioned above, which leads to larger electrostatic field for ion acceleration at the nanowire back surface as compared with the one at the front.

The expanding electrons and ions later fill the vacuum. As indicated by figures 3(a) and (b), the maximum $\gamma$-factor of accelerated electrons exceeds 750. Therefore, the plasma undergoes relativistic transparency [45], and the peak of the laser can further penetrate into the target, until it is completely dissipated. As a result, the nanowires located deep inside the target are also effectively heated, and they expand into rather homogeneous plasma with an electron density of roughly $85n_e$, as shown in figure 2(c), despite that the electron density at the laser axis is slightly lower than that at the periphery due to the ponderomotive force from the finite laser spot size.

4. High energy density plasma formation

In addition to the foam target, we carried out two new simulations as reference cases, i.e. homogeneous target case and solid target case, to illustrate the characteristics of HED plasma generated from different target structures. In the former case, homogeneous plasma with an electron density $85n_e$ and ion density $14n_e$ is placed at $x > 0$. The particle density here is identical to the average particle density of the foam. It can be considered as a result of laser prepulse heating or produced by another laser with moderate intensity beforehand. In the solid target case, uniform plasma with an electron density $480n_e$ and ion density $80n_e$ is used, which are identical to that of nanowires, representing solid carbon targets.

Distinct energy density distributions are observed in the three cases, as shown in figure 4. In the foam case, as shown in figure 4(a), because of large specific surface area of the foam and deep laser penetration, the target is heated holistically. Therefore, the electron energy density is quite uniform, regardless of the initial random distribution of the nanowires. The highest local electron energy density of $3.9 \text{ TJ cm}^{-3}$ is found at around $x = 4 \mu m$, where the laser pulse front reaches. In the homogeneous case as shown in figure 4(b), the plasma is opaque for the rising edge of the laser, the interaction region is limited at the front surface of the target. The $j \times B$ force from laser linear polarization accelerates electrons into the target. Those high energy electron bunches are separated by half the laser wavelength, and adjacent bunches possess opposite divergence in the $y$ direction due to the fast oscillating laser field. As they propagate into the target, these bunches split into two groups, and bunches in each group are separated by one laser wavelength. As the peak of the pulse arrives, the
plasma becomes relativistically transparent. We observe self-channeling and associated laser self-focusing [50]. The highest local energy density is found at the channel wall, accompanied by dephased direct-laser-accelerated electrons [51–53] separated by half the laser wavelength at the channel front. For the solid target, electron dynamics is less complicated, as shown in figure 4(c). The interaction region is limited within skin layers of the front surface, electron bunches separated by half the laser wavelength are accelerated by the \( j \times B \) force into the target, heating the target bulk.

The ion density distributions are presented in figures 4(d)–(f). In the foam target case, as the dominate heating mechanism of ions is coulomb explosion, the whole target turns into hot dense plasma with quite uniformly distributed ion energy density, whereas in the latter two cases, the ion energy densities are rather localized due to the different ion heating mechanisms from the former. We see in the homogeneous case, figure 4(e), ions are heated mainly at the channel wall. The channel wall forms a collisionless shock and accelerates the background ions by reflecting them at the shock front, forming spike structures while the rest ions remain cold. The ion front reaches \( x = 4 \mu m \) as shown in figure 4(e). In the solid target case, the high energy ions are simply accelerated by the laser light pressure and propagate into the target. Only ions located at \( x < 2 \mu m \) are effectively heated according to figure 4(f). The ion energy density located narrowly around \( x = 6 \mu m \) in figure 4(e) is caused by the boundary effect, which does not affect the main physics and results.

The particle energy densities (the sum of electron and ion energy densities) averaged over \( x > 0 \) correspond to 0.16, 0.11, and 0.08 TJ cm\(^{-3}\) for the foam, homogeneous and solid target cases, respectively. It is worth mentioning that there is also certain amount of energy stored in the self-generated fields (see figure 6(d)), which may eventually convert to thermal energy and irradiation. We see that by utilizing the foam target, the average plasma energy density doubles as compared with the simple solid target, and the maximum value reaches the unexplored TJ cm\(^{-3}\) regime. However, nanowire thermal expansion caused by the laser prepulse can be somewhat detrimental for HED plasma formation at this intensity regime. We see the average value of particle energy density decreases slightly and its distribution tends to resemble that of solid targets.

The energy spectra of electrons and ions (including those that have left the simulation box) for the three cases are illustrated in figure 5. The electron energy spectra for the foam and homogeneous target cases are quite similar. As compared with the solid target case, the numbers of hot electrons in the foam and homogeneous target cases increase by one order of magnitude while the temperatures remain as low as 22 MeV. A large amount of hot electrons is important for the generation of x- and \( \gamma \)-rays. Ion spectra are found to be dramatically enhanced in the foam and homogeneous target cases, due to coulomb explosion and shock acceleration, respectively.
Figure 5. (a) Electron energy spectra for different cases at $t = 35T_L$, when the laser pulse has been fully dissipated in all the three cases. (b) Same as (a) but for ion energy spectra. Particles that have left the simulation box are included in the spectra.

Figure 6. Energy conversion efficiencies from laser to (a) particles (electrons and ions) and self-generated fields, (b) electrons, (c) ions, and (d) self-generated fields as a function of laser intensity. The conversion efficiencies are calculated at $t = 35T_L$ at $10^{23}$ W cm$^{-2}$ irradiation and $t = 30T_L$ at $10^{21}$ and $10^{22}$ W cm$^{-2}$ irradiation, when the laser pulse has been fully dissipated.
We note the launch of shock waves in the homogeneous target is critical for the enhancement of ion spectrum, which depends closely on the matching condition of plasma density (i.e. the filling factor) with laser intensities. For the solid target case, the spectrum simply shows hole boring features \[^{55}\] with much lower temperature and cutoff energy. Our scheme also provides a possible routine for laser-driven heavy-ion acceleration.

5. Scaling with laser intensity

A parameter scan is conducted to obtain the dependence of energy conversion efficiencies on laser intensities, as shown in figure 6. Here only electrons with energy above \(5 \times \sqrt{I/I_{53}}\) MeV and ions with energy above \(15 \times \sqrt{I/I_{53}}\) MeV are taken into account, since those energetic particles are of interest to us. Here \(I\) is the laser peak intensity and \(I_{53} = 10^{23} \text{ W cm}^{-2}\). We see in figure 6(a) that the energy absorption rate of the foam target case almost triples as compared with the simple solid one. In addition, the absorption rate keeps around 50% for a wide range of laser intensities from \(10^{21}\) to \(10^{23} \text{ W cm}^{-2}\). For both the homogeneous and solid target cases, the absorption rates increase with laser intensity, agreeing with previous results \[^{55}\]. In particular, when the laser intensity reaches \(10^{23} \text{ W cm}^{-2}\), the homogeneous target becomes relativistically transparent, thus the absorption rate increases dramatically from 14% to 42%. We find that the QED effects are not too important here, since the high energy electrons copropagate with the laser pulse. Only 7% of the laser energy is transferred to photons for both the foam and homogeneous cases. These rather negligible energy losses to photons barely affect the obtained particle energy density (to be discussed later in figure 7). Energy conversion efficiencies from laser to particles also increase with laser intensity, as shown in figures 6(b) and (c). The average energy density over the target area can be estimated as \(\eta/WV\), where \(\eta\) is the energy conversion efficiencies from laser to particles, \(W\) is the laser energy, and \(V\) is the volume taken up by the target. It gives 0.13, 0.11, and 0.05 TJ cm\(^{-3}\) for the foam, homogeneous and solid target, respectively. The slight discrepancy with that obtained directly from the simulation results in section 4 can be due to our thresholds in calculating the conversion efficiencies, high energy particles leaving the simulation box, different timings at which the average energy densities are obtained in the two methods, general expansion of the targets to the \(x < 0\) area, etc. It is indicated from figure 6(d) that at a moderate laser intensity, there is a considerable amount of energy stored in the self-generated fields in the foam target case. The energy will eventually transfer to particles and irradiation. However, such a process might take up in nanosecond timescales, which is difficult for PIC simulations.

Figure 7 shows that for all the cases, the dependence of obtained particle energy density on laser intensity can be well described by the power law \(U \sim \alpha I^{18}\), where \(I_{18} = 10^{18} \text{ W cm}^{-2}\) and \(\alpha = 7.9 \times 10^{5}, 4.2 \times 10^{5}, 5.9 \times 10^{4}\), \(\beta = 1.06, 1.48, 1.22\) for the foam, homogeneous, and solid target cases, respectively. It is worth mentioning that due to a considerable energy stored in self-generated fields, the presented energy density in foam targets at a moderate laser intensities may be underestimated. The obtained scaling law indicates that at moderate laser intensities, foam targets are advantageous for HED plasma formation. With the increase of laser intensity, preheating foam targets by laser prepulses or additional lasers with moderated intensities can potentially lead to a more extreme HED state.

6. Discussion

The impact of laser prepulses on the foam structure can be very complicated. In this paper, only the simplest condition, i.e nanowires expanding into homogeneous plasma, is considered. The actual plasma profile can vary with different pre-pulse energies. Generally speaking, prepulses can lead to the thermal expansion of the nanowires, and the plasma profile may be in between the foam and homogeneous ones for low-level prepulses. One may thus arbitrarily speculate that low-level prepulses only marginally change the results. However, the detailed study requires elaboration with hydrodynamic simulations, and will be considered in a further work.

In conclusion, we demonstrate by 3D PIC simulations that TJ cm\(^{-3}\) high energy density plasma can be produced from intense laser-irradiated foam targets composed of disordered carbon nanowires. The energy absorption rate is found to be approximately three times larger as compared with simple solid targets. However, nanowire thermal expansion caused by the laser prepulse can be somewhat detrimental for HED plasma formation at this intensity regime. The average value of particle energy density decreases slightly and its distribution tends to resemble that of solid targets. In addition, energy conversion efficiencies as well as energy density scaling with laser intensities are given. For foam targets, the absorption rate keeps at around 50% for laser intensities ranging from \(10^{21}\) to
10^{23} \text{ W cm}^{-2}$, and the QED effects, where the energy is transferred to photons, are negligible.

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