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ABSTRACT

We are proposing hot electrons source, which are suitable for external injection into a wakefield accelerator. Hot electrons with energies up to 3 MeV were generated by the interaction of femtosecond laser at an intensity of $I = 3.5 \times 10^{18}$ W/cm$^2$ with the preplasma produced in 25 μm holes, drilled in 1 μm Au foils targets. The preplasma created by the 1 ns prepulse preceding the intense main laser pulse generates an elongated plasma under the critical density and scale length of tens of microns. This plasma channel enables generation of high energy and collimated electron beam. The proposed approach can allow minimizing current, laser based electron accelerators, to produce a new X-ray source, to generate relatively long, high density plasma source, which important for study of nonlinear effects related to Laser Fusion and other applications.

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Laser wakefield acceleration (LWFA) has been studied since it was proposed at 1979 by Tajima and Dawson.1 In this scheme, an electron beam injected into a plasma medium can be accelerated by the electric field created during the interaction of high intensity laser pulse with the plasma medium. Several techniques for electron injection were demonstrated since then, like self-injection in the so-called bubble regime,2,3 colliding laser pulses,4,5 ionization triggered injection,6,7 and injection in downward density ramp.8,9

The use of external electron injection is challenging, since femto-second and micrometer levels of synchronization are required. The use of same laser pulse for both external electron production and LWFA at low plasma density was first suggested by Palchan et al. in 2006.10 In that scheme the injection electrons were produced by the interaction of the laser pulse with a thin wire target mounted in front of capillary discharge device. The undisturbed part of the laser pulse would be used to produce the wakefield in the underdensed plasma in the capillary and accelerate the electron beam created by the wire target. Nanometer scale thick solid foil targets were also suggested recently as hot electron source targets.11

Trapping electrons in the plasma wave requires minimum initial electron energy.12 For moderate laser intensity of about $10^{17}$ W/cm$^2$ the minimum electron energy required for trapping in plasma wave is about 1 MeV.

In this work we propose a simple target as a potential source for external electron injection for LWFA. The proposed target is a 1 μm width gold (Au) foil, with a drilled hole in it. Relatively high Amplified Spontaneous Emission (ASE) of the laser pulse creates an elongated, underdense plasma channel, 1 ns before arrival of the main pulse. We are reporting on generation of a few MeV electron bunch accelerated in the laser forward propagation direction.

Measurements of the electrons energy spectrum, and their spatial distribution as well as spectral measurements of backscattered light from the plasma channel are presented. Generation of elongated plasma created by the ASE in the hole was analyzed using 2D radiation hydrodynamic code.

The experiments were performed using the 120 mJ 70 fs Ti:sapphire laser system at Soreq NRC, Plasma lab. The laser beam was focused using off-axis parabolic mirror to a 8 μm diameter spot,
FIG. 1. Experimental set up. The laser is focused by f/6 off-axis parabolic mirror on the target. The electrons emitted from the back of the target pass through the collimator and are detected by the electron spectrometer.

resulting in intensity of about $3.5 \times 10^{18}$ W/cm$^2$ at the focal spot. The main pulse arrives about 0.6-1 ns after the ASE rise time. The contrast ration of the ASE is about $10^{-5}$, resulting ASE pulse with intensity of about $1 \times 10^{13}$ W/cm$^2$. The experimental set up is shown in Fig. 1. Initially, a low energy laser pulse was focused onto a 1 μm thick Au foil to create a 25 μm hole in the foil. Then a full power laser pulse was delivered. The focus spot diameter of the ASE pulse was 120 μm, larger than the hole size and the main pulse laser spot diameter.

The generated electrons energy distribution was measured using electron spectrometer composed of 1.5 mm diameter cylindrical collimator, 120 mT permanent magnets, and a Ce:YAG scintillator coupled to CCD camera as detector. The collimator was made from a 50 mm long graphite bulk and 1 mm width lead. The scintillator was covered with 40 μm Al foil, to block the laser. The set up was adjusted to measure electron energies within the range of 800 keV – 3 MeV. Experiments were conducted also with 1 μm width Au foil with no hole for comparison. The hot electrons spatial distribution was measured with the same scintillator, positioned 4 cm after the target, and coupled to the CCD camera. In addition to the electron measurements, backscattered light was collected by an optical spectrometer with 200-1000 nm bandwidth.

Figure 2 shows the electron spectra imaged by the CCD from a foil target [Fig. 2(a)] and a hole target [Fig. 2(b)], in experiments with the magnet mounted. Figure 2(c) shows the electrons image from an experiment with a hole target without the use of a magnet.

The hot electron energy distribution was estimated by fitting the measured spectra to a Boltzmann distribution

$$f(E) \sim E^{1/2}/T_h^{3/2}\exp(-E/kT_h)$$

The fitted temperatures were ~ 300 keV and 630 keV for a 1 μm Au foil, and a hole target, respectively, as shown in Fig. 3. The electron temperature for the foil target derived from the Boltzmann fit is in good agreement with the ponderomotive scaling law

$$kT_h = m_0c^2 \left( \sqrt{1 + 0.73I_0/\lambda^2} \left[ W/cm^2 \mu m^2 \right] \right) - 1$$

This scaling results in electron temperature of ~ 350 keV for laser intensity $3.5 \times 10^{18}$ W/cm$^2$. The measured amount of hot electrons above 1.5 MeV is more than one order higher in the hole target compared to foil target as shown in Fig. 3.

Figure 4 shows electron angular distributions for a 1 μm thick Au foil target [Fig. 4(a)], and a 25 μm hole target [Fig. 4(b)]. The color bar is different for each figure due to display limitation. The intensity represents the camera digital level. The intensity at the center is 10 times higher for the hole target compared to the plain foil target [Fig. 4(c)], which can be attributed to a collimated large amount of higher electron energy on same spot on the scintillator.

The backscattered light from the laser plasma interaction in the wavelength range 200-1000 nm is shown in Fig. 5. The 800 nm backscattered light was reduced by two orders of magnitude, after...
the 800 nm narrowband mirror mounted before the optical spectrometer (T.M. mirror in Fig. 1). Figure 5 shows differences in the laser plasma interaction for foil and hole targets, and possible laser plasma instabilities (LPI). The high signal above 900 nm might be associated with Stimulated Raman Scattering instability (SRS), and the strong signal between 480-740 nm (3\(\omega_0/2\)) may be the result of the laser interaction with the plasmons created by the LPI in the hole target. The 2\(\omega_0\) radiation at 400 nm is lower in the hole target experiment, indicating that the laser interacts mostly with underdense plasma.

2-D radiation hydrodynamics simulations were done to describe the plasma conditions created by the ASE preceding the main pulse. The simulations were done with an ALE code, on a fixed Eulerian grid, with cylindrical symmetry. In the simulation the target is illuminated by the laser ASE part with 1 ns pulse duration, 120 \(\mu m\) focal spot diameter, and 50 mJ energy. The assumed laser spatial profile is super-Gaussian. The laser energy absorption is modeled by ray-tracing and the radiation transport is solved by a Monte Carlo algorithm using non-local thermodynamic equilibrium (NLTE) multi group opacities and emissivities tables calculated using the SEMILLAC atomic code (Frank, 2014). Tabulated SESAME equations of state were used. The electron heat conduction is modeled as flux-limited diffusion with flux limiter 0.05. 1 \(\mu m\) width disk, and disk with 25 \(\mu m\) diameter hole were used in the simulation. The center of the hole is at \(y(0)\) at the \(y\) axis. The \(x\) axis is the laser direction, and \(x(0)\) is the initial location of the target. Figure 6 shows the simulated plasma density profile for a foil and a hole target 0.8 ns after the arrival of the ASE to the target. The plasma density profile has an approximated exponential profile for the foil target case, with plasma scale length \(L \approx 5 \mu m\) at the critical density, and \(L \approx 13.5 \mu m\) at \(n_e = n_c/4\). The plasma density in the hole target is complex. After 0.5 ns, stagnation at the
center of the hole begins to evolve. Around the $n_c = n_i/4$ there is quasi-homogenous plasma density profile, $L/\lambda \gg 1$ along the laser direction over tens of microns, where plasma instabilities can be generated.

The plasma generated by the ASE in the hole target configuration is strongly dependent on the ASE properties and its time duration. The laser propagates into a quasi-homogenous plasma at quarter critical density with scale length of tens of microns [Fig. 6(b)]. At these conditions LPI may be excited. The $3\omega/2$ harmonic radiation may be generated from the interaction of the laser with plasmon with frequency of $\omega_0/2$. The two main parametrical instabilities responsible for $\omega_0/2$ plasmon are Two Plasmon Decay (TPD), and SRS. The long scale length at the quarter critical density associated with the high laser intensity is well above the threshold for TPD and SRS plasma instabilities. The tens of microns of quasi-homogenous plasma density profile at densities 0.25 $n_c$ and below, as demonstrated in Fig. 6(b), can sustain the acceleration of electrons to relativistic energy by high velocity plasma waves.9 We acknowledge helpful discussion of the LPI, with I. Dey. This work was supported by Pazy Foundation.

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