Study of novel plasma devices generated by high power lasers coupled with a micro-pulse power technology

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Abstract. The authors have proposed introducing a micro pulse power technology in high power laser plasma experiments to boost up the return current, resulting in efficiently guiding of energetic electrons. High current pulse power generators with a pulse laser trigger system generate high-density plasma that is well conductor. To efficiently guiding by using a micro pulse power, we estimated parameter of a micro pulse power system that is voltage of rise time, current, charging voltage and capacitance.

1. Introduction

High-intensity femto second-laser interaction with matter can create plasmas that are extremely energetic and simultaneously dense [1]. An exciting outcome of such interaction is the production of ultra short bursts of charged particles at MeV energies, fueling prospects for novel accelerators [2] and other related applications, such as fast ignition fusion [1,3], etc. Protons, which have been produced with energies as high as few tens of MeV with a petawatt (PW) scale laser, are attracting particular attention [4]. But these applications had been limited in the control of the high power laser technology and their optics. However, now we have a novel tool to control the intense light and high density of energetic particles, which is called plasma photonic devices consisted of transient high energy density plasmas[5]. One of the functions of the devices is control of high density MeV electrons generated by ultra-intense light taking account of return current in high density plasmas. High temperature plasmas is well conductor to propagate the return current and the energetic electrons follow the conductors. Energy PW lasers can creates high density energetic electrons with a large amount of the total energy, resulting in guide of the energetic electrons with self generated high density and high temperature plasmas. On the other hand, table top lasers can generate energetic electrons but no high temperature conditions to be a well conductor.
In this paper, we have proposed introducing a micro pulse power technology in high power laser plasma experiments to boost up the return current in low temperature plasmas, resulting in efficiently guiding of energetic electrons. High current pulse power generators with a rise time of nsec, which is switched by a pulse laser trigger system, are developed as a role of booster of the return current in the cone-wire device to guide the energetic electrons.

2. The micro pulse power assists guiding of the high energetic electrons

PW lasers have much energy that generate easily high energetic electrons and high density plasmas. But table top laser don’t have so much energy than high power lasers. If we will try efficiently guiding of the high density energetic electrons in table top size, we should inject energy in a wire by other methods. When high density electrons propagate the wire, this high energetic particles is bent the orbit by own electric field, and cannot throw the current more than constancy. However the energetic electrons though high density plasmas is to cancel electrons-generated electric fields and to allow the propagate very high current. So, it is necessary to generate high density plasmas or to throw the current from opposite direction that corresponds to the high energetic electron beam that is generated by laser matter interactions. When we assumed that 5% of the energy of the ultra-intense laser (Energy:400mJ,Pulse length:40fs) were converted into a high energetic electrons, a large current of 500 kA/MeV transient the wire. Therefore, the circuit causes the dielectric breakdown when it tries to throw the high current from opposite direction that corresponds to the high energetic electrons. Here, we proposed that a micro pulse power system which generate large current will heat the wire before laser shot. Pulse power technologies have the feature which can efficiently input the energy in minute space so that it maybe represented by Z pinch.

![Figure 1](image)

**Figure 1** High power laser couple with a micro pulse power

Now, we are talking about a carbon wire-cone target which used previous experiment [5]. The electric conductivity of the carbon is simple to change with temperature and expansion velocity is more slowly than metals. The conductivity of carbon is three orders of magnitude smaller than that of metals. But the electric conductivity goes up with the temperature, and becomes almost the same electric conductivity as the metal about 5eV (1.02 $\times 10^7/\Omega \cdot m^{-1}$)[6]. On the other hand, for example, the conductivity of aluminum is the lowest state from 10eV to 40eV[7] and conductivities do not change as simply as the carbons with the temperature. An aluminum wire needs more heating to become good conductor. Therefore, it is easy to treat the carbon than other materials in this experiment.

The general sequences of high energetic electrons propagate in the fine fiber to use the micro-pulse power technology can be subdivided as follows. First high current which generated by
the micro pulse power technology can increase temperature by the energy deposited in the wire during the ohmic heating process. The conductivity of the wire increases with increasing temperature (hot conductor). Second Ultra-intense laser shot into the cone-wire target after the wire preheating finished. The energetic electrons which are generated by laser matter interactions propagate the preheated wire. At this time, return current flows the surface of the wire in the opposite direction to high energetic electrons. Return current more heating the wire and become a fibre plasma. Return current flows smoothly by having heated with pulse power, resulting in efficiently guiding of energetic electrons. In addition, electric potential works between the wire so that a high density electrons are easy to propagate and it is keep flowing to high current in the wire with the micro pulse power technology, the high density electrons are efficiently flow by these effects. Propagation of the high energetic electrons outside the wire induces a strong radial electric field surrounding the fiber like plasmas, and acts to pinch the high energetic electrons along the fiber length.

3. Calculation of a micro pulse power system parameters

(a) We calculated rise time of voltage of a micro pulse power system. Wire explosion is occurred by current energy deposition. Therefore, electron density of pulse power is decrease and high energetic electrons efficiently propagating become difficult. When we assume a carbon wire expansion velocity is about 2µm/ns and LTSG jitter is 1ns, increases of wire volume 20times than initial one become about 10nsec. When wire volume is 20 times as large as initial one, intensity of high energetic current is same as irradiation to the solid. Thus, a high current pulse power generator needs rise time of voltage 10nsec.

\[
\int \frac{\Delta t}{R_{\text{carbon}} + \frac{R_{\text{carbon}} - R_{\text{plasma}}}{\Delta t} t} dt
\]

Where \(R_{\text{carbon}}\) is electrical resistance of initial carbon wire, \(R_{\text{plasma}}\) is the electrical resistance of plasmas, \(E\) is required energy of creating the carbon plasmas and \(I\) is the return current. When we assume that the carbon wire heating and creating a plasma fibre 1ns after the switch turn on, current need about 3.6kA.

(b) We calculated current to make the carbon wire plasma. The wire is connected to charged capacitors and are directly heated and discharged. Since the pulsed current heats the plasma almost adiabatically, the pulse wire discharge is good efficiency. Carbon plasmas C\(^{2+}\) with electrical temperature is 50eV is created by pulse power current. We assumed that 20% of the energy injected into the wire to have been used to heat the wire, the energy needs 166mJ to make the carbon plasma. Carbon plasma created by Joule heating describe

\[
E = \int \left( R_{\text{carbon}} + \frac{R_{\text{carbon}} - R_{\text{plasma}}}{\Delta t} t \right) dt
\]

(c) We calculated value of voltage and capacitor bank to flow high current into the wire to use equivalent circuit of a micro pulse power system as Figure.2. This circuit consists of charged capacitor bank, wave-guide of strip line and a carbon wire.

Figure 2 Equivalent circuit of a wire discharge system
Where $C_{\text{bank}}$ is capacitance of condenser bank, $R_{\text{line}}$ and $C_{\text{line}}$ is wave-guide resistance and capacitor and $R_{\text{target}}$ that is 41 $\Omega$ is resistance of wire target. We assumed that time constant of RC that square waveform of voltage was inputted is $\bar{R}C = 10\text{nsec} = \text{rise time of voltage}$ and the current is 3.6kA in this circuit. We design low resistance of the strip line that resistance $R_{\text{line}}$ is 1 $\Omega$ and capacitance is 19.86nF. Low resistance line decrease energy loss a point different from the wire. Then we knew the total resistance in this circuit that is 42 $\Omega$ and calculate the charging energy of the capacitor bank. Total impedance of this circuit is about 58 $\Omega$. We got the parameter of charging voltage of making a carbon wire plasma needs about 209kV by using Ohm’s law equation.

| Components          | Resistance |
|---------------------|------------|
| Capacitor bank      | 12.5 $\Omega$ |
| Line                | 1.0 $\Omega$ |
| Line’s capacitor    | 2.02 $\Omega$ |
| Wire                | 42.0 $\Omega$ |

4. Summary

We have proposed introducing a micro pulse power technology in high power laser plasma experiments to boost up the return current, resulting in efficiently guiding of energetic electrons. High current pulse power generators with a rise time of 10nsec, which is switched by a pulse laser trigger system, are developed as a role of booster of the return current in a cone-wire device to guide the energetic electrons. To efficiently guiding by using a micro pulse power, we estimated parameters of a micro pulse power system that is boost up the return current. The micro pulse power system need 0.17nF capacitor bank, with a charging voltage is about 209kV that rise time is 10ns, provides the high current that value is 3.6kA to drive the wire heating and creating high density carbon plasma. This system heated the carbon wire up to 50eV and that high density plasmas decreases energy loss of energetic particles. Near Feature, we make this system and study of efficiently guiding of energetic electrons with couple of high power laser and a micro pulse power technology.

References

[1] M.Tabak et al., 1994 Phys. Plasmas 1, 1626
[2] A. Modena et al., 1995 Nature 377, 606
[3] P. A. Norreys et al., Phys. Plasmas 7, 3721
[4] E. L. Clark et al., 2000 Phys. Rev. Lett. 84, 670
[5] R. Kodama et al., 2004 Nature 432,1005
[6] J.Haun et al., 2002 Phys. Rev. Lett.E 65, 046407
[7] Arvinder S. Sandhu et al., 2005 J. Appl. Phy 97,023526