Phases of plasma produced with nanosecond laser

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Abstract — Recent experimental studies have shown that the current balancing the charge occurred on a target irradiated with a laser can be used as a basic parameter for characterization of laser ablation. The time-resolved target current indicates the occurrence of various phases of the laser-produced plasma. During the first plasma phase defined by the duration of laser-target interaction, the time derivative of the target current matches the time-resolved laser intensity. The second phase of the laser-produced plasma starts after termination of the laser-matter interaction. For the entire duration of this active phase, the plasma surviving on the target surface emits transient electromagnetic radiation (EMP), X-ray radiation, and slow ions. This surface plasma causes the target charging balanced by a return target current on a time scale of 100 ns. Then the target holder acts as a probe, the signal of which can indicate a residual plasma persisting inside the target chamber on a time scale of microseconds.

The separation of charges occurred in laser-produced plasma leads to the charging of the target during which the target's voltage can reach a value in the order of hundreds of kV [1-5]. This target polarization, which can drive up to 10-kA current between the target and the ground, can last several hundreds of nanoseconds till the time when the charge on the target is neutralized [6-9]. To our knowledge, the first evidence of a current flow between the laser-produced plasma and target surface was reported in [10]. The applied surface probe technique, which was based on a small wire probe embedded in the target and insulated from it, allowed for determination of radial distribution of current flow to and from the irradiated target surface. M. G. Drouet and R. Bolton [10] observed on a time scale of hundred nanoseconds that the conventional current flows along the laser beam axis into the target through the plasma-target interface for a period of hundreds of nanoseconds. The wire probe located out of the focal spot indicated a reverse current polarity. There is a part of the target surface, centred on the laser axis, with conventional current flowing into the target, surrounded by an annular anode surface with current flowing out of the target. This annular current distribution affects the annular x-ray emitting region at the focal spot [11]. However, the partial current paths are not closed and the target current, $I_T(t)$, between the ablated crater on the target surface and the ground can flow. About 40 years later it was observed that $I_T(t)$ caused by a low laser intensity reverses its direction, i.e. the $I_T(t)$ polarity revers from positive to negative. It was observed that the duration of positive phase and negative one of $I_T(t)$ is up to a few microseconds and tens of microseconds, respectively [6 - 9]. A detailed analysis has revealed three phases of the target current [9]. During the first phase, which has been called the ignition plasma phase, the electron emission from the laser-produced plasma is driven by the laser pulse and the positive charge generated on the target is balanced by electrons coming from the ground through the target holder. A number of partial stages as, for example, electronic excitation inside the target, the electron ejection due to photoelectric effect and thermionic emission, and plasma heating take a part in this phase. At post-laser-pulse times, a peaked waveform of the target current is typical for the active phase of the plasma. This second plasma phase can give information on the material composition of the ablated surface layers [8]. The last plasma phase called the afterglow phase is determined by a current of electrons flowing from the target to the ground because the target current exhibits reverse polarity, i.e. $I_T(t) < 0$ [6 - 9]. If a laser pulse delivers onto a target very high energy, only the first two phases of the plasma evolution have been observed [12]. It can be caused by a low contribution of the third plasma phase to $I_T(t)$ in comparison with the contribution of the active plasma phase. It was observed the heights and durations of target probe voltage pulses are also dependent on the size of the interaction chamber [2]. Moreover, the waveform of target current depends on laser wavelength, delivered laser intensity and target material [8].

In this contribution, we present variations in the target current waveform which are caused by increase in intensity from 10^{14} to 10^{16} W/cm^2 focused on targets in 350 ps. The target current was measured with the use of an inductive probe [5] and with a 57-mΩ resistance probe implemented into the target holder. Experiments were carried out at the Institute of Plasma Physics of the Czech Academy of Sciences on the PALS facility operated at 1315 nm.

Fig. 1 shows the Cu target currents oscillating between the irradiated target and ground, which were induced by 1.5- and 110-J laser energy. The duration of electron flow from the ground to the target irradiated with a 1.5-J energy is about 650 ns. Then the target becomes negatively charged for about 10 μs. The positive $I_T(t)$ reaches a maximum at ≈30 ns after the laser-target interaction. At this time, the corresponding difference between total currents of electrons and ions $I_{RTP}(t) = \int\{I_e(\boldsymbol{r},t) - I_i(\boldsymbol{r},t)\}d\boldsymbol{r}$ reaches a value of 20 A. The quasi-steady-state driver of electron emission can be the heat accumulated in a large hot zone around the target crater [13]. The crater zone cooling and, thus, the electron emission depend not only on energy loses by particle and radiative emission but also on the thermal energy spread via electron conductivity of the target [13]. The $I_T(t)$ waveform is similar to ones observed in other experiments [8]. The target current driven by a 110-J energy reaches a maximum value of ≈ 2100 A at ≈ 2 ns after the laser-target interaction, while the duration of the plasma ignition phase is only ≈1ns.

This first phase of the plasma driven by the 1.5-J laser energy is not distinguishable in Fig. 1a due to degradation of the resistor-probe signal by interference with an electromagnetic pulse (EMP) emitted by the target holder. The range of interfering frequency is from ~100 to ~800 MHz. This frequency spectrum depends on the geometry of the interaction chamber and accessories localized within it [12]. Contrary to the resistive probe, the signal of which is easily degraded by EMP interference, the use of the inductive target probe [5] allowed us to observe the $I_T(t)$ undisturbed during the plasma ignition phase, as presented in detail in [12].

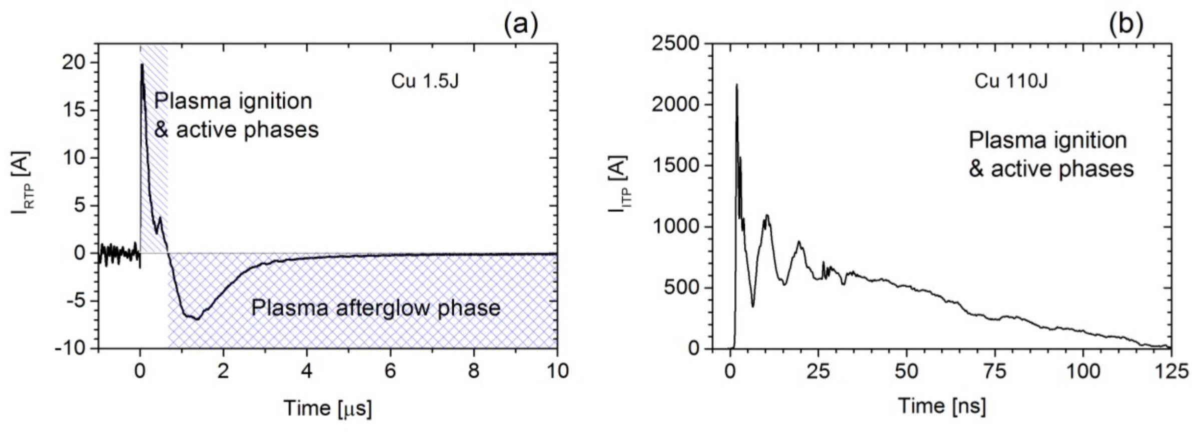

Fig. 1. (a) Bipolar waveform of the current flowing between the Cu target and ground induced by 1.5-J laser energy. (b) Target current induced by 110-J laser pulse. The duration of the plasma ignition phase is about 1 ns.

Theoretical models usually cover either the first phase of plasma formation, i.e. the ignition plasma phase, with inner phenomena occurred on picosecond and sub-nanosecond timescales, or the final stage of expansion with a lifetime typically on the 10-μs scale, where the plasma plumes exhibit a three-dimensional evolution that can be described using hydrodynamics. The latest theoretical approaches based on the use of hydrodynamic models in a nondifferentiable (fractal) space-time have been established to account the development of the plasma during its transient active phase triggered with laser intensity of GW/cm^2 [14]. The observed splitting of the plasma plume into two patterns during the active plasma phase was successfully simulated by these models [15, 16]. The plasma splitting could correlate with the peaked structure of the $I_T(t) > 0$ after the termination of the laser-matter interaction, shown in Fig. 1. The afterglow phase of the plasma, during which $I_T(t) < 0$, gives evidence that the plasma conditions within the chamber have been fully changed. The ionized species of the plasma plume hit the grounded accessories and chamber walls, and the temperate of the crater zone on the target becomes low. The target acts as a probe inhered into an ionized residual gas.

In conclusion, the target current is a parameter allowing us to distinguish distinct phases of evolution of the charge separation during the expansion of the laser-produced plasma.

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