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TEMPERATURE RELAXATION PROCESS AND EXPANSION OF LASER INDUCED PLASMA

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Abstract. We present results obtained from the hybrid particle-LTE simulation developed by Skocic and Bukvic, 2016. Simulation is conducted for pulsed nanosecond 532 nm Nd-YAG laser for the copper target placed in vacuum. Initial number density of the plasma and temperatures are set to $n_p \approx 1.3 \cdot 10^{27}$ m^{-3}, $T_e \approx 70000$ K, and $T_h \approx 8000$ K, respectively.

Presented results deal with initial moments of LIP temperature relaxation process, with an emphasis on the first couple of nanoseconds. Results indicate that plasma is in thermal equilibrium just after 1 ns for the given initial conditions. Thus, plasma temperature after 1 ns is about $T \approx 55000$ K. After 40 ns number of copper ions and atoms is the same, while after that moment neutral atoms are the most abundant species. Energy transfer to heavy particle is intensive, especially in the first 40 ns.

1. INTRODUCTION

This paper considers energy transfers in plasma created with the interaction of high power nanosecond laser with a metal target. When the target is illuminated by the laser pulse free electrons in metal absorb electromagnetic radiation and immediately transfer energy to the lattice, since the relaxation time for this process is only 10^{-13}s. Due to large amount of absorbed energy, metal melts and evaporates in the surrounding space for the duration of the laser pulse. Temperature of the evaporated material is sufficiently high and provides initial ionization of the vapor while inverse bremsstrahlung ensures direct absorbtion of the laser energy during the remaining time of the laser pulse (Bogaerts et al. 2003, Itina et al. 2002). Electrons lose energy gained from the laser in the excitation and ionization processes as well as in elastic collisions with ions and atoms. After the laser pulse is finished the main process is cooling of the plasma due to fast expansion.

The aim of this paper is to study relaxation of electrons and heavy particles temperature in the early time of plasma lifetime and effects of energy transfer from ionization potential energy and electron kinetic energy on expansion velocity (center of mass velocity) of Laser Induced Plasma (LIP) in later stages of plasma expansion. All results are obtained from the modified simulation developed earlier by Skocic and Bukvic, 2016.

2. MODEL

Our model is a hybrid two temperatures, particle-LTE model and it is intended to describe expansion of LIP created on metal target in vacuum or low pressure ambient gas. Within the simulation heavy particles (atoms and ions) and electrons are considered in a different way. Each heavy particle is represented by its mass, position and velocity vector, at a given time. Movement and *elastic* collisions of heavy particles are monitored in detail. However, details regarding the motion of electrons are ignored completely, the free electrons are represented only by the local density and temperature. Concentrations of the heavy particles are related to the electron density and temperature via the Saha equation, supposing the existence of Local Thermodynamic Equilibrium (LTE). In this way, all *inelastic* collisions are substituted by the Saha equation. *Elastic* collisions of electrons with atoms and ions (e-a and e-i) are maintained separately. Physics of the LIP plasma expansion is described by the kinematics of heavy particles, which is insensitive on details of the plasma state (whether plasma is in LTE or not).

3. RELEVANT PARAMETERS AND INITIAL MOMENT

The most important parameters that must be supplied to simulation at the beginning are density of the heavy particles n_p, average energy per particle E_{av} and temperature of the heavy particles T_h. The temperature of the heavy particles is estimated assuming that metal target (copper) explodes when its temperature approaches critical point temperature. According to Autrique et al, 2013 this temperature is about 8000 K and does not depend on the laser irradiance. n_p is estimated knowing drilling depth and initial volume of plasma, both quantities are available in experiment. Estimation of E_{av} is based on calculated value for fraction of total laser energy absorbed by plasma, see works Bogaerts et al, 2003, 2005. For $I = 5$ GW/cm^2 the average energy is $E_{av} \sim 29$ eV, plasma number density $n_p = 1.3 \cdot 10^{27}$ m^{-3} and T_h=8000 K.

4. RESULTS AND DISCUSSION

Simulation is conducted for pulsed nanosecond 532 nm Nd-YAG laser for the copper target placed in vacuum. In Fig. 1 we present the evolution of plasma parameters in the first 120 ns from the laser pulse. On the left part of the Fig. 1 temperature relaxation among the plasma species for entire plasma life time (120 ns) is given, and on the inset, temperature relaxation in the first 1.0 ns. On the right part of Fig. 1 we present number density evolution of plasma species. Number density change is directly related to plasma expansion and electron temperature decrease.

In the initial moment, estimated average energy is distributed to the potential energy of ionization and to the kinetic energy of the plasma species. We obtained values $T_e \approx 70000$ K, $n_e \approx 1.8 \cdot 10^{27}$ m^{-3}, and $T_h \approx 8000$ K, $n_p \approx 1.3 \cdot 10^{27}$ m^{-3} ($n_{CuI} \approx 8.2 \cdot 10^{25}$ m^{-3}, $n_{CuII} \approx 6.1 \cdot 10^{26}$ m^{-3}, $n_{CuIII} \approx 5.8 \cdot 10^{26}$ m^{-3}). Observing the ionization degree ($x_{Cu_I}/n_p = 0.06$, $x_{Cu_{II}}/n_p = 0.48$, and $x_{Cu_{III}}/n_p = 0.46$) one can see that considerable energy is used in ionization of copper. In the initial moment, T_e is more than 10 times larger than the temperature of the atoms/ions. In the following 1 ns, T_e is reducing while the temperatures of the heavy particles

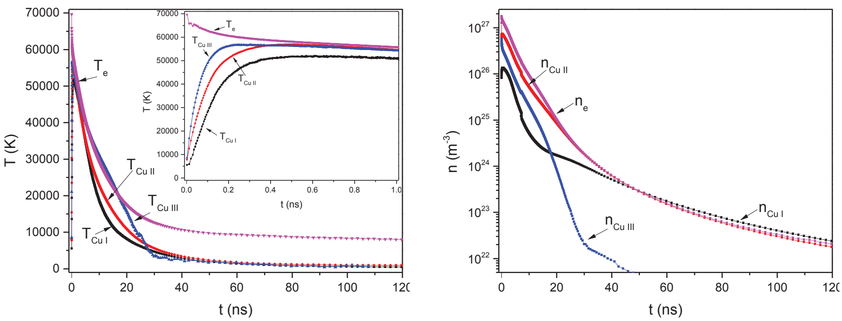

Figure 1: Average values for the plasma species temperatures (Left panel) and number densities (right panel). Inset: Temperatures for the first 1.00 ns after the laser pulse. We present values for Cu atoms (black), singly ionized Cu (red), doubly ionized Cu (blue) and electrons (violet).

are increasing, leading to the common value of ≈ 55000 K. This relaxation process is related to electron-atom and electron-ion elastic collisions (also, electrons loses energy to radiation). It can be observed that in the first ns atoms temperature (T_{CuI}) and ions temperatures (T_{CuII}, T_{CuIII}) are not the same. This effect is due to different electron-atom and electron-ion collision frequencies ($\nu_{e-CuIII} > \nu_{e-CuII} > \nu_{e-CuI}$). The species temperature difference occurs also at later times, and it will be discussed in next paragraph.

After the initial relaxation (thermalisation) plasma starts to expand into the surrounding space. This expansion results in rapid plasma cooling. Plasma temperature evolution is shown on the left part of the Fig. 1. The temperature of the plasma species is different in the entire process of plasma expansion. This could be due to the different processes that influence temperature decrease. Heavy particles are dominantly cooling due to expansion, while electrons are cooling due to collision with the heavy particles and bremsstrahlung radiation. Ionization potential energy is available to particle kinetic energy through the three body recombination process (electrons gain energy in this process). Energy gained in recombination process is transferred to heavy particles via e-i and e-a collisions. At first glance, it is strange that the temperature of atom and ions are not the same. Since atoms and ions have the same mass, the energy relaxation time is much faster than ion-electron or atom-electron relaxation times. The difference between the heavy particle temperatures is only because we present average temperatures while ions and atoms are not evenly distributed in the plasma volume. This is also evident for the temperature of Cu III species in the region between 10 ns to 50 ns.

It is interesting to see how kinetic and potential energy are evolving in time, see Fig. 2. In the initial moment all energy is stored in thermal energy of electrons (blue) and heavy particles (red), and in the potential energy of ionization (violet). In the first ~ 40 ns, energy conversion to E_{cm} (black) is intensive, and heavy particles are predominately accelerating. One can see that after the initial ~ 40 ns, values for E_{cm}, E_{pot}, E_{Th}, and E_{Te} are almost constant. This evidently coincide with curves on Fig.

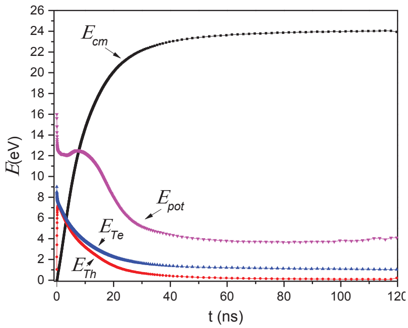

Figure 2: Energy transfer process. Black: the energy stored in expansion velocity (flux) of the heavy particles. Red: thermal energy of the heavy particles. Blue: thermal energy of the electrons. Violet: potential energy of ionization.

1, where after $\sim$ 40 ns the dominant species in the plasma are neutral atoms.

There are several processes responsible for accelerating of the heavy particles. Since plasma is expanding, thermal energy of the heavy particles is directly transferred to the center of mass energy (chaotic movement to directional movement). The potential energy stored ionization energy is transferred to electrons via tree body recombination. Electrons transfer energy to heavy particles in elastic collisions; thus heating/accelerating the heavy particles.

5. CONCLUSION

The presented results are obtained from the simulation conducted for pulsed nanosecond 532 nm Nd-YAG laser for the copper target placed in the vacuum. Simulation is based on hybrid particle-LTE simulation developed by Skocic and Bukvic, 2016. Initial number density of the plasma and temperatures are $n_p \approx 1.3 \cdot 10^{27}$ m^{-3}, $T_e \approx 70000$ K, and $T_h \approx 8000$ K, respectively. Initial volume is set to $r_0^2 z_0 \pi = 100^2 10\pi$ μm^3. Presented results deal with initial moments of LIP temperature relaxation process, with an emphasis on the first couple of ns. Results indicate that plasma is in thermal equilibrium just after 1 ns for given initial conditions. After the initial relaxation, plasma temperature is about $T \sim 55000$ K. After 40 ns number of copper ions and atoms is the same, while after that moment neutral atoms are the most abundant species. Energy transfer to heavy particle is intensive, especially in the first 40 ns.

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