Publ. Astron. Obs. Belgrade No. 102 (2022), 101 - 104 *Contributed Paper*

ANALYTICAL PREDICTION AND NUMERICAL ANALYSIS OF PLASMA MEDIATED ABLATION OF SKIN TISSUE SAMPLES WITH NANOSECOND-TO-FEMTOSECOND LASER PULSES

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Abstract. Based on the assumption initially developed by Jiao and Guo 2012, in this paper, we have introduced an analytical tool that performs analysis on the free-electron evolution (FEE) in plasma-mediated ablation of the skin tissue samples. Using the proposed calculations, the FEE can be determined in an excellent agreement with that resulting from (Jiao and Guo 2012) on the nanosecond time scale. However, the compatibility between the presented analytical approaches is not satisfactory for the ultrashort laser pulses. To eliminate such inconsistency, a simple modification to the rate equation for the free-electron density has been made when including the tunneling rate instead of the multiphoton rate. Our findings confirm that the results of the presented analytical models of both short and ultra-short laser ionization process in skin tissues may have direct biomedical applications based on the use of various pulses.

1. INTRODUCTION

Throughout the past few decades, lasers have found their way into many areas of medicine and biology, with a variety of applications ranging from basic research to clinical trials (Ilina and Sitnikov 2021). While keeping up with medical advancements in the field, a theoretical understanding of laser-tissue interaction mechanisms using short and ultrashort pulsed lasers became increasingly important. As a consequence, a few models have been proposed to explain distinct laser ablation mechanisms (Ravi–Kumar et al. 2019; Zheng and Shen 2022). Among different approaches, the plasma-mediated ablation approach presented by Noack and Vogel 1999 has been most commonly used to explain the laser-induced breakdown (LIB) phenomenon while considering the case when the plasma is induced by a strong electromagnetic field. However, a small percentage of investigators remain focused on determining the "breakdown threshold" in terms of finding an exact analytical solution to calculate a critical number of free electrons generated within the laser-tissue interaction region.

The difficulties in answering questions about the optical breakdown structure for the ablation of skin tissue have been attributed to the complex nature of the processes, which are dependent on both the laser properties, as well as the time-dependent plasma–particle interaction processes. In order to shed more light on the LIB phenomenon, a temporal model for examining the breakdown threshold and form of laser-induced plasma (LIP) in skin tissue samples is developed by revising the general form of the well-known rate equation (Noack and Vogel 1999) and simultaneously, accounting for the tunneling, multiphoton, cascade, thermal, and chromophore ionization influences on short and ultrashort laser pulse propagation. Besides, electron loss processes due to diffusion out of the focal volume and recombination were also investigated. In this study, plasma-mediated ablation is postulated as two distinct processes during different time stages: *(i)* multiphoton and cascade ionization operated in the short-range pulse regime and *(ii)* tunneling and cascade ionization while observing ultrashort events. The rate equation for each stage is solved analytically. The conditions under which different ionization mechanisms occur and prevail in the plasma-mediated laser ablation process are validated using developed analytical models in combination with available experimental findings and numerical modeling. The presented approach is further extended to investigate the temperature evolution in the focal volume and threshold intensity dependence on laser pulse duration.

2. MODEL DESCRIPTION

The skin tissue is composed of multiple layers containing distinct cellular populations, making it challenging to understand the processes that occur under the interaction of laser with skin. According to (Rogov et al. 2014), water (70%) is the predominant constituent of the skin, which is why, in a first approximation, the human skin tissue can be thought of as a water-like tissue media. This phenomenon has attracted wide attention for its significance in the fundamental research on laser-matter interaction and as a baseline model for studying the ablation of skin tissues. The primary mechanism of optical ablation in the present work is plasma-induced ablation during short and ultrashort pulses, hence describing the process demands taking into account a variety of ionization processes.

This paper is comprised of two major subsystems:

1. *The free-electron density*. Photoionization (PI) mechanisms (that are predominantly in the tunneling (TI) or in the multiphoton (MPI) regimes), cascade ionization (CI), thermal ionization (TI), chromophore ionization (ChI) and free-electron absorption (FEA) may all be triggered depending on the intensity of the incident radiation. Phenomena that generate free-electrons are namely MPI, TI and CI. The free electron density will be reduced by recombination effects as well as free carrier diffusion.
2. *The free-electron temperature.* The absorbed laser energy will first be stored in the free-electrons before it is transferred via electron-phonon scattering events. The density in the free electron subsystem can be denoted as the sum of the kinetic energy and bandgap energy per unit of volume. Energy

transfer is herewith described by the well-known two-temperature model (Uehlein et al. 2022), which is derived under the assumption that electron and phonon energy transport is described by the classical Fourier law.

3. RESULTS

The solution of the free-electron density rate equation could provide insight into the differences between the breakdown mechanisms at different pulse durations. To discuss these differences, Figure 1(a) displays the comparison of the free-electron density between the analytical and numerical predictions for ablation in the skin tissue sample, while Figure 1(b) shows the evolution of the free-electron density for laser pulses of different duration.

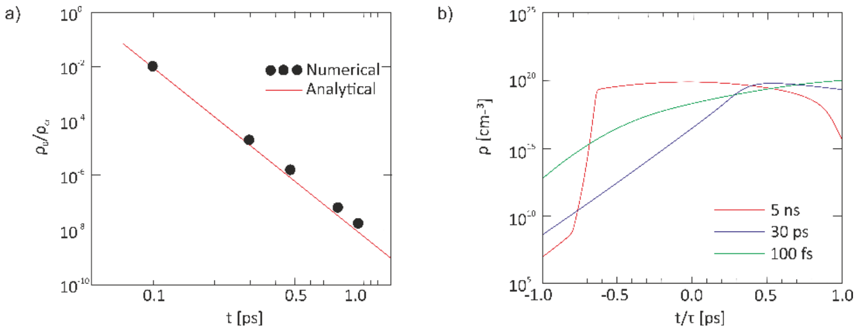

Figure 1: (a) Comparison of the free-electron density between the analytical and numerical predictions, (b) evolution of the free-electron density at threshold irradiance for laser pulses of different durations. All curves were calculated for $\lambda = 532$ nm.

Table 1 lists the irradiance thresholds for optical breakdown in skin tissue for wavelengths of 532 nm and 355 nm, and pulse durations of 5 ns, 30 ps and 100 fs.

Pulse duration	ρ_{cr} [cm^{-3}]	I_{th} [10^{11} Wcm^{-2}]	
		355 nm	532 nm
5 ns	10^{20}	1.2	0.5
30 ps	10^{21}	7.8	3.7
100 fs	10^{21}	68.5	80.5

Table 1: Calculated irradiance thresholds I_{th} for LIB in skin tissue. The values chosen for ρ_{cr} yielded the best agreement between calculated and experimental findings.

4. CONCLUSION

We derived analytical solutions for the free-electron evolution of skin tissue media based on the postulate developed in (Jiao and Guo 2012). The theoretical model is validated via comparisons with the available experimental findings of the ablation threshold in skin tissue samples. A complete numerical model with all the ionization and loss mechanisms is also employed in the comparison to verify the conditions when CI prevails in the plasma-mediated laser ablation process. The proposed model is useful for ablation with both short and ultrashort pulses.

Acknowledgements

This work was supported by the RS MESTD, Project No. OI 171020, and COST Action CA17126 "Towards understanding and modelling intense electronic excitation".

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