Effect of non-equilibrium ionization and excitation on radiation absorption and plasma shielding in laser-induced plumes

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In recent literature, the model of Saha-Boltzmann ionization and excitation equilibrium is routinely used to predict ionization and radiation absorption in plumes induced by irradiation of materials targets with ns laser pulses. In the present work, the equilibrium ionization model (EQM) and non-equilibrium collisional-radiative model (CRM) are compared under typical conditions of ns pulsed laser ablation to reveal the effect of plasma non-equilibrium on radiation absorption and degree of plasma shielding. The simulations of plume expansion induced by irradiation of a copper target in vacuum or 1 atm argon background gas with Gaussian and flat-top laser pulses of 5 – 60 ns duration at wavelengths of 266 nm and 1064 nm are performed with a hybrid computational model (Fig. 1(a)). The model includes a thermal model of the irradiated target, a model of radiation transfer, and a lumped particle direction simulation Monte Carlo (ℓDSMC) method coupled with either CRM or EQM. The simulations show that EQM can strongly underestimate the effects of ionization and radiation absorption compared to CRM (Fig. 1(b)). As a result, the ablation depth and electron temperature predicted by CRM are in much closer agreement with experimental data available from the literature compared to EQM. These results are explained by the coupling between plume expansion and dynamics of electron temperature and ion population densities of the excited states in CRM and EQM. The simulations extended to "bursts" of pulses with high intra-burst repetition rates showed that the non-equilibrium effects dominate the optimum number of pulses in a burst, which minimizes the degree of plasma shielding while maximizing the material removal. Thus, this study indicates that the model of Saha-Boltzmann equilibrium cannot be used for the prediction of radiation absorption, ionizations, and degree of plasma shielding in nanosecond laser ablation.

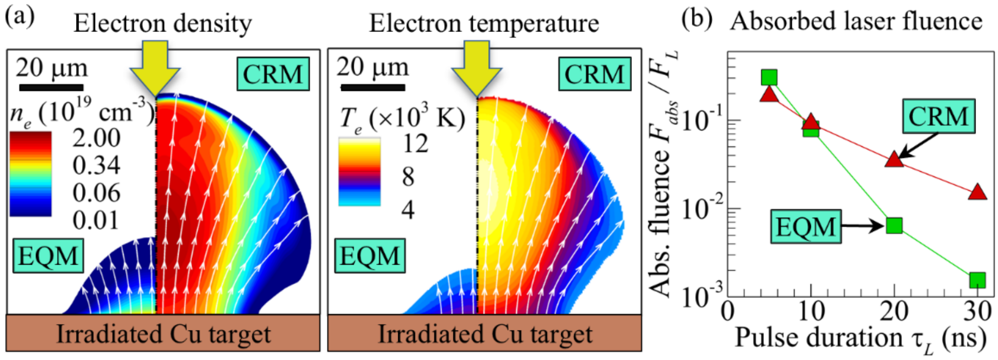

Figure 1: (a) Electron density and temperature fields at nanosecond laser ablation of copper into 1 atm argon gas obtained with EQM (left side from the axis of symmetry) and CRM (right side) for a flattop laser pulse of wavelength 266 nm, duration $\tau_L = 60$ ns, and peak fluence $F_L = 16.6$ Jcm^{-2}; (b) Fraction of peak fluence absorbed in the plume F_{abs} versus τ_L obtained with EQM (squares) and CRM (triangles) at $F_L = 8$ Jcm^{-2}.

Acknowledgements:

This work was supported by the National Science Foundation, USA through RII-Track-1 Future Technologies and Enabling Plasma Processes project (award OIA-2148653) and MKS Instruments, Inc. M.A.S. also acknowledges support from the Alabama EPSCoR Graduate Research Scholars Program.