Atomic collisions in plasma transport modeling of the laser-produced Cu plasma in air and in vacuum

A. Stancalie, A. Matea, A. Mihailescu, V. F. Pais, V. Stancalie

National Institute for Laser, Plasma and Radiation Physics, Magurele-Ilfov,Romania

Introduction

Plasma created by intense laser irradiation of solid targets is the subject of many scientific works in the field of laser-plasma sources, X-ray lasers, inertial confinement fusion and laboratory astrophysics. This work presents results from a series of calculations intended specifically to model the time dependent ionization processes in copper plasma created in air and in vacuum by the second harmonic of a Q-swiched pulsed Nd:Yag laser irradiation [1]. The distributions of electron temperature and density were determined in a prior step by measurements. In addition, to check the departure of the copper ions from the local thermodynamic equilibrium conditions (LTE), the results from synthetic spectra generated by Atomic Data Analysis System (ADAS) [2] and FLYCHK [3] program packages have been compared with measurements. Of central importance to the generation of opacity, the ensemble of level populations has been calculated self-consistently taking into account the time dependence of plasma parameters.

Method of calculation and results

Full details on the experimental set-up and measurements are given in the Ref. [1]. We only recall here the main ideas and results. The second harmonic (λ = 0.532 μm, 180 mJ energy), of a Q-switched Nd:YAG laser (λ=1,064 μm, 360mJ energy in the first harmonic), 4.5 ns pulse duration, 0.1 ÷ 10Hz frequency, has been used for excitation. The laser beam was focused through a 25cm focal length convergent lens on a plane copper target in air, at atmospheric pressure. The target was rotated. The spectral dependence of the radiation emitted by the ablation plasma was detected and analyzed, with time resolution, using an Acton Research spectrometer with a 0.75m focal length and a resolution of about 1mm/nm and an OMA4 2D CCD system. The spectral resolution was about 60pm (~3pixels). We reproduce for completeness, in Figure 1, the emission spectrum of the laser-produced copper plasma in air. The experimentally observed line intensities have been used to extract the excitation temperature using Boltzmann plot method whereas the electron number density has been determined from the Stark broadened line profiles. The plasma emission spectrum contains mainly atomic lines belonging to copper, oxygen and nitrogen atoms and their ions. The experiments indicated: a) radiative transfer into the laser-produced plasma in air for two Cu I resonance lines at 324.75 and 327.40nm, and b) no absorption effects for the same resonance lines in laser-produced Cu plasma in vacuum.

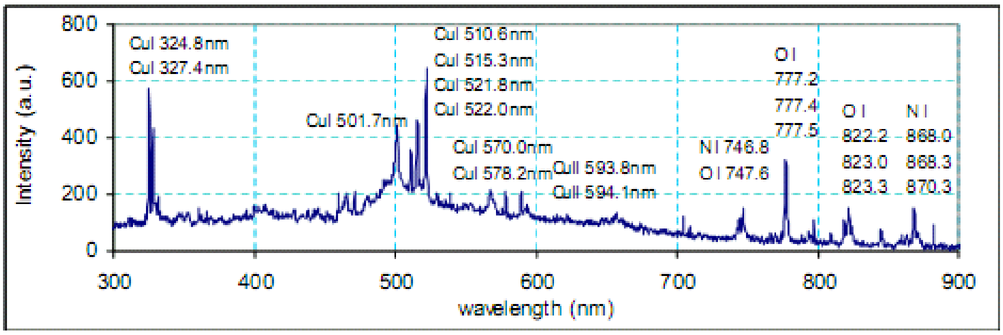

Fig. 1. Experimental emission spectrum of the laser-produced copper plasma in air [1].

In the present work, an initial kinetic calculation has been done using the ADAS routines. We have calculated the rates for the elementary processes, and the population density distribution over the excited states solving the coupled rate equations in the collisional radiative model. These calculations do predict that the shape, both overall strength and width, of the $\Delta n = 0$ features are sensitive to temperature. The plasma measured parameters, have been used as input data in the history file in FLYCHK. Photoionization processes are included to study the effects of the radiation field on the charge state distribution. Figures 2 and 3 give the steady state - and the time dependent- distribution, respectively.

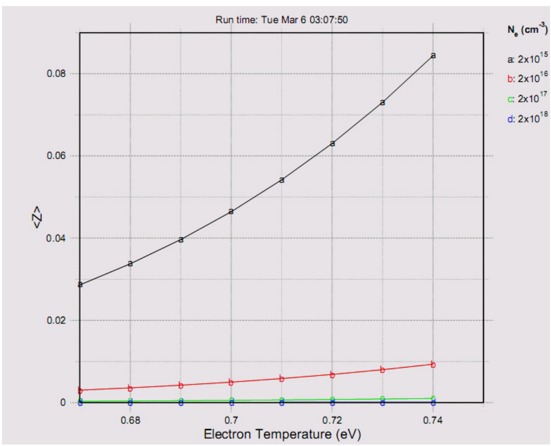

Fig. 2. The steady state distribution of the average charge <Z> at a given set of electron temperatures and densities. A FLYCHK simulation

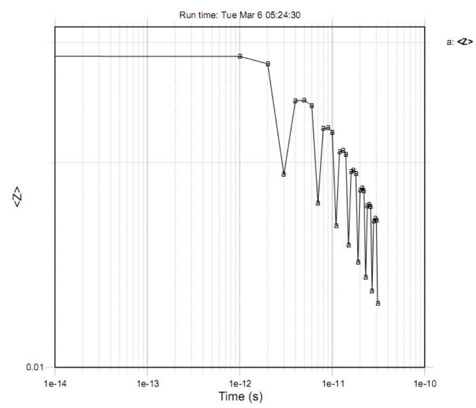

Fig. 3. The time dependent distribution of the average charge <Z>. A FLYCHK simulation

In order to examine the relevance of the plasma thermodynamic regime on the spectrally resolved intensities we have performed a temporal analysis of the plasma parameters based on FLYCHK code. Results are presented in Figures 4 and 5, respectively.

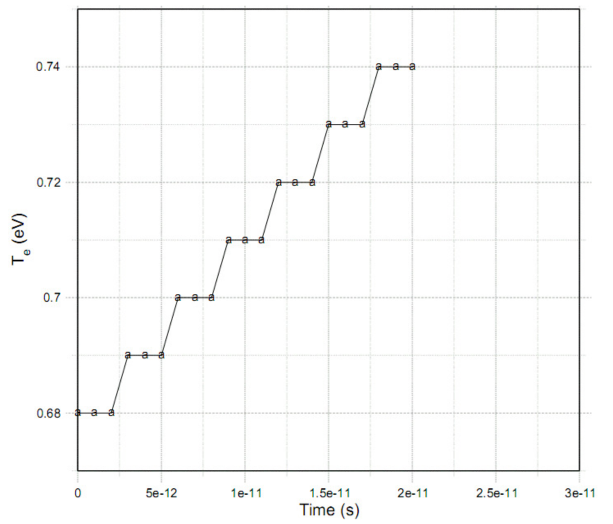

Fig. 4. The electron temperature (in eV units) as function of the plasma evolution time (in s).

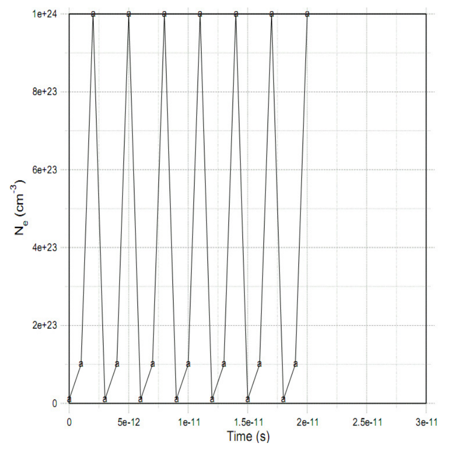

Fig. 5. The electron density (in cm^{-3} units) as function of time (in s)

When calculating the excited state populations the escape factor approximation is used in ADAS routine to modify the Einstein *A*-values taking into account the reabsorption of the emitted radiation (the target geometry and its size are included).

Due to re-absorption the escape intensity from the plasma is less than the integrated emission along the line-of-sight. A secondary effect is that the population distribution of the absorbing atom or ion state could be altered. We have calculated the total power loss for a wide range of density and temperature. Results are shown in the Figure 6.

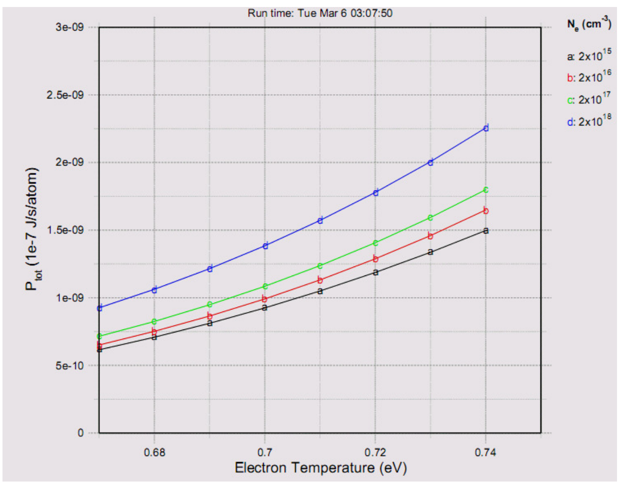

Fig. 6. The total power loss for a wide range of density and temperature

The bound-free, free-free and bound-bound contribution to line emissivity has been also integrated in the simulation. We give in Figure 7, as an example, the bound-free emissivity as function of energy. Once populations have been determined, the emission spectrum is predicted. Line ratios are a function of electron temperature and density, but also of opacity. The simulated spectrum is shown in Figure 8

To generate the spectrum, the emissivity, ε_ν, and opacity, κ_ν, of the plasma as function of frequency, or equivalently, energy are calculated. It was assumed that the plasma is a slab with uniform temperature and density giving rise to the emitted intensity: $I_\nu = S_\nu(1-e^{-\tau_\nu})$ (ergs/cm^2/sec/Hz/Ω) where S_ν is the source function

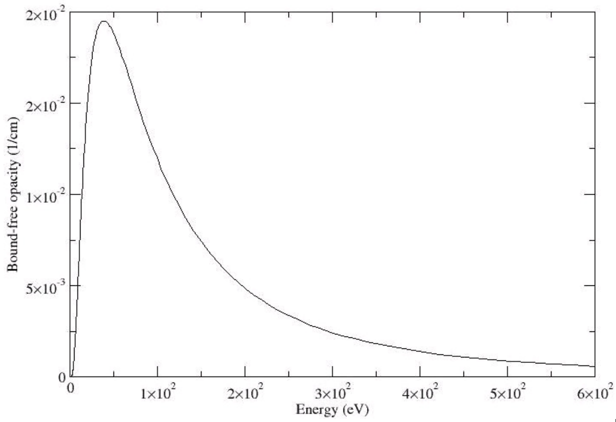

Fig. 7. Bound-free opacity as function of energy (in eV units).

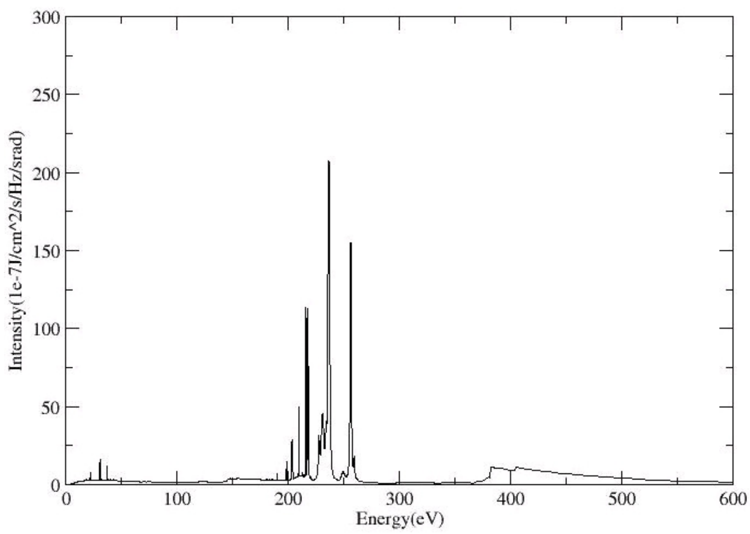

Fig.8. Simulated emission spectrum as function of the energy (eV)

Conclusions. We have performed a series of calculations intended specifically to model the radiation transfer into a high intensity laser produced copper plasma in air and in vacuum. Results as output from two package of programs have been analyzed comparatively in order to define their range of accuracy. This work will continue.

References

[1] S.S. Ciobanu et al., 2008, 35th EPS Conf. on Plasma Phys., Hersonissos, ECA Vol 32D, P-5.144

[2] http://www.adas.ac.uk

[3] H.K.Chung et al, HEDP **1**, 3, (2005).