Observation of ultrafast non-equilibrium collective dynamics in warm dense hydrogen

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The investigation of Warm Dense Matter (WDM) is one of the grand challenges of contemporary physics [1, 2]. WDM is a plasma state characterized by moderate-to-strong inter-particle coupling which takes place at free electron temperatures of several eV and free electron densities around solid density [1]. It is present in many physical environments, such as planetary interiors [3], gravitationally collapsing protostellar disks, laser matter interaction and particularly during the implosion of an inertial confinement fusion capsule [4].

We investigate ultrafast (fs) electron dynamics in a liquid hydrogen sample, isochorically and volumetrically heated to a moderately coupled plasma state using $91.8\,\mathrm{eV}$ FLASH radiation [5]. During the $\sim 40\,\mathrm{fs}$ heating process, a fraction of the radiation is Thomson scattered. The scattered radiation is recorded spectrally using a specially designed spectrograph [6]. The spectral structure is dominated by two inelastically scattered peaks, the plasmons, from collective Thomson scattering. From their photon energy shift with respect to the incident radiation we can determine the plasma free electron density. The free electron temperature can be inferred from the intensity ratio of the two peaks via detailed balance. To determine these plasma parameters we fit the recorded spectrum with simulations (fig. 1) and obtain a free electron temperature and density of $13\,\mathrm{eV}$ and $2.8 \times 10^{20}\,\mathrm{cm}^{-3}$, respectively. Furthermore, the measurements show that the hydrogen plasma has been driven to a non-thermal state with an ion temperature below $0.1\,\mathrm{eV}$ [5].

We have simulated [5, 7] the evolution of the electron kinetic energy distribution during and after the FEL irradiation and have compare these density and temperature trajectories with our measurements (fig. 2). In the simulation we can study the influence of different cross sections for impact ionization, which is the dominant mechanism on this time scale. We used the National Institute of Standards and Technology database for molecular hydrogen bases on the Binary Encounter Bethe (BEB) model as well as a classical expression based on free electron collisions. The models deviate up to a factor of four in the relevant electron energy range. Simulations with the classical model yield results which match our measurement significantly better than BEB (fig. 2). A possible interpretation is that the atomic structure (as treated in BEB) does not play a significant role in the context of dense plasmas where, due to screening and correlation effects, high lying atomic states are removed and the electron interaction is more properly described with a classical ionic background.

This is an important step towards the investigation of strongly coupled plasmas which are within reach of current and future light sources such as LCLS and the European XFEL.

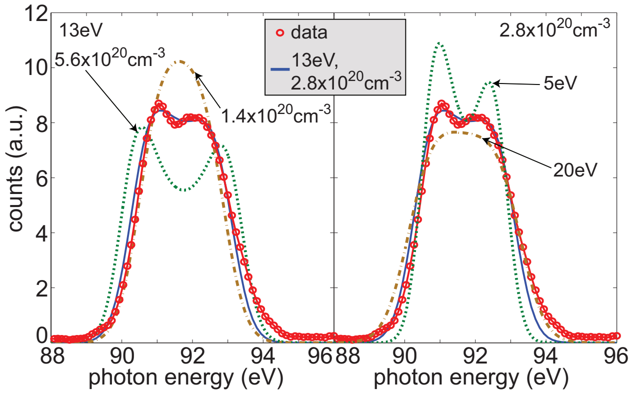

Figure 1: Experimental spectrum integrated over 4500 pulses (red circles) and the best fit of a calculated spectrum with $n_e = 2.8 \times 10^{20}\,\mathrm{cm}^{-3}$ and $T_e = 13\,\mathrm{eV}$ (solid blue line). Comparison to fits with variation in density (left graph), $5.6 \times 10^{20}\,\mathrm{cm}^{-3}$ (dashed green) and $1.4 \times 10^{20}\,\mathrm{cm}^{-3}$ (dash-dotted brown), and in temperature (right graph), $20\,\mathrm{eV}$ (dash-dotted brown) and $5\,\mathrm{eV}$ (dashed green), are shown.

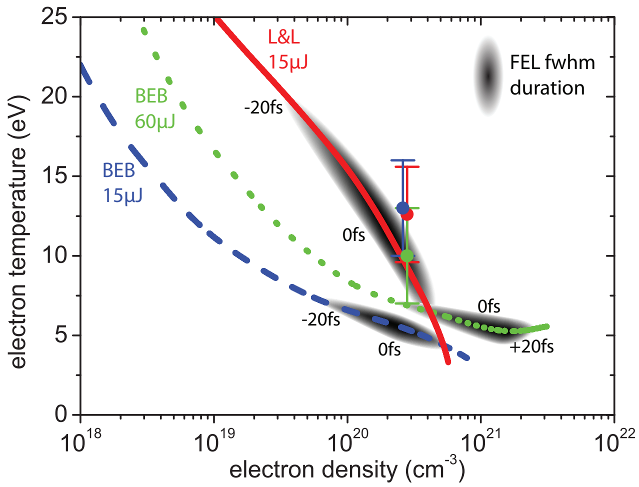

Figure 2: Measurements (colored circles) compared to the simulated evolution of the target's free electron density and temperature using different impact ionization cross sections: classical electron-electron collisons (solid red, $15\,\mu\mathrm{J}$) and the BEB model ($15\,\mu\mathrm{J}$ dashed blue, $60\,\mu\mathrm{J}$ dotted green). The pulse energy in the experiment was $15\,\mu\mathrm{J}$. The FEL full width half maximum duration is indicated in gray scale.

References

[1] National Research Council, *Frontiers in high energy density physics: The x-games of contemporary science*, National Academies Press, 2003.

[2] S. H. Glenzer and R. Redmer, Rev. Mod. Phys. **81**(4), 1625-1663 (2009).

[3] N. Nettelmann et al., Astrophys. J. **683**(2), 1217 (2008).

[4] J. D. Lindl et al., Phys. Plasmas **11**(2), 339-491 (2004).

[5] R. Fäustlin et al., Phys. Rev. Lett., accepted (2010).

[6] R. Fäustlin et al., J. Inst. **5**(02), P02004 (2010).

[7] B. Ziaja et al., Phys. Rev. Lett. **102**(20), 205002 (2009).