Measurement of preheat due to nonlocal electron transport in warm dense matter

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This work presents a novel approach to study electron transport in warm dense matter. It also includes the first x-ray Thomson Scattering (XRTS) measurement from low-density CH foams compressed by a strong laser-driven shock at the OMEGA laser facility. The XRTS measurement was combined with VISAR and optical pyrometry (SOP) providing a robust measurement of thermodynamic conditions in the shock. Evidence of significant preheat contributing to elevated temperatures reaching $17.5-35$ eV in shocked CH foam was measured by XRTS. These measurements were complemented by abnormally high shock velocities observed by VISAR and early emission seen by SOP. These results were compared to radiation hydrodynamics simulations that include first-principles treatment of nonlocal electron transport in WDM with excellent agreement. Additional simulations confirmed that the x-ray contribution to this preheat is negligible.

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The thermodynamic properties and dynamic behavior of materials at extreme conditions of high energy density (HED) states are relevant to many astrophysical objects [1] and Inertial Confinement Fusion (ICF) [2]. A particularly problematic state is Warm Dense Matter (WDM) defined by moderately high temperatures of 0.1–100 eV, solid densities, and pressures above 1 Mbar. Under such conditions, ions are strongly correlated and the electron population is partially or fully degenerate making the theoretical description of WDM very challenging. Thus robust measurements of the equation of state (EOS), structure and transport properties of WDM are crucial to the understanding of many processes in the formation and structure of astrophysical objects such as Jovian planets or white dwarfs as well as the dynamics of the ICF implosions [3, 4]. Heat and radiative transport through various layers influences the layer structure and convection of astrophysical objects, and electrical conductivity strongly affects magnetic fields generated by planetary core dynamos [5]. Alternative fusion schemes such as fast ignition rely on heating of fusion targets by energy deposition of electrons [6, 7]. Preheat of target components due to x-rays and energetic particles in laser-driven HED systems is a well-known problem causing changes in initial conditions and multiple hydrodynamic instabilities in EOS and ICF experiments [9]. Specifically electron transport in dense laser-heated plasmas holds the key to understanding many fundamental questions [10].

Despite great challenges, much progress has been made in the theoretical description of structure, EOS as well as transport properties of WDM [11, 12]. Examples of remarkable work include *ab initio* quantum molecular dynamics (QMD) simulations obtaining thermal conductivity of warm dense hydrogen [13], resistivity saturation in warm dense Al [14], and charged particle stopping powers, and transport has been described both by using pure theory as well as with molecular dynamics (MD) simulations [15, 16]. The concept of nonlocal electron transport modeling in hydrodynamic simulations was first introduced to compute the delocalization strategy of the classical diffusion approach [17]. This model had a great impact and led to a consequent improvement of the hydrodynamic simulations in experimental data prediction. It was not until much later that the first attempt to include a real nonlocal transport model retaining on a first-principles approach based on kinetics came and addressed the necessity of using the proper physics [18].

In this article we present our recent work where we utilize a platform previously developed for direct measurements of temperature and shock velocity in order to study nonlocal electron transport in WDM [19]. The analysis of our data showed that the stronger drive used in this experiment caused nonlocal electrons to preheat the CH sample. A detailed theoretical study confirmed that this effect leads to observed shock velocities and temperatures well above those expected without preheat. In past years, there have been some experiments measuring the transport properties of electrons in dense plasmas [23] and radiation transport in standard materials [24, 25], however no full characterization including complete measurement of plasma conditions with *in situ* measurements of transport coefficients has been achieved to date. A newly established diagnostic technique of x-ray Thomson Scattering (XRTS) opens a novel path towards studying structure and transport properties in WDM [26]. XRTS is capable of obtaining information about temperature, density, ionization state as well as microscopic properties of dense plasmas. If combined with other diagnostics such as velocity interferometry (VISAR), streaked optical pyrometry (SOP) or radiography, it can then provide a comprehensive measurement of thermodynamic properties of WDM [19, 27].