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Resistivity and anisotropic return currents in warm dense plasmas

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In an ultra-intense laser interaction with a solid, the electrons from the hot plasma are accelerated to extreme energies by the laser and stream into the solid material behind, creating a warm, dense matter in the bulk. This provides a laboratory method for creating matter in states like those believed to occur in brown dwarf stars and larger exoplanets[1]. Material resistivity and equation of states are fundamental and crucial to determining the structure of these systems[2]. Heat transport models at high density and pressure are complex[3,4,5] and need testing. Here we describe an experimental study of electron transport in plastic at solid density and temperatures of 200 eV. Through doping the plastic with sulphur and observing the polarisation of emitted x-rays, we observe anisotropic current distributions that drive the heat transport. Matching the measured current anisotropy enables the first tests of resistivity models. Our experimental measurements show a high, positive x-ray polarisation and that the Spitzer[6] like model under-estimates the resistivity. This suggests that the background resistivity in dense plasmas, and at the centre of a brown dwarf star, is higher than one would determine from commonly used models.

Intense laser interactions with matter provide us with the ability to probe the conditions present at the core of dense stars in the laboratory. Brown dwarfs are an unusual case, as they occupy the same mass range as the larger exoplanets, whilst having been formed in the same manner as stars. An upper limit on the mass of brown dwarfs has been defined as ~0.07 solar masses[7] , whilst the minimum mass for hydrogen burning is 0.1 solar masses, and as such they lie below this hydrogen burning limit. The resistivity and EOS of these low mass systems are incredibly complex and require detailed modelling, and in order to further understand these systems it is necessary to reproduce these conditions in the laboratory. Our experiment was performed using the Vulcan Petawatt laser at the Central Laser Facility; with on target intensities of ~5×10^{20}Wcm^{-2} with sulphur-doped plastic targets ($C_{27}H_{26}O_6S$) (for the full description of the experimental set-up, including laser parameters and diagnostics see figure 1 and methods section). Plasma polarization spectroscopy provides us with a powerful method of probing the electron transport inside warm dense plasma environments[8,9,10]. In these ultra-intense laser plasma interactions, beams of relativistic hot electrons are driven from the interaction region[11] into materials of much higher density. Measuring the degree of polarization provides a close link with anisotropy in the electron distribution function (EDF)[9,10,12] and we use this study of electron anisotropy to evaluate the resistivity generated in the regime applicable to the study of brown dwarfs.

The degree of polarization of x-rays emitted in this ultra-intense interaction was measured with an orthogonal pair of Bragg HOPG crystals and is calculated by $P = \frac{I_\pi - I_\sigma}{I_\pi + I_\sigma}$ [8], and the sign of the polarization indicates whether it is due to electrons with energies close to or far exceeding the excitation potential. The quantisation axis for our experiment is defined as the direction of the free electron and when we view the bound electron as a classical oscillator, a low-energy free electron will perturb the bound atomic electron with an electric field that is mostly parallel to the quantisation axis. As a result, the atomic electron will oscillate accordingly and emit π-polarized dipole radiation (i.e. $P>0$). In contrast, a hot free electron will exert a pulse of electric field that is perpendicular to the quantisation axis as it passes the atom, causing the bound electron to oscillate and emit σ-polarized radiation (i.e. $P<0$).

From observations of the Ly-α transitions of sulphur from our doped plastic target, we obtain a polarization, $P=+0.16\pm0.04$, obtained from the data shown in Fig. 2 (see methods section). This is a high positive polarization indicating the presence of beams of cold electrons in the return current at this energy. As we have observed $P>0$ experimentally, we have explored the non-equilibrium, non-thermal velocity distribution of the return current to allow us to put constraints on the simulations with a technique that is insensitive to the depolarising influence of the cool and isotropic part of the return current.

These measurements are modelled using a combination of plasma hybrid electron kinetics and atomic magnetic sub-level population kinetics simulations using the codes ZEPHYROS[13] and POLAR[15] (see methods section). By using this combination of models for polysulphone, we obtain a zero dimensional estimate of the polarization, $P=+0.14$ for an EDF with three electron populations and temperatures[14]; background temperature $T_b=200$eV, return current temperature $T_{rc}=600$eV, and hot electron fraction $\alpha=0.0032$. ZEPHYROS models the plasma conditions with different resistivity models and comparisons have been made of the electron temperature profiles for both the Spitzer[6] and Lee-More[3] models with a variety of initial conditions. By varying these start conditions; we obtain a resistivity model which gives an electron temperature profile that most closely matches the experimental observations.

By varying the inputs to the codes, we find that there is a balance to be achieved between T_b, T_{rc} and α that maximises the degree of polarization. If T_b is too high, the depolarizing Maxwellian electrons will equilibrate P towards zero and equally if T_{rc} is too low the beam is ineffective in driving anisotropy. The depolarizing effect of the isotropic background electron population becomes significant as T_b increases and depolarisation starts to dominate once T_{rc} rises above and moves away from the collisional excitation energy of the Ly-α_1 transition (ΔE=2.6keV). The ZEPHYROS simulations for these EDF parameters are shown in Fig. 3 and in the region shown heating is dominated by Ohmic heating of the target via the anisotropic return current.

Simulations performed of the electron temperature profile with different resistivity models are shown in figure 4. As we have seen, the region responsible for heating the plasma to the K-shell, Ly-α transitions arise from a region in the plasma heated to approximately 200eV. In the first case of a standard Lee-More based model starting with a minimum mean free path of 2×r_s (where r_s is the inter-atomic spacing) we can see that the plasma has a volumetric region at 200eV large enough to dominate the polarization. However this situation becomes much clearer with models where we impose a higher resistivity at low temperatures (e.g. the second case of a Spitzer model with a 50eV start, which shows a much larger volume at 200eV than arises from the Lee-More case) than the resistivity one would calculate from a straightforward application of the Lee-More model. These simulations show us that the observed polarisation is much more clearly reproduced in cases where the resistivity curve is higher at lower temperatures. Resistivity models with an overall lower resistivity than the standard Lee-More based model with a minimum mean free path of 2×r_s would not agree well with our experimental results. Since the modelling of EOS and resistivity in the case of brown dwarfs is so complex, it is clearly necessary to consider in more detail the resistivity curves used in such modelling.

Through a combination of experimental measurements of inner shell x-ray polarimetry and 3-D particle hybrid and atomic kinetics modelling, we have demonstrated measurements of an anisotropy generated in return current electron distributions during ultra-intense laser-matter interactions. The measurements show large positive polarizations in atomic transitions with excitation potentials at 2.6keV respectively and our interpretation indicates that this arises from a non-equilibrium state in the electron distribution of the return current at these energies. The use of our unique combination of computational models allows us to observe a beam-like return current, with primary responsibility for the observed degree of polarization. Further, this is the first observation of resistivity models in detail in plastic in comparison with experimental data and demonstrates that a highly resistive model at low temperatures is necessary to obtain the level of polarization that we observe, and indicates that the background resistivity in dense plasmas, and at the centre of a brown dwarf star, is higher than one would determine from commonly used models, and needs much more careful consideration.

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Author Contributions

The experiment was conceived by N.C.W., G.G. and P.P.R. The experiment, planning and analysis were carried out by N.B. and N.C.W. with contributions from R.J.C., D.D., L.A.G., G.G, P.K., L.L., T.L., B.L., M.M., J.P., P.P.R., D.R., E.W. R.J.D. and J.N.W. Simulations were carried out by A.P.L.R., P.H. and R.C.M. N.B., P.H., A.P.L.R., P.P.R and N.C.W. prepared the manuscript.

Figure 1. The generation of polarised x-rays in an ultra-intense laser-plasma interaction. The target geometry of a high intensity ($I \approx 5\times10^{20}$ Wcm^{-2}) pulse, incident on a foil target produces polarised x-rays. These polarised x-rays are recorded by an orthogonal pair of HOPG crystals positioned above the target (not to scale) to measure each polarisation independently in a single shot.

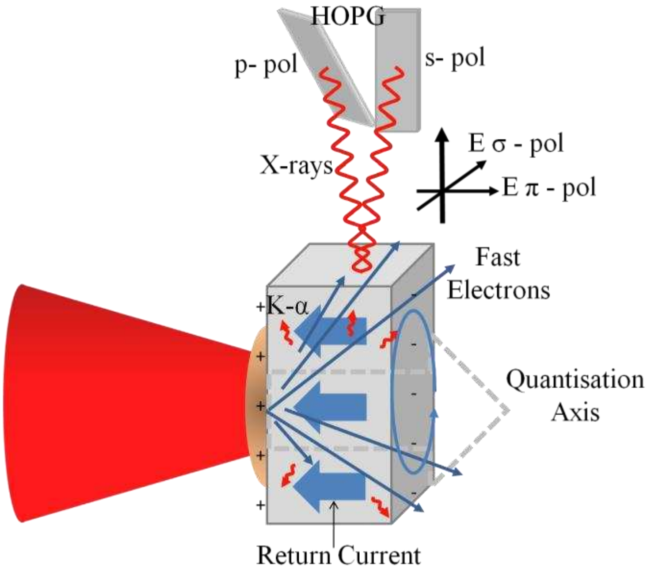


Figure 2. Shows the X-ray spectrum from 25μm thickness PS targets for π-polarised X-rays (–) and for σ-polarised X-rays (······). The degree of polarization observed in the He-α and K-α_1 lines differ from those of the Ly-α, as these lines are a result of interplay between direct collisional excitation within the He-like ion as well as electron capture from the ground state[15].

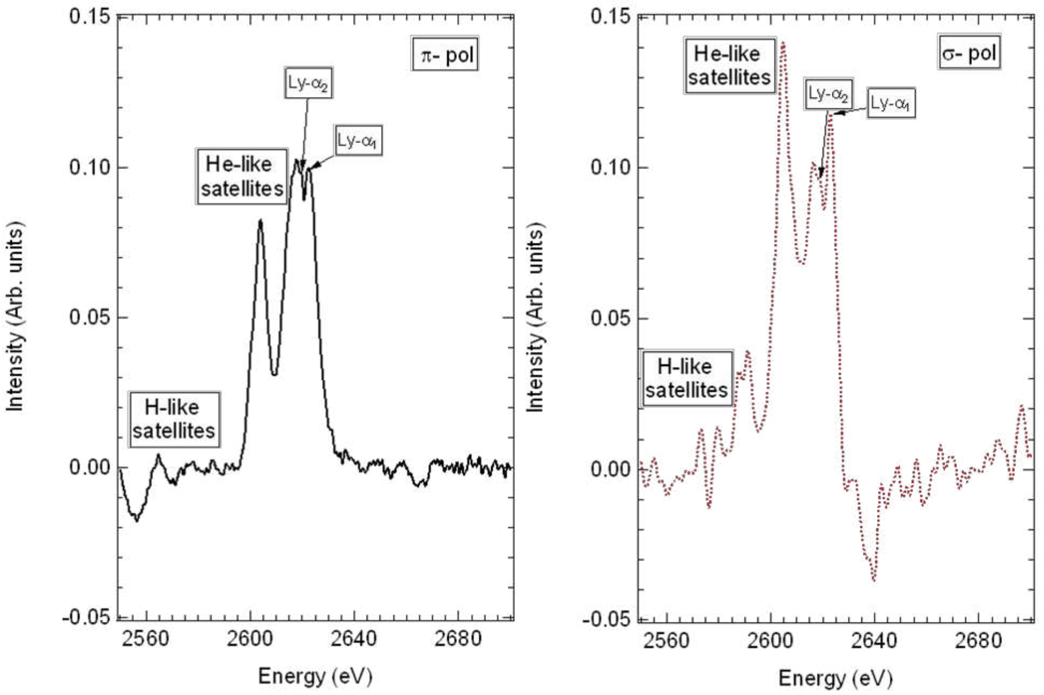
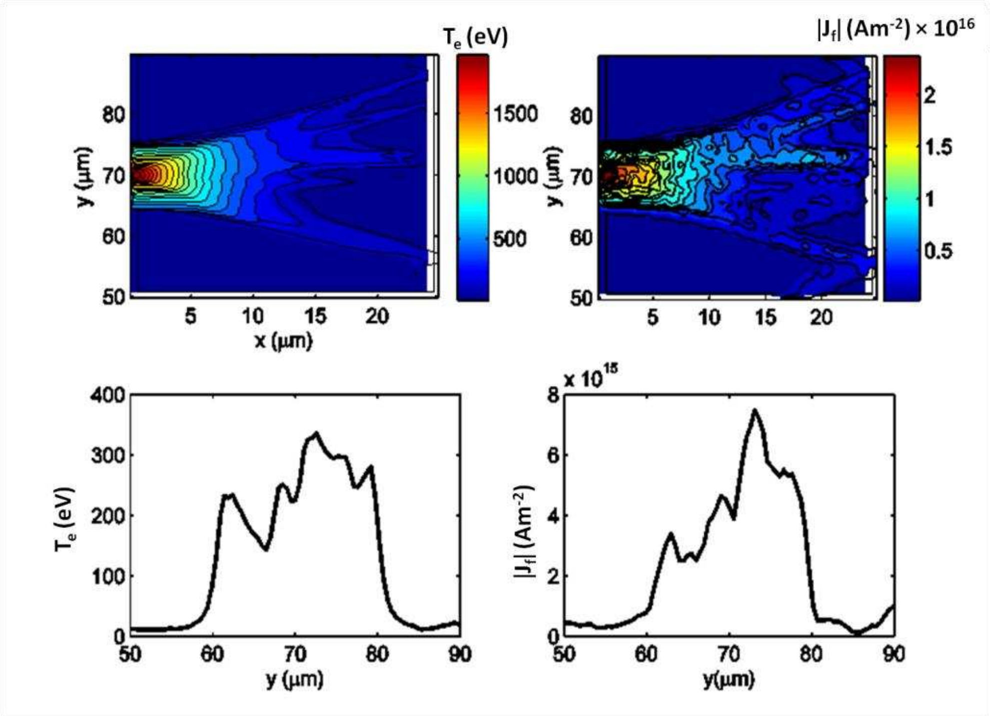
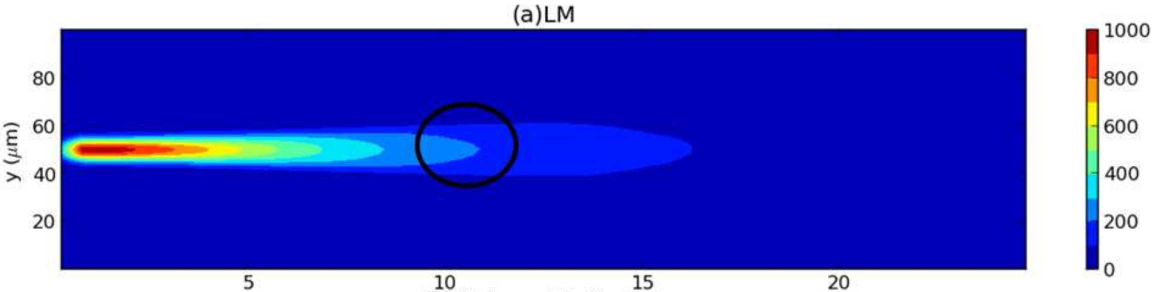
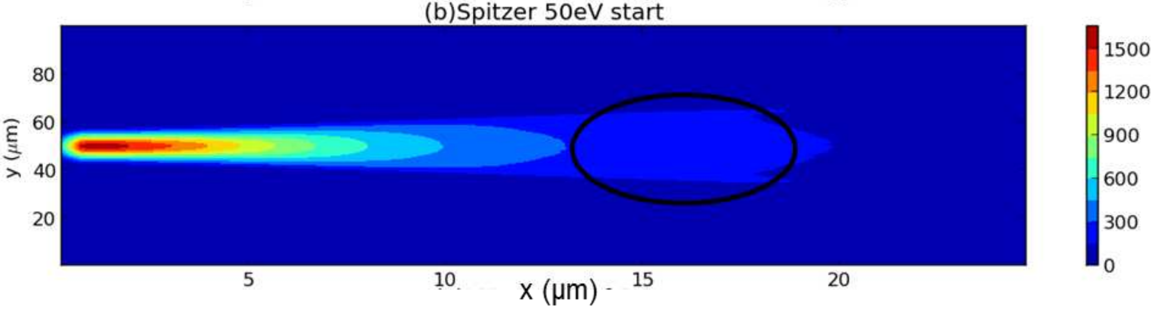


Fig. 3 ZEPHYROS simulations of the sulphur target conditions using a combination of plasma hybrid electron kinetics and atomic magnetic sub-level population kinetics to obtain the plasma parameters T_b = 200 eV, T_{rc} = 600 eV, and α = 0.0032.





(a)LM



(b)Spitzer 50eV start

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