White Paper for *Frontiers of Plasma Science Panel*

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Title:	Developing first-principles temperature measurements of Ultrahigh Density Plasmas
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- ***Describe the research frontier*** **and importance of the scientific challenge.**

We are proposing the development of inelastic x-ray scattering from plasmon oscillations for first-principles temperature measurements of ultrahigh density ($\rho \sim 40$ g/cm^3; $n_e \sim 10^{25}$ cm^{-3}) plasmas at near-degenerate conditions. Such states of matter are encountered, for example, in astrophysical objects [1] and in inertial confinement fusion (ICF) [2,3] capsule implosions close to stagnation. An accurate understanding of plasmas at extreme densities is therefore highly desirable, yet this regime – often referred to as warm dense matter (WDM) - is challenging to model because of the high degree of correlations between the plasma constituents. Atoms are tightly squeezed together causing atomic orbitals to overlap and giving rise to new phenomena like ionization potential lowering. It is thus very important to provide high quality experimental measurements of high-density plasma conditions that can serve as benchmarks for plasma modeling efforts. First, it is a challenge to create such states of matter in a controlled and repeatable fashion. To date, the National Ignition Facility (NIF) [4] is the only machine where such conditions can be reached in a laboratory setting. Secondly, an accurate measurement of the temperature of near degenerate matter remains a particular challenge. These systems are optically thick for any significant transition or bremsstrahlung emission from the bulk. X-ray Thomson scattering (XRTS) at photon energies high enough to penetrate plasmas at solid density and above has been developed to diagnose density and temperature of bulk plasmas [5,6]. However, in the widely used non-collective regime (Compton scattering from individual electrons), near or at electron degeneracy the shape of the

Compton profile has only weak or no sensitivity to the electron temperature T_e. A much more accurate T_e measurement can be done in the collective scattering regime, where x-rays scatter of plasma oscillations [7]. Such measurements are extremely difficult (see below), but increasing the plasma density (by ~ 10x compared to previously published experiments on the Omega laser) favorably extends the parameter range (in terms of E_{photon} and scattering angle), where high-quality plasmon scattering measurements are possible. At extreme densities, the ionization potential depression [8-10], a fundamental phenomenon in plasmas caused by the free charges perturbing the ionic potential, can approach and exceed the K-shell binding energies (of Be), which is expected to lead to pressure ionization of K-shell electrons. At the same time, the Fermi energy (~150 eV) will become comparable as well. In the highly degenerate states, which are achieved at the NIF in indirectly driven capsule implosions, Pauli blocking by occupied electron states below the Fermi energy might significantly alter the ionization balance. The proposed experiments will therefore test ionization potential depression modeling not only at densities almost 10x higher than any experiment before, but also in a qualitatively different regime. Ionization balance modeling is crucial to the understanding of high energy density matter as it determines many important plasma properties.
The work proposed here will greatly advance the scientific frontier by providing a novel temperature measurement capability for conditions of great interest to the dense matter community and that can only be reached at NIF. The data interpretation relies on the principle of detailed balance and will provide a benchmark not only for dense plasma modeling, but also for all other techniques of this field.

- ***Describe the approach to advancing the frontier and indicate if new research tools or capabilities are required.***

X-ray Thomson scattering (XRTS) has been developed over the last decade [5,6] at laser facilities around the world, in particular the Omega laser [8,11-13], the Jupiter laser facility at LLNL [14,15], and using Free Electron Lasers like FLASH [16] and LCLS [17,18]. These experiments have demonstrated XRTS as a robust and flexible diagnostic capability for temperature, density, charge balance and structure factors over a wide range of plasma conditions. Only recently, our collaboration has started to develop XRTS measurements at the NIF [19,20]. In particular, a suitable high-efficiency x-ray spectrometer for XRTS for a Zn He-α x-ray source at 9 keV was built and fielded [21]. Current efforts aim at developing an optimized platform for XRTS measurements in the non-collective regime at 120˚ scattering angle, see Fig. 1(a). First NIF experiments have demonstrated the measurement of high quality XRTS data from imploding CH capsules [22]. We are in the process of designing a drive to achieve electron densities near 10^{25} cm^{-3} close to stagnation of an imploding ICF capsule (Fig. 1(b)). The predicted temperatures (50 – 100 eV) are below the Fermi energy (~ 150 eV), and the plasma is therefore nearly degenerate, where the T_e sensitivity of the shape of the Compton profile is weak.
To achieve better sensitivity to T_e, the experiment has to be conducted in the collective regime where x-rays are scattered from plasmons, i.e. electron plasma oscillations. The collectivity parameter, defined as $\alpha = 1/(k\lambda_{scr})$ with λ_{scr} the screening length, and $k = 4\pi(E_{ph}/hc)\sin(\theta/2)$ the momentum transfer in the scattering process, enables to discriminate between the collective ($\alpha > 1$) and the non-collective scattering regimes ($\alpha < 1$). α mainly depends on the x-ray probe energy E_0, the scattering angle θ, and the plasma conditions. The inelastic collective scattering signal consists of two plasmon features, up- and down-shifted by $\hbar\omega_{res}$ from the quasi-elastic Rayleigh signal (see Fig. 2 for conditions expected in the NIF experiments). The up-shifted plasmon is reduced by a factor of $\exp\{-(\hbar\omega_{res})/(k_B T_e)\}$ compared to the down-shifted feature as given by detailed balance [11] which is a powerful tool to measure T_e since it is based on first principles. In addition, the plasmon shift $\hbar\omega_{res}$ depends on n_e and T_e and thus provides an additional electron density measurement.
In order to access the collective scattering regime in the proposed NIF experiments requires reducing the scattering angle to 30˚ or below. The related challenges require (1) obtaining sufficient angular resolution, $\Delta\theta/\theta$ (and thus $\Delta k/k$), and (2) the development of narrow bandwidth x-ray sources and high-resolution spectrometers to resolve the spectrum of collective plasmon oscillations shifted from the incident x-ray

energy by about 100 eV. The larger target and laser energy scales on the NIF help to fulfill these requirements: (i) an increase of the standoff distance of the x-ray source from the hohlraum center will reduce the k-vector blurring ($\Delta k/k$) while keeping the x-ray photon flux on the sample comparable to previous Omega experiments. (ii) In addition, we will utilize a Cu K-edge filter (K-edge at 8.979 keV) to reduce the x-ray bandwidth, $\Delta E/E_{photon}$, of the Zn He-alpha line to < 0.5%. This will improve the spectral purity of the x-ray source by a factor of two over previous capabilities and will allow to clearly resolving the plasmon signals from elastic scattering.
While we are confident that the currently achievable x-ray source brightness of ~ 0.2 TW/sr, based on 1% backlighter conversion efficiency into Zn He-a [23], is sufficient to record high-quality collective scattering spectra, future experiments would benefit from further backlighter optimization. First promising results from high-brightness x-ray source development efforts at the NIF have been published [24]. The described approach can be extended to higher Z elements/ higher photon energies, which are required for diagnosing higher-Z (than Be) samples at high compression. Conceptually it is straightforward to include an additional dispersive element (e.g. Bragg crystal) to create a narrowband, well-collimated x-ray source.

- ***Describe the impact of this research on plasma science and related disciplines and any potential for societal benefit.***

In summary, the development of collective x-ray scattering on plasmons envisioned for the NIF will greatly enhance the scientific capabilities of high-density plasma community, specifically enabling temperature measurements in nearly degenerate plasmas based on first principles. It will greatly enhance our scientific understanding of extremely dense plasmas at pressures, where experimental data are scarce and where x-ray probing never has been attempted. The proposed measurements will help improving the modeling of astrophysical objects and of ICF capsule implosion, where these states of matter are encountered. This proposal is currently unique to the NIF, because only the NIF allows producing compressed samples at conditions of interest at large enough volumes, which are required to obtain high-quality scattering data within a single shot.

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Figures

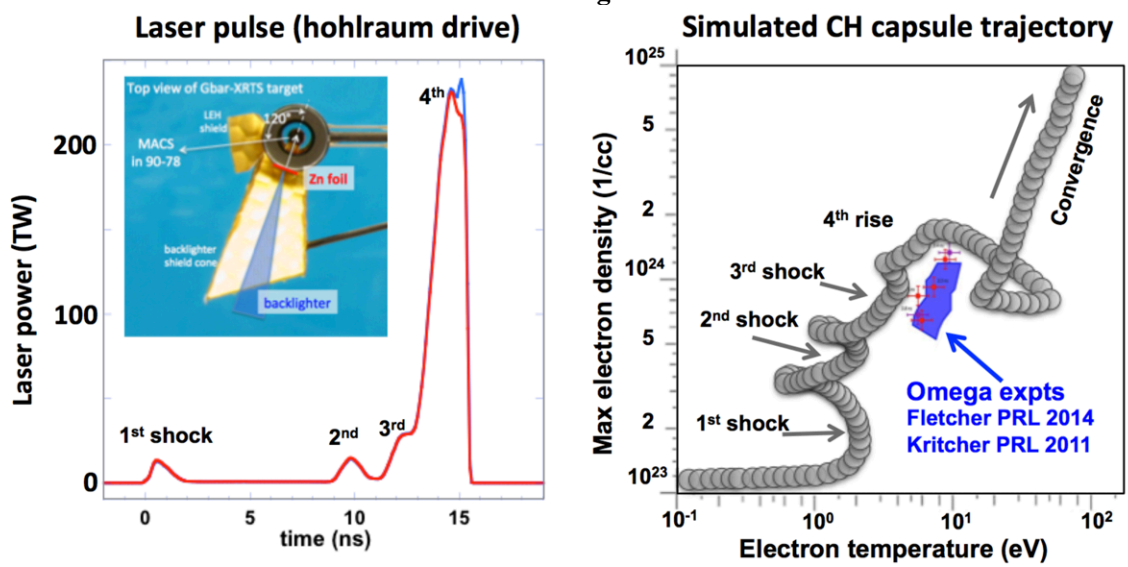

Fig. 1: left: NIF target for x-ray Thomson scattering (XRTS) measurements from an imploding ICF capsule, indirectly driven by a 4-shock laser drive. Right: Simulated CH capsule trajectory in n_e-T_e space in comparison to previous experiments on the Omega laser. At stagnation ~10x higher electron densities are predicted at the NIF ($n_e = 10^{25}$ cm^{-3} corresponds to a Fermi temperature of 170 eV).

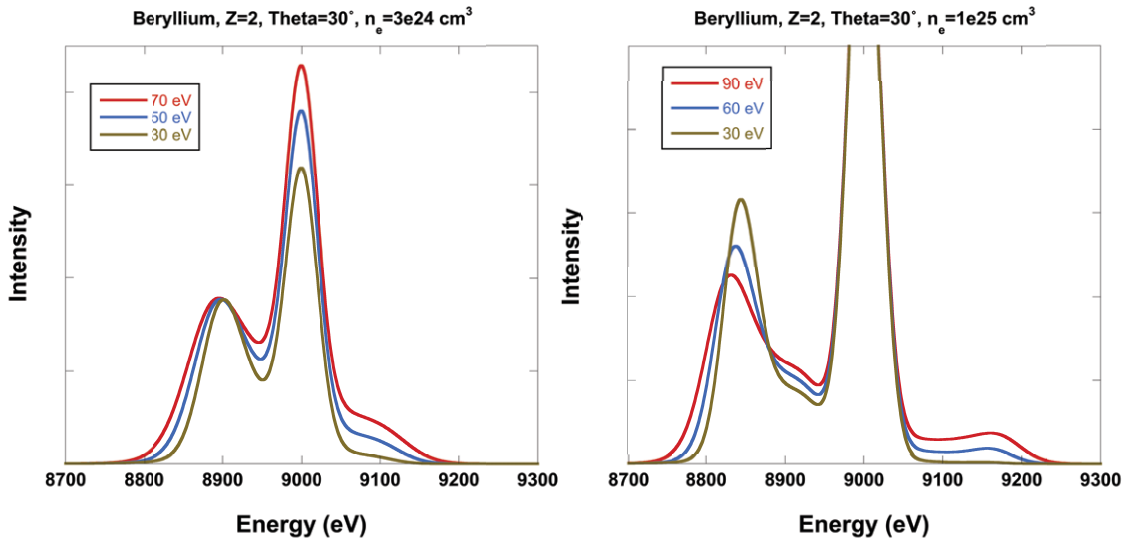

Fig. 2: Inelastic forward x-ray scattering spectra show a strong plasmon resonances downshifted in energy >100 eV. With increasing temperature up-shifted plasmons occur as a signature of detailed balance. The intensity ratio of the two inelastic plasmon scattering features provides temperature from first principles. In addition, the plasmon energy shift is sensitive to the electron density thus providing highly accurate density measurements; here the leading term in the dispersion relation is the plasma frequency. These measurements allow to accurately characterize dense plasma states where no previous experimental data exists.