Platform for spectrally resolved x-ray scattering from imploding capsules at the National Ignition Facility

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Abstract. We present a new experimental platform to perform spectrally resolved x-ray scattering measurements of ionization, density and temperature in imploding CH or beryllium capsules at the National Ignition Facility. Scattered x-rays at 9 keV from a zinc He-alpha plasma source at a scattering angle of 120 degrees are highly sensitive to K-shell ionization, while at the same time constraining density and temperature. This platform will allow for x-ray scattering studies of dense plasmas with free electron densities up to 10^{25} cm^{-3} giving the possibility to investigate effects of pressure ionization and Pauli blocking on the ablator ionization state right before or shortly after stagnation of the implosion.

1. Introduction

A precise knowledge of ionization at given temperature and density is crucial in order to properly model compressibility and heat capacity of inertial confinement fusion (ICF) ablator materials for efficient implosions producing energy gain [1]. Spectrally resolved x-ray scattering [2] has been proven as outstanding tool to characterize such dense plasma parameters and experiments at the OMEGA laser facility of University of Rochester on directly driven beryllium and plastic (CH) capsules could investigate electron densities up to $10^{24}\,\mathrm{cm}^{-3}$ [3, 4]. With the availability of the National Ignition Facility (NIF), these studies can be extended to much higher densities: The experimental platform presented here aims for densities approaching and eventually exceeding $10^{25}\,\mathrm{cm}^{-3}$. These states of matter are strongly affected by pressure ionization and, besides ICF, highly relevant for modeling astrophysical objects like brown dwarfs and stars [5]. These conditions can currently only be accessed experimentally at NIF [6, 7].

2. Experiment

Our approach utilizes all 192 beams of the NIF laser: 184 beams are focused into a standard ICF hohlraum to implode and compress a CH or beryllium capsule and 8 beams are directed to a zinc foil in order to create intense Zn He-alpha line emission at 9 keV as x-ray source for

Journal of Physics: Conference Series **717** (2016) 012067 doi:10.1088/1742-6596/717/1/012067

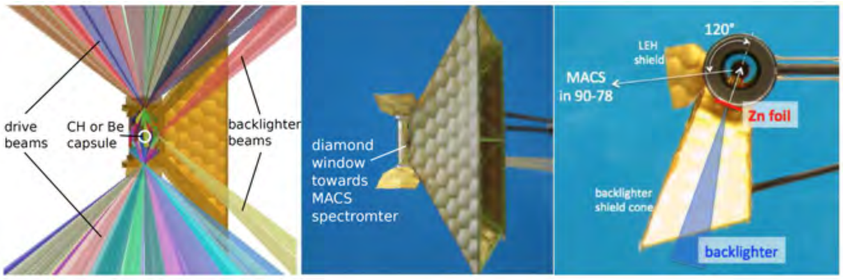

Figure 1. Target design of the new experimental platform to measure x-ray Thomson scattering from imploding capsules on the National Ignition Facility. X-rays created by irradiation of a Zn foil attached to the hohlraum wall are guided by a gold cone towards the imploded sample. The highly efficient MACS spectrometer records the scattered photons in the equatorial plane. Left: schematic showing the laser pathways onto the target. Middle: side-view of finished target. Right: top-view of finished target.

the scattering diagnostics (see Fig. 1). The x-rays are guided onto the imploding capsule by a gold cone which sticks into the hohlraum and initially holds the capsule [8]. Scattered x-rays can escape from the hohlraum through a diamond window of 80 μm thickness at a scattering angle of 120 degrees in the equatorial plane. The areal size of the window can be adjusted to the expected size of the imploding capsule at the time of probing. An additional larger diamond window on the opposite side ensures that the scattered x-rays are not overlaid by continuum or line emission from the gold hohlraum wall. The scattered x-rays are collected by the highly efficient Mono Angle Crystal Spectrometer (MACS) which can apply different HOPG crystals as dispersive element towards a 4-strip gated x-ray detector (GXD) [9]. A cylindrically curved crystal focusing the signal on a single strip allows for maximum collection efficiency, but is limited to a single probe time in the experiment. A flat crystal illuminates all four strips and thus can probe four different times in the implosion while providing 10x less scattered intensity on a single strip compared to the cylindrically curved crystal. An intermediate solution can be obtained by a two-segment cylindrically curved crystal focusing the collected x-rays on two strips of the GXD and thus giving the possibility to probe the implosion at two different times while delivering reasonable signal levels. The spectrometer is protected from a direct line-of-sight to the Zn source plasma by a gold cone that is mounted onto the hohlraum wall. It extends 12.5 mm from target chamber center in order to prevent the plasma plume from being imaged onto relevant areas of the MACS detector.

For the analysis of the x-ray scattering signal, it needs to be considered that the whole plasma volume that is reached by the source radiation and is visible to the spectrometer contributes to the measured spectrum. Thus, a three-dimensional analysis scheme has been developed which accounts for spatial gradients by volumetric and density weight as well as absorption losses inside the probe volume [10]. In previous work, we found that density-weighted averages of density, temperature and ionization as single parameters can describe the scattering spectrum of such an inhomogeneous target reasonably well as long as opacity losses in the imploded capsule are not significant [11].

The left panel of Fig. 2 shows conditions which can be achieved in a standard low-adiabat ICF implosion at the maximum density in comparison to previous experiments at the OMEGA laser facility. Highest densities approaching $10^{25}\,\mathrm{cm}^{-3}$ are present in the final convergence phase very close to stagnation. The right panel of Fig. 2 shows radial profiles of density and temperature close to stagnation of the implosion. In order to limit the sensitivity of the x-ray scattering diagnostics to the most dense regions, scattering from the low density coronal plasma needs to

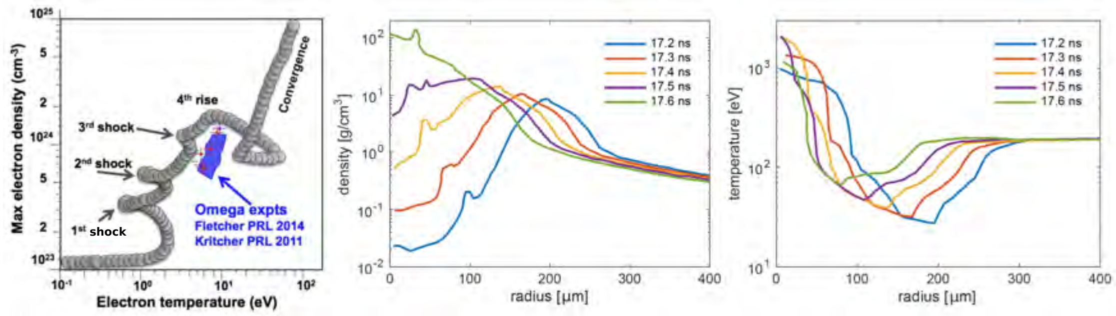

Figure 2. Left: conditions at maximum electron density in an exemplary CH four-shock low adiabat ICF implosion. Middle: radial density lineouts approaching stagnation. Right: radial temperature lineouts approaching stagnation.

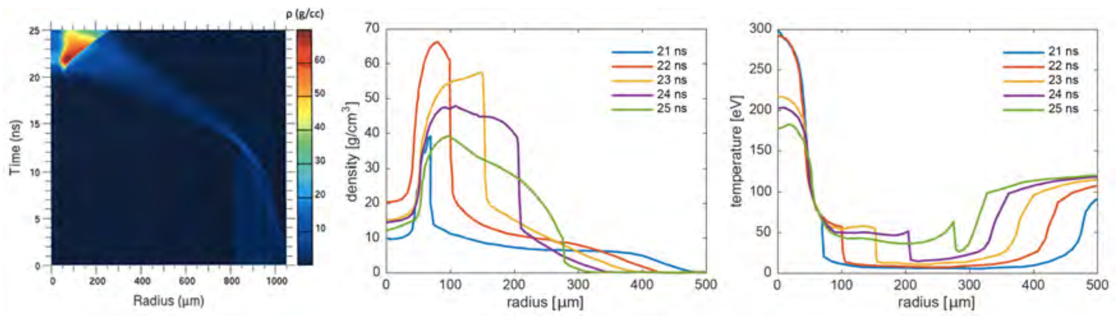

Figure 3. Left: one-dimensional simulation results of density at given radius and time of a beryllium capsule driven by using a truncated ICF pulse shape. Middle: radial lineouts of electron temperature at given times around stagnation. Right: radial lineouts of density at given times around stagnation.

be shielded. This is achieved by a corresponding opening of the cone which holds the capsule as well as the diamond window dimensions in the hohlraum wall. These dimensions can be adjusted depending on the exact timing during the implosion that will be probed in the experiment.

Figure 3 shows simulations for beryllium capsules using a drive which is optimized for achieving relatively homogeneous conditions at high densities and moderate temperatures. In order to realize this, the driving pulse is strongly truncated resulting in a reduced implosion velocity. The inward moving material is then accumulating around the central hot spot which does not exceed temperatures of 300 eV due to the slow implosion. The outgoing shock produces relatively homogeneous conditions in density and temperature.

Beryllium is a useful material to study pressure ionization of K-shell electrons: Since inner-shell electrons are more weakly bound than in carbon, ionization potential depression will have a stronger effect on K-shell ionization for given density and temperature compared to carbon. Moreover, as a single component system, modeling of scattering spectra is generally simpler than for CH. Figure 4 shows the effect of ionization potential depression with increasing density at zero temperature using the interpolation formula by Stewart and Pyatt (ΔI_{SP}). At electron densities around 10^{25} cm^{-3}, ΔI_{SP} exceeds the single atom ionization potential for Be^{3+}, meaning that beryllium would be fully ionized at this density. At the same time, the Fermi energy of the free electrons reaches comparable values. This starts to suppress ionization since the state, where an additional free electron would end up after an ionization process, might already be occupied

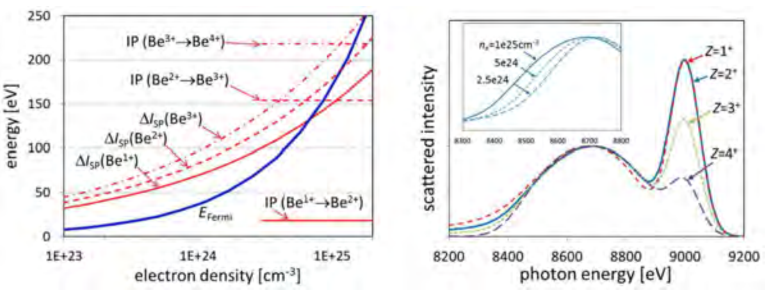

Figure 4. Left: comparison of ionization potentials, ionization potential depression given by the Stewart-Pyatt formula, and Fermi energy for beryllium. Right: Simulated scattering spectra for various charge states and for different electron densities (inset).

(Pauli-blocking). The right panel of Fig. 4 illustrates the sensitivity of spectrally resolved x-ray scattering to ionization and density of dense degenerate beryllium plasma. The elastic scattering is dominated by scattering from K-shell electrons and thus highly sensitive to K-shell ionization. The inelastic scattering from the electrons is shifted by the Compton energy and broadened by the energy distribution of the electrons. For a dense degenerate plasma, this is given by a Fermi distribution and hence, the width of the inelastic feature is strongly sensitive to density. For higher temperatures, the distribution steadily transforms into a Boltzmann distribution where the width is set by temperature. Thus, in the intermediate regime of dense degenerate plasmas with finite temperature, sensitivity to both density and temperature can be achieved by spectrally resolved x-ray scattering.

3. Conclusions

The presented platform allows for unique studies of pressure ionization effects in ICF ablator materials at extreme densities. The applied scattering diagnostics is strongly sensitive to K-shell ionization while at the same time constraining density and pressure. First experiments will be performed using well-tested standard ICF drives for CH capsules to demonstrate the functionality of the platform. Further experiments will then use an optimized drive for beryllium capsules in order to achieve relatively homogeneous conditions at extreme densities and moderate temperatures.

Acknowledgments

This work was performed with the assistance of Lawrence Livermore National Laboratory (LLNL) under Contract DE-AC52-07NA27344 and supported by Laboratory Directed Research and Development (LDRD) grants 11-ER-050 and 13-ERD-073. RWF and DK acknowledge support from SSAA program Contract No. DE-FG52-06NA26212.

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