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Study of the Ionization Dynamics and Equation of State of a Strongly Coupled Plasma

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Abstract

Preliminary experiments to study the ionization dynamics and equation of state of a strongly coupled plasma have been performed at the LLNL COMET laser facility. In these experiment, a 1.0 J, 500 fs, 532 nm laser was used to create a uniform, warm dense plasma.The primary diagnostic, Fourier Domain Interferometry (FDI), was used to provide information about the position of the critical density of the target and thus the expansion hydrodynamics, laying the ground work for the plasma characterization. The plasmas were determined to be strongly coupled. In addition work was performed characterizing the back-lighter. A von Hamòs spectrograph coupled to a 500 fs X-ray streak camera (TREX-VHS) developed at LLNL was used for these measurements. This diagnostic combines high collection efficiency ($\approx 10^{-4}$ steradians) with fast temporal response ($\approx$ 500 fs), allowing resolution of extremely transient spectral variations. The TREX-VHS will be used to determine the time history, intensity, and spectral content of the back-lighter resulting in absorption measurements that provide insight into bound states in strongly coupled conditions.

Key words: Strongly coupled plasma, opacity, short pulse laser

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1 Introduction

The development of high intensity, short pulse lasers offer a new way to study high energy-density plasmas[1]. When short pulse, <1 ps, lasers with intensities in the range of 10^{15} to 10^{16} W/cm^{2}are used to illuminate solid targets impulse heating followed by rapid heat conduction produces a high density, high temperature plasma with little hydrodynamic expansion. Although transient, the plasma parameters generated by heating solids with short pulse lasers can result in physical states that are difficult to achieve using other techniques. In these plasmas, the temperature is relatively low (< 100 eV) while the density remains its initial value, in the present case close to solid. The result is a state where the interparticle shielding becomes insufficient to neutralize the charge of the individual ions, a state that can be characterized by the dimensionless parameter Γ, defined as the ratio of the particle potential energy to the kinetic energy:

$$\Gamma_{ii} \equiv \frac{\langle PotentialEnergy \rangle}{\langle KineticEnergy \rangle} = \frac{\bar{Z}^2 e^2}{r_i K_B T}; r_i = \left(\frac{3}{4\pi N_i} \right)^{1/3}. \tag{1}$$

When Γ approaches 1 the ions become correlated and the bound states begin to overlap in such a way that is difficult to predict ionization balance. Here we report on a new experimental technique to study the ionization balance in dense, moderate to strongly coupled plasmas. The technique uses an ultra short pulse laser to create a thin, high-density plasma slab with small gradients in density and temperature. A temporally long X-ray pulse is used to backlight the slab and the time resolved absorption spectra is gathered with an X-ray streak camera.

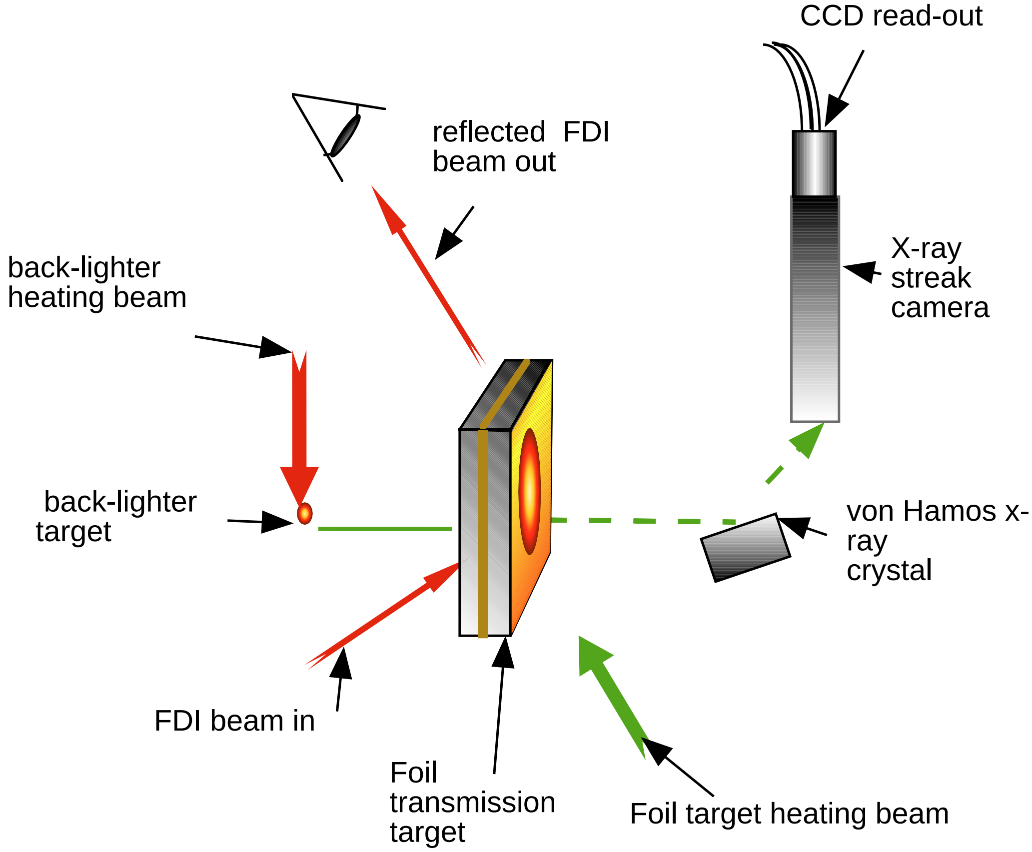
The plasma characteristics are inferred from Fourier Domain Interferometry (FDI) measurements of the expansion velocity of the critical surface. The measured expansion velocity is compared to simulations to extract the plasma parameters. We discuss preliminary results that suggest the potential of this technique for future experiments.

2 Experimental Setup

The experiment was performed at the COMET facility using one 500 fs beam, one 50 ps beam, and one 600 ps beam. The experimental layout is shown in Fig. 2.

The source of all three beams is a 100 fs, Ti:Sapphire oscillator. The oscillator pulse is temporally stretched using chirped-pulse amplification (CPA)[2] and

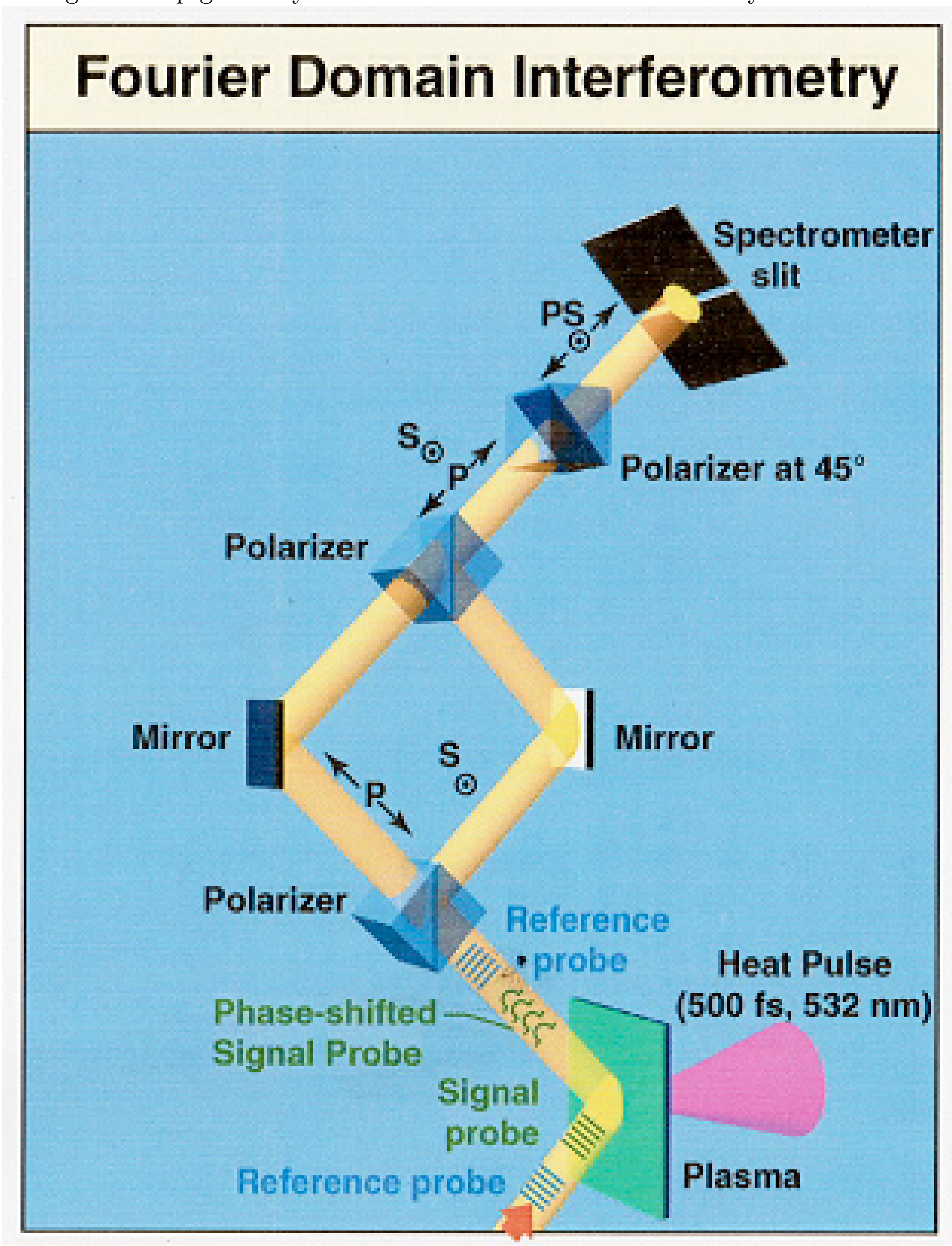
Fig. 1. Layout for the experiment



amplified to produce a 1.2 ns, 350 mJ beam. Before further amplification, a small portion of the beam was extracted to provide a laser probe pulse for the FDI using a beam splitter. The remaining beam is amplified in a mixed Nd:phosphate chain. After the Nd:phosphate amplifiers, the beam has an energy $>$ 11.0 J and a pulse duration $\approx$ 600 ps. At this point in the chain a second beam splitter is inserted to create two beams, a 5.0 J beam, frequency doubled, and used for the X-ray back-lighter. The remaining 6 J beam is recompressed to 500 fs, frequency doubled (to 2.7 J) and used to heat the target. A delay line was placed between the 600 ps back-lighter beam and the 500 fs heating beam to synchronize the peak X-ray emission from a long-pulse heated back-lighter target with the 500 fs pulse used to heat the foil. Both beams were frequency doubled to 532 nm. The long pulse back-lighter beam was focused with a lens to a spot size of 10 μm, producing a peak focused intensity of 1 x 10^{15} W/cm^2. The short pulse beam was focused with an off-axis parabola to a spot size of 400 μm, producing a peak focused intensity of 1 x 10^{15} W/cm^2.

The FDI is based on a Mach-Zehnder configuration. The interferometer uses S and P polarized light to produce spatial interference fringes by overlapping and tilting the relative wavefronts of beams of opposite polarization [3,4] as shown in Fig. 4.

Fig. 2. Setup geometry for the Fourier Domain Interferometry measurement



A beam splitter is used to reflect a small portion of the 700 ps long stretched pulse into an air compressor. The pulse is compressed to approximately 50 ps, sent through a half-wave plate, then reflects off the target surface. After reflection the pulse passes through a lens that images the target surface onto the entrance prism of the Mach-Zehnder interferometer with a magnification of 3.5. The polarizations are separated at the prism, propagated along their respective path lengths, and recombined with a second prism. The arms are adjusted to produce a spatial tilt between the two relative wave fronts of perturbed and unperturbed beams of opposite polarization. The entrance prism is imaged onto the slit of a 1-m Czerny-Turner spectrometer with a magnification of 4. The heating pulse is timed such that target heating occurs during the probe pulse reflection off the target surface, resulting in a fringe shift that is proportional, to first order, to the motion of the reflecting surface.

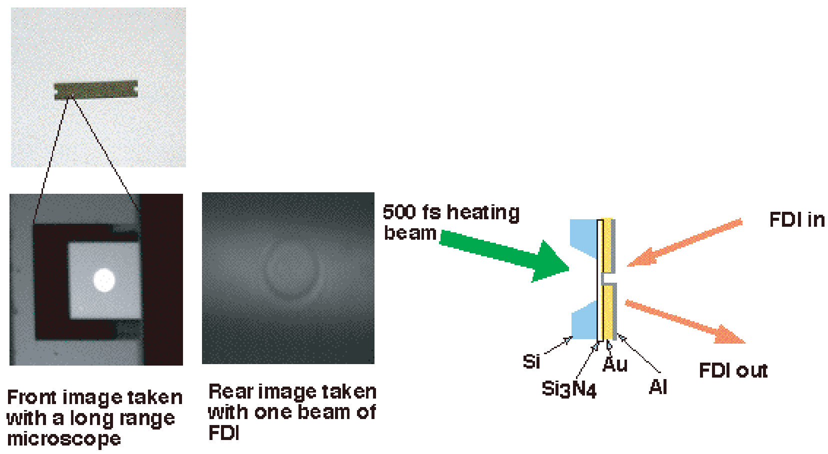
The X-ray back-lighter characterization data were collected using a 3 cm radius cylindrical potassium hydrogen phthalate (KAP) crystal interfaced to a fast X-ray streak camera arranged in the von Hamòs geometry[5]. The X-rays emitted from the Eu/Gd/Sm/Nd "cocktail" back-lighter were focused into the 25.4 mm long, 120 μm wide slit of the X-ray streak camera. The spectral coverage was from 8.4 Å to 7.4 Å, allowing the observation of the aluminum absorption features from the He-like to O-like ions. The signal brightness was increased with a 40 mm diameter image intensifier, reduced with a 2:1 fiber optic reducer, and displayed using a fiber optic coupled, 1024 x 1024 CCD camera interfaced to a computer. Assuming a 150 μm upper bound on the swept spatial resolution, the spectral resolution was estimated to be 0.006 Å providing a resolving power of E/ΔE=1200-1400. The streak camera used in the experiment has a 500 fs temporal resolution and was operated with a sweep-speed of 1.42 ps/mm, resulting in 72 ps of temporal data per shot. As indicated in Fig. 2, the back-lighter was oriented such that the emitted X-rays propagated through the foil and were viewed normal to foil surface.

Optical quality smoothness was required on the target surface to perform the FDI measurements. This was achieved by coating Si_3N_4 on one side of a 500 μm thick, 5 mm wide, 50 mm long silicon wafer. After coating, the silicon was etched from a 2 mm x 2 mm square area, leaving an optically flat, 250 ÅSi_4N_3 window (see Fig. 2).

The targets were fabricated by first coating 5000 Åof Au on the entire window except a 300 μm central region, leaving a small clear aperture in the center of the foil. Next the window was coated with 500 Å of aluminum on the Au side. Finally, carbon was added to the Si_3N_4 of the target to eliminate direct laser heating of the Al sample. Later, some target were sandwiched with an additional 350 Åcarbon layer to reduce the Al expansion. To minimize the chamber venting/pumping cycle, five foil targets were etched into a single wafer, spaced by 8 mm. This proved to be unsuccessful as all the targets on one wafer were destroyed in a single shot due to propagation of a shock along the wafer surface.

The back-lighter targets were coated with 1 μm of Eu/Gd/Sm/Nd cocktail (in equal amounts by weight) along the edge of a 50 mm long aluminum wedge. The cocktail-coated edge was placed 1.5 mm away from the rear surface of the foil target.

Fig. 3. Setup geometry for the Fourier Domain Interferometry measurement



3 Data and Analysis

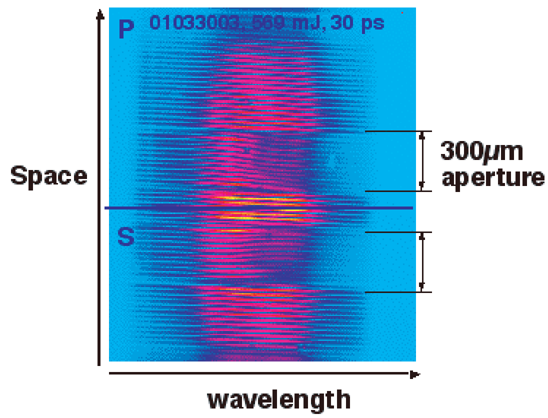
The phase shift data gathered with the FDI was used to determine the expansion velocity of the reflecting surface. Knowing the expansion velocity, the density and temperature was inferred by comparing the experimental results to hydrodynamic simulations performed using the 1-D hydrodynamic codes FILM[6] and LASNEX[7].

3.1 Fourier Domain Interferometry

Phase shift data obtained with the FDI diagnostic is displayed in Fig. 4.

The FDI data was analyzed using a reconstruction routine written to deconvolve the time and frequency components intertwined by the linear chirp[3]. The phase shift difference between the S and P polarized beams is used to determine the plasma gradient scale length[4]. The time-dependent phase of the reflected light is simulated using the hydrodynamics code FILM. Further simulations were performed using the hydrodynamics code LASNEX. From the slope of the phase We can determine the sound speed assuming uniform temperature on the back target and an exponential density profile. Assuming

Fig. 4. Raw FDI data



Z=5 and knowing the slope we infer the temperature. The deconvolved phase data suggest a plasma with the temperature displayed in Fig. 3.1, where we show the temperature conditions are for the plasma at the rear of the foil, $\approx$ 1 ps after the heating pulse.

The density close to solid during this period, even at the higher intensity ($\approx 0.5\,\rho_0$).

3.2 Back-lighter characterization data

Because of the high sweep-speed, the path length of X-rays of different energy reflecting off the crystal results in a time delay between the lower energy X-rays and the higher energy X-rays. When corrected, the result is a temporal sweep across the spectral range of interest. This effect limits the temporal window to $\approx$30 ps where one can simultaneously observe the charge states from O-like through Be-like. In Fig. 3.2 we show data from a samarium back-lighter.

The back-lighter was generated using a 532 nm, 600 ps pulse focused to 1×10^{15} W/cm^2. The samarium emission suggests too much spectral structure exist in this spectral regime. The spectral structure is dominated by M-shell unresolved transition array (UTA) emission from the various materials. By

Fig. 5. Temperature vs laser intensity

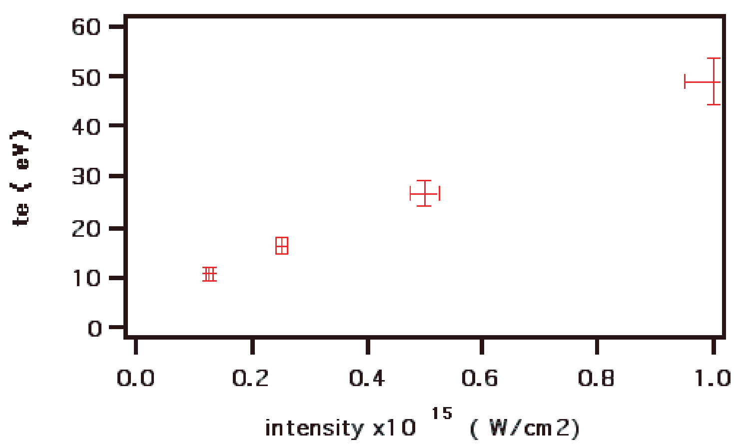


Fig. 6. Emission from the Sm back-lighter

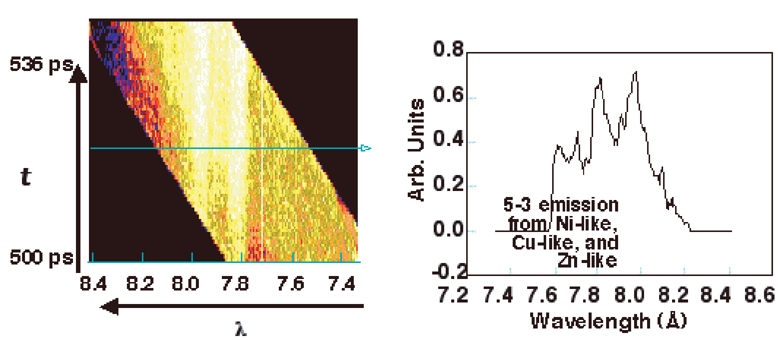
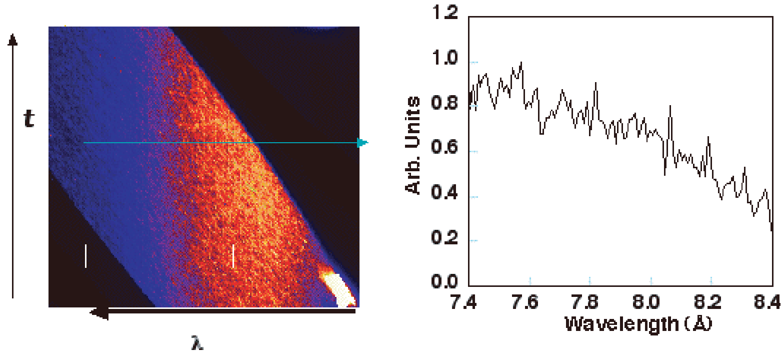


Fig. 7. Emission from the cocktail back-lighter



post-processing hydrodynamic data from the hydrodynamics code LASNEX with the atomic physics package STA (Super Transition Array)[8], the UTAs were identified as emission from the 5-3 manifolds of Ni-like, Cu-like, and Zn-like samarium. By adding the Eu, Gd, and Nd, the spectral structure was dramatically smoothed (see Fig. 3.2).

The average temporal variation over the spectral window was found to be 10 % over the duration recorded. The spectral structure was found to be consistent shot to shot.

The final step in the experiment will be to perform the absorption measurements. These experiments are scheduled for the summer of this year (FY03). Future work will make comparisons with both LTE and NTLE calculations.

4 Conclusions

We have performed preliminary experiments on formation of plasma in the moderate to strongly coupled regime using a novel technique. Using FDI, the plasma parameters are deduced from the expansion velocity by comparing measured phase shift data to values calculated using hydrodynamics codes. Additionally, we have completed the characterization of the back-lighter for these experiments. The back-lighter characterization data shows a Eu/Sm/Gd/Nd "cocktail" produces a spectrally uniform emission in the 8.2-7.2 Åregime.

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