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Abstract

Preliminary experiments using a long pulse laser generated X-ray source to back-light a short pulse laser heated thin foil have been performed at the Laboratoire pour l'Utilisation des Lasers Intenses (LULI) at Ecole Polytechnique in France. In these experiment, a 2 J, 300 ps, 532 nm laser was used to create the X-ray back-lighter. The primary diagnostic was a von Hamòs spectrograph coupled to a 500 fs X-ray streak camera (TREX-VHS) developed at LLNL . 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 was used to determine the time history, intensity, and spectral content of the back-lighter. The second diagnostic, Fourier Domain Interferometry (FDI), provides 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 moderately to strongly coupled, resulting in absorption measurements that provide insight into bound states under such 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_{ii}. It is defined as the ratio of the particle potential energy to the kinetic energy,

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

where $\bar{Z}$ is the average charge state, T the electron temperature and N_i the ion density. When Γ_{ii} approaches 1 the ions become correlated and the bound states begin to overlap in such a way that it is difficult to predict ionization balance. Using absorption spectroscopy, one can infer the ionization balance in the plasma and compare these measurements to code predictions. Further, the detailed shape of the absorption features provide information about the effects of contiuum lowering and collisional broadening of upper states that are partially filled.

X-ray and laser heated targets have been used for studying bound state absorption in hot, dense plasmas in the past[4][5][6]. Additionally, recent experiments have utilized ultra short pulse lasers for point-projection spectroscopy of expanding plasmas, providing space and time resolved ionformation on the average ionization[7]. These experiments have shown a need for experimental data to test complex absorption theories used to model radiation transport. 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 fairly uniform 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 were inferred from Fourier Domain Interferometry (FDI) measurements of the expansion velocity of the critical surface. The measured expansion velocity was compared to simulations to extract the plasma parameters. We show results from a proof of principle experiment. The experiment demonstrates the ability to measure absorption potassium hydrogen phthalate (KAP) crystal interfaced to a fast X-ray streak camera arranged in the von Hamòs geometry[11]. The X-rays emitted from the samarium 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 7.4 Å to 8.4 Å, looking at the K_α aluminum absorption features between the He-like and F-like ions. The signal brightness was increased with an image intensifier and displayed using a fiber optic coupled, 1024 x 1024 CCD camera. 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 $E/\Delta E$=1200-1400. The streak camera used in the experiment had a 500 fs temporal resolution and was operated with a sweep-speed of 1.42 ps/mm, resulting in 36 ps of temporal data per shot. As indicated in Fig. 1, 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. The low cost of silicon wafers and the ability to readily etch silicon in a controlled manner made it an excellent choice for producing thin foil substrates for targets. This was achieved by coating 250Å of Si_3N_4 on one side of a 500 μm thick silicon wafer. After coating, a mask containing twelve 2 x 2 mm square openings spaced by 500 μm was placed on the silicon side of the wafer. Within each 2 x 2 mm area, the exposed silicon was etched away completely, leaving only an optically flat 250Å Si_3N_4 window within each of the twelve 2 x 2 mm square openings. The windows were next coated with 500 Å of aluminum and 150 Å of carbon on top of the aluminum, sandwiching the aluminum between the carbon and Si_4N_3 to reduce the initial expansion. The back-lighter targets were coated with 1 μm of samarium along the edge of a 50 mm long aluminum wedge. The samarium coated edge was placed 3 mm away from the rear surface of the foil target.

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 one can infer the density, temperture, and thickness of the absorbing layer by matching the experimental phase shifts to phase shifts calculated using hydrodynamic simulations performed using the 1-D hydrodynamic codes FILM[12] and LASNEX[13]. The expansion velocity,the transmitted and incident back-lighter intensities, were measured on seperate shots where the laser intensity was simular.

3.1 Fourier Domain Interferometry

Phase shift data obtained with the FDI diagnostic are displayed in Fig. 3. The time dependent phase of the reflected light was simulated using the hydrodynamics code FILM. The measured phase shift data for three shots are shown in Fig. 4. The measurements are compared with phase shift values calculated using FILM, showing very good agreement. The good agreement found with FILM deconvolved phase data suggest that the plasma follows the dynamics displayed in Fig. 5, where we show the temperature and density conditions as a function of time at the center of the foil. Further simulations were performed using the hydrodynamics code LASNEX. In Fig. 6 we show the corrsponding NLTE and LTE average ionization and the parameter Γ_{ii}. The simulations clearly show that the plasma departs from LTE at late times.

3.2 X-ray Absorption Data

The high sweep-speed and change in X-ray path length with dispersed energy produces a measurable difference in the arrival of the low and high energy X-rays. This effect is illustrated in Fig. 7, where we have illuminated the samarium back-lighter with the 300 fs laser at low irradiance. When corrected, the result is a temporal sweep across the spectral range of interest. This effect limits the temporal window to ≈ 13 ps that simultaneously contains O-like to Be-like charge states. In Fig. 8 we show typical data from the samarium back-lighter. The back-lighter was generated using a 532 nm, 500 ps pulse focused to 10^{15} W/cm^2. The spectral structure is dominated by M-shell unresolved transition array (UTA) emission. By post-processing hydrodynamic data from the code LASNEX with the atomic physics package STA (Super Transition Array)[14], the UTAs were identified as emission from the 4-3 manifolds of V-like samarium around 8.2 Å and the 5-3 manifolds of Ni-like, Cu-like, and Zn-like samarium. The temporal variation of the spectral window of strongest emission was found to be 20 % over the duration recorded. The spectral structure was found to be consistant from shot to shot.

In Fig. 9, we show data plots at delays estimated as 0, 4, 8 and 12 ps after the heating of the foil. For spectral smoothing, the reduced data was averaged over 750 fs. No timing fiducial was used on the streak camera so the heating time was estimated from the absorption features in the data. Due to uncertainty in the thermal background of the CCD, the absolute magnitude of the measured absorption could not be determined. At t=0, the O-like absorption feature has been clipped slightly due to the spectral sweep mentioned above. At this early period, the only features that are destinctive the data are those of the Be-like and Li-like charge states. The data clearly shows a significant amount of Benature of the experiment. Future experiments are planned for NLTE and LTE comparisons.

5 Acknowledgment

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Fig. 1. Layout for the experiment

Fig. 2. Setup geometry for the Fourier Domain Interferometry

Fig. 3. Deconvolved phase (in S and P polarizations) as a function of space along a diameter of the focal spot and time.

Fig. 4. Phase-shift data compared to simulation performed with FILM and spatially dependent conditions at 1 ps

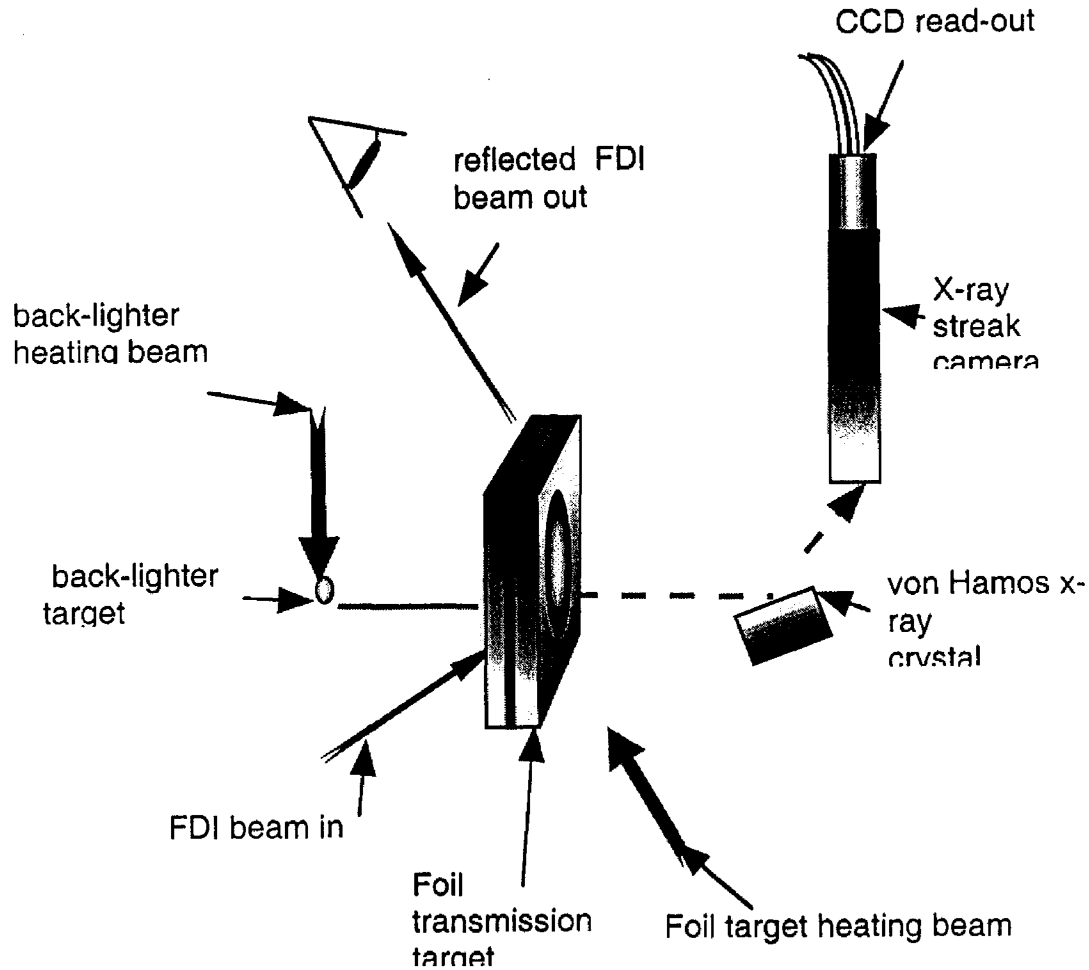
Fig. 5. Time-dependent hydrodynamics of the central cell of the foil

Fig. 6. Comparison of NLTE and LTE average ionization and a plot of the NLTE Γ_{ii}.

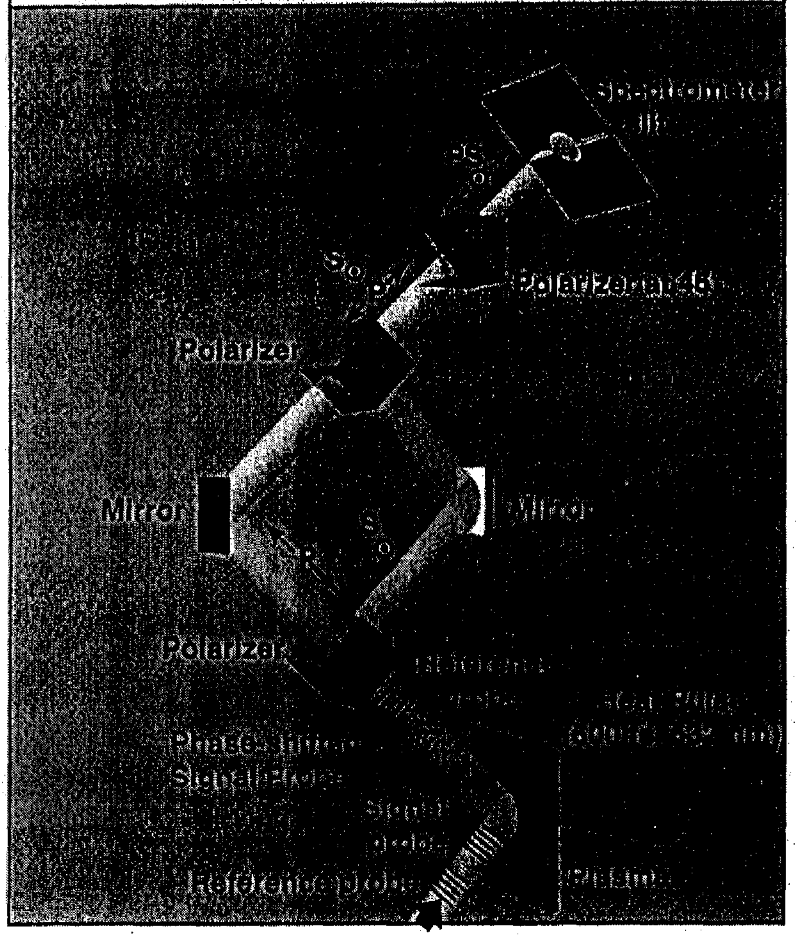
Fig. 7. Streaked samarium spectrum heated with a 300 fs laser pulse at low energy. The high sweep-speed produces a sloped display due to the difference in the transit time of X-rays of different energies. This kind of shot was used to determine the time origin of streaked data.

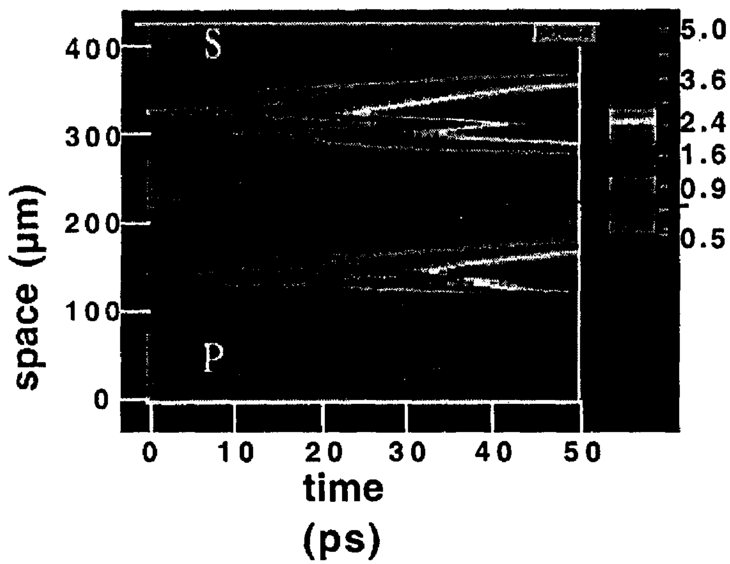
Fig. 8. (Left) Typical data, after time distortion correction, from the time-resolved samarium back-lighter. (Right) Lineout of the spectrum between 7.6 and 8.2 Å.

Fig. 9. Measured transmission at four times and a comparison with the opacity code OPAL at t=12 ps

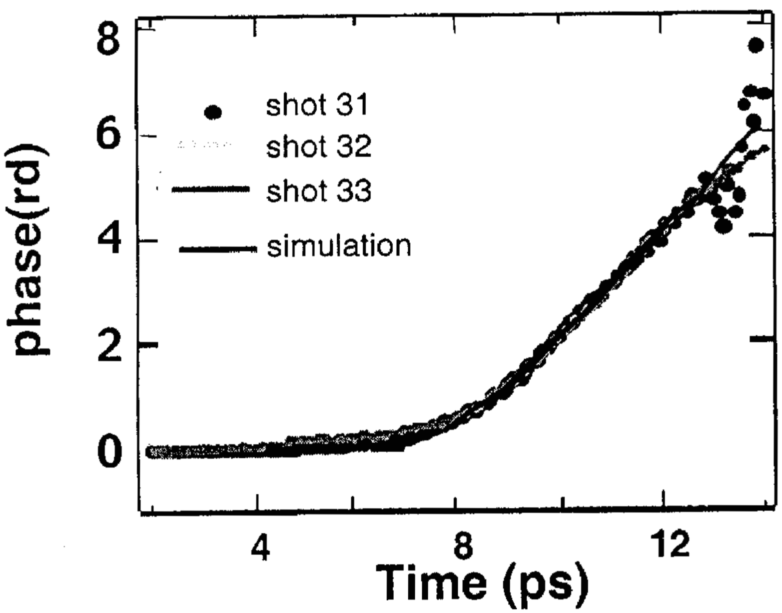

CCD read-out
reflected FDI beam out
X-ray streak camera
back-lighter heating beam
back-lighter target
von Hamos x-ray crystal
FDI beam in
Foil transmission target
Foil target heating beam

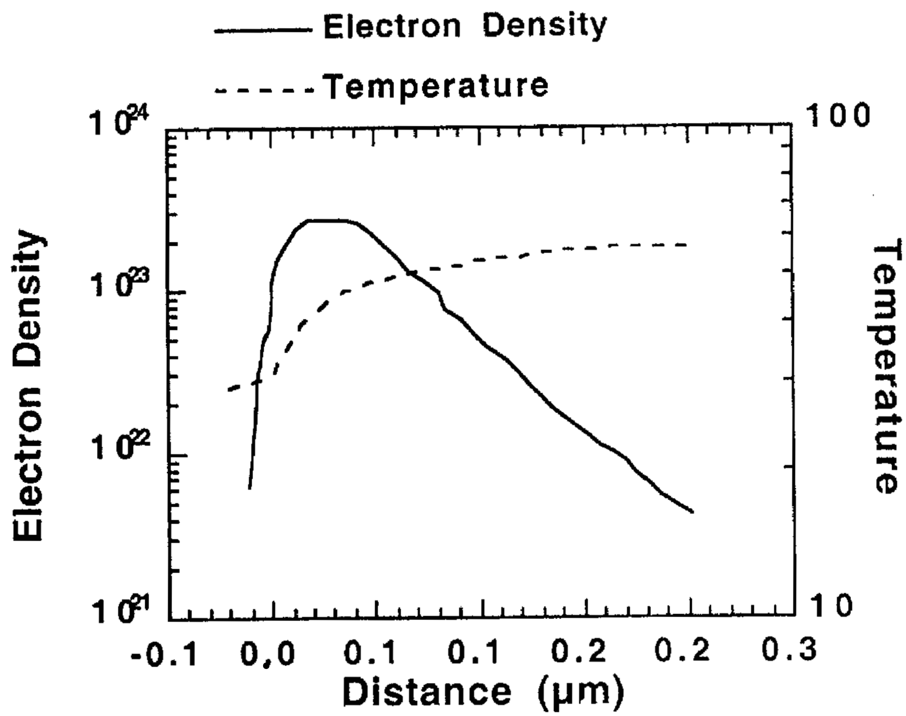
Fourier Domain Interferometry

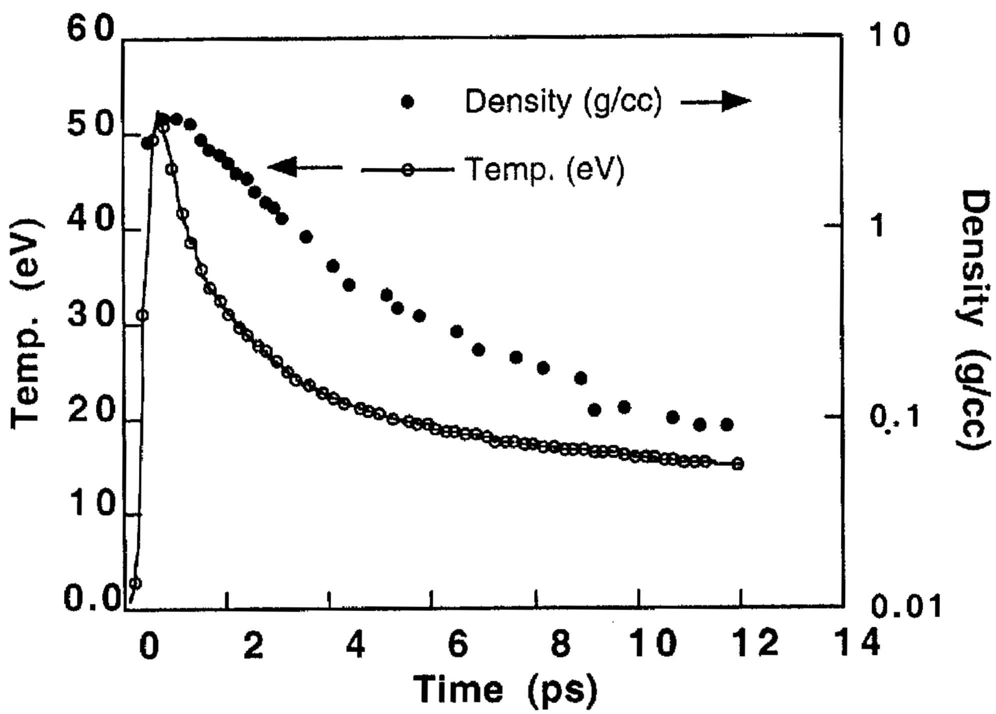


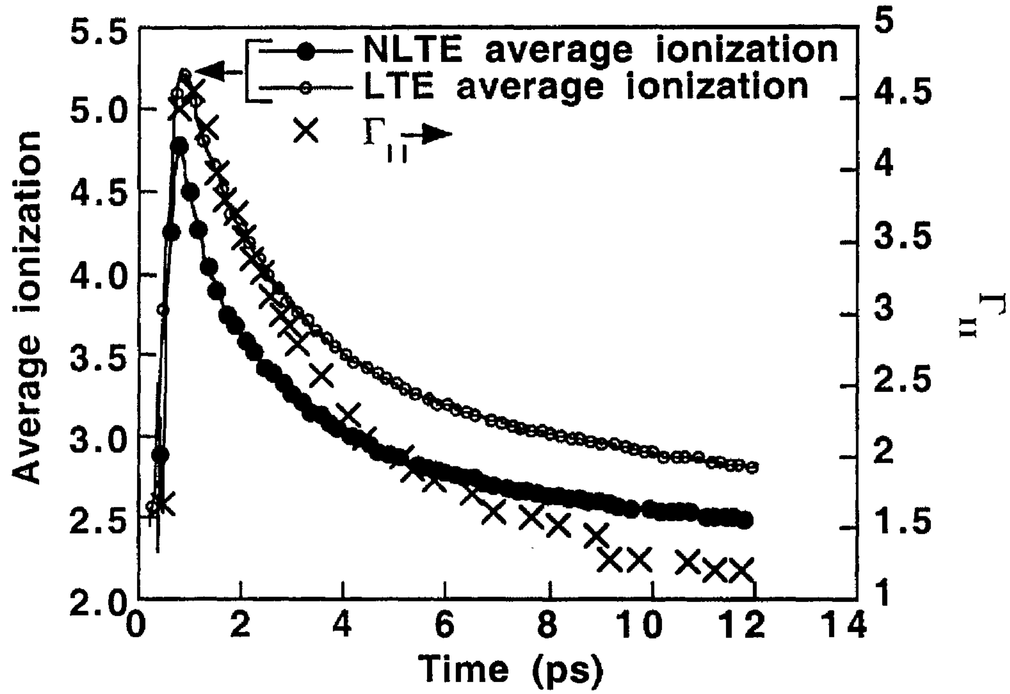


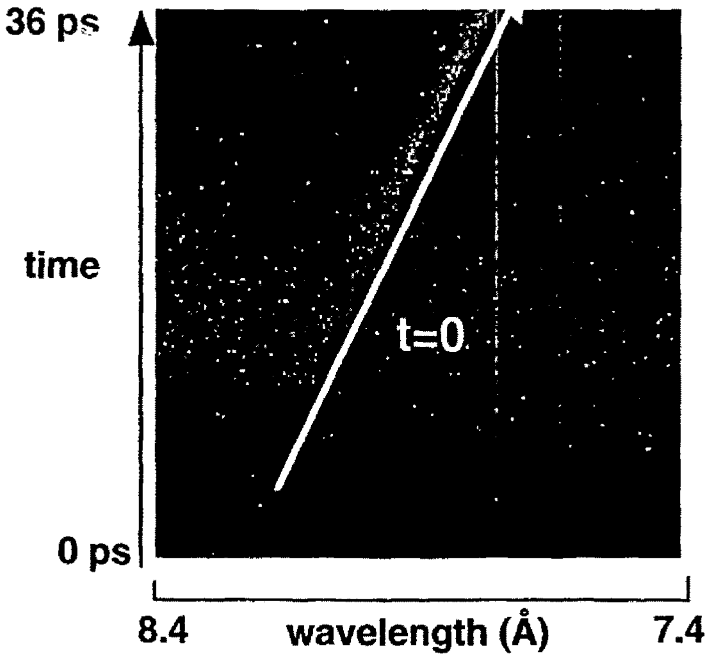
space (μm)
400
300
200
100
0
S
P
0
10
20
30
40
50
time
(ps)
5.0
3.6
2.4
1.6
0.9
0.5


shot 31
shot 32
shot 33
simulation
phase(rd)
Time (ps)

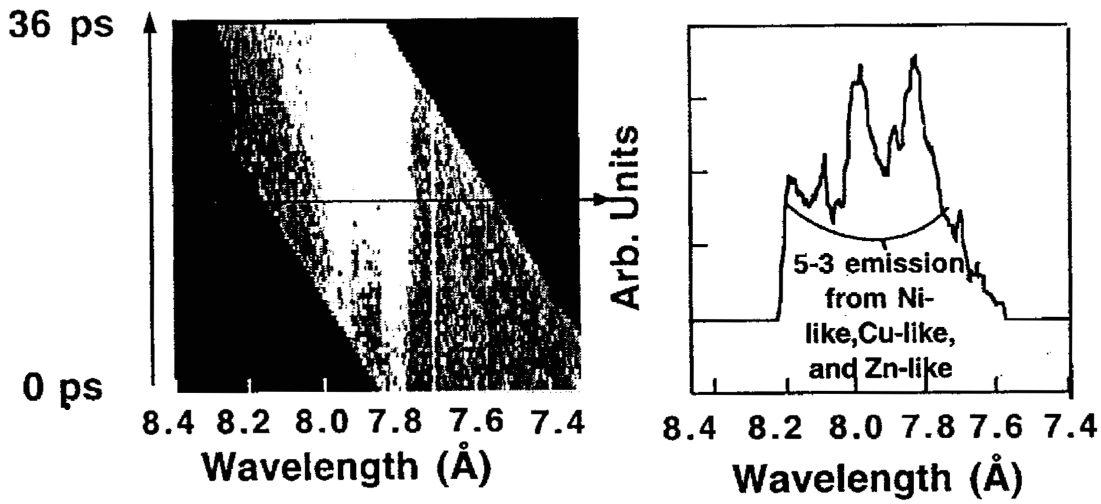

Electron Density
Temperature
Electron Density
Temperature
Distance (µm)

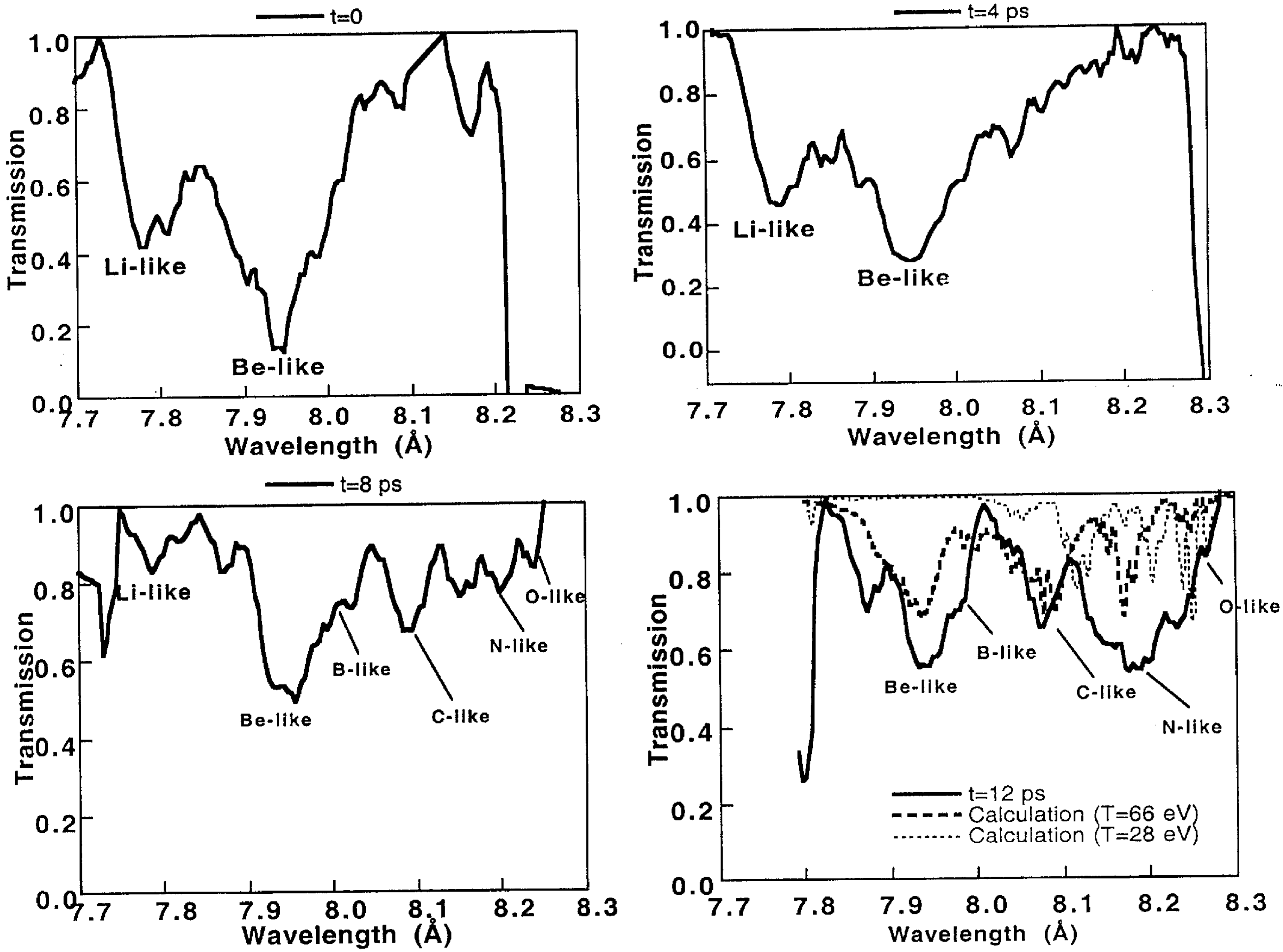

Density (g/cc)
Temp. (eV)
Temp. (eV)
Density (g/cc)
Time (ps)
60
50
40
30
20
10
0.0
10
1
0.1
0.01
0
2
4
6
8
10
12
14


NLTE average ionization
LTE average ionization
Γ_{II}
Average ionization
Time (ps)
Γ_{II}



36 ps
time
t=0
0 ps
8.4
wavelength (Å)
7.4


36 ps
0 ps
8.4 8.2 8.0 7.8 7.6 7.4
Wavelength (Å)
Arb. Units
5-3 emission from Ni-like,Cu-like, and Zn-like
8.4 8.2 8.0 7.8 7.6 7.4
Wavelength (Å)


t=0
Transmission
Li-like
Be-like
Wavelength (Å)
t=4 ps
Transmission
Li-like
Be-like
Wavelength (Å)
t=8 ps
Transmission
Li-like
Be-like
B-like
C-like
N-like
O-like
Wavelength (Å)
Transmission
Be-like
B-like
C-like
N-like
O-like
t=12 ps
Calculation (T=66 eV)
Calculation (T=28 eV)
Wavelength (Å)