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SPECTROSCOPIC ANALYSIS OF THE DENSITY AND TEMPERATURE GRADIENTS IN THE LASER-HEATED GAS JET*


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Abstract

We have performed an analysis of the x-ray spectra produced by a 1.0TW, $\lambda = 0.53\mu$m laser-irradiated gas jet. Plasmas produced by ionization of neon, argon and $N_2\cdot SF_6$ gases were included in those measurements. Plasma electron density and temperature gradients were obtained by comparison of measured spectra with those produced by computer modeling. Density gradients were also obtained using laser interferometry. The limitations of this technique for plasma diagnosis will be discussed.

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For laser fusion targets the characterization of plasma conditions has become a major issue. Because of the large sizes associated with these plasmas interferometric methods are restricted to studying electron densities \(n_e \approx 10^{20} \text{ cm}^{-3}\) (0.1 critical for \(\lambda = 1.06 \mu \text{m}\) wavelength laser). In addition, no viable methods to study temperature gradients have been suggested. In theory, x-ray line spectroscopy can be used to determine both plasma density and temperature gradients in large volume plasmas over a relatively broad regime of \(\text{He}\) and \(\text{Te}\). The spectroscopy method is, however, to some extent, underdeveloped and untested. Fortunately, the KMSF gas jet experiments have provided an excellent opportunity to develop this spectroscopic method. The density gradients have been determined for the gas jet using laser interferometry and to some extent the electron temperature is also known. In this work, we attempt to verify our spectroscopic method by comparison of deduced density and temperature profiles to those determined by other measurements at KMSF.

The experimental method is illustrated in Figure 1. In essence, we attempt to measure the density gradient in one dimension by spatially-resolving He-like line intensity ratios from suitably chosen gases (either pure or a mixture). In the same manner we can determine the temperature gradient by spatially-resolving lines from different charge states, namely, He-like to H-like or Li-like to He-like line intensity ratios.

3\(\overline{\text{Te}}\) time averaged measurements can easily be obtained for a steady-state plasma (which the gas jet reasonably approximates) by spatially-resolving (along the \(Z\) axis) x-ray lines from different ionic charge states. The x-ray lines most frequently observed in laser-produced plasmas stem from \(\text{H}\) and He-like ions. We have computer codes \(^1\) which can accurately calculate the line intensity ratios for transitions from \(\text{H}\) and He-like atoms. The sensitivity of the Lyman alpha \((2P -1S)\) and He-like resonance \((1S2P^0(\text{P})_1 - 1S^2(5))\) line intensity ratio to electron temperature is well known. Particularly for electron temperatures less than 1 keV, the observable, namely the
intensity, is a very sensitive function of temperature. Therefore, even a crude measurement of the intensity ratio can accurately determine electron temperature. Figure 1 then illustrates the measurement principle for the KMSF gas jet experiment. The spatially-resolving (in one dimension) spectrograph averages along its line of sight (perpendicular to laser beam) which means it measures the mean x-ray emission in a plane equivalent to the laser spot diameter which is 120\(\mu\)m for the KMSF experiments. It is relatively easy to achieve spatial resolution on the order of 20\(\mu\)m which is quite sufficient to study 100\(\mu\)m scale length plasmas. We can choose a gas having appropriate sensitivity to almost any temperature regime between 200 eV to 7000 eV. Disk experiments at SHIVA with similar laser intensity and pulse length as proposed here suggest that the plasma only reaches temperature of \(\sim 500\) eV in the region where the maximum line emission occurs (usually at 3-4\(\times\)\(n_{\text{cr}}\)). Gases containing Si, P or S would be ideal for mapping this temperature region. In our first phase experiments we used neon and then argon to bracket the temperature region of interest. If we had overstripped neon we could have used the slope of the free bound emission to estimate temperature. Moreover, if we understrip argon it will be evident from the absence of H-like lines and therefore indicate that we must use a lower Z gas.

\(3\text{Ne}\) time averaged measurements using x-ray line spectroscopy can proceed in several different ways all of which utilize spatial resolution of lines to determine \(N_{\text{e}}(Z)\). Indeed, some of the reasons for developing this technique with the gas jet are so that we can determine which technique is the most practical and accurate. First, if the temperature gradient is known from a separate measurement and it is small (i.e., steady state density conditions) then an absolute line intensity measurement can give the density. Recall that

\[ I_{21} = A_{21} N_2, \]

where the intensity for transition from level \(Z-1\) is \(I_{21}\), \(A_{21}\) is the radiative rate (sec\(^{-1}\)) and \(N_2\) is the level \(Z\) ion population density (cm\(^{-3}\)). \(A_{21}\) is known to reasonable accuracy for most He-like and all H-like transitions, thus an accurate measurement of...
\( I_{21} \) constitutes a measurement of \( N_2 \) which can be related to the ion ground state density and ultimately the plasma electron density. This method has two fundamental weaknesses: 1) we must know the line emission time and 2) the emission volume, both of which are difficult to determine a priori. Perhaps a better technique is to measure the ratio of two lines which is density but not temperature sensitive. V. Boiko, et.al., and other plasma spectroscopists have advocated studying the He-like resonance \( 1S2p(1P_1) - 1S(1S_0) \) to intercombination \( 1S2p(3P_1) - 1S(1S_0) \) line intensity ratio because it is sensitive only to electron density. Figure 2 illustrates the ratio as a function of electron density for various \( Z \) elements. We can thus choose an element having line intensity ratio which is sensitive to the electron density regime of interest. For example, to cover the Ne regime near \( N_{cr} \) for \( \lambda=1.06\mu m \) would require the use of sulphur or phosphorus which conveniently are the same gases we thought might be necessary to make the temperature gradient measurement. To extrapolate, measurements using green laser light, where \( N_{cr}=4\times10^{21} \text{ cm}^{-3} \), could be easily performed using either Cl or Ar gases, and etc. The problems with this method are 1) do we have a high enough \( T_e \) throughout the density scale-length of interest to turn on the lines? and 2) what is the accuracy calculation? Problem 1) is solvable by trying different gases and 2) is directly measurable by comparison to the interferometric determination of \( N_e(Z) \). There are, of course, other density sensitive lines such as the Lyman alpha spectator or doubly excited state transitions, i.e., \( 1S2P \rightarrow 2P^2 \) as well as some of the Li-like lines. The doubly excited state transitions are weak in intensity compared to the He-like transition that are suggested by Boiko and, therefore, may be impractical to use. The Li-like lines are indeed practical, and are studied as part of our gas jet experimental series.

Figure 3 in a color enhanced reproduction of an x-ray pinhole photo filtered to view x-rays at less than 1.0keV. X-rays emitted from the tip of the nozzle are evident on the left hand side of the photo. The x-ray emitting plasma has a "rocket exhaust" appearance typified by flat emission contours on the high density side of the nozzle and more rounded
contours towards the lower plasma density regime (right hand side). A strong transverse (to gas jet long axis) gradient in emission strength is also evident. Presuming a relatively shallow transverse density gradient this could imply a steep temperature profile. Obviously, the time evolution of the plasma must also be considered before full interpretation of the pinhole photo can be accomplished.

Figure 4 represents the increased longitudinal plasma density profile (solid line) as compared to the neutral gas profile. Both profiles were determined by interferometry using transverse probing at a $4\omega_0$ laser frequency. The neutral gas density is modeled as $1/r^2$ from the nozzle tip and as $e^{-r}$ in the near field. Further details of the gas jet density profiles can be determined from the KMSF 1980 Annual Report. Note, that the gas jet produces a rather shallow gradient plasma (L~100 microns). In addition, verify that, as speculated, the interferometry cannot produce plasma density information for $N_e > 3 \times 10^{20} \text{cm}^{-3}$ or roughly $1/3 n_{\text{critical}}$.

Figure 5 represents a typical x-ray spectrum from $\lambda_e=0.56\mu\text{m}$ irradiation of a SF$_6$+H$_2$ gas jet. The ion density of sulfur was small so that the lines are optically thin although this represents a time and spatial average. The "average" temperature derived from an analysis of the H-to He-like line intensity ratios indicates a $T \approx 600 \text{eV}$. This represents a crude estimate, however, since the analysis assumed a uniform temperature and density plasma. A more sophisticated analysis is presented later.

Figure 6 represents a measurement of the variation in electron temperatures along the longitudinal direction in the gas jet. Recall that 1 dimensional x-ray imaging techniques average over variations along the other two space dimensions so that this temperature represents the average for a thin disk like volume whose edge is perpendicular to the imaging spectrograph. The $\rightarrow$ (arrow) is the point in space where the maximum x-ray line intensity occurs. The electron temperatures were deduced using the variation in the Li- to He-like line intensity ratio. Calculation of the temperature variation in these dielectronic satellite spectra has been performed by Bhalla, Gabriel and Presnyakov. These measurements could be influenced by optical depth effects on the He-like resonance line. Preliminary analysis of data indicates that these
optical depths are small, however. These measurements are also influenced by transverse temperature gradients since we average over that dimension. A detailed line simulation code (see paper 3k15 by R. Lee and D. Matthews) has been applied to this data and indicates that temperatures range from \( \approx 800-1000 \text{eV} \) near \( n_{\text{cr}} \) for argon plasmas irradiated with \( \lambda_L = 0.5 \text{ micron} \). These calculations do not take account of time averaging effects. Note, that the temperature variation is rather insignificant over a large distance along the gas jet.

Figure 7 illustrates a tentative longitudinal density profile determined using the He-like sulfur resonance to intercombination line intensity ratio. We call the measurements tentative since they have not been confirmed by comparison with interferometry. The density dependence of these ratios was estimated from the calculations of Vinogradov, et al.\(^5\). No corrections for opacity were applied since the sulfur ground state ion density is low. A weak dependence on electron temperature has also been noted in the calculations of Vinogradov, et al. However, no temperature connection were applied to this data because of the small longitudinal variation in temperatures demonstrated in Figure 6. The maximum density achieved was only \( 1.4 \times 10^{21} \text{ cm}^{-3} \) whereas \( n_{\text{cr}} \) for \( \lambda_L = 0.5 \text{ um} \) irradiation is \( 4 \times 10^{21} \text{ cm}^{-3} \). This measured low value could be the result of the transverse averaging due to the one dimensional imaging technique. The decrease in density for distances closer to the gas jet nozzle disagrees with measurements discussed earlier (see Figure 4). It can simply indicate that \( \lambda \) and hence the free electron density is decreasing due to the inhibition of heat flow to the higher density regions. The longitudinal density scale length deduced from these measurements is \( L \approx 120 \text{ microns} \) in agreement with earlier discussed interferometric determinations. Note that unlike the interferometry this method determines density easily up to \( n_{e-critical} \).

In the previous data we have not attempted to illustrate the effects of transverse temperature profiles on the measured spectra nor have we illustrated changes due to time integration. In an attempt to do this we have taken the dependence of \( T_e \) on time and radial position from a PIC hydro code and input these values into a line production and transport code\(^1\). The PIC code simulations were done by F. Mayer and M. Dunning.
at KMSF\textsuperscript{3}. Plots of the two dimensional variation of density and plasma temperature on time are shown in Figures 8a, 9a, 10a for t=12, 45 and 74 psec, respectively. Input (boundary) conditions for PIC code are shown in Table I. Basically, the calculations were performed for a 90 psec $\lambda_{\text{L}}=1.06\mu\text{m}$ irradiation of a nitrogen gas jet. The plots illustrate the temperature evolution of a plasma expanding through the gas-jet density profile. Energy is deposited via inverse bremsstrahlung absorption. On these timescales the hydrodynamics are negligible compared to heat conduction, thus the density profile remains unchanged from the initial profile. The symbol "x" on the plots is located in regions where the ratio of classical to flux-limited heat conduction is greater than 1.0, implying the heat conduction is flux limited ($f=0.32$ for this data). The laser was on for 90 psec. The density profile is generated as $(1/r^2)$ in the far field and $(.5 1/r^2+.5e^{-r})$ in the near field, except in the upper left side of the calculational mesh where the density gradient was decreased for numeric purposes.

Since these density and temperature profiles are not expected to change dramatically with slightly higher $Z$ gases we have taken the above calculations for $T_e(r,t)$ and applied them to an argon plasma to facilitate comparison of line spectra with experiment. Figures 8b, 9b, and 10b represent a calculated time-evolving x-ray spectra for the plasma density and temperature produced by the PIC code. The calculated spectra represent what an x-ray measurement would observe at $90^\circ$ to the longitudinal axis of the gas jet and at a fixed position on the longitudinal density profile (namely, $N_e=n_{\text{cr}}$). The PIC code simulations indicate that a) the plasma expands rapidly in the transverse dimension, b) the plasma never propagates inside of $n_e=2n_{\text{crit}}$, c) there is a strong radial temperature dependence with $T_e>2000\text{keV}$ at $r=0$ cooling to $T_e<100$ at $r>200$ to 300 microns. The x-ray spectra calculations indicate significant populations of H-like ion species under these high temperature conditions. Figure 11 illustrates a measured time-averaged argon spectrum produced under conditions similar to those employed in the simulation. The absence of a H-like line indicates a cooler plasma environment than predicted by time integration of the calculated line spectra. Experimentally, we can thus restrict all
but the most negligible volumes of plasma to electron temperatures of 1keV or less.

In summary, we have performed a more detailed analysis of the plasma gas jet that previously reported. We conclude that even the influence of transverse temperature gradients and time varying plasma conditions cannot modify the interpretation of measured spectra sufficiently to support the 1.5 to 2.0keV plasma electron temperatures in a significant volume of the plasma gas jet. We have also shown that longitudinal temperature and density gradients can be determined using the spectroscopic method. The accuracy of these techniques awaits comparison to other methods.
References


6. M. Dunning, Univ. of Michigan and F. Mayer, KMSF; private communication.

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SPECTROSCOPIC DETERMINATION OF GAS JET $N_e$ AND $T_e$ GRADIENTS

Figure 1
The dependence of the intensity ratio of the resonance $R(1s^2 \, ^1S_0 - 1s2p \, ^1P_1)$ and intercombination $I(1s^2 \, ^1S_0 - 1s2p \, ^3P_1)$ lines of He-like ions

COMPARISON OF INTERFEROMETRICALLY DETERMINED DENSITY PROFILE FOR NEUTRAL GAS (---) AND PLASMA (-----)

\[ \text{Ne} = \rho_o e^{-1.7 \frac{r}{D}} \]

\[ \text{Ne} = 0.2 \rho_o \frac{D^2}{r^2} \]

Shot 4766

Distance from orifice (\(\mu\text{m}\))

Electron density (\(\text{cm}^{-3}\))

Figure 4
Figure 5

SF$_6$ gas jet
\( \lambda_L = 0.53 \mu m \)

\( T_e \sim 600 \text{ eV} \)
\( \tau_L \sim 10 \times 100 \text{ ps} \)
Te DEDUCED FROM Li/He-like LINE INTENSITY RATIO – ARGON GAS JET $E_L = 6.2 \text{ J}, t_L = 100 \text{ ps}, \lambda_L = 2 \omega_0$

![Graph showing Te (eV) vs. Distance along jet (microns)]
\[ \text{Ne} (Z) \text{ profile for kms} \]
Gas jet \(-2\omega_0, \tau_L = 10 \times 100 \text{ ps}\)
\[ E_L = 62 \text{ J}, \text{SF}_6 + \text{N}_2 \text{ gas} \]

![Graph showing the Ne (Z) profile with average electron density vs. Z (microns) with critical and 1/4 critical annotations.](image-url)
Figure 10b
SPATIALLY-AVERAGED SPECTRUM FROM LASER-IRRADIATED GAS JET

Ar gas jet
\[ \lambda_L = 1.06 \, \mu m \]
\[ \tau_L = 100 \, \text{ps} \]

Fluence (keV/keV-sphere)

Photon energy (keV)

Figure 11