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Feasibility of Measuring Density and Temperature of Laser Produced Plasmas Using Spectroscopic Techniques

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Abstract: A wide variety of experiments on the Z-Beamlet laser involve the creation of laser produced plasmas. Having a direct measurement of the density and temperature of these plasma would an extremely useful tool, as understanding how these quantities evolve in space and time gives insight into the causes of changes in other physical processes, such as x-ray generation and opacity. We propose to investigate the possibility of diagnosing the density and temperature of laser-produced plasma using temporally and spatially resolved spectroscopic techniques that are similar to ones that have been successfully fielded on other systems. Various researchers[1-9] have measured the density and temperature of laboratory plasmas by looking at the width and intensity ratio of various characteristic lines in gasses such as nitrogen and hydrogen, as well as in plasmas produced off of solid targets such as zinc. The plasma conditions produce two major measureable effects on the characteristic spectral lines of that plasma. The 1st is the Stark broadening of an individual line, which depends on the electron density of the plasma, with higher densities leading to broader lines. The second effect is a change in the ratio of various lines in the plasma corresponding to different ionization states. By looking at the ratio of these lines, we can gain some understanding of the plasma ionization state and consequently its temperature (and ion density when coupled with the broadening measurement). The hotter a plasma is, the higher greater the intensity of lines corresponding to higher ionization states. We would like to investigate fielding a system on the Z-Beamlet laser chamber to spectroscopically study laser produced plasmas from different material targets.

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For this LDRD, we have performed an examination of the literature, focusing on efforts to derive the density and temperature of a plasma from its spectroscopic properties. We have researched spectroscopic analysis of plasmas produced from a number of different targets from hydrogen gas[4] to iron foils[2]. In each case we will reference the authors used the intensity of various spectroscopic lines to determine the properties of the plasma.

For each plasma studied in the literature we found that there were unique conditions that had to be taken into account, and that these conditions influenced the lines examined and the analysis techniques employed, however, there were also general trends in analysis techniques that emerged. One general conclusion that can be garnered is that an examination of Stark broadening of spectroscopic lines is the consensus choice for determining the electron density of a plasma.

Stark broadening, also called collisional broadening or pressure broadening, occurs due to the effect of other particles in the plasma (principally through their electric field) on the emitting atom. For an individual line the dependence of the line-width on the density of the material varies according to its Stark broadening coefficient and is different for each line. These coefficients are only known for a limited number of lines in a few materials, and can only be theoretically calculated for the lightest atoms. As such a literature search such as the one conducted for this report is a valuable exercise to examine the various coefficients known.

There are other effects that can broaden a spectral line: Doppler broadening and instrument broadening. Instrument broadening arises from the finite resolution of an instrument and can be measured using a known spectral line, such as that from a mercury lamp and corrected for. Doppler broadening arises from the velocity of emitting atoms due to thermal motion. In all the cases of laser produced plasmas we researched the density of the material is such that Stark broadening completely overwhelms any Doppler broadening, thus making it a negligible effect.

In order to determine the temperature of a plasma, two different techniques were used: measuring the intensity ratio of two spectral lines corresponding to two different ionization states or looking at the continuum emission. The use of the continuum assumes some form of thermal equilibrium and is not likely applicable for most laser produced plasmas, therefore the other method should be employed for such experiments. The ratio of lines associated with different ionization states will change with the relative population of those states. By knowing the average ionization state of the material, we can estimate the temperature of the plasma. The exact form of the relationship between the two lines will depend on the individual lines.

For a given plasma, the choice of lines used to analyze the plasma state will depend on the plasma material and conditions. For the temperature measurement, one wants two lines that correspond to ionization states that will be present in significant amounts in the plasma. During our literature search we found this fact explicitly illustrated for argon plasmas. We examined two different papers[8, 9] that studied argon plasmas. In the 1st[8] argon plasma was created by irradiation of a 2kW CO2 laser on an argon jet, this created a relatively cool, low density plasma which meant lines in the 420nm-480nm range were used to examine the plasma. In contrast during and ICF experiment[9], the density and temperature reached by the argon doped ICF core the temperature and density were orders of magnitude higher and so much higher energy lines had to be examined, around 0.35nm. Therefore it is important to have some idea of what the conditions of the plasma will be before doing a detailed analysis of the density and temperature.

If for a given plasma material one does not know the proper Stark coefficients or temperature dependence of the material at those conditions, it is possible to utilize a dopant to probe the density and temperature of the plasma. For instance some researchers have used[2] hydrogen or helium gas surrounding a solid target to act as a diagnostic of the plasma conditions.

During the course of our examination of the literature we have examined experiments looking at a number of different plasma materials with a wide range of conditions. The various materials and lines examined are summarized in the following table:

Plasma Material	Line(s) used for Ne	Line(s) used for Te
Argon (ICF drive)[9]	0.3365 nm	.3365nm and .343nm
Argon (Jet)[8]	438nm, 480.6nm	427nm, 428nm, 438nm, etc
Nitrogen[6]	463nm	463nm, 463.4nm
Aluminum[7]	466.3nm	282nm,466nm,559nm
Ti (He dopant)[5]	588nm,389nm,447nm,469nm	Various TiI and TiII lines
Hydrogen[4]	656.2nm, 486.1nm	656.2nm, 486.1nm
Copper[3]	510nm,515nm,522nm	521nm,515nm,510nm,406nm
Iron[2]	459.3nm,458.4nm	442.25nm,442.73nm
Xe (H dopant)[1]	Unsuccessful	Continuum

As we can see there are a number of different line combinations that have been used to look at plasma conditions, and this is by no means an exhaustive list, but contains many materials that could be of interest for laser produced plasmas. There are a number of experiments each year on the ZBL facility that involve the irradiation of a metal foil with a laser, the techniques used for titanium may have application to these experiments. In addition, a number of experiments in gas are also performed, and the experiments in nitrogen may be particularly useful there as the plasma was created by a relatively large ns-scale pulse laser.

One key aspect of this diagnostic is the accuracy we can expect. With a sub-nm spectrometer, the error in these measurements seems to be around 30%-40% for the density measurement and 10%-20% for the temperature. The difference comes because the density measurement depends linearly on the line width while the temperature calculation depends on an exponential function of the line-intensity ratio.

We have also begun an examination of what materials would be required for implementation of a diagnostic to measure such properties at the Z-Backlighter facility. There are a few main components of such a system:

1) Optical imaging system (cylindrical lens, turning mirrors etc) to transport the desired lines out of the target chamber and to the spectroscopic diagnostics.
2) High resolution (<1nm) spectrometer and gratings for the appropriate wavelength range for the chosen spectral lines.
3) Short temporal response CCD camera or other recording device to take a snapshot of the plasma conditions at the time of peak interest.

We currently posses a number of these elements including turning mirrors and a high speed ccd. To actually implement this diagnostic would primarily require the purchase of an appropriate spectrometer. We are currently attempting to field another spectrometer on the Z-Beamlet target chamber for use in a different experiment. Information from this experiment will help guide the final design of the spectrometer to be used for the plasma diagnostic.

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