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Time and Space Resolved Spectroscopy of X-Ray Laser Experiments*

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MASTER

INTRODUCTION

"Each new reality strains our old philosophies and challenges us to new solutions."

Over the past two decades x-ray spectroscopy has played an important role in the diagnosis and characterization of laser produced plasmas [1]. Recently there has emerged a new class of laser-plasma x-ray source, the laboratory x-ray laser [2]. The unique x-ray emission characteristics and diagnostic needs of laboratory x-ray laser experiments is straining existing measurement capabilities and spawning a new generation of x-ray instrumentation better suited to these challenges [3].

We report experimental data from one of the first of this new generation of instruments designed specifically for laboratory x-ray laser diagnosis. Representative TGSS-EM [4] data are presented from three different x-ray laser inversion schemes [5]: collisional excitation of neon-like selenium ($\lambda = 206, 209\text{\AA}$); resonant photoexcitation of hydrogen-like fluorine ($\lambda = 81\text{\AA}$); and recombination of hydrogen-like magnesium ($\lambda \approx 130\text{\AA}$). The data illustrate the measurement capabilities of the TGSS-EM and provide insight to the dynamics and emission characteristics of this new class of laser produced plasmas.

GENERAL PRINCIPLES AND INSTRUMENT DESCRIPTION

A great deal of attention has focused in recent months on the measurement and characterization of amplified spontaneous emission (ASE) from laser produced plasmas. The combined characteristics of the ASE and the background plasma from which it is likely to emerge make this a challenging task. ASE signal levels are typically quite small and of short duration. The emission has very narrow linewidth, is highly anisotropic, and has relatively long wavelength. The region of emission is typically quite small and can be unpredictable in location and intensity by virtue of the nonlinearity of the processes involved. By contrast the laser produced plasma from which the ASE emerges produces a rather intense, broad bandwidth, isotropic, background x-ray flux of relatively long duration. As an illustration of these features, Table I lists typical x-ray characteristics of ASE and background plasma radiation for recent LLNL laboratory x-ray laser experiments on collisionally excited selenium [2].

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These combined source and background radiation characteristics drive the design of diagnostic instruments. In particular the characterization of ASE requires a spectrometer with good spectral resolution and good higher order suppression. For optimum signal/background discrimination, the instrument should have a radiation collection solid angle matched to the divergence of the ASE. The spectrometer should be time resolved, and have an imaging capability. In addition it should have a large dynamic range (to account for non-linear fluctuations in signal level), and be able to cover a large spectral range (to accommodate many different XRL schemes at many different wavelengths).

From these measurement criteria emerged the time resolved, imaging spectrometer TGSS-EM [4]. The instrument is schematically illustrated in Fig. 1. An ellipsoidal mirror images the output of the x-ray laser onto the photocathode of an x-ray streak camera. An x-ray transmission grating, placed in the path of the focussed x-ray emission, disperses the spectrum along the slit of an x-ray streak camera. The streak camera can be moved along the dispersion direction in the detection plane to sample the desired portion of the x-ray spectrum. Table II provides a summary of the performance specifications of the TGSS-EM.

The geometrical solid angle of the TGSS-EM is apertured at the transmission grating to match the 10 mr divergence of the ASE. This provides the best signal/background discrimination, but requires instrument/target co-alignment to better than ± 1 mr. The exceptional sensitivity of the TGSS-EM may be attributed to its large geometrical solid angle and the quantum efficiency of the streak camera photocathode. The sensitivity value quoted in Table II is significantly below the expected background continuum radiation from the laser produced plasma. Since the instrument spectral resolution ($\approx 1\text{\AA}$) is significantly greater than anticipated ASE linewidth ($\approx .04\text{\AA}$), the actual signal strength ($\text{watt/cm}^2\text{-sr-}\text{\AA}$) must be significantly greater than the fluctuations in the background to be distinguished from it.

DATA PRESENTATION

The TGSS-EM was used as a primary diagnostic in a recent x-ray laser experimental series conducted at the LLNL Novette laser facility. In this series three different population inversion schemes were investigated with varying degrees of success in generating ASE. Data illustrating the capability of the TGSS-EM to extract information about x-ray laser target performance is presented for each of the three inversion schemes. The basic format for raw data records is illustrated in Fig. 2. The figure shows a hypothetical source feature with a spectral distribution incorporating two lines at λ_2 and λ_1 and a broad continuum ($\Delta\lambda$). The emission from the source feature is dispersed (by the transmission grating) and its spectral components are imaged (by the ellipsoidal mirror) onto the narrow slit of the x-ray streak camera. The distribution across the streak camera slit is a convolution of the spatial and spectral content of the source with the spatial and spectral impulse response of the TGSS-EM. The distributed x-ray signal is then streaked in time to provide a 2-D data record of spectrally dispersed image vs. time. Typically on a TGSS-EM streak record there are two fiducial features: an absorption edge (E) to provide a wavelength reference, and a wire shadow (W) to check focus and spatial resolution. Detailed data records follow:

Collisionally pumped Ne-like Se: ($\lambda = 206.3\text{\AA}, 209.6\text{\AA}$)

The kinetics of the most successful population inversion scheme tested in this series are illustrated in Fig. 3. In this case a thin, formvar supported selenium foil (750\AA thick) is irradiated by a short, intense pulse of frequency doubled ($\lambda = 0.53\mu\text{m}$) Nd laser light (0.45 nsec; 5×10^{13} watt/cm²). Calculations show that a significant fraction of selenium atoms are rapidly ionized to the neon-like state ($Z = 10$) in a plasma having an electron temperature close to 1 keV and electron density in the range $10^{20} - 10^{21}$ e/cm³. Under these conditions, the kinetics are quite favorable for the establishment of a population inversion between the 3p and 3s manifolds of the neon-like selenium. Collisional excitation of 3p levels is very rapid from the $2p^6$ ground state ($\tau \sim 0.1$ nsec), whereas the $3p \rightarrow 2p$ decay is dipole forbidden. In addition, the collisional excitation of the 3s levels ($\tau \approx 1$ nsec) is quite slow compared to the $3s \rightarrow 2p$ decay ($\tau = 0.5$ psec). As illustrated in Fig. 3 two possible $3p \rightarrow 3s$ lasings transitions for this scheme are the $^1D_2 - ^1P_1$ transition at 209.6\AA and the $^3P_2 - ^3P_1$ transition at 206.3\AA. These transitions, denoted C and B in Fig. 4, are observed to be quite strong.*

TGSS-EM data records for four different XRL experiments illustrating the variation of spectral signal with length of gain medium are presented in Fig. 4. Immediately beneath each film data record is a linear plot of the x-ray spectrum taken at the peak of the x-ray emission. Features of interest in the different data records are indicated as follows:

- A: the $3p \rightarrow 3s$ transition in Na-like Se at 201.1\AA
- B: the $2p^{5/3p} (^3P_2) \rightarrow 2p^{5/3s} (^3P_1)$ transition in Ne-like Se at 206.3\AA
- C: the $2p^{5/3p} (^1D_2) \rightarrow 2p^{5/3s} (^1P_1)$ transition in Ne-like Se at 209.6\AA
- D: the $2p^{5/3p} (^1P_1) \rightarrow 2p^{5/3s} (^3D_1)$ transition in Ne-like Se at 220.2\AA
- E: the 2nd order Be-edge wavelength fiducial at 222\AA
- W: the wire shadow spatial resolution fiducial

Particularly worthy of note in Fig. 4 is the non-linear growth in intensity of the Ne-like laser lines (B,C) relative to the optically thick Na-like line (A). At the 5 mm target length, lines A, B, C are of similar intensity. At 11 mm and 17 mm, transitions in Ne-like Se have significantly increased intensity whereas the signal level of the Na-like transition is virtually unchanged. At 21 mm the signal is heavily filtered to keep the Neon-like lines within the dynamic range of the TGSS-EM. Under these conditions, the Na-like line is hardly detectable.

*Although we use the LS coupling term symbols throughout this manuscript, the actual coupling mechanism is more complex for these highly ionized, intermediate Z ions.

Additional features of the TGSS-EM data are illustrated in Figs. 5,6. In Fig. 5 the time history of the Ne-like laser line at 206.3Å is displayed versus target length. The emission narrows significantly at long gain length (e.g. $L = 21$ mm). Figure 6 compares the time history of three different lines for a given target experiment (at $L = 16.6$ mm). All three lines have similar rise times, however, the decay time of the Na-like emission at 201Å is comparatively long (~ 1 nsec), relative to the Ne-like emission at 206Å and 220Å ($\tau \sim .25$ nsec).

Resonant Photoexcitation: ($\lambda = 81\text{\AA}$)

Another population inversion scheme pursued in this experimental series was optical pumping of hydrogen-like fluorine with resonant line radiation from beryllium-like manganese. The population inversion strategy for this scheme is illustrated in Fig. 7. A 100 psec burst of green laser light at $\sim 10^{14}$ watt/cm² illuminates a 500Å thick Mn foil, which serves as an x-ray flashlamp. Radiation from the Mn plasma performs two functions: (i) it strips the (physically separated) cold lasant gas (in this case CF₄) down to a hydrogen-like condition, and (ii) it resonantly pumps the hydrogen-like fluorine (1s) to an excited level (3p). The 3p and 3d levels of the F (IX) ion are collisionally coupled thereby leading to a population inversion between the 3d and 2p levels.

Figure 8 is a schematic illustration of the target designed to implement the resonant photoexcitation scheme [6]. Note that the Mn flashlamp foils are symmetrically placed on either side of, and are physically separated from the CF₄ lasant gas. The CF₄ is contained within a narrow (nominal 75 μ m wide) approximately 1 cm long channel. The TGSS-EM views the laser illuminated target edge-on as seen in Fig. 8.

TGSS-EM data from a resonant photoexcitation target are presented in Fig. 9. In this experiment the spectral range is shifted to cover a band from approximately (55-115)Å. The wire shadow W, is used as the spectral reference at $107 \pm 0.5\text{\AA}$. Its position was calibrated using a Boron K-edge absorption filter ($\lambda = 66\text{\AA}$) on a prior target shot.

Data from resonant photoexcitation targets serve to illustrate the advantages of the spatial and temporal resolution of the TGSS-EM. The streak record illustrates the presence of an early signal (F) at precisely $\lambda = 81\text{\AA}$. The line is presumably the 3d $\rightarrow$ 2p transition in the resonantly pumped hydrogen-like fluorine ion. Plotted below the raw data record is the spectral distribution of the emission at early time when the 81Å signal dominates the spectrum. The width of the line at 81Å is approximately 0.5Å, broadened by source size and the spatial resolution limitations of the x-ray streak camera. Using the TGSS-EM spatial resolution $\approx 75 \mu$ m, one calculates a source size of approximately 85 μ m, confirming that the 81Å emission comes from a small region roughly the size of the cavity filled with the CF₄ gas. In addition, time resolution was vitally important to this measurement. The early signal, F, is followed very quickly (< 100 psec) by a continuum orders of magnitude more intense. The onset of the continuum precludes an accurate measurement of the temporal duration of the 81Å line. Nevertheless, in the absence of the temporal resolution of the TGSS-EM (≤ 40 psec) the feature at F would have been lost in the bright continuum. The TGSS-EM

also shows a clear "double-hump" (on the nanosecond time scale) in the continuum emission. This is perhaps associated with implosion dynamics of the two-sided laser irradiation of the target. The data also serve to illustrate the dynamic range of the instrument in that both the line at 81Å ($\approx 3 \text{ KW/Å-sr}$) and the bright continuum ($\approx \text{MW/Å-sr}$) are recorded on the same data record without saturation.

Recombination of H-like Mg: ($\lambda = 130\text{Å}$)

The final population inversion scheme studied involved three body recombination in hydrogen-like magnesium ions (Mg XII). In this case a thin Mg foil is irradiated by a short pulse of intense laser light ($\tau \approx 120 \text{ psec}$, $I \approx 3 \times 10^{14} \text{ watt/cm}^2$, $\lambda = 0.53\mu\text{m}$). The resulting plasma of bare Mg nuclei recombine to form hydrogenic ions. The density and temperature of the plasma are such that a population inversion results between the $n = 4$ and 3 levels. This occurs because the higher energy levels are strongly coupled by electron collisions thereby keeping the $n = 4$ level well populated, while the lower energy level is radiatively depopulated during the rapid cooling resulting from the adiabatic expansion of the exploding plasma into vacuum.

TGSS-EM data from the magnesium recombination experiment are presented in Fig. 10. Shown are: (a) the two-dimensional streak record, (b) the spectral distribution of the emission at a time just after the peak of the broadband continuum (this provides better definition of the line spectrum in the recombining plasma), and (c) the time history of the dominant spectral lines (designated S, α , β , γ). The wavelength fiducial, E, is provided by the Be K-absorption edge at 111Å. Wavelength information and identification of the four dominant spectral features in the data record are as follows:

<u>Symbol</u>	<u>Measured Wavelength</u>	<u>Identification</u>
α :	$120.6 \pm (0.7)\text{Å}$	(3p $\rightarrow$ 2s) in He-like oxygen
β :	$128.8 \pm (0.7)\text{Å}$	(3d $\rightarrow$ 2p) in He-like oxygen
γ :	$130.7 \pm (0.7)\text{Å}$	($n = 4 \rightarrow 3$) H-like Mg
S:	$100.5 \pm (0.7)\text{Å}$ (2nd order)	(3d $\rightarrow$ 2p) in He-like Mg

Of great interest in Fig. 10(a) is the apparent splitting of the lines designated as (α, β) at approximately 1-2 nsec into the experiment. A better understanding of the data is facilitated by a schematic representation of the Mg target before and after laser irradiation, Fig. 11. The magnesium target actually consists of a thin Mg layer sandwiched between two formvar foils. Upon two sided irradiation, the sandwich explodes symmetrically as shown in the figure. The oxygen lines (α, β) emitted from the formvar emerge from two spatially separated regions of the expanding plasma. As a result, when the separation between the formvar foils exceeds the spatial resolution of the TGSS-EM, the oxygen lines from the formvar appear to split. The magnesium emission region does not undergo a spatial separation, and so the line does not split.

The streak record provides a measurement of the separation speed of the two formvar foils. It is approximately $(3-5) \times 10^7$ cm/sec. The viability of the spectral line identification is further supported by the time histories, shown in Fig. 10(c). The two He-like oxygen lines (α, β) have very similar rise and decay times. The hydrogen-like Mg line (γ) has a similar rise time but a slightly faster decay than the He-like oxygen lines. The line designated, S, since it appears above the Be edge is no doubt a higher order component of a line at shorter wavelength. The very different (rise and decay) time history of the S line is also indicative of a distinctly different kinetics than observed for the α, β, γ lines.

CONCLUSION

Time and space resolved spectroscopy of recent laboratory x-ray laser experiments at LLNL has provided valuable insights to dynamical processes occurring in these complicated laser plasma experiments. In collisionally excited neon-like selenium strong ASE (≈ 4 MW/A-sr) was observed (at $\lambda \approx 206.3\text{\AA}$ and $209.6\text{\AA}$), and detailed time resolved spectra were recorded as a function of target length. In resonantly photoexcited hydrogen-like fluorine a relatively weak (~ 3 KW/A-sr), short rise time signal was observed at $\lambda \approx 81\text{\AA}$, indicating the importance of time resolved spectroscopy in these experiments. In experiments investigating three body recombination of hydrogen-like magnesium, the time-resolved imaging spectroscopy provided information on the expansion dynamics of the plasma as well as time histories of the lines of interest.

It seems at this stage quite clear that the diagnostic needs of this new class of laboratory x-ray sources are sufficiently complex to keep the field active and interesting for a long time to come.

ACKNOWLEDGMENTS

This paper is an invited review of the work of a large number of individuals, who as a team, made the x-ray laser experiments and the TGSS-EM measurements possible. The x-ray laser experimental team lead by Dennis Matthews was a relentless crew in search of the golden fleece. Their heroic efforts will not be soon forgotten. Their names comprise the author list of Reference 2. Those most intimately associated with the data presented here are the other members of the TGSS-EM team. The genius of Hector Medecky and the persevering, "can-do" professionalism of Gary Howe and Gary Stone served time and time again to make achieving the impossible standard operating procedure.

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Table I

Characteristic	ASE	Background X-Radiation
1. Directionality	Anisotropic, divergence ≈ 10 mr	Isotropic
2. Signal Level	$\lesssim 10^{-6}$ joule/pulse	~ 100 j/pulse
3. Spectrum	Narrowband ($\sim .04\text{\AA}$) @ $\lambda \approx 200\text{\AA}$	Plasma at $kT_e \approx 1$ keV
4. Source Cross Sectional Area	$\sim (100 \times 100) \mu\text{m}^2$	$\sim (300 \times 300) \mu\text{m}^2$
5. Duration	(100 - 200) psec	(2-3) nsec

Table II

TGSS-EM Specifications

Acceptance Solid Angle	$\approx 10^{-4}$ sr	(matched to 10 mr divergence of ASE)
Maximum Sensitivity	(50-100) watt/sr	(photocathode dependent)
Spectral Resolution	$\approx (0.3 - 1) \text{ \AA}$	(source size limited)
Temporal Resolution	≈ 40 psec	(source size limited)
Spatial Resolution	$\approx (75) \mu\text{m}$	(limited by streak camera resolution)
Dynamic Range Spectral Range	$\approx 10^3$ $\Delta\lambda \approx 60\text{\AA}$	(streak camera limited) (adjustable over a range 0 $\rightarrow$ 260\AA)

FIGURE CAPTIONS

Fig. 1. Schematic representation of the time resolved imaging spectrometer TGSS-EM. The instrument is comprised of an ellipsoidal mirror, a submicron period transmission grating, and an x-ray streak camera.

Fig. 2 Raw data format of the TGSS-EM. A source feature is dispersed into its spectral components and imaged onto the slit of the x-ray streak camera. The data is then streaked in time.

Fig. 3. Simplified kinetics for the population inversion scheme involving collisionally excited neon-like selenium. (The term symbol representation of states is not entirely accurate since the LS coupling approximation starts to break down for such highly ionized, intermediate Z ions).

Fig. 4. TGSS-EM data records for four different target shots illustrate the variation of spectral signal with target length (L). To be noted is the nonlinear increase in intensity of the neon-like lines (J,C) with target length.

Fig. 5. The temporal history of the 206.3Å line (B in Fig. 4) is plotted for four different experiments of differing target lengths. Noteworthy is the apparent narrowing of the dominant first emission peak for the L = 20.9 mm long target.

Fig. 6. The temporal histories of lines A ($\lambda = 201.1\text{\AA}$), B ($\lambda = 206.3\text{\AA}$), and D ($\lambda = 220.2\text{\AA}$) are compared for a single target experiment (L = 16.6 mm). The emission from the Na-like ion ($\lambda = 201.1\text{\AA}$) has a significantly longer lifetime than the Ne-like emissions (B,D).

Fig. 7. Schematic representation of the population inversion scheme for resonant photoexcitation of hydrogen-like fluoroine.

Fig. 8. Target used for resonant photoexcitation experiments.

Fig. 9. TGSS-EM data from the resonant photoexcitation of hydrogen-like fluoroine. The raw data show the presence of an early signal (F) at $\lambda = 81\text{\AA}$. Plotted below the raw data is the spectral distribution of the emission at early time when the 81Å signal dominates the spectrum.

Fig. 10. TGSS-EM data from the recombination of hydrogen-like magnesium. The dominant spectral features in the data are the hydrogen-like magnesium line at 130Å (γ), and the helium-like oxygen lines at 121Å (α) and 129Å (β). The spectral, spatial, and temporal features of these lines provide information on target hydrodynamics and recombination processes.

Fig. 11. Details of the magnesium recombination laser target help the interpretation of the TGSS-EM data of Fig. 10.

Fig. 1

Fig. 2

Emissions at 206Å, 209Å are transitions in neon-like Se:

$n_e \approx 5 \times 10^{20} \text{ cm}^{-3}$
 $T_e \approx 1 \text{ keV}$

40-01-1184-4477

Fig. 3

20-01-0585-2009

Fig. 4

20-01-0585-1854
[82002 81708 81403 83807]

Fig. 5

20-01-0586-1353
[81403]

Fig. 6

Fig. 7

**Novette x-ray laser
cross-section — components**

62-32-0384-0732

Fig. 8

Fig. 9

20-01-0685-2502

[073109]

Fig. 10

20-01-0685-2524

[072702]

Before irradiation:

After irradiation:

Fig. 11