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Vacuum Ultraviolet Emission from a Neon-Seeded Theta Pinch

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ABSTRACT

Plasma properties and line radiation were observed with a high-density θ pinch filled with a few torr of deuterium or helium, seeded with several percent neon. The θ pinch, driven by a 60-kV, 180-kJ capacitor bank, achieves 90 kG, within a 3- μ sec quarter period, in a 25-cm-long, 8.2-cm-i.d. θ coil. The predominant emission is in the 50- to 200- $\text{\AA}$ vacuum ultraviolet range. Most of the strong lines of Ne VI, Ne VII, and Ne VIII identified by others were observed on SWR or SC-7 film with a 2.2-m vacuum grazing incidence spectrograph. Radial-view spectra taken through a radial hole at the center of the θ coil indicate a more homogeneous plasma temperature than those spectra taken axially. The He II 4686- $\text{\AA}$ line profile and nearby continuum were observed with a monochromator and photomultiplier, compared with theoretical calculations, and used to obtain electron temperature and density values. A typical case for He + 2% Ne at about 1 torr yields ~ 40 eV at $\sim 6 \times 10^{17}$ e/cm³. This plasma was observed by laser holography and exhibits excellent containment for about 1.0 μ sec—the time of the line-profile measurements—but is followed immediately by apparently severe instabilities.

A goal for follow-on experiments is to refine the temperature measurements and to observe the continuum underlying the strong neon lines so that tests can be performed on computational models used for opacity calculations.

I. INTRODUCTION

A neon-seeded θ pinch¹ was used as the plasma source from which to observe vacuum ultraviolet (VUV) emissions as a function of the plasma parameters.

One of our goals is to compare the observed emission spectra from the plasma with predictions from theoretical programs as a test of the computational models used, as suggested in the initial proposal by Huebner et al.²

The most direct tests of opacity calculations would come from absorption measurements, which would require the development of a very intense pulsed VUV continuum source to shine through the θ pinch. However, we confined our experiments to the observation of

emission spectra, which, in LTE, may be related to the absorption if the temperature is accurately known.

The θ pinch was operated most typically at peak temperatures of ~ 30 eV and densities of $\leq 10^{18}$ electrons and ions/cm³, using a gas fill of helium or deuterium, seeded with several percent neon. The most prominent ion species observed at ~ 30 eV are Ne VI, Ne VII, and Ne VIII.³ Using a 2.2-m grazing incidence vacuum spectrometer, we observed that the predominant line emission is in the general range of 50 to 200 $\text{\AA}$.

Line profiles and line-to-continuum ratios of the He II 4686- $\text{\AA}$ line were used to estimate neon-seeded plasma temperatures and densities. We chose a neon-seeded plasma temperature of ~ 30 eV and a density of

$\sim 10^{18} \text{ e/cm}^3$ as the first regime of interest for the opacity studies. At these conditions, the 50- to 200-Å region contains a number of lines that should be observable in absorption,² and one or more edges that should be observable in emission.² Observation of these phenomenon should provide significant tests of the opacity models.

The experiments performed thus far were to determine the θ -pinch parameters necessary to achieve the desired plasma and to develop diagnostic techniques for measuring the temperature, density, containment, and VUV emission characteristics of the plasma. These experiments are discussed in detail in several Los Alamos Scientific Laboratory (LASL) internal reports.⁴

This report summarizes some of the more significant plasma properties and emission characteristics observed during the preliminary phases of this study.

II. THE SCYLLAR THETA PINCH

A. General Description

For these experiments, the θ pinch was driven by axial drive fields of 80-90 kG within a risetime (quarter period) of $\sim 3 \mu\text{sec}$ in a 25-cm-long, 8.2-cm-i.d. θ coil. The energy source for this drive field was obtained from a low-inductance high-energy ($\sim 180 \text{ kJ}$) capacitor bank consisting of 54 capacitors (60 kV, 1.8 μF), each switched with a low-inductance 4-electrode spark gap.⁵ The coil dimensions and drive current risetime are similar to Scylla III values.⁶

A 7.5- μF capacitor (charged to 15 kV), with ignitron switch and crowbar, was cabled to hollow electrodes at the discharge tube ends to supply a linear discharge for preionization. An auxiliary ignitron-switched capacitor bank (1500 μF , 0-6 kV), inductively coupled to the θ coil, was used to supply the reverse bias field (typically -1500 kG) when desired. Figures 1 and 2 show the complete system as it existed in the Sherwood "Pit."

A typical operation involved filling the discharge tube with 1000-2000 mtorr deuterium (or helium), firing the linear discharge (with or without reverse bias field), followed by applying the axial drive field $\sim 37 \mu\text{sec}$ after the start of the preionization current. Figure 3 shows a typical integrated pickup loop signal of the main drive field.

Preionization measurements and first tests of the complete system were conducted using quartz discharge tubes. Because of tube breakage on each complete θ -pinch shot, we changed to ceramic tubes, each of which typically lasts several hundred shots or more. We believe the quartz tube breakage is due to high ultraviolet radiation rates.

Fig. 1.

Experimental apparatus used to obtain axial-view emission spectra from Scyllar. The large VUV grazing incidence spectrometer is on the left, viewing down the z-axis of the θ pinch. The θ coil, covered with insulation and a reverse-field coil pair, is in the middle. Preionization electrodes are on each side of the θ coil. The two-foil soft x-ray detector is on the right, along the z-axis. The 180-kJ capacitor bank, including cables and header, is in the upper right and center. A spare 25-cm-long θ coil is on the floor, lower center.

Fig. 2.

Experimental setup for Scyllar with the VUV spectrometer positioned for radial-view spectra. The 1.2-cm-i.d. ceramic tube, which provides a vacuum LOS from the θ tube to the spectrometer, is shown protruding from the θ coil.

Fig. 3.

Oscilloscope traces (1 $\mu\text{sec}/\text{cm}$) showing time behavior of Scyllar. The upper trace is the integrated pickup loop signal at 0.2 V/cm, proportional to the main drive field (92 kG). The lower trace shows a typical soft x-ray signal through a 0.22-mil aluminum foil at 1.0 V/cm. The filling gas was $\text{D}_2 + 5\% \text{CO}_2$ at 200 mtorr.

This Scylla-like θ pinch was named Scyllar, to indicate the high-density operation and radiation studies for which it is used. Details of the operation are discussed in Ref. 4.

B. Operation with Pure Deuterium

In the first Scyllar experiments, we used a pure deuterium fill gas over a wide range of filling densities to check the general operation of the θ pinch and the two-foil soft x-ray technique⁷ to measure the electron temperature. The two-channel x-ray detector was coupled to the vacuum system (Fig. 1) so that each channel viewed the central plasma down the z-axis through a small pinhole. In each channel, the radiation from the plasma (2-200 $\text{\AA}$) passed through a thin foil (~ 0.2 , 0.4-mil aluminum, etc.) of known attenuation and produced a pulse of light in a thin plastic scintillator (~ 20 mil), which was detected with a 6810A photomultiplier and oscilloscope. Comparison of the pulse amplitudes for the two different foil attenuations enabled a determination of T_e . This method is generally most accurate at $T_e > 100$ eV, but was extended here down to $T_e \sim 50$ eV by using very thin foils.

The lower trace in Fig. 3 shows a typical soft x-ray signal. Because a soft x-ray detector is most sensitive

to the hard (short λ) components of the radiation, we believe the signals reflect the hottest region of the plasma in time and space. As in Fig. 3, these time-resolved signals generally showed a maximum intensity 1.6 to 1.8 μsec after start of the drive field (risetime = 2.8 μsec with the θ coil of Fig. 1) with a half-width of ~ 0.5 to 1.5 μsec (depending on foil thickness, etc.). These results indicate hot plasma lifetimes of 1.5 to 2.0 μsec , which roughly agree with anticipated lifetimes of hot plasma in short (~ 25 -cm) θ coils, i.e., Scylla III, Scyllacita, Scylla IA, etc.

Figure 4 shows the measured values of T_e vs filling pressure over a range of pure deuterium filling pressures of 100 to ~ 1700 mtorr. Temperature values of ~ 600 eV to ~ 40 eV were measured. The smooth curves represent theoretical predictions of T_e vs filling pressure computed with a simplified θ -pinch scaling model code by K. J. Ewing. The code is described in Ref. 8. Code calculations are given in Fig. 4 for the assumption that the radiation loss is bremsstrahlung for pure deuterium ($\text{D}_2 \times 1$) and for radiation enhancement of arbitrary amounts, i.e., $\text{D}_2 \times 50$, $\text{D}_2 \times 100$, etc., as is expected with high-Z seeding. The case $\text{D}_2 \times 50$ means, for example, that the deuterium bremsstrahlung radiation is enhanced by a factor of 50.

Fig. 4.

Plot of electron temperatures vs deuterium filling pressures for Scyllar. The plotted points are values measured at the signal peak with the two-foil soft x-ray detector. The smooth curves were obtained from the simplified θ -pinch scaling model code.

Figure 4 shows predictions of the code for T_e (at $t = 2 \mu\text{sec}$) computed for the Scyllar drive conditions of Fig. 3. Considerably more data are needed to improve the accuracy, and reduce the scatter, of these T_e measurements. However, the scaling model appears to be a useful guide as to the variation in T_e vs filling pressure for pure deuterium. Figure 4 also shows that for pure deuterium, the Scyllar operation is "conventional."

C. Operation With Neon Seeding

For most of our plasma observations, we used deuterium or helium as the base gas, seeded with several percent neon. The grazing incidence vacuum spectrograph was used extensively to study the VUV emission of the neon-seeded plasma. These observations are discussed in detail in Secs. III and IV. Our observations of the higher ionization stages of neon, i.e., Ne VI, Ne VII, and Ne VIII, indicate that a plasma temperature of several tens of electron volts is reached in Scyllar for the high-density (10^{17} - 10^{18} e/cm^3) neon-seeded cases.

We used the two-foil soft x-ray technique for the case of $D_2 + 5\% \text{ Ne}$. However, the lowest temperature that could be measured by this method was about 60 eV, presumably because the neon "softens" the spectra (raises the average wavelength emitted) so that most of the emission cannot pass through the thin aluminum foils. This distortion from a pure bremsstrahlung emission also complicates the calculation of foil attenuation vs T_e used for the measurement. Therefore, we concluded that the present two-foil attenuation technique cannot be used to determine accurately T_e at 30 eV with neon seeding.

To provide definitive tests of the opacity models, it is highly desirable² to obtain T_e measurements independent of the VUV emission spectra in the $T_e \sim 30 \text{ eV}$ region. The base gas was therefore changed from deuterium to helium so that observations of the He II 4686-Å line could be made.

D. Temperature Measurements with the He II 4686-Å Line

Line profiles of well-defined lines of helium and other ion species have been used frequently⁹ to determine plasma temperatures and densities. For example, Griem's calculations⁹ for the He II 4686-Å line give T_e vs the line-to-continuum ratio at $\sim 30 \text{ eV}$.

With helium as the base gas, and with helium plus a few percent neon, we obtained time-resolved line profiles of the 4686-Å line using a JACO monochromator and an EMI quartz window photomultiplier. The photomultiplier output is recorded on a Tektronix 556 oscilloscope. A

separate shot of the θ pinch is required for each wavelength setting of the monochromator, so that a complete line profile requires several dozen discharges.

Figure 5 shows experimental points of the 4686-Å line profile. Each point represents a separate discharge of the pure helium θ pinch. The points were read at the peak pulse height of the photomultiplier output, about 1.0 μsec after the start of the θ pinch.

The experimental points in Fig. 5 were obtained using an optical system that enabled us to place the monochromator inside the screen room where electrical noise was reduced. Thus, smaller photomultiplier signals could be observed, and we could operate in the linear region of the photomultiplier output. Operation with large signals had resulted in a nonlinear photomultiplier response.

Figure 5 shows a theoretical profile by Merts and Magee¹⁰ for $n_e = 7.4 \times 10^{17} \text{ /cm}^3$ at 30 eV. For pure helium, the computed line-to-continuum ratio increases as the temperature decreases from 30 eV. The close agreement between experiment and theory for the line profile in Fig. 5 led to considerable confidence in the feasibility of the line-to-continuum method for T_e and n_e measurements.

Theoretical curves computed by Merts and Magee¹⁰ were used to obtain T_e and n_e values from the measured line-to-continuum ratios and measured half-widths for the 4686-Å line for cases of helium seeded with neon. These

Fig. 5.

Comparison of experimental and theoretical line profiles of the He II 4686-Å line for Scyllar filled with pure helium at 2000 mtorr. Each experimental point represents a relative output of the JACO monochromator as measured on oscilloscope traces at the peak pulse height, which occurred here at 1.0 μsec after start of the θ pinch. Each point represents a separate shot, with the wavelength set at the value plotted. The solid line represents a theoretical profile computed by Merts and Magee for a case of $n_e = 7.4 \times 10^{17} \text{ /cm}^3$ and $T_e = 30 \text{ eV}$.

values are given for the case of He + 2% Ne in Ref. 11. Also given in Ref. 11 is a least-squares fit of the experimental data taken at 0.8 μ sec with Scyllar filled with He + 2% Ne at a pressure of 780 mtorr. Here the values $T_e = 44$ eV and $n_e = 6 \times 10^{17}$ e/cm³ are indicated.

The Merts and Magee calculations also include a family of curves for He + 5% Ne from which T_e and n_e may be inferred from measured line-to-continuum ratios and corresponding line half-widths. Huebner and Merts note that all of these calculations are model-dependent; thus, an independent measurement of T_e and/or n_e for at least one specific case is desirable to normalize the model used. Table I lists T_e and n_e values inferred from the Merts and Magee calculations using the measured line profiles for various Scyllar operating conditions.

E. Plasma Containment and Density Measurements

Observations were made to determine the gross motion and containment of the θ -pinch plasma and to estimate the particle density.

1. **Streak Pictures.** An Imicon (Type H.E. 700) streak camera was used to observe, end-on, the radial plasma

motion. For each plasma condition, different light filters were used in an effort to show the central plasma motion and distinguish it from end effects.

Figure 6 shows typical results for a pure helium plasma. Figures 6a, 6b, and 6c show cases of 2000-, 1000-, and 500-mtorr filling densities, respectively. These figures indicate a strong radial shock heating stage followed by radial containment of varying quality, depending on filling density. No field asymmetries are indicated. Preliminary pictures also were taken for cases of He + 5% Ne, but the interpretation of the central plasma behavior was less conclusive.

2. **Laser Holography.** We used the holographic interferometer technique, described by Jahoda and Siemon,¹² with a pulsed laser source, to measure the electron density and plasma containment. With this method, the incident laser beam is split into a "scene beam," which traverses the plasma region with a diameter greater than the discharge tube, and a "reference beam," which bypasses the plasma and is superimposed on the scene beam at the detector film plane. Use of a laser source enables coherent addition of the scene beam and reference beam at the detector.

TABLE I
SUMMARY OF MEASURED SCYLLAR TEMPERATURES AND DENSITIES

Species	Fill (mtorr)	Time (μ sec)	B(t) (kG)	A_l/A_c	$\delta^{1/2}$ ($\text{\AA}$)	T_e (eV)	$n_e \times 10^{17}/\text{cm}^3$	$n_e + n_i \times 10^{17}/\text{cm}^3$	β
He only	1040	1.0	42	1.65	14.5	33	7.4	11.1	0.83
He only		1.8	69	1.2	12.5	45 ^a	7.4 ^a	11.1	0.42
He + 2% Ne	780	0.8	37	~1.0	11	44	6.0	8.6	1.08
He + 2% Ne		1.2	54	1.35	6.2	34	3.5	5.0	0.23
He + 2% Ne	40	0.5	23		3	~50	2.0	2.8	~1.0
He + 5% Ne	1040	1.0	42	2.4	28	17	10.8	15.7	0.61
He + 5% Ne		1.5	60	4	18	13	6.1	9.1	0.13
He + 5% Ne	520	1.0	46.5 ^b	1.3	8	27	3.9	5.6	0.28
He + 5% Ne		1.5	66 ^b	3	8.5	17	3.3	4.9	0.08
He + 5% Ne	260	0.7	33 ^b	2.0	3	21	1.4	2.0	0.15
He + 5% Ne		1.5	66 ^b	1.2	3.5	30	2.1	3.0	0.08

^aExtrapolated from available curves.

^bCases where $-B_0 = 2$ kG, ($\neq 0$).

Note: Where A_l/A_c = line-to-continuum area ratio, $\beta = (n_e + n_i)T_e/B^2/8\pi$, and t = time where the line profile is computed, where $B(0) = 0$.

Fig. 6.

Typical end-on Imicon camera streak pictures of the Scyllar plasma. Time increases from left to right, and the vertical axis shows the plasma diameter in the plane of the feed slot. Figure 6a illustrates pure helium at 2000-mtorr filling pressure. Fig. 6b, at 1000 mtorr; and Fig. 6c, at 500 mtorr.

A Korad KIQH laser (pulse width = 30 nsec) was used as the source, and Agfa-Gavert 10E75 glass plates were used as the film detector. The technique involved two laser shots for each film exposure, with a phase shift between the two successive shots induced by a minute shift of position of one of the reference beam mirrors. When there is no plasma present in the θ tube, the mirror shift results in straight line interference fringes on the film. When there is plasma in the θ tube, a phase shift is induced in the scene beam and is proportional to the

product ($n_e \ell$) of the electron density and the plasma length. Because the θ -pinch plasma generally exhibits circular symmetry, the fringe shift shows up as circular fringes, and a count of the fringe shift gives the product $n_e \ell$, and hence a determination of n_e .

Figure 7 shows a time sequence of holograms for Scyllar for a case of relatively low filling density (He + 2% Ne at 40 mtorr), where the fringe shift can be counted unambiguously and the electron density can be computed directly. In Figs. 7a and 7b, the plasma is viewed down the z-axis, with laser exposures at 0.57 and 0.88 μsec , respectively. Time is measured from the start of current in the θ coil, where the quarter period for the current rise is 3.0 μsec . The peak plasma density is $0.9 \times 10^{17} \text{ e/cm}^3$ at 0.88 μsec .

Figure 8 shows a sequence of holograms for the typical Scyllar case of filling pressure He + 2% Ne at 780 mtorr. The laser exposures are at 0.5, 0.6, 0.85, and 1.3 μsec . As in Fig. 7, the straight line fringes indicate regions of undisturbed plasma, i.e., the lower density preionization plasma, or vacuum. The solid gray regions on the holograms indicate regions where the density and density gradient of the θ pinch are so great that the laser light is refracted out of the field of view, and a fringe shift measurement cannot be made.

The early time holograms indicate an inward moving cylindrical plasma sheath with a hollow core. The plasma appears conventional and "well behaved" for at least 0.85 μsec . Containment appears to deteriorate rapidly at $\sim 1.3 \mu\text{sec}$. Because the laser scene beam views the plasma along the entire length of the θ coil, the observed instabilities may occur at early times near the ends of the coil.

If one assumes that all of the initial gas fill (780 mtorr) is ionized and swept up by the plasma sheath and that no plasma losses occur for the first 0.85 μsec , the compressed plasma diameter leads to a density of $\sim 5 \times 10^{17} \text{ e/cm}^3$. This compares with a value of $6.2 \times 10^{17} \text{ e/cm}^3$ computed by Merts and Magee¹⁰ from the measured He II 4686-Å line profile for this case (Table I). By counting the unambiguous part of the fringe shift in the 0.6- μsec hologram of Fig. 8, then comparing area ratios with the 0.85- μsec holograms, one can estimate a lower limit of density of about $3.8 \times 10^{17} \text{ e/cm}^3$ at 0.85 μsec .

3. Plasma Containment. The values of

$$\beta = \frac{(n_e + n_i)T_e}{B^2/8\pi},$$

given in Table 1, give the ratios of the plasma particle kinetic pressure to the external magnetic pressure. The ideal case of a perfectly diamagnetic plasma from which

Fig. 7a. Laser exposure at 0.57 μ sec.

Fig. 7b. Laser exposure at 0.88 μ sec.

Fig. 7.

Holograms of the Scyllar θ pinch for the case of He + 2% Ne at 40-mtorr filling pressure. The peak field is 90 kG, and the reverse field is zero.

the magnetic field is completely excluded is given by $\beta = 1$. From Table I, and from the case of the 0.85- μ sec hologram of Fig. 8, it appears that this case gives the highest density where the plasma is contained at "high β " (defined here as $\beta \geq 0.8$), recorded thus far with the neon-seeded Scyllar.

These results indicate that the higher density neon-seeded helium plasmas in Scyllar do not appear to be contained at "high β " for as long ($\approx 1.0 \mu$ sec) as were the lower density pure deuterium plasmas in Scylla III⁶ and Scylla IA,¹³ where "high β " containment lasted $\approx 2.0 \mu$ sec. This might be due to higher resistivity of the lower T_e neon-seeded cases, but has not yet been investigated.

III. VUV SPECTROSCOPY

A. The Spectrograph (SPEX)

The VUV emission spectra were observed with a 2.2-m grazing incidence vacuum spectrograph,¹⁴ using a 1200-line/mm Bausch & Lomb grating. Spectroscopy in the observed 30- to 500- $\text{\AA}$ range requires a vacuum line-of-sight (LOS) from the hot plasma source to the grating to the film plane. The spectrograph is encased in a large vacuum tank, and is equipped with its own heavy-duty fore pump, diffusion pump, and cold trap. Differential pumping through the entrance slit is used when the spectrograph is in operation with Scyllar.

For these data, the spectrograph viewed the plasma down the z-axis, as in Fig. 1, or radially from the side at the axial center as in Fig. 2. The time-integrated spectrum was recorded on 65-cm lengths of Kodak SWR 35-mm film. Kodak SC-7 film, which is more sensitive, but grainier, was also used. Four of five Scyllar shots have generally been sufficient to give good exposures of the stronger spectral lines on the film.

With the axial view (Fig. 1), over 50 lines, believed to be neon, were observed in the first region of interest, 50-200 $\text{\AA}$, at each of several different filling densities of $D_2 + 5\%$ Ne. More than 150 lines were observed over the 30- to 500- $\text{\AA}$ range. The basic wavelength calibration was first obtained with He II lines (303.78 $\text{\AA}$ and 256.32 $\text{\AA}$), which could be observed with 10 to 30 shots of the linear discharge with a helium gas fill. This basic calibration, $\lambda = 0.351 x + (8.21 \times 10^{-4}) x^2 \pm 1 \text{\AA}$ ($x = \text{mm}$ along the film), was corrected on any given spectrum by a constant shift ($\leq 1 \text{\AA}$) over the range as various strong neon lines were isolated and identified. In particular, the strong Ne VIII lines at 67.4, 73.55, 88.11, 98.11, 103.0 $\text{\AA}$, etc., and similar Ne VII lines were observed with such regularity as to become good wavelength standards.

Fig. 8a. Time = 0.5 μ sec.

Fig. 8b. Time = 0.6 μ sec.

Fig. 8c. Time = 0.85 μ sec.

Fig. 8d. Time = 1.3 μ sec.

Fig. 8.

Holograms of the Scyllar θ pinch for the case of He + 2% Ne at 780-mtorr filling pressure. The peak field is 90 kG, and the reverse field is zero. The time sequence is: upper left at 0.5 μ sec, upper right at 0.6 μ sec, lower left at 0.85 μ sec, and lower right at 1.3 μ sec.

B. Spectral Observations

Spectrograms were obtained for each of the following conditions:

- (1) Axial view (along the z-axis) with a pure deuterium filling gas.
- (2) Axial view with a filling gas of $D_2 + 5\% \text{ Ne}$ at each of several filling densities.
- (3) Radial view with a filling gas of $D_2 + 6\% \text{ Ne}$ at each of several filling densities.
- (4) Radial view with a filling gas of $\text{He} + 5\text{-}1/2\% \text{ Ne}$ at a filling density of 520 mtorr.
- (5) Radial view with a filling gas of $\text{He} + 2\% \text{ Ne}$ at a filling density of 780 mtorr.

These spectrograms were made by time-integrated exposures on Kodak SWR film (some cases were repeated using SC-7 film for increased sensitivity). An exposure of the film for six shots of the linear discharge preionization showed very little exposure on the film, indicating that essentially all of the film exposure seen thus far had come from the θ -pinch plasma or its aftermath.

Figures 9 through 14 shows spectrograms typical of each of the cases studied. Figures 10, 12, 13, and 14 show densitometer traces of the original spectrograms. It is easier to identify individual lines on the original spectrograms, but the densitometer traces enable a more quantitative comparison of relative intensities. Table II lists the lines measured from a film similar to the spectrograms of Fig. 9 taken with $D_2 + 5\% \text{ Ne}$ at 750 mtorr. For identified lines, the wavelength values from the literature are given, and there is general agreement to within 0.3 Å or better. The values for the unidentified lines were obtained by interpolations.

Some general characteristics observed with this series of spectrograms are summarized below.

1. *Impurity Spectra.* The spectrograms taken with pure deuterium show several dozen strong lines, particularly in the 40- to 250-Å wavelength range. These lines must be impurity lines, and many of them may be seen on the "pure deuterium" axial-view case in Fig. 9. Likely sources of impurities include carbon from the pump oil,

Fig. 9.

Photograph of the 40- to 220-Å region of three spectrograms (on SWR film) taken with the VUV grazing incidence spectrometer viewing Scyllar down the z-axis (end view). The upper spectrum is for seven shots of Scyllar filled with $D_2 + 5\% \text{ Ne}$ at 250 mtorr. The middle spectrum is for four shots with a gas fill of $D_2 + 5\% \text{ Ne}$ at 1750 mtorr. The lower spectrum is for four shots with a gas fill of deuterium only at 1800 mtorr.

Fig. 14.

Densitometer trace of the 41- to 127-Å region of a radial-view spectrogram of eight shots of Scyllar filled with He + 2% Ne at 780 mtorr. The drive field was 90 kG, and the reverse field was zero.

and aluminum and oxygen from the ceramic tube wall. The lower spectrum of Fig. 9 was obtained with four shots using a filling of 1.8 torr of deuterium only.

Lines of O V and O VI were strong in the 150- to 200-Å region. Strong lines in the 40- to 70-Å region were seen, but good identification was not found for them. Some lines were also observed in the 200- to 500-Å region, but again good assignments were not found.

A single end-view spectrum was made of six shots with 700-mtorr helium. It showed some weak lines, but only the He II 303- and 256-Å lines were tentatively identified. The many unidentified lines may come from highly ionized impurity species, such as aluminum and oxygen, from the walls of the plasma tube as above.

2. Observation of the Neon Spectra. Most of the strong impurity lines of Fig. 9 become weak, or disappear, when the fill gas is seeded with neon. This result was observed on several spectrograms, and is illustrated by the comparison shown in Fig. 9. Comparison of the lines in the 40- to 65-Å and 160- to 210-Å region particularly demonstrates this point. Careful wavelength analysis of the neon-seeded cases shows that most of the lines agree in wavelength with neon lines observed by previous

experimenters, as compiled by Kelly.¹⁵ It would thus appear that the character of the plasma is strongly affected by the neon seed, i.e., there is high radiation loss and cooling at early times. One might then postulate that many of the impurity lines seen with pure deuterium are caused by late time effects of an energetic plasma, perhaps after some plasma has hit the tube wall. It has been convenient that the impurity effects have not seriously hampered observation of the neon spectra. This conclusion was arrived at by similar comparison of "deuterium only" with "D₂ + 5% CO₂."

Considerable effort was spent in measuring the wavelengths of individual neon lines and comparing them with individual lines identified by others. For the axial-view cases at lower filling densities (750 and 250 mtorr), the observed strong lines are well separated in the 400- to 500-Å range. About 20 lines, mostly Ne V and Ne VI, can be readily identified, as shown in Table II.

Figure 10 shows the stronger of these lines. Many lines were observed in the 300- to 400-Å range and some appear to be Ne IV and Ne V, while some are as low as Ne III. The greatest density of lines was between 60 and 220 Å.

TABLE II

**SPECTROGRAM LINE MEASUREMENTS (IN Å) OF FOUR
SHOTS OF SCYLLAR FILLED WITH D₂ + 5% Ne AT 750 mtorr**

56.10 Ne VIII	108.4	144.30 Ne IV	183.16 Ne IV	226.7	357.83 Ne IV
57.79 Ne VIII	109.5	147.13 Ne V	183.6	228.1	358.47 Ne V
60.81 Ne VIII	110.41 Ne VI	147.7	184.73 Ne V	230.3	359.39 Ne V
61.6	111.14 Ne VI	148.66 Ne IV	185.48 Ne IV	232.7	363.2
62.9	112.3	148.79 Ne IV	186.78 Ne IV	233.5	365.59 Ne V
64.1	114.5	148.94 Ne IV	186.92 Ne IV	234.32 Ne IV	379.31 Ne III
65.89 Ne VIII	115.52 Ne VII	151.46 Ne IV	190.57 Ne IV	237.8	384.2
67.39 Ne VIII	116.66 Ne VII	151.82 Ne IV	191.4	240.6	387.2
68.4	117.7	152.8	192.5	241.2	388.2
69.4	118.84 Ne V	153.8	194.28 Ne IV	245.1	399.82 Ne VI
70.3	120.32 Ne VII	154.50 Ne IV	194.94 Ne VI	247.42 Ne IV	401.14 Ne VI
71.5	121.14 Ne VI	156.50 Ne IV	195.62 Ne V	277.1	401.94 Ne VI
73.55 Ne VIII	122.68 Ne VI	158.82 Ne IV	196.8	282.50 Ne III	403.26 Ne VI
74.97 Ne VII	123.71 Ne V	160.47 Ne IV	197.3	282.61 Ne VIII?	409.97 O VIII?
75.78 Ne VII	125.2	162.1	199.0 Ne VIII?	283.69 Ne III	416.20 Ne V
77.6	126.8	164.02 Ne V	199.8 Ne VIII?	289.3	416.83 Ne V
79.0	127.65 Ne VII	164.29 Ne V	200.9	292.47 Ne VIII	420.95 Ne V
80.62 Ne VII	129.03 Ne V	166.11 Ne IV	202.0	293.95 Ne IV	422.35 Ne V
82.26 Ne VII	130.5	167.92 Ne IV	203.3	295.0	427.84 Ne III?
84.34 Ne VII	132.20 O VI?	168.01 Ne IV	204.27 Ne IV	301.12 Ne III	431.5
85.4	133.6	168.6	206.6	305.6	433.18 Ne VI
88.11 Ne VIII	133.7	170.5	208.49 Ne IV	308.56 Ne III	435.65 Ne VI
89.41 Ne VII	134.82 Ne VII	171.21 Ne VI	210.0	309.2	440.40 Ne VI
91.7	135.0	172.49 Ne IV	212.56 Ne IV?	312.2	451.84 Ne VI
94.33 Ne VII	136.22 Ne V	172.62 Ne IV	215.0	316.7	452.75 Ne VI
94.99 Ne VII	138.63	174.12 Ne IV	215.39 Ne IV	318.3	454.07 Ne VI
95.86 Ne VII	140.13 Ne IV?	174.30 Ne IV	217.8 Ne IV	329.7	459.2
98.27 Ne VIII	140.72 Ne V	174.92 Ne IV	218.77 Ne IV	332.0	465.22 Ne VII
103.10 Ne VIII	Ne V	176.00 Ne IV	219.7	333.7	468.0
104.4	142.93 Ne IV	177.16 Ne IV	220.5	335.5	469.77 Ne IV
105.0	142.4- 7 Ne V	177.8	221.8	346.2	476.6
107.70 Ne VII	143.3 lines	180.0	222.06 Ne IV	347.6	480.41 Ne V
107.8	143.6	181.2	224.0	351.0	481.36 Ne V
					482.99 Ne V

3. Variation with Filling Density. For the case of higher filling density (1750 mtorr) in axial view, most or all of the lines in the 300- to 500-Å range become much weaker or disappear, compared with the spectrograms taken at lower filling densities, particularly those as low as 250 mtorr. This effect is at least partly due to absorption at the higher wavelengths by the higher density cool gas between the θ pinch and the spectrograph slit. Cross sections by Henke and Elgin¹⁶ were used to estimate this effect.

If one assumes un-ionized helium or deuterium at the initial density in the LOS tube, the plasma radiation should be strongly attenuated above 150 Å for helium and above 300 Å for deuterium. Extensive ionization of gas in this tube will change this result. Adding 6% Ne will not appreciably change the helium case, but for D₂ + 6% Ne, attenuation is expected above 250 Å.

4. Comparison of Radial and Axial View. A comparison of radial-view spectra with axial-view spectra was made

at 250, 750, and 1750 mtorr. Figure 1 shows the axial-view case, and Fig. 2 shows the radial-view case. The radial view was accomplished by using a 1.2-cm-diam ceramic tube, which gives a vacuum LOS from the spectrograph through the θ coil to the plasma, as seen in Fig. 2. Torr-seal is used for the vacuum seal at the joint of the ceramic viewing tube and ceramic discharge tube. Individually poured plastic (Mask coat No. 2, Western Coating Company) serves as the high-voltage insulation. Usually a new assembly will last for several hundred shots before joint failure.

Figure 11 gives a comparison of radial-view and axial-view spectra. The strong Ne VIII lines at 73.55, 88.11, 98.27, 103.1 Å, etc., are more evident in radial view than in axial view. However, the many Ne IV lines ($\lambda > 140$ Å) and Ne V lines ($\lambda > 118$ Å), which are more evident in axial view, disappear in radial view or are much weaker. We concluded that temperature homogeneity of the observed plasma sample is much improved in radial view as compared with axial view. This is presumably because the effective plasma sample in radial view does not contain as much "cold" plasma as the axial-view case, which gets a contribution from the ends of the discharge tube.

Figure 15 shows W. F. Huebner's computations of the percentage of each stage of ionization as a function of temperature. By observing the various stages of ionization, one can make rough estimates of the range of temperatures involved.

5. Use of Helium Base Gas. Figures 13 and 14 are densitometer traces of spectrograms for cases of a filling gas of helium seeded with neon. Comparison with Fig. 12 and the other neon-seeded deuterium cases shows that essentially the same Ne VII and Ne VIII lines are the

Fig. 15.

Percentage of neon in a given ionization stage vs electron temperature.

stronger lines for the helium-base gas cases as for the deuterium-base gas cases.

C. Pulsed Light Source

A simple pulsed VUV source was made using a 5-cm-long end-view discharge in impure helium. A good exposure was obtained from 100 discharges from a 1.2-μF condenser at 10 kV. Approximately 0.5 torr of helium flowed through this source. Many lines were observed, including the 118-Å doublet of Si V (from the quartz discharge liner), over 30 lines of O IV through V, the N IV and C IV impurity lines, and the expected He I and He II lines. This source is useful for wavelength calibration, spectrograph alignment and focusing, and film exposure calibration.

IV. DISCUSSION OF THE NEON SPECTRA

Although much remains to be done before we have a complete understanding of these VUV spectra, a preliminary discussion seems worthwhile. Spectra of θ -pinch light sources have been studied for some time, and several groups have observed neon plasmas.^{17,22} In fact, most of the information on Ne VII and Ne VIII comes from these sources.

An energy-level diagram is a useful method of visualizing transitions for a given species. Figure 16 shows the relatively simple Ne VIII energy-level diagram consisting of observed lines from several sources.^{17,22} We have observed most of the Ne VIII lines of Fig. 16. The exceptions were at the longest and shortest wavelengths. The doublet separations have generally not been resolved. A diagram for Ne VII is given in Ref. 17* and is more complicated than that for Ne VIII. Figure 16 shows why most of the Ne VIII transitions are in the VUV range. Although only one transition (actually a doublet at 2860 and 2820 Å) has been observed outside of the VUV range, others can be predicted (i.e., $4p \rightarrow 4s \sim 6700$ Å and $3d \rightarrow 3p \sim 8500$ Å), but can be expected to be rather weak. A few other infrared transitions can be predicted, but they should also be quite weak. Some VUV transitions, such as $4p \rightarrow 3d$ (297 Å) and $5d \rightarrow 3p$ (195 Å) can be predicted, but have not been seen, probably because of inadequate intensity.

Recent work by Hermansdorfer¹⁸ is somewhat similar to the experiments reported here. Using up to 6% Ne in deuterium at 100 to 200 mtorr, his θ -pinch bank was larger (660 kJ) than Scyllar, but the current did not rise

*Figure 2 of this reference should read "Term Scheme of Ne VII."

Other techniques, such as using magnetic probe data combined with holograms, as in Figs. 7 and 8, may be investigated to get an additional estimate for n_e and T_e .

B. Time-Resolved VUV Spectroscopy

The radial-view spectra discussed above give a reasonable estimate for the VUV emission from a plasma sample at a specific temperature. However, for testing opacity calculations, it is desirable to have a plasma sample as homogeneous in T_e as possible.

If spectrograms, such as those presented in this report, can be obtained with an accurately timed shutter, the contribution of the radiation corresponding to the time-resolved temperature measurement should be optimized. This would lead to a more accurate test of theoretical predictions of spectra as a function of T_e . Such a shutter must present a vacuum LOS from the plasma to the spectrograph, and must be fast ($<1\text{-}\mu\text{sec}$ open time) if good accuracy is to be obtained. Such a shutter would also reduce stray light on the film and protect the grating from plasma debris.

Time-resolved VUV spectra might also be obtained using some form of electronic photodetector with a slit on the Rowland circle. Because a separate θ -pinch shot is needed for each wavelength setting, this method may be more appropriate to studying emission continuum than to detailed studies of many lines. Photoelectric detection may prove more sensitive than film, and could also be helpful in observing weak photoemission edges.

C. VUV Sources

An improved calibration source, either pulsed or direct current, is needed to produce known lines in the 50- to 100-Å region. Data taken with the source discussed in Sec. III-C have so far failed to give the calibration function $S(\lambda)$.

VI. SUMMARY

A 180-kJ capacitor bank was used to drive a neon-seeded θ pinch so that the VUV emission could be studied as a function of T_e and n_e . The θ coil is 25 cm long, with an i.d. of 8.2 cm. The axial drive field rises to about 90 kG within a 3- μsec quarter period. With a pure deuterium gas fill, the θ -pinch temperature was varied from $\sim 40\text{ eV}$ to $\sim 600\text{ eV}$ by adjusting the filling pressure. Several different cases with neon-seeded fill gas were studied using deuterium, then helium, as the base gas.

Observation of the He II 4686-Å line profile and line-to-continuum ratio provides a measure of electron densities and temperatures on a time-resolved basis. This technique was used for filling gas cases of helium only, and of neon-seeded helium at the higher filling densities. A typical case of He + 2% Ne at 780 mtorr gave a peak temperature of about 40 eV and a density of $6 \times 10^{17}\text{ e/cm}^3$. The temperature can be varied by changing the percentage of neon, as well as by varying the fill-gas pressure.

A 2.2-m grazing incidence spectrometer was used to record the time-integrated VUV emission on film. Spectra were observed in the 40- to 500-Å range. With neon seeding, the predominant emission in axial view was at wavelengths corresponding to lines of the ion species of Ne VIII, Ne VII, Ne VI, Ne V, and Ne IV, as identified by other investigators. Radial view spectra taken at the center of the θ coil showed a predominance of Ne VIII and Ne VII lines, and higher levels of Ne VI. This result is taken to indicate observation of a plasma sample more homogeneous in temperature with radial view than in axial view by the elimination of end effects in the observed sample.

Spectrograms taken at a measured peak temperature of 30-40 eV show most of the previously observed strong Ne VII and Ne VIII lines reported in the literature. The stronger lines of Ne VIII, for example, appear to be well defined and described.

Much work remains to be done to obtain time-resolved spectra, to improve the accuracy of the T_e measurements, and to determine accurately the presence and strength of such effects as, for example, the weak emission edge predicted in the 50- to 60-Å region relevant for testing opacity codes.

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