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Temperature Diagnostics Using Lithium-Like Satellites

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Temperature Diagnostics Using Lithium-Like Satellites

R. U. Datla*
L. A. Jones
D. B. Thomson

*Visiting Scientist. Department of Physics, University of Maryland, College Park, MD 20740.

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TEMPERATURE DIAGNOSTICS USING LITHIUM-LIKE SATELLITES

by

R. U. Datla, L. A. Jones, and D. B. Thomson

ABSTRACT

A 60-kJ θ-pinch was operated at a filling pressure of 16 mtorr using a gas mixture of 2% neon and 98% helium. The resonance and intercombination lines from Ne IX and the Li-like satellites were observed with a Bragg crystal monochromator. The electron temperature of the plasma was deduced from the intensity ratios of the Ne IX resonance line and the dielectronic satellites using recent theoretical calculations. The temperature values ranged from 210 eV to 340 eV during the time of occurrence of these satellites. The temperature measured at 1.0 μs by laser scattering for a similar plasma condition was in close agreement with that obtained by the resonance line/satellite ratio. This lends confidence to use of the satellite technique for temperature measurements in other plasmas.

I. INTRODUCTION

The temperature dependence of the ratio of the intensities of Li-like satellites to the He-like resonance line from ions of various elements has been the subject of considerable theoretical investigation[1,2] in recent years. This ratio is a useful diagnostic tool for determining the electron temperatures, especially for hard to diagnose plasmas, such as those produced by lasers[3,4] and particle beams, and for astrophysical plasmas like solar flares.[2] We used known plasma conditions to experimentally verify electron temperatures predicted by this technique.[5,6] Our experiment was done on the 60-kJ Scyllar θ-pinch at the Los Alamos Scientific Laboratory (LASL), and we measured the temperatures by using the intensity ratios of Li-like satellites to the He-like resonance line in Ne IX. At 1.0 μs, the electron temperature agreed closely with the temperature measured previously[7] using laser scattering in a plasma condition that was equivalent except that the filling pressure was 20 mtorr instead of 16 mtorr. We also observed the resonance line of H-like neon, Ne X, which has an excitation potential of ~922 eV.

II. MEASUREMENTS

A. X-Ray and VUV Spectroscopy

The 60-kJ Scyllar θ-pinch at LASL was described in Ref. 7. We used the same bank parameters and firing sequence that were given in that article. The discharge tube was filled to a pressure of 16 mtorr with a gas mixture of 98% helium and 2% neon. The He-like resonance line from Ne IX, and its Li-like satellites, were observed end-on with a Bragg crystal monochromator using a KAP crystal, a pilot B scintillator, and a photomultiplier detector. A 0.075° soller slit was used between the source and the crystal for the collimation of x rays. A 1-μm thick Al foil was used in front of the soller slit and the detector to block visible light and reduce the background.

Several photoelectric scans were made with the Bragg monochromator over the He-like resonance and Li-like satellite region. The spectra were very reproducible. The shot-to-shot variation in intensity was less than 5%. At least three shots were taken at each wavelength setting and were averaged.

Figures 1-4 show the spectra with intensities measured at 1.0, 1.5, 2.0, and 2.5 μs, respectively, from the observed continuous time histories. The intensities of the He-like resonance line and the intercombination line are plotted on the same axis as the satellite intensities. (The units are arbitrary.) The dispersion of the Bragg crystal monochromator was found to be slightly nonlinear in the spectral region of interest. It was 16 mÅ per division at the satellite region and 14 mÅ per division at the region of the He-like resonance and intercombination line. The identification of satellites, as shown in Figs. 1-4, was possible because they occurred close to the predicted wavelength. However, no attempt was made to calibrate precisely the Bragg monochromator. The soller slit limited the resolution to 30 mÅ. The transitions of the satellites are given in Table I along with the short notation used in Ref. 2 to identify them. Table I also lists the transitions and wavelengths of other Ne IX and X lines observed in this experiment.

A 2.2-m grazing incidence monochromator viewed the plasma side-on and the time histories of the Ne VIII 2s—3p (88.1 Å) and 2p—3d (98.2 Å) lines were observed as monitors of the plasma condition. The time histories were very reproducible from shot to shot.

1. **Satellite Time Histories.** The time histories of the satellites (j,k), (a,d), and (q,r) together with time histories of the Ne VIII and Ne IX lines are shown in Fig. 5. The satellites (j,k) had a Ne IX time history and were resolved from the satellites (q,r) and (a,d). The satellites (a,d) had a Ne VIII time history, and the satellites (q,r) had both a Ne VIII and Ne IX time history in agreement with theory.[1,2] The satellites (a,d) and (q,r) are blended together and only a graphic deconvolution is shown in Figs. 1-4 as dashed triangles. However, the satellites (j,k) are clearly resolved as shown by the solid triangles, and their peak intensity is used for determination of electron temperatures.

Note that at 1.0 μs, the intensities of the satellites (a,d) and (q,r) are a factor of 2.0 to 2.5 higher than the purely dielectronic satellites (j,k). This signifies the rapid ionization of Ne VIII and the dominance of inner-shell excitation. At 2.5 μs, the (j,k) satellite is strong, indicating an increase in the dielectronic process.

2. **Optical-Depth Considerations.** The resonance line and the intercombination line were studied for any optical-depth corrections to be made to them. The intensities of these lines were measured with different concentrations of neon, all at 16 mtorr filling pressure. The resulting plots of intensity vs percentage of neon are shown in Figs. 6 and 7. As seen in Fig. 6, no optical-depth correction was needed for the intercombination line at these plasma conditions. However, the resonance line required a correction for optical depth, as can be seen from Fig. 7. The intensity of the resonance line started deviating from linearity at 0.8% neon. The intensity ratios of the resonance line to the intercombination lines, measured in the linear regime (no self-absorption), were 1.54 at 1.7 and 2.0 μs, and 1.47 at 2.5 μs. The average ratio was 1.5 ± 0.1. The ratio obtained at 1.0 μs from the time histories in the 2% neon plasma condition was 1.59, as seen in Fig. 1. We conclude that the resonance line had no self-absorption at 1.0 μs at these plasma conditions. For later times, the resonance-line intensity was obtained by multiplying the intercombination-line intensity by 1.5. From theoretical considerations given in Ref. 8, this ratio for Ne IX should be independent of electron density in the density range of our present experiment. The variation with density is also discussed in Refs. 9 and 10.

B. Observation of the Ne X Resonance Line (1s—2p)

The Lyman-α line of Ne X was observed photographically with a lead stearate crystal, as well as photoelectrically with the Bragg crystal monochromator. The intensity of this resonance line was an order of magnitude smaller than that of the Ne IX resonance line. The time history of this Ne X line and the time histories of the Ne VIII and Ne IX lines are shown in Fig. 5a. The time history of the Ne X line was found to be reproducible from shot to shot. However, the peak intensity varied within a factor of 2 from shot to shot, suggesting that plasma losses and instabilities become important at times greater than 2.0 μs. The time histories of the Ne VIII, Ne IX and Ne X lines, normalized to their peak intensities, are shown in Fig. 5b.

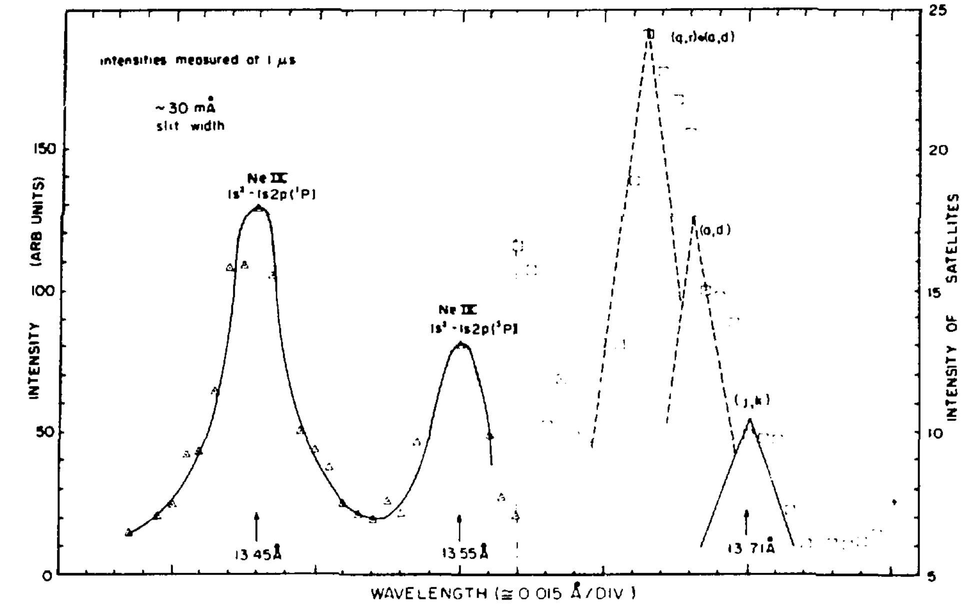


Fig. 1.

The spectrum of the Ne IX resonance line, intercombination line, and Li-like satellites. The plasma was observed axially with the Bragg crystal using a photomultiplier detector and oscilloscope. Each point is the pulse height measured at $t = 1.0$ μs with the spectrometer set at the plotted wavelength. The plot of the resonance and intercombination lines uses the intensity scale on the left. The satellite lines are much weaker and are plotted with the right-hand scale. The fill was 16 mtorr.

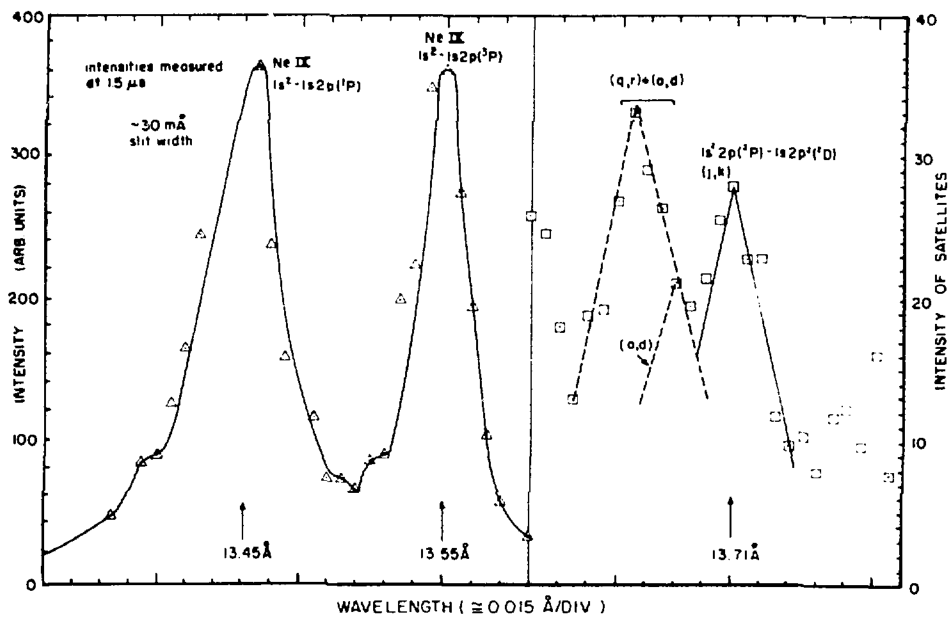


Fig. 2.

The spectrum of the Ne IX resonance line, intercombination line, and Li-like satellites measured at 1.5 μs.

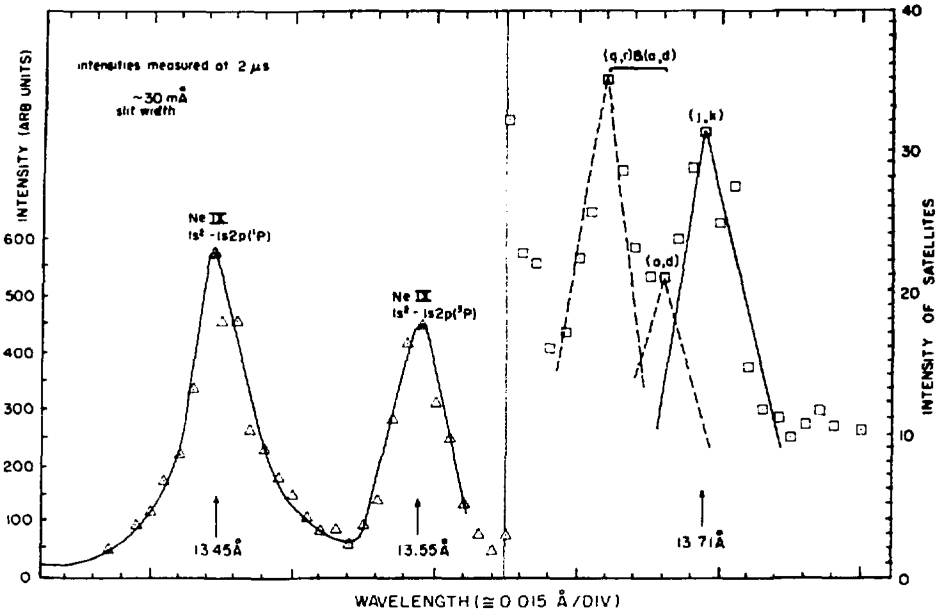


Fig. 3.
The spectrum of the Ne IX resonance line, intercombination line, and Li-like satellites measured at 2.0 μs.

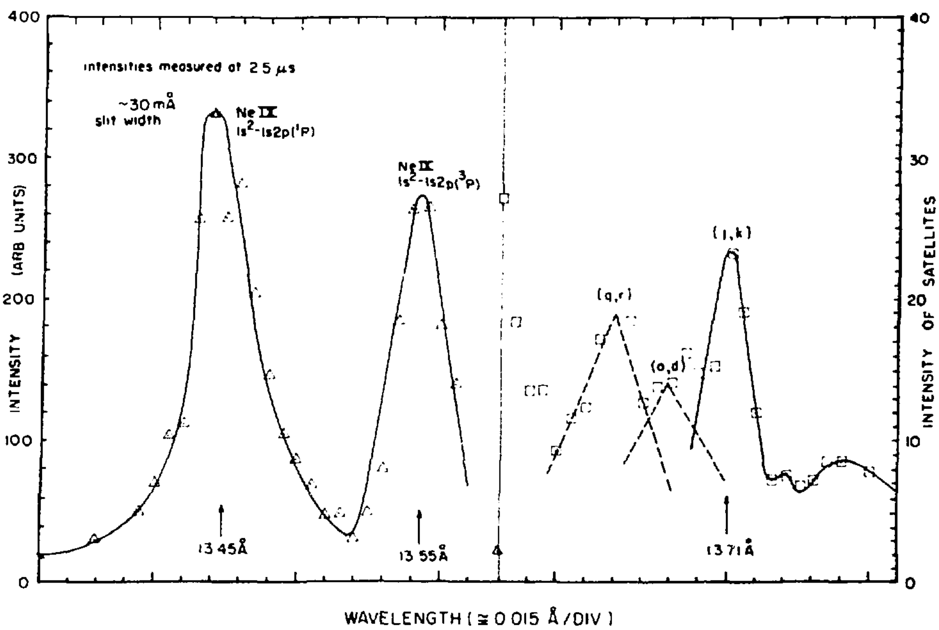


Fig. 4.
The spectrum of the Ne IX resonance line, intercombination line, and Li-like satellites measured at 2.5 μs.

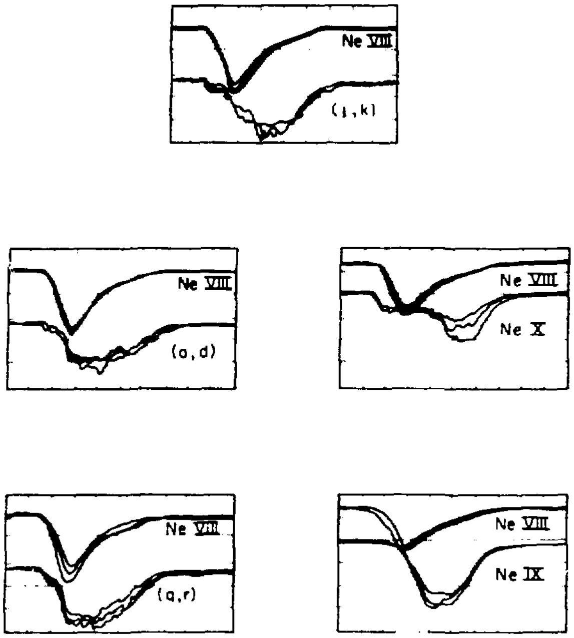


Fig. 5a.

Oscillosope pictures showing the time histories of the Ne VIII satellites (j,k)(a,d) and (q,r), the 13.55 Å intercombination line of Ne IX, and the 12.13 Å resonance line of Ne X. Each was observed with the Bragg spectrometer in axial view and is displayed on the lower trace for each picture. The upper trace on each picture displays the time history of the 88.1 Å line of Ne VIII as observed simultaneously in radial view with the McPherson 247 VUV monochromator. The sweep speeds were all 0.5 μs/division.

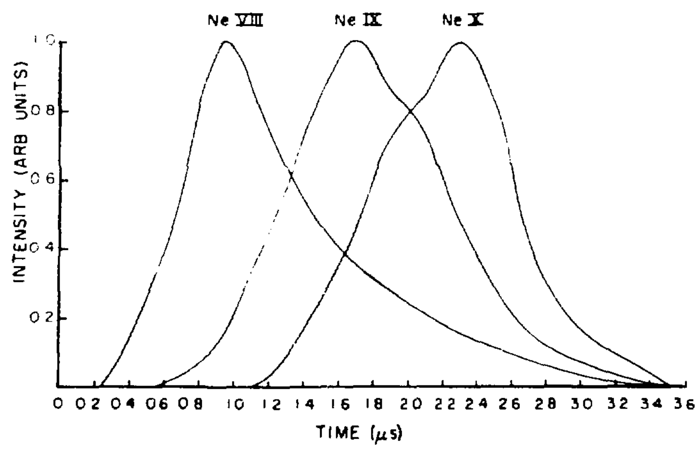


Fig. 5b.

Time histories of the Ne VIII, Ne IX, and Ne X lines obtained from oscilloscope traces such as in 5a and normalized to their peak intensities. Stray light background has been subtracted for each line.

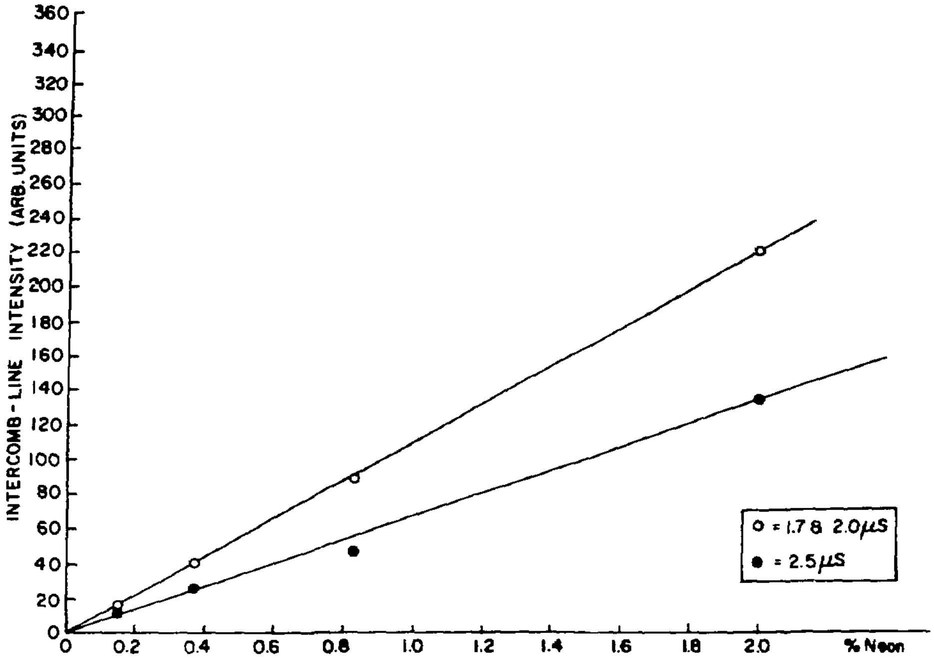


Fig. 6.
The variation of the Ne IX intercombination-line intensity with neon concentration measured at 1.7 and 2.0 μs, and at 2.5 μs.

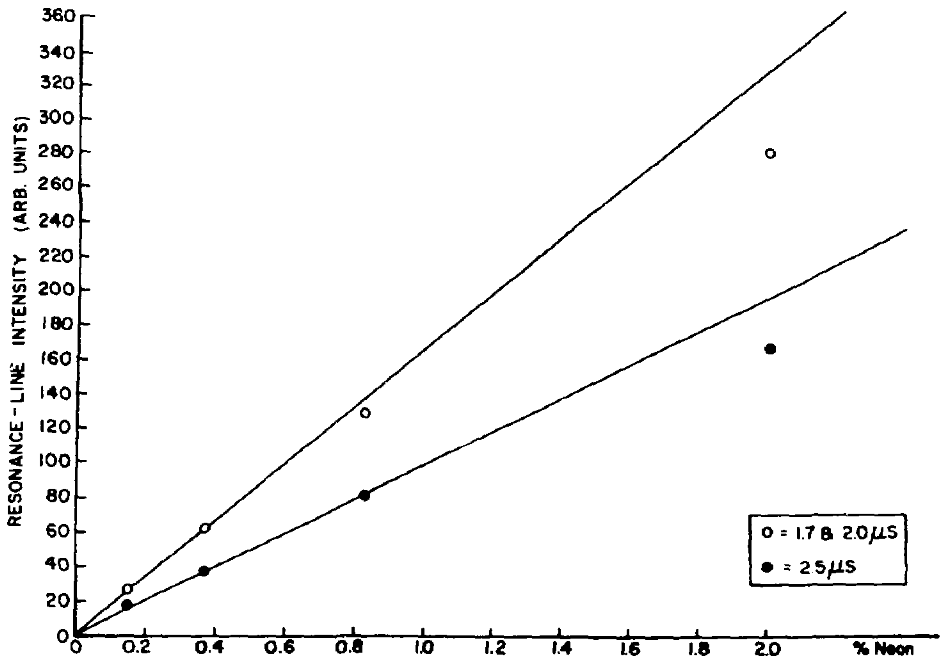


Fig. 7.
The variation of the Ne IX resonance-line intensity with neon concentration measured at 1.7 and 2.0 μs and at 2.5 μs.

TABLE I

OBSERVED LINES

Transitions	Notation	Wavelength (Å)[a]
	Li-Like Satellites (Observed Near the Ne IX Resonance and Intercombination Line)	
$1s^2\ 2s\ (^2S)—1s\ 2p\ (^1P)\ 2s\ (^2P)$	(q,r)	13.65
$1s^2\ 2p\ (^2P)—1s\ 2p^2\ (^2P)$	(a,d)	13.67
$1s^2\ 2p\ (^2P)—1s\ 2p^2\ (^2D)$	(j,k)	13.71
	Ne IX Resonance Line	
$1s^2—1s\ 2p\ (^1P)$		13.45
	Ne IX Intercombination Line	
$1s^2—1s\ 2p\ (^3P)$		13.55
	Ne X Resonance Line	
$1s—2p\ (^2P)$		12.13

[a]Wavelengths from Ref. 1.

C. Laser Holography

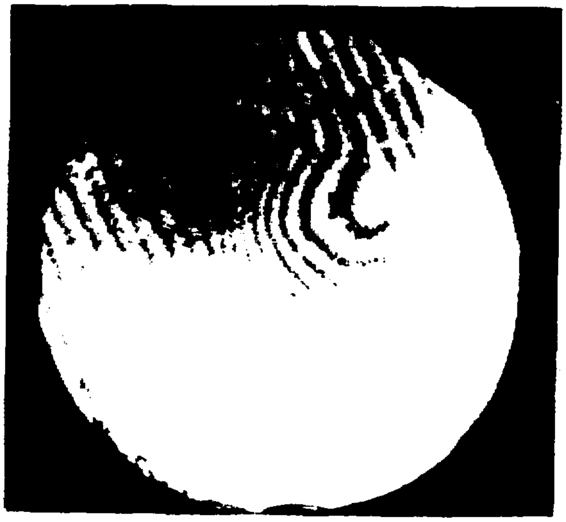
The electron density along the end-on line of sight was measured by holographic interferometry using a ruby laser, as described in Ref. 7. The holograms showed uniform and symmetric compression until 1.8 μs, then the uniformity slowly gave way to the onset of instabilities. The holograms taken at 0.55, 1.16, 1.86, and 2.06 μs are shown in Fig. 8. The electron density on axis vs time is shown in Fig. 9. The large shot-to-shot variations in density starting at 1.75 μs clearly indicate the beginning of an instability. The measured electron density varied from 2×10^{16} to 4×10^{16} cm^{-3} from 0.5 to 1.75 μs, as shown in Fig. 9.

III. RESULTS AND DISCUSSIONS

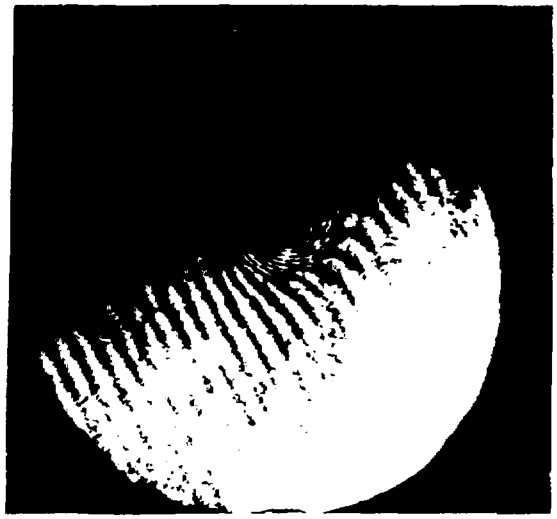
A. *Theoretical Considerations*

The theoretical basis for understanding the production of satellite transitions was developed by Gabriel.[1] Two mechanisms were considered, dielectronic recombination from the He-like ion and inner-shell excitation of the Li-like ion. The relative contribution of these two processes to the satellite intensities and the interpretation of the intensity ratio of the dielectric satellite to the resonance line in terms of electron temperature T_e were discussed in detail by Bhalla, Gabriel, and Presnyakov.[2] The satellite transitions (j,k)$[1s^2\ 2p\ (^2P)—1s\ 2p^2\ (^2D)]$ for neon were classified as possible only due to dielectronic recombination because their calculated oscillator strengths for inner-shell excitation were found to be negligible. The ratios of the intensity of the He-like resonance line in Ne IX to the total intensities of the (j,k) satellites were derived as a function of electron temperature from the theoretical calculations[2] and are given in Table II. This functional dependence is plotted in Fig. 10. We have interpolated between calculated points.

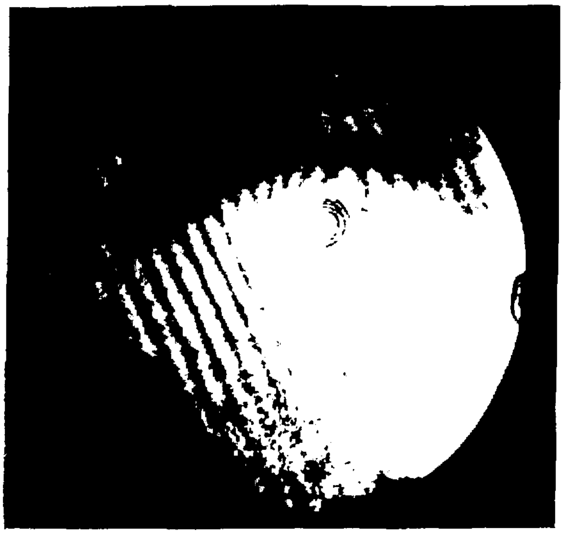
Note that the resonance/satellite line ratios given in Table II are applicable for electron density regimes below 5×10^{14} cm^{-3} for Ne IX as discussed in Refs. 1 and 2. For electron densities above this value, Gabriel et al.[1,2] suggest dividing each of the ratios in Table II by 0.8 to take into account the enhancement of the resonance line by the decay of the $1s\ 2s\ (^1S)$ level by way of the $1s\ 2p\ (^1P)$ level. Gabriel et al.[1,2,5] conclude that the ratios given in Table II should be independent of electron density except for the difference between the density regime separated by the critical density as discussed above. However, Weisheit shows in Ref. 10 that the



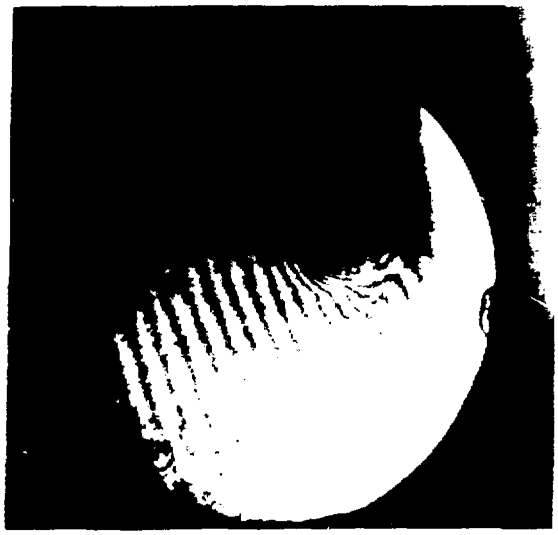
0.55 μs



1.16 μs



1.86 μs



2.06 μs

Fig. 8.
Holograms taken at 0.55, 1.16, 1.86 and 2.06 μs at the 16 mtorr filling pressure.

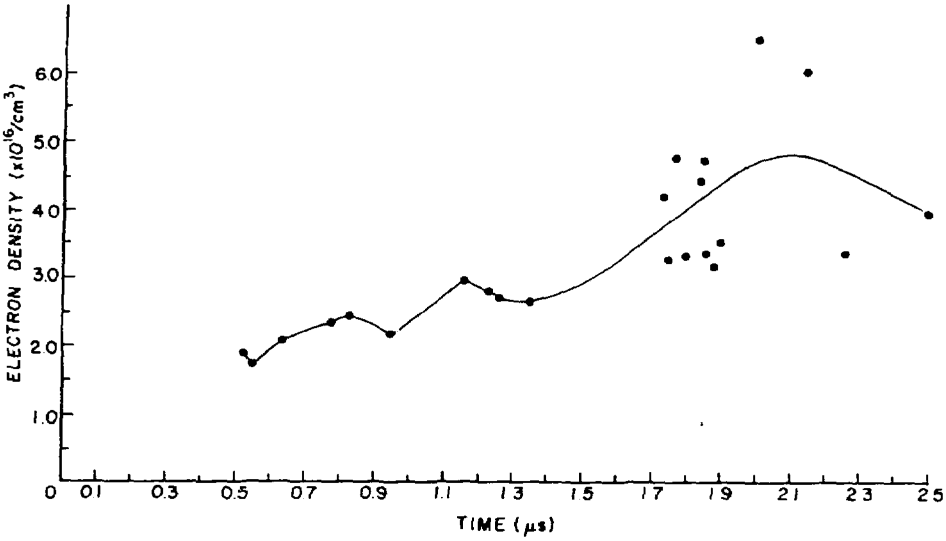


Fig. 9.
Average electron density on axis at 16 mtorr filling pressure (98% He and 2% Ne), obtained by holographic interferometry.

TABLE II

CALCULATED INTENSITY RATIOS[a] OF THE Ne IX RESONANCE LINE TO ITS DIELECTRONIC SATELLITES (j,k) AS A FUNCTION OF ELECTRON TEMPERATURE

T_e (eV)	$I(1s^2—1s\ 2p)/I(j,k)$
63.7	0.67
82.8	1.89
107.7	4.46
140.0	9.10
182.1	16.8
236.6	28.3
307.6	45.1
399.9	68.4
519.9	100.1
676.8	142.6
879.8	198.4
1141.3	273.0
1485.8	369.2

[a]Calculated from Tables VII and X in Ref. 2.

plasma screening effect and collisional interruption of dielectronic satellite intensities become important at electron densities above 10^{21} cm^{-3}.

B. Electron Temperature Measurements Using Li-like Dielectronic Satellites (j,k) in Neon

The intensities of the (j,k) satellites and the resonance line measured from Figs. 1-4 are listed in Table III. The predicted electron temperatures using the ratios given in column 3 and Fig. 10 are presented in column 4. In column 5, the electron temperature at 1.0 μs measured[7] by laser scattering at 20 mtorr (98% He and 2% Ne) is given and agrees closely with the temperature measured by the satellite technique. Note that the time histories of Ne VIII lines in both plasma conditions were identical, supporting this agreement. Also, the observation of the Ne X Lyman-α line with an excitation potential of 922 eV is in accordance with a peak electron temperature of 340 eV measured by the satellite technique. However, if we consider the effect of higher electron densities, as discussed for Ne IX in Refs. 1 and 2, the temperatures derived from the satellite technique should be decreased by about 12%. Our results do not appear to agree with this estimate[1,2] for the density dependence. The critical density estimated for neon may be too low.

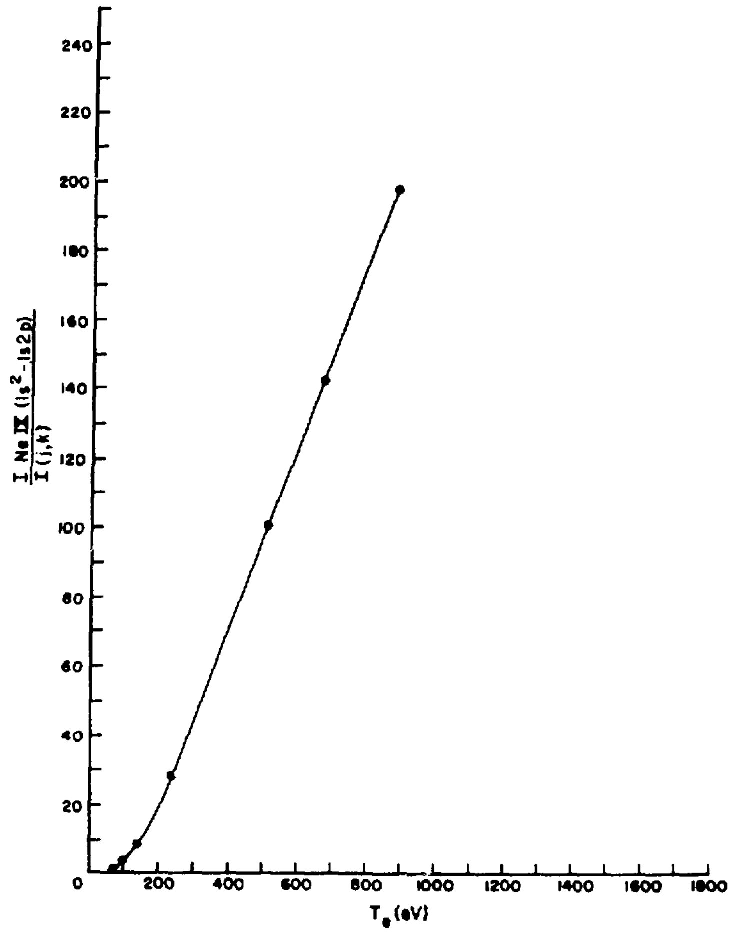


Fig. 10.
Intensity ratio of the He-like Ne IX resonance line to its dielectronic satellites as a function of electron temperature (See Ref. 2).

The satellite technique is not very sensitive to variations as small as 5% in the ratio of resonance-line to satellite-line intensities. Our experimental error is estimated to be ± 5%. One limitation of the satellite technique is that the resonance line tends to become optically thick. Thus to use the line ratios to obtain the electron temperature, the optical-depth correction must be determined as was done in the present experiment.

IV. SUGGESTIONS FOR FUTURE WORK

The time histories of Ne VIII, Ne IX and Ne X lines are shown in Fig. 5b and contain the information about the rate of ionization of these ionic species. For example, the ionization rate of Ne VIII was deduced from its time history in Ref. 7, and the method is described in detail in Ref. 8. In fusion plasmas, the ionization rate is an important quantity that should be accurately known for calculations of radiation losses because of impurities. There is a great need for measurements of these rates in the fusion program. In the present experiment, the ionization rate measurements could not be obtained for Ne IX and Ne X because plasma losses and instabilities made accurate determination of the electron density and temperature very difficult beyond 1.7 μs. From the time histories observed in the present experiment, one can predict that such measurements could be obtained if the plasma lifetime can be extended to ≥ 2.5 μs at θ-pinch

TABLE III

ELECTRON TEMPERATURE EXPERIMENTALLY DETERMINED FROM THE INTENSITY RATIOS OF THE Ne IX RESONANCE LINE TO THE DIELECTRONIC SATELLITES

Time	Line Intensities (Arbitrary Units)		Intensity Ratio $1s^2$—1s 2p ($^1P_1$)	Electron Temp by Satellite Technique[a]	Electron Temp by Laser Scattering[b]
(μs)	(j,k)	$1s^2$—1s 2p ($^1P_1$)	(j,k)	(eV)	(eV)
1.0	6	122	20	210	225
1.5	20	1042[c]	52	340	~400
2.0	23	668[c]	29	240	---
2.5	16	385[c]	24	220	---

[a]See Ref. 2.
[b]*With 98% He and 2% Ne at 20 mtorr filling pressure, from Ref. 7.*
[c]Corrected for optical depth as explained in the text.

conditions similar to those used in this experiment. This could be accomplished by using a longer θ coil, say $\ell \geq$ 0.5 m, as suggested in Ref. 11.

V. CONCLUSIONS

The electron temperatures of a θ-pinch discharge were obtained as a function of time using the intensity ratios of the Ne IX resonance line to its dielectronic satellites. The gas fill was 98% He and 2% Ne at 16 mtorr. The temperature determined by this method was in agreement with a measurement done by laser scattering for a similar plasma condition. The resonance line was found to be optically thick, and the correction was determined experimentally.

We conclude that this satellite technique may be used to measure electron temperatures when the optical depth of the resonance line is suitably accounted for.

ACKNOWLEDGMENTS

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