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XUV AND XRAY SPECTRA FROM TEXAS EXPERIMENTAL TOKAMAK PLASMAS.(U)
MAY 82 R D BLEACH, P G BURKHALTER, D J NAGEL DE-AI01-76-ET-53028
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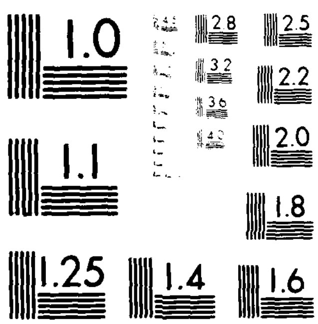

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The first XUV and x-ray spectra were recorded from TEXT with a grazing-incidence grating spectrograph and new crystal spectrographs. Time- and space-integrated data yielded a qualitative description of the plasma. Line radiation from O, Cr, Fe, and Ni ions was recorded and identified with the aid of ab initio atomic structure calculations. Approximate values of plasma characteristics were obtained from the spectra. A derived electron temperature of 800 eV and electron density of 2×10^{13} cm^{-3} are consistent

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20. ABSTRACT (Continued)

with results from other diagnostics. Spectrometers which will provide time- and space-resolved data are being designed for quantitative rate and transport studies.

CONTENTS

XUV AND X-RAY SPECTRA FROM TEXAS EXPERIMENTAL TOKAMAK PLASMAS

I. INTRODUCTION

Tokamaks are primary research devices for development of fusion energy by magnetic confinement of plasmas having ion temperatures in the 10-100 million K range.[1] Many Tokamaks of generally increasing size and performance have been constructed over the past two decades to obtain data on confinement and scaling. Thermonuclear ignition is expected in the generation of machines presently under construction: JET in Europe, TFTR in the U.S., JT-60 in Japan, and T-15 in the USSR.

A new Tokamak TEXT (Texas Experimental Tokamak) at the University of Texas in Austin has recently been put into use to provide a facility for fusion experiments which will not interfere with the performance or schedules of the principal magnetic confinement machines.[2] Plasma currents of about 300 kA are produced with a centerline field of 3 Tesla in discharges lasting about 300 ms. The inner surfaces of TEXT are stainless steel type 304 which contains 67% Fe, 20% Cr, and 12% Ni. The limiter is also stainless steel. Some of the stainless steel and oxygen contained in the walls and limiter of TEXT enters the plasma and emits radiation in the XUV and x-ray regions.

Emission spectroscopy of impurity elements is a valuable method for diagnosis of Tokamak performance. Radiation with energies ranging from the infrared to the x-ray region has provided information on plasma composition, temperature, density, and particle motion.

Many spectral measurements of Tokamak plasmas have been made in the 60 to 600 eV range which provide data on highly ionized atoms in the plasmas.[3,4,5,6] At higher photon energies work involving spatially resolved spectra has provided information on plasma stability.[7] X-ray measurements with spectral, spatial, and temporal resolution have been made with Si (Li) detectors.[8,9,10]

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Recently, high resolution x-ray spectra above 1 keV have been obtained with Bragg crystals and time-resolving detectors.[11,12,13]

TEXT will have a relatively complete set of diagnostic instrumentation to measure the visible through x-ray range. Data taken with visible and UV spectrometers have already been reported.[14]

This report covers initial XUV and x-ray spectroscopic experiments which were performed in June 1981. Spectra consisting of line emission from different elements in the plasma were obtained in the 30 eV to 7 keV (2-400 A) range. Analysis yielded information on plasma composition and provided measurements of temperature and density in the plasma. The data have no temporal or spatial resolution. Spectra were integrated over many shots in order to accumulate intensity on film. The variety of temperatures produced in different regions of the plasma during the discharge allows many ionization stages of the impurity elements to be created and radiate at x-ray and XUV energies. Results of these experiments can be used to select specific line radiation for time- and space-resolved spectroscopy. Further quantitative experiments to determine energy losses, ionization rates, and transport mechanisms in the plasma are planned.

II. INSTRUMENTATION

A vacuum housing 38 cm high, 20 cm wide, and 60 cm deep was coupled to a TEXT port via a gate valve. A photograph of the housing is shown in Figure 1 and a schematic is shown in Figure 2. Either the grazing-incidence grating or multiple crystal spectrographs can be mounted in a light tight box which is inserted into the vacuum housing.

A grazing-incidence grating spectrograph was used to observe radiation in the 30-300 A range.[15] This instrument contains a 1200 lines per mm blazed grating mounted on a 1 m diameter Rowland circle. It is compact, portable, and capable of being positioned close to the plasma. One major advantage of such an instrument is that it can be setup in a relatively short time to take initial surveys of plasma composition. Spectral resolution of this instrument is 0.15 A over the 30 to 300 A range using a point source. This provides enough dispersion to identify lines from various ions in the plasma, leaving measurements of line shapes to higher resolution instruments. The spectrograph was oriented so that its entrance slit was parallel to plane containing the toroidal plasma and is shown schematically in Figure 2. Spectra were recorded on Kodak 101 film.

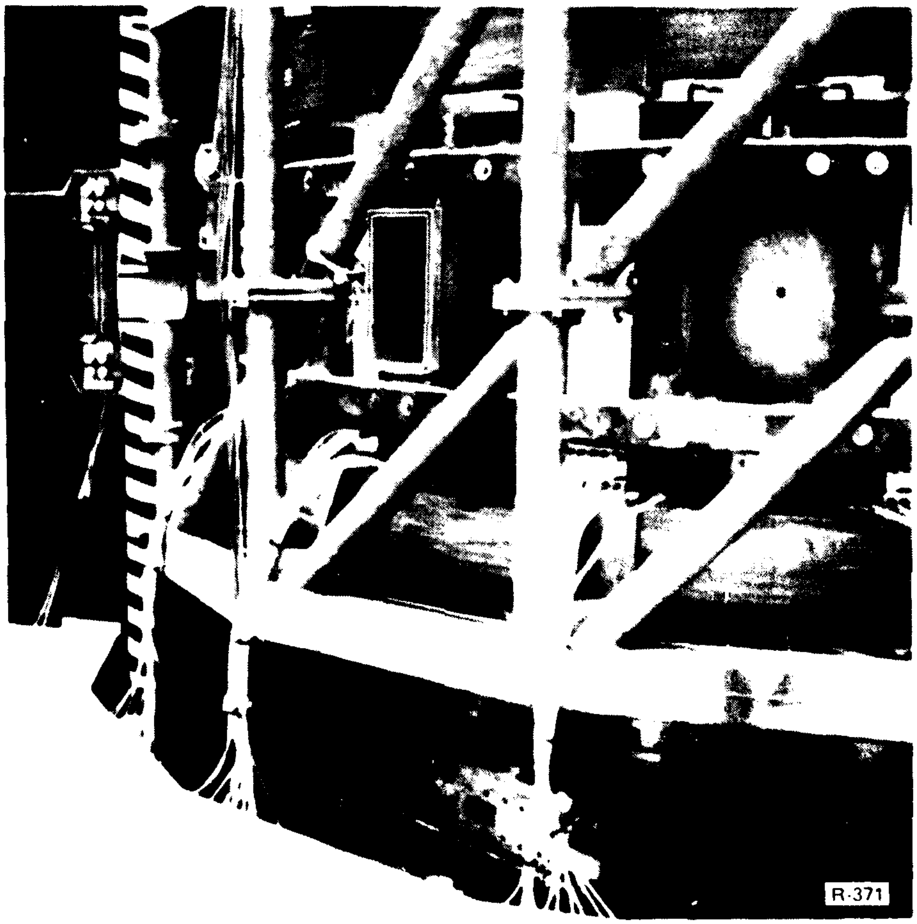

Fig. 1 — A photograph of the vacuum box attached to TEXT into which the spectrograph box was placed.

An x-ray crystal spectrograph was designed and constructed using concave focussing crystals to measure radiation from the L shell of Fe ions in the 15-19 A range and K shell radiation of oxygen ions in the 18-20 A range. Concave focussing crystals were chosen to increase the collecting efficiency of radiation from the plasma. A schematic of the spectrograph setup is shown in Figure 2. Crystals of KAP and mica with a 28 cm radius of curvature were used. Both crystals and film can be positioned along the 28 cm diameter Rowland circle.

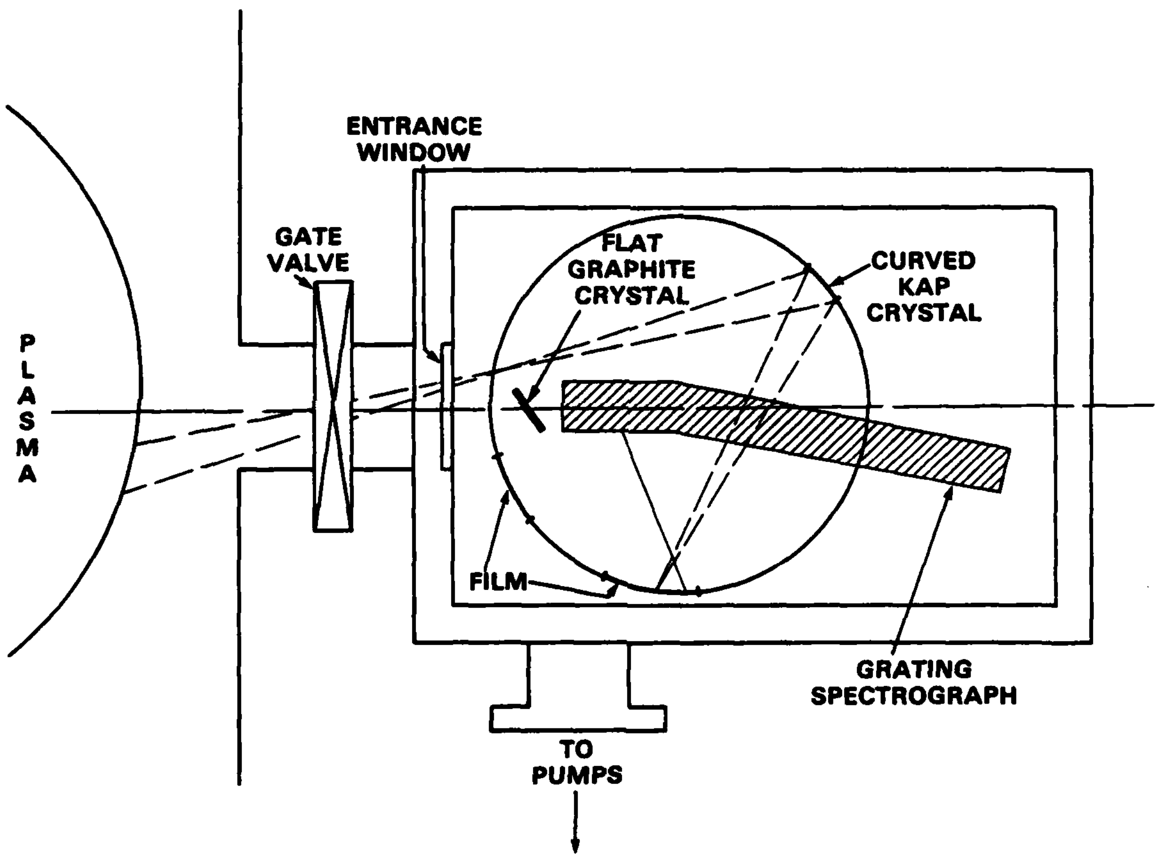

Fig. 2 — A schematic of the experimental setup showing a grazing-incidence grating spectrograph and curved and flat crystal spectrographs. The focusing crystal is mounted on a 28 cm diameter Rowland circle. Either the crystal spectrographs or the grating instrument are used at any one time.

Each curved crystal was 1.3x5.0 cm and was selected to maximize the dispersion of the line being observed. A KAP crystal was positioned to record the O VII $1s^2$ - 1s2p line at 21.6 A. Mica crystals were positioned to view the Fe XVII 2p-3s line at 16.8 A and the O VIII 1s-2p line at 19.0 A. Radiation passed through a thin light-tight entrance window made of 1 μm polypropylene coated with 1500 A of aluminum and was diffracted off each crystal. Spectra were recorded on Kodak No-Screen film.

A flat, high-efficiency graphite crystal was used in the setup shown in Figure 2 to survey radiation emitted by the plasma in the 1.9 to 3.7 A range where Kα radiation from Fe and Cr ions occurs. A 2x2 mm entrance slit was placed between the crystal and the plasma to define the location of the observed plasma. Spectra were recorded on Kodak No-Screen film.

III. RESULTS

The spectra obtained are described prior to discussing plasma characteristics which are derived from them.

A. Spectra

The grazing-incidence grating spectrograph was used to obtain spectra from O, Cr, Fe, and Ni ions. These data were integrated over 23 consecutive shots. Figure 3 is a spectrum in the 50 to 300 A range, and Figure 4 is a densitometer trace of a portion of this spectrum with some of the prominent lines identified. Line identifications were made by referencing the TEXT spectrum to a spectrum from an exploding stainless steel wire plasma taken with the same instrument.[15] Fe XVI lines appearing as strong lines in the exploding wire spectra also appeared in the TEXT spectra with less intensity. These lines provided fiducial wavelengths for second order polynomial fits to the measured distances on the film. Fits were made to distances measured with both an optical comparator and a computerized densitometer. Agreement of wavelengths calculated by these fits to published wavelengths[16] was within 0.1 A.

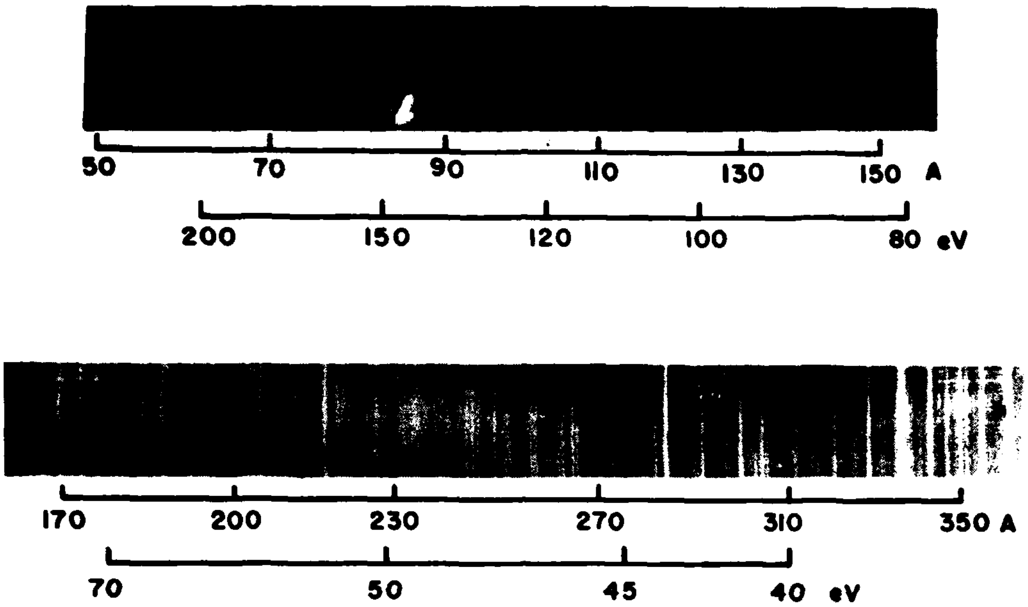

Fig. 3 — A spectrum obtained with the grazing incidence grating spectrograph showing line radiation from O, Cr, Fe, and Ni ions.

Many of the observed lines from Fe IX to Fe XXII are $\Delta n=0$ transitions falling in the 100 to 200 A range. It was expected that these lines would be abundant since the excitation rates are larger for these transitions than the rates for $\Delta n=1$ transitions in the 5 to 15 A range. The $\Delta n=1$ transitions could not be observed with the grating spectrograph to confirm this expectation. Lines from Fe XIX were more abundant than lines from other Fe ionization stages. Lists of some observed lines are given in Tables I-III.

Some of the lines have widths which are greater than the instrumental resolution of 0.15 A. This may be due to blending and Doppler broadening of the lines. We have attempted only to separate blends of lines. For example, the O VII 2s-4p transition at 91.02 A coincides with the Fe XIX 2s-2p transition at 91.03 A and Fe XVIII, Ni XXI, and Fe XX lines coincide at about 93.9 A. Published spectra of Tokamak plasmas show that many lines observed in TEXT are the same as previously reported[17,18].

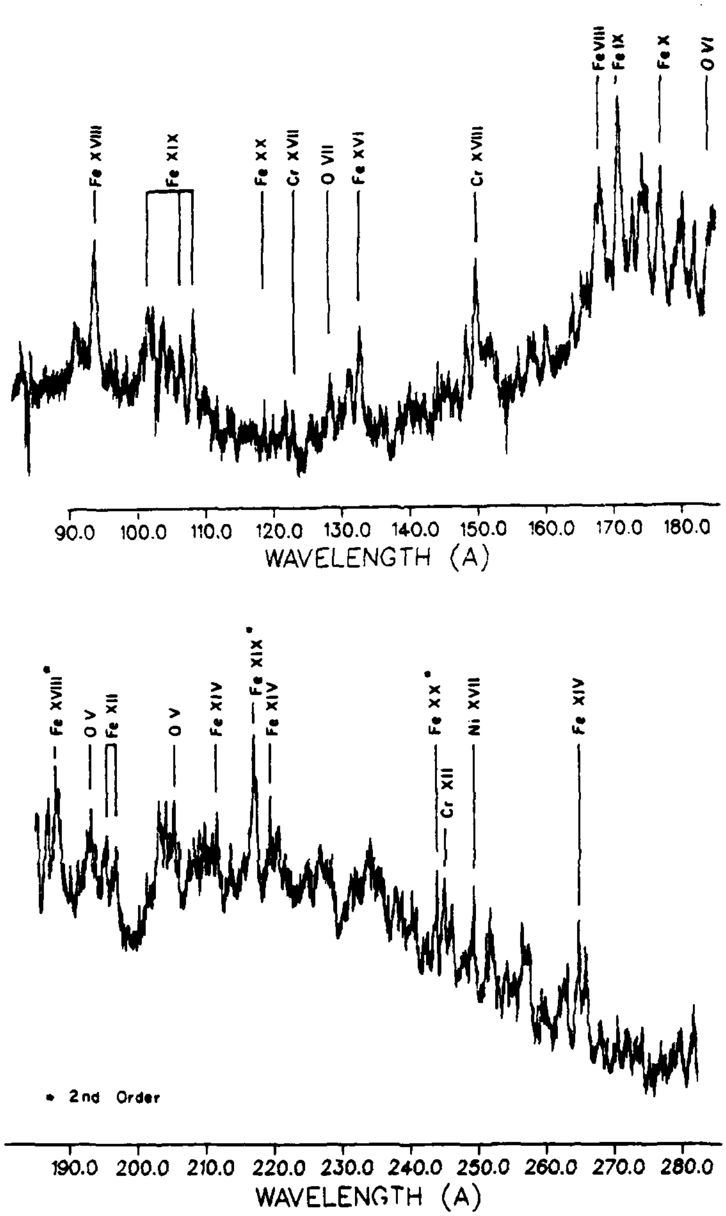

Fig. 4 — A densitometer trace of the spectrum shown in Figure 3. Some of the more prominent lines are identified.

An atomic structure code[19] was used to confirm the identification of observed lines from Fe XVIII and Fe XIX and to predict oscillator strengths for use in plasma temperature estimates discussed below. Table IV gives the predicted wavelengths and oscillator strengths compared with the observed wavelengths. In general, relative intensities of observed lines correlate with the relative oscillator strengths. Lines with oscillator strengths less than 0.06 were not observed.

A spectrum was obtained with the curved KAP spectograph in three shots. The shortest wavelength observed is believed to be the resonance line from helium-like O VII ($1s^2$-1s2p) at 21.6 A. A series of lines at wavelengths near 22 A are believed to be the second order spectrum from Fe or Ni ions. Additional spectra are needed to verify these results. An O VII line at 1623 A was observed with a spectrometer which was used as a radiation monitor[14].

The flat graphite crystal spectrograph produced a spectrum integrated over 43 shots which contains two features shown in Figure 5.

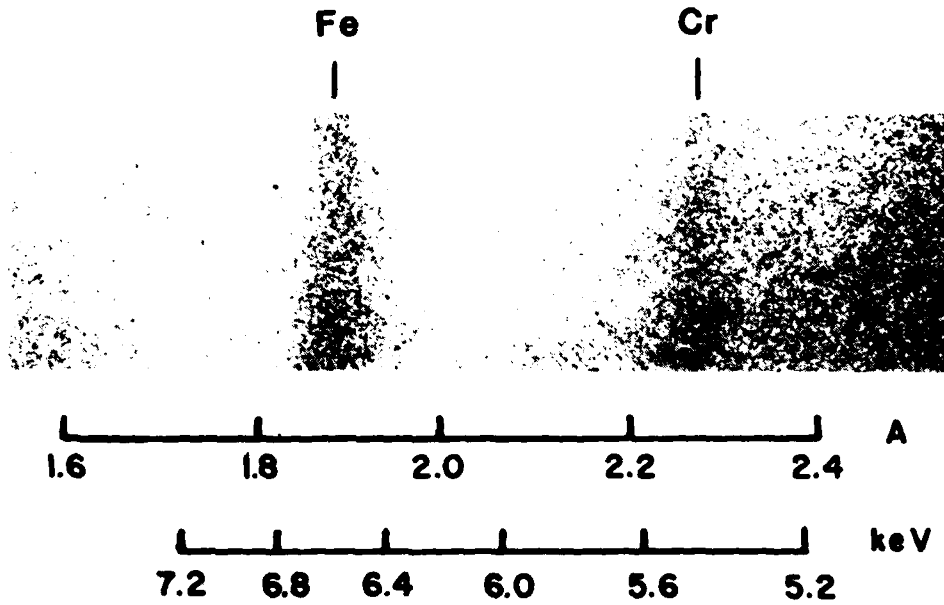

Fig. 5 — A spectrum integrated over 43 shots of Kα radiation from Fe XXI to Fe XXII and Cr XVI to Cr XVIII ions obtained with a flat graphite crystal.

The band of radiation at the left covers the wavelength range of Kα radiation from Fe XXI to Fe XXII. The other band corresponds to Kα radiation from Cr XVI to Cr XVIII. Both of the features in Figure 5 are unresolved because of the finite entrance slit used and, to a lesser extent, the wide rocking curve of the graphite crystal. For these reasons, the data were used only to show consistency with other plasma temperature measurements. These lines have been previously observed in Tokamak plasmas at Princeton University[12] and in the USSR[20] with sufficient spectral resolution to separate radiation from individual charge states.

The film was densitometered and converted to exposure by using calibrations[21] and theoretical film response calculations.[22] Measured integral reflection coefficients for graphite[23] were then used to convert the measured exposures on film to intensity of radiation emitted by the plasma. Assuming an optically thin plasma, Fe Kα radiation emitted by Fe XXI-Fe XXII ions was 5.4×10^7 phot/cm^3-sec-sr and Cr Kα radiation was 2.9×10^7 phot/cm^3-sec-sr from Cr XVI-Cr XVIII ions.

B. Temperature and Density Determinations

Figure 6 shows the most abundant ionization state of Fe vs. electron temperature calculated using a coronal model.[24] The data point at Fe XIX obtained from lines observed with the grazing-incidence grating spectrograph indicates an electron temperature of about 800 eV. This value agrees with peak electron temperatures obtained from electrical conductivity measurements.[14] Data from observed XUV lines of Cr and Ni ions are also consistent with an 800 eV temperature.

Calculations of the Kα radiation as a function of plasma temperature from ionization stages of Fe have been made to determine the concentration and radial variation of Fe impurities in Tokamaks at Princeton.[11] The Fe charge state radiating with the most Kα intensity vs. electron temperature is shown in Figure 7. The measured wavelength of the centroid of the Fe lines shown in Figure 5 corresponds to Kα radiation from Fe XX and Fe XXI. This gives an electron temperature of about 800 eV as shown by the data point in Figure 7.

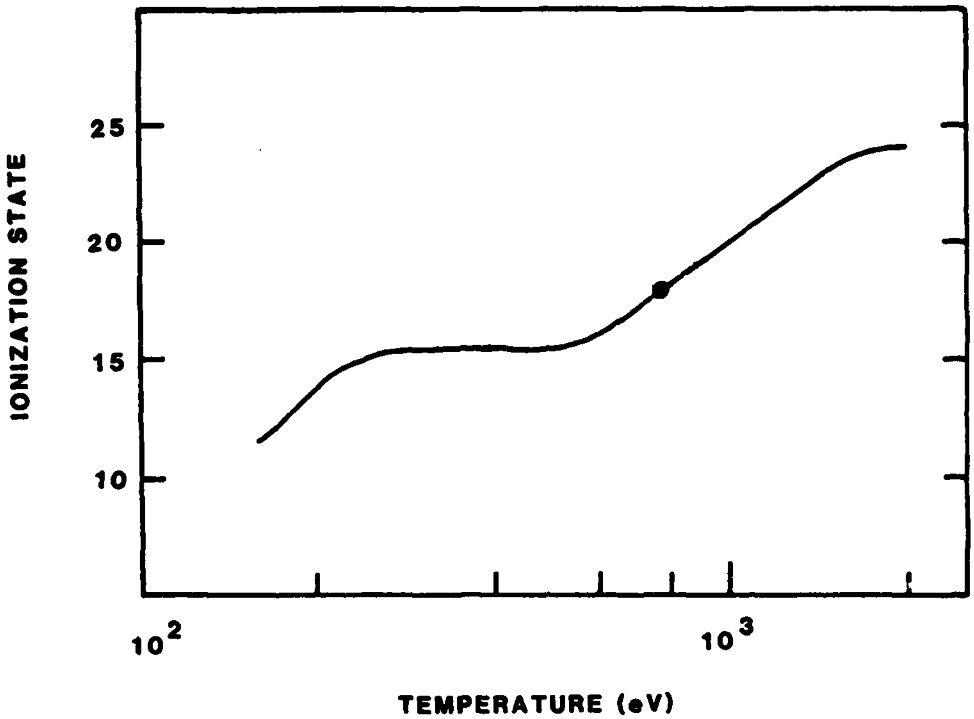

Fig. 6 — An Fe coronal model calculation of the most abundant ionization stage vs electron temperature.[24] For Fe XIX an electron temperature of 800 eV is obtained from the spectrum in Figure 3 as indicated by the data point.

The electron density along line of sight in the TEXT plasma was determined from the measured relative line intensities of Fe lines. The number of photons produced is given by:

$$I_{ij} = \frac{A_{ji}}{4\pi} \int_{\Delta V} N_j \, dV \quad (\text{photons-sec}^{-1}\text{-sr}^{-1}) \tag{1}$$

where V is the observed plasma volume in which line emission occurs, N is the number of ions per unit volume at energy level j, and A is the transition probability from level j to i. Taking the ratio of equation 1 for two different lines we get:

$$\frac{I_{ij}}{I_{kl}} = \frac{A_{ji} \int n_j \, N_T \, dV}{A_{lk} \int n_l \, N_T \, dV} \tag{2}$$

where n is the fraction of ions residing at a given level and N_T is the total ion population. If we assume that n_j and n_l do not vary much over the emitting volume then:

$$\frac{I_{ij}}{I_{kl}} \approx \frac{A_{ji}\ n_j}{A_{lk}\ n_l} \qquad 3)$$

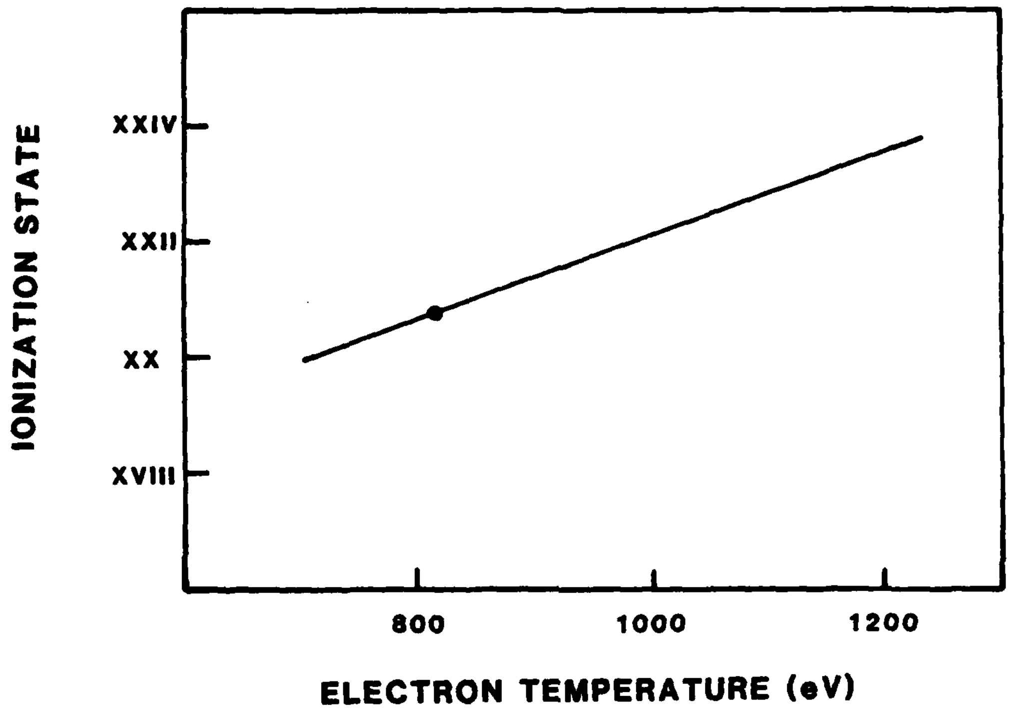

Fig. 7 — The ionization state of Fe which emits the most Kα radiation vs electron temperature. An electron temperature of about 800 eV is obtained as indicated by the data point.

The relative populations of levels as a function of electron density in several ionization stages of Cr, Fe, and Ni have been published.[25] Figure 8 uses some of these data to show the intensity ratio of Fe XIX transition vs. electron density averaged over the line of sight. Transition probabilities were obtained[19,25] for several lines observed in the TEXT spectra.

Fe XIX IONS

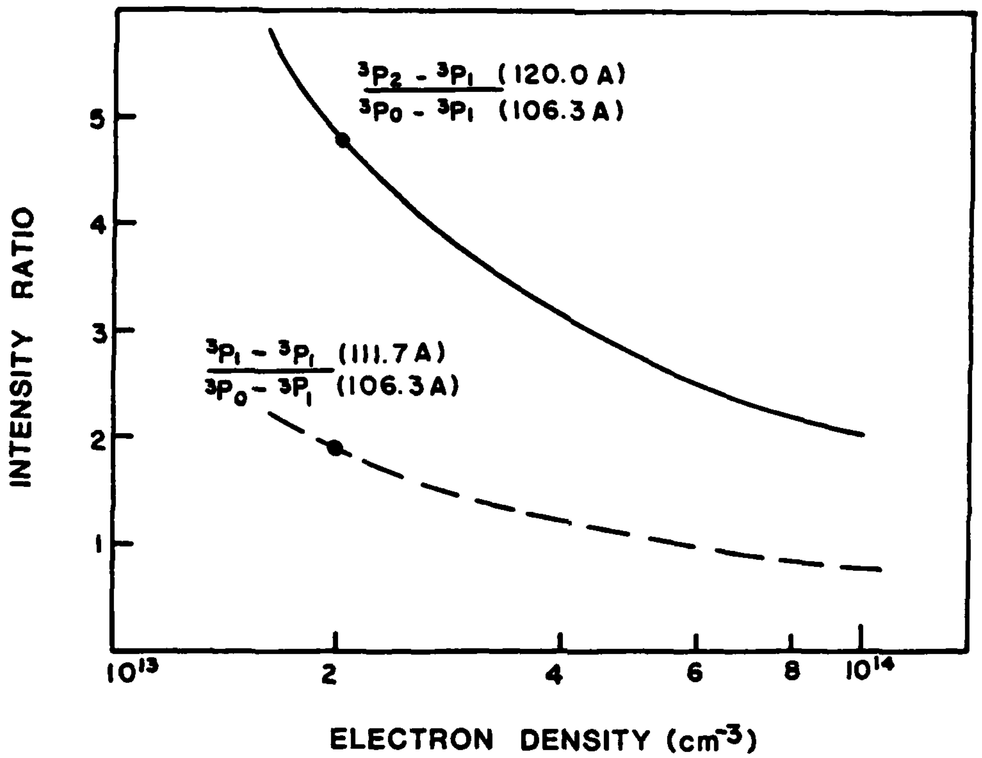

Fig. 8 — The intensity ratio of several Fe XIX transitions as a function of electron density according to plasma calculations.[19,25] For observed lines, the ratios give an electron density of 2×10^{13} cm^{-3} as indicated by the data points.

The intensity ratio of the Fe XIX line $2p^4\ (^3P_1)$-$2s2p^5\ (^3P^0{}_1)$ at 117.7 A to the Fe XIX $2p^4\ (^3P_1)$-$2s2p^5\ (^3P^0{}_0)$ line at 106.3 A gives an electron density of 2×10^{13} cm^{-3} as shown by the data point in Figure 8 and the ratio of the intensities of the Fe XIX $2p^4\ (^3P_1)$-$2s2p^5\ (^3P^0{}_2)$ line at 120.0 A to the Fe XIX $2p^4\ (^3P_1)$-$2s2p^5\ (^3P^0{}_0)$ line at 106.3 A also gives an electron density of 2×10^{13} cm^{-3}. Film density ratios were used instead of actual line intensities. It was assumed that the film and grating efficiencies at the two wavelengths of ratioed lines do not vary much. These average densities integrated along the line of sight agree approximately with the density determined by 2 mm microwave interferometry.[14]

IV. FUTURE EXPERIMENTS

The x-ray and XUV data collected to date on film provide information which is useful for designing instruments which will resolve radiation in time and space. Temporal resolution of emission from individual ionization states is necessary in order to measure the temperature and density changes in the plasma. Spatial resolution will permit the size and shape of the emitting volume to be measured. A crystal spectrometer which can measure individual photon arrival times is being designed. Later, a mechanical assembly which can rotate the spectrometer will allow measurements along different chords through the plasma to be made. This arrangement will be used to obtain the spatial distribution of ions in the plasma. Initially, both configurations will be set up to record individual lines. Spectral resolution on a single shot will be possible using position sensing detectors in these instruments.

V. SUMMARY

Time- and space-integrated spectra recorded with several spectrographs covering the 30 eV to 7 keV range showed that oxygen, iron, chromium, and nickel ions were present in the TEXT plasmas. Line identifications were made with the aid of ab initio atomic structure calculations.[19] Transitions from many ionization stages were observed because of the changing plasma temperature throughout the discharge. Lines from Fe XIX were abundant in the XUV region and were used to determine a coronal equilibrium electron temperature of 800 eV. This is consistent with electron temperatures determined from the x-ray data and electrical conductivity measurements. An average electron density of 2×10^{13} cm^{-3} was determined from the line ratios of several Fe XIX lines which are weakly dependent upon electron density in the 10^{13} to 10^{14} cm^{-3} range. This value agrees with the value determined from microwave interferometry.

Further time- and space-resolved spectral experiments are planned to measure ionization and transport rates.

Acknowledgments:

We appreciate the support of the TEXT crew for these experiments. K. Gentle, Director of the TEXT facility, generously provided advice and materials for setting up the experiment. We thank Karrol Hudson for his contribution to the construction and set up of vacuum pumps and the experimental housing at TEXT. R. Cowan of Los Alamos Scientific Laboratory provided his atomic structure code, which was converted for use on the NRL Advanced Scientific Computer by Brian Sweeney.

TABLE I

OBSERVED Fe LINES

WAVELENGTH (A)	TRANSITION	ION
66.26	3d-4f	Fe XVI
91.02	2s-2p	Fe XIX
93.94	2s-2p	Fe XVIII
101.56	2s-2p	Fe XIX
103.96	2s-2p	Fe XVIII
106.33	2s-2p	Fe XIX
108.37	2s-2p	Fe XIX
110.63	2s-2p	Fe XX
111.70	2s-2p	Fe XIX
113.34	2s-2p	Fe XX
117.12	2s-2p	Fe XXII
118.66	2s-2p	Fe XX
120.00	2s-2p	Fe XIX
121.16	2s-2p	Fe XXI
121.83	2s-2p	Fe XX
167.49	3p-3d	Fe VIII
171.08	3d-4f	Fe IX
174.53	3p-3d	Fe X
179.76	3p-3d	Fe XI
193.52	3p-3d	Fe XII
200.03	3p-3d	Fe XIII
211.32	3p-3d	Fe XIV
284.15	3s-3p	Fe XV

TABLE II

OBSERVED Cr LINES

WAVELENGTH (A)	TRANSITION	ION
106.60	2s-2p	Cr XVI
115.27	2s-2p	Cr XVI
122.91	2s-2p	Cr XVII
125.35	2s-2p	Cr XVII
132.76	2s-2p	Cr XVII
136.52	2s-2p	Cr XVIII
139.87	2s-2p	Cr XVIII
156.00	2s-2p	Cr XX

TABLE III

OBSERVED O LINES

WAVELENGTH (A)	TRANSITION	ION
120.3	2s-3p	O VII
128.5	2p-3d	O VII
129.8	2p-4d	O VI
132.8	2p-3s	O VII
135.8	2p-3d	O VII
150.1	2s-3p	O VI
172.9	2p-3d	O VI
183.9	2p-3s	O VI

TABLE IV

COMPARISON OF SOME OBSERVED AND CALCULATED Fe LINES

Measured Wavelength A	Calculated Wavelength A [20]	Calculated gf [20]	Ion	Transition
91.02	92.46	0.533	Fe XIX	$2s^22p^4\ ^1D_2 - 2s2p^5\ ^1P_1$
93.94	92.99	0.241	Fe XVIII	$2s^22p^5\ ^2P_{3/2} - 2s2p^6\ ^2S_{1/2}$
101.56	100.97	0.151	Fe XIX	$2s^22p^4\ ^3P_2 - 2s2p^6\ ^3P_1$
103.96	103.09	0.109	Fe XVIII	$2s^22p^5\ ^2P_{1/2} - 2s2p^6\ ^2S_{1/2}$
106.33	105.70	0.102	Fe XIX	$2s^22p^4\ ^3P_1 - 2s2p^5\ ^3P_0$
108.37	107.74	0.332	Fe XIX	$^3P_2 - {}^3P_2$
*	109.22	0.092	Fe XIX	$^3P_0 - {}^3P_1$
*	109.26	0.092	Fe XIX	$^1S_0 - {}^1P_1$
111.70	111.32	0.070	Fe XIX	$^3P_1 - {}^3P_1$
120.00	119.60	0.113	Fe XIX	$^3P_1 - {}^3P_2$

* not observed

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