DOE/ET53006-7

MASTER

EXTREME ULTRAVIOLET AND SOFT X-RAY DIAGNOSTICS OF HIGH-TEMPERATURE PLASMAS

Annual Progress Report

Prepared By

H. Warren Moos and L. Armstrong, Jr.

The Johns Hopkins University
Baltimore, Maryland

October 1, 1980 - September 30, 1981

PREPARED FOR THE U.S. DEPARTMENT OF ENERGY

UNDER CONTRACT DE-AS02-76ET53006

DISCLAIMER

RESEARCH STAFF:

Professor H. Warren Moos, Co-Research Contract Director

Professor L. Armstrong, Jr., Co-Research Contract Director

Professor Wm. G. Fastie

William L. Hodge, Jr., Associate Research Scientist

Michael Finkenthal	Postdoctoral Fellow
Mina Vajed-Samii	Postdoctoral Fellow
Ronald Bell	Research Assistant
Russell Benjamin	Research Assistant
James Castracane	Research Assistant
William Fielder	Research Assistant
Oliver T. Strand	Research Assistant
Brent Stratton	Research Assistant
Tong-Lai Yu	Research Assistant
William Ruff	Research Technician
Margery Neikirk	Administrative Assistant

TABLE OF CONTENTS

ABSTRACT

The work performed from May 1980 through March 1981 is described. EUV diagnostic studies have been performed at the Alcator A, Alcator C and TFR 600 tokamaks and on TMX. The central molybdenum concentration in Alcator C has been shown to be much lower than that in Alcator A. Impurity concentration and radiative power losses have been determined in the center cell of TMX. A grazing incidence spectrograph with 1024 detector elements is under construction.

I. INTRODUCTION

This report describes the work performed by this laboratory for the Office of Fusion Energy of the Department of Energy from May 1980 through March 1981.

The program divides naturally into several areas of effort which are covered in separate sections. Section II describes the diagnostic studies of high temperature magnetically confined plasmas. Ionic structure calculations in support of diagnostic experiments done both by this laboratory and others are covered in Section III. The supporting laboratory calibration studies are described in section IV. Section V discusses specific instrumentation systems which are under development for diagnostic studies.

Diagnostic studies were performed on the Alcator A and C tokamaks, the TFR-600 tokamak and the Tandem Mirror Experiment. The time resolving EUV spectrograph which uses a microchannel plate intensifier feeding a solid state array has been checked out on both the Alcator A and TFR-600 tokamaks. Molybdenum impurity levels and plasma instabilities are being studied on the Alcator C tokamak. The impurity levels in the center cell of TMX have been measured; impurity injection experiments have also been performed on this device to better understand the radial transport. Precise photometric calibration of the instrumentation using equipment constructed in previous years has continued; these calibration procedures are being extended to shorter wavelengths. A grazing incidence time resolving spectrograph is under development. This instrument uses a microchannel plate detector similar in principle to that in the EUV instrument mentioned above, but with the design substantially modified for grazing incidence.

Calculations of transition energies and probabilities for atoms in the B and Cl isoelectronic sequences were completed. In addition, numerous calculations were made for problems of special interest to the experimental part of this program.

II. DIAGNOSTIC STUDIES

A. Alcator A

Experiments at the Alcator A tokamak were conducted using the time resolving spectrograph described in section V-A. The purpose of the experiments was threefold:

(1) To serve as an initial shakedown of the new spectrograph;

(2) To survey the EUV emissions from both light and heavy impurities; and

(3) To conduct impurity injection experiments using the laser blow-off technique.

The instrument shakedown was done concurrently with the initial survey of the EUV emissions of the plasma. (See also Section V-A.) During this time, lines from the tokamak plasma served to complete the wavelength calibration of the instrument and the software, used to process and display the data, was optimized for speed and utility.

It is clear from observations of Alcator A plasmas that a survey instrument can immediately identify conditions that may affect the normal evolution of a plasma discharge. Interaction between the plasma and limiter, often associated with the final disruption of the plasma, can be identified by the sudden appearance of lines of Mo, the limiter material. (See Fig. 1) Plasma wall interactions can be identified by the presence of lines of Fe and Cr, indicating an interaction with the stainless steel vacuum chamber. Other minor disruptions affecting the "normal" are associated with sudden changes in the C to O or N to O line intensities. Any air leaks that develop in the system can be immediately recognized by the increase in N line intensities. All of these lines mentioned above can be monitored simultaneously with the spectrograph, even while performing experiments in which none of these lines are involved.

During the impurity injection experiments atoms of Si and Mo were injected into the plasma. All new lines appearing at the time of injection could clearly be identified as belonging to these elements. Low states of Si (Si III, Si IV) and high states (Si XII, Si XIII) could be monitored simultaneously. Silicon was injected into both H_2 and D_2 working gases and at both high and low plasma densities. The molybdenum spectrum during both laser injection and plasma disruptions (see Fig. 1) has been studied. Mo was injected into plasmas of low, medium and high densities to study impurity confinement as a function of density. Lines from Mo VI to Mo XIV have been observed and new lines have been identified including a forbidden magnetic quadrupole line of Mo XIII.[1]

A "natural" injection of Ti was observed in which lines of Ti VI through Ti XII were recorded. This event was unexpected since Ti is not an intrinsic impurity in Alcator A. The source of Ti was presumably from material sputtered from a titanium carbide coated graphite limiter once tested in Alcator A.

1. M. Finkenthal, et. al., Physics Letters, Vol. 82A, 3 (16 March 1981).

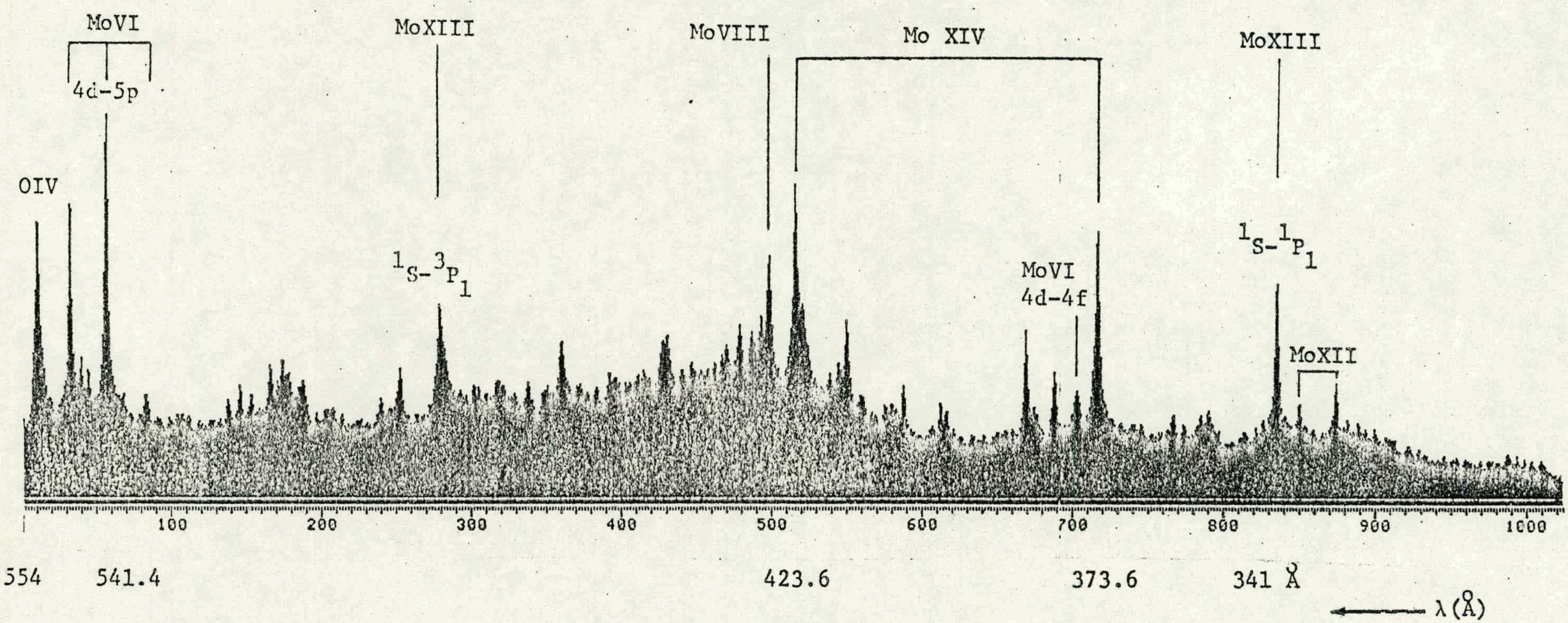

Fig. 1. Molybdenum spectrum between 300-560 Å at final disruption.

B. Alcator C

Impurity Study. In order to understand the role played by high-Z impurity ions in the evolution of the tokamak plasma discharge, spectroscopic measurements of emissions from these ions were carried out. Radiative losses from high-Z elements must be minimized to allow the ohmic input power to heat the plasma efficiently. In particular, highly ionized molybdenum (from plasma-limiter interactions) is an efficient radiator even at the hot plasma center where it is only partially stripped.

Measurements of the absolute brightness and radial profile of emissions from molybdenum indicate a small contribution to radiative losses. The brightness of a pseudo continuum (65-90 Å) attributed to highly charged Mo ions is almost an order of magnitude less than on Alcator A. Measurements on both tokamaks were made with the same one-meter grazing incidence monochromator.

The temporal behavior of the emissions from these ions showed that on-axis impurity accumulation does not occur. In fact, natural injections arising from spontaneous plasma-limiter contact show a decay time of 10 - 15 msec. Observations of line transitions from various stages of ionization were made. Those of Mo XIII, XXV and XXXI display noticeable differences in temporal behavior, representative of low, middle and high states. While the lower states are characterized by a rapid burnout spike followed by a choppy behavior, the middle and upper states have a smoother profile with the emission intensity showing a gradual rise later in the discharge as the temperature rises.

In addition to the rather extensive study of molybdenum, transitions from iron, aluminum, sulfur and chlorine were observed. Overall, it appears that radiative losses arise primarily from low Z impurities such as carbon, nitrogen and oxygen.

Evidence was also gathered which could be compared to predictions based on the coronal equilibrium model of a plasma discharge. The reactions of emissions from certain ionization states of Mo to changes in plasma parameters (T_e, n_e) lend supportive evidence to the coronal model as a first order picture of the distribution of ionization states.

Oscillatory Disruptions. In the process of measuring impurity emissions characteristics on the Alcator C tokamak, the appearance of an oscillatory disturbance involving the entire discharge was noted for certain types of discharges. These periodic (≈ 10 msec) phenomena are manifested by oscillations in many of the measurable plasma parameters. Soft x-ray emissions display a behavior distinct from the usual sawtooth activity. The electron density, electron temperature, plasma position and impurity emissions show noticeable reactions to the onset of the disruptions.

That these phenomena are unique and separate from the usual sawtooth activity may be demonstrated by their increased period and the involvement of a large portion of the plasma. The instability which is earmarked by sawteeth on the x-ray signal is confined to the region near the plasma axis ($r < 4$ cm.). The appearance of certain MHD instabilities implies an unstable current profile is evolving leading to repeated disruptions.

One scenario currently under investigation is the flattening of the current profile out to the q = 2 surface followed by an ohmic reheating. As the temperature increases, the profile becomes peaked on axis with a fairly steep gradient near the q = 2 surface (r ≈ 10 cm). This situation appears to be unstable, indicated by a noticeable increase in the MHD activity (m = 2,3), and a collapse of the electron temperature profile occurs. At this point, the brightness of line emissions from certain impurity ions increases dramatically. The change in the equilibrium condition of the plasma affects recombination and ionization balances. The atomic as well as plasma physics aspects of these phenomena are currently under investigation.

C. TFR-600

Experiments were performed at the TFR-600 tokamak in Fontenay-aux-Roses, France in cooperation with the TFR-600 spectroscopists using the time-resolving EUV spectrograph described in section V-A. The purposes of the experiments were:

(1) to study the EUV emissions in the high temperature TFR discharge (Te(0) ≈ 1.5 – 2.0 KeV);

(2) to study the effect of neutral beam heating on the impurity emissions;

(3) to conduct impurity injection experiments; and search for forbidden lines which might be suitable for Doppler broadening measurements.

Each of these studies exploited the spectrograph's ability to simultaneously monitor a broad spectral range.

Spatial scans of the upper TFR plasma were done with both survey gratings (covering the 300 Å - 2200 Å range) on high temperature ($T_e(0) \approx 2$ KeV) plasma discharges. From this data volume emission profiles can be obtained for Lyman alpha and all lines of OII-OVI and CII-CIV in this region. EUV emissions of both heavy and light impurities, recorded during neutral beam heating experiments, can be used to study the effects of charge exchange in the plasma.

The injection of impurities into the plasma by the vaporization of metal foils with a laser was studied in conjunction with a grazing incidence duochromator which monitored the 100 Å - 300 Å spectral range. Atoms of Al, Ti, V, Cr, Fe, Ni and Mo were injected into the plasma. Forbidden lines of V XV, Cr XVI and Ni XX have been identified. Additional spatial scans of the plasma were conducted during the injection of Cr and V. Analysis of this data is continuing.

D. The Tandem Mirror Experiment

TMX consisted of three separate sections - two minimum-B, 2XIIB type end cells connected by a long solenoid. A major concern was whether the two end plugs which electrostatically confine the center cell plasma would produce an enhanced concentration of impurities in the center cell. This work showed that the impurities and the associated radiative losses are not abnormally high.

In order to maximize the data taking capability, three EUV monochromators were mounted on TMX, one on each section. The spatial imaging 0.4 m monochromator used on Alcator A and described in a previous annual report was mounted on one end cell. A similar spatial imaging 0.4 m monochromator constructed by LLL and specially designed for the larger plasma radius and lower signal levels of the central cell, was located on that section of TMX. The other end cell was monitored by the first instrument (see the previous annual report) taken to TMX, another 0.4 m monochromator capable of viewing a single chord of the plasma at a time. This instrument was previously used on Versator and Alcator A at MIT and on 2XIIB at LLL. Data was acquired using this array of instruments during the last five months of TMX operation.

The additional data provided by having three instruments mounted on TMX allowed a more detailed study of the EUV emissions. In particular, the radial profiles obtained from the central cell indicated that the impurities had a nearly constant density distribution over the plasma radius. Knowing the radial impurity distribution allows a more accurate determination of impurity concentrations. Table I lists the impurity concentrations and radiated power losses observed in the central cell of TMX. The impurity concentrations comprise approximately 0.6% of the total density. Radiated power losses were also low, approximately 5% of the total input power was lost to radiation.

Table I. Impurities in the TMX central cell

Species	Concentration (%)[a]	Radiated power (kw)[a,b]
O	0.3	4
N	0.2	4
C	0.05	1.5
Ti	0.05[c]	6[c]
$D(L_\alpha)$	-	5

[a]factor of 2 uncertainty

[b]typical trapped input power = 450 kw

[c]obtained from observed brightnesses and using coronal model and cooling rate calculations

A series of impurity injection experiments were performed on TMX by injecting a variety of gases into the central cell plasmas in order to study penetration and confinement. Figure 2 shows radial brightness profiles as a function of time when neon and oxygen were injected at 12 ms into the TMX shot (the background levels for oxygen have been subtracted out). Initial results indicate that the puffed gases penetrate readily to the center of the plasma; these central concentrations are maintained for the remainder of the discharge. Modelling is currently in progress to determine the

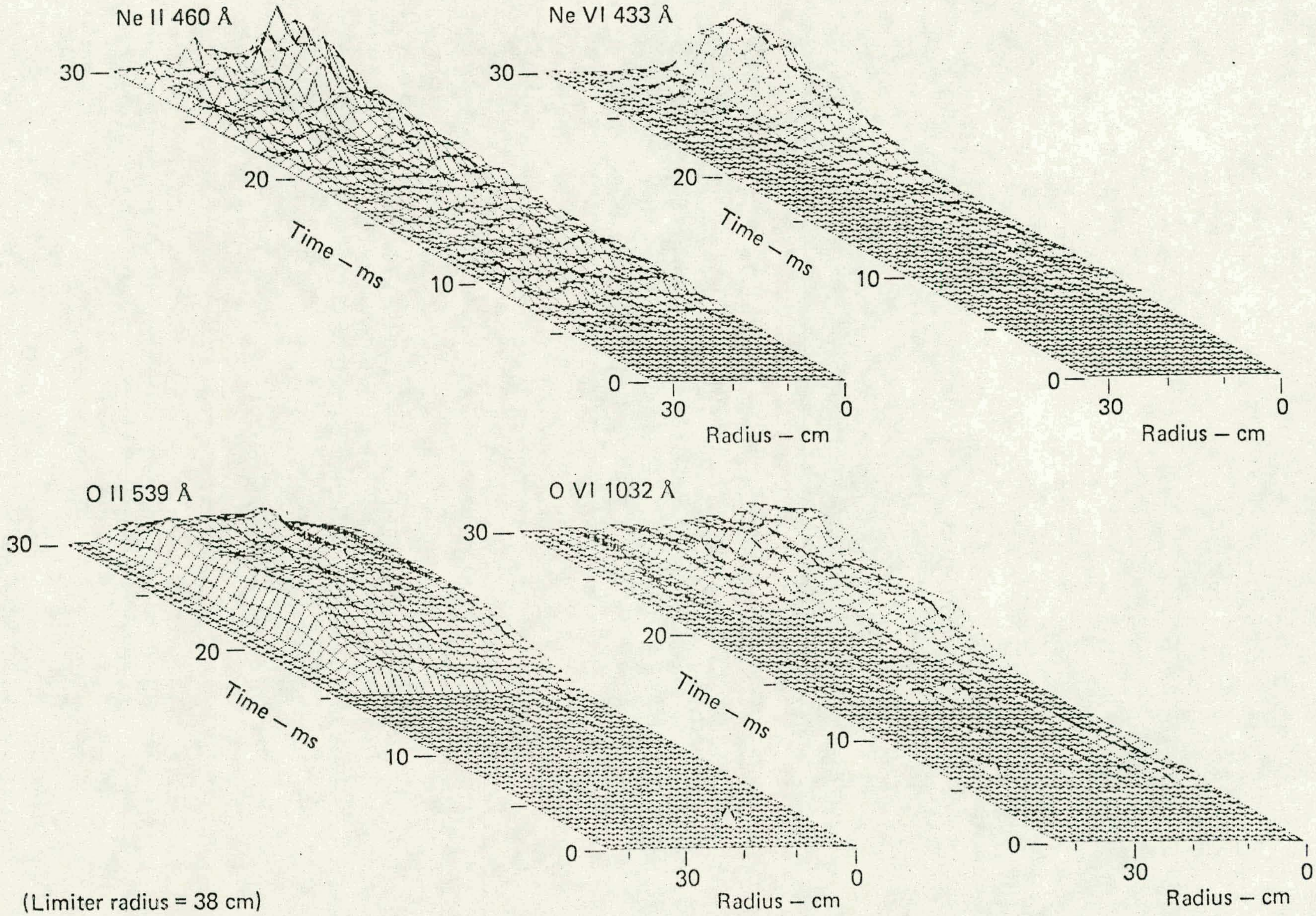

FIG. 2. Radial brightness profiles versus time for oxygen and neon puffing.

effects of confinement time and recycling on this behavior.

Additional computer modelling is underway to study the radial profiles of the intrinsic impurities observed in TMX. Codes are being written to determine what confinement times, impurity fluxes and radial transport are needed to match the observed radial profiles.

III. IONIC STRUCTURE

During the present contract period, we have concentrated mainly on two areas: (1) calculation of transition probabilities and energies in the B and Cl isoelectronic sequences; and (2) making specific calculations of use to the Hopkins experimental group. In both of these areas, we have used the relativistic multiconfiguration Dirac-Fock program of Desclaux[1] to calculate energies and wavefunctions. A paper describing the B-sequence calculations will appear in Phys. Rev. A; a paper describing the Cl sequence results has been submitted to Atomic and Nuclear Data.

In both of these isoelectronic sequences, we have encountered considerable difficulty in obtaining the desired accuracy in our calculations. In particular, we find large (factors of almost two in some cases) discrepancies between length and velocity forms of the dipole oscillator strength at fairly high values of nuclear charge. These discrepancies have remained even when fairly large numbers of configurations are included. For example, for some elements of the Cl sequence, we used 35 ground state and 40 excited state configurations. These discrepancies imply that our wavefunctions are still only moderately good approximation to the correct wavefunctions. We note that other approaches[2] have also had great difficulty in obtaining good wavefunctions for elements in these sequences, leading one to the conclusion that the calculation of oscillator strengths in even relatively simple open shell systems is, in fact, a quite complicated problem. In an effort to improve our approach to this problem, we have begun to investigate alternative methods of calculating oscillator strengths. One possible new method involves applying variational principles to the oscillator strength itself, thus obtaining a form of the oscillator strength which is stationary under small changes in the wavefunctions. We are currently studying the implications of this approach.

In the second of the areas mentioned above, specific calculations for the Hopkins group, we obtained M1 transition energies for several first row atoms. We also did as thorough a job as we could on the E1 and M1 transition energies in Cl-like Mo, in order to facilitate searches being made for certain of these lines. In addition, we have trained some of the research assistants in the experimental group to use our programs in straightforward situations, so that they can make rough preliminary calculations of parameters of interest to them.

In a related area, the calculation of the photoionization cross section of Cl was finished in early October, 1980. The knowledge obtained from this calculation, which is considered to obtain the most accurate results for Cl, was of great help in our calculations in the Cl sequence. This work is currently being prepared for publication.

References

1. J. P. Desclaux, Comput. Phys. Commun. 9, 31 (1975).

2. B-like ions

   a) A. W. Weiss, Phys. Rev. 188, 119 (1969)

   b) W. Dankwort and E. Trefitz, J. Phys. B, 10, 2541 (1977); Astron. Astrophys. 65, 93 (1978).

   c) R. Glass, J. Phys. B, 13, 15 (1980); 13, 899 (1980)

   d) J. Migdalek and W. E. Baylis in Abstracts of the 7th International Conference on Atomic Physics, MIT (1980)

   Cl-like ions

   a) H. E. Mason, Mont. Nat. R. Astr. Soc. 170, 651 (1975).

   b) H. Nussbaumer, Astron. & Astrophys. 48, 93 (1976).

   c) G. E. Bromage, R. D. Cowan, and B. C. Fawcett, Physica Scripta 15, 177 (1977).

   d) J. E. Hansen, J. Opt. Soc. Am. 67, 754 (1977).

IV. LABORATORY STUDIES

A. EUV and Soft X-ray Calibration

The laboratory program of grating and detector evaluation and instrument calibration described in previous annual reports has continued. During the previous year we have started to upgrade our capabilities at shorter wavelengths. As a result of the need to absolutely photometrically calibrate short wavelength spectrographs (in particular the time-resolving grazing incidence instrument described in Section V-B) in the region from 10 Å to 100 Å, a soft x-ray calibration apparatus has been designed and is currently under construction.

This design uses as a source of radiation a soft x-ray tube of the type developed by Henke.[1] It is easily disassembled to allow anodes of different materials to be used and will produce K, L, and M characteristic lines in the region from 8 Å to 114 Å, with a low background of continuum emissions. Because an oil-free high vacuum is maintained inside the x-ray tube, it may be viewed directly by the spectrograph under calibration; the wavelengths of the characteristic lines for various anode materials are well known so this provides a wavelength calibration of the instrument. Eight different anodes will be used, giving a calibration at eight points between 8 Å and 114 Å.

To perform a photometric calibration, the brightness of the radiation emitted by the x-ray tube must be accurately determined. For this purpose, a vacuum tank and beam line system have been designed which will allow the emitting anode area of the x-ray tube to be viewed simultaneously by the spectrograph and by a gas flow proportional counter which will be operated at sub-atmospheric pressures (20-200 torr). Except near the C-K edge at 44 Å, the proportional counter can be operated at efficiencies between 80% and 100%. These values can be accurately calculated at a given wavelength from the gas pressure.[1] The efficiency of a set of proportional counter windows will be determined by measuring the change in signal while they are moved in and out of the x-ray beam on a vacuum feedthrough. With the overall efficiency of the proportional counter known at the eight calibration wavelengths, the brightness of the x-ray tube can be determined and the spectrograph may be photometrically calibrated.

The x-ray tube and pumping system have been assembled and are currently being tested with the proportional counter and gas flow control system. The vacuum tank and beam line system are under construction.

[1]B. L. Henke; M. A. Tester ; "Techniques of Low Energy X-ray Spectroscopy (0.1 to 2 keV region)" in Advances in X-ray Analysis, Vol. 18, Plenum Press (1975).

V. INSTRUMENTATION

A. Time-resolving EUV Spectrograph

A time-resolving spectrograph for use at extreme ultraviolet wavelengths, which was described in the previous progress report, has been calibrated and field tested during the past year. The spectrograph incorporates a detector consisting of a windowless microchannel plate/phosphor screen image intensifier coupled by fiber optics to an integrated photodiode array with 1024 sensing elements. This detector operates in a manner suggestive of an electronic photographic plate: the spectrum is imaged onto the detector which is "exposed" for a time as short as 3.7 ms; the accumulated image is then "developed" by the scanning electronics digitized and stored by a small computer; and re-exposed again, repeating the process up to 80 times during a single plasma discharge. The versatility of the spectrograph is enhanced by using seven gratings: two which span the region between 300 Å and 2200 Å for survey work; and five which cover adjacent intervals of this region at higher spectral resolution.

In late May 1980,the spectrograph was photometrically calibrated at the NBS SURF II electron storage ring. In July and August 1980 it was used to study the Alcator A tokamak at the Massachusetts Institute of Technology, Francis Bitter National Magnet Laboratory. In September 1980, the spectrograph was transported to the TFR tokamak, Fontenay-aux-Roses, France for a two month study of the TFR plasma. In March 1981, a recalibration was done at NBS SURF II. The wavelength calibration was partially done in the laboratory using a Penning discharge lamp and completed in the field using lines produced in tokamak plasmas.

The spectrograph has demonstrated both its electrical and mechanical reliability during these field experiments. The instrument was transported under high vacuum, and its high vacuum was maintained even during shipment between the U.S. and France during which its ion pump remained off for a period of eight days. The spectrograph is operable in any position: it was mounted on a top port of Alcator so that it was pointing vertically downward; on TFR it was mounted 10° from horizontal. Signals from the detector to the control room were free of spurious electrical pickup at both machines. Effects of hard x-rays were negligible. Installation on each tokamak took only a single day and data was taken starting with the first shot after installation at both Alcator and TFR.

B. Grazing Incidence Time-Resolving Spectrograph

As magnetic fusion devices reach higher electron and ion temperatures, lower wavelength photons play a more important role in plasma diagnostics. Since grazing incidence optics is much more efficient than normal incident optics for the lower wavelength radiation, a grazing incidence time-resolving spectrograph has been designed (see the previous annual report) and is currently being assembled and evaluated. The instrument is a logical extension of the normal incidence time-resolving spectrograph (see the previous subsection) that allows detection of radiation down to 10 Å. The two instruments complement each other with an overlap region between

300 to 350 Å when a 1200 l/mm grating is used. The multichannel detector makes the instrument essentially 1000 times more powerful than conventional single channel instruments. The microchannel plate intensified silicon diode array detector and the Minuteman one meter grazing incidence spectrometer have been evaluated, and the efficiency of the assembled spectrograph will be measured at the NBS SURF II facility soon. Three different interchangeable gratings will be used allowing a versatile wavelength range. A 2400 l/m grating covers a spectral region of 8 to 175 Å with ∿ 0.2 Å resolution. The 1200 l/m will span the 15 to 350 Å region with ∿ 0.4 Å resolution, and the 300 l/m survey grating would cover 40 - 1200 Å with ∿ 1 Å resolution. The instrument will be photometrically calibrated using both synchrotron radiation at NBS and discrete radiation from a Henke x-ray tube. During the summer, the instrument will be mounted on PDX at Princeton to study impurity radiation.

VI. PUBLICATIONS AND ABSTRACTS

W. Hodge, J. Castracane, W. Moos, Photometric Calibration of a One Meter Grazing Incidence Spectrometer for Plasma Fusion Diagnostics, Nuclear Instruments & Methods, 172, 97 (1980).

R. P. Drake and H. W. Moos, Extreme Ultraviolet Study of the 2XIIB Neutral-Beam-Heated Mirror Machine, Nuclear Fusion, 20, 599, (1980).

E. S. Marmar, J. E. Rice and S. L. Allen, Confinement of Injected Silicon in the Alcator A Tokamak, Phys. Rev. Lett., 45, 2025 (1980).

M. Vajed-Samii, D. Ton-That and Lloyd Armstrong, Jr., Relativistic Study of E1 and M1 Transitions in the Boron Isoelectronic Sequence, Physical Review, to be published.

S. L. Allen, H. W. Moos, E. S. Marmar, and J. E. Rice, A Study of the Transport of Injected Impurities in the Alcator A Tokamak, submitted to Nuclear Fusion, July 1980.

M. Finkenthal, R. E. Bell, H. W. Moos, A. K. Bhatia, E. S. Marmar, J. L. Terry, and J. E. Rice, The Molybdenum Spectrum Emitted by a Tokamak Plasma in the 300-550 Å Range, Physics Letters, 82A, 123 (1981).

J. E. Rice, E. S. Marmar, T. Coan, S. L. Allen, R. D. Cowan, Molybdenum and Chlorine X-ray Emission from Alcator A, Physical Review A, 22, 310 (1980).

S. L. Allen, H. W. Moos, and R. K. Richards, The Influence of the Limiter on EUV Emissions from Light Impurities in the Alcator A Tokamak, Nuclear Fusion, 21, 251 (1981).

R. P. Drake, Extreme Ultraviolet Diagnosis of a Neutral-Beam-Heated Mirror Machine, Lawrence Livermore Laboratory Report UCRL-52751, July 1980.

S. L. Allen, O. T. Strand, H. W. Moos, R. J. Fortner, T. J. Nash, D. D. Dietrich, An Impurity Study of TMX Using Ultraviolet Spectroscopy, Lawrence Livermore Laboratory Report UCID-18883, January 31, 1981.

W. L. Hodge, J. Castracane, H. W. Moos and E. S. Marmar, A Study of Molybdenum Radiation from Alcator A, submitted to Nuclear Fusion, April 1981.

J. Castracane, H. W. Moos, and J. E. Rice, Observations of Oscillatory Disruptions in the Alcator C Tokamak, Conference on Atomic Processes in High Temperature Plasmas, Baton Rouge, LA, February 25-27, 1981

S. L. Allen, H. W. Moos, E. S. Marmar, J. E. Rice, A Study of Injected Impurities on the Alcator A Tokamak, 1980 IEEE International Conference on Plasma Science, May 19-21, 1980.

R. E. Bell, H. W. Moos, and M. Finkenthal, Time-resolving EUV Spectrograph for Fusion Plasma Diagnostics, APS Div. of Plasma Physics 22nd Annual Meeting, San Diego, November 10-14, 1980.

J. Castracane, W. L. Hodge, M. Finkenthal, H. W. Moos, and E. S. Marmar, High-Z Impurity Emissions in the Alcator C Tokamak, APS Div. of Plasma Physics 22nd Annual Meeting, San Diego, November 10-14, 1980.

W. L. Hodge, T. L. Yu, H. W. Moos, An Intensified Reticon Detector for a Grazing Incidence Time Resolved Spectrograph, APS Div. of Plasma Physics 22nd Annual Meeting, San Diego, November 10-14, 1980.

J. Castracane, EUV Study of the Alcator C Tokamak, Fourth Workshop on the Use of XUV and X-ray Roadiometry in Plasma Diagnostics 5 eV to 10 KeV, National Bureau of Standards, April 24, 1981

R. E. Bell, and H. W. Moos, Photometric Calibration of a Time-Resolving EUV Spectrograph for Plasma Diagnostics, Fourth Workshop on the Use of XUV and X-ray Radiometry in Plasma Diagnostics 5 eV to 10 KeV, NBS, April 24, 1981.

B. Stratton, W. Hodge, and H. W. Moos, A Time Resolving Soft X-ray Spectrograph for Plasma Diagnostics, Fourth Workshop on the Use of XUV and X-ray Radiometry in Plasma Diagnostics 5 eV to 10 KeV, National Bureau of Standards, April 24, 1981.

M. Vajed-Samii, K. MacDonald, L. Armstrong, Jr., Electric Dipole Transitions for the Chlorine Isoelectronic Sequence, Bulletin of the Am. Phys. Soc. 25, 1146 (1980).