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OF HIGH-TEMPERATURE PLASMAS

Annual Progress Report

Prepared By

H. Warren Moos, L. Armstrong, Jr., and Wm. G. Fastie

The Johns Hopkins University
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RESEARCH STAFF:

Professor H. Warren Moos, Co-Research Contract Director

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

Professor Wm. G. Fastie

Professor B. R. Judd

Roger Richards	Postdoctoral Fellow
Dinh Ton-That	Postdoctoral Fellow
Dong Liang Lin	Postdoctoral Fellow
Earl S. Warden	Postdoctoral Fellow
Steven Allen	Research Assistant
Kuo-In Chen	Research Assistant
R. Paul Drake	Research Assistant
William Fielder	Research Assistant
Oliver T. Strand	Research Assistant
Richard Swanson	Research Assistant
James Terry	Research Assistant
John Tyson	Research Assistant
Harold Weaver	Research Assistant
Ronald Bell	Research Assistant
Daniel Cross-Cole	Research Technician

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ABSTRACT

The research program at this laboratory from 1 February 1977 to mid-February 1978 is described. Spatial scans of Alcator Tokamak have led to a more direct determination of the oxygen and nitrogen concentrations. These scans have also shown that grad B and curvature drifts are significant transport mechanisms in this device. Spatial scans of Elmo Bumpy Torus from both the top and the side have produced two dimensional plots of the impurity concentrations. Preliminary results from 2XIIB show that oxygen is the dominant impurity; nitrogen, carbon, and titanium are also present. The Spatial Imaging Detector System is discussed; construction is complete and it is being prepared for installation on a plasma machine. EUV photometric calibration techniques at this laboratory are described. The accuracy and stability of this calibration is discussed. Theoretical calculations of relativistic transition rates and energies have continued, and studies of electron-impact ionization and excitation cross sections have begun.

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I. INTRODUCTION

This report describes the work of the last year in the research program at this laboratory using extreme ultraviolet (EUV) and soft x-ray emissions to investigate the properties of the high temperature plasmas of magnetic fusion research. The research effort has been an integrated one, bringing to bear instrumentation development, laboratory studies, plasma diagnostic measurements and the theory of ionic structure in order to study these high temperature plasmas.

The research discussed in this report covers the period from 1 February 1977 through mid-February 1978. Below are listed a few examples of the activities of this program during this time period. The major new diagnostic study undertaken during the past year is at 2XIIB. This neutral beam heated mirror machine is unique and this is the first time EUV diagnostics had been used to study it. Although the data gathering and analysis is not yet complete, it is clear that the EUV emission provide dramatic insight into the nature and sources (walls, plasma guns, neutral beams, etc.) of the impurities. The work on impurities, fluxes, concentrations and transport at Alcator is complete; J. Terry and K. Chen are preparing Ph.D. dissertations based on the data. Construction of the Spatial Imaging Detector System has been completed and it is being prepared for installation on a plasma machine this spring.

The theoretical portion of this program has concentrated mainly on the calculation of transition energies and probabilities for highly ionized atoms. Work was finished or published during the last year on the Ar, Ne, K, and Be sequences. In addition, studies of electron impact ionization and excitation have been started.

The report is divided according to the subject areas of the first paragraph. Johns Hopkins University personnel associated with each project are listed in the appropriate subsection.

We note that the major part of the effort has been in the diagnostic and instrumentation studies. Our expectation is that it will continue for the next year, although the emphasis will change as new needs are perceived.

II. THEORY OF HIGHLY IONIZED ATOMS

We have continued our studies of transition probabilities and transition energies of highly ionized atoms. Distorted wave Born calculations have been started using techniques for calculating continuum wavefunctions which were developed on this contract during 1976-77. Electron-rare gas impact ionization cross sections have been carried out in the Born approximation in order to study the importance of improvements in target state wavefunctions.

A. Transition Probabilities. (W. Fielder, D. Lin, D. Ton-That, L. Armstrong) We have calculated transition energies and oscillator strengths for several transitions in the Be, Ar, K, and Ne isoelectronic sequences. Calculations have been carried out using both relativistic and non-relativistic multiconfiguration Hartree-Fock programs. We have carried out calculations for E1 transitions of the type 3p-3d, 4d, 4s in the Ar sequence, 2p-3d, 3s in the Ne sequence, and 4s-4p, 3d-4p in the K sequence. In addition, we have studied M2 transitions of the type 2s-3p in the Be sequence, and 2p-3d, 3s in the Ne sequence. In all cases, the heaviest atom studied was U.

We have made a careful study of all of these calculations in order to ascertain where relativistic effects were most important. Our conclusions are essentially unchanged from last year: 1) relativistic effects on the transition energy of $\Delta n=0$ transitions are very large; and 2) the other relativistic effect of importance is the breakdown of LS coupling due to the spin orbit interaction. The latter is particularly important for $\Delta n \neq 0$ transitions.

The Be results have been published in the Astrophysical Journal (1); the Ar results in Physical Review (2). The K results were discussed at the conference on Atomic Processes in High Temperature Plasmas (Knoxville, Feb. 16, 1977). The Ne results will soon be submitted to the Physical Review.

B. Electron-Atom Collisions. (R. Swanson, D. Ton-That, L. Armstrong)

In conjunction with Prof. S. Manson of Georgia State University, we have carried out a study of the influence of the quality of target state wavefunctions on the Born approximation calculation of electron impact ionization cross sections. The rare gases have been studied using Herman-Skillman (3), Hartree-Fock (4), and multiconfiguration Hartree-Fock (4) wavefunctions for the target atoms. The wavefunction for the ionized electron was obtained by solving Schrodinger's equation for an electron moving in either a Herman-Skillman potential, or in a $V^{(N-1)}$ (5). It was found that the improvement in the atomic wavefunctions caused significant changes in the contributions due to some of the partial waves of the ionized electron. This work will be discussed at the Washington meeting of the APS in April 1978.

We are now beginning similar studies for excitation cross sections of ions. In this case, we hope to eventually study the influence of target wavefunctions on both Coulomb-Born and Distorted-wave Born excitation cross sections. We will also assess the importance of certain types of final state correlations on the distorted wave results by calculating the continuum wavefunctions in a multiconfiguration V^{N-1} , which was developed by us last year in our studies of

photoionization cross sections (6). This type of calculation includes effects on the continuum wavefunction produced by excitations in the ionic core.

C. Fundamental Studies. (D. Lin, L. Armstrong) D. Lin has carried out an investigation of the gauge properties of the Hartree-Fock and random phase approximations in order to try to understand from a fundamental viewpoint why length and velocity forms of dipole transition operators are not, or are, respectively, equal in these two approximations. It is hoped that this will lead to a better understanding of the class of perturbation theories in which length and velocity transition operators will be equivalent. This work was published in Physical Review (7).

The work discussed in the last annual report relating to nonexponential decay of He-like metastable states has been published in Physical Review (8). In this paper, we concluded that the observed nonexponential decay in He-like metastables was probably produced by Li-like ions in the beam.

REFERENCES FOR SECTION II

1. D. Lin, W. Fielder, Jr., L. Armstrong, Jr., Astrophysical Journal, 219, 1093 (1978).
2. D. Lin, W. Fielder, Jr., L. Armstrong, Jr., Phys. Rev. 16, 589 (1977).
3. F. Herman and S. Skillman, Atomic Structure Calculations (Prentice Hall, New Jersey, 1963).
4. C. Froese-Fisher, private communication.
5. M. Ya Amusia, N. A. Cherepkov, and L. V. Chernysheva, Zh. Eksp. Teor. Fiz. 60 (1971) [Sov. Phys. JETP 33, 90 (1971)].
6. J. R. Swanson and L. Armstrong, Jr., Phys. Rev. A 16, 1117 (1977).
7. D. L. Lin, Phys. Rev. A 16, 600 (1977).
8. D. L. Lin and L. Armstrong, Jr., Phys. Rev. A 16, 791 (1977).

III. DIAGNOSTIC STUDIES OF HIGH TEMPERATURE PLASMAS

Ultraviolet spectroscopic studies have been conducted during the past year on Alcator at the Massachusetts Institute of Technology, Elmo Bumpy Torus at Oak Ridge National Laboratory and 2XIIIB at Lawrence Livermore Laboratory. At Alcator, the determination of the impurity concentrations and power loss through impurity line radiation have been the primary goals. In addition the unexpected importance of transport effects due to grad-B and curvature drifts was discovered. At EBT, spatial scans of both the top and the bottom of the plasma and computer codes utilizing algebraic reconstruction techniques have obtained concentrations, spatial distributions and confinement times of carbon and aluminum impurities. At 2XIIIB, EUV spectroscopy is being used to determine impurity concentrations and the relative sources (neutral beams, plasma guns, walls, etc.) of these impurities.

A. Alcator. (K. Chen, W. Moos, J. Terry)

1. Introduction. The set-up and preliminary results of our first diagnostic experiment on the Alcator Tokamak were discussed in the previous annual reports(1). Also presented was a description of the 0.4 m, normal incidence monochromator used in that experiment and in the spatially resolved study which followed. Since that time, both that first experiment, based on a single line-of-sight view (2,3), and a second study in which impurity emissions were spatially resolved (4) have been completed. The primary goals of both studies were to deduce impurity concentrations (allowing calculation of Z_{eff}) and to estimate the power lost through impurity line radiation. However,

the spatial information obtained in the second experiment also enabled the unexpected discovery of an impurity transport effect (VB drift transport). In the course of the second study, experiments relating to impurity control were also performed.

2. Impurity concentrations and radiated power loss.

a. Single line-of-sight view. Single-view emission measurements were obtained in the time period from December 1976 through February 1977. Line radiation from ions of the major impurities was detected: O II-O VI, N II-N V, C II-C III, and Mo XIII-Mo XIV. The instrumental line-of-sight was along a horizontal minor diameter, 180° away from the limiter. In Fig. III-1 we show typical time histories of line radiation from oxygen ions (the major impurity). To simplify the analysis, the emission time histories have been divided into four phases; these are labelled in Fig. III-1. The burnout phase is shown as a spike in emission near the beginning of the discharge and is characterized by rapid ionization through the lower ionization states until these states establish themselves spatially in ring structures. The low and high density plateaus are the relatively quiescent periods before and after deuterium has been pulsed into the discharge. The transition rise is the sharp increase in emission which occurs as the plasma density begins to rise.

Impurity fluxes and concentrations during each phase, except the transition rise, have been determined from data of this type. The values during low and high density plateau were calculated using two different models, each of which related the measured absolute

Figure III-1 Observed oxygen emission with plasma current (I_p) and average electron density ($\bar{n}_e$) in the discharge phases: (1) burnout (0-5 msec), (2) low density plateau (5-15 msec), (3) transition rise (15-80 msec), (4) high density plateau (80-120 msec). The upper value of $\bar{n}_e$ is from the 2 mm microwave interferometer; the lower value is from the 0.119 mm alcohol laser interferometer--1 fringe = 10^{14} cm^{-3} .

brightness along the central chord to the quantity of interest. One of the models we called the "direct estimate": the line-of-sight brightness was directly related to the line integral of the local ion density times the local excitation rate using a simple model for transport, ionization, and excitation. The second model utilized a more comprehensive computer simulation of the atomic emission process, including spatially varying densities and temperatures and one dimensional (radial) impurity transport (5). This code, developed by our co-worker E. Marmar of the Alcator staff, was used only for oxygen. A summary of the results is found in Table III-1.

The power lost through line radiation from light impurity ions was also calculated. Since only radiation from O VI-O III, N V-N III and C III-C II ions was included, our calculation yielded a lower limit. However, the actual value is expected to be close (within a factor of two) to the quoted value. The calculation considered all $\Delta n=0$ transitions ending in a ground or metastable state; the populations of these levels were obtained by measuring the brightness of a directly connected line and by assuming that the emitting ion existed in a shell at a specific radius. During the low density plateau the power radiated by these impurity ions was less than 1% of the input power. At the high density plateau the analogous figure was about 10%. Inclusion of radiation lost through deuterium Ly α , Ly α line emission raised this percentage another 2%.

b. Spatially resolved emission measurements. At the end of April, 1977, our EUV experiment was moved to the charge-exchange port,

TABLE III-1

SUMMARY OF IMPURITY DENSITIES AND FLUXES

Line of Sight Measurements					
		Oxygen	Nitrogen	Carbon	Molybdenum
BURNOUT:	Flux ($10^{12} \text{ cm}^{-2} \text{ sec}^{-1}$)	-	-	-	5
$n_{\text{oe}} = 4.5 \times 10^{13} \text{ cm}^{-3}$	Density (10^{10} cm^{-3})	3.2 (1.5)	6.4	1.1	0.2
$Z_{\text{eff}} = 1.15$					
LOW DENSITY PLATEAU:	Flux ($10^{12} \text{ cm}^{-2} \text{ sec}^{-1}$)	16 (12)	27	4	0.1
$n_{\text{oe}} = 4.0 \times 10^{13} \text{ cm}^{-3}$	Density (10^9 cm^{-3})	8.9 -	15	2	0.6
$Z_{\text{eff}} = 1.04$					
HIGH DENSITY PLATEAU:	Flux ($10^{13} \text{ cm}^{-2} \text{ sec}^{-1}$)	15 (5)	12	0.8	0.1
$n_{\text{oe}} = 6.0 \times 10^{14} \text{ cm}^{-3}$	Density (10^{11} cm^{-3})	9.9 -	8.0	0.5	0.09
$Z_{\text{eff}} = 1.16$					

The values shown in parentheses for O were determined by direct estimates rather than by a code. The means for determining the values for N, C and Mo are discussed in the text. The values of Z_{eff} are at the center for nuclear O, N and C, and Mo XXXI.

90° from the limiter, with a full up-down view of the plasma. Measurements were made until August of the same year. Spatial scanning was accomplished by sweeping the instrumental field of view vertically across the plasma on a shot by shot basis. A bellows in the beamline allowed the actual tilting of the instrument, while an adjustable preslit gave the appropriate spatial resolution (typically 1 cm (vert.) x 3 cm (hor) at the plasma).

Emissions from the O V 630 Å, O VI 1032 Å, and N V 1238 Å lines were spatially scanned. Figure III-2 shows line-of-sight brightness vs. column height for O VI emission at high and low densities. The up-down asymmetry evident at high density profile was unexpected; the causes of this asymmetry are discussed in detail in the next section. This poloidal asymmetry implies that the volume emission rate (number of photons/cm³ sec) is not only a function of radius but also a function of poloidal angle; thus the usual Abell inversion technique is not applicable.

Theoretically, the mechanism causing the up-down asymmetry should cause no in-out asymmetry. Thus assuming that the volume emission rate had a poloidal angle dependence which maintained in-out symmetry, the line-of-sight scans were numerically inverted to yield volume emission rates. Using the profiles of the electron density and temperature, $n_i(r, \theta)$ the impurity ion density was found. The total oxygen density at the radius of O VI density peak was evaluated by adding the densities of other oxygen ions existing at that radius. Only O VII and O V make significant contributions. Since no O VII

Figure III-2. Two emission profiles in O VI 1032 Å light. "Column height" refers to height of the line of sight above or below the torus midplane. For this toroidal field direction the ion VB drift is up. (a) Asymmetric high-density profile for discharge conditions $\bar{n}_e = 3.6 \times 10^{14} \text{ cm}^{-3}$, $B_T = 60 \text{ kG}$, $q(a) = 2.9$. (b) Symmetric low-density profile with $\bar{n}_e = 4.0 \times 10^{13} \text{ cm}^{-3}$, $B_T = 60 \text{ kG}$, $q(a) = 3.9$.

measurements were possible, its contribution was estimated by simulating (with a computer code) impurity transport for differing diffusion rates. These considerations indicated that an O VII contribution of 2.5 times the O VI density was reasonable. The concentrations found in this manner are given in Table III-2 for the

CONCENTRATION IN % of $N_e(R)$

OXYGEN	0.05 - 0.1%
NITROGEN	0.08 - 0.15%

TABLE III-2. Concentrations from spatial resolved measurements.

oxygen and nitrogen impurities. Note the good agreement with the previous estimate based on the single line-of-sight measurements.

By knowing the spatial profiles of the impurity, the power lost through impurity line radiation can be calculated directly: $P = h\nu \int E dV$; where $h\nu$ is the photon energy and E is the volume emission rate. Hence, the power loss through impurity line radiation was 10-20% of the total power input at the high density plateau phase.

3. Poloidal asymmetry due to ∇B -curvature drifts. Initially the up-down emission asymmetry evident in the high density profile of Fig. III-2 was surprising. Theoretical considerations indicated that (to first order) particle densities of both ions and electrons were constant over (poloidally symmetric) magnetic flux surfaces. These ideas were based on the fact that the helical field lines, basic to the field geometry of a tokamak, force radial cancellation of the

vertical, ∇B -curvature drifts. For example, an upward drift, which is radially out when the particle is in the top half of the torus, is radially in when the particle is in the bottom half of the torus. Thus, radial cancellation will occur only if the particle alternately spends time above and below the torus midplane. The cancellation can arise either from motion along the helical field lines or from diamagnetic drifts (for electrons). In the previous transport theories (6) it was implicitly assumed that cancellation did in fact occur.

Alcator plasmas are both clean ($Z_{\text{eff}}=1$) and extremely dense ($\bar{n}_e = 4 \times 10^{14} \text{ cm}^{-3}$). This means that impurities near the edge diffuse along field lines at a relatively slow rate. In fact, when we calculated the vertical distance an O VI ion would ∇B drift in diffusing through a poloidal angle of only 1 radian, we found that at high densities this distance was comparable to the minor radius of the machine! At low densities however, the distance was quite small. Thus, these calculations were consistent with the observations illustrated by Fig. III-2. A number of experiments were then performed in order to test the hypothesis that the observed asymmetries were due to uncompensated ∇B -curvature drifts of the impurity ions. The most convincing results are: 1) Plasma parameters were varied so this ' ∇B drift-distance' changed over a one order of magnitude range (actually about a factor of 20); and the strength of the asymmetry was found to increase monotonically as this distance was increased. 2) The vertical direction of the drift was reversed by reversing the direction of the toroidal field, and

asymmetry was observed in each case. The results are shown in Fig. III-3; there was an obvious reversal in the sense of the asymmetry.

Figure III-3. O VI 1032 Å emission profiles for each toroidal field direction. The solid line indicates the emission profile with a field direction such that the ion drift is upward; the dashed line shows emission with the field and drift directions reversed. In each case the deuterium plasma conditions were $\bar{n}_e = 2.5 \times 10^{14} \text{ cm}^{-3}$, $B_T = 50 \text{ kG}$, $q(a) = 4.8$.

The ∇B impurity transport has a number of implications for highly collisional plasmas (4). The most important, however, is that the theoretical models of impurity transport in this regime must be

made two-dimensional, thus significantly increasing their complexity. An additional practical implication for diagnostic studies is that at least one, and possibly two, full-plasma views are required for the reconstruction of the volume emissivity. Finally, the fact that the VB drift contribution to impurity transport is unidirectional in the vertical direction may have an impact on limiter and diverter design.

4. Warm wall experiments. In order to lower their resistance, the Alcator magnets are kept at LN_2 temperature during normal tokamak operation. Thus, the walls of the vacuum vessel are also maintained at LN_2 temperature. To determine whether the cold walls are responsible in part for the extremely high purity of the Alcator plasmas, two sets of experiments were carried out. The first concerned normal tokamak discharges. The emissions from the light impurities (O VI 1032 Å, O VIII 19 Å, N V 1238 Å, C IV 1549 Å), monitored by the 0.4 m monochromator and a 2 m grazing incidence spectrometer, were compared for two runs. In one run, the walls were held at LN_2 temperature. As shown in Fig. III-4, the O VI signal did not change significantly during the run. In the other run shown in the same figure, the run began with warm walls ($\sim 175^\circ\text{C}$) which were then gradually cooled to -200°C . In the second case, there was a marked decrease in the impurity emission as the wall temperature dropped. In addition, both the nitrogen and carbon signals (not shown) were approximately constant.

A second set of experiments concerned the effects of wall cooling and low-power discharge cleaning. It was found that both discharge cleaning and the cooling at the vacuum walls could independently reduce oxygen contamination.

Figure III-4. Oxygen Signal vs. Wall Temperature.

In conclusion, we have found that the cold walls of the Alcator Tokamak can significantly reduce the amount of oxygen entering the discharge. This may account in part for the low impurity level and the low ratio (Tables III-1 and III-2) between the oxygen and nitrogen concentrations found in Alcator).

B. Elmo Bumpy Torus. (W. Moos, R. Richards, J. Tyson, E. Warden)

1. Introduction. As described in the previous annual report (1), we are studying EBT in the 1150 to 2500 Å region using a miniature calibrated Ebert spectrophotometer. Spatial resolution has been obtained by rotating a mirror at the top of the plasma to obtain views along a series of chords. Building upon the previous work we have added a second view and developed an algebraic reconstruction computer program to invert the data, thus obtaining two dimensional profiles of $n_e n_i$ for ions of carbon and aluminum in EBT.

2. Instrumentation. The experimental setup is described in the annual report for 1976-1977; only pertinent alterations will be discussed here. The most significant change in instrumentation has been the addition of a second view--from the side (see Figure III-5). It was necessary to include an extra mirror at 45° incidence to deflect the side view into the spectrometer. It is believed that azimuthal symmetry is not present in EBT, making the standard Abel inversion inappropriate. The second view makes possible the reconstruction of the volume emission rate without assuming cylindrical symmetry.

SCHEMATIC OF UV SPECTROSCOPY EXPERIMENT ON EBT

Figure III-5.

3. Inversion Technique. A program to perform the inversion to obtain the volume emission rates has been completed. It has been applied to various test cases to check its reliability and is now being used to invert the data. The method used is an algebraic reconstruction technique analogous to that used in medical tomography. Because of the limited viewing, the results are necessarily crude but they provide significant information on the impurity distribution in the EBT device.

The midplane of one of EBT's sections is broken into a 20×20 matrix and the volume emission rate is assumed to be constant in each cell in a distribution approximating a gaussian peaked at the center. Brightness curves that would be expected from this initial guess are calculated and compared to the input brightness curves. From these differences increments are calculated for each element of the volume emission rate matrix and added into the matrix. Then the process is repeated until the calculated brightness curves converge to the input curves. Due to the limited number of views, anomalous features appeared in early results. To minimize these features, we took advantage of up-down symmetry expected in EBT and insisted that the volume emission rate matrix be symmetric about the horizontal plane after each stage of the iteration. In its present state the program faithfully locates features in test cases and the error in any particular cell of the volume emission rate matrix seems to be about 15% of the maximum value in the matrix.

4. Results. Data for both views of resonant lines of C II, C III, C IV, HO, Al I, Al II, and Al III were taken and inverted to profiles of $n_e n_i$ for the various species. Figure III-6 shows the C II volume emission rate as an example. There has been some concern caused by the degradation in reflectivity of the two scanning mirrors, which are directly exposed to the plasma. Besides affecting the absolute numbers, it has been feared that the degradation could alter the shapes of brightness curves. Exhaustive study, however, has shown that these fears were unfounded--the form of the $n_e n_i$ plots are not significantly changed due to changes in reflectivity.

Table I gives values of n_i/n_e obtained for the center of the core plasma. (In this position n_e is known to be $2 \times 10^{12} \text{ cm}^{-3}$.)

TABLE III-3

Species	$\lambda(\text{\AA})$	n_i/n_e
C II	1336	3.36×10^{-5}
C III	1176	5.6×10^{-5}
C IV	1548	8.27×10^{-6}
C V ($T_e=150 \text{ eV}$)	2274	$<1.4 \times 10^{-5}$
HO	1216	8.65×10^{-3}
Al I	2151	2.7×10^{-7}
Al II	1671	4.7×10^{-5}
Al III	1855	2×10^{-4}

(a) Volume Emission Rate Profile for C II.

(b) Typical Data: Brightness Curves Before and After Reconstruction.

The cross sections used (7) for the carbon species are more reliable than the Seaton cross sections that we had been using and hence the results are more reliable. These values show that the impurity concentrations are quite low in the center of the core. Although details of the profile of n_e are not known, it is believed (8) that n_e increases on going from outside to inside the toroidal core. However, the inversions of $n_e n_i$ vary slowly in this region implying a decrease in n_i on entering the core. Thus, the evidence indicates that the impurity concentrations (n_i) decrease on going from outside to inside the core.

In summary, analysis of two one-dimensional line-of-sight scans separated by 90° have yielded the profile of $n_e n_i$ for various charge states of C and Al. The profiles indicate that impurity densities in the core are lower than those outside the core. The absolute numbers indicate that the impurity concentrations in EBT are low.

C. 2XIIB. (K. Chen, P. Drake, W. Moos, J. Terry)

1. Introduction. The 2XIIB plasma device is a neutral beam heated minimum-B geometry plasma confinement device. It produces high beta ($\beta \sim 1$) plasmas with an 8 ms duration. The electron temperature is about 130 eV and the ion temperature approximately 13 keV. The central vacuum field is normally 6.7 kG. The line density achieved is up to $1.5 \times 10^{-15} \text{ cm}^{-2}$ with a 7 cm radius and a gaussian radial profile. The hot plasma is about 30 cm long.

The goal of JHU efforts at 2XIIB is to investigate the character and implications of the EUV emissions from the central 2XIIB plasma.

Lyman alpha radiation and impurity emissions are to be studied.

The experiment will address the questions of impurity concentrations, confinement lifetimes, sources (neutral beams, plasma guns, walls, etc.), transport, and power loss.

2. Experimental Details. The JHU 0.4 m normal incidence vacuum ultraviolet monochromator is in use at 2XIIB. It utilizes a 2400 line/mm platinum coated grating blazed at $300 \text{ \AA}$ and a windowless photomultiplier tube with a Cu I photosensitive surface to obtain a spectral range of $300 \text{ \AA}$ to $1700 \text{ \AA}$. The time resolution of the spectrometer system is 70 microseconds.

The instrument has been absolutely calibrated at NBS (on the SURF II synchrotron radiation source) and at JHU using NBS diode detectors as the calibration reference (see Section V-D). The estimated total uncertainty in the absolute sensitivities is $\pm 20\%$ but is subject to revision after a post-experiment calibration.

Some special preparations for the 2XIIB experiment were made. The absolute brightness calibration was repeated. New magnetic shielding was designed, constructed, and tested to protect the photomultiplier from the high (500 gauss) fields near 2XIIB. A carriage was constructed to hold the instrument in the vertical position on 2XIIB, and the wavelength calibration was checked with the instrument in the vertical position. An alignment jig was constructed and aligned to enable a laser beam to be directed along the optical axis of the instrument to facilitate installation and alignment on 2XIIB.

The JHU instrument is mounted on top of 2XIIB and looks down through the yin yang coils into the midplane region. Its line-of-sight is through the hot plasma in the center of 2XIIB. The entrance slit is 2.9 m from the machine center, about 13 degrees north and 3 degrees east of the vertical axis.

The spectrometer was initially aligned on the 2XIIB using the alignment jig described above. The alignment was tested by spatially scanning the plasma, and was found to be approximately correct. A motor drive was installed on the instrument carriage which permitted remote spatial scanning of the plasma from the control room.

3. Results. The impurity study at 2XIIB is not complete and the results given here are preliminary. Brightnesses have been measured along a central chord of the plasma. Spatial scans have just begun, and investigations of Doppler broadening spectral lines remain to be completed. Transport experiments involving the introduction of neon into the 2XIIB plasma are planned.

Four impurity species have been identified in 2XIIB. These are oxygen, nitrogen, carbon and titanium. The O VI 1032 Å emission line, the brightest line observed, has a peak brightness greater than 10^{18} photons $\text{sec}^{-1}\text{cm}^{-2}/\text{ster}$. An O V 630 Å time history is shown on Fig. III-7. The initial peak is believed to result from ionization of oxygen in the target plasma, which is created by titanium washer guns. Oxygen is the dominant impurity in 2XIIB. Determination of the oxygen concentration is model-dependent, and hence this is difficult without good spatial information. A preliminary estimate of the

Figure III-7. Typical Brightness Time History for 0 V 630 Å Emission from Central Region of 2XIIB.

impurity density is 3%, but this could be off a factor of 3 either way. The large brightness of the oxygen emissions (the O II 539 Å brightness is about 10^{16} photons $\text{sec}^{-1} \text{cm}^{-2}$) suggest the existence of a large oxygen flux by comparison with the Alcator Tokamak (where O II has a brightness of an order of magnitude lower).

Despite the existence of large impurity fluxes into 2XIIB, the power loss from the central hot plasma region due to the observed impurities is small, due to both the small volume of this region and the large amount of power put into this volume by the neutral beams. The impurity power loss is at most 150 kW, but is probably less than 50 kW. This power loss has at most a 10% effect on the electron temperature. (However note that the power loss from the much larger end fan regions has not been studied.)

A study of the spectral profile of the deuterium Lyman alpha line has also been performed. This line is several angstroms broad. The Lyman alpha radiation results from emissions by charge exchange atoms, neutral beam atoms, and cold gas atoms surrounding the plasma in a thin neutral sheath. The observed brightness and line shape are consistent with the understanding of these atoms gained by other diagnostics and from theoretical consideration, but at the present time do not significantly improve upon their results. This experiment may be considered a prototype demonstration of a Lyman alpha diagnostic to measure neutral deuterium velocity distributions.

REFERENCES FOR SECTION III

1. H. W. Moos, L. Armstrong, Jr. and W. G. Fastie, ERDA Annual Progress Reports COO-2711-1 (1976), COO-2711-2 (1977).
2. J. L. Terry, K. Chen, H. W. Moos and E. S. Marmor, ERDA Technical Report COO-271103 (1977).
3. J. L. Terry, K. Chen, H. W. Moos and E. S. Marmor, to be published in Nuclear Fusion.
4. J. L. Terry, E. S. Marmor, K. Chen and H. W. Moos, Phys. Rev. Lett. 39, 1615 (1977).
5. S. A. Cohen, J. L. Cecchi and E. S. Marmor, Phys. Rev. Lett. 35, 1507 (1975).
6. P. H. Rutherford, Phys. Fluids 16, 1749 (1973).
7. N. H. Magee, Jr., J. B. Mann, A. L. Merts and W. D. Robb, Electron Impact Excitation of Carbon and Oxygen Ions, Informal Report LA-6691-MS, Los Alamos Scientific Laboratory, April, 1977.
8. R. A. Dandl, H. O. Eason, G. E. Guest, C. H. Hedrick, H. Ikegami and D. B. Nelson, "Plasma Confinement and Heating in the Elmo Bumpy Torus," Plasma Physics and Controlled Nuclear Fusion Research, Vol. II, 1974. (Proceedings, Vth Conf., IAEA, Tokyo).

IV. LABORATORY STUDIES

These studies are undertaken to support the diagnostics and instrumentation efforts. During the past year we have emphasized the development of cw sources of short wavelength radiation for instrumentation calibration and the evaluation of new, state-of-the-art gratings at short wavelengths. Also described in detail are the calibration techniques and the Extreme Ultraviolet Calibration Equipment (ECE) which was mentioned briefly in the first annual report (1).

A. Spectral Sources. (T. Strand, D. Cross-Cole, H. Weaver, E. Warden)
In previous reports (1,2) we have summarized our work on the Penning Ionization Gauge (PIG) source. This discharge operates by immersing a set of cathodes and an anode in a magnetic field such that the field is parallel to a line between the two cathodes. This field then traps electrons emitted from the cathodes. These electrons collide with and ionize not only atoms of the fill gas leaked into the systems but also atoms of sputtered cathode material. The ionized atoms then continue to be ionized to higher and higher ionization states by repeated electron bombardment. In general, the higher the ionization state, the shorter the wavelength of the emitted radiation. As we reported previously, spectra have been obtained down to $160 \text{ \AA}$; some of the lines have cw brightnesses comparable with the metal lines from a tokamak. The richness of the line spectrum is analagous to that of high temperature fusion plasmas. Clearly

such a source is extremely useful for instrument evaluation and photometric calibration.

The source has been modified in a number of ways during the past year. These included larger current capacity, higher magnetic fields and improved vacuum systems leading to improved light stability and reproducibility as well as increased brightness. It has also been possible to extend the lower wavelength limit from 160 to 85 Å. We are continuing to improve the properties of this source as well as develop more convenient versions for laboratory use.

This laboratory has also developed a compact soft x-ray source for work below 100 Å. Comparable sources are not available commercially. The source is simple in construction and stable. Anodes can be interchanged easily to change the wavelength coverage. The use of an air cooled anode removes many of the frequent maintenance problems associated with many similar sources.

B. Grating Evaluations 44-740 Å. (D. Cross-Cole, T. Strand) Although extensive studies of gratings in normal incidence are becoming available (3,1), much less is known about the properties of grazing incidence gratings. Using the grazing incidence spectrometer (see Section V-C) we have evaluated one holographic and three classically ruled gratings (see Table IV-1) at an incidence angle of 4.5°. Three of these gratings represent most recent state-of-the-art; the fourth, older manufacturing techniques. The holographic grating was prepared at our request for maximum efficiency between 40 and 850 Å.

TABLE IV-1

GRATING COMPARISON STUDY

Serial Number	Manufacturer	Date of Ruling or Holographic Manufacture	Blaze Wavelength (at 4.5° Grazing Angle)
2367.51-1	Bausch & Lomb	1965	180 Å
12630	Jobin Yvon	1977	40-850 Å
321M	Hyperfine	1977	80 Å
321-2-3	Hyperfine	1977	80 Å

All gratings have 1200 lines/mm and are gold coated.

The Hyperfine master (321M) was one of a family of gratings manufactured for the Harvard experiment on the National Aeronautics and Space Administration's Solar Maximum Mission. (These gratings were considered to be the best available for short wavelength spectroscopy until August, 1977 when they were surpassed by a holographic grating produced by M. C. Hutley of the National Physical Laboratory, England and reported at the Vth International Conference on Vacuum Ultraviolet Radiation Physics at Montpellier, France.) The Hyperfine replica (321-2-3) is one of the first replicas of one of these short wavelength masters and was included to evaluate the effects of the replication process. The Hyperfine master was evaluated in the grating reflectivity facility at Imperial College, London and found to have a reflectivity of 6.4% for a 4.3° incidence angle at 44 Å (4). Thus our comparison data is absolutely calibrated at that point.

The Bausch and Lomb grating was chosen for its blaze properties during the early construction phases of the one meter grazing incidence spectrometers.

The gratings were compared by substitution in the mount of the one meter monochromator. In general, the spectra of either the PIG or soft x-ray sources would be measured using grating A; grating B would be substituted and the process repeated. Finally, grating A would be replaced to ensure that the source had not drifted. This process was repeated to check on discontinuous source changes. The relative intensities are estimated to be accurate to $\pm 20\%$.

Figure IV-1 shows the relative transmission of the three new gratings. The data is normalized to the holographic grating from 44 Å to 740 Å. The classically ruled gratings are below the holographic grating at wavelengths above 100 Å--which may be a blaze effect--but increase sharply at 44 Å. The transmission of the classically ruled master and its replica are similar throughout the wavelength range; at 44 Å this results is especially encouraging, indicating that the high transmission at short wavelengths of these gratings can be maintained through the replication process. The measurements are being extended to shorter wavelengths. The older grating (not shown in the graph) has a higher transmission at wavelengths above 200 Å which also is probably due to blaze effects; however, at short wavelengths its transmission is less than half that of the holographic grating.

FIGURE IV-1 RELATIVE REFLECTIVITIES:
COMPARISON OF RULED MASTER AND REPLICA TO HOLOGRAPHIC GRATING

The scattered light was estimated by illuminating the grating with a PIG source as a means of simulating the spectroscopic conditions in a magnetic fusion device. The two new classically ruled gratings were very similar to the holographic grating indicating low scattered light. On the other hand, the older grating was comparable at wavelengths greater than 250 Å but the scattered light increased sharply at short wavelengths.

C. Extreme Ultraviolet Calibration Equipment. (K. Chen, W. Moos, J. Terry) We have utilized two methods for photometric calibration of the EUV instruments. In this spectral region electron synchrotron radiation is considered to be a standard (5), thus it is desirable to calibrate directly against such a source and we have done so. However, it is often much more convenient to transfer the calibration in the laboratory from secondary standards such as the National Bureau of Standards (NBS) calibrated photodiodes which span the spectral region with a sensitivity uncertainty of ± 6 to 10% (6). These transfers also permit the use of spectral lines rather than continua, the former being much better for the evaluation of scattered light and overlapping orders. In order to accurately transfer the NBS photometric calibrations to our instruments, we have constructed the Extreme Ultraviolet Calibration Equipment (ECE) shown schematically in Fig. IV-2. Because of its importance in evaluating the spectrometer system; a detailed description of the ECE, which has not been described in detail elsewhere, is included here. The ECE functions in a manner

Figure IV-2. Schematic Drawing of Extreme-Ultraviolet Calibration Equipment

similar to the facility for the spectral region above 1150 Å described by Fastie and Kerr (7). However, below this wavelength, windowless discharges must be used and the number of reflections minimized. Vacuum quality must also be optimized in order to prevent the buildup of hydrocarbon compounds on reflecting surfaces. An attempt to keep elastomer (Viton) seals to a minimum and the use of polyphenyl ether fluid in the diffusion pump, with liquid nitrogen trapping appeared to be satisfactory. Typically, vacuums of 2×10^{-7} Torr were obtained without baking.

As shown in Fig. IV-2, spectral lines from atomic and ionic species are generated in a high power hollow cathode lamp (8). After passing through a differentially pumped preslit, the radiation enters a 400 mm premonochromator which selects a given spectral line. The premonochromator grating drive is a hand cranked version of that used for the 0.4 m normal incidence monochromator (1). To assure constant operating condition the entrance and exit slits are fixed, typically 700 wide by 2 mm long. The tilting mirror, overcoated with gold is masked to reduce the solid angle from $f/20$ to $f/40$. External micrometers acting through vacuum bellows control the mirror so that the image can be placed at any point in the spectrometer entrance slit or on the reference detector. In most applications this reference detector is a NBS calibrated photodiode placed sufficiently out of focus so that the illuminated spot size is comparable to that used in the calibration at NBS. Thus, the reference detector calibration is transferred directly to the instrument in a short time, making lamp drifts negligible. The sensitivity can be mapped as a function

of position in the entrance slit by tilting the mirror. Similarly, the spatial variation of a cathode's sensitivity can be mapped when the detector is placed at the beam focus. The beam solid angle is less than that of most instruments, but the sensitivity throughout the instrumental solid angle can be obtained if necessary by pivoting the instrument about the entrance slit (accomplished by inserting a bellows in the beam line).

The accuracy of the transfer of the photometric calibration to the diagnostic instruments by means of the ECE is typically $\pm 10\%$. Note that transfers of a few percent can be achieved with techniques of this type and have in fact been demonstrated (9,7). However, such precision is not necessary for most plasma physics measurements, where the atomic physics parameters have a much higher uncertainty, and the required increase in effort is not justified at this time. A comparison of calibrations obtained with the ECE and with a synchrotron radiation source are discussed in Section V-D-2.

REFERENCES FOR SECTION IV

1. H. W. Moos, L. Armstrong, Jr. and W. G. Fastie, ERDA Annual Progress Reports COO-2711-1 (1976, COO-2711-2 (1977).
2. E. S. Warden and H. W. Moos, "The Penning Discharge as a Photoelectric Spectroscopy Source," Appl. Opt. 16, 1902 (1977).
3. G. H. Mount and W. G. Fastie, "Comprehensive Analysis of Gratings for Ultraviolet Space Instruments," submitted to Applied Optics.
4. G. Timothy, private communication.
5. R. P. Madden, "Synchrotron Radiation and Applications", in X-Ray Spectroscopy, ed. by L. Azaroff, McGraw Hill, New York (1974).
6. L. R. Canfield, R. G. Johnston, and R. P. Madden, Appl. Optics 12, 1611 (1973).
7. W. G. Fastie and D. E. Kerr, Appl. Optics 14, 2133 (1975).
8. F. Parasce, S. Kuman and C. S. Bowyer, Appl. Optics 10, 1904 (1971).
9. H. W. Moos, W. G. Fastie and A. F. Davidsen, "Techniques for Ultraviolet Astrophysical Studies from Space Vehicles" in Proceedings of Symposium on New Instrumentation for Space Astronomy, Tel Aviv, Israel, 1977.

V. INSTRUMENTATION

A. Spatial Imaging Detector System. (S. Allen, W. Moos, R. Richards)

In the previous progress report an investigation of a Spatial Imaging Detector System (SIDS) was presented. Since then the design has been finalized and construction of the detector system completed. This detector will simultaneously measure extreme ultraviolet emissions at a particular wavelength from many different parts of the plasma. An important application of this detector would be to monitor impurity concentrations and fluxes in tokamaks and other pulsed devices. Because tokamaks may pulse only once every few minutes a single detector may require several hours of pulsing to determine an impurity profile whereas the SIDS can determine this profile from a single pulse.

The SIDS resolves spatial elements as shown in Fig. V-1. Spatial resolution is achieved by the one-to-one correspondence between the angle of a photon entering the spectrometer slit from the plasma and the angle leaving the exit slit. Thus photons from points A and B in the plasma fall on points A' and B' respectively on the detector. Since the imaging is essentially a one dimensional analogue to a pinhole camera, the detector is not limited for use with a particular type of spectrometer and can be used with either a grazing incidence or a normal incidence spectrometer. We are currently planning to use the SIDS with the 0.4 m spectrometers described in Sections V-D and V-E of this report. This spectrometer with a conventional detector has

Fig. V. 1. Optical system for imaging of the plasma onto a multi-element detector.

been used on Alcator and 2XIIB to monitor impurities. The only modification of the spectrometer for the SIDS detector is to substitute a wider (40 mm instead of 20 mm) grating with 3600 1/mm. This change is not necessary but does improve the versatility of the detector. The increased width will increase the field-of-view of the spectrometer and allow a larger area of the plasma to be observed.

With a sufficiently wide grating, the spatial resolution of the detector is determined by the width of each detector element and the ratio of the lengths from the entrance slit to the plasma and the exit slit to the detector. By varying the distance between the exit slit and the detector, the spatial resolution at the plasma can be adjusted. This can be seen in Fig. V-1. For example, by moving the detector closer to the exit slit of the spectrometer the distance between A' and B' decreases; since the size of the detector is fixed and it has discrete elements which determine the spatial resolution, it will now view a greater portion of the plasma with decreased spatial resolution.

The detector is built around microchannel plates (MCP's). These detectors have been used in some of our other programs and have proven to have the desirable qualities of low noise, good spatial resolution characteristics, and general availability from a number of suppliers. Their primary disadvantage is a low maximum signal current which is proportional to the product of gain times the rate of photo events. As discussed in the previous annual report, tests of the MCP's show that the maximum signal is limited by the bias or strip current (J_s) of

the plate. The maximum linear current signal was found to be $\sim 0.1 J_s$. Thus to keep the output signal linear either the gain or the input flux must be limited, however it is desirable to have both of these as large as possible. As a compromise a gain of 10^5 was chosen. At present, the highest strip current plates presently available have $J_s \approx 7 \mu\text{A}/\text{cm}^2$ allowing a maximum counting rate of $\sim 2 \times 10^6$ counts/sec over an area of $.06 \text{ cm}^2$.

The signal from the MCP is collected by 22 anodes, each $.0635 \text{ cm}$ wide and 1 cm long. The anodes were etched on a ceramic base and this ceramic base brazed to a stainless steel ring. This unit forms the header for the detector. To reduce beam spread and the subsequent loss of spatial resolution due to space charge repulsion, the MCP's were mounted above the anodes with only a 100μ gap. At a gain of 10^5 this produced a beam spread of 100μ on the anode surface. The photoelectron pulses to the anodes are counted rather than measuring the average anode current. Because the plates operate at a gain lower than that used in most pulse counting applications, a standard pulse amplifier--discriminator (PAD) cannot be used. For this 22 extremely sensitive PAD's were constructed to back the 22 anodes; their threshold is set to detect pulses at a gain of 7×10^4 . The results of a test at Alcator presented in the previous annual progress report show that at such a threshold the PAD's will operate satisfactorily in a tokamak environment. The dead time for a PAD is 250 nsec. , a limit on the maximum count rate which is compatible with that due to MCP saturation.

The pulse output from the PAD are collected in a data box in the control room. This box contains counters, buffers, and a clock to control the data collection rate. Pulses from the PAD's are connected to the data box through 100 feet of shielded cable. These pulses are counted by 22 counters over a set counting period. At the end of this counting period the counters value is stored in buffers as data and during the subsequent counting period the buffers are unloaded sequentially (see Fig. V-2). This string of 22 15 bit data words is stored through direct memory access (DMA) in a HP 9825A calculator. The counting period, or time resolution of the detector, is variable but is limited to periods greater than 100 μ sec by the maximum rate at which the 9825A will accept data. The memory in the 9825A is sufficient to store data entries from 400 counting periods, at the end of a shot the contents of the memory are entered on a cassette tape which acts as a permanent storage of the data. Time profiles from each of the 22 anodes can be displayed on a plotter. Typically, the storage of the data on the cassette, processing and plotting of the 22 time profiles requires about one minute. Since most machines have several minutes between pulses, this allows time for further processing of the data including Abel inversions of the profiles at several time periods.

The SIDS system will be complete after testing and calibration. This is to be accomplished on the ECE testing facility used to calibrate the 0.4 m spectrometer (see Section IV-C). Initial results of that calibration indicate a uniform photon detection response

Fig. V-2
DATA ACQUISITION SCHEMATIC
FOR SIDS

across the detector.

The first set of experiments for the SIDS is to be on Alcator. Top-bottom asymmetries of impurity profiles have been seen on Alcator (Section II, A-3) due to the VB drifts which were found by scanning the plasma with a spectrometer with a single detector on a shot by shot basis. We plan to investigate impurity profiles from a top port. The simultaneous measurement of many spatial elements will be particularly useful for metal impurities which tend to have erratic time histories. The ability to measure in-out symmetry or asymmetry will depend on the viewing access which is less convenient than from the side port. We are investigating methods for improving this access. SIDS will also be used to monitor the effect that the heating experiments have on the impurity profiles. We plan to move the thoroughly debugged SIDS system to Alcator shortly after it is running in a reproducible manner.

B. Grazing Incidence Double Monochromator. (W. Fastie, T. Strand)

The description of the 2 m grazing incidence double monochromator (1) has been given in some detail in the progress reports for the previous two years. As the name suggests, it uses two gratings of 2 meter radius of curvature employed at grazing incidence which are mounted in intersecting Rowland circles. Although this device uses well-known optical principles its design is unique in that each grating is constrained to move along its Rowland circle by being fastened to the end of a 1 meter long steel rod pivoted at the center of each Rowland circle. A single drive mechanism is used

to rotate both gratings about their respective axes. There are three sets of slits in fixed positions such that there is an angle of 170° between each incident and diffracted beam. Besides the entrance and exit slits, separated by about 60 cm, there is an intermediate slit located at the midpoint where the two Rowland circles intersect. The construction is such that one section may be used separately as a single monochromator, or the two sections may be connected to form the double monochromator.

Designed for the spectral range below $250 \text{ \AA}$, the 2 meter grazing incidence double monochromator has many advantages for controlled thermonuclear research studies at short wavelengths. The fixed exit slit will be able to accommodate detectors which are capable of either spatial or spectral resolution (see Section V-A). The system of two monochromators in series will greatly reduce scattered light. It can also be used to evaluate optical components by the substitution method as well as to provide a means of absolute calibration at short wavelengths.

The construction of the double monochromator is complete and the process of grating alignment is underway. Testing of the first section as a single monochromator should begin in April, 1978. After a careful evaluation, both sections will be connected and tested as a double monochromator. Final modifications and adjustments which prove to be necessary should be finished by the summer of 1978. The instrument will then be ready for laboratory and field experiments either as a single or a double monochromator.

C. One Meter Grazing Incidence Spectrometer. (D. Cross-Cole, E. Warden)

There is a need in magnetic fusion research for a portable, high vacuum quality grazing incidence instrument. Such an instrument can be used to transfer calibrations from photometric standard sources such as the NBS SURF II synchrotron source to magnetic fusion diagnostics. It can also be used directly as a diagnostic instrument for magnetic fusion devices. Over the past two years we have developed such an instrument (1). The design has undergone a number of iterations but is now essentially complete and the instrument is under evaluation. Improvements during the past year have included an all metal gasketed and ion pumped vacuum system, upgrading the wavelength drive to 0.1 Å wavelength reproducibility, selection of detectors (a 10 mhz channeltron was adopted) and evaluation of possible gratings (see Section IV-B). A sketch of this system is shown in Fig. V-3. Not shown is the vacuum tank and ion pump. Minor changes in the design will be completed shortly and evaluation at SURF II will begin this spring.

D. Calibration History and Performance of the 0.4 m Normal Incidence Spectrometer. (K. Chen, W. Moos, J. Terry)

1. Introduction. As described in the previous annual reports (1) a spectrophotometer covering the 300 to 2500 Å range and specifically designed for magnetic fusion device diagnostics has been constructed. The instrument can be used in any orientation, is portable and quite rugged. The instrumental vacuum quality

Figure V-3. One Meter Grazing Incidence Spectrometer.

is extremely good making it compatible with both high purity plasma devices and synchrotron radiation sources for photometric calibration.

In this report, we discuss the calibration history and practical performance of the instrument as a diagnostic over the last 18 months. As will be seen below the instrument not only can be given a photometric calibration against NBS standards in our laboratory which is comparable with that obtained from synchrotron radiation, but it holds this calibration over months of hard use as a diagnostic. Further, the spectrometer has demonstrated its utility as a diagnostic instrument on three plasma machines.

2. Photometric Accuracy and Stability. Two concerns of critical importance were the accuracy and stability of the photometric calibration. It was necessary to demonstrate by direct comparison with an electron synchrotron radiation source that the ECE calibration produced no systematic errors. This is discussed in the next paragraph. It was also important to see if significant sensitivity drifts occurred during measurements on a plasma machine. In addition, although the instrument was maintained in a vacuum at all times, including during shipping, it was possible that unforeseen effects due to shipping, ion pumping, or other causes could affect the calibration. Therefore it was important to carefully document the photometric calibration history; as a result the instrument was calibrated ten times over the 18 month period discussed here. Our conclusion is that there were

no serious long term drifts. For instance, the instrument was calibrated at this laboratory on October 30, 1976, taken to the Tokamak Alcator at the Massachusetts Institute of Technology and returned to Baltimore for calibration on March 21, 1977. The sensitivity decrease (400-1200 Å) during this five month period produced an uncertainty in the photometric calibration of about $\pm 15\%$. This is comparable with the calibration precision itself which, including both transfer and standard uncertainties, is better than $\pm 14\%$.

Since the first uncertainty is not necessarily random--the sensitivity value probably decreased linearly in time--it is not clear how to combine these uncertainties. However, an uncertainty value of $\pm 20\%$ which is more than adequate for most plasma physics experiments, is reasonable.

Figure V-4 addresses both of the concerns mentioned at the beginning of this section: long term photometric stability and cross calibration with synchrotron radiation. In March 1977, a CuI overcoated detector was installed to improve instrumental sensitivity at long wavelengths (2); the improvement was substantial, increasing the sensitivity a factor of 2.7 at 1216 Å and a factor greater than 10^2 at 1550 Å. Calibration, using the ECE, was completed March 29, 1977. The instrument was then transported to the SURF-II facility at NBS for calibration on April 4-6, 1977. The synchrotron radiation from the SURF II is essentially parallel and highly polarized. In order to compare with the ECE measurements which covered the central f/40

Figure V-4. The Photometric Calibration of the 0.4 m Monochromator.

solid angle, the instrument was calibrated in both polarizations and the grating mapped by pivoting about a point near the entrance slit. As Fig. V-5 shows, the ECE calibration and the SURF II calibration are in remarkable agreement below 900 Å. The average percentage error of the 4 ECE points from the SURF II curve is small. Longward of 900 Å, the second order contribution, which is difficult to separate in a continuum source, causes the SURF II photometric sensitivity curve to rise too high. However, the insertion of a MgF_2 filter in the light path eliminated second order contamination making it possible to obtain a reliable SURF II calibration at long wavelengths which was used for the plasma measurements.

The instrument was then transported to Boston, installed on the Alcator Tokamak, and used steadily until August, obtaining data on about 1400 shots. As can be seen from Fig. V-4 the calibration on August 11 upon returning to Baltimore showed only a small decrease at all wavelengths.

In summary, our experience shows that not only were the photometric calibrations obtained in this laboratory in close agreement with those obtained using the primary standard, synchrotron radiation, but those photometric calibrations were maintained through shipping and hard use of the instrument on plasma machines over extended periods.

3. Wavelength Accuracy. The instrument is calibrated in wavelength by illuminating the entrance slit directly with a hollow cathode source. The spectrometer resolution at 584 Å was measured to be 0.16 Å (full width half maximum). Typically, the accuracy of a

wavelength setting from day to day in a given laboratory was better than $\pm 0.25 \text{ \AA}$. The ability to reset a given wavelength after transportation was $\sim \pm 0.5 \text{ \AA}$. We believe that the precision can be improved by reduction of thermal inputs to the spectrometer housing from the ion pump and by increasing the torque of the stepper motor; this is being implemented in succeeding versions of this instrument.

4. Application to Plasma Diagnostics. The instrument has been used to study plasmas in three machines over an 18 month period as shown in Table V-1.

The experimental results have been covered in this (Section III-A, C) and the previous annual reports (1) and will not be covered here.

TABLE V-1

PLASMA DIAGNOSTIC APPLICATIONS

Experiment		N_e 10^{14} cm^{-3}	T_e KeV	Dates
Plasma Transport During a Disruption	Versator Research Laboratory of Electronics, M.I.T.	0.2	0.1	July to October, 1976
Impurity Fluxes	Alcator Francis Bitter National Magnet Laboratory, M.I.T.	10	1	November 1976 to March 1977
Impurity Transport and Concentration	Alcator Francis Bitter National Magnet Laboratory, M.I.T.	10	1	April 1977 to August 1977
Impurity Fluxes and Temperatures	2XIIB Lawrence Livermore Laboratory	0.5	0.2	September 1977 to Present

Spatial scans on a shot by shot basis have been an important tool in the tokamak experiments. Typical spatial resolution required in all of the diagnostics corresponds to an area of a few cm^2 at the plasma, accomplished by adjusting the preslit and hence the angular view.

As the instrument is typically two meters from the plasma, the angles subtended are small and good instrumental sensitivity is required.

Reliable absolute photometric calibration has permitted an accurate determination of impurity concentrations. All of the experiments have required photometric accuracy over a wide dynamic range ($\sim 10^5$).

At 2XIIB the instrument is being used to measure brightnesses and impurity ion temperatures from doppler broadening.

A significant characteristic associated with Alcator is the extremely high purity discharge. This puts stringent requirements on the vacuum cleanliness of diagnostics. The spectrometer vacuum cleanliness was found to be more than adequate; there were no deleterious effects upon the discharge. This was evidenced by the fact that qualitative indicators of discharge purity such as the voltage-current characteristics and hard x-ray signals showed no dependence on the opening of the beam line valve to the spectrometer. No evidence for vacuum contamination was found on either of the other machines. Likewise, a residual gas analyzer check for detrimental contaminants was made at SURF II just prior to starting the calibration. It showed essentially no signals above background, thus providing additional evidence for the high vacuum quality which was one of the primary design objectives.

Another property of many machines is the limited number of ports forcing the use of a common port for multiple diagnostics or requiring unusual orientations of diagnostic instruments. At Alcator, where four experiments shared the same port, the small size of the instrument was extremely convenient; at 2XIIB the instrument is almost vertical.

Spurious pick up by the signal lines or detectors in the severe electromagnetic environments, including hard x-ray contamination, has been negligible at all machines. At Alcator, only unusual discharges when very hard x-rays were generated have caused detector pick up.

In conclusion, the instrument has demonstrated its capabilities through a number of calibrations and by obtaining high quality data in each of several plasma experiments. Our experience indicates even smaller instruments can be developed with equivalent capabilities. However, the real challenge for the future is the production of similar small high quality grazing incidence instruments for short wavelength diagnostics and the adaptation of both normal and grazing incidence instruments to multiple spectral and spatial element detectors.

E. 400 mm Spectrometer Design Improvements. (S. Allen, W. Moos)

Building on the experience acquired with the first instrument, discussed in Section V-D, a second upgraded monochromator has been constructed. The major improvements include a longer, precision-lapped screw on the wavelength drive and a more powerful stepping motor driving this screw. The change in the length of the screw has increased the wavelength coverage, while both the screw precision and the higher

torque motor drive have increased the ability to reset a given wavelength to about $0.2 \text{ \AA}$ compared to the previous $0.5 \text{ \AA}$ with a 2400 gr/mm grating. Pulse counting electronics rather than analog electronics also have been incorporated in order to upgrade the sensitivity.

Most of the rest of the design has remained unchanged: the portability, ruggedness, reliability in a tokamak environment, and vacuum quality are still of major importance (typical base pressure is about 1×10^{-7} Torr). One major change is that a new integrated instrument control box has been used so that all spectrometer controls are available in one portable suitcase. The new design allows the experimenter to easily monitor the operating voltages of all the electronic power supplies, enabling quick diagnosis of problems if they should occur. Signal output, high voltage to the detector package, and the wavelength drive are all monitored and controlled from this location.

F. Stigmatic Grazing Incidence Plane Grating Monochromator. (W. Fastie, W. Moos) As described in previous progress reports we have designed an instrument consisting of a parabola to collimate the light, a plane dispersing element and a second parabola to form the image of the dispersed light. The parabolas are used in grazing incidence but the plane grating can be either a transmission or grazing incidence reflection grating.

Such an instrument would be mechanically simple with very good optical quality and stigmatic imaging in the XUV-soft x-ray region. The most critical problem is the quality of the surfaces which,

at soft x-ray wavelengths must be extremely smooth. We have investigated the production of such surfaces using special polishing techniques. A more economical method would be diamond turning; we are in the process of deciding whether the increase in roughness caused by using this fabrication technique is acceptable.

We are also investigating the relative merits of crystal spectrometers for ultra soft x-rays. The instrument described above is designed for optimal use at $20 \text{ \AA}$. In general, $10 \text{ \AA}$ is a watershed between the two techniques; gratings are of increasing utility above this wavelength whereas at the present time crystal spectrometers appear to be better below this wavelength. Of course, improvements in technology and in particular the ability to produce smooth surfaces may shift this dividing wavelength.

Reprints & Preprints Removed

REFERENCES FOR SECTION V

1. H. W. Moos, L. Armstrong, Jr. and W. G. Fastie, ERDA Annual Progress Reports C00-2711-1 (1976), C00-2711-2 (1977).
2. See Section V-B of H. W. Moos, L. Armstrong, Jr. and W. G. Fastie, ERDA Annual Progress Report C00-2711-2 (1977).

PUBLICATIONS AND ABSTRACTS

L. Armstrong, Jr., "Relativistic Effects in Highly Ionized Atoms", in Physics of Highly Ionized Heavy Atoms, ed. by I. Sellin (Springer-Verlaag, 1978).

K. Chen, J. Terry, E. Marmar, R. Geller, E. Apgar, H. Helava and D. Overskei, The Effects of Wall Temperature on Light Impurities in Alcator, Bull. A.P.S. 22, 1147 (1977).

W. Fielder, Jr., Dong L. Lin and Lloyd Armstrong, Jr., E1 and M2 Transitions in the Neon Isoelectronic Sequence, Bull. A.P.S. 22, 1334 (1977).

R. Geller, E. S. Marmar and K. I. Chen, VUV Emission from Heavy Metal Impurities in Alcator, Bull. A.P.S. 22, 1147 (1977).

D. L. Lin, Foldy-Wouthuysen Transformation of Quantum Electrodynamics and Relativistic Corrections to Transition Operator in Two-Electron System, Phys. Rev. A 15, 2325 (1977).

D. L. Lin, The Gauge Property of Hartree-Fock and Random Phase Approximations, Phys. Rev. A 16, 600 (1977).

Dong L. Lin, The Velocity Form of Oscillator Strengths and Quantum Electrodynamics, submitted to J. Phys. B, March 1977.

Dong L. Lin and Lloyd Armstrong, Jr., Nonexponential Decay Profile of the 2^3S_1 State of He-like Ions, Phys. Rev. A 16, 791 (1977).

D. L. Lin, W. Fielder, Jr. and Lloyd Armstrong, Jr., Multiconfiguration Hartree-Fock Calculation of Magnetic Quadrupole Transitions of Be Isoelectronic Sequence, Astrophys. J. 219, 1093 (1978).

D. L. Lin, W. Fielder, Jr. and L. Armstrong, Jr., Relativistic Oscillator Strengths for E1 Transitions in the Argon Isoelectronic Sequence, Phys. Rev. A 16, 589 (1977).

E. S. Marmar, J. L. Terry, K. I. Chen and H. W. Moos, Poloidal Asymmetry of Impurity Ions in Alcator, Bull. A.P.S. 22, 1091 (1977).

H. W. Moos, Report to Working Group on Ruled and Holographic Devices, EUV Instrumentation for Plasma Research, Vth Intl. Conf. on Vacuum Ultraviolet Radiation Physics, Montpellier, France, Sept. 5-9, 1977.

H. W. Moos, W. G. Fastie and R. K. Richards, EUV Spectroscopic Instrumentation for Plasma Diagnostics, Bull. A.P.S. (2nd Topical Conf. on High Temp. Plasma Diagnostics, Santa Fe, N.M., 1-3 March 1978).

H. W. Moos, R. K. Richards and Wm. G. Fastie, Extreme Ultraviolet Instrumentation for Plasma Research, Vth Intl. Conf. on Vacuum Ultraviolet Radiation Physics, Montpellier, France, Sept. 5-9, 1977.

A. Msezane, R. F. Feilman, S. Manson, J. R. Swanson, and L. Armstrong, Jr., Photoionization of Positive Ions: Outer P Subshells of the Noble Gas Isoelectronic Sequence. Phys. Rev. A 15, 668 (1977).

R. K. Richards, Broadband Stable Detector for Ultraviolet (300-1700 Å) Plasma Spectroscopy, to be published in Rev. Sci. Inst. April 1978.

R. K. Richards and H. W. Moos, A Spatial Imaging Detector for an EUV Monochromator, Bull. A.P.S. (2nd Topical Conf. on High Temperature Plasma Diagnostics, Santa Fe, N. M., 1-3 March 1978).

R. K. Richards, H. W. Moos and R. P. Drake, A Spatial Imaging Detector for an EUV Monochromator, Bull. A.P.S. 22, 1195 (1977).

J. R. Swanson and L. Armstrong, Jr., Multiconfiguration Hartree Fock Calculation of Photoionization Cross Sections of the Rare Gases, Phys. Rev. A 15, 661 (1977).

J. R. Swanson and Lloyd Armstrong, Jr., Multiconfiguration Hartree-Fock Calculation of Photoionization Cross Sections of the Rare Gases. II. Final State Correlation. Phys. Rev. A 16, 1117 (1977).

J. L. Terry, K. I. Chen, H. W. Moos and E. S. Marmar, EUV Impurity Study of the Alcator Tokamak, to be published in Nuclear Fusion.

J. L. Terry, K. I. Chen, H. W. Moos and E. S. Marmar, EUV Impurity Study of the Alcator Tokamak, Technical Report C00-2711-3, June, 1977, The Johns Hopkins University, Baltimore, Md. 21218.

J. Terry, K. Chen, H. W. Moos, E. Marmar, and R. Geller, Impurity Concentrations and Radiated Power Loss in Alcator, Bull. A.P.S. 22, 1091 (1977).

J. Terry, K. Chen, H. W. Moos and R. Richards, Photometric Calibration History of a Portable EUV (300-2500 Å) Spectrophotometer for Plasma Diagnostics, 2nd Workshop on the Use of XUV and X-Ray Radiometry in Plasma Diagnostics, 5 eV to 10 keV, Santa Fe, N. M., 2/28/78.

J. L. Terry, E. S. Marmar, K. I. Chen and H. W. Moos, Observation of a Poloidal Asymmetry in Impurity Ion Emission due to VB Drifts, Phys. Rev. Lett. 39, 1615 (1977).

J. M. Tyson, R. K. Richards, E. S. Warden, H. W. Moos and N. H. Lazar, Spectrophotometric Studies of Impurity Distribution in EBT, Bull. A.P.S. 22, 1146 (1977).

E. S. Warden and H. W. Moos, The Penning Discharge as a Photoelectric Spectroscopy Source, Appl. Opt. 16, 1902 (1977).