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

Annual Progress Report

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MASTER

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ABSTRACT

The results of the research program at this laboratory from mid February 1976 until January 31, 1977 are described. The four major research areas of the program, diagnostic studies of magnetically confined high temperature plasmas, supporting laboratory studies, theoretical studies of highly ionized atoms, and instrument development are discussed. Spatially resolved ultraviolet measurements on Elmo Bumpy Torus have determined impurity confinement times. The measured oxygen densities and fluxes are being determined at Alcator; the spectroscopic studies show that hydrogen discharges in this tokamak have an effective Z close to one. A laboratory study of the Penning discharge between 100 and 300 Å shows that it is a bright source for evaluation of EUV diagnostic instrumentation. Design of a multispatial element spectrometer system is complete and construction has begun. A spectrophotometer compatible with both types of facilities is available for absolute intensity calibration transfer from the NBS SURF II facility to ERDA plasma facilities. Computer programs needed for relativistic calculation of transition probabilities and wavelengths have been completed and applied to calculations in the Li, Be, Ar, and K isoelectronic sequences.

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I. INTRODUCTION

The report period has been used to achieve several goals. Ultraviolet diagnostic studies are underway at two major ERDA facilities, Elmo Bumpy Torus at Oak Ridge National Laboratory and Alcator at Massachusetts Institute of Technology. Oxygen, carbon and nitrogen concentrations are being determined for Alcator. Impurity confinement times have been measured for EBT. These studies emphasize not only the impurity ion spectra and their time evolution but also the spatial distribution of impurities. To improve the measurement of impurity spatial distributions, a detector system which will simultaneously observe many different parts of the plasma is being constructed. Spectrophotometric instrument construction has continued, extending our capability to shorter wavelengths. The grazing incidence double monochromator is 80% complete, it will be available for calibration and grating studies by the end of the contract year. A portable normal incidence instrument is in operation and a similar grazing incidence spectrometer is almost complete. The instruments have very high vacuum quality and are suitable as transfer standards between National Bureau of Standards Synchrotron Ultraviolet Radiation Facility, SURF-II and ERDA laboratories. The laboratory studies have emphasized new sources and the properties of optical components.

Relativistic and non-relativistic transition probabilities in the Li, Be, Ar and K sequences have been calculated for numerous elements up to U. Relativistic effects on transition integrals at very high Z are found to be easily predicted using a hydrogen-like approximation. Large relativistic effects are also seen in some lines at very low stages of ionization; these effects cannot be easily evaluated using simple models. We have shown that photoionization cross sections can be accurately evaluated for higher stages of ionization where the Cooper minimum has moved into the discrete spectrum by using a Herman-Skillman type of calculation; for lower stages of ionization more sophisticated techniques are called for. Preliminary results have been obtained in the application of our theoretical techniques to electron-atom scattering.

II. THEORY OF HIGHLY IONIZED ATOMS

Development of the basic computer programs used in this work has been completed. These programs have been used to study transition probabilities and photoionization cross sections along isoelectronic sequences. Preliminary results have been obtained for electron-rare gas collision cross sections. A newly developed method of evaluating certain correlation effects in continuum states should be very useful in further electron-atom collision studies. Finally, an analysis has been carried out of experimentally observed (1) non-exponential decay in highly ionized atoms; our analysis suggests that such decay is not due to any breakdown of the exponential decay law, but rather to the characteristics of the experiment itself.

A. Transition Probabilities. (D. Lin, W. Fielder, and L. Armstrong) Transition energies and oscillator strengths for several transitions in Li, Be, Ar and K-like atoms have been evaluated using both relativistic and non-relativistic multiconfiguration Hartree-Fock wavefunctions. The heaviest element considered in all cases was U. It was found that relativistic effects are important in the transition energies of $\Delta n=0$ transitions, but not in the evaluation of one electron transition matrix elements. Breakdown of LS coupling is generally not important in $\Delta n=0$ transitions until fairly high Z. For $\Delta n \neq 0$ transitions,

relativistic effects on transition energies are relatively small, but there may be significant effects on the one-electron transition matrix elements. The relativistic effects at high Z were found to be hydrogenic in nature; that is, the relativistic transition matrix elements could be reproduced almost exactly by multiplying the non-relativistic matrix element by the ratio of the relativistic hydrogenic matrix element to the non-relativistic hydrogenic matrix element. This procedure was suggested by Younger and Weiss (2) for use in simple atomic systems and seems to be valid also for highly ionized members of more complex systems such as the Ar-like ions. Rather surprisingly, large relativistic effects were found in some $\Delta n \neq 0$ transition integrals for neutral and slightly ionized atoms in the Ar sequence. These effects were observed in transitions such as the 3p-4d where large cancellation effects are present in the integration; there seems to be no simple model which will predict the magnitude of these effects. Finally, we found that the breakdown of LS coupling occurred at fairly low Z for $\Delta n \neq 0$ transitions.

The results for Li- and Be-like ions have been published (3); an article describing the calculations in Ar-like ions has been submitted to Phys. Rev. A; and a manuscript describing the results for K-like ions is in preparation. In addition, we have carried out calculations

relating to specific transitions for experimentalists elsewhere (e.g., D. Pegg, ORNL). We feel that our programs have reached a stage of development such that we can now be of use to experimentalists and will welcome their requests for specific calculations.

B. Photoionization Cross Sections. (R. Swanson and L. Armstrong). We have demonstrated that the multiconfiguration Hartree Fock procedure can be used to evaluate a large number of groundstate correlation effects in photoionization cross sections. Using such a procedure--which is very straightforward to use and not very time consuming--we were able to obtain cross sections (4) for the rare gases which are comparable in accuracy to results obtained using much more complicated procedures such as the RPA (5) or R matrix (6). Because of the simplicity of our approach, we were able to apply it to a number of elements in the rare gas isoelectronic sequences, thus obtaining what should be very accurate results for ionic photoionization cross sections. By comparing our values with results obtained by S. Manson and co-workers (Georgia State) using the much simpler, but intrinsically less accurate, Herman-Skillman (7) method, we were able to determine where along the isoelectronic sequences the simpler method began to give adequate results(8). Essentially, it was found that once the state of ionization is high enough that the Cooper minimum has moved well

into the discrete spectrum, the complicated correlation calculation is no longer needed and the simpler methods can be used.

A difficulty related to these multiconfiguration Hartree Fock studies was that only ground state correlation was included, with no correlation being considered for the photoelectron. Although this difficulty was not very significant in the photoionization cross sections of the rare gases where final state correlations contribute less than about 10% of the total correlation effect, it is important for questions of electron-atom scattering which will be considered in the next section. We have therefore developed a new and straightforward technique for evaluation of excited state correlations. In this approach, the ground state multiconfiguration Hartree Fock wavefunction is "projected onto the excited state" by annihilating a bound state electron and replacing it with a continuum electron; the radial wavefunction of this continuum electron is then obtained in the field provided by this multiconfiguration wavefunction. Using this technique, we have obtained essentially all of the excited state correlations in the photoionization of the rare gases. A paper is currently being prepared describing these results.

C. Electron-Atom Scattering. (R. Swanson and L. Armstrong) We have used our multiconfiguration ground state wavefunctions for the rare gases to evaluate generalized oscillator strengths for ionization producing an ϵ d electron. This is the partial wave which should be most sensitive to ground state correlations. Calculations for other partial waves are being carried out by S Manson and co-workers using the simpler Herman-Skillman technique. When they are finished, the generalized oscillator strengths will be combined to produce Born cross sections for ionization of the rare gases. It is not known at this point if the ground state correlations we have evaluated will be important to the total cross section.

We intend in the very near future to apply our new technique for final state correlations (described above) to distorted wave Born calculations of electron-atom scattering. We will probably consider excitation, rather than ionization, cross sections.

D. Fundamental Studies. (D. Lin and L. Armstrong) We have also carried out two studies which, although not directly related to the calculations described above, seemed very pertinent to our more general studies of radiation from highly ionized atoms. In the first, D. Lin derived a second quantized form of the Foldy-Wouthuysen transformation. This enabled him to study the non-relativistic expansions

of transition operators directly within the second quantized picture. A manuscript describing this work has been accepted by Physical Review. In the second, we considered the nonexponential decay which has recently been observed for the metastable 2^3S state of highly ionized helium-like ions (1). It is not known whether this nonexponential decay is somehow characteristic of highly ionized atoms (which might have strong implications for the present program) or whether it is somehow produced by the experiment (beam-foil) itself. Our calculations would seem to indicate that the latter is the case. We have evaluated in a very approximate way the effects on the measurements of mixtures in the beam of Li-like ions in the state $[(1s2s)^3S_{n\ell}]^2_{\ell}$, where $2 \leq n \leq 100$ in our calculation. Such ions can decay to $[1s^2 1S_{n\ell}]^2_{\ell}$, producing a photon which would be almost indistinguishable from the photon from the He-like atom, or they can decay via cascades to $(1s^2 1S_{2s})^2S$ without emitting a photon of the energy to be observed. The overall effect is to produce a nonexponential decay curve if one observes only the $1s2s-1s^2$ transition. A paper describing this work has been submitted to Phys. Rev. Letters.

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III. DIAGNOSTIC STUDIES OF HIGH TEMPERATURE PLASMAS

Ultraviolet spectroscopic studies have been conducted during the past year on Alcator and Versator I at the Massachusetts Institute of Technology and Elmo Bumpy Tours at the Oak Ridge National Laboratory. At Alcator we are determining the concentration of light impurities and plan to investigate the transport mechanisms for these impurities. At EBT, spatial scans of the plasma are being used to deduce the impurity distribution. It is possible to produce a highly reproducible disruptive instability at Versator I; spatial scans have been used to study the plasma transport during the disruption.

A. Alcator. (J. Terry, K. I. Chen, H. W. Moos--J.H.U., E. S. Marmor--M.I.T.) This machine is a tokamak device with a limiter of radius equal to 9.5 cm and typical toroidal field of ~ 70 kG. The two remarkable characteristics of the machine are the high plasma purity and the ability to achieve high densities with τ_E increasing roughly as n_e . The overall goal of this study is to understand the interaction of the plasma column with its environment and the resulting flow of impurities into the plasma. The spectral range of 300 to 1700 Å is ideal for determining the concentration of light impurities. The first objective is to measure the light impurity concentrations, confirming the measured values of Z_{eff} . Other objectives are to measure impurity fluxes, elucidate

the role of transport for these impurities, study the evolution of impurities as a function of time especially during the pulsed gas release to increase the density, and to measure the effects of vacuum technique such as wall temperature and surface preparation. The initial studies rely on codes developed at the Johns Hopkins University (no transport) and the Princeton Plasma Physics Laboratory (transport included) to interpret the data observed along a central chord. Later, we will use spatial scans--which are very costly in terms of plasma machine time--to confirm the codes.

In December 1976, the 40 cm concave grating spectrometer (see Section V-A-1) began taking data on a horizontal port, 180° from the limiter. At present, the spectrometer field of view is along a central chord with a typical height of one cm at the center of the plasma. The initial effort was devoted to ensuring that the instrumentation functioned correctly. We are now surveying spectral lines and obtaining "standard" time evolution profiles for comparison with changes in machine parameters.

The results reported here are based on this initial work and hence are preliminary. Figure III-1 shows the time evolution of the O VI, 1032 Å line during a typical shot. Also shown is the Balmer α intensity near the limiter, which measurements with the alcohol laser have shown to be proportional to n_e (D. Overskei, private communication). During the low density part of the discharge the time

Fig. III-1. Typical O VI emissions during an Alcator discharge. One unit of $H\alpha$ corresponds to approximately a value of $\bar{n}_e = 10^{13} \text{ cm}^{-3}$.

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behavior is typical, a burnout peak followed by a low plateau. From both the O VI and O V (not shown) burnout peaks, the concentration at that time is estimated to be on the order of a few tenths of a percent; there are shot to shot and day to day drifts. A comparison with the Princeton code shows that the O flux into the plasma during the low density plateau is about 1×10^{13} atoms/cm² sec. This is to be compared with the TFR results of 1.5×10^{15} atoms/cm² sec (1). At the low flux measured here, it would require on the order of 15 ms to double the O concentration from the burnout value if nothing is lost. Thus the oxygen emissions are consistent with a value of Z_{eff} close to one. Starting at approximately 15 ms, H₂ was injected into the discharge in order to sharply increase the density. As Figure III-1 shows, during the high density phase of the discharge there is a definite delay in the rise of O VI ions compared to the rise of n_e . This is observed for all ionization states, but the shape of the rise depends on the degree of ionization. We are investigating the causes of this shape, which is probably related to the diffusion of the injected cold gas at the periphery into the plasma and the resulting changes in the temperature and density distribution. The value of the O flux is less than 1×10^{14} atoms/cm² sec at the peak implying a value of Z_{eff} close to one for the high density phase also. The O concentration is found to be a function of vacuum quality, discharge cleaning and wall loading

during a run. We plan a series of experiments to delineate these effects more fully.

Carbon, nitrogen and molybdenum have also been observed. The C and N intensities are much lower than those for O. The injection of molybdenum into the discharge appears to be related to the value of q at the limiter.

We plan to study the spatial distribution of oxygen and its transport from the periphery of the plasma inward. The port we are using now permits only limited spatial scanning. The instrument will be moved to a port 90° from the limiter in order to scan on a shot by shot basis out to the plasma radius. This spring the sensitivity calibration of the instrument will be checked at the NBS SURF II facility. At the same time, the long wavelength detector cathode sensitivity will be upgraded to permit studies of O VII near $1640 \text{ \AA}$ and possibly O I $1304 \text{ \AA}$.

B. Versator I. (J.L. Terry, H.W. Moos--J.H.U., B. Richards, G. Bekefi--M.I.T., B. Yaakobi--U. of Rochester). Although this work was first planned as a means of testing instruments, it has shown that ultraviolet emissions are a new way to study the plasma transport during a disruptive instability. Most of the work was accomplished using observations along a central chord with a 22.5 cm concave grating spectrometer based on the design for a rocket borne instrument. Spatial

scans which confirmed the model deduced from the central chord measurements were obtained with the 40 cm instrument discussed in Section V-A-1 and later used on Alcator.

Versator I has a major radius of 54 cm, a plasma diameter ~ 7 cm and no copper shell or limiter. It could be operated in either a stable or unstable mode by adjustment of the ohmic heating current. In the stable mode, emission from impurities showed a qualitative evolution similar to that found in other machines; in the unstable mode a highly reproducible disruptive instability was produced 0.88 msec into the discharge. It produced a sharp increase in the line intensity from low ionization states whereas lines from high ionization states showed a decrease. (See Fig. III-2). This was assumed to be due to the expansion of the current channel at the time of the disruption. Utilizing the absolute flux from the oxygen resonance lines between 450 Å and 1600 Å and well documented atomic parameters with a code allowed us to simulate a model of the space time development of the instability. Fig. III-2 also shows O II and O V emission from the normal and unstable discharges compared with the predictions of the model.

To check the predictions of the model, the discharges were scanned on a shot by shot basis and the data Abel inverted. These data confirm the assumption of expansion during the

Fig. III. 2. O II and O V emission from a stable discharge (left hand side) and one with an instability at 0.88 ms (right hand side). The dashed lines show predictions from the model.

instability. From the inverted data it is also possible to obtain a lower limit on the transport of O ions during disruption by treating the data in a manner similar to that described by the TFR group (2). See Fig. III-3. The true flux after disruption may be higher than shown; the observed signal could have been affected by the 70 μ sec response time of the electronics.

Further details of these experiments have been reported elsewhere (3-6).

The 22.5 cm instrument with a new high sensitivity cathode (see Section V-B-2) is being used by G. Lasché of M.I.T. to study diffusion of controlled gas releases in Versator I.

C. Elmo Bumpy Torus. (E.S. Warden, H.W. Moos--J.H.U., N.H. Lazar--O.R.N.L.) Spatial scans of the ultraviolet emissions from EBT in the 1150 to 2400 Å band have been made using a tilting mirror and an 1/8 m Ebert spectrometer originally used for rocket experiments. Spectral lines from H, C II, C III, C IV, Al II, Al III and H₂ have been identified.

Partial analysis of the results on the impurity spectra show loss times of about 300 μ secs for the surface plasma in EBT. The absence of a measureable CV signal seems to indicate the core plasma as being relatively free of impurities. The amount of carbon

Fig. III-3. Transport of O VI during a disruption in the Versator plasma.

impurity, seemingly a result of introduction of carbon into the machine during its past history has been decreasing.

Analysis of the Lyman alpha signals, which are sensitive to the electron density in the core plasma, are in remarkable agreement with theory--on an absolute basis (Fig. III-4). Molecular hydrogen light, which probably masks the $A\lambda$ IV emissions, has as yet received little attention, but it is probably an important tool in understanding energy diffusion in EBT.

Because the drift surfaces in EBT do not have a coaxial cylindrical symmetry, it is difficult to extract quantitative density distributions from a single view of the plasma. The original experimental design made provisions for a second view, at right angles to the first view, which will shortly be operational. The two views will permit inversion of the data to obtain volume emission rates.

This work was reported at the meeting of the Division of Plasma Physics of the American Physical Society in San Francisco (7, 8). A memorandum describing a preliminary analysis of the low charge state impurities is incorporated into this report as an appendix to this section.

Comparison of Theoretical Light Intensity with
"Toroidal" Light Intensity.

Figure III. 4.

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APPENDIX TO SECTION III

OBSERVATIONS OF LOW CHARGE STATE IMPURITIES IN EBT

I. INTRODUCTION

Measurement of impurity ion densities should allow one to establish the ion loss times with a knowledge of the electron temperature. The ion charge states for ions of a given atomic number are connected through the rate equations

$$\begin{aligned} \frac{dn_j}{dt} = & n_e n_{j-1} S_{j-1} - n_e n_j S_j - \frac{n_j}{\tau_j} \\ & + n_e n_{j+1} R_{j+1} - n_e n_j R_j \end{aligned} \quad (1)$$

where n_e is the electron density, n_j is the ion density of the j th charge state, S_j is the rate coefficient for ionization of species j , R_j is the rate coefficient for recombination of species j , and τ_j is the loss time.

In a steady state machine such as EBT all quantities are independent of time. The recombination rate coefficients for low charge states in the density range and temperature range of EBT are sufficiently small that these processes may be neglected. Thus a solution for $n_e \tau_j$ may be written as

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$$(n_e \tau_j)^{-1} = S_{j-1} \left\{ \frac{n_{j-1}}{n_j} - \frac{S_j}{S_{j-1}} \right\} \quad (2)$$

From the formula one can see that the ratio of the ion densities forms the basis of a good measurement of the ion loss times for $n_e \tau_j$ not much greater than the inverse of the ionization rate coefficient for species $j-1$. Conversely, a knowledge of $n_e \tau_j$ permits a prediction of the ratio of two adjacent charge states

$$\frac{n_j}{n_{j-1}} = \frac{n_e \tau_j S_{j-1}}{1 + n_e \tau_j S_j} \quad (3)$$

This formula is applicable even in the case where ionization and recombination rates are comparable provided the inverse of $n_e \tau_j$ is much larger than the recombination rates.

The ionization rate coefficients for the series of carbon ions have been listed by Lotz (1, 2) and are plotted in Fig. 1. Fig. 2 shows a similar plot for the Aluminium ions. Also listed on the figures are the ionization energies for each charge state. The large gap in ionization rate between C IV and C V, and which should lead to pileup in the higher charge state, is obvious.

Appendix. Figure III. 1. Ionization rate coefficients and ionization potentials for Carbon (ref. 1).

Appendix. Figure III. 2. Ionization rate coefficients and ionization potentials for Aluminum (computed from ref. 2).

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II. EXPERIMENTAL DETAILS

We have made intensive efforts to obtain quantitative spatially resolved density measurements for the various carbon and aluminium charge states in an attempt to establish the ion lifetimes. These measurements, based primarily on the vacuum ultraviolet resonant line intensities, were made using a miniature Ebert ultraviolet spectrometer calibrated at the Johns Hopkins University against NBS standards (3).

The experimental geometry is shown in Fig. 3. Light from the plasma passes through a slot in the midplane of one of the 24 microwave cavities of EBT. (To prevent the escape of microwave radiation the slot is covered with a 30% average transmission microwave cutoff screen.) The light strikes a rotatable scanning mirror which deflects it. One particular set of rays defining a chord across the plasma is selected by a mask. These rays pass two and a half meters down an evacuated tube, through the x-ray wall surrounding EBT and strike a focusing mirror which focuses the selected set of rays onto the entrance slit of an eighth meter Ebert spectrometer. The spectral range covered during the course of the measurements

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Appendix. Figure III. 3. Geometry for Optical Scanning.

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was from 1150 $\text{\AA}$ to 2400 $\text{\AA}$. The detection electronics are operated in a pulse counting mode and a baffle acting as a mirror stop is adjusted so that dead time corrections are negligible.

The spectrometer has a theoretical resolving power of 90,000 ($.02 \text{ \AA}$ at $1800 \text{ \AA}$). It was operated here with a resolution of one Angstrom. This resolution was sufficient to resolve, or partially resolve most of the identified Carbon and Aluminium multiplets. Impurity lines of C II, III, IV, Al II and Al III were identified. These lines were rather simply connected to the ground state or the metastable state.

All optical components were absolutely calibrated at the Johns Hopkins University both before and after data runs.

Because of the lack of symmetry of the drift surfaces in EBT, it is not simple to extract quantitative density distributions from this single view of the plasma but simplistic modeling of particular plasma regions does, in fact, yield approximate results. Spatial scans of some of the transitions which have been measured are shown in Fig. 4 and the line intensities have been partially analyzed.

Appendix.

Figure III. 4. Typical spatial scan profiles. Peaks are normalized to a value of ten. X is the distance from the center of the vacuum cavity to the scanning chord.

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III. DISCUSSION

The EBT plasma is comprised of two components: a toroidal (core) plasma and a mirror confined (surface) plasma. Due to a combination of geometric effects and single particle drifts, the loss rates in the mirror confined plasma are much greater than in the toroidal plasma leading to higher electron temperature and densities in the toroidal core (~ 300 eV; $2 \times 10^{12} \text{ cm}^{-3}$) than in the mirror plasma (~ 50 eV; $3 \times 10^{11} \text{ cm}^{-3}$). Analysis of the loss rates in the mirror confined plasma can be made by restricting data analysis to those chords which do not pass through the toroidal region. The results shown in Table I and Table II, indicate an n_e^T of about $10^8 \text{ cm}^{-3} \text{ sec}$.

The excitation rate for all observed species is a rather insensitive function of electron temperature as the excitation energies are about 10 eV. An electron temperature of 50 eV was assumed in calculating excitation rates from the formula (4).

$$\langle \sigma_v \rangle = 3.2 \times 10^{-7} \frac{f_{ik} \langle \bar{g} \rangle \sqrt{x} e^{-x}}{\left(\frac{\Delta E_\lambda}{13.6} \right)^{3/2}} \text{ cm}^3/\text{sec} \quad (4)$$

In the formula, f_{ik} is the oscillator strength for the transition taken from Wiese, Smith and Glennon (5) or Hummer and Norcross (6), ΔE_λ is the

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TABLE 1

$$N_e N_I (10^{20} \text{ cm}^{-5})$$

(T = 50 eV)

Species θ	0°	10°	20°	30°
C _{II}	23	19	10	4.5
C _{III}	34	26	13	5.8
C _{IV}	16	15	5.0	2.0
C _V (150 eV)	< 5.4			
A _{II} ²	3.8	3.4	1.3	.54
A _{III} ²	7.6	7.5	1.2	.67

TABLE 2

$$n_e \tau_I (10^8 \text{ cm}^{-3} \text{ sec}^{-1})$$

Species θ	0°	10°	20°	30°
C _{III}	1.3	1.2	.96	1.1
C _{IV}	1.2	1.6	1.0	.85
A _{III} ²	1.2	1.5	.37	.59

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energy of the transition in electron volts, x equals $\Delta E/T_e$, and $\langle \bar{g} \rangle$ is a semi-empirical term given by Van Regemorter (7). For $T_e \gtrsim \Delta E_\lambda$, the term $\langle \bar{g} \rangle \sqrt{x} e^{-x}$ is about 0.1 to 0.15 over a very large range of energy.

For CII, CIII, and AlII a considerable number of ions are in the metastable level. Direct measurement of the ground state and metastable population was made for CIII and AlII. The CII metastable population was assumed to be the same as from previous measurements through the center of the midplane.

Measurements of ion densities in the toroidal plasma were attempted by looking for the 2275 Å line of CV--which was unobserved. This line has the same upper level as the 40.7 Å transition from the ground state. Since population of the upper level comes initially from a 300 eV transition, the core plasma should be much more effective in exciting this level than the surface plasma.

The population of the triplet states from the singlet ground state in helium-like ions has been studied by Elton and Köppendörfer (8), Prasad and El-Menshawly (9), and Kunze et al. (10). All these authors find that the transition rates to the triplet levels are about one half the rates to the singlet states even though the singlet-triplet transitions would normally be spin-forbidden. Using this data, and the radiative

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probability for the $1S-3P$ transition calculated by Elton(11) and Drake and Dalgarno(12) ($A_{ki} = 0.26$) and the value for the $2274 \text{ \AA } 3S - 3P$ transition given by Wiese et al. ($A_{ki} = 0.565$), we may place upper limits on the density of CV.

Assuming an $n_e \tau$ for CV to be the same in the surface plasma as measured for the lower charge states and using the rate equation we find the predicted $2274 \text{ \AA}$ radiation to be well below detectable levels.

For the case of the toroidal plasma, the situation is somewhat different. Neither the CIV density, nor the appropriate loss time is known for this region. The loss time for this plasma should be much longer and the excitation rate much higher than in the surface plasma. Table II shows the upper limit on integrated column density of $n_e n_{CV}$ for a chord passing through the center of the cavity and an assumed 150 eV temperature. Were the core plasma in coronal equilibrium, the amount of C IV would be more than a thousand times less than the amount of C V (13) and the C IV signal at this scan angle due entirely to surface plasma.

Assuming the toroidal C IV density to be equal to the surface C IV density requires the $n_e \tau$ of the core plasma to equal or exceed that of the surface plasma. For hydrogen in the core plasma,

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$n_e \tau$ is known to be approximately 10^{11} . Either the loss rates for impurities must greatly exceed those of hydrogen by means of some unknown mechanism, or more likely, the toroidal C IV density is much less than the surface C IV density.

SUMMARY

Spatial scans of the impurity radiation in the ultraviolet from EBT show impurity loss times in the surface plasma on the order of 300 μ secs. Absence of a detectable signal from the 2774 $\text{\AA}$ line of C V indicates that either the core plasma is relatively free of impurities or that the loss times for the core plasma impurities are much smaller than those previously measured for hydrogen.

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IV. LABORATORY STUDIES

A. The Penning Discharge Spectroscopic Source. (E. S. Warden and H. W. Moos) The measurement of plasma impurity radiation in the grazing incidence region is of current interest for controlled thermonuclear research. An electrically quiet continuous line source providing high fluxes of photons in the region would ease the problems involved with photometric and wavelength calibration of instruments designed to work in this region.

Soft x-ray sources above 100 Å and hollow cathode sources below 250 Å are of limited utility and there is a special need for strong sources for this spectral region. The Penning Discharge or Phillips Ionization Gauge (PIG) operates by using crossed electric and magnetic fields in order to trap electrons emitted from the cathode. The ions formed in the filling gas drift in a region outside the cathode that is essentially free from electric fields for a lifetime essentially equal to their distance between cathodes divided by the ion thermal speed. Previous photographic work by Deslattes et al. (1) demonstrated that the PIG source produced light from multiple ionized species. The spectral output of a PIG discharge was investigated between 100 Å and 300 Å at this laboratory to determine if it was a useful high flux source for photoelectric spectroscopy at short wavelengths.

The source, modeled after that of Deslattes et al. (1), had reasonable stability--10% over an hour's operation. Bright spectral lines observed were a mixture of lines from the filling gas (Ne) and from the sputtered cathode material (Al). The observed spectra, and a comparison to a hollow cathode output, is shown in Fig. IV-1.

It appears that the Penning discharge is indeed a useful source of bright emission lines with reasonable stability.

Modern magnet materials and design make feasible the construction of compact Penning discharges and their use as a routine tool in photoelectric spectroscopy. The major disadvantage of the Penning discharge is cathode erosion. This erosion occurs mainly when the discharge is run at high currents, e.g., 0.5 - 1 amp, where the erosion rate is on the order of 2 mm/per hour with Ne fill gas. However, complete refurbishing of the discharge requires only one man hour of work. Also, it is anticipated that the need for high current operation is limited to high flux measurements at short wavelengths and that lamps of this type would be run at high currents for only a small percentage of their total operation. (A commercial design for low current operation is presently available from Jobin-Yvon but is not suitable for obtaining the high ionization states reported here.)

It should be noted the PIG discharge needs no differential pumping, offers less chance of grating contamination

Fig. IV. 1. Spectra from Neon discharges. Upper: hollow cathode run at 0.5 ampere discharge current. Lower: Penning discharge run at 1.0 ampere discharge current, 850 volt. Note that the lower trace was taken ten times smaller sensitivity than the upper trace.

than the hollow cathode because the cathode is not in the direct line of sight, and is a more intense light source below 200 Å. In addition, it offers a strong line at 160 Å midway between the 113 Å beryllium x-ray and the 237 Å helium line. Further investigation and development of this type of light source seems warranted.

This work will be published as an article in Applied Optics.

B. Aluminum Satellite Lines. (E. S. Warden and D. L. Lin)
Dielectronic recombination satellite lines of Neon line Aluminum (Fig. IV-2) were observed when the Penning discharge source was run with Aluminum cathodes. The wavelengths of these lines were confirmed by theoretical estimates. The problem of dielectronic recombination in the context of CTR devices has been considered. The implications of these Aluminum satellite lines is discussed below.

Most estimates of dielectronic recombination rates neglect recombination on the $n=3$ level since the amount of recombination is supposedly the same for each level for a large number of levels. Yet, from Fig. V-2 it is clear that the strength of the satellite lines are 25% of that of the main line which contains all of the $n>3$ transitions. Even if one assumes that most of the light in the main lines is due to recombination, it is clear from the figure that at least one fourth of the recombination took place on this

Fig. IV. 2. Detail of $A\lambda$ IV lines and their satellites.

level. It is expected that the high percentage of the total recombination on this level is a function of the electron density, since at higher electron densities the atom in the upper excited states are more likely to be reionized. (2).

The Penning discharge was operated at a pressure of 10^{-3} to 10^{-4} Torr--thus the electron density may not be too different from that of tokamaks.

Secondly, there is normally a large gap in ionization energy at electron configurations with closed shells which may lead to pileup of impurities at those ionization states. In particular, the TFR group (3) recently noted that the Mo impurity (presumably from the limiter) is approaching equilibrium at the Neon like state. This case is roughly analagous to the Penning discharge where the recombination gave rise to some of the strongest lines in the observed spectrum. Ionization rates are often larger than excitation rates. This would mean that in an equilibrium where dielectronic recombination dominates, each ionization is balanced by a recombination and hence a radiation of a dielectronic satellite. The impurity radiation losses would be concentrated in radiation by the satellite lines. Since the $n=3$ satellites come almost exclusively from dielectronic recombination they also could provide a good measure of the recombination rate from this source and might serve as a diagnostic tool.

C. Optical Components. (Wm. G. Fastie, G. Mount, K. I. Chen) This laboratory has evaluated gratings not only for CTR use (4) but also for satellite and rocket experiments. Much of the latter work is reported elsewhere(5). One of the most interesting results is the variability of high density holographic gratings. These gratings are particularly desirable because they should be ghost free and have low scattered light. FigIV-3 shows the "grating efficiency"(obtained by dividing the measured efficiency by the reflectivity of Pt) of a 5670 groove/mm holographic grating blazed near 1000 Å. The anomaly near 800 Å is noteworthy since these gratings are supposed to be symmetric in their blaze properties. FigIV-4 shows similar data for a grating which was designed to be blazed near 300 Å. The anomalous fall off--at the blaze wavelength--is striking. This is to be compared with classically ruled gratings of 2400 g/mm and the same blaze ordered from the Bausch and Lomb catalog. It showed "grating efficiencies" of 13%, 24% and 5% at 304 Å, 504 Å and 1216 Å respectively. We have also obtained acceptable holographic gratings with high density rulings but with blazes >1000 Å. As techniques for ruling these gratings have progressed rapidly in the past five years, further improvements can be expected. With the completion of the grazing incidence double monochromator (see Section V-A-2) tests will begin on gratings in grazing incidence.

Fig. IV. 3. Grating efficiency (measured values divided by Pt reflectivity; a reflectivity of 3% was used at 304 Å) for a 5670 groove/mm grating blazed at 1000 Å.

Fig. IV.4. Grating efficiency (see Figure 3) for a 5670 groove/mm grating blazed at $300\text{\AA}$.

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V. INSTRUMENTATION

A. Spectrometers. We have completed or are constructing several instruments to obtain the following goals: 1) compatibility with very high vacuum requirements, 2) stability of absolute sensitivity calibration, 3) portability, 4) a wavelength coverage down to $10 \text{ \AA}$, 5) reliability in a CTR machine environment, 6) adaptability to multiple spatial and spectral element detectors.

1. EUV Scanning Monochromator. (Wm. G. Fastie, K. I. Chen, and H. W. Moos) | During the first contract year, a major instrumentation effort was the design and construction of an f/20, 40 cm focal length concave grating normal incidence spectrometer. (See the previous progress report for details of the design and construction.) The methods employed in maintaining focus while rotating the grating are not new, similar ones are employed in several commercially available instruments. However, the instrument has an extremely clean vacuum, is compatible with CTR machines and their environment yet is compact and portable. In addition, the modular assembly permits the use of multi-element detectors with spectral and spatial resolution simply by replacing the slit assembly.

We now have had an opportunity to assess the performance of this instrument both in the laboratory and in a CTR environment using a 2400 line/mm Pt coated grating. Although there are several minor flaws of the

type expected in a first model which will be corrected, the instrument is extremely satisfactory. The vacuum quality is excellent, producing no deleterious effects on tokamak discharges. Conversely, the CTR environment does not affect the instrument adversely due to the effects of the magnetic field on the detector, pick up, or hard x-rays. Our precautions against these seem to be more than adequate. The sensitivity calibration is quite stable; the only drift has been at short wavelengths and is not unexpected. A calibration check of the instrument at the NBS SURF II facility is scheduled in the spring followed by a return to Alcator for further diagnostic studies. The spectral resolution is $\sim 0.2 \text{ \AA}$ and the ability to reset to a given point on the wavelength drive from day to day (and city to city) is about $\pm 0.35 \text{ \AA}$. This value is probably due to varying thermal inputs from the ion pump. A ceramic break will isolate the pump and remove this effect. The compactness and portability has made it possible to calibrate and evaluate the instrument at J.H.U. while doing experiments on Versator I and Alcator at M.I.T.; it is usually carried as excess baggage between the two cities. The compactness has also made it possible to share closely spaced ports with other diagnostics.

In summary, the performance of the instrument as a tokamak diagnostic device is quite good; we believe that instruments of this type will be of general applicability in the study of high temperature magnetically confined plasmas.

2. Grazing Incidence Double Monochromator. (Wm. G. Fastie and D. Cross-Cole). The description of this instrument is given in some detail in the progress report for the previous contract year. Designed for the spectral range below 250 Å, it employs two gratings at grazing incidence, has entrance, intermediate and exit slits in fixed positions and uses a single drive mechanism to rotate both gratings about axes at the center of the two Rowland circles.

The instrument uses gratings with 2 meter radius of curvature with 170° between the incident and diffracted beams. The entrance and exit slits are separated by about 60 cm with the intermediate slit at the midpoint. The f number of the monochromator is about $f/60$. The construction is such that a monochromator may be used singly or the two monochromators ganged together in series.

While the optical design uses well known principles, this is the first time, so far as we know, that an instrument of this type has been constructed.

The fixed exit slit and reduction of scattered light by the double monochromator arrangement are distinct advantages for CTR studies at short wavelengths. The stainless steel construction, placement of slit and drive components external to the vacuum, with their action through bellows, copper gasket seals and ion pumping will ensure vacuum compatibility for diagnostic measurements. In addition to the above

applications, the system can be used to evaluate optical components by the substitution method and to determine the light scattering and polarizing properties of optical components. It also provides a means of sensitivity calibration, since the measured output of the first monochromator can be used to measure the transmission of the second monochromator and vice versa.

The instrument is under construction; the tankage and drive are largely complete. Delivery of the slits is expected shortly. The expected completion date is May, 1977. Evaluation of the instrument and use of the instrument will begin at that time.

3. Stigmatic Grazing Incidence Plane Grating Monochromator.

(Wm. G. Fastie and E. Warden). As described in the previous progress report, the instrument will consist of a parabola to collimate the light, a plane dispersing element and a second parabola to form an image of the dispersed light; all elements of course are used in grazing incidence. This will yield a mechanically simple monochromator with good optical quality and stigmatic imaging in the XUV-soft x-ray region. Conceptual design has been completed and computer ray tracing shows that a high quality image is formed. The most critical problem at soft x-ray wavelengths is the quality of the surfaces which must be extraordinarily smooth. The group at National Physical Laboratory,

Teddington, England has developed processes for producing such surfaces and also for producing very efficient gratings in this range. These processes are now available commercially through Ion Tech Ltd. of Teddington. At our request they assessed the feasibility and cost of constructing the optical components. A quotation was received in November and we are now investigating the trade off in this vs. more conventional means of optical component manufacture. Although the design will be completed this year, procurement of components will not begin until the next contract year as discussed in the accompanying proposal.

4. One Meter Grazing Incidence Monochromator. (E. S. Warden, S. Allen and D. Cross-Cole). The one meter grazing incidence monochromator constructed last year for laboratory use has been modified in order to make it more compatible with usage on pulsed CTR machines. To avoid problems with high counting rates, a photomultiplier with associated magnetic-radiation shielding is now being used as the detector instead of the channeltron previously in use. A portable vacuum tank with metal gasket seals and an ion vacuum pump has been constructed to house the instrument. Ruggedized electronics for field use have been purchased. A wavelength drive with remote readout will

shortly be installed. The high quality vacuum will permit using the instrument both at the NBS SURF II calibration facility and plasma machines. Thus the instrument can be used as an UV intensity transfer standard for the 100 Å to 600 Å range in the same way as is available from 400 Å to 1700 Å with the 40 cm normal incidence instrument (Section V-A-1).

B. Detectors. As described below, the major effort in this area has concentrated on the design and development of a multielement detector to provide spatial resolution. As described in the second subsection, we are also studying the use of CuI as a broadband stable photocathode material.

1. Multielement Detectors. (R. Richards and H.W. Moos)

In CTR research it is important to simultaneously measure extreme ultraviolet emissions at a particular wavelength from many different parts of the plasma. In the measurement of impurity distributions, transport and fluctuations, a faster and more accurate means than a single element detector is desirable. For example, in present tokamak devices which pulse once every few minutes a single element detector may take several hours of pulsing to determine an impurity profile whereas a multielement detector will determine this profile in a single

pulse. Perhaps of more importance than the time saved is the fact that the multielement detector will be more accurate since all the data was taken in a single pulse and there is no problem with the drift of tokamak parameters; this drift, which is often significant, could then be studied. To accomplish this, we are developing a Spatially Imaging Detector System (SIDS).

The SIDS requires an optical means of spatially resolving photons emitted from the plasma. After considering a number of systems, the optical design depicted in Fig. V-1 has been chosen. Spatial resolution is achieved because there is a 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. This is essentially a one dimensional analogue to a pinhole camera; in this case the one dimensional imaging is performed by the spectrometer slits. The use of external mirrors for part of the beam will permit coverage of widely separated parts of the plasma; such coverage is convenient for enhancing the measurement of plasma fluctuations or for the study of complex geometries such as will be found in PDX. We have investigated the compatibility of the SIDS with Alcator, PDX and ISX. It should be noted that similar "pinhole camera" approaches can be used with grazing incidence

OPTICAL SYSTEM

Fig. V. 1. Optical system for imaging of the plasma onto a multielement detector.

spectrometers and thus this type of detector system is of very general applicability. Tests were performed in the visible using a 600 line/mm grating in order to evaluate the capability of a spectrometer to achieve this spatial resolution. They showed that $\sim 10^{-3}$ radians, or 100 chords of a 20 cm plasma at 2 meters, could be resolved.

The possibility of mechanical scanning instead of a multianode detector was considered. This has the two fold disadvantage that different parts of the plasma are observed at different times and the photoelectron signal is reduced by n where n is the number of spatial elements. In the case of a high purity machine such as Alcator, this would significantly reduce the quality of the data.

The detector system is being built around microchannel plates which have been studied and used in some of our other programs. These detectors are attractive because of their 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. The maximum signal current is limited by the bias (or strip) current, J_s , drawn by the microchannel plate. Plates with the highest strip current presently available ($J_s \approx 5 \mu \text{ A/cm}^2$ at $V_{\text{bias}} = 1 \text{ kv}$) were

purchased for testing. The measured maximum signal current was $\sim 1/3 J_s$ and the maximum linear signal, $\sim 0.1 J_s$. The results for two plates in tandem and a 1 cm^2 anode are shown in Fig.V-2. Thus, keeping this detector's operation linear would require either limiting the gain or input flux, or developing microchannel plates with a higher strip current. Discussions with manufacturers indicate that a substantial increase in the strip current of microchannel plates is not expected within the next few years and charges for development would be in the neighborhood of \$20,000 per batch of plates from a new material with a high uncertainty that the trial would be successful. Hence either the gain or input flux must be limited. It is desirable to have both of these as large as possible, the flux in order to provide a reasonable number of photon events per time resolution element, and the gain to guard against pick up noise in the readout electronics. As a compromise, a gain of 10^5 was chosen, allowing $\sim 10^6$ counts/sec over an area of 0.04 cm^2 .

After consulting with Electronic Vision Corporation we have completed the design of the microchannel detector.

Fig. V. 2. Nonlinear current response of a chevron array of microchannel plates to increasing light level.

This detector will be built at Hopkins utilizing our capabilities in that area with Electronic Vision Corporation serving as a consultant on the anode array. The signal from the microchannel plate will be collected on twenty anodes. To avoid the problems associated with the gain characteristics and stability, reduce the problem of beam spread between the microchannel plate and the anode, and to achieve better accuracy in short time intervals, pulse counting rather than analogue current measurements will be used. 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 an extremely sensitive PAD constructed to our specifications by Spacom Electronics has been evaluated. Measurements in our laboratory indicate this PAD could detect pulses down to 4×10^4 electrons.

The operation of the PAD was also evaluated in a CTR environment (Alcator). Results from the test at Alcator showed that this PAD operated satisfactorily at gain thresholds below 10^5 during a tokamak discharge. Spurious pulses were generated only at the very low thresholds; one pulse per 10 msec occurred at a threshold of 4×10^4 . With a predetermined signal to the PAD from a photomultiplier only a small change in the PAD output was found.

The design of the electronic readout system is largely complete. Pulses from the PAD will feed into counters. The counters will be sequentially strobed and the data stored by direct memory access (DMA) in a mini computer. The Hewlett Packard 9825 A is being considered for this last component of the system; it has high speed DMA, a large memory, keyboard, a cassette for permanent storage, and is in one lightweight portable unit about the size of a portable typewriter.

2. CuI as a Broadband Photocathode. (R. Richards and H. W. Moos) There is a need for a stable detector spanning the region 300 to 1700 Å. Most halide photocathodes are water vapor sensitive and have to be mounted in sealed vacuum tubes with windows which transmit only above 1050 Å. Typical cathode materials for windowless detectors have reasonable quantum efficiencies only below 1200 Å. CuI appears to be an extremely good compromise. It has good long term stability and a quantum efficiency above 2% from 400 to 1600 Å.

We have tested the stability of a CuI coating on the cathode of a windowless detector, an EMR 510W photomultiplier. Without a coating the sensitivity of such a detector drops rapidly with increasing wavelengths above 1200 Å. For this test the detector was calibrated and then sent to M.I.T. where it was used on the Versator tokamak with a 225 mm spectrometer. After approximately six months

and 5,000 tokamak discharges the detector was brought back to Johns Hopkins for a recalibration. A comparison of the sensitivities (before and after use) is shown in Fig. V-3.

It appears that the CuI coating does remain stable even in the harsh environment of a tokamak making possible detectors spanning the region 300 to 1700 Å.

Fig. V. 3. Quantum efficiency of a CuI coated windowless photomultiplier (EMR 510W) as a function of wavelength.

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