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ABSTRACT

Spatially resolved profiles of low charge state carbon and aluminum ion impurity radiation from EBT were obtained in the vacuum ultraviolet. The data shows EBT to be remarkably free from impurities. Loss times in the surface plasma are found to be approximately 300 μsec. Thus about one fourth of the input power supports the surface plasma. The measurement places an upper limit on the C V density in the core plasma which indicates that the core plasma is shielded from the impurities in the surface plasma.

This letter reports an initial study of impurity ions in EBT. Impurities are of central concern in toroidal fusion devices, because their presence in the hot plasma regions would influence both particle confinement and energy loss. Further, the interface between the energetic plasma and the vacuum wall is filled with a cooler surface plasma whose sustenance is a power drain which must ultimately be considered in power balance considerations. In the steady-state ELMO Bumpy Torus (EBT) [1] concept, particular care must be taken that this surface plasma both acts as an effective ionization shield for incoming impurities and consumes minimum power in reactor configurations.

We have obtained quantitative, spatially resolved density measurements for the various carbon and aluminum charge states in order 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 Johns Hopkins University against NBS standards [2].

The experimental geometry is shown in Fig. 1. 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 and is deflected. One particular set of rays defining a chord across the plasma is selected by a mask. These rays pass 2.5 m 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 the 1/8-m Ebert spectrometer.

The reflection of plasma light from the cavity walls is a possible source of error in the measurement. This light has been greatly reduced by an optical trap in the midplane opposite the scanning mirror. This trap consists of recessed wells in the cavity walls viewed by the scanning mirror with cover plates which are drilled with a hexagonal, close-packed array of small holes. The scattered light is reduced by more than an order of magnitude.

The spectral range covered during the course of the measurements was 1150-2400 Å. 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.

Originally designed as a rocket instrument, the spectrometer has a theoretical resolving power of 90,000. It was operated here with a resolution of one angstrom, which was sufficient to resolve or partially resolve most of the identified carbon and aluminum multiplets. Impurity lines of C II, C III, C 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 Johns Hopkins University both before and after data runs. The degradation in quantum transmission between calibrations was typically 10%. Thus, changes in calibration should not affect the quality of the data.

Because of the lack of symmetry of the drift surfaces in EBT, it is not simple to extract density distributions with high precision from this single view of the plasma but simple models of particular plasma regions do, in fact, yield approximate results. Shown in Fig. 2 are spatial scans of some of the emission line intensities which have been partially analyzed.

The EBT plasma [1] is composed of two components: a hot, toroidal, core plasma and a colder surface plasma. Due to a combination of geometric effects and single particle drifts, the loss rates in the surface plasma are much greater than in the toroidal plasma, leading to higher electron temperature and densities in the toroidal core (~300 eV; 2×10^{12} cm^{-3}) than in the surface plasma (~50 eV; 3×10^{11} cm^{-3}). Analysis of the loss rates in the surface plasma can be made by restricting data analysis to those chords which do not pass through the toroidal region.

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 [3]

$$\langle \sigma v \rangle = 3.2 \times 10^{-7} \frac{f_{ik} \langle \bar{g} \rangle \sqrt{x} e^{-x}}{\left(\frac{\Delta E_\lambda}{13.6}\right)^{3/2}} \text{ cm}^3/\text{sec} \qquad (1)$$

where f_{ik} is the oscillator strength of the transition taken from Wiese, Smith, and Glennon [4] or from Hummer and Norcross [5]; ΔE_λ is the energy of the transition in electron volts; $x = \Delta E/T_e$; and $\langle \bar{g} \rangle$ is a semi-empirical term given by Van Regemorter [6]. For $T_e \geqslant \Delta E_\lambda$, the term $\langle \bar{g} \rangle \sqrt{x} e^{-x}$ is ~0.1-0.15 over a very large range of energy.

For C II, C III, and Al II a considerable number of ions are in metastable levels. Direct measurements of the ground state and metastable population were made for C III and Al II. The C II and C III metastable populations were assumed to be the same as those obtained from previous measurements through the center of the midplane. Table I gives values of the product $n_e n_i$ integrated along the line of sight for several scan angles. Except for the scan angle of 0°, the line of sight for these scan angles passes only through the surface plasma and does not intersect the toroidal plasma. The ion charge states for ions of a given atomic number are connected through the rate equations

$$\frac{dn_j}{dt} = n_e n_{j-1} S_{j-1} - n_e n_j S_j - \frac{n_j}{\tau_j} + n_e n_{j+1} R_{j+1} - n_e n_j R_j \tag{2}$$

where n_e is the electron density, n_j is the ion density of the jth 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 and temperature range of EBT are also sufficiently small that these processes may be neglected. With these simplifications, a solution for $n_e\tau_j$ may be written as

$$(n_e\tau_j)^{-1} = S_{j-1} \left\{\frac{n_{j-1}}{n_j} - \frac{S_j}{S_{j-1}}\right\} \tag{3}$$

A measurement of the ratio of the ion densities thus forms the basis of a good measurement of the ion loss times for $n_e\tau_j$ not much greater than the inverse of S_{j-i}. Alternately, a knowledge of $n_e\tau_j$ permits a prediction of the ratio of the densities of two adjacent charge states:

$$\frac{n_j}{n_{j-1}} = \frac{n_e\tau_j S_{j-1}}{1 + n_e\tau_j S_j} \tag{4}$$

Provided the inverse of $n_e\tau_j$ is much larger than the recombination rates, the above formula is valid even in the case where ionization and recombination rates in Eq. (2) are comparable.

Table II lists the values of $n_e\tau_j$ calculated from the values of $n_e n_j$ given in Table I. The ionization rate coefficients used in the calculation were those given by Lotz [7-8]. (Kunze [9] reports on the basis of experimental results that the ionization rate coefficients given by Lotz appear to be too high by approximately a factor of two. However, this discrepancy has not yet been resolved and we have used Lotz's compilation here.) The value for $n_e\tau$ of about 10^8 sec-cm^{-3} for both carbon and aluminum ions leads to a loss time of about 300 μsec, assuming an electron density in the surface plasma of 3×10^{11} cm^{-3}.

Using the results in Table I and assuming that the reflux for hydrogen is the same as for impurities in the surface, we may calculate the power expended in the surface plasma. With surface plasma density averaging 3×10^{11} cm^{-3}, $n_e\tau \approx 10^8$ cm^{-3}sec, ~100 eV of energy loss for an electron-proton pair (including ionization energy and kinetic energy of both particles), and surface plasma volume about three-fourths of the total volume (1350 liters) the power loss from wall reflux is calculated to be 15 kW.

The total microwave power used in these runs was 6 kW at 10.6 GHz and 50 kW at 18 GHz. The fraction of the total volume occupied by the surface plasma is naturally dependent on the drift surface configuration, which will be modified in planned future experiments; thus, the rather large fractional power expended to sustain this relatively cold part of the plasma is not expected to be typical of future experiments.

An attempt was made to measure carbon ion densities in the toroidal plasma by looking for the 2275-Å line from the triplet states of C V — which was unobserved. The upper limit was a brightness of 3×10^9 photons sec^{-1} cm^{-2} sr^{-1}. This line has the same upper level as the 40.7-Å transition from the ground state. Because the 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 [10], Prasad and El-Menshawy [11], and Kunze et al. [12]. All these authors find that the excitation rate coefficients to the triplet levels are about half the rate coefficients to the singlet states, even though the singlet-triplet radiative transitions are spin-forbidden. Using these data, the radiative transition rate for the $^1S-^3P$ transition calculated by Elton [13] and by Drake and Dalgarno [14] ($A_{ki} = 0.26 \times 10^8$ sec^{-1}), and the value for the 2274-Å $^3S-^3P$ transition given by Wiese et al. [4] ($A_{ki} = 0.565 \times 10^8$ sec^{-1}), we may place upper limits on the density of C V.

Assuming an $n_c\tau$ for C V to be the same in the surface plasma as measured for the lower charge states and using the measured C IV density and Eq. (4), we find the predicted 2275-Å radiation to be well below detectable levels, as expected. Therefore, the absence of observable C V light is in agreement with the measured C IV density.

For the case of the toroidal plasma, the situation is somewhat different. 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 $n_e n_{C\ V}$ for a chord passing through the center of the cavity and an assumed 150-eV temperature.

If one assumes the toroidal C IV density to be equal to the surface C IV density, the absence of a measurable C V signal would require the $n_e \tau_{C\ V}$ of the core plasma to be less than approximately 10^8 cm^{-3} sec, the same value or less than that measured for the surface plasma. However, for hydrogen in the core plasma, $n_e \tau$ is known to be approximately 10^{11} cm^{-3} sec^1. Hence, either the loss rates for impurities in the core plasma must greatly exceed (by $\sim 10^3$) those of hydrogen because of unknown mechanisms, or (more likely) the toroidal C IV density is much less than the surface C IV density.

For a chord passing through the center of the cavity where the electron line density is $n_e \ell \sim 2 \times 10^{13}$ cm^2 and $T_e \geqslant 150$ eV, assuming that $n_e \tau_{C\ V}$ is the same as for hydrogen ions in the toroidal plasma, we would estimate from Eq. (2)

$$\frac{n(C\ V)}{n(C\ IV)} \sim 50$$

With this density ratio, since we observe no light from C V, the light intensity observed from C IV must all originate <u>outside</u> the core.

The upper limit on C V density combined with an assumed $n_e \tau$ of 10^{11} cm^{-3} sec for the core plasma allows one to estimate [using Eq. (4)] the total carbon ion density in the core plasma as being less than 6×10^{-5} of the electron density. It is not unreasonable to assume that there is even less aluminum impurity in the core plasma, as this is true of the surface plasma. In the surface plasma, where the electron density averages 3×10^{11} cm^{-3}, the total carbon impurity density amounts to 2×10^{-3} of the electron density. Including an estimate for Al IV, the total aluminum impurity density is 5×10^{-4} of the electron density in the surface plasma.

Summarizing the results of these measurements, spatial scans of the impurity radiation in the ultraviolet from EBT show impurity loss times in the surface plasma on the order of 300 μsec and also show that about one fourth of the input power supports the reflux of surface plasma from the walls. Absence of a detectable signal from the 2274-Å line of C V indicates that the core plasma is almost entirely free of impurities.

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TABLE I

$n_e n_i \times \ell (10^{20}\ cm^{-5})$

(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			
Al II	3.8	3.4	1.3	0.54
Al III	7.6	7.5	1.2	0.67

TABLE II

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

Species \ θ	0°	10°	20°	30°
C III	1.3	1.2	0.96	1.1
C IV	1.2	1.6	1.0	0.85
Al III	1.2	1.5	0.37	0.59

Figure Captions

Fig. 1. Geometry for optical scanning.

Fig. 2. Typical spatial scan profiles. Peaks are normalized to a value of 10. X is the distance from the center of the vacuum cavity to the scanning chord.

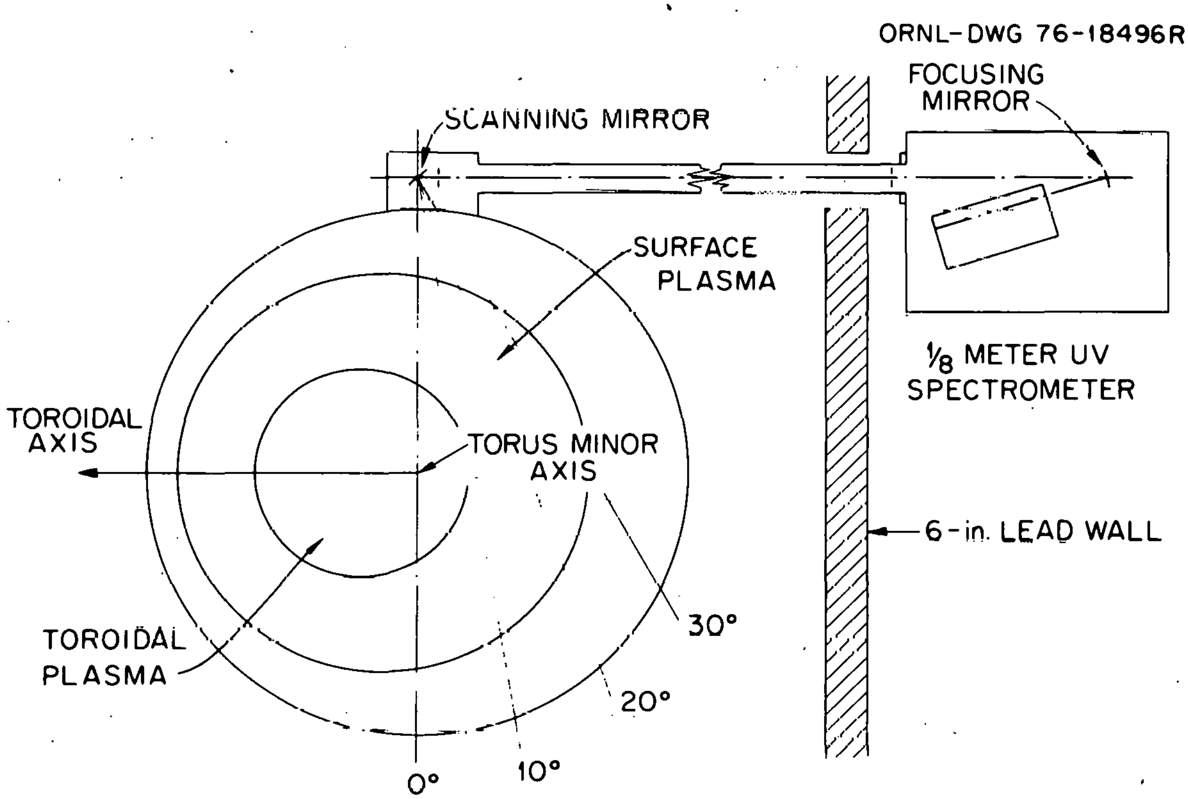

Fig. 1. Geometry for optical scanning.

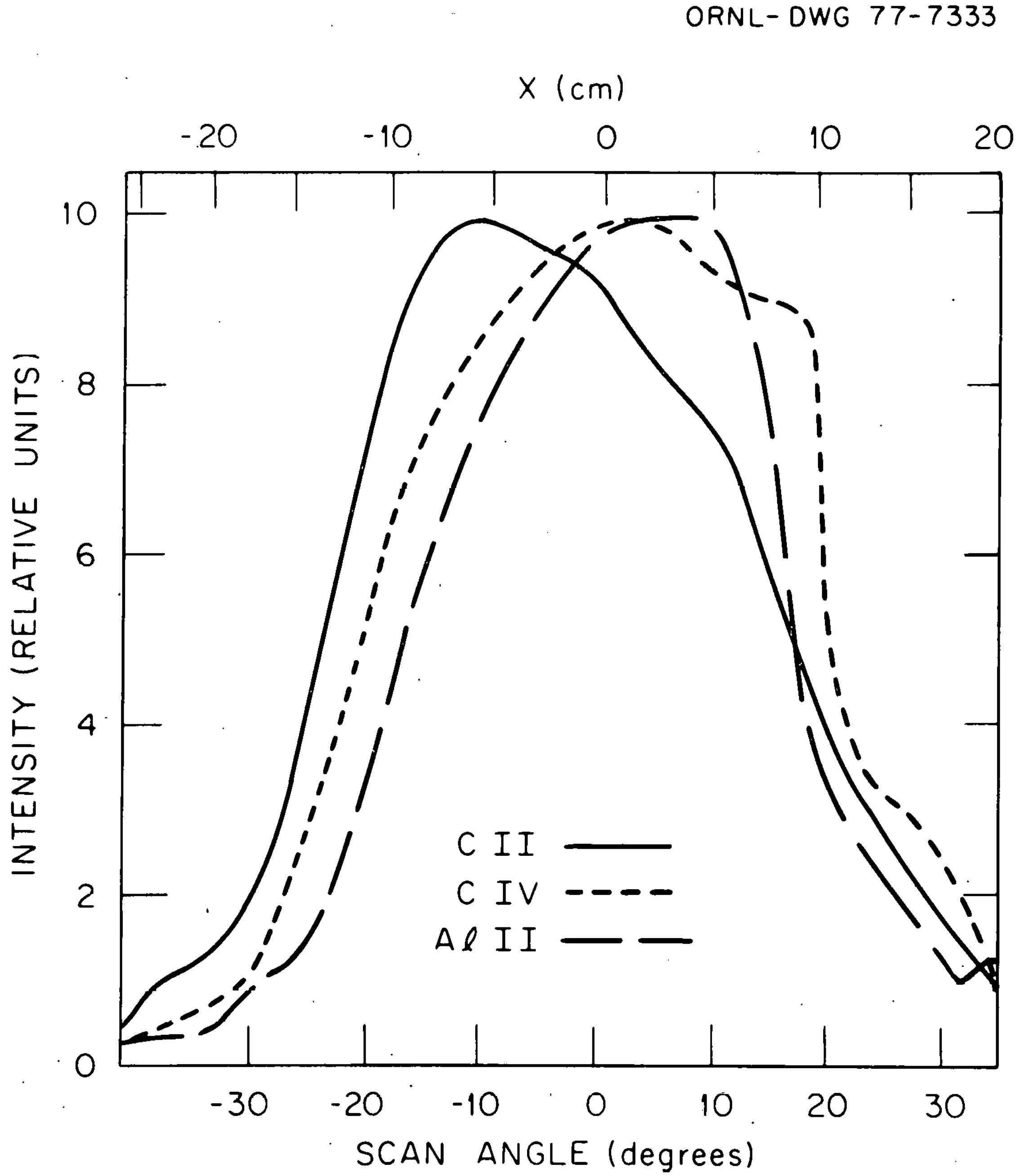

Fig. 2. Typical spatial scan profiles. Peaks are normalized to a value of 10. X is the distance from the center of the vacuum cavity to the scanning chord.

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