27
3-16-81
JWA
24 b KT IS

(1)

R-2725

MASTER

UCID- 18883

AN IMPURITY STUDY OF TMX USING
ULTRAVIOLET SPECTROSCOPY

S. L. Allen, O. T. Strand, H. W. Moos,
R. J. Fortner, T. J. Nash, D. D. Dietrich

January 31, 1981

Lawrence
Livermore
Laboratory

This is an informal report intended primarily for internal or limited external distribution. The opinions and conclusions stated are those of the author and may or may not be those of the Laboratory.

Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore Laboratory under Contract W-7405-Eng-48.

NOT FOR DISTRIBUTION

AN IMPURITY STUDY OF 1MX USING ULTRAVIOLET SPECTROSCOPY

S. L. Allen, O. T. Strand,* H. W. Moos,* K. J. Fortner,
T. J. Nash, and D. D. Dietrich

*Johns Hopkins University, Baltimore, MD.

DISCLAIMER

TABLE OF CONTENTS

ABSTRACT	1
1. INTRODUCTION	1
1.1 Impurity Studies in Linear Devices	1
1.2 Summary of Impurity Study on TMX	4
2. EXPERIMENTAL DETAILS	5
2.1 Survey Spectrograph	5
2.1.1 Normal Incidence	5
2.1.2 Grazing Incidence	8
2.2 Absolutely-Calibrated Single-Channel Monochromator	8
2.3 Absolutely-Calibrated 22-Channel Monochromator (SIDS)	8
2.4 Location of Instruments on the TMX Experiment	10
2.5 Characteristic TMX Plasma Parameters	12
3. EXPERIMENTAL RESULTS	14
3.1 Spectrograph Surveys	14
3.2 Impurity Line Study - General	17
3.3 General Characteristics of Impurity Emission in the TMX Plug	17
3.3.1 Comparison with 2XII B	22
3.4 General Characteristics - TMX Central Cell	22
3.4.1 Typical Time Histories	26
3.4.2 Radial Profiles	26
3.4.3 Radial Profiles - Inversions	29
3.5 Impurity Density Determination	31
3.5.1 Measurements of Metastable Populations	33
3.5.2 Emission Model	35
3.5.3 Impurity Density Results	37
3.6 Radiated Power	38
3.6.1 Radiated Power from Light Impurities and D ₂	38
3.6.2 Radiated Power - Titanium	39

TABLE OF CONTENTS (Continued)

4.	EXPERIMENTAL TRENDS - WALL CONDITIONS	41
4.1	Gettering	41
4.2	Liner Experiments	43
5.	SUMMARY OF OTHER IMPURITY EXPERIMENTS	43
5.1	Central Cell Heating Experiment	43
5.2	Impurity Injection Equipments	45
5.2.1	Experimental Procedure	45
5.2.2	Experimental Results and Discussion	46
6.	DISCUSSION OF CONCLUSIONS	49
	REFERENCES	50

ABSTRACT

An extreme ultraviolet (EUV) study of the emissions from intrinsic and injected impurities in TMX is presented. Two survey spectrographs were used to determine that the major impurities present were oxygen, nitrogen, carbon, and titanium. Three absolutely-calibrated monochromators were used to measure the time histories and radial profiles of these impurity emissions in the central cell and each plug. Two of these instruments were capable of obtaining radial profiles as a function of time in a single shot.

The general characteristics of impurity emission in the TMX end plug were similar to those observed in the 2X11B device; in particular, the results were consistent with beam-injected oxygen. The major impurity in the TMX central cell was oxygen, with a concentration of approximately 0.3%. It was found that the density of light impurities in the central cell was influenced by wall conditions, such as gettering. The total radiated power from impurities in the central cell was estimated to be 20-30 kW, approximately 10% of the total input power.

Observations of impurity emissions during central-cell neutral-beam heating experiments are presented. In addition, results and preliminary analysis of an impurity injection experiment are discussed.

1. INTRODUCTION

It is well known that impurities can significantly influence a plasma in several ways. As shown in Table 1, the power loss by line radiation from impurities can be an appreciable fraction of the input power in a fusion device. In some extreme cases, hollow electron temperature profiles have been caused by radiation from impurities.⁷ In addition, impurities can drive or enhance instabilities in the plasma.

1.1 IMPURITY STUDIES IN LINEAR DEVICES

There have been many impurity studies of tokamaks;¹⁻⁷ as a result, impurity behavior is fairly well understood in these devices. In contrast, there have been very few impurity measurements on linear devices. Simple mirror machines are expected to expel impurities⁸ because of the positive

TABLE 1. Power loss by impurity radiation

Device	Input power lost, %	Date, yr.	Ref.
C-stellarator	30-50	1962	1
ST tokamak	30-40	1974	2
ATC tokamak	≈ 20	1975	3
TFR tokamak	40-60	1975	4
PLT tokamak	15-25	1976	5
Alcator tokamak	≈ 20	1978	6
2XIIIB	5-10	1979	12

ambipolar potential present in the center of the mirror. In addition, low energy impurity ions are expected to rapidly scatter ($\sim \sqrt{M_i} E_i^{3/2} Z^{-4}$) into a region of phase space where they are not confined by the magnetic mirrors.⁸ The first detailed impurity study⁹ of a beam-fueled linear machine was performed on 2XIIIB.¹⁰ The major results were:^{9,11} (a) oxygen was shown to be the major light impurity (2 to 3%), while carbon, nitrogen, and titanium emissions also identified, (b) oxygen was shown to be injected by the neutral beams, (c) the OII brightness was shown to scale with the beam current as $I_b^{1.6}$, (d) a small fraction of the input power was lost through impurity radiation, and (e) low-energy injected impurities were found to be poorly confined by the mirrors. (Ref. 12 presents more detail.)

We present here the results of a major impurity study on the Tandem Mirror Experiment;¹³ it represents the second study on a beam-fueled linear device and the first investigation of a tandem mirror. The tandem mirror concept uses two plugs similar to 2XIIIB (min-B mirrors, beam-driven) to confine a plasma in a central cell. From the standpoint of impurities, this configuration provides a mixture of possible impurity sources: high energy beam-injected impurities in the plugs and desorbed impurities from the surfaces of the vacuum vessel, particularly in the central cell. The presence of electrostatic confinement¹⁴ in TMX (Fig. 1) adds another dimension to the impurity plasma interaction. A positive impurity ion existing in the central

FIG. 1. Electrostatic confinement in the TMX Device.

cell should be confined by this positive electrostatic potential, ϕ_i . An impurity ion existing in the central region of the plug, on the other hand, may flow into the central cell or out of the machine depending on its energy and position, with the majority expected to flow out. Therefore, the conditions are favorable, at least from the standpoint of potential, for the impurity ion to flow out of the machine. The purpose of this impurity study was to experimentally measure the impurity characteristics in a tandem mirror device, with emphasis on the central cell plasma.

1.2 SUMMARY OF IMPURITY STUDY ON TMX

Two survey spectrographs were used to measure the impurity emissions (averaged over several shots) from the central cell; the major impurities were found to be oxygen, carbon, nitrogen, and titanium. The instruments are discussed in paragraphs 2.1.1 and 2.1.2, and the results are presented in paragraph 3.1.

One single chord and two 22-chord monochromators were used to measure the time histories and radial profiles of the emissions from the major impurities; these instruments are described in paragraphs 2.2 and 2.3. The location of each instrument on TMX is shown in paragraph 2.4., Fig. 5, and typical TMX plasma parameters are listed in paragraph 2.5, Table 3.

The results obtained in the TMX plug were similar to those found on the 2XIIIB device; in particular they were consistent with beam-injected oxygen. These results are discussed in paragraph 3.3. The characteristics of impurity emissions in the central cell are presented in paragraph 3.4; these radial brightness profiles were used to obtain the impurity density (0.1% for oxygen and lesser amounts for carbon and nitrogen) and the total radiated power (20-30 kW).

Observations made of impurity behavior during vacuum chamber preparation, gettering, and the use of cold liners, are discussed in Section 4. This data shows that the density of light impurities in the central cell is influenced by the wall conditions. Finally, Section 5 is concerned with the impurity behavior during central-cell neutral-beam heating experiments. In addition, a pulsed-gas valve was used to introduce oxygen and neon into the plasma; experimental results and preliminary analysis are presented. Overall conclusions are discussed in Section 6.

2. EXPERIMENTAL DETAILS

The impurity study on TMX had several goals: (a) The identification of the important impurity species; (b) The measurement of the densities of these impurities as a function of time and space; (c) The estimation of the radiated power from these impurity species, and (d) An understanding of the sources of the impurities and their transport, particularly in the central cell. The spectroscopic instruments used for this study were selected with these goals in mind. To accomplish item (a), a spectrograph (paragraph 2.1) was used to survey a large wavelength region. To accomplish items (b) and (c), absolutely-calibrated monochromators (paragraphs 2.2 and 2.3) were used to determine the absolute brightness profiles of the resonance and metastable transitions of the important ionization states; the total impurity density and radiated power were obtained by calculation from these results. Finally, impurity transport, item (d), was studied by obtaining time-resolved spatial profiles of emissions from injected and intrinsic impurities (paragraph 2.3). A short description of the instrumentation follows.

2.1 SURVEY SPECTROGRAPH

2.1.1 Normal incidence

The identification of the most important impurities was obtained by survey spectrographs which were supplied and operated by R. L. Fortner, T. J. Nash, and co-workers from E-Division at LLNL. The normal-incidence instrument was a McPherson (Model 225) vacuum spectrograph equipped with a 30-mm film cassette. It was located on the north side of the TMX central cell at $z = 0$. The instrument has a 1.0-m focal length and an $f/50$ (horizontal) by $f/11$ (vertical) field of view; external baffles and a vacuum beam line enabled a ± 12 -cm vertical view (along the radius) of the plasma and a ± 12 -cm horizontal view (along z).

Two gratings were used in the survey instrument to cover different wavelength regions. A 1200-gr/mm grating, blazed at approximately 1500 Å (the peak of the efficiency curve is at the blaze wavelength in first order) enabled a useful spectral range from 250 to 3000 Å with a 0.1 Å resolution; a 600 gr/mm grating, blazed at 5000 Å covered a range from 250 to 6000 Å with 0.2 Å

resolution. Kodak 101.05 film in 35-mm cassettes was used to record the spectrum; typically 800 Å would fit on the film for each exposure. A movable baffle was used to select various sections of the film so that several exposures could be made on a single piece of film.

A hollow-cathode platinum lamp source¹⁵ was mounted on the beamline of the instrument; a 45° mirror could be inserted into the beamline so that the well-known Pt spectrum could be recorded (Fig. 2). By moving the baffle, a platinum spectrum could be recorded on the same piece of film as the spectrum from the plasma, thus enabling accurate determination of wavelength and instrumental resolution. (See Table 2 for a summary of the instrument parameters).

FIG. 2. Schematic diagram of the 1.0-m McPherson spectrograph with calibration source.

TABLE 2. Summary of instrument parameters.

	Normal inc. survey	Grazing inc. survey	Single channel	22 channel (two)
Spectral region (Å)	250-3000 ^a 250-6000 ^b	50-2000	300-1700	300-1700 ^c 300-1200 ^d
Spectral resolution (Å)	0.15	1.0	0.15 1 ^e	0.2 1 ^e
Time resolution	----	----	70 μ s	125 μ s
Spatial scanning	----	----	Shot-by-shot	Single-shot
Spatial resolution (radial)				1.6 cm ^c 0.7 cm ^d
Calibration	(f)	(f)	Absolutely Calibrated	Absolutely Calibrated
Detector	Film	Film	Photomulti- plier	Micro- channel plate
Location	CC	CC	West Plug	CC East Plug

^a1200 grid lines/mm grating^b600 grid lines/mm grating^cCC instrument^dEast plug instrument^eTypical resolution used in experiment^fEstimated by cross calibration with calibrated instruments

2.1.2 Grazing incidence

A McPherson (Model 247) spectrograph was used to survey the wavelength region from 50 to 2000 Å, with special emphasis on the short wavelength (50 to 250 Å) region not covered by the normal-incidence instrument. A 300 gr/mm grating blazed at 400 Å was used in the 2.0 m focal length spectrograph; the f-number was f/50 and the angle of incidence was 82°. The instrumental resolution was approximately 1.0 Å. Kodak 101.01 plates were used to record the spectrum. This instrument was also located on the central cell (although not concurrently with the normal-incidence survey instrument).

2.2 ABSOLUTELY-CALIBRATED SINGLE-CHANNEL MONOCHROMATOR

An absolutely-calibrated single-channel monochromator was used for initial measurements on the central cell and later, the west plug. This same instrument was used for impurity studies on the Alcator A tokamak^{16,17} and 2XII-B.⁹ It was developed by Johns Hopkins University and its operation is discussed thoroughly elsewhere.¹⁸ A schematic is included in Fig. 3. In summary, it is a 0.4-m focal length, normal incidence monochromator that has been absolutely calibrated in both wavelength and flux. The absolute calibration was performed at the Johns Hopkins University; this calibration has been transferred from the National Bureau of Standards. The 510W windowless photomultiplier is used in the analog mode, with a practical time resolution of 70 μ s. The instrumental resolution is approximately 0.2 Å, but most experimental conditions required only 1 to 2 Å resolution. The system was equipped with magnetic, electric, and radiation shielding and has its own pumping system capable of maintaining a pressure of at least 10^{-8} torr. A remote control tilting mechanism allows shot-by-shot spatial scanning of a single spectral line.

2.3 ABSOLUTELY-CALIBRATED 22-CHANNEL MONOCHROMATOR (SIDS)

A 0.4-m monochromator similar to that discussed in paragraph 2.2 and purchased by LLNL was modified and a Spatial Imaging Detector System¹⁹ developed by Johns Hopkins University was added so that 22 chords of the plasma could be observed simultaneously. The spatial imaging detector system (SIDS)

FIG. 3. Schematic diagram of the absolutely calibrated 0.4-m monochromator (single chord).

allows acquisition of an ultraviolet image of the plasma every 125 μ s. It should be noted that other imaging systems employed on pulsed-plasma machines have used a rotating mirror. Because the total duration of the TMX plasma is approximately 25 to 30 ms, only a few spatial scans (each requiring about 5 ms) could be performed with this technique. In addition, these chords are not measured simultaneously, so this method is useful only in steady-state situations.

Because the SIDS has been thoroughly described elsewhere,^{19,20} only a short general description will be presented here. A schematic diagram of the system is included in Fig. 4. Imaging is accomplished by using the entrance slit as a one-dimensional analog of a pinhole camera; each position A in the plasma has a corresponding point A' on the detector. The desired wavelength is selected by rotating the grating (accomplished by a remote-control grating drive), directing a monochromatic image of the plasma on the detector.

FIG. 4. Schematic representation of the spatial imaging detector system (SIDS) which views 22 chords of the plasma simultaneously.

The SIDS consists of a pair of microchannel plates (MCPs) in the chevron configuration which are in essence millions of photomultipliers. Twenty-two discrete anodes are placed behind the MCPs to collect the charge. Each anode has a pulse amplifier discriminator (PAD) and a counter. The data is stored by transferring it from the counters to an HP-9845 computer via direct memory access. Two such instruments were used on TMX and a system was developed so that both instruments could be controlled from a single HP-9845 computer. Data from both instruments was displayed and recorded on magnetic tape between shots. In addition, Abel or matrix inversions of the radial brightness profiles could be performed.

Table 2 summarizes the major characteristics of the instruments.

2.4 LOCATION OF INSTRUMENTS ON THE TMX EXPERIMENT

The location of spectroscopic instruments on TMX is shown in Fig. 5. Each survey instrument was located on the north side of TMX at $Z = 0$ in the central cell and viewed a horizontal chord.

FIG. 5. Experimental configuration of the spectroscopic instruments on TMX.

The single-chord instrument was used from July 1979 to March 1980 to measure the central chord brightness of impurity emissions in the central cell. In January of 1980, a 22-channel instrument was mounted on the east plug. In March of 1980, this instrument was moved to the central cell, viewing the plasma from above. (At the same time, the single-channel instrument was moved to the west plug.) Approximately 37 cm of the plasma was imaged on a single shot with 1.65-cm spatial resolution; two shots were required to obtain a complete radial scan of both halves of the plasma. Typically, more shots (3 to 4) were used with overlap between the radial scans to insure reliable data and to detect if shot-to-shot variations were present. Both halves of the plasma were measured to determine if asymmetries in the emission were present.

In April of 1980, a second 22-channel instrument was supplied by Johns Hopkins University. This instrument was similar to that owned by LLNL, but was designed for the high counting rates encountered in tokamaks. Hence it

was suited for use on the plug where the brightnesses are usually greater. Fig. 5 shows the final experimental configuration with the four instruments: (a) a 22-channel (high-count rate) instrument on the east plug, capable of imaging the plug plasma in one shot, (b) a 22-channel instrument on the central cell, capable of imaging half of the plasma, (c) a single channel instrument on the west plug, capable of shot-to-shot scanning, and (d) a survey instrument on the central cell, that integrates several shots.

2.5 CHARACTERISTIC TMX PLASMA PARAMETERS

The typical plasma parameters (electron density, electron temperature, etc.) have been described in detail elsewhere;^{21, 22} Table 3 lists the typical plasma parameters. In addition, there are some machine and plasma characteristics that are particularly relevant to the study of impurities; these are presented next.

A combination of glow-discharge cleaning and gettering are used for preparation of the vacuum vessel surfaces and for impurity control. The base vacuum is typically 10^{-8} torr when gettering and liquid nitrogen liners are used. In most cases, gettering is performed on every shot or, at least, every other shot.

The procedure used to create and maintain the plasma (the streaming guns and the neutral beams) also affects the impurity species and densities in the TMX. The stream guns create a plasma by striking an arc and bombarding a deuterated titanium washer. Plasma flows along field lines to create a target for the beams. The neutral beams are a source of oxygen in the plug, as shown on 2XIIB.⁹ Finally, two methods of fueling the central cell plasma are commonly used: (1) normal gas-box operation, where cold deuterium or hydrogen is injected in the throat of the plug, and (2) "puffer" operation, where cold deuterium or hydrogen is injected in the central cell by means of a pulsed gas valve. These pulsed gas valves were also used to inject oxygen and neon impurities into the plasma.

TABLE 3. TMX plasma parameters with deuterium and 0.1-T, central cell field strength.

	TMX max.	Puffer valve Shot 57 (9/28/79) TMX	Gas box Shot 46 (9/26/79) TMX
Plug density, n_p (10^{13} cm^{-3})	4	1.35	2.5
Central-cell loss current density, j_c (mA cm^{-2}) at central-cell midplane	200	44	180
Plug electron temperature, T_{ep} (eV)	260	103	140
Central-cell density, n_c (10^{13} cm^{-3})	3	0.52	1.0
Central-cell ion temperature, T_{ic} (eV)	250	27	52
Central-cell confining potential, ϕ_c (V)	100 to 300	98	128 ^a
Central-cell confine- ment parameter, nT_c ($10^{10} \text{ cm}^{-3} \text{ s}$)	7	3.0	3.1
Electrostatic enhance- ment in confinement, nT_c/n_T	9	2.0	2.9
Central-cell beta, $\beta_c(z)$	10	1.4	4.2

^a $\phi_c = T_e \ln (n_p/n_c)$.

3. EXPERIMENTAL RESULTS

3.1 SPECTROGRAPH SURVEYS

The normal incidence and grazing-incidence spectrographs were used to record emissions from the central-cell plasma. Typically, a large number (40 to 50) of plasma discharges were recorded on a photographic plate; this was to insure that even the weakest impurity emissions were recorded. The photographic plates were then digitized with a recording densitometer. A sample portion of the spectrum between 275 Å and 310 Å (the total scan was from 150 to 1300 Å) is shown in Fig. 6. Note the titanium lines that have been identified. In addition, emissions from ionization states of oxygen and nitrogen were present in this spectral region.

Figure 7 shows a segment of a spectrum obtained from the normal incidence spectrograph. The total spectral range from 1700 to 2000 Å was covered on this scan (first order wavelength); the spectral region shown is from 1875 to 1940 Å. Carbon emissions are identified in this region.

In summary, the primary impurity constituents identified by the survey were carbon, nitrogen, oxygen, and titanium; these are the same impurity species that were identified on 2XII-B. Ionization states up to lithium-like (CIV, NV, and OVI) were observed. The absence of He-like emissions from these light impurities is caused by the expected low density of the 3S state at the electron temperatures found in the central cell.

While the survey study was extremely useful to identify the most prominent impurity species, it was difficult to determine impurity densities and radiated power from these measurements as the instruments were uncalibrated in sensitivity. In addition, plasma parameters often varied from shot to shot. Furthermore, intensity ratios were valid over only a short wavelength region. Therefore, the absolutely calibrated monochromators were used to measure the emissions identified in the survey study.

FIG. 6. Spectrum between 275 Å and 310 Å from the grazing incidence spectrograph showing titanium, nitrogen, and oxygen emissions.

FIG. 7. Spectrum between 1875 Å and 1940 Å from the normal incidence spectrograph showing carbon emissions.

3.2 IMPURITY LINE STUDY - GENERAL

As discussed above, the absolutely-calibrated instruments used in this study were sensitive from 300 Å to 1500 Å. For the light impurities (carbon, nitrogen, and oxygen) there are $\Delta n = 0$ ground state resonance transitions in this wavelength region; Δn is the principal quantum number. In most cases, the metastable transitions (from Be-like and B-like ionization states, for example) are also in this region. In addition, there are some ionization states of Ti which can be observed.

Each transition was carefully scanned and identified; the emissions from the various ionization states that were measured are shown in Table 4. These emissions were observed under various plasma conditions to ascertain "typical" time histories, radial profiles, and absolute brightnesses.

3.3 GENERAL CHARACTERISTICS OF IMPURITY EMISSION IN THE TMX PLUG

Each plug of the TMX experiment is similar to the 2XIB experiment, so it is important to compare the two from the standpoint of impurities. One characteristic of the emissions from 2XIB and the TMX plug is that the spectral lines are quite broad; shot-to-shot spectral scans of OIV- α 36 Å and L_{α} - 1216 Å are shown in Fig. 8. The instrumental resolution in this case was approximately 1 Å as determined by the entrance and exit slits; the spectral line is broadened substantially. As discussed in Ref. 14, this is consistent with the model that high-energy neutral oxygen is introduced by the neutral beam injectors.

The typical time history of the light impurity emission in the TMX plug is presented in Fig. 9. (The sum of the radial chords for OIV-554 Å is shown for the east plug.) The timing sequence is shown for reference. The large increase in the signal at the beginning of the sequence (roughly 5 ms) is caused by the stream-gun plasma; the decrease after approximately 5 ms is due to the turnoff of these stream guns. The time evolution reaches a steady state soon after the stream gun turnoff, and the signal remains roughly constant until the end of the discharge.

The radial profile of the brightness as a function of time for OVI-1032 Å is shown in Fig. 10. There is some influence from the stream guns in the first 5 ms of the discharge; after this, the profile is well characterized by

TABLE 4. Observed ions and transitions.^a

Ion	(Å)	Transition	
D I	1216	$1s - 2p$	$2S - 2P$
O VI	1038	$2s - 2p$	$2S - 2P$
O VI	1032	$2s - 2p$	$2S - 2P$
O V	760 ^b	$2s2p - 2p^2$	$3P - 3P$
O V	630	$2s^2 - 2s2p$	$1S - 1P$
O IV	789	$2s^22p - 2s2p^2$	$2P - 2D$
O IV	554	$2s^22p - 2s2p^2$	$2P - 2P$
O IV	625 ^b	$2s^22p - 2p^3$	$4P - 4S$
O III	703	$2s^22p^2 - 2s2p^3$	$3P - 3P$
O III	600 ^b	$2s^22p^2 - 2s2p^3$	$1D - 1D$
O II	718 ^b	$2s^22p^3 - 2s2p^4$	$2D - 2D$
O II	539	$2p^3 - 2p^23s$	$4S - 4P$
C IV	1548	$2s - 2p$	$2S - 2P$
C III	977	$2s^2 - 2s2p$	$1S - 1P$
N V	1239	$2s - 2p$	$2S - 2P$
N IV	923 ^b	$2s2p - 2p^2$	$3P - 3P$
N III	685	$2s^22p - 2s2p^2$	$2P - 2P$
Ti VIII	522	$3s^23p^4 - 3s3p^5$	$3P - 3P$
Ti VI	524	$3s^23p^5 - 3s3p^6$	$2P - 2S$
Ti IV	779	$3d - 4p$	$2D - 2P$

^a Unmarked transitions are ground state resonance transitions.^b Metastable resonance transitions.

FIG. 6. Shot-by-shot spectrum scan of O V 630 Å and D 1216 Å showing doppler broadening.

FIG. 9. Time history of OIV-554 Å in the east plug of TMX. The timing sequence is also shown for reference.

FIG. 10. Radial brightness profile of OVI-band λ in the east plane.

a Gaussian profile. As was found in 2XIIB, the width of the brightness profile is somewhat narrower than the electron density profile for the high ionization states. The behavior of the streaming plasma is even more evident in the emissions from deuterium at 1216 Å. Figure 11(a) shows the chord brightness of L_{α} at 9 ms in the discharge; note the large peaks which correspond to the position of the stream-gun plasma. At 10 ms, the stream guns are turned off, and the profile at 16 ms [Fig. 11(b)] is quite smooth. The time history of the radial brightness profile is summarized in Fig. 12; here the influence of the emission at the edge due to the stream guns is seen dramatically.

3.3.1 Comparison with 2XIIB

It is also important to compare the impurity density in a TMX plug with the results from 2XIIB. In both cases, the principal impurity in most circumstances was oxygen. The density of oxygen in 2XIIB was estimated to be approximately 4% (factor of 2 uncertainty).¹² A similar analysis indicates that the density of oxygen in a TMX plug is approximately 0.5%, an order of magnitude less. However, the typical beam currents used in TMX were less than those in 2XIIB, and the source of oxygen has been shown to be the neutral beams. Furthermore, it has been shown in 2XIIB¹² that the OII brightness (and hence the OII density) scaled with the beam current; the scaling of the other ionization states with beam current was not measured. In comparing the oxygen density in the TMX plug with 2XIIB, we have assumed a linear dependence on the beam current.

Table 5 shows the absolute brightnesses for 2XIIB and TMX cases with $T_e \sim 60$ eV and with the stream guns on (the stream guns were on during the whole plasma shot in 2XIIB). The beam current in the 2XIIB case was 405 A, with 125 A for the TMX case. The electron density profiles (but not absolute magnitudes) were similar. When the values for each ionization state in the TMX case are scaled, the results agree to within a factor of 2. (Note this is a qualitative comparison.)

3.4 GENERAL CHARACTERISTICS - TMX CENTRAL CELL

The main focus of the impurity study in TMX was to determine the general characteristics of the impurity emission in the central cell. As discussed

FIG. 11. (a) Radial brightness profile of L_{α} -1216 Å at 9 ms. Note the large peaks corresponding to the stream gun plasma. (b) Radial brightness profile at 20 ms.

FIG. 12. Three dimensional graph of $L-1216 \text{ \AA}$ versus radius and time. Note the influence of the stream guns.

TABLE 5. Oxygen densities. 2XIIB compared to TMX east plug by scaling neutral beam current (I_b).

Species	Brightness ^a		Fractional Densities, % ^{b,c}		
	2XIIB ($\times 10^{16}$)	TMX ($\times 10^{14}$)	2XIIB	TMX	TMX $\times \left(\frac{I_b(2XIIB)}{I_b(TM\!X)} \right)$
OIII	1.6	2	0.06	0.04	0.13
OIV	19	20	0.50	0.24	0.78
OV	56	10	0.88	0.08	0.26
OVI	43	7	<u>0.88</u>	<u>0.07</u>	<u>0.23</u>
TOTALS			2.3	0.4	1.4

Note: TMX scaled and 2XIIB show factor of 2 agreement.

^a Units of photons - $s^{-1} cm^{-2} sr^{-1}$

$$b \left(\frac{4\pi}{\langle \sigma v \rangle_{ex} n_e} \right) \frac{B}{\int n_e dl}$$

^c Densities of observed transitions. Contributions from metastable levels are not included.

Machine Parameters

	2XIIB	TMX
I_b , A	405	125
$\int n_e dl$, cm^{-2}	8.5×10^{14}	1.4×10^{14}
T_e , eV	60	60
Stream guns	on	on

above, some preliminary measurements were obtained with a single chord calibrated monochromator, but the majority of the measurements were obtained with the 22-channel SIDS instrument.

3.4.1 Typical time histories

Figure 13 shows the typical time histories of OII-539 Å, OIII-703 Å, OIV-554 Å, OV-630 Å, and OVI-1032 Å for both the central cell plasma and the east plug. For the central-cell data the sum of the signals for 22 chords near the center of the plasma are shown; a detailed analysis shows that the time history of each chord is similar. The east plug data is indicative of the center of the plasma; it does not show the initial feature (5 to 10 ms) (as was present in Fig. 9), as the chords which include the stream guns were not included in the sum.

The most obvious difference in the time histories is the initial rise. While the plug signals rise quickly because of the interaction of the plasma injected by the stream guns with the neutral beams, the central cell signals show a delay which is indicative of the onset of plasma buildup in the central cell. In both cases, the signal is quite constant after the initial rise, showing that the impurity emission is well behaved in the steady-state plasma.

3.4.2 Radial profiles

The radial profiles of three ionization states of oxygen - OII (539 Å), OIV (554 Å), OV (630 Å) and OVI (1032 Å) at 16 ms are shown in Fig. 14. This data was obtained during typical running when the plasma was fueled with the gas box. The most obvious trend in the data is that the spatial profiles become more peaked with increasing ionization state. These profiles are quite constant in time; that is, in cases where the total emission increases, the profile shape is fairly constant.

The fact that the brightness profiles are quite broad for OII, rather than a strong shell structure, is either a signature of the source of the oxygen, or an indication of transport effects on the impurities. The exact mechanism is currently undergoing analysis by comparing the data with the results from computer modeling.

FIG. 13. A comparison of the time histories of oxygen emissions in the central cell and the east plug.

FIG. 14. Spatial profiles of OII, OIV, OV, and OVI at 16 ms.

The spatial profiles during puffer operation were qualitatively different from those obtained during gas box operation. Figure 15 compares the radial brightness profile of OII-539 Å during puffer (top) and gas box (bottom) operation. Note that the puffer brightness profile is quite broad; the volume emission rate computed from a matrix inversion is a radial shell at the edge. The inverted brightness profile in the gas box case is peaked on axis (the inversion process is discussed more fully in the next section). The difference in these profiles indicated a qualitatively different impurity source or source-plasma interaction.

3.4.3 Radial profiles - Inversions

The radial profiles of impurity ions are important for impurity density, power loss, and transport calculations. To more fully understand the usefulness of this data, a short digression on photometric measurements is necessary. The actual quantity measured by the spectroscopic instrument is a chord-average brightness. The brightness is simply the flux received per unit solid angle per unit projected area, with units of photons $\text{cm}^{-2} \text{sec}^{-1} \text{sr}^{-1}$. In the simplest case, the conversion of counting rate to absolute brightness $B(y)$ is given by:

$$B(y) = \frac{(CR) D_p^2}{(QT) A_s A_p},$$

where

(CR) is the observed counting rate,

(QT) is the efficiency of the instrument,

A_s is the area of the entrance slit,

A_p is the area of the plasma that is viewed, and

D_p is the distance from the plasma to the entrance slit.

Without modeling of the spatial distribution of the emission source, the brightness profiles are useful only for qualitative comparisons. The quantity required for impurity density and radiated power calculations is the spatial distribution of each ionization state. In the cylindrically symmetric case, the data can be "inverted" to yield the volume emission rate. Mathematically,

FIG. 15. (a) OII radial brightness profile at 16 ms - puffer operation. (b) OII radial brightness profile at 16 ms - gas box operations.

$$B(y) = \frac{1}{4\pi} \int E(r) dl = \frac{1}{2\pi} \int_0^{r_0} \frac{E(r) r dr}{(r^2 - y^2)^{1/2}},$$

where $E(r)$ is integrated along the line of sight, y is the chord height, and r_0 is the plasma radius. Assuming cylindrical symmetry, the common technique used to obtain $E(r)$ is the Abel transform.²³ We have used a matrix technique which is equivalent to the Abel inversion, but is much faster. As shown in Fig. 16, the plasma is divided into shells; each data point is centered on a shell. The outer-most shell has no contribution from other shells, so

$$E_4 = \frac{4\pi B_4}{L_{44}}.$$

The next chord sees contributions from two shells; by subtracting the contribution from the outer shell, E_3 can be obtained. This subtractive technique can be formulated in matrix terms:

$$\underline{B} = \underline{L} \underline{E},$$

where $\underline{L}$ is the "length" matrix containing the length of the various chords. Then

$$\underline{L}^{-1} \underline{B} = \underline{E}.$$

Because $(\underline{L}^{-1})$ is constant as long as the radial chord positions are constant, the inversion process is a simple matrix multiplication. This is especially useful when several inversions (e.g., brightness profiles vs. time) all having a common geometry are required.

3.5 IMPURITY DENSITY DETERMINATION

Once the volume emission rate profiles are measured, the ion density can be obtained. We use the coronal model to describe the excitation and subsequent emission process. This model assumes that collisional excitation is the most prominent mechanism; photo-excitation is negligible (i.e., the plasma is optically thin). Second, the spontaneous emission rates are much faster than collisional de-excitation rates. Finally, ionization and recombination times

FIG. 16. The matrix inversion technique.

are much longer than the characteristic decay times. Hence, the volume emission rate E for a given transition is given by

$$E = n_e n_i \langle \sigma V \rangle_{ex} ,$$

where

n_e = electron density,

n_i = ion density, and

$\langle \sigma V \rangle_{ex}$ = rate coefficient for excitation.

In the central cell plasma, electron impact excitation is the most prominent mechanism; $\langle \sigma V \rangle_{ex}$ is the cross section averaged over a Maxwellian electron energy distribution. A convenient expression is given by Davis (Ref. 24) for optically allowed transitions:

$$\langle \sigma V \rangle_{ex} = \frac{1.6 \times 10^{-5} f_{ik} \langle \bar{g} \rangle}{\Delta E (KT)^{1/2}} e^{-\Delta E/KT} ,$$

where

- f_{ik} = absorption oscillator strength,
 ΔE = transition energy (eV),
 KT = electron temperature (eV), and
 $\bar{g}$ = average Gaunt factor.

The Gaunt factor is a semi-empirically determined quantity which is very close to one for resonance transitions. For most resonance transitions, the rate coefficient is fairly insensitive to temperature in the region of interest.

3.5.1 Measurements of metastable populations

The determination of the total impurity density requires measuring the density of each ionization state. In the case of ions with no metastable levels, such as OVI, the volume emission rate is related directly to the density of the ground state. In B-like and Be-like atoms which have metastable levels, the situation is more complicated, as the metastable level can be populated by direct ionization from the next lower state or by collisional excitation from the ground state. An example of an ionization state with a metastable level is OV, as shown in Fig. 17. The ratio of the volume emission rate of the ground transition to the metastable transition is

$$\frac{E_{12}}{E_{34}} = \frac{E(^1S - ^1P^0)}{E(^3P^0 - ^3P)} = \frac{n_e n_1 R_{12} + n_e n_3 R_{32}}{n_e n_3 R_{34} + n_e n_1 R_{14}}$$

where each R is the rate for collisional excitation (Fig. 17). Solving for the metastable density ratio

$$\frac{n_1}{n_3} = \frac{n(^1S)}{n(^3P^0)} = \frac{E_{12} R_{34} - E_{34} R_{32}}{E_{34} R_{12} - E_{12} R_{14}}.$$

For most cases, it is found that $E_{12} \cong E_{34}$, and as shown by (Ref. 25), $R_{32} \ll R_{34}$ and $R_{14} \ll R_{12}$, hence

$$\frac{n_g}{n_m} = \frac{n_1}{n_3} = \frac{E_{12} R_{34}}{E_{34} R_{12}}.$$

FIG. 17. Example of metastable levels - OV.

Then

$$N_{\text{total}} = n_g + n_m = \frac{E_{12}}{R_{12} n_e} + \frac{E_{34}}{R_{34} B_e} ;$$

hence both E_{12} and E_{34} are required to obtain the density of the ionization state. This is true for all states which have metastable levels. In many cases, the ratio of the ground to metastable densities can be estimated. In the Alcator A Tokamak, the n_m/n_g ratio for OV was measured to be 2.6;²⁶ a similar result was found on 2KIIb.¹² However, on the TMX central cell, the ratio was found to vary, hence it was important to measure the metastable ratio for each set of conditions.

The variation of the metastable ratio is easily explained when it is noted that the electron density in the central-cell of TMX is much lower than

either 2X11B or Alcator. As predicted by McWhirter,²⁷ this ratio should depend nearly linearly on the electron density in the range from 10^{11} to 10^{13} cm^{-3} ; with a plateau (i.e., constant value) above approximately $1 \cdot 10^{13}$ cm^{-3} . This theoretical treatment is consistent with the TMX results, which show a density dependence, and the 2X11B and Alcator results, which are in the density-independent regime.

3.5.2 Emission model

It is useful to characterize the impurity emission and therefore its density with a model. This facilitates comparison with other data, and in many cases greatly simplifies calculations. In particular, these simple models for the ion density were tried:

1. Constant Density Model $n_i(r)$ is a constant. Since

$$B = \frac{1}{4\pi} \int n_e(r) n_i(r) dV_{ex} ,$$

the brightness profile and volume emission profile are proportional to n_e , as long as the T_e profile is sufficiently broad so that $dV_{ex} = \text{constant}$.

2. Constant Concentration Model $n_i(r)/n_e(r)$ is a constant, so the shape of $n_i(r)$ is similar to that of $n_e(r)$. Hence, the brightness profile is proportional to the density squared; for a Gaussian profile, the width of the brightness profile is less by a factor of $\sqrt{2}$.

3. Shell Model - When the ionization states exist in narrow shells, the brightness is given by:

$$B = \frac{1}{4\pi} n_e n_i 2\pi W ,$$

where W is the width of the emission shell and n_e and n_i are assumed roughly constant over the width of the shell.

Figure 18 shows the radial brightness profile of OV - 630 Å and the volume emission profile obtained from it by matrix inversion. In addition, the chord average ($\langle n_e \rangle$) profile obtained by neutral beam attenuation is included. The $\langle n_e \rangle$ profile is well-fitted by a Gaussian profile, so the n_e profile will have a similar shape (as the inversion of a Gaussian profile yields a Gaussian). The fact that the brightness and volume emission rate profiles are so similar suggests that this data is also well characterized by

FIG. 18. Spatial profile of brightness and volume emission rate for OV-630 Å. The best fit of $\int n_e dl$ is also known.

a Gaussian profile; furthermore $B(r) \propto E(r) \propto n_e(r)$ which implies that a constant density model is the appropriate choice for this data. A similar result was obtained for OIV; these two ionization states were examined most carefully as they contain the major fraction of oxygen density in the TMX central cell.

3.5.3 Impurity density results

Using the constant density model; the ion density is simply

$$n_i = \frac{4\pi B}{\int n_e dl \langle \sigma v \rangle_{ex}},$$

where B is the central chord brightness. Table 6 presents the density of the oxygen states obtained during a single run on November 1, 1979, during gas box operation. The OV metastable to ground density ratio was measured to be 0.7 in these conditions; the other metastable ratios were assumed to be similar to the 2XIIIB case. Note that most of the oxygen density is in OIV and OV, with a smaller amount in OVI.

Similar calculations were carried out for carbon and nitrogen, and the results are summarized as follows (factor of 2 uncertainty):

Oxygen	0.3%
Carbon	0.05%
Nitrogen	0.2%

The concentration is defined to be $n_i/\bar{n}_e$ where $\bar{n}_e = \int_0^{r_p} n_e(r) r dl$. For a Gaussian profile, $\bar{n}_e = 0.632 \hat{n}_e$ ($\hat{n}_e$ = peak density). It should be noted that this emphasizes the section $r < r_p$; this was chosen because the impurity and electron density behavior is less well known outside of this region. However, if one defines the concentration to be n_i (total)/ n_e (total), the result is only 40% greater. Comparisons with data from other runs indicate that these results, to within a factor of two, are typical densities of the light impurities. In some cases, the relative populations of the ionization states changed (which would be expected if the electron temperature changed), but the overall density remained fairly constant.

TABLE 6. Central-cell oxygen densities.^a

Shot	Species	%
37	OII	0.006
26	OIII	0.03
20	OIV	0.10
13	OV	0.13
40	OVI	0.05
	TOTAL	0.3

^a11/01/79

3.6 RADIATED POWER

3.6.1 Radiated power from light impurities and D₂

As discussed above, it is also important to determine the amount of radiated power caused by line radiation from the impurities present in the plasma. One approach would be to measure every spectral emission feature and its radial profile; the sum of these measurements would be the total radiated power. This is impractical with a monochromator as shot-by-shot spectral scans would be required over a large spectral range. However, certain simplifying assumptions can be made so that measurement of the radial profiles of the resonance and metastable transitions is sufficient. These assumptions are justifiable from a knowledge of the atomic physics of the ionization states. Namely:

1. The principal excitation mechanism is electron impact excitation.
2. Only ground and low-level metastable levels are populated significantly.
3. $\Delta n = 0$ (n = principal quantum number) are the most significant transitions, followed by $\Delta n = 1$.
4. For $\Delta n = 0$ transitions, the effective Gaunt factor $\langle \bar{g} \rangle$ in the excitation rate coefficient is nearly 1; for $\Delta n = 1$ transitions it is less. We will assume $\langle \bar{g} \rangle = 1$ for $\Delta n = 0$ and $\langle \bar{g} \rangle = 0.5$ for $\Delta n = 1$. This is based on results by Davis.²³

With these assumptions, by measuring the resonance transition and the metastable transition of a certain ionization state, the radiated power from all of the transitions can be calculated. Specifically, the volume emission rate is proportional to $\langle \sigma V \rangle_{\text{ex}}$, so the radiated power is given by

$$P_o = \frac{A \langle \sigma V \rangle_{\text{ex } o}}{\lambda_o},$$

where o denotes the measured resonance or metastable transition and A is the proportionally constant; then for another transition

$$P_j = \frac{A \langle \sigma V \rangle_{\text{ex } j}}{\lambda_j}.$$

And finally, expressing the power in the j^{th} transition in terms of o equals

$$P_j = \left(\frac{P_j}{P_o} \right) P_o$$

$$= \frac{\lambda_o \langle \sigma V \rangle_{\text{ex } j}}{\lambda_j \langle \sigma V \rangle_{\text{ex } o}} P_o.$$

To complete the total radiated power, P_j must be summed over all of the relevant resonance and metastable transitions. In turn, to compute the total power from one species, all of the power in each ionization state must be added up.

The results of the impurity radiated power calculation are summarized in Table 7; the impurity densities are also included. In the case of oxygen, the majority of the power comes from OIV and OV; recall these ionization states also contain most of the density. The power loss from deuterium radiation was estimated in a similar fashion.

3.6.2 Radiated power - titanium

The estimation of radiated power from titanium radiation is more difficult, as the atomic physics coefficients are not well known for these ions. A crude estimate was performed by cross-calibrating the survey instrument with the calibrated single channel instrument in the central cell. Specifically, a photographic spectrum was obtained which included the major oxygen emissions

TABLE 7. Impurities in TMX central cell.

Species	Density, % (factor of 2)	Radiated power, ^a kW (factor of 2)
O	0.3	4
N	0.2	4
C	0.05	1.5
Ti	(b)	6 ^c
D-L _α	—	5

Plug oxygen densities, %

TMX	TMX scaled ^d	2XIIB
0.25	1.5	3

^a Typical trapped beam power = 450 kW

^b Not obtainable from data

^c Estimated

^d Linear scaling was assumed

and several titanium lines on the same plate. During the discharges, the absolutely-calibrated monochromator measured the oxygen emissions. By adding up all of the titanium emissions (nearly 300), an estimate of the radiated power from titanium relative to oxygen was obtained. The results are also included in Table 7.

It should be noted that this was only a crude estimate (factor of 3 to 4 uncertainty); the measurement assumes that most of the important emissions were measured, and that the radial profiles are not substantially different when compared to other impurity species. Transfer of the absolute calibration from the monochromator to the film and shot-to-shot variations in the emissions are probably the largest sources of error.

4. EXPERIMENTAL TRENDS - WALL CONDITIONS

It is a well known fact that the wall conditions in a plasma device can significantly influence the plasma conditions. Normally, a low temperature plasma (discharge cleaning²⁸) and/or titanium gettering is used for wall preparation. In addition, it has been shown by the Alcator group²⁹ that the wall temperature can influence the light impurity density both during discharge cleaning and the plasma discharge. This section discusses the results of two experiments on TMX which examined the effect of wall conditions on the plasma.

4.1 GETTERING

The first experiment was to measure the effect of titanium gettering on the oxygen density in the central cell plasma. On September 25, 1980, a specific set of wall conditions existed in the central cell because of previous experiments: the whole machine had been gettered except for a section between the limiters in the central cell (to protect the ICRH antenna). On shots 4 to 15, the machine was run in the same configuration and emissions from oxygen and carbon were monitored. The machine (except for the section noted) was gettered on every shot. On shots 16 to 25, the entire gettering system was used (including the east section of the central cell) and these emissions were again monitored. The results are shown in Table 8; $B/n_{e,d1}$, which is proportional to the impurity density, is used for comparison. The discharges shown were similar; the electron density decreased approximately 30% after the new panel was gettered. The results show that gettering does affect the central-cell impurity density, as expected.

Secondly, it was noted during the initial phases of several runs. To prolong the lifetime of the gettering system, it is sometimes used only on alternate shots. During this time, OII - 539 Å emission was monitored and changes in the brightness were observed to correlate with the gettering. That is, $B/n_{e,d1}$ was approximately 40% greater on nongettered shots than on those with gettering. This sequence usually persisted until shot 15 to 20 of the run (often, a switch to gettering before each shot was made when this mode was detected); after this time, the emission dropped to a plateau and was quite constant even if gettering was performed on alternate shots. This result suggests that the central cell wall conditions influence the impurity density in this region.

TABLE 8. Impurity brightness before and after localized central-cell gettering.

Shot	Species	Wavelength,		Brightness	Getter		Decrease ^a
		Å			Before	After	
4	OII	539		3.3×10^{13}	x		
8				2.7×10^{13}	x		
9				2.5×10^{13}	x		
11				2.5×10^{13}	x		
12				3×10^{13}	x		
16	OII	539		1×10^{13}		x	0.66
5	OIII	703		1×10^{13}	x		
17				4×10^{12}		x	0.66
6	CII	904		1×10^{13}	x		
19				8×10^{12}		x	0.2
7	CIII	977		3.2×10^{14}	x		
20				8×10^{13}		x	0.75

^a
$$\frac{\text{Brightness}_{\text{getter}} - \text{Brightness}_{\text{nogetter}}}{\text{Brightness}_{\text{getter}}}$$

4.2 LINER EXPERIMENTS

As discussed in (Ref. 30), liners filled with liquid nitrogen are used in TMX for additional vacuum pumping. These liners are used in the ends of the central cell (outside of the plasma radius) and in both plugs. Emissions from light impurities were monitored before and after the liners were filled to determine their affect on the impurity density. Decreases in the measured brightness in the central cell were observed after the liners were filled in some cases; however in other cases, no change was seen. (In all cases the ambient pressure was decreased at least a factor of 5.) However, the brightness measured in the plug was normally unchanged by liner operation. This result is consistent with a wall-source of impurities in the central cell and primarily beam-induced oxygen in the plugs.

5. SUMMARY OF OTHER IMPURITY EXPERIMENTS

5.1 CENTRAL CELL HEATING EXPERIMENT

For a short period, TMX was operated with three neutral-beam injectors mounted on the central cell at approximately $Z = 0$. The single-channel Monochromator was also mounted on the central cell, but at approximately $Z = 40$ cm; hence it did not view the beams directly. The central-cell injectors were turned on at 14 ms and off at 20 ms for the data presented here.

The central-cell brightness divided by the line integrated density versus time for OIV - 554 Å, OV - 630 Å, and OVI - 1032 Å are shown in Fig. 19. The central cell injected beam current was 60 A, while the east and west were 55 and 35 A, respectively. Note the dramatic increase in OIV, which is accompanied by a rapid increase in OV and a slower increase in OVI. After 2 to 3 ms, the OIV signal decreases, while the OV decreases slightly and the OVI continues to increase.

We interpret these results to be an indication that the electron temperature in the central cell is increasing when the central cell beams are turned on. In addition, the oxygen density increases, as the OIII and OIV brightness are approximately the same before and after the beams are on. That is, if the only the electron temperature were increasing, a shift to the higher ionization states with a corresponding decrease in the lowest states would be

FIG. 19. Impurity behavior during the central cell beam heating experiment.

expected. Because the spectrometer is well separated from the injectors, the increase is interpreted as an indication of the bulk electron behavior, as opposed to a local effect present only near the beam. It should also be noted that this dramatic behavior was observed only when the plug and central cell beam currents were of the same order. For example, with $I_p \geq 100$ A per plug and $I_c = 60$ A, the dramatic increases were not seen.

5.2 IMPURITY INJECTION EXPERIMENTS

A series of impurity injection experiments was performed on TMX to study three main issues: (1) impurity confinement, (2) impurity sources and penetration, and (3) radial transport in the central cell. These experiments involved puffing gas into the central cell and the measurement of the emissions from this impurity as a function of time. Paragraph 5.2.1 will describe the experimental configuration and the procedure used; in paragraph 5.2.2 the data and a initial qualitative analysis are presented.

5.2.1 Experimental Procedure

Deuterium, oxygen, and neon were introduced into the central cell by means of a fast pulsed valve which was located at $Z = 0$. Two different valve timing sequences were used. In the first case, the valve was opened for 5 ms starting 1 ms before the shot sequence (i.e. -1 ms to +4 ms). In this way, the impurity was distributed before the plasma was initiated, minimizing gas penetration effects in the initial phases of the plasma. In the second case, the valve was turned on at 12 ms and off at 17 ms, which introduces the impurity during steady-state plasma conditions. This should allow a determination of the impurity penetration rates and a measure of radial transport in the central cell.

Neon was initially chosen for injection because it is not an intrinsic impurity in TMX. Oxygen was used because it is much more readily pumped by the cold liner surfaces and gettered walls than neon; this provides a different source and presumably different edge plasma conditions. Finally, deuterium was injected because it is the plasma working gas. (In passing, it should be noted that neutral oxygen and deuterium are also similar in that their ionization potentials are equal.) When oxygen and deuterium were injected, the contribution due to the intrinsic levels of these species was subtracted.

The 22-channel monochromator (SIDS) mounted on the central cell was the main diagnostic used during the impurity injection experiments. Time-resolved radial profiles of several ionization states of neon, oxygen, and deuterium were monitored; a list of the observed transitions is shown in Table 9. In addition, the monochromators on the plugs were also used to measure the amount of the impurity which penetrated into the plugs from the central cell.

TABLE 9. Lines observed during impurity injection experiments.

Gas	Species	λ , Å	Ionization Potential, eV
Deuterium	D	1216	13.6
Oxygen	OII	539	35.1
	OIII	705	54.9
	OIV	554	77.4
	OV	630	113.9
	OVI	1032	138.1
Neon	Ne II	460	41.0
	Ne III	490	63.5
	Ne IV	542	97.1
	Ne V	481	126.2
	Ne VI	433	157.9

5.2.2 Experimental Results and Discussion

When neon was puffed into the central cell before the shot, the emission from the ionization states of neon remained roughly constant throughout the entire discharge. Oxygen injection increased the brightness by a factor of approximately 5 over the intrinsic level; again a constant time evolution was noted. Because recycling most certainly influences these results, it is difficult to ascertain estimates of impurity confinement times until a more detailed analysis is completed.

Neon and oxygen puffing from 12 to 17 μ s during the discharge yielded time histories as shown in Fig. 20. The radial brightness profiles versus time are shown in Fig. 21. Note that the brightness of each ionization state

FIG. 20. The time evolution of emissions during neon puffing.

FIG. 21. Radial profiles versus time for oxygen and neon puffing.

starts to increase at essentially the same time and continues to rise until the end of the shot. In the case of neon, the brightness of each ionization state increases in a region near the plasma axis rather than first appearing at the plasma edge. This suggests that the neon penetrates the plasma much more deeply than the oxygen before being ionized.

Another general observation was that the emission in the plug was influenced very little by the injected species. This supports the theory that the central cell ions are confined axially by the electrostatic potential between the plugs and the central cell and that the ions do not penetrate into the plug.

Finally, these results are currently undergoing comparisons with a simple computer model. Further analysis should yield information on the confinement times and recycling rates of impurities in TMX.

6. DISCUSSION OF CONCLUSIONS

The results presented here are the first comprehensive impurity study of a tandem mirror machine. The impurity measurements in the TMX plug show that the general features are similar to that of 2XIIB. Namely:

- (a) Oxygen is injected by the neutral beams,
- (b) the ~0.3% oxygen density measured on TMX when scaled to 2XIIB parameters is in qualitative agreement with the oxygen density measured on 2XIIB, and
- (c) the emission from the ions is significantly doppler broadened indicating an effective energy near 10 keV.

The major focus of this study was impurity behavior in the central-cell plasma. Time resolved radial emission profiles were used to calculate the density of light impurities (factor of 2 uncertainty): 0.3% oxygen, 0.2% nitrogen, and 0.05% carbon. The total radiated power from the impurities was estimated to be 20 to 30 kW, which is approximately 10% of the input power. In general, the central-cell impurity concentration was found to be influenced significantly by vacuum vessel conditions such as, gettering, and in some cases, use of cold liners.

Finally, oxygen and neon gases were introduced into the plasma to study the details of impurity behavior. While the analyses of these results are incomplete, the spatial profiles of the emission as a function of time were qualitatively different for each gas.

REFERENCES

1. E. Hinnov, Princeton Plasma Physics Laboratory Report MATT-194, Princeton, NJ (1962).
2. N. Bretz, et al., Nucl. Fusion 15, 313 (1975).
3. K. Bol, et al., in Proc. Intl. Conf. Plasma Phys. and Controlled Fusion Res., 5th, Tokyo, 1975, 1, 83 (1975).
4. TFR Group, "Space- and Time-Resolved Study of Impurities in TFR Tokamak Plasmas," Phys. Rev. Lett. 36, 1306 (1976).
5. D. Grove, et al., in Proc. Intl. Conf. Plasma Phys. and Controlled Res., 6th, Bertchesgaden, 1977, 1, 21.
6. J. L. Terry, et al., Nucl. Fusion 18, 485 (1978).
7. E. Hinnov, et al., Bull. Am. Phys. Soc. 22, 2F3 (1977).
8. T. C. Simonen, F. H. Coensgen, W. F. Cummins, and W. E. Nexsen, Nucl. Fusion 15, 813 (1975).
9. E. P. Drake and H. W. Moos, Nucl. Fusion 19, 407 (1979).
10. F. H. Coensgen, et al., Phys. Rev. Lett. 35, 1501 (1975).
11. R. P. Drake and H. W. Moos, Nucl. Fusion 20, 599 (1980).
12. R. P. Drake, Lawrence Livermore National Laboratory Report UCRL-52751 (1980).
13. F. H. Coensgen, et al., TMX Major Project Proposal, Lawrence Livermore National Laboratory, LLNL-Prop.-148.
14. F. H. Coensgen, et al., Phys. Rev. Lett. 44, 1132 (1980).
15. G. Mount, et al., Applied Optics 16, 591 (1977).
16. J. L. Terry, et al., Nucl. Fusion 18, 485 (1978).
17. K. I. Chen, et al., Applied Optics 16, 591 (1977).
18. H. W. Moos, K. I. Chen, J. L. Terry, and W. G. Fastie, Applied Optics, 18, 1209 (1979).
19. R. K. Richards, H. W. Moos, and S. L. Allen, Rev. Sci. Instrum. 51, 1 (1980).
20. S. L. Allen, Ph.D. thesis, Johns Hopkins University, Baltimore, MD (1980).
21. D. E. Baldwin, B. G. Logan, and T. C. Simonen, eds., Lawrence Livermore National Laboratory Report UCID-18496, pt. 1 (1980).

22. S. L. Allen, et al., D. L. Correll and R. P. Drake, eds., "Results of TMX Operations: January - July 1980," Lawrence Livermore National Laboratory Report UCID-18803 (1980).
23. H. R. Griem, Plasma Spectroscopy, McGraw-Hill, New York (1964), p. 176.
24. J. Davis, J. Quant. Spectrosc. Radiat. Transfer 14, 549 (1974).
25. W. D. Johnston and H. J. Kunze, Phys. Rev. A 4, 962 (1971).
26. J. L. Terry, K. I. Chen, H. W. Moos, and E. S. Marmor, Technical Report COO-2711-3 (1977).
27. R. W. P. McWhirter, The Spectroscopy of Laboratory and Astronomical Plasmas, Appleton Laboratory, Abingdon, UK, circa (1972-1980).
28. R. J. Taylor, J. Nucl. Mat. 76 & 77, 41 (1978).
29. E. S. Marmor, et al., Nucl. Fusion 1, 485 (1979).
30. J. Jolly, J. Parkinson, and D. Swan, Lawrence Livermore National Laboratory Report UCRL-82886 (1979).

WS/jbs
2301c