RESULTS OF TMX OPERATIONS: JANUARY - JULY 1980

MASTER

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PREFACE

This report describes results from the TMX experiment during the period January through July 1980. TMX will shutdown for modifications to TMX Upgrade at the beginning of October 1980. Subsequently, a final report summarizing TMX results will be written as well as several individual journal papers. This interim report aided in the planning of the final TMX experiments. To help others in the division prepare for the San Diego APS meeting, this report is being issued without polished artwork as well as without the customary group review and criticism. Instead, we expect this report will stimulate the work and discussions that are needed to put together the more complete and consistent final report.

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ABSTRACT

This interim report summarizes results from the Tandem Mirror Experiment (TMX) during the period January to July 1980 and describes the physics experiments, the machine operation, and the diagnostics that were added to TMX during this period. This operating period followed the initial proof-of-principle TMX experiments and predated the ongoing final experiments preceding TMX shutdown for modification to TMX Upgrade. The results described in this report include measurements of plasma parameters and plasma behavior which confirm the initial TMX results that demonstrated that the tandem mirror configuration can be generated and sustained by neutral beam injection and that the tandem mirror configuration improves confinement of magnetic mirror systems.

1. INTRODUCTION

(D. L. Correll and R. P. Drake)

This document describes the results obtained from operation of the Tandem Mirror Experiment (TMX) at LLNL during January through July 1980. During this period our experimental goals have reflected an improved understanding of plasma stability, the need to test the physics concepts introduced by MFTF-B, and difficulties with the operation of the TMX facility. Our results are summarized in this introduction.

The tandem mirror concept was demonstrated by the initial operation of TMX (July to December 1979). During that series of proof-of-principle experiments, we produced and measured tandem-mirror density and potential profiles, we demonstrated electrostatic end-plugging, and we achieved better electron-energy confinement than by previous, single-plug, mirror machines.¹⁻³ We have also reported that plasma fluctuations at the ion-cyclotron frequency of the end plugs degraded the central-cell-ion confinement,⁴ and described TMX results, beginning in late 1979 and extending through July 1980, that had not been previously reported.

During early 1980, we showed quantitatively that the central-cell-ion lifetime is limited by the need of the end-cell plasma for central-cell losses to stabilize loss-cone instabilities.⁴ We determined that TMX operated essentially as expected on the basis of microstability. We began a series of plug-optimization experiments aimed at substantially reducing the level of fluctuations in the end cell. We hoped these experiments would extend the range over which the central-cell confinement is determined by Coulomb scattering processes. Additional stabilizing plasma from outside gas boxes was able to sustain the end-cell plasmas without any central-cell gas feed but was not able to reduce the plasma fluctuations (with or without central-cell gas feed). The total level of plasma fluctuations was not suppressed by injecting 0.2 to 2.0 MW of e-beam power, although a 50% increase of the electron temperature of a single plug was achieved (90 eV to 140 eV). We reduced the end losses through one end plug by a factor of two by using 40-kV beams (compared to the normal 20-kV beams) on that end plug. Additional plug-optimization experiments included the variation of magnetic mirror ratios and the use of different end-cell and central-cell ion masses to break the ion-cyclotron resonance.

New physics concepts incorporated in MFTF-B have also influenced the course of TMX experiments. Sloshing-ion distributions should lead to microstable end plugs, and thermal barriers will improve tandem-mirror performance. After considerable analysis and some experimentation, we saw that a new magnet set would be required to test these concepts in TMX. The TMX Upgrade is the result of this understanding and of the strong recommendation by the MFTF-B Mirror Senior Review Panel that experimental tests of these concepts be given high priority. We have scheduled some experiments for the TMX Upgrade which were originally scheduled for TMX, such as ECRH of the end-cell electrons.

Continuing experiments on TMX are exploring physics issues which are fundamental to tandem mirrors. In particular, we are studying cross-field transport, power and particle balance, and impurity confinement. We have also begun ICRF heating experiments in the central cell of TMX. These experiments have required the construction and installation of new diagnostics and hardware, as well as a substantial expansion of our data-handling capability and computer processing.

Finally, during recent months we have encountered several difficulties in the operation of TMX. An extended shutdown was required during February and March to install the cooling-water system for MFTF. TMX twice experienced voltage breakdowns in the leads of the baseball magnets; each accident caused a couple weeks of down time. The lower electron temperatures produced by TMX during 1980 ($T_e \lesssim 120$ eV) compared to 1979 ($T_e \gtrsim 120$ eV) have led to investigations of the magnet system and the vacuum system. The magnet alignment has been verified to be adequate, but a subtle, pulsed leak was discovered in one magnet. Control problems in the getter system have been identified, and small leaks in the LN_2 liners were identified.

This document presents our current understanding of the recent results from TMX. Most of the material is preliminary and will be discussed further in later reports. The next section describes the physics results. Section III describes the physics operation of the TMX facility. Finally, our new diagnostics and some diagnostic results are presented in Section IV.

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II. PHYSICS RESULTS

II.A THE SCALING OF TMX CONFINEMENT

(R. P. Drake)

The end-cell plasmas in TMX must be stabilized by losses from the central cell to saturate the drift-cyclotron-loss-cone instability. The required central-cell loss current for TMX at the end-cell midplane (in A/cm⁻² per end) is^{1,2}

$$j_s = \frac{3.8 \times 10^{-12} n_p \phi_{pm}^{3/2}}{E_p (R_p - 1) M_i^{1/2}} \left(\frac{r_p}{a_i} \right)^{-4/3} \quad (1)$$

In this expression, n_p (cm⁻³) is the density of the end-cell plasma; ϕ_{pm} (keV) is the potential drop from the midplane to the outer magnetic mirror of the end cell; E_p (keV), R_p , and M_i (AMU) are the ion energy, mirror ratio, and ion mass in the end cell; and r_p/a_i is the ratio of end-cell plasma radius to ion gyroradius. The function of this loss current is to provide the warm, unconfined plasma required at the end-cell midplane for stability.

The above loss current determines a maximum stable confinement for the central cell. This is

$$(n\tau)_{cmax} = \frac{q n_c^2 L_c}{2 j_s} \left(\frac{R_c}{R_p} \right), \quad (2)$$

in which n_c , L_c , and R_c are the density (cm⁻³), length (314 cm), and mirror ratio (20) of the central cell. If the neutral beam trapping in the end-cell supplies stabilizing current, the required central-cell losses decrease and $(n\tau)_{cmax}$ increases. This effect was not significant during 1979 but may be important for the low T_e operation of 1980.

When the central-cell confinement increases, the current density, j_c , flowing through the end plugs decreases. If j_c decreases below that required for the microstability, end-plug fluctuations increase. This effect is illustrated in Fig. II.A-1. In this experiment, we increased the neutral-beam current while maintaining a fixed, central-cell gas feed. According to theory, the stable limit on the end-plug-to-center-cell density ratio, n_p/n_c , was 3 for this experiment. As n_p/n_c increased from 3 to 7, the fluctuations at the ion-cyclotron frequency in the end cell (detected in the central cell) increased an order of magnitude.

At low fluctuation levels, the observed axial confinement was classical and significantly exceeded the confinement expected without electrostatic plugging. As the fluctuation level increased, central-cell axial confinement decreased, consistent with the theory of Matsuda and Rognlien³ which describes the effects of plasma fluctuations on central-cell confinement.

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Fig. II.A-1. Measurements of TMX central-cell confinement show two regimes. At low fluctuation levels, tandem-mirror confinement is Coulomb and well above that of an unplugged mirror. In TMX, when n_p/n_c exceeds 3, plug ion-cyclotron fluctuations increase and degrade central-cell confinement. To apply the theory to these data from 9/28/79, we assume E (V/cm on axis) $\approx 1.5 \bar{\phi}$ (V_{pp} at probe).

II.B RADIO FREQUENCY STUDIES

(T. A. Casper)

Electrostatic fluctuations have been observed by means of a high-impedance probe, in the east end cell of TMX. The probe has five identical tungsten tips, 1-mm-diameter, spaced 1 cm apart. The probe works by means of digital spectral estimation techniques to provide information concerning the oscillation frequency and wave number of floating potential fluctuations. It has also been used to monitor the envelope of rf activity and serve as a measure of plug stability. Using data from the rf scan 12/13/79 (considered to be good TMX operation, though no attempt was made to optimize performance), we observed the following spectral characteristics:

- $\omega_0 < \omega_{cio}$ where ω_0 is the observed peak of the power spectrum (Fig. II-B-1), and ω_{cio} is the cyclotron frequency evaluated at the plug minimum-vacuum magnetic field. Neither errors in the requested field nor β -depression can totally account for the observed frequency shift to $\omega_0 \approx 0.85 \omega_{cio}$ generally present.
- $k_{\perp}$ is small; $k_{\perp} \approx m/r$ gives $m \sim 3$ to 4.
- The direction of propagation as determined from the sign of phase-shifts across the array tends to be opposite the ion diamagnetic-drift direction.
- Some evidence exists for the simultaneous presence of two modes near ω_{cio} . The weaker mode shows up in the power spectrum at a slightly higher frequency than ω_0 given above. The presence of the strong mode prevents an accurate determination of $k_{\perp}$ for this mode by techniques presently used.
- Harmonics at $2\omega_0$ and $3\omega_0$ have been observed, generally at a reduced power level, with $3\omega_0$ approaching the resolution limits of existing equipment.

Given the nature of the spectral characteristics observed, it is difficult to resolve them as unstable DCLC fluctuations. For this reason, alternatives to the DCLC mode are also presently being considered.

Central-cell fluctuations have been observed by using a single (no $k_{\perp}$ resolution), high-impedance, disk probe located at $z = 50$ cm, $r = 40$ cm. The fluctuations exhibit the following spectral characteristics:

Fig. II.B-1. Cross power spectrum obtained by east-end-cell rf probe, $\Delta R = 3$ cm.

- $\omega_{acc} = \omega_{op}$; that is, the dominant central-cell mode has a frequency characteristic of oscillations near the plug ion cyclotron frequency (Fig. II.B-2).

- Some evidence exists for low frequency ($\omega < \omega_{cicc}$) fluctuations.

- In general, coherent oscillations at ω_{cicc} have not been observed.

Forward-angle scattering of microwaves using signals derived from the 2-mm interferometer system has generally verified the oscillation frequencies detected by the probes. Wave number measurements, however, are not provided by the present microwave system.

During low T_e operation, rf levels observed in the east end cell and central cell have varied widely. This is possible evidence of the importance associated with the quality of electron stream supplied by the central cell in stabilizing of the plugs. As data from 4/10/80 indicated, the rf level actually observed in a given end cell (the east here) is critically dependent upon the operation of TMX as a whole. It is possible for a single end cell to dominate the observed central-cell rf while, in theory, the other end cell is quiet. This is particularly true if there is inadequate balance between the end-cell plasmas. For this reason, investigations concerning the total stability of TMX, as indicated by rf levels, must include detailed measurements in all three regions. This has led to the addition of rf-probe arrays in the west end-cell and central-cell regions, which is discussed in subsection IV.L.

Fig. II.B-2. Power spectrum obtained by central-cell disk probe.

II.C POWER AND PARTICLE BALANCE

(D. P. Grubb, D. L. Correll, R. P. Drake, J. H. Foote, A. P. Futch, R. K. Goodman, E. B. Hooper, C. V. Karmendy, and W. E. Nexsen)

During the period December 1979 to July 1980, we have continued to improve our understanding of the power and particle balances in TMX. We have done so by improving our theoretical and computational skills¹⁻⁵ and by increasing our capability to measure the plasma parameters.

Theoretical Studies: Several of the computational studies we conducted were aimed at increasing our understanding of the atomic processes involved in gas-box/puffer-valve fueling of the central cell. These studies have shown that only 40 to 60% of the neutral gas particles introduced in the gas boxes actually ionize in the core of the plasma. The other 40 to 60% of the particles are temporarily trapped in the walls of the gas box and are pumped out between shots. The percentage of particles ionized in the core of the plasma appears to be relatively insensitive to the plasma density and ion temperature but is sensitive to the electron temperature and radial profile especially in the range $T_e \lesssim 100$ eV which is typical of the electron temperature in the TMX central cell (inferred from diamagnetic loop measurements).

It should be noted that the codes used to model the neutral-gas fueling of the central cell do not contain information on a self-consistent power balance. These codes in their present state, therefore, are useful for modeling central-cell fueling according to actually measured plasma parameters. Caution should be used when interpreting the parametric dependencies predicted by these codes, since they may be based upon plasma density and temperature profiles which are not physically realizable.

Much of the computational and theoretical study of neutral-gas fueling of the central cell was motivated by the need to understand the observation that the central cell line density did not decrease when the east-end plug was allowed to decay away. A plausible explanation for this phenomena is that the fueling of the central cell changed when the east plug was turned off, because there were significant changes in the plasma parameters, especially the radial profile of the electron temperature. We have recently obtained experimental evidence which supports this thesis. As Fig. II.C-1 shows, the density of the central cell plasma actually does decrease when the central cell is fueled

Fig. II-C-1. Comparison of east end loss current, east plug density, and central-cell density with time. After the east beams are turned off at 24 ms, the east plug density decreases and the east end loss current increases. Note the decrease in central-cell density with low gas.

with an incident neutral-gas flux equivalent to 650 atom amperes. However, the decrease on the central-cell density is barely noticeable when a fueling rate of 1100 atom amperes (which is typical of our previously reported data) was used. In the upcoming months, we will continue to improve our theoretical models and diagnostic measurements so we can better understand this phenomena.

Power and Particle Balance Scan: Since our last report on power and particle balance⁶ we have made significant additions to our diagnostic system so that we can better measure the flow of power and particles in TMX (Fig. II.C-2). On July 17 and 18, 1980, TMX was operated under constant conditions so that shot-to-shot reproducibility was as great as possible. This allowed us to scan the diagnostic systems so that we could obtain as much information as possible about power and particle balance in TMX.

The plasmas studied were not representative of good TMX operation. The electron temperature was low, $T_e \approx 80$ eV, and so was the central-cell confinement parameter, $nT_c/nT_T \approx 1.7$. Comparisons of this data with that from high- T_e running show that during low- T_e operation, the quasi-linear stream current (J_{QL}) required by the plugs is approximately equal to the fraction of the neutral beam current trapped by ionization (J_{BT}) in the plugs. The end loss current (J_{EL}), however, is much greater than the quasilinear stream requirement: $J_{QL} \approx J_{BT} \ll J_{EL}$. This implies that the end losses from the central cell are not contributing to the stability of the plug plasma. In high- T_e operation, $J_{QL} \approx J_{EL} \gg J_{BT}$, so the central cell is a good stream source. The changes in the plasma which cause the quality of the central-cell plasma as a stream source to change are not well understood at this time. We are presently studying the characteristics of the plasma fluctuations during high- and low- T_e operation in order to gain more insight.

Plasma parameters averaged over several shots are presented in Tables II.C-1 and II.C-2. These are shown as a mean value plus or minus the standard deviation. The deviation gives an indication of the shot-to-shot reproducibility of the data. The analysis of this data is still progressing. However, the data presented in Tables II.C-1 and II.C-2 indicate that a rough power balance can be attempted (Fig. II.C-3.) This preliminary analysis, indicates that, under poor running conditions (July 17 and 18, 1980), there may be significant radial power loss. For shots 24-27 on July 18, the power balance for the east plug indicated that approximately 260 kW of net neutral-beam power was trapped in the east plug. Of this, approximately 80 kW

Fig. II.C-2. TMX power- and particle-loss diagnostics, July 17 and 18, 1980.

TABLE II.C-1. Mean value plus or minus standard deviations for July 18, 1980, study of power balance for shots 46-49 and 62-66, TMX east and west plugs.

Parameter		East plug	West plug
f_{nd1}	cm^{-2}	2.7 E14	2.0 ± 0.3 E14
n_p	cm^{-3}	1.6 ± 0.2 E13	1.2 E13
r_p	cm	9.4 ± 0.8	-- (used east values)
$L_p(\text{outside})$	cm	$13. \pm 0.4$	-- (used east values)
$L_p(\text{central cell side})$	cm	$18. \pm 2.6$	-- (used east values)
J_{EL}	A/cm^2	0.21 ± 0.02	0.33 ± 0.03
ϕ_p	eV	430 ± 176	340 ± 53
T_{EL}	eV	840 ± 166	1030 ± 85
Outer Loop	A-m^2	175 ± 52	86 ± 24
J_{QL}	A/cm^2	0.057	0.050
$J_{BT_{20}}$	A/cm^2	0.046 ± 0.005	0.03 ± 0.002
$I_{B_{40}}$	A	148 ± 14	126 ± 9
I_B	A	24 ± 15	30 ± 3
V_{Accel}	keV	18	16
W_I	keV	12	7.6
P_{ioniz}	kW	167	96
P_{cx}	kW	35	75
P_{NET}	kW	200	171
$P_{EL}(i)^a$	kW	50	78
$P_{EL}(e-)^a$	kW	5	7
I_{EL}^a	A	58	92
T_e	eV	78 ± 23	-- (used east values)

^aBased on end-loss analyzer only.

TABLE II.C-2. Mean value plus or minus standard deviations for July 18, 1980, study of power balance for shots 46-49 and 62-66 in TMX central cell.

Parameter		Central cell
n_c	cm^{-3}	$3.3 \pm 0.9 \text{ E12}$
r_c	cm	25 ± 4.0
T_{ic}	eV	50 ± 25
$n\tau_c/n\tau_T$		1.7 ± 0.6

appeared as end-loss power. There was a net discrepancy, therefore, of 180 kW. The Yushmanov calorimeter data for these shots indicated that about as 100 kW of power could have been lost radially in this region of the east plug (see subsection IV.D). The nature of this power loss (plug ions, central-cell ions, radiation, etc.) is not known.

This result can be contrasted to power balances performed for runs which were indicative of better TMX operation⁷ (see Fig. II.C-4). The September 28, 1979, data analyzed to produce Fig. II.C-4 had an average electron temperature of 163 ± 20 eV and a confinement parameter $n\tau_c/n\tau_T$ of 2.8 ± 1.1 . The same analysis techniques used to generate Fig. II.C-3 were used to obtain Fig. II.C-4. However, as shown in Fig. IIC-4, for the operating conditions of September 28, 1979, it appears that we can account for the net trapped neutral-beam power in terms of the end-loss power.⁸

While TMX was at air during late July, 1980, we installed an array of beam-attenuation detectors in the west plug and arrays of Faraday cups and calorimeters on the east and west end walls. These new diagnostics will significantly improve our capability to measure the power input to the west plug and the axial power and particle losses.

- Observation - End Loss Power $\neq$ Net input power

Net Power in from Beams = 370 kW

Net End Loss Power = 140 kW

Fig. II.C-3. Preliminary power balance for TMX data obtained July 18, 1980.

- Conclusion - Obtain Approximate Power Balance

Net Power In From Beams = 220 kW

Net Power Out By End Loss = 250 kW

Fig. II.G-4. Low- I_B (low- I_B) shots in TMX. Data for September 28, 1979.

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II.D E-BEAM STABILIZATION EXPERIMENTS

(P. Poulsen and D. Grubb)

In separate experiments, e-beams were injected into the TMX plasma from positions in the end fan and along the centerline magnetic-field line. The approximate position of the e-guns for the experiments are shown in Figure II.D-1. The position marked "a" corresponds to the experiments in which the e-guns were mounted on the east-end flange of TMX. In succeeding experiments, e-guns were placed on the centerline of the machine, first 30 cm outside the outer mirror points "b," and then 5 cm outside the outside mirror points "c."

The experiments, discussed in detail by Poulsen and Grubb,¹ showed that injection of the e-beams did not in general affect the fluctuation level and the plasma parameters. At high plasma densities in the end plug ($n > 10^{13} \text{ cm}^{-3}$), neither the rf level nor any of the plasma parameters were affected by injection of the e-beam. At low plasma densities ($n \lesssim 10^{13} \text{ cm}^{-3}$) in the end plugs such that $\omega_p \lesssim \omega_c$ at $B_{\min}$ and at low fluctuation levels, instances of reduction in the ion cyclotron frequency and bulk heating of electrons were found. The ion cyclotron fluctuations at low plasma densities are observed to be weak and a sensitive function of the plasma parameters and boundary conditions. The e-beams did not consistently reduce the fluctuations, and the effects noted could be ascribed to perturbations of the plasma and its boundaries due to the injection of the e-beams. Heating of the electrons occurred in a set of experiments in which the east plug only was operated. The electron temperature increased from approximately 90 to 140 eV. The plug was started with streaming guns and, 0.5 ms after they turned off, the e-beams were injected. The e-beams had no significant effect on the ion cyclotron fluctuations under these conditions.

Injection of the e-beams into the normal TMX configuration did not produce hard ($> 50\text{-keV}$) x rays because of the presence of mirror-confined electrons and did not increase the bulk electron temperature. These results are at variance with the results² obtained in previous experiments in which e-beam were injected into plasmas of similar density and magnetic field. The difference in results points to a difference in the mechanism of either the beam-plasma interaction or a difference in the wave absorption.

Analysis of the interaction of electron beams with a mirror-confined plasma shows that the mechanism for wave absorption depends upon the axial profiles of density and magnetic field. The waves are generated at a

Fig. II.D-1. Schematic of TMX indicating e-gun positions. Points marked are (a) positions of guns for end-fan experiments, (b) positions of guns for first axial-injection experiment, and (c) positions of guns for second axial-injection experiment.

frequency between the upper hybrid, $(\omega_c^2 + \omega_p^2)^{1/2}$, and the greater of the plasma frequency, ω_p , and the electron cyclotron frequency, ω_c (see Ref. 3). At low density ($n < 10^{13} \text{ cm}^{-3}$), the propagating waves in a TMX plug will encounter an electron cyclotron resonance, as indicated in Fig. II.D-2. However, we hypothesize that the absorption is not efficient because of the relatively low density in the resonance region. At densities greater than $2 \times 10^{13} \text{ cm}^{-3}$ (illustrated in Fig. II.D-3), the waves can reflect from the envelope of the upper hybrid cut-off and be absorbed at a plasma resonance. In neither the 2XIB⁴ or the TMX experiments has bulk electron heating been observed under these conditions. Absorption at the plasma resonance tends to add energy to the electrons in a direction parallel to the magnetic field lines.⁵ It is possible, therefore, that the electrons that gain energy from the waves will leave the plasma if allowed to do so by the ambipolar potential and the collisionality of the plasma. Since the wave potentials can exceed the ambipolar potential and the collisionality of the electrons is small, these conditions can be satisfied in TMX.

We find, therefore, that absorption at the cyclotron resonances in TMX is inhibited by the peaked axial density distribution, and that hot, mirror confined electron are not produced. Under conditions where it is plausible that the axial density profile is less peaked, i.e., after stream gun turn off, an increase in bulk electron temperature with beam injection was measured. The ion cyclotron fluctuations were not significantly affected by injection of the electron beam for the range of plasma parameters investigated.

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Fig. II.D-2. The frequency plot (a) indicates the axial position of the fundamental electron cyclotron resonance. The corresponding density of the absorption region is indicated in (b).

Fig. II.D-3. Frequency plot of plasma having a highly peaked axial density distribution. The waves that are generated may be trapped within the upper hybrid cutoff and absorbed by the plasma resonance.

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II.E OUTSIDE GAS BOX

(R. P. Drake)

We have found that the scaling of central-cell confinement in TMX is limited by the stability of the end-cell plasmas.¹ The central-cell must supply a certain minimum loss current. In order to reduce or eliminate this limitation on central-cell confinement, we installed gas boxes near the outer mirrors of TMX. We used these gas boxes to maintain the end-cell plasmas, just as the gas box in 2XII-B was used.² While attempting to obtain an extended electrostatic scaling of central-cell confinement, we obtained instead evidence of apparent inward radial transport in the central-cell of TMX.

We installed an outside gas box on each end of TMX. These gas boxes extended 10 cm along the magnetic field; their outer jaw was positioned at the outer magnetic mirror of the end cell. The opening in the gas-box jaws was shaped to conform to the flux surface defined by a circle of 15-cm radius at the end-cell midplane. Each gas box was equipped with four piezoelectric valves controlled and operated by the same techniques used to run the inside gas boxes.

The type and amount of gas fueling affected the plasma parameters. Some of these effects are illustrated in Fig. II.E-1. The left column shows the effects of fueling with roughly 550 A of outside-gas-box current only. When both gas boxes were used (1170 A total), the central-cell density increased, the end-plug density increased slightly, and n_p/n_c decreased a factor of 2, as the central column shows. Then, when only the inside gas box was used, the central-cell density again increased, and n_p/n_c decreased to the characteristic value of 3 to 4 (shown in the right column). The use of the outside gas boxes did not substantially reduce the level of plasma fluctuations.

These results are quite unexpected. We thought the outside gas box would further stabilize the end plug and allow both the end plug and the central-cell density to increase. In contrast, use of the outside gas box led to a decrease in central-cell density.

Evidence regarding radial transport is provided by the end-loss current and the radial profile of ion-saturation current. As Fig. II.E-1 shows, the end-losses on centerline are independent of the gas fueling technique. However, the radial profile of end losses varies substantially, as Fig. II.E-2

shows. The end-loss profiles at the east end wall were measured by using ion-saturation-current detectors biased at -1000 V. The signal on these probes is proportional to the ion loss current, but the calibration is not known. Use of the outside gas box alone creates hollow end-loss profiles, as one expects. The inside gas box alone, with nearly the same gas feed, produced a peaked end-loss profile. Compared to the outside-gas-box shots, there were less total losses but the same loss current on centerline. When both gas boxes were used, a flat profile of end losses was observed.

Two aspects of the end-loss-profile data are significant. First, we inject the same amount of gas and find much less end-loss current. It is plausible that two-thirds of the gas feed escapes the gas box or is deposited in the gas box wall. Second, the observation of a peaked end-loss profile is not well understood.

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Fig. II.E-1. Plasma parameters depend on gas-fueling. Electron temperature (T_e), end-loss current (j_{ELA}), end-cell to central-cell density ratio (n_P/n_C), end-cell density (n_P), and central-cell density (n_C) are shown.

• GOAL: OBTAIN CONFINEMENT SCALING
INDEPENDENT OF END-PLUG STABILITY

• METHOD: USE OUTSIDE GAS BOXES TO
SUSTAIN END PLUG AND/OR TO REDUCE
PLASMA FLUCTUATIONS

• RESULTS:

- > END PLUGS SUSTAINED BY OUTSIDE GAS BOXES
- > PLASMA FLUCTUATIONS NOT REDUCED
- > CONFINEMENT SCALINGS OBSCURED BY PLASMA FLUCTUATIONS
- > EVIDENCE SUGGESTS INWARD RADIAL TRANSPORT IN CENTRAL CELL

Fig. II.E-2. End loss profiles, measured by ion-saturation current detectors, are shown for various gas fueling techniques.

II.F PLUG OPTIMIZATION EXPERIMENTS

II.F.1. SINGLE PLUG, BEAM ENERGY SCAN

(W. E. Nexsen and D. L. Correll)

The TMX concept involves the use of center-cell end losses to stabilize the plugs. The data from the beam energy variation experiments furnish an opportunity to test whether or not this process is occurring. The scaling with energy indicates that, at least for the conditions of this run, such stabilization occurs.

The experimental arrangement was $B_{cc} = 1$ kG, $B_{plug} = 8.5$ kG (3715 A = 83% in the baseball coils and 100% everywhere else), deuterium gas box at 400 T, and deuterium plug beams (no center-cell beams were used). The gas box feed varied from 680 to 920 A of D^0 . Note that normally at 400 Torr we observe a pressure drop more like 1360 A. The west plug was sustained with a constant 85 A of injected beam current at $V_{beam} = 16$ kV. The east plug was run in three modes: (1) 70 A at $V_{beam} = 16$ kV; (2) 50 A at 32 kV and 20 A at 16 kV (beam attenuation detector beam) which gives a $\langle V_{beam} \rangle = 27.5$ kV; and (3) 70 A at $V_{beam} = 11$ kV.

We determine experimentally the ratio of the particle containment parameter, $n\tau$, to that expected for collision dominated flow from

$$\frac{\langle n\tau \rangle}{2 \langle n\tau_{flow} \rangle} = \frac{(n_c T_{ic})^{1/2}}{2 \sqrt{T_e m} R J} ; \quad (1)$$

if the end losses are determined simply by collision-dominated flow over a potential hill,

$$\phi = T_e \ln (n_p / n_c) ,$$

then we expect

$$\frac{\langle n\tau \rangle}{2 \langle n\tau_{flow} \rangle} = \left(\frac{n_p}{n_c} \right)^{T_e / T_{ic}} , \quad (2)$$

where n_p is plug density, n_c is central-cell density, T_e is plug electron temperature, T_{ic} is central-cell ion temperature, R is mirror ratio between the central cell and the center of the plug, and J is the end-loss current out of the plug, mapped back to the center plane of the plug. We have direct measurements of all of these parameters except T_{ic} . The method to determine

T_{ic} on the centerline is to assume the central-cell electron and ion temperatures are equal and that both have a radial scale length equal to the radial density scale length. With this model we find

$$\hat{T}_{ic} = \hat{T}_{ec} = (\bar{T}_{ic} + \bar{T}_{ec}) = \frac{3.55 \times 10^{10} m B_z}{n L_c r_c}$$

where as have assumed that

$$\frac{\langle T_{ic} \rangle + \langle T_{ec} \rangle}{\hat{T}_{ic}} = 1$$

Here m is the central-cell magnetic moment obtained by reducing the diamagnetic-loop signal. Using this model, we have plotted in Fig. 11.F-1 the experimental values of Eq. (1) versus Eq. (2). Here each point is the mean of several shots with beam accel voltage (in kV) as designated by the number by the point. While there is not an exact equality of Eq. (1) to Eq. (2), the trend is in the right direction. The lack of better agreement is probably due to our model for T_{ic} ; in fact, considering the sensitivity of Eq. (2) to T_{ic} , it is perhaps surprising what good agreement we have.

The warm plasma end-loss current necessary for stabilizing the DCLC scales as

$$J \propto \frac{n_p T_e^{3/2}}{E_p}, \quad (3)$$

where E_p is the average plug ion energy, obtainable from reduction of the plug diamagnetic signal. In Fig. 11.F-2, we plot the experimental values of end-loss current versus the values of Eq. (3), having normalized both to the 11-kV injection values. We see that the end losses appear to obey Eq. (3) quite well. For comparison of the magnitude of the experimental end-loss current with the value predicted by the quasilinear theory, we use two equations for the quasilinear stabilization current,

$$J_{QL} = \frac{6.3 \times 10^{-13} (e\phi/r_e)^{3/2} n_p T_e^{3/2}}{(R-1) A^{1/2} \bar{E}_p}, \quad (4)$$

and

$$J_{QL} = \frac{1.9 \times 10^{-12} (e\phi/r_e)^{3/2} n_p T_e^{3/2}}{(R-1) A^{1/2} \bar{E}_p} (R_p/a_i)^{4/3}, \quad (5)$$

II.F PLUG OPTIMIZATION EXPERIMENTS

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where as have assumed that

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Here m is the central-cell magnetic moment obtained by reducing the diamagnetic-loop signal. Using this model, we have plotted in Fig. II.F-1 the experimental values of Eq. (1) versus Eq. (2). Here each point is the mean of several shots with beam accel voltage (in kV) as designated by the number by the point. While there is not an exact equality of Eq. (1) to Eq. (2), the trend is in the right direction. The lack of better agreement is probably due to our model for T_{ic} ; in fact, considering the sensitivity of Eq. (2) to T_{ic} , it is perhaps surprising what good agreement we have.

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and

$$J_{QL} = \frac{1.9 \times 10^{-12} (e\phi/T_e)^{3/2} n_p T_e^{3/2}}{(R-1) A^{1/2} \bar{E}_p} (R_p/a_i)^{4/3}, \quad (5)$$

Fig. II.F-1. Comparison of tandem confinement with theory.

Fig. II.F-2. Comparison of end-loss current with theory.

where Eq. (5) includes the effects of (R_p/a_i) scaling on the quasilinear requirements. Here T_e, E_p are in keV, n_p in cm^{-3} , R is the effective mirror ratio, A is the ion mass in amu and $(e\phi/T_e) \approx 3.5$. For the values tabulated in Table II.F-1 we use $(R-1) = 1$, and $A = 2$. It appears that Eq. (4) gives a more nearly constant value for the ratio of J_E/J_{QL} than does Eq. (5). Equations (4) and (5) assume equal flow of stabilizing current out both ends of the plug. If the flow is mainly from central cell through the plugs, then the quasilinear requirement is a factor of two higher. Thus, by this model we expect the agreement between the experimental values and twice Eq. (4) indicated in Table II.F-1 ($J_E/2J_{QL} = 1$) and in Fig. II.F-2.

The minimum quasilinear current of Eq. (4) occurs when the stabilizing temperature T_w is equal to the hole temperature, or $T_w \approx 3-6 T_e \approx 300-600$ eV while experimental values of the center-ion temperatures are of the order of 50 eV. With such a low temperature stream the plasma is predicted to be unstable to "double-humped" modes. The quasilinear model shows that the nonlinear effect of these double-humped modes is to heat the lower energy component. This may explain why the apparent temperature of the end-loss current appears to be quite a bit higher than the values of T_{ic} inferred from the diamagnetic-loop measurements. Baldwin has pointed out that, if this process is important, we would not expect to have $(R_p/a_i)^{-4/3}$ scaling, i.e., that Eq. (4), which best fits the data, is the proper relation to use.

TABLE II.F-1. Comparison of data for beam energy scan.

Case	A	B	C
V_{inj} (kV)	11	16	27.5
I_{inj} (A)	70A	70	50A @ 32 kV 20A @ 16 kV
E_{Eplug} (keV)	5.7	9.2	14.6
T_e (eV)	96 ± 21	121 ± 35	133 ± 20
n_p (10^{13} cm^{-3})	1.1	1	0.84
p (%)	3.5	5.1	6.8
n_c (10^{12} cm^{-3})	3.9	4.8	3.7
T_{ic} (eV)	62	44	48
β_{cc} (%)	1.9	1.7	1.4
$(n_p/n_c)^{T_e/T_{ic}}$	4.9	7.7	10.0
$n_E/2 n_{flow}$	4.3	5	8.2
T_{ic} (eV)	66	53	52
α	0.94	0.83	0.92
J_E (A/cm ²)	0.32	0.28	0.14
J_{QL} (A/cm ²), Eq. (4)	0.168	0.134	0.082
J_{QL} (A/cm ²), Eq. (5)	0.062	0.061	0.052
$J_E/2 J_{QL}$, Eq. (4)	0.95	1.05	0.85
$J_E/2 J_{QL}$, Eq. (5)	2.6	2.3	1.35

II.F.2. UNLIKE MASSES--He IN PLUGS, D IN CENTRAL CELL

(A. H. Futch)

We investigated the possibility of producing helium plasmas in TMX. The advantages of a helium plasma are that it would enable us to test theoretical models dealing with atomic processes, microinstability resonance processes, more intense coulomb coupling, etc. We devoted a couple days to operating the neutral beams on helium, and were able to deliver 75 atom amperes of energetic helium. These 75-A experiments were unsuccessful, as one would expect on examining the buildup rate for helium derived from cross-section data. In light of the urgency of other experiments we did not devote the time or effort needed to obtain more helium neutral-beam current. The simple buildup equation is

$$\frac{dn}{dt} = \frac{IL}{V} n + \sigma_{cx} + \sigma_i + \frac{\sigma_i^e v_r}{v_b} - \frac{n}{\tau_{loss}} .$$

A comparison of cross sections for He⁰ beams at 20 keV with H₀ beams of 20 keV (full energy), 10 keV (1/2 energy) and 6.7 keV (1/3 energy) is given in Table II.F-2. We assume T_e is 25 eV for the target plasma in all cases.

The effective cross section for hydrogen is obtained by multiplying the total cross section for each component by the relative number of particles at that energy. The ratio of the component-weighted cross sections for H⁰ to the cross sections for He is 2.5. The 75 atom A of He are therefore equal to the hydrogen equivalent current of 75/2.5 = 30 A. Past experience with hydrogen beams tell us that this is too low to expect buildup to occur.

Since helium gas was used as the neutralizer for He⁺, the neutralizing efficiency is approximately the same as for H⁺ on H₂. The neutralizers were assumed to give the same neutral-beam currents for the same beam input.

TABLE II.F-2. Comparison of cross sections for He⁰ beams at full energy with H₀ beams at full, half and third energies.

Cross sections	He ⁰ (20 keV)	H ⁰
		<u>58% full energy - 20 keV</u>
Charge exchange, σ_{cx}	4.7×10^{-16}	6.3×10^{-16}
Ion impact, σ_i	0.5×10^{-16}	1.35×10^{-16}
Electron impact, $\sigma_i^e v_r/v_b$	0.7×10^{-16}	0.61×10^{-16}
Total	5.9×10^{-16}	$8.26 \times 10^{-16} \times (58\%) = 4.79 \times 10^{-16}$
		<u>38% half energy - 10 keV</u>
Charge exchange, σ_{cx}		9.5×10^{-16}
Ion impact, σ_i^i		0.9×10^{-16}
Electron impact, $\sigma_i^e v_r/v_b$		0.9×10^{-16}
Total		$11.3 \times 10^{-16} \times (2 \times 38\%)$ $= 8.59 \times 10^{-16}$
		<u>4% third energy - 6.7 keV</u>
Charge exchange, σ_{cx}		11×10^{-16}
Ion impact, σ_i^i		0.5×10^{-16}
Electron impact, $\sigma_i^e v_r/v_b$		1.01×10^{-16}
Total		$12.5 \times 10^{-16} \times (3 \times 4\%)$ $= 1.51 \times 10^{-16}$
		TOTAL H ⁰ = 14.9×10^{-16}

II.G IMPURITY STUDIES

(O. T. Strand and S. Allen)

The addition of two absolutely calibrated, spatial-imaging, extreme-ultraviolet monochromators to TMX (see subsection IV.N), one on the east plug and one on the central cell, has permitted more extensive investigations of impurity radiation. Further analysis of impurity concentrations in the TMX central cell continues to indicate low impurity levels (see Table II.G-1). Radial scans in the central cell show a cold edge plasma extending out to large radius, approximately 38 cm. Neon and oxygen have also been injected into the central cell to enable us to investigate impurity sources, confinement and transport. Initial results indicate that the injected impurity penetrates the plasma and maintains a steady-state density for the duration of the shot.

Radial scans in the central cell have provided several interesting facts. Figure II.G-1 shows radial brightness profiles in the central cell. Four shots are required for a full spatial scan. Observations of deuterium and singly ionized nitrogen, both of which exist in very cold parts of the plasma, have shown that a cold plasma exists at very large radii. Deuterium radiation appears out beyond 38 cm, which is where a beam attenuation detector is located. These spatial scans also indicate that an asymmetry was present on the day this data was taken. This may be due to probes which were inserted into the plasma then.

Radial scans provide other useful information as well. The radial locations of the highest density of a given ionization state provide an indication of the electron temperature at that position. Scanning several ionization states should provide a radial profile of electron temperature in the central cell.

Two neon- and oxygen-injection experiments were performed. First, the impurity gas was puffed (injected) into the central cell before the shot in order to observe confinement. The impurity signals do not decay by the end of the shot. This indicates either a long confinement time or heavy recycling from the walls. The data are being analyzed to study this question further, since neon and oxygen interact differently with the plasma boundary than they do with the wall. The second experiment was to puff the impurity in after the plasma had fully developed (see Fig. II.G-2). The impurity gases penetrate the plasma quite differently. Oxygen at a low ionization state (OII 539 A) appears at the plasma edge, moves inward and ionizes to

TABLE II.G-1. Impurities in the TMX central cell and end plug.

Species	Density (factor of 2) (%)	Radiated power ^a (factor of 2) (kW)
Central cell		
O	0.3	4
N	0.2	4
C	0.05	1.5
Ti	- ^b	6 ^c
L-Ly _α	-	6
End plug		
O	0.25 ^d	2

^aTypical trapped beam power = 450 kW.

^bNot obtainable from data.

^cEstimated.

^dSimilar to 2XIIIB with $(I_B)^{1.6}$ scaling.

higher-charge states. The neon, however, appears mainly in the center of the plasma for all charge states. Further experiments are planned to study these differences, since the above measurements were taken on different days under different plasma conditions. Careful observation of the plasma boundary is crucial to this question also.

Fig. II.G-1. Radial brightness profiles for the central cell (22-channel EUV).

Fig. II.G-2. Impurity puffing experiment. Graphs show brightness vs radius and time for puffs of 12 to 17 ms into the central cell.

II.H THERMAL BARRIER

(T. C. Simonen)

Following the development of the thermal-barrier concept, we considered a wide number of possibilities to obtain experimental tests of thermal-barrier principles. While many features of the barrier concept have been experimentally studied in other contexts,¹ they have not been tested in a compound experimental configuration nor at thermonuclear temperatures. General technical considerations for such tandem-mirror, thermal-barrier experiments are summarized in a report by Drake.² The experiments considered for TMX may be classified as follows:

- Operate TMX so as to obtain data relevant to the thermal-barrier concept. The following sections describe results from a limited number of such experiments.
- Add additional diagnostics to study phenomena related to thermal barriers. A Yushmanov microwave interferometer was installed on TMX to determine if any density depression spontaneously develops between the plug midplane and the magnetic-mirror peak (Section IV describes results from these measurements). A central-cell Thomson scattering system has been built to determine if the central-cell electron temperature equals the end-plug electron temperature.
- Several possible modifications were considered for TMX, such as adding magnets to the central cell or outboard the end plugs to create possible magnetic field profiles to be used to support thermal barriers. No suitable designs evolved.
- A major modification to TMX, the TMX Upgrade, was developed. TMX Upgrade is described in the TMX Upgrade Major Project Proposal.³

ANALYSIS OF END PLUG ELECTRON TEMPERATURE AND CENTRAL CELL DIAMAGNETIC LOOP DATA

TMX data were analyzed to see if any evidence could be obtained for an electron temperature difference between the end plug and the central cell.

We used diamagnetic-loop measurements to estimate the central-cell electron temperature. This analysis requires an assumption about the temperature radial profile: we assumed a Gaussian profile of the same shape as the central-cell density profile. In Fig. II.H-1, we plot the total

Fig. II.H-1. TMX operating regimes.

perpendicular temperature (ion + electron) on axis versus the on-axis end-plug electron temperature measured by Thomson scattering. We have divided this plane into three regions:

1. $\hat{T}_{ic} + \hat{T}_{ec} > 2\hat{T}_{ep}$ --In this regime we postulate that rf fluctuations increase the central-cell ion temperature above the electron temperature.
2. $\hat{T}_{ep} < \hat{T}_{ic} + \hat{T}_{ec} < 2\hat{T}_{ep}$ --In this regime we postulate that the electron temperatures are nearly equal and the central-cell ion temperature is somewhat lower. This is the standard collisional regime described in the TMX proposal and by the TAMRAC code.
3. $\hat{T}_{ic} + \hat{T}_{ec} < \hat{T}_{ep}$ --In this regime we can conclude that the central-cell electron temperature is lower than the end-plug electron temperature. This is the thermal barrier mode.

Analysis of this TMX data, shown in Fig. II.H-1, indicates that under some TMX operating conditions an electron temperature gradient probably exists along magnetic field lines. The purpose of the central-cell Thomson scattering is to confirm this conclusion and to help document under what conditions, and why, such a gradient exists.

TMX BARRIER FILLING AND TEMPERATURE GRADIENT EXPERIMENTS

The existing TMX magnetic-field configuration is similar to one-half of an A-cell-barrier system and can be used to explore some aspects of thermal-barrier physics. The arrangement indicated in Fig. II.H-2 was used in a preliminary investigation. Diagnostic information can be obtained at the locations shown. The major regions may be summarized as follows:

- The central-cell plasma is simulated by a plasma gun augmented by gas puffing at the end wall.
- One of the TMX end plugs serves as the main plug.
- A thermal barrier should be created by the central-cell on a transient basis, since it will fill slowly because of its large volume. Gas feed can be used to vary the barrier density.
- An A-cell is created in the other TMX end plug and auxiliary electron heating can be applied with electron beams.

The thermal-barrier density plays a critical role in barrier performance, and the rate at which ions fill the barrier determines the barrier pumping

Fig. II.R-2. TMX thermal-barrier-related experiments with schematic illustration of possible diagnostic measurements.

rates. Data from such a TMX barrier-filling experiment are shown in Fig. II.H-3. East stream guns are on during the period of 5 to 15 ms. The west end-loss analyzer shows that this plasma flows through the entire system. The east-plug density builds up within 10 ms. The central-cell fills with a 4- to 5-ms time constant. This filling rate is not inconsistent with our present knowledge of the mean ion energy, although further analysis and experiments are needed.

The next step in these preliminary thermal barrier experiments was to attempt to establish an electron temperature gradient along the magnetic field lines by heating one end plug with more beam power and electron beams and cooling the other with gas feed. Experiments in 2XIIB have shown that gradients are possible at high density where axial heat flow is limited by collisional processes. The present TMX experiments are aimed at obtaining such electron temperature gradients by inhibiting heat flow by the low density barrier region, a technique more suitable for reactor applications. To measure an electron temperature difference between the A-cell and the main plug with only one Thomson scattering system, we reversed the roles of the ends of the machine. Results of electron temperature measurements indicated that no electron temperature gradients were produced. While classical processes in this case could generate only a modest thermal barrier, we speculated that possibly the electron beam might add a new ingredient. Besides providing heating power at the outside of the plug, the associated wave turbulence might establish an rf thermal barrier. Evidently the electron beam did not generate such a condition.

REFERENCES

1. F. H. Coensgen, R. P. Drake and T. C. Simonen, Tandem Mirror Thermal Barrier Experimental Program Plan, Lawrence Livermore National Laboratory, Livermore, CA, UCID-18505 (1980).
2. R. P. Drake, Small-Scale Experimental Tests of Tandem Mirror Machines With Thermal Barriers, Lawrence Livermore National Laboratory, Livermore, CA, UCID-18274 (1979).
3. F. H. Coensgen, T. C. Simonen, A. K. Chargin and B. G. Logan, TMX Upgrade Major Project Proposal, Lawrence Livermore National Laboratory, Livermore, CA, LLL-PROP-172 (1980).

Fig. II.H-3. Example of TMX thermal barrier related experimental data.

II.1 DIRECT CONVERTER

(W. L. Barr)

A plasma direct energy converter was tested on TMX. This small, single-stage module recovered 80 W of power at a net efficiency of 50% after allowing for interception and power consumption at the grids. This efficiency is what is expected on the basis of the converter design and the measured end-loss energy spectra of ions exiting TMX. Similar efficiencies (50 to 60%) are assumed for present tandem mirror reactor designs.

The direct energy converter has also been employed to measure the energy spectrum of end losses to double check the results of the end-loss analyzers. Because its purpose is to recover energy, the direct converter differs from a retarding-potential energy analyzer in 3 ways: (1) it has a large aperture; (2) it has transparent grids; and (3) ions are collected at high positive potential. The collector potential is generated across a string of zener diodes with taps every 102 V. Therefore, the potential is constant during a shot and is changed between shots. Data are recorded on a scope. A sketch of the direct converter is shown in Fig. II.1-1.

When shot-to-shot reproducibility is good, an I vs. V curve can be constructed for any time during the shot as plotted in Fig. II.1-2. It indicated $\phi = 565$ V, $T_i = 365$ eV. Also, the fact that -500 V was required on the suppressor grid is consistent with $T_e = 78$ eV as measured by other diagnostics. The calculated potential between wires in the grid is -363 V, which should stop all but 1% of the electrons when $T_e = 78$ eV.

The unfiltered signal from the direct converter had a signal-to-noise ratio less than one. An R-C filter with a 300- μ s time constant removed nearly all of the noise.

These results support our design concepts for direct conversion and lend confidence in our ability to scale up to future tandem mirror machines.

Fig. II.I-1. Direct converter on TMX east end.

Fig. II.1-2. Direct converter data taken midway through the pulse. Each point is from a different shot.

III.A TMX OPERATIONS

(J. C. Davis, D. L. Correll, and W. L. Pickles)

During the period from January to July 1980 the TMX experiment operated on a 16-hour-per-day schedule with one day per week reserved for maintenance. Major experiments performed during this time requiring machine modifications were e-beam startup and stabilization experiments and plug stabilization measurements with outside gas boxes.

Unplanned interruptions of a week or more in the operational schedule were caused by the Livermore earthquake of January 24, 1980, a five-week shutdown of the MFE area low-conductivity water system for modification and improvement, and flashovers in the trunk lines for the east and west baseball magnets. The detailed history of machine operations is given in Fig.

III.A-1. A total of 2351 data shots have been recorded during this time. The maximum number of data shots taken in a single day was 102; there were twenty-one days on which more than 50 shots were taken. On a typical experimental day, another 25-50 magnet and/or neutral beam shots are taken for system checkout and calibrations.

In addition to the e-beam and outside gas box experiments, power balance and impurity transport experiments were undertaken, and studies and diagnostic scans were made. The availability of the neutral-beam system increased as a result of systematic noise hardening of control circuits and power-handling modifications in the controls and power supplies.

Fig. III.A-1. TMX operational summary, January - July 1980.

III.B TMX DIAGNOSTICS

(J. C. Davis)

The diagnostic set installed on TMX at the time of initial operation was selected to demonstrate as quickly as possible that the physics objectives required for proof-of-principle evaluation of the tandem mirror concept were accomplished. With the basics of the tandem mirror confinement concept established, the diagnostic efforts were directed to more detailed questions of radial transport, overall power balance, impurity levels, and fluctuations in the device. The expanded data set now in operation in TMX is shown in Table III.B-1. The expansion of the number of data channels is illustrated in Fig. III.B-1. Where in the original data set a single point measurement was acquired (axial loss at one radius, single chord $\int n dl$ through the plasma etc.), the present 358 diagnostic channels provide multiple measurements to allow calculation of axial or radial profiles or global sums that are not model dependent. More accurate determination of device power balance and power losses is possible. The TMX computer system has been able to acquire and process this increased data flow without lengthening the 4-5 minute intershot period. A further expansion of the diagnostic system is planned for the TMX Upgrade; computer-system upgrade will be required to handle the approximately 500 data channels planned.

TABLE III.B-1. TMX diagnostic instrumentation (August 1980).

Plasma parameters	Diagnostic systems	No. diagnostic channels		
		East plug	Central cell	West plug
Electron temperature/density	Thomson scattering	4	1	-
Plasma density profiles	Beam attenuation	23	7	22
Electron line density	Microwave interferometers	4	2	2
Plasma energy	Diamagnetic loops	2	6	2
Axial loss current/energy	End-loss analyzer	2	-	2
Central-cell plasma potential	Thallium-beam probe	-	1	-
End loss current profile	Faraday cups	13	-	13
Exterior density/temperature	Emissive probes	1	-	-
Potential fluctuations	RF probes	18	28	15
Density fluctuations	Microwave scattering	3	2	1
Charge-exchange flux	Secondary emission detector	1	2	1
Neutron production rate	Neutron detectors	1	-	1
Neutral gas pressure	Fast-ion gauge	1	2	1
Neutral-beam power and focus	Neutral-beam calorimeter	1	-	1
Impurity concentration	EUV spectrometer	22	22	1
Doppler broadening	UV spectrometer	-	1	-
Light monitor	Visible light	2	1	-
Electron energy	X rays	4	1	1
Ion energy	Charge-exchange analysis	-	1	-
Plasma pressure	Piezoelectric probe	-	1	-
Power losses	Calorimeter	12	3	12
Power losses	Pyroelectric probe	-	1	-
Wall interaction	Sandia probes	1	1	-
Electron temperature	$2\omega_{ce}$ radiometer	1	-	-
Magnetic field strength	Magnet currents	6	6	6
Neutral-beam power	Beam voltage/current	24	-	24
Plasma-gun output	Gun current	2	-	2
Gas-feed current	Gas-valve timing/output	4	1	4
TOTAL		152	95	111

Fig. III.B-1. Expansion of TMX diagnostics.

III.C THE TMX COMPUTER SYSTEM (J. F. Clauser and W. C. Cummins)

SYSTEM SOFTWARE CONFIGURATION

The TMX computer system has been set up to provide for rapid data acquisition and intershot processing, as well as to provide convenient user's access to the data base. Through experience, we have evolved a system for data flow to effect this requirement. It is shown in Fig. III.C-1.

The data base is composed of three types of files: raw-data files, processed data files, and journal files.

The data-acquisition system acquires the data at DMA speed via a Camac parallel branch highway (and a variety of other interfaces) and writes the raw diagnostic data directly onto the raw-data file, along with the associated diagnostic parameters. The subsequent processing of the data occurs on several levels. First, a series of programs called primary processors reads data from the raw-data files for each diagnostic and produces numbers in physical units that are representative of a given diagnostics measurement of the plasma. These results are then written to the processed-data file. Next, several layers of secondary processors read data from the processed-data files. These results are accumulated onto the processed-data file. Thus, the system is modular, so that complex calculations may be made which require data from more than one diagnostic and/or preceding calculation. In this way, calculations may be performed to any degree of complexity, with the results available between shots. Moreover, additional processing may be performed later and the results added to the processed-data files. Once the raw and processed files are in some sense complete, they are archived on magnetic tape.

A system for data-base search and retrieval is currently being implemented. It will excerpt important parameters from the processed-data files (a small subset of the data) and save these on a "journal" disk file. Thus more than six months worth of data are immediately available. These files are automatically extendable so that additional parameters may be added to them at any time by additional processing. Selection and retrieval of data from the journal files is done by an interactive routine. It will (1) scan the files for the requested data, (2) convert the structure from a hierarchical form ("tree" structure) to a relational form (rectangular-array structure), (3) find and resolve ambiguities, (4) display relations among the

Fig. III.C-1. TMX computer system data flow diagram.

data and the associated processing information, (5) allow the user to select desired small subsets of these data, (6) save the retrieval commands and the selected data itself on additional private disk files, and (7) write a skeleton user's Fortran program for analysis of these data.

TMX PHYSICS APPLICATIONS SOFTWARE

Recently written examples of especially useful primary and secondary processors are:

ELANA--Calculates plug potential ion end-loss energy spectra and ion end-loss current, both as a function of time throughout the shot. The input data for this processor is that from the voltage-swept gridded end-loss analyzers.

GALOP--Calculates electron temperature and density from Thomson scattering data (and error limits for these numbers).

DMLPS--Calculates plug and central-cell time-dependent magnetic moments from diamagnetic loop data.

PLANC--Calculates the time-dependent end-loss current profile from arrays of biased Langmuir probes on the end wall. Integrates the profile.

DPROP, BADII, AND XLNTH--Calculate radii, plasma density, lengths, and axial symmetry for central-cell and plug plasmas from beam-attenuation data.

MVDEN--Calculates densities at various plasma chords from microwave interferometer data.

PSDRD--Calculates a fast Fourier transform of rf probe data. It can produce power spectra and cross-power spectra for one or between two probes.

LYSM--Calculates total currents and average beam energies from plug and central-cell neutral-beam telemetry data.

FIFCX--Calculates ionization and charge-exchange coefficients for analysis of neutral-beam power and current deposition.

CCPAR--Calculates for the central cell the confinement parameter n actually achieved, as well as various other parameters such as central-cell average energy. It also calculates various theoretical predictions for n for use as a comparison with the actual performance.

NEBET--In progress. Calculates plug average ion energy from plug magnetic moments and dimensions. Currently being written are additional secondary processors to calculate: (1) Plug power balance from plasma electron temperatures, densities, dimensions, average ion energies, ionization and charge-exchange coefficients, etc. (2) Warm plasma current necessary for plug

stability. (3) Plug energy and particle-confinement parameters. (4) Plug ion energies from neutron-emission data.

SYSTEM OPTIMIZATION AND HARDWARE CONFIGURATION

A great deal of effort has been spent optimizing the throughput of this system. A diagram of the hardware configurations is shown in Figs. III.C-2 and III.C-3. A Hewlett-Packard 2100 computer system handles data acquisition. It is linked by a high-speed interface to a Hewlett Packard 21MXF computer system with a high-performance memory, high-speed floating-point processor, and vector instruction set. The 21MXF handles the data processing and data-base management. A second off-line remote 21MXF computer system is linked to the first 21MXF, and serves for off-line data analysis and program development.

Detailed timing measurements have been performed on this system. Better than a factor-of-2 improvement has been achieved, through system software refinements. Future redesign of the acquisition and processing control-system software will allow even greater throughput of the basic data-flow structure.

The data-flow structure of Fig. III.C-1 should work well for the TMX-Upgrade computer system. For it, an expanded hardware configuration (Fig. III.C-4) will be installed in October 1980. The upgrade system consists of several Hewlett Packard 21MXE computers handling the data acquisition.

COMPACTION

Present and future MFE experiments generate multi-megabyte data sets from each shot. Given finite input/output bandwidths and storage media on any computer system, it is necessary to find methods to reduce the size of the data volume which the system must handle without materially affecting the information content. Using the myriad signal types available in the TMX data, the degree and efficiency of redundancy and Huffman's encoding algorithms coupled with pre-encoding data transforms have been measured. The results show that redundancy encoding, although not yielding quite the byte-count reduction of the Huffman scheme, is several times more efficient. A typical raw-data set was reduced overall by a factor of 2.7 at an acceptable rate of 160 ms per 8192 byte record. Simple and rapid transforms of the original data array can, in specific cases, improve the reduction by a factor of 1.5. The obtainable data-volume reduction is greater for processed data than for raw; since physics processing is essentially a filtering procedure. These data compaction routines will be installed in the TMX-upgrade system.

Fig. III.C-2. TMX diagnostics computer system--July 1980

Fig. III.C-3. TMX off-line computer system—July 1980.

Fig. III.C-4. TMX-Upgrade computer system.

TMX COMPUTER GRAPHICS

Experience has shown that efficient operation requires at least four different types of graphics output:

(1) A certain amount of graphics hard-copy output is required during intershot processing. Plotting hardware (Tektronics terminals and hard-copy units) speeds limit this to a subset of all possible graphical outputs. The selection of which outputs occur between shots depends upon the current experimental study.

(2) Both hard- and soft-copy graphics are available between shots upon a user's request to the computers. These are displayed on Hewlett-Packard 2648A graphics terminals. These may be used typically to obtain graphical outputs not included in (1) above. Graphical outputs may be thus produced from raw or processed data files that are still on disk (typically the preceding 20 shots).

(3) A complete set of graphical outputs and tabulation of data in "standard form" is available (usually by the day following acquisition) bound in notebooks. These books are useful for quick access to data for any shots in the history of the machine. Additional "nonstandard" graphical and tabulated data may be added to this reference library upon a users request. [This library is essentially a completion of (1) above].

(4) Graphical representations of intershot correlations may be displayed by the user by using the journal-file system skeleton programs and the graphics software library.

Improvements to this system currently under implementation include adding the DI-3000 device-independent graphics system, spooling graphics, expansion and improvement of the user-request access systems, [see (2) above] as well as better integration of the graphics scheduling into the overall processor and acquisition scheduling.

III.D TMX VACUUM CONDITIONS AND T_e

(W. E. Nexsen and D. L. Correll)

Since the December shutdown, the average TMX electron temperature has tended to be lower than that observed in earlier runs. This is shown in Fig. III.D-1, where the daily average electron temperature over the past year is plotted. Figure III.D-2 shows the daily average T_e versus the east injected-beam current. We see from both figures that the earlier runs were better. In addition, it appears that T_e was independent of I_b before December, whereas since then the scaling has resembled that of 2XIIB with $T_e \propto I_b$.

Since the west plug was realigned in December, it was at first assumed that these differences were caused by a magnetic field misalignment, however, electron-beam mapping of the axes of the various coil groups did not turn up sufficient misalignment to explain the poor runs. (see Appendices A and B).

Once we had eliminated misalignment as the cause of the low T_e , the next most likely candidate seemed to be poor vacuum conditions in a critical area. It had been standard practice to cool liners at the beginning of a run before T_e measurement had commenced. In a recent run, we operated for a number of shots while gettering on warm liners and observed electron temperatures in the higher range of last year's operations. When the west liners were cooled, the electron temperature in the east plug was reduced by almost a factor of 2. Since these same liners were cold for the good runs of last year, we surmised that a cold leak was present in one of the west liners and that such a leak was destroying the active pumping surfaces in a critical region. The leaking liner was found and turned off. We also observed the effect on electron temperature of cooling various groups of liners one at a time. No direct correlation was found after all known leaking liners were either fixed or turned off. Since this time, T_e above 100 eV has been measured with warm and with cool liners.

We have also identified a problem in our getter system's line-voltage regulation. Although the line voltage to each getter power supply is regulated, only one phase of the three-phase system is monitored. Variations of the voltage on each phase can therefore cause unbalanced gettering levels inside the machine.

Fig. III.D-1. Daily average electron temperature vs date shows lower values in 1980. On a given day higher and lower temperatures are measured.

Fig. III.D-2. Daily average electron temperature vs east neutral beam current.

IV.A BEAM ATTENUATION DETECTORS

(J. H. Foote)

During the last several months, we have expanded the east-plug and central-cell arrays of beam-attenuation detectors,¹ and have recently installed a detector array in the west plug. A total of 54 beam-attenuation detectors are now mounted in TMX, giving us the following capability to obtain f_{nd1} data.

- East plug array has 23 detectors. With expanded electronics and cabling, we can regularly obtain an axial f_{nd1} profile with nine detectors covering the axial range from 12 cm east of the plug midplane (away from the central cell) to 19 cm west. The radial or vertical profile consists of as many as 13 detectors, extending 12 cm above and below the magnetic axis.
- The central-cell vertical array has been expanded from four to seven detectors to give a radial plasma profile near the central-cell midplane extending from 11 cm below the magnetic axis to 37 cm above.
- An array of 24 detectors has now been built and installed in the west plug, of which we can regularly monitor 21. These cover the axial range from 12 cm east of the plug midplane to 23 cm west (away from the central cell), and thus measure plasma densities up to 11 cm further toward the end wall than does the east plug array. The radial profiles again extend to 10 to 12 cm above and below the magnetic axis.

The computer software to handle and analyze the data from this large number of detectors has been considerably expanded and improved over the last several months. In particular:

- More channels of raw data can be conveniently converted to f_{nd1} versus time.
- Radial profiles of f_{nd1} data at selected times during a shot are fitted with a Gaussian curve, and the data and fitting curve are plotted. Figures IV.A-1 and IV.A-2 are examples of these results for the east plug and central cell. Values of peak density and $1/e$ radius for the Gaussian fit are printed out on each plot.
- From the Gaussian fitting of the radial data, plots of peak density and $1/e$ radius versus time can be conveniently obtained for the plugs and center cell.

• Axial f_{nd1} results for the plugs at selected times are plotted and the values joined by straight lines. Figure IV.A-3 gives two examples of east end-plug data, showing the variation in axial shape observed as plasma conditions are changed. There is also a computer program that calculates Gaussian and quadratic fits to the axial-profile data.

Plots such as those described above are usually obtained during the between-shot processing, so are quickly available during a run for determining plasma conditions.

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Fig. IV.A-1. Example of east-plug radial-profile data fitted with a Gaussian (peak line density = $2.29 \times 10^{14} \text{ cm}^{-2}$, $1/e$ radius = 8.45 cm).

Fig. IV.A-2. Example of central-cell radial-profile data fitted with a Gaussian (peak line density = $1.62 \times 10^{14} \text{ cm}^{-2}$, $1/e$ radius = 24.6 cm).

fig. IV.A-3. Two different observed shapes of east plug axial profiles:
 (a) Shot 55 of 7/18/80, (b) Shot 18 of 7/15/80.

IV.B END-WALL EMISSIVE-PROBE ARRAY

(P. Coakley)

The end-wall emissive-probe array consists of two emissive probes, located at 2 and 10 cm from the end wall; two collecting probes, also located at 2 and 10 cm; and seven button probes, located in the plane of the end wall. The probes are positioned in the midplane of the mirror fan and map into 4 to 5 cm in the plug. The emissive probes, designed at the University of Iowa,¹ are used to measure the local plasma potential. The collecting probes are used to measure the electron distribution, a localized measurement if the surrounding plasma is at a relatively uniform potential.

The plasma potential near the wall, as measured with the emissive probes, varies from between 7 and 15 V shot to shot. The probe at 10 cm indicates a plasma potential 1 to 2 V more positive than the probe at 2 cm. Since the potential structure in this region is relatively flat (i.e., $e\Delta\phi/T_e \ll L/\lambda_D$, where T_e is the local electron temperature as determined from a collecting probe at 10 cm and L is the distance between the two emissive probes) then a collecting probe placed in this region may be used to make a localized measurement of the distribution of electrons. From the collecting probe at 10 cm, a two-species electron distribution has been measured. The quantities measured are

- $5 \times 10^7 < n_1 < 2 \times 10^9 \text{ cm}^{-3}$; $T_1 < 4 \text{ eV}$ at $\phi \sim 0$
- $2 \times 10^9 < n_2 < 2 \times 10^{10} \text{ cm}^{-3}$; $5 < T_2 < 15 \text{ eV}$ at $\phi \sim 10 \text{ V} = V_p$,

where V_p is the local plasma potential.

The floating potential of the collecting probe at 10 cm is close to zero (the potential of the wall). The balance of current from the end-loss-analyzer data and collecting-probe data also points to zero net current at zero volts. From the end-loss data and the probe data, it is not unreasonable to assume a sheath at the wall of 10 V and a thickness d between 0.1 and 0.3 cm ($5\lambda_D$); based on the large density of the species of cold electrons ($T_2 < 15 \text{ eV}$, $n_2 > 2 \times 10^9 \text{ cm}^{-3}$) measured at 10 cm, and the relatively flat potential profile that is observed between 2 and 10 cm. There exists no detailed theoretical analysis as to how the potential structure and electron distribution should vary (at the end wall). However, a 10 V sheath and a cold electron species ($T_e < 15 \text{ eV}$) at the wall is not inconsistent with previous theoretical models used to determine the loss-cone distribution of electrons in TMX. In the fokker-Planck models, electrons which can exit the system (i.e., are in

the loss cone) are able to pick up 10 eV in energy in a final single pass of the machine. As such, electrons lost to the loss cone may form part of a cold-electron species outside the ambipolar potential region (part of the cold-electron distribution may be formed by cold-plasma production near the wall). A small sheath at the wall is then established to balance the flux of ions exiting through the ambipolar potential and the cold electron species present at the wall.²

From the collecting probe data a second colder species of electrons is indicated at $\phi \approx 0$ with $T_e < 4$ eV. This species is possibly a species of secondary electrons. The data is only preliminary, but thus far it provides remarkable evidence for secondary electrons. The evidence follows:

1. The potential at which the "secondary" species is collected is zero volts--regardless of the plasma potential measured with the probe at 10 cm.

2. The energy spread of the species is less than 4 eV. Secondary electrons have an energy spread of 2 eV.

3. The density of the species is within the value predicted by space-charge flow, assuming a 10 V sheath with a thickness less than 0.3 cm.

4. The density of the species is consistent with the value predicted from incident ion flux, basing the secondary emission on ion-wall bombardment.

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1. J. R. Smith, N. Hershkowitz, and P. Coakley, Rev. Sci. Instrum. 50, 210 (1979)
2. G. D. Porter, "Effect of Gas Recycling and Secondary Electron Emission," in Physics Basis for MFTF-B, Lawrence Livermore National Laboratory, Livermore, CA, UCID-18496-Part 2 (1980), p. IV-151.

IV.C YUSHMANOV REGION DENSITY MEASUREMENTS

(D. P. Grubb, T. A. Casper, J. H. Foote, A. H. Futch, and E. B. Hooper)

We report on the analysis of density measurements made in the Yushmanov trapped region of the east plug of TMX. TMX was operated in the normal tandem mirror configurations with neutral beams in both plugs and only a diagnostic beam in the central cell. The magnetic field configuration was the 1-kG, 10-cm field case. Data are reported for both puffer valve and inner gas box fueling of the central cell. Our analysis shows that the plasma density in the Yushmanov region is equal to or greater than that in the central cell.

It had been proposed that uncompensated quadrupole drifts of the Yushmanov-trapped particles (Fig. IV.C-1) could lead to rapid radial transport of these ions. Baldwin proposed that the resulting density depression in this region could create a thermal barrier. Ryutov and collaborators at Milan have proposed that the radial transport in this region would lead to an unstable velocity-space distribution which could drive an instability. This instability would then fill in this region faster than classical scattering. The result would be large scale radial losses of the central-cell ions in the Yushmanov regions of a tandem. More recent analysis by Byers, however, indicates that, within uncertainties about the radial electric field in this region, the quadrupole drifts will not be an important transport mechanism in this region of TMX.

To experimentally investigate this phenomena in TMX, a 4-mm (1 fringe = $5 \times 10^{13} \text{ cm}^{-2}$) microwave interferometer was installed in the Yushmanov region of the east plug (Fig. IV.C-1) at an axial position 34.3 cm to the west of center of the east plug. An interferometer is also located at the 10-kG point on the central-cell side of the magnetic field peak (mirror).

The microwave interferometers measure the plasma line density between the two horns in these regions. For example, in the Yushmanov region, the horn separation is 20.4 cm. However, the gas-box jaws serve as a plasma limiter which restricts the maximum size of the TMX plasmas to 15-cm radius (measured at 10 kG -- plug midplane). This maps to a maximum plasma dimension of 7.8 cm between the microwave horns. The microwave data was reduced according to

$$\hat{n}_Y = \frac{\int n dl \text{ (measured)}}{\pi (1/\epsilon)^{1/2} (B_{cc}/B_Y)^{1/2} r_c} \quad (1)$$

Fig. IV.C-1. Axial profile of magnetic field and density for gas-box and puffer operation.

where $1/\epsilon = 2.6/25.4$ is a measure of the ellipticity of the plasma fan, B_{cc} is the central-cell magnetic field (900 G), B_Y is the magnetic field strength at the axial position of the microwave horns (13.5 kG), and r_c is the radius of the central-cell plasma. Equation (1) is derived by mapping the circular central-cell flux bundle into the Yushmanov region requiring conservation of magnetic flux and using the ellipticity coefficient obtained from computer calculations (MAPCO) of the field-line mapping. Assumptions were made in deriving this equation: (1) The radial scale length, r_c , can be mapped along field lines; this is equivalent to assuming that the radial loss of particles between the central cell and Yushmanov region is not a function of radial position, and (2) there is no plasma in the region between the microwave horns beyond the cutoff imposed by the gas-box jaws.

A more correct equation for the peak density in the Yushmanov region is given by

$$\hat{n}_Y = \frac{\int n dl \text{ (measured)}}{(\pi)^{1/2} (1/\epsilon)^{1/2} (B_{cc}/B_Y)^{1/2} r_c} \frac{1}{\text{erf} \left[\frac{r_c / (B_p/B_{cc})^{1/2}}{15} \right]} \quad (2)$$

where the erf is introduced by the fact that the Gaussian profile of the density is cut off by the 15-cm (relative to the plug midplane) limiter of the gas-box jaws. However, the term cancels out when the ratio of $\hat{n}_Y/\hat{n}_c$ is determined because the same correction comes into the calculation of $\hat{n}_c$.

The peak density in the Yushmanov region thus computed was compared with the central-cell density for data of 5/27/80 (Table IV.C-1). The plug-plasma density at this axial position was estimated from axial beam attenuation measurements and found to be small. The results of this analysis show that n_Y and n_c are about equal.

More extensive measurements made during operation in August and September, 1980, are summarized in Fig. IV.C-1. The results for $-332 \leq z \leq 300$ cm and for $z = 0$ cm were obtained from measurements using neutral beam attenuation. The values for $z = 0$ and -320 cm were obtained using the attenuation along chords located at several radial positions. The measurements do not preclude the possibility of a cold plasma "blanket" contribution to the apparent maximum in density observed in the range $-286 < z < -221$ cm during gas box operation. However, extrapolation of the density profile from the central cell ($z = 0$) and the plug midplane ($z = 320$ cm) agreed to within 25%,

TABLE IV.C-1. Data from 5/27/80 for $B_{cc} = 1$ kG (90%) and $B_y = 15$ kG (90%).

Shot	$\int n_{dl},$ n_Y cm^{-2}	$r_c,$ cm	$n_Y,$ cm	$n_c,$ cm^{-3}	n_Y/n_c	Comment
15	0.7E13	51.7	9.2E11	1.0E12	0.92	Puffer valve 40 lbs., 1 turn
16	1.0E13	44.4	1.5E12	1.8E12	0.88	
18	0.6E13	41.3	9.9E11	1.2E12	0.82	
20	0.9E13	51.2	1.2E12	1.1E12	1.1	
58	2.4E13	27.6	5.9E12	2.9E12	2.0	Inner gas box 250 T, p 1.6 T
59	2.4E13	23.4	7.0E12	4.5E12	1.6	
60	2.0E13	23.0	5.9E12	5.8E12	1.0	
61	2.0E13	26.4	5.2E12	4.9E12	1.1	

implying that if there is a blanket its density drops rapidly between the gas box and the plug midplane.

These results indicate that when the central cell is fueled by the puffer valve(s) or by the gas box at a low pressure ($I_{gas\ box} \lesssim 650$ A) that $\hat{n}_Y \simeq \hat{n}_c$. However, when the pressure in the gas box is raised such that $I_{gas\ box} > 650$ A, a density maximum appears somewhere between the east-plug midplane and the central cell. It is not illogical to suppose that this maximum occurs in or near the east gas box.

It is worth noting that the axial beam attenuation array in the west plug does not indicate a similar density peak in or near the west gas box.

IV.D CALORIMETER MEASUREMENTS

(R. S. Hornady)

IV.D.1. CENTER CELL AND END WALL POWER MEASUREMENTS ON TMX

Energy loss to the central-cell walls of TMX is measured with an array of eight calorimeters. Four are located 52 cm west of the midplane equally spaced azimuthally at 52-cm radius. Three more are located on the same radius but 21 cm, 122 cm, and 193 cm east of the midplane. The last calorimeter is 13 cm above the centerline and 198 cm east of the midplane. It is above the flat part of the plasma fan. These calorimeters are the standard units used on TMX (16-cm² copper plate with thermistor and calibration resistor).

Data was taken during gas-box operation (27 May, 29 May, 17 and 18 July) puffer operation (27 May), and gas-box-with-puffer-impurity-injection operation (30 May). No signal is detected during background shots or any other shots in which plasma is not built up. No significant variation in energy was found on the azimuthal array. The calorimeters along the axis detect similar signal levels up to 122 cm. Calorimeter 7 always has a small signal, consistent with its position viewing the edge of the fan-shaped plasma. The signal on calorimeter 8 is approximately two times the signal detected on calorimeters 1 to 6, consistent with being close (13-cm radius) to a low-loss plasma. The calorimeters are not colimated and there are too few of them to deduce an axial power loss-profile, so the usual effective length of 314 cm is used in the data reduction and total power calculated. The results are presented in Table IV.D-1. The beam current was 120 A to 150 A in east and west plugs and electron temperature was 80 eV to 120 eV for this run.

During 17 and 18 July operation, calorimeters on the east and west end walls, close to the end-loss analyzers were also operated. These measurements were all gas-box operation with beam current and electron temperature as indicated above.

The average energy in the west is greater by the ratio of the duration of the beams (21 ms in the east to 26 ms in the west) during the 17 July run. Similar data on the 18 July run includes shots of beam and stream but no gas-box fueling. The end-loss energy during the stream-gun pulse (-6 ms) is 0.034 J/cm² and 0.048 J/cm² in the east and west ends respectively. This energy was subtracted and the shot duration adjusted for calculating the data of Table IV.D-2. The energy value in Table IV.D-2 is referenced to the end

TABLE IV.D-1. Measured central-cell power loss.

Type of operation	Average power loss
Gas box: $I_{\text{gas}} = 530 \text{ A}$	31 kW
Gas box: $I_{\text{gas}} = 530 \text{ A}$ & neon impurity = 750 A	42 kW
Puffer: $I_{\text{gas}} = 1540 \text{ A}$	116 kW

TABLE IV.D-2. Measured end wall power loss: gas-box operation, $I_{\text{gas}} = 500 \text{ A}$

Beam duration		Energy (J/cm^2)	Power
17 July	East 21 ms	0.101	106 kW
	West 25 ms	0.124	105 kW
18 July	East 21 ms	0.063	92 kW
	West 25 ms	0.191	131 kW

wall of the vacuum chamber where the magnetic field is 70 Gauss. The end-loss power assumes 7-cm radius plasmas in the 10-kGauss plug. The results indicate that while approximately 30 kW is lost radially, roughly 200 kW is lost axially.

IV.D.2 YUSHMANOV CALORIMETER

The "Yushmanov" calorimeter, located in the east plug, was operated during the diagnostic scan of 17, 18 July 1990. It is located at 4.5, -7.0, -286.0 cm (x, y, z). This point maps into a 17.6-cm radius flux surface at the plug midplane. The magnetic field modulus is 1.14 T and the field components are $B(r)$, $B(\theta)$, $B(z)$: -0.596, 0.183, 0.942 T. The calorimeter is a copper

disk .025 cm thick by 16 cm^2 surface area. The sensing thermistor and calibration resistor are bonded with thermal conducting epoxy to the copper.

Data was taken during 4 types of shots: Full duration shots, beam- and stream-only shots, background shots, and stream only shots. In full-duration shots the signals were huge relative to the design values so the calibration resistor cannot be used to calibrate the calorimeter; furthermore, for such large changes the thermistor nonlinearity is significant. The data was reduced by measuring the bridge values, calculating the thermistor resistance change, reading the temperature change from the thermistor calibration curve, and calculating the energy from the physical parameters of the calorimeter.

Table IV.D-3 shows the results of the four types of shots. The background and stream-beam contributions have been subtracted from the full-duration shots in order to estimate the power loss. The subtraction scheme is depicted in Figure IV.D-1.

The loss power in this region is nearly 40 W/cm^2 . To estimate the total power lost from the plug during a shot, the emission rate is assumed uniform and an equivalent loss area is estimated. In the location of the calorimeter, the plasma is a thin ellipse with the calorimeter parallel to the major axis of the ellipse, so the power measured should not be influenced by the distance between calorimeter and plasma (Fig. IV.D-2). Further, the emission area is reasonably estimated by the projected area of the plasma. The lower estimate of the area is taken to be the region from the magnetic mirror peak at -271 cm to the location where the ambipolar potential is one-half the peak value and the upper estimate is taken to be the region from the mirror peak to the midplane.

Assume that $\phi = T_e \ln(n_p/n_c)$ and that $n_p(z) = n_0 \exp(-z^2/\ell^2)$, then

$$\phi(z) = T_e \ln n_0/n_c - T_e z^2/\ell^2.$$

The axial scale length (ℓ) is 18 cm (from beam attenuation measurements), so the axial position at which $\phi(z)/\phi_0 = 1/2$ is $z \approx 12 \text{ cm}$ for $n_0/n_c \approx 3$.

The estimated areas are then 0.35 m^2 for the low and 0.42 m^2 for the high estimate. The power emitted is then 133 kW/plug to 160 kW/plug. This is not expected to be due to charge exchange because the calorimeter is 34 cm from the plug midplane and the energetic charge-exchange flux is emitted in a narrow-core perpendicular axis.

TABLE IV.D-3. Yushmanov calorimeter data.

Shot #	Energy Deposited, Joules/cm ²	Shot duration, s	Power ^a	Type of shot
19	0.13	21	6.19 (w/cm ²)	Background
20	0.12	21	5.71	Background
21	0			Stream only
22	0.81	6	120 ^b	Beam & stream
23	0.78	6	115 ^b	Beam & stream
24	1.38	21	39 ^c	Full duration shots with gas box
25	1.29	21	33 ^c	Full duration shots with gas box
26	0.99	21	13 ^c	Full duration shots with gas box
27	1.36	21	38 ^c	Full duration shots with gas box

^aSee Fig. IV.D-1 power formula^bAfter subtracting beam component^cAfter subtracting beam and stream component

Fig. IV.D-1. Yushmanov calorimeter background subtraction scheme.

$$\text{AREA} = \frac{(320 - 271)}{2} \cdot (33 + 10) \cdot 2 \cdot 2$$

$$= 0.42 \text{ m}^2$$

$$\text{AREA} = \frac{(308 - 271)}{2} \cdot (33 + 15) \cdot 2 \cdot 2$$

$$= 0.35 \text{ m}^2$$

Fig. IV.D-2. Yushmanov calorimeter emission data.

IV.E SANDIA CARBON/SILICON PROBE RESULTS

(R. Bastasz*, W. Bauer*, L. G. Haggmark*, A. E. Pontau*,
W. R. Wampler*, K. L. Wilson*, and R. P. Drake)

A series of carbon and silicon samples were exposed to the TMX plasma on July 17 and 18 using the central-cell Sandia probe at 30 cm. The results are summarized in Fig. IV.E-1. We use the saturation behavior of the carbon to extract an energy for the implanted deuterium. Based on the analysis shown in this figure, the incident D energy is approximately 100 eV. Note that the energy analysis is consistent with our assumptions of a Maxwellian energy distribution and cosine incidence. Approximately 10^{16} D/cm² are incident on the probe per shot, which extrapolates to a plasma density of $1-5 \times 10^{11}$ D/cm³. The carbon samples are presently being analyzed for impurity deposition.

Silicon samples were exposed simultaneously, and were analyzed by secondary-ion mass spectrometry (SIMS). Figure IV.E-2 shows SIMS deuterium-depth profiles of three silicon samples exposed to 3, 10, and 26 shots at 30-cm radius on July 17. A near-surface maximum in the D⁻ signal is evident and its magnitude appears to be correlated with the exposure period. This peak occurs at about 2 nm below the surface and can be attributed to the implantation of approximately 100-eV deuterium.

Figure IV.E-3 shows a negative SIMS spectrum (m/e: 1-30) from just below the surface of a silicon sample exposed to 41 shots on July 18. In addition to deuterium, negative secondary ions of many impurity species are observed. Ions containing carbon (m/e: 12-15, 24-28) and oxygen (m/e: 16-18) appear to dominate in this mass region. Each of these signals can be used to obtain a depth profile of the corresponding atomic or molecular ion fragment, allowing implanted impurities to be distinguished from surface absorption.

Depth profiles of O, OH, and OD were recorded from a silicon sample exposed to 41 discharges in the central cell of TMX on July 18. Due to possible secondary ion yield, variations these profiles do not necessarily give quantitative information about the abundance of these species. Figure IV.E-4 shows the normalized negative secondary ion intensity of mass 16 (O⁻) before and after exposure. It appears that the subsurface oxygen level in the

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silicon sample increased as a result of the TMX exposure. This may have resulted from either implantation of oxygen impurities in the plasma or radiation-enhanced diffusion of absorbed oxygen into the silicon. Figure IV.E-5 shows the profile of mass 16 along with those of masses 17 (OH^-) and 18 (OD^-). The OH profile contains no subsurface structure except for possibly a slight enhancement that is correlated with the structure in the O profile. In contrast, the OD profile contains structure reminiscent of the D profiles obtained previously. The formation of OD^- during the sputtering process is apparently related to the levels of both oxygen and implanted deuterium.

REFERENCE

1. S. A. Cohen and G. M. McCracken, J. Nucl. Mater. 84 (1979) 157.

Fig. IV.E-1. Deuterium retention data for carbon probes exposed to TMX compared with calculated deuterium saturation behavior in carbon from Ref. 1.

Fig. IV.E-2. Deuterium profiles of silicon samples exposed to central-cell discharges, obtained by monitoring the ejection of D^- during Ar^+ sputtering.

Fig. IV.E-3. Negative SIMS spectrum of a silicon sample exposed to 41 discharges.

MASS 16 PROFILES IN SILICON - BEFORE AND AFTER TMX EXPOSURE

Fig. IV.E-4. Oxygen-depth profiles of silicon samples before and after being exposed to 41 discharges.

TMX CENTER CELL SI PROBE "6" - 41 SHOTS

Fig. IV.E-5. Depth profiles of O, OH, and OD from a silicon sample exposed to 41 discharges.

IV.F HEAVY-ION-BEAM PROBE

(G.A. Hallock*)

Single-shot radial scans of the central-cell plasma have been obtained. A 4-ms sweep period is typically used, yielding five diameter scans per TMX shot. The potential is relatively flat to about 13 cm, followed by about 20 V/cm falloff for 10 cm. The secondary current level for shot 12 on July 18, 1980 is shown in Fig. IV.F-1. Preliminary processing of the raw data yields the potential profile in Fig. IV.F-2, where the radial sweep signal (± 17 cm) is also indicated. Processing has not included entrance angle variations in the secondary beam entering the analyzer, which may introduce 50 V or more error. The scan from 15 to 20 ms has been expanded in Fig. IV.F-3, showing the flat potential profile near the plasma center (which may actually be slightly hollow) and the falloff after 13 cm.

Computer codes for obtaining space potential profiles from raw beam-probe data have been developed for multiple shot radial scans (where the detection volume is held fixed during the shot for continuous temporal profiles and radial scans are obtained during constant-condition diagnostic runs). Preliminary codes for single-shot radial scans are operational. Hardware to transfer data from the beam probe's LSI-11 control computer (where data reduction is presently done) to the TMX diagnostic computer has been partially installed and interface software has been written.

Calibration of the system probe has increased space potential measurement accuracies to 30 volts. Spatial resolution has been increased to about 0.8 cm. The angular gain dependence of the secondary ion detector (an electrostatic energy analyzer) has been reduced for improved resolution during radial plasma scans. The axial gain dependence of the analyzer has been measured. Computer orbit simulations of the ion trajectories during calibration have reduced absolute calibration uncertainties.

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Fig. IV.F-1. Secondary current level (vertical scale, 20 nA/div; horizontal scale, 4 ms/div).

Fig. IV.F-2. Space potential profile and radial sweep waveform (vertical scale, 100 V/div; horizontal scale, 4 ms/div; sweep, 117 cm).

Fig. IV.F-3. Radial potential scan from 15-20 ms (vertical scale, 100 V/div; horizontal scale, 0.5 ms/div).

IV.G NEUTRON DIAGNOSTICS ON TMX

(D. Slaughter)

Neutron measurements have been extended to the west end plug using a shielded recoil proton spectrometer similar to that already in place on the east end plug¹. Absolute neutron-yield measurements have been used in conjunction with line-density and plasma-length data to determine $\langle\sigma v\rangle$ in the end plug plasmas. Since $\langle\sigma v\rangle$ is a rapidly rising function of the ion energies, (at least 3rd order) $\bar{W}_i$ may be determined from $\langle\sigma v\rangle$ with only slight dependence on the model assumed for the ion energy distribution. This calculation is carried out for selected shots on both end plugs.

The recoil proton detectors consist of a liquid-hydrocarbon scintillator (NE213). In addition to discrimination of neutron- and photon-induced scintillation based on differences in fluorescence decay time, the light output is pulse-height analyzed during some runs to obtain the energy spectrum of recoil protons. This data is then unfolded to obtain the neutron energy spectrum at the detector location. That is important since it allows a determination of the contribution of scattered neutrons at the monitor location so that the background is determined under plasma-source conditions. As a result, absolute neutron yield may be measured on each end plug with estimated errors of $\pm 15\%$.

Figure IV.G-1 shows the results of neutron spectra measurements on July 17, 1980: (a) shows the neutron spectrum at the east plug, (b) the spectrum at the west plug. Spectral intensity in these data show that scattered neutrons contribute $\approx 40\%$ of the neutron intensity above 1.0 MeV. The energy threshold established for counting is normally 1.0 MeV in order to partially suppress the monitor's response to scattered neutrons.

The spectral peak in a fusion-neutron spectrum has dispersion due to the Doppler effect resulting from center-of-mass motion of the reacting ions. For D-D fusion, the spectral width due to Maxwellian motion is ΔE_n (FWHM) = $82.7 \text{ keV } \sqrt{T_i}$ (keV) where T_i is the ion temperature. Since the instrument line shape has a width FWHM $\approx 200 \text{ keV}$ in these data, the broadening due to $\bar{W}_i$ in the range 4-7 keV is not sufficient to provide an unambiguous measurement of $\bar{W}_i$ directly. However, the observed spectral width is consistent with $\bar{W}_i$ inferred from the yield. At higher $\bar{W}_i$, a direct measurement should be possible.

REFERENCE

1. D. R. Slaughter, Neutron Yield Measurements on a TMX Endplug, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-52923 (1980).

(a)

(b)

Fig. IV.G-1. Neutron energy spectrum measured at TMX end plugs. Data accumulated during shots 39-68 on July 17, 1980. (a) East end plug. (b) West end plug.

IV.H PYROELECTRIC DETECT MEASUREMENTS

(W. L. Barr)

The pyroelectric detector measures the absorbed fraction of the total incident power flux, which consists of photons and charge-exchange neutrals. Because of the black chrome plating on the detector, the absorption of photons should be nearly complete (~80%). The energy absorption from D^0 depends on incident energy. (For H, T, or He on Cu, it varies from 60% at 50 eV to 80% at 400 eV). The strong points of the pyroelectric detector are: it has fast response; it is rugged, simple, and not affected by magnetic field or gravity. Its weak points are: it is very sensitive to microphonics, to charge-up of its surfaces, and to capacitive coupling to its surroundings.

The detector is mounted on the bottom of the central cell as shown in Fig. IV.H-1. It is about 1.68 m from the axis of the machine and views about a 30-cm length and width of plasma.

Calibration with a high-intensity lamp that produced 5 W/cm^2 showed that the lead zirconate-lead titanate (PZT) ceramic detector gives 10 nA per absorbed W/cm^2 . The I-to-V converter has a gain of $2 \times 10^6 \text{ V/A}$, giving a final calibration factor of $0.02 \text{ V/W}\cdot\text{cm}^{-2}$.

The equivalent circuit of the detector is a current source in parallel with the capacitance C of the detector. A current-to-voltage converter produces a voltage proportional to the heat flux. The advantage of the I-V converter is that its low input impedance allows it to be located far from the detector. Then, a series resistor R at the input to the I-V converter can provide filtering by controlling the response time $\tau = RC_{in}$; and C_{in} is almost entirely due to the cable since $C = 150 \text{ pF}$ for the detector on TMX. The series resistor also serves to isolate the I-V converter from C_{in} , which would tend to cause it to oscillate.

The cylindrical detectors are cemented to BNC connectors with silastic which gives mechanical isolation and also shields the signal lead from stray current. Since the signal current amounts to only $10 \text{ nA/W}\cdot\text{cm}^{-2}$, the signal lead must be well shielded from plasma. Also, the sides of the cylinders tend to charge up and produce noise. This charge-up was apparently the reason that the detector did not work on the end wall. Solid shielding of the sides makes mechanical coupling and gives much more microphonic noise.

Noise can also be coupled into the signal through stray capacitance to the output face of the detector. For this pickup to be small,

$$(C_{\text{stray}}) \frac{d}{dt} (\Delta V) \ll I ,$$

where ΔV is the voltage difference across the stray capacitance C_{stray} . For example, if the machine ground changes by 0.1 V in 1 ms when $I = 10$ nA, we would have to keep $C_{\text{stray}} \ll 100$ pF between machine ground and the output face. The present holder satisfied this by having the mounting spool held at diagnostic room ground and insulated from the machine.

Fig. IV.H-2 shows a recorded signal together with that from an identical detector whose view of the plasma is blocked off. This data is taken with 1-kG central-cell field with gas-box feed of approximately 500 atom amperes. These data were taken under rather poor operating conditions. The neutral beam currents were 150 and 160 atom amperes in the east and west plugs respectively. That the background signal is near zero indicates that the signal from the open detector is not noise pickup. The power losses are highest when streaming-plasma guns are on.

Normally the signal is not detectable on the pyroelectric detector (less than 0.4 W/cm^2). Detectable signals are usually obtained on the first few shots of the day, or as shown in Fig. IV.H-2, before cooling the liquid nitrogen (LN) liners. Because the vacuum improved on July 15, 1980, we were able to observe that the pyroelectric signal decreased into the noise level as indicated in Table IV.H-1. This behavior indicates that the pyroelectric detector signal is related to machine vacuum conditions.

TABLE IV.H-1. Pyroelectric detector signal for data of July 15, 1980.

Shot	LN liners	Central-cell pressure (Torr)	Pyroelectric detector signal (W/cm^2)
17	Warm	4.2×10^{-7}	2.5 to 2.0
27	Warm	3.7×10^{-7}	0.7
36	Cool	1.0×10^{-7}	<0.2

We estimate the central-cell power loss for the large-signal case of Fig. IV.H-2 as follows. The detector collects about 2 W. Its area is about 1 cm², so that the power density is about 2 W/cm². Since the detector is 168 cm from the plasma axis, we estimate the equivalent surface area to be about fifty square meters. Thus, the central-cell power losses are about a megawatt, if the power is lost uniformly and not concentrated in the midsection near the pyroelectric detector. This is comparable to the power than we trap into TMX. We do not understand why this measurement gave such a large signal on this day during these shots, but generally the power is not detectable (less than 0.4 W/cm²) or that the total power is less than 280 kW.

Fig. IV.H-1. Location of the pyroelectric detector on TMX.

Fig. IV.B-2. Signal from the pyroelectric detector and reference detector.

IV.1 FARADAY CUP MEASUREMENTS

(C. V. Karmendy and E. B. Hooper)

Preliminary studies with a single Faraday cup mounted near the center of the east wall substantiate the current level as measured by the end-loss analyzer to within better than a factor of two. Two recently installed 13-channel arrays (one across either end fan) are designed to determine the ion saturation current as a function of radius. The advantages of Faraday cups over simple biased disks include accurate knowledge of the collection area and the elimination of cold-plasma effects by the use of suppressor and bias voltage. Results from this array are shown in Fig. IV.1-1.

Comparison of the current density as measured by the Faraday cup (FC) and east end-loss analyzer (ELA) yields $j_{FC}/j_{ELA} = 0.68 \pm 0.15$. The uncertainty includes 0.14 standard deviation (12 shots on 7/15/80 to 7/17/80), and a possible systematic error of 10% (5% from hole diameter and 5% from load resistor and scope calibration). The statistical and systematic errors are combined as rms.

The Faraday-cup aperture was measured carefully on an optical comparator, yielding a diameter of 0.019 ± 0.0005 in., including an "out-of-round" contribution. The hole was beveled, yielding an edge estimated at 0.001- to 0.002-in. radius. In operation, the FC suppressor was biased to repel electrons (typically -500 to -1000 V) and the collector biased to repel cold plasma ions (25 to 150 V) which originate near the end wall.

The above calibration is in good agreement with Bill Barr's direct converter measurement. For the above operation, the direct-converter current density $j_{dc} = 0.155 \text{ A/cm}^2$, compared with an average of 0.21 on the ELA; $j_{dc}/j_{ELA} = 0.74$.

Fig. IV.I-1. East end-wall Faraday-cup array referenced to plug midplane.

IV.J ANALYSIS OF END-LOSS IONS

(D. P. Grubb, T. A. Casper, and J. F. Clauser)

During the period January - July, 1980, we significantly improved our ability to analyze the current density and energy spectrum of the end-loss ions. A second high-voltage amplifier was obtained so that we could ramp the ion-repeller grids on both the east and west end-loss analyzers. In addition, we were able to extend the range of the high-voltage ramp so that we can now sweep the ion-repeller grid from 0 to 2 kV in approximately 360 μ s. The ability to bias the repeller voltage to 2 kV is necessitated by the fact that the plug potential, ϕ_p , often exceeds 1 kV under good running conditions.

An example of the end-loss data after it has undergone baseline subtraction and multiplication by the appropriate scale factor is shown in Fig. IV.J-1. The attenuation of the measured end-loss flux by the ion repeller is clearly seen.

Perhaps the most significant improvement in the analysis of end losses during this period was the development of the ELANA code by Casper, Clauser, and Friedman. This code determines the end-loss current density, J (A/cm^2), the plug potential, ϕ_p (V), and the mean energy of the end loss ions, T_i (eV). The quality of the fit to the data depends upon the fluctuations in the end-loss current which are caused by bursting. In Fig. IV.J-2 the fluctuation of the current around the fit line is due to bursting which occurs on a time scale which is shorter than the ramping time. As seen in Fig. IV.J-3, there was less bursting of the east end losses on this shot so a better fit to the data was obtained.

The output of this code is available either in tabular or graphical format. Figures IV.J-4 and IV.J-5 are examples of the graphical output. The stepped nature of the graphs represents the fact that the plotted data points represent an average over the duration of the voltage ramp.

As is seen in Fig. IV.J-4 and 5, it is often the case that the end-loss ion energy is greater than the plug potential. We have also noted that the end-loss energy and plug potential appear to be fluctuating on a time scale that is fast compared to variations in most other measured plasma parameters (n_p , r_p , diamagnetism, etc.). These observations are not yet understood.

Analysis is also underway at this time that compares the measured current density and energy spectra of the end-loss ions to those values predicted by our codes which model the confinement of the central-cell ions

and the effects of plug driven rf on that confinement. It is hoped that this analysis will further increase our understanding of the role that plug rf plays in central-cell confinement.

Lastly, we note that the analysis of the end-loss ions yields a measure of the power being carried to the end walls by the central cell ions. This information is valuable in power-balance studies.

Fig. IV,J-1. End loss current density vs time for east and west ends of TMX (above) and swept ion repeller voltage vs time (below).

Fig. IV.J-2. West end loss energy spectra at four different times.

7/18/80 Shot 25 BKS 20 END LOSS ANALYZE EAST

Fig. IV.J-3. East end loss energy spectra at four different times.

Fig. IV.J-4. East end loss current density and plug potential vs time.

7/18/80 SHOT# 25 BKND SHOT# 20 PLOT INTERVAL: 100.00 USEC
 15.00 DIAG # 110 END LOSS ANALYZE PROCESSOR: S. ANA

Fig. IV.J-5. Energy of end loss ions vs time.

IV.K NET END-WALL CURRENT MEASUREMENTS

(E. B. Hooper and C. V. Karmendy)

We have used the end-wall button probes in a net-current-collection fashion. That is, by terminating each of the button probes with a $50\ \Omega$ resistor to machine ground, we measure the total current density at 13 points along a chord running through the fan at either end of the machine. We find, in general, that the loss is predominantly electronic via the end walls, indicating a net ionic loss elsewhere, either to some limiter (such as the gas-box jaws) or by radial diffusion and loss to the cylindrical parts of the tank.

The net-current profiles show some scatter from shot to shot, and retain a spatial variation after shot averaging (see Figs. IV.K-1 and IV.K-2). This variation is not more than about 50% around a mean value, which is typically around -200 mamps/cm² for the west wall and -300 mamps/cm² for the east wall. (Current density is referred to plug midplane.) The profile drops at one edge of each end fan: the north edge of the west fan (possibly because of an interference by an obstacle along the field line) and the lower edge of the east fan (of unknown cause).

Upon correlation of the net-current profile to the ion-saturation current, one can obtain an estimate of the radial diffusion of ions, assuming that cross-field transport of electrons is comparatively small, and assuming some model for the departure of the diffusion from an axisymmetric form. If one assumes axisymmetry, a rather high central-cell ion radial-diffusion coefficient is obtained:

$$D_{i,cc} \approx 10^4 \text{ cm}^2/\text{s} .$$

Detailed results require the ion-saturation-current profile, and may require modification pending Faraday cup array data.

Fig. IV.K-1. Net current density to east end wall.

Fig. IV.K-2. Net current density to west end wall.

IV.L RADIO-FREQUENCY PROBES

(T. A. Casper)

In order to expand our knowledge of the nature of fluctuations in TMX, additional radio-frequency (rf) probe arrays have been designed and installed in the west end cell and central cell regions, Fig. IV.L-1. The west end-cell probe is a 5-tip array of high-impedance probes identical to the east-plug array except that one end tip has a larger separation (4 cm). This gives a maximum spacing of 7 cm (tip 1 to 5) for resolution of $|k|$ due to long wavelength perturbations. The probe is located at a geometrical location approximately equivalent to the east probe position. This allows for a direct comparison of the relative stability of the TMX end-cell plasmas. Preliminary data has been acquired using this probe, but is limited to the low T_e running of TMX. With this in mind, the following comparisons between east and west end-cell fluctuations have been noted:

1. The nature of the instabilities observed in the two end-cells can change dramatically depending upon the relative quality of the plug plasmas. The rms fluctuation level, bursting nature, and mode structure are sensitive to plug parameters. A detailed study of both end cells, including variations with line density, SED signals, and beam current input (power input), is required to answer the overall stability questions.

2. Generally, the east end cell appeared more unstable than the west and therefore, had a greater influence on the central-cell rf. This may be totally a consequence of the low T_e operation. It has also been observed that $\omega_{oe} \approx \omega_{cio}$ with larger $k_{\perp}$ values ($m \approx 10$) and phase shifts consistent with propagation in the ion diamagnetic drift direction (and therefore opposite the 12/13/79 data, section II).

3. Have observed $\omega_{ow} \lesssim \omega_{cio}$ (and therefore $\omega_{ow} < \omega_{oe}$) with small $k_{\perp}$ values which tend to be opposite the ion diamagnetic-drift direction.

4. Observations (2) and (3) can change on a shot-to-shot basis thus implying a sensitivity of TMX fluctuations to details of operation.

5. Some shots have given results for both plugs which are consistent with the rf scan on 12/13/79.

The extrapolation of these results to the relative plug stability at high T_e is obviously in question since the preliminary data is apparently in contradiction with past (single-plug) rf measurements.

The two new central-cell probes consist of eight tips each--six high-impedance probes to observe electrostatic fluctuations and provide k_1 measurements plus two magnetic pickup loops oriented to be sensitive to $\hat{B}_\theta$ and $\hat{B}_z$. The probes are located at $z = \pm 150$ cm and can move radially along the $\theta = 45^\circ$ azimuthal line on the upper north side of TMX central cell. Since the central-cell disk probe observed fluctuations near the plug cyclotron frequency, these probes are intended to provide wave number measurements, k_{1cc} , for comparison with plug values. The two axial locations are intended to give rudimentary information concerning the parallel mode structure in the central cell. It has been suggested that low-frequency fluctuations in the TMX central cell could be a result of unstable drift waves. Horton¹ shows that the most unstable mode exhibits an antisymmetric wave function in the parallel direction. This could be verified using the probe arrays in TMX. To date, these probes have been used during low T_e operation. The following observations have been made:

1. $\omega_{occ} \approx \omega_{oplugs}$ as observed by the central-cell electrostatic probes in agreement with the disk probe results, Fig. IV.L-2. No k_1 data has been analyzed since timing fiducials for the transient recorders were not available.
2. Evidence exists for low-frequency, broad-band fluctuations, dc to ≈ 500 kHz, as observed by electrostatic probes, Fig. IV.L-3.
3. $\hat{B}_\theta$ loop observes fluctuations similar in nature to the electrostatic probes, i.e., both plug ω_{ci} and low frequency perturbations. The $\hat{B}_z$ loop sees very little, if any, signal.
4. ω_{cicc} has not been observed.

Experiments concerning the relative plug stability and central-cell fluctuations have only recently begun and are presently limited to low T_e operation. A detailed rf scan has been planned for the near future to identify the central-cell fluctuations and to resolve some of the apparent contradictions in the observed spectra of end-cell fluctuations. Finally, a magnetic pickup probe consisting of three loops, $\hat{B}_r$, $\hat{B}_\theta$, and $\hat{B}_z$ has been constructed to investigate the electromagnetic character of modes observed in the east end cell. Preliminary data indicate oscillations at frequencies near the ion-cyclotron frequency of the end cell with $|\hat{B}_r|$ and $|\hat{B}_\theta|$ greatly exceeding the $|\hat{B}_z|$ level.

REFERENCE

1. W. Horton, Nuclear Fusion 20, 321 (1980)

Fig. IV.L-1. Radio-frequency probe arrays.

Fig. IV.L-2. Power spectrum, central-cell electrostatic probe.

Fig. IV.L-3. Power spectrum, central cell turbulent fluctuations.

IV.M ULTRAVIOLET SPECTROSCOPIC STUDY OF THE TMX CENTRAL-CELL PLASMA

(T. Nash, R. J. Fortner, and D. Dietrich)

We have studied ultraviolet emissions from the TMX central cell using a 2-m normal-incidence spectrometer. The normal-incidence spectrometer on the north central cell offers sufficient resolution with a 1200 l/mm grating to observe line broadening. Assuming all broadening is due to thermal motion, ion temperatures are found from line widths by the equation,

$$kT = A \cdot \frac{(\Delta\lambda)^2 - (\Delta\lambda_{ins})^2}{(m\lambda)^2} \cdot 1.664 \cdot 10^8 \text{ eV} ,$$

where

- A = ion atomic weight,
- $\Delta\lambda$ = observed line width, FWHM,
- $\Delta\lambda_{ins}$ = instrumental line width,
- m = order, and
- λ = wave length.

From the cleanup runs of August 11, film was exposed to 54 plasma shots. The spectra obtained were digitized and then analyzed. Several lines from a wide range of ionization states of C, N, and O, as well as Al III were seen. Figure IV.M-1 illustrates the broadening of the C I line at 1930.9 Å. Figure IV.M-2 gives an instrumental line width obtained from a Pt-Ne hollow-cathode discharge tube.

The spectra observed is between 1700 and 2100 Å. Table IV.M-1 identifies several lines and ion temperatures as determined by line widths.

Figure IV.M-3 shows the C IV lines at 1548.2 and 1550.8 Å in second order, as obtained on July 2 from TMX shots 24-29. The asymmetry of each line is readily apparent, and may be due to a $\vec{E} \times \vec{B}$ drift. Figure IV.M-4 gives an instrumental line width of 0.16 Å near the C IV lines.

Some of the width of other plasma lines may be due to an $\vec{E} \times \vec{B}$ drift. In this case all the values of the ion temperatures given in Table IV.M-1 must be considered upper bounds. By installing a cylindrical mirror in front of the spectrometer, and thereby obtaining spatial resolution, we will resolve the question of exactly what is causing the broadening, and also obtain radial profiles of ion temperatures and densities.

Fig. IV.M-1. Doppler broadening of C I line.

Fig. IV.M-2. Instrumental line width.

TABLE IV.M-1. Ultraviolet spectra and ion temperatures
for N, O, C, and Al ions.

Ion	(Å)	Order	kT (eV)
N III	989.8	2	71
N IV	923.22	2	143
O III	703.85	3	57
O IV	625.852	3	184
O IV	609.829	3	159
O V	629.7	3	213
O VI	1037.6	2	180
C I	1930.9	1	78
C II	1037.0	2	80
Al III	1854.7	1	183

Fig. IV.M-3. Doppler broadening of C IV line.

Fig. IV.M-4. Instrumental line width.

IV.N NEW EUV DIAGNOSTICS

(O. T. Strand*)

The instrumentation for studying extreme ultraviolet (EUV) impurity radiation from TMX has been expanded since January 1980. The original experiment called for one time-resolving monochromator (400 to 1600 Å), which views a single chord of plasma to be used. This instrument was portable enough to be easily moved from the central cell to one of the plugs in order to examine and compare the three regions of TMX. Recently, however, this instrument was moved to the west plug and two new instruments were added--one to the east plug and one to the central cell--so that each region of TMX can be observed during a single shot. One of these new instruments was purchased by LLNL, the other belongs to Johns Hopkins University (JHU), as does the original instrument. The new monochromators are also time resolving in the same wavelength range (400 to 1600 Å) but differ from the original one in that they each view simultaneously 22 spacial chords of their respective plasma. This greatly reduces the number of shots required for full spacial scans and for comparisons of the three regions of TMX. The spatial imaging monochromator belonging to JHU has been described in the literature,¹ the LLL instrument is similar. The imaging is achieved by using the small dimension of the entrance slit as a one-dimensional pin hole and by setting the detector far enough behind the exit slit to provide the desired spatial resolution and field of view. The detector is made of a pair of micro-channel plates backed by 22 discrete anodes. The signals from the anodes are pulse-counted simultaneously, stored in the memory of a minicomputer, and then processed at the end of the plasma shot. The instrument on the east plug views 21 cm of the plasma with 0.95-cm spatial resolution while the central cell instrument views 36 cm with 1.65-cm resolution. The time resolution on each of these instruments can be varied from 125 μs to 256 ms, but is presently set at 500 μs. Both of these instruments are absolutely calibrated for brightness, as is the original instrument, so that radiated power losses and impurity densities may be obtained.

*Johns Hopkins University, Baltimore, MD.

REFERENCE

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IV.O CENTER CELL IMAGING (H. Koehler)

X-ray diagnostics will play an important role in TMX Upgrade when electron-cyclotron resonance heating (ECRH) will be employed. We have recently demonstrated a system developed in L-Division which could be used on TMX Upgrade to obtain images of the spatial distribution of hot electrons generated in the thermal barrier regions by ECRH.

The x-ray pinhole cameras used during the start-up of TMX which recorded images on film have been supplemented with an imaging system which provides greater sensitivity, time resolution with 1-ms frame rate, and instant data display. This new system consists of a 50 x 50 Reticon photodiode-array camera, high-speed memory, and a microprocessor. The camera has a 55-cm-diam field of view located slightly west of the center of the central cell of TMX and consists of a pinhole, filter, fiber-optic (FO) coupler, microchannel plate intensifier (MCPI), and FO reducer. The 15-mil-diam pinhole provides 1.9-cm resolution at the plasma location (pinhole limited).

The spectral region recorded can be selected by using Be (0.4, 0.8) μ , Al (0.2, 0.4) μ , or LiF filters, which are installed in the filter wheel (5 locations are available). A dry-run light (LED) is used for checking the proper operation of the system; it occupies one of the openings in the filter wheel. A layer of sodium salicylate on the FO coupler converts x-rays and UV photons to visible photons [approx 4500 $\text{\AA}$ at a relatively high and uniform quantum yield (10%)]. The MCPI with a S-25 photocathode and P-46 anode provides gain (approx 150) with no loss of spatial resolution. The FO reducer (2.5:1) couples the 18-mm-diam MCPI to the 0.5 x 0.5 cm^2 Si-photodiode array. Preparations are also made to adapt a Chevron plate with a 5:1 FO reducer to the Reticon camera. The variable gain of the MCP ($1-10^6$) greatly enhances the UV/x-ray sensitivity of the imaging system.

The Reticon camera is calibrated in digitizer values (counts) versus energy per pixel or resolution element. Also, the exact field of view of the camera is measured for the center cell.

The images obtained with the camera are digitized (3.3 MHz) and stored in a large, high-speed memory. Exposure time, number of exposures, and start of the first exposure can be varied. The minimum exposure time (temporal resolution) is determined by the time gate of the MCPI (no gate is presently used). The minimum framing time and thus the maximum number of frames is

fixed by the readout time of the photodiode array, i.e., 0.9 msec. The memory can store 45 images.

A local microprocessor (LSI-11) provides instant processing and display of the data. Raw data and background-subtracted data (background frame taken at -5 ms) can be presented as dot plots, frequency plots (histograms), and intensity plots (row/columns). Ordinarily, the intensity is scaled automatically in 36 steps. Any one, two, three, or four frames may be selected or deleted from memory (quick look) and if desired stored on a floppy disk for future reference. The instant-replay feature may be expanded onto a TV monitor in the TMX control room.

The data stored on floppy disks can then be further processed on OCTOPUS. Pseudo-color plots, color contour plots, and three-dimensional plots can be obtained from the raw data, as well as from any desired arithmetic transformation of the data. An Abel inversion can also be made on the processed data.

Figures IV.O-1 and IV.O-2 show cross sections of plasma images obtained with and without a 4000 Å Be filter. This foil blocks off X-rays with energy less than about 50 eV. The differences indicated in the figures suggest strong UV emission from the boundaries of the plasma and shell surrounding a hot central core. The 1/e radius of these two images are 13 and 17 cm respectively. For comparison the central-cell plasma radius measured by beam-attenuation detectors is 21 cm. These measurements indicate good up-down symmetry and centering of the TMX central-cell plasma about 2 cm below the geometrical center of the machine.

Fig. IV.O-1. Plasma image cross section with a $4000 \text{ \AA}$ Be filter.

Fig. IV.0-2. Plasma image cross section without a filter.

IV.P SPECTROMETER X-RAY MEASUREMENTS ON TMX

(J. P. Stoering, G. A. Burginyon, H. D. Snyder, A. Toor,
C. Anderson, R. Crabb, M. E. McGee, P. Poulsen)

A medium resolution (about 0.1 keV) reflection-refraction spectrometer,¹ which allows spectral diagnosis of bursts of x-radiation from about 0.5 keV to 8.0 keV, was used to measure x-rays from TMX plasmas.

The spectrometer is illustrated in Fig. IV.P-1. Incident x-rays, accepted by the collimator-slit system, pass through a selected filter and a thin light barrier before reflection at grazing incidence from a polished vitreous carbon mirror to the face of a fluor-photomultiplier tube. The photomultiplier tube was optically bonded to a thin (about 0.3 mil) NE102 fluor. A thin scintillator was chosen to minimize neutron background. The detector angle was kept sufficiently grazing ($<9^\circ$ with respect to the reflected beam) to guarantee 100% absorption of all x-rays <1.5 keV reflected by the carbon mirror. X-rays below about 0.17 keV are reflected from the detector and are undetected. The current from the photomultiplier is a direct time-dependent measure of the contents of a selected energy band from the incident spectrum into the scintillator. The lower and higher energy cuts of the x-ray band are determined by the appropriate filter selection and carbon mirror angle respectively.

As shown in Fig. IV.P-1, the carbon mirror and detector are mounted on separate goniometers. The detector goniometer rides on a translation stage to maintain proper θ to 2θ geometry for various settings of carbon mirror angle. In addition, this translation stage can move the detector in and out of the x-ray beam for purposes of background determinations. Both goniometers as well as the translation stage and filter wheel are remotely controlled. Angular settings are accurate to $\pm 0.01^\circ$ and the translation stage can be set to within 0.02% (about 12 μm) of full travel.

Earlier TMX experiments have confirmed that our measured signals are indeed x-rays, with no optical or ultraviolet contribution. The possibility of a UV contribution was eliminated by experiments using a LiF filter, opaque to x-rays but transparent to UV below 10 eV. This, in combination with an experiment in which one x-ray bin was gradually closed to x-rays by increasing the carbon mirror angle, provided final confirmation.

All spectrometer measurements were normalized to signals from a four-channel x-ray detector. Three x-ray channels incorporate filters having lower edge transmission half values at 0.65, 0.75, and 0.95 keV. The remaining channel, having a thick filter (black to x-rays) is used as a shot-to-shot neutron monitor.

PRELIMINARY RESULTS

Figure IV.P-2 shows the preliminary average TMX spectrum measured for the diagnostic runs of July 17 and 18 by the DREXS spectrometer. The spectrum was deconvoluted from single-channel energy responses recorded one at a time for each shot. Several measurements for each response function were recorded at different times during the diagnostic run by stepping systematically through the response functions from shot to shot. The data for each channel were normalized to the total x-ray energy separately measured for each shot by four thin filter-scintillator photomultiplier tubes. The spectra shown in Fig. IV.P-2 have been smoothed since any structure present in the spectrum could not be uniquely inferred from the data. The integrals of the product of the measured spectrum times each response function agree within a factor of two with our average measured current for each channel that gave statistically significant signal. A comparison of Art Toor's calculations based on coronal equilibrium is included.² These calculations are now being modified to include a more realistic electron distribution than the assumed Maxwellian, to include the effects on the ionic populations caused by charge exchange from the neutral beam interactions, and more realistic impurity abundances. The model spectra in Fig. IV.P-2 are identified by their $T(0,0)$ temperatures. The curve labeled $ALL_{(T)}$ is the averaged spectrum for the measured Thomson scattering temperature distribution.

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2. A. Toor, "Calculated Emission Spectra for MFE Plasmas," XRM-78-168, December 18, 1978.

Fig. IV.P-1. Double reflection x-ray spectrometer (DREXS).

Fig. IV.P-2. Preliminary TMI x-ray spectrum for diagnostic runs of July 17 and 18.

IV.Q VISIBLE SPECTRAL SURVEY OF TMX CENTRAL-CELL PLASMA

(A. M. Frank, C. A. Anderson, and M. P. Paul)

A spectral survey was performed on the TMX central cell using an electronic spectrograph covering the range 370 to 690 nm. The primary purpose was to survey the wavelength regions where Thomson scattering signals would appear. This study indicated that central cell Thomson scattering would be feasible.

The plasma is viewed with a 6-in.-diameter achromatic lens looking up through the central cell one pitch west of center. The spectrometer uses a modified B & L half-meter monochromator and the signal is detected with a microchannel-plate (S-20 photo cathode) coupled through a phosphor to a 1024-linear silicon-diode array (Reticon). The array is read in 5 ms with a 10-bit A/D converter by an 8080 microprocessor. Background levels are subtracted by the microprocessor and data is output to a video display. Data can also be output to an X-Y plotter or to punched tape. Punched-tape data is smoothed and plotted using SOCKITTOME on the OCTOPUS system.

With a 600 g/mm grating used in the first order, the system covers 500 Å with a resolution (intensifier-limited) of 30 Å. Wavelength calibration with a mercury source and known deuterium lines allows spectral calibration to better than ± 5 Å. The absolute spectral response of the system will be calibrated after measurements on TMX are completed. The spectral response of the photocathode is given in Fig. IV.Q-1. The optics cutoff (somewhere below 3700Å) and the grating efficiency are not presently known but will be determined during the calibration. The response of the reticon is linear, saturating at about 950 counts.

Fig. IV.Q-1. S-20 spectral response.

The spectrum in Fig. IV.Q-2 is a composite of 10 spectra surveying the spectral range of the instrument. The data was taken on 7/15-16 using an integration time of 25 ms starting at $T + 5$ ms. Note that the double peaks of D_{α} and 464 nm are fluctuations from the computer smoothing of the saturated detector. Also note that the individual spectra used in the composite were taken over two days running of TMX with varying machine conditions. Consequently the intensities of lines in the composite can only be compared when they occur in the same individual spectrum. The individual spectra are labeled, A-I and one is unlabeled.

The results of the survey indicate the presence of molecular N_2 bands, at $\lambda = 646.8$ and 678.8 nm. These N_2 bands appear to be responsible for much of the limiting background radiation currently seen by the Thomson Scattering system. The brightness of these lines was correlated with the N_2 level of the RCA. The band at 646.8 nm was the strongest, up to 10% of the D_{α} emission. This band is responsible for the failure of channel 10 of the Thomson Scattering system. It might be useful to monitor Channel 10 as a measure of the amount of N_2 in the machine during a shot.

Fig. IV.Q-2. Composite spectrum of the TMX central cell.

V.A MAGNET ALIGNMENT

(R. S. Hornady)

The initial and subsequent alignments of the TMX magnet set are described in this section. Because of the effort expended in alignment, we believe that the TMX magnet set, which comprises 18 coils in 12 individually movable units, is well aligned. In this context, "well aligned" means that there is no evident deleterious effect on the plasma traceable to errors in magnet geometry. In this section, we describe the various magnet alignments in chronological order. Section V.B describes field calculations with the measured coil displacements.

INITIAL ALIGNMENT

During the assembly of TMX, a fixed z-axis was defined by cross hairs mounted at the ends of the central-cell tank. The magnets are all mounted in the fixed vacuum tanks. The z-axis defined by the cross hairs may shift relative to the pit; however, the relative alignment of the magnets should be unchanged because the entire unit of fixed tanks plus central-cell tank is a "stiff beam." The initial magnet alignment was judged to be accurate within 0.45 cm of translation and 1.5° of rotation. More detail is provided in Ref. 1.

JUNE 1979 ALIGNMENT

Photographs of the plasmas created by the plasma guns were taken during the Spring of 1979. These photographs, and the plasma-gun marks in the machine, led first to proper alignment of the plasma guns in April 1979. Further photographs showed that the west baseball coil was out of alignment. On June 29, 1979, this coil set was rotated 2° about a vertical axis. Subsequent photographs showed a substantial improvement.

DECEMBER 1979 ALIGNMENT

The west baseball coil set was moved with the aid of the electron beam, in order to improve the performance of the light ion beam probe (LIBP). The reference axis was determined by a line through the cross wire at the west outer C-coil and the LIBP analyzer. No comparison was made with any other machine centerline. The east end of the west baseball coil set was lowered 1 cm, and the west end was moved 0.8 cm to the south.

FEBRUARY 1980 ALIGNMENT

This alignment was done using the cross-hair wires. A reference axis was established using two wires in the east baseball coil set and one wire each in the east transition set and the west transition set. The west baseball set was moved.

JUNE 1980 ALIGNMENT

The magnetic axes of the east and west plug magnets were determined during the June shutdown by means of an e-beam. This device contains an electron gun and an accelerating structure in an evacuated glass tube. The electrons may be accelerated up to 500 V; a current of 1 to 5 mA is extracted. At these low energies, the electrons follow field lines well. The entire beam trajectory is visible because the electrons cause the residual gas in the tube to fluoresce.

The original line-of-sight axis was reestablished by bringing a transit into coincidence with the line determined by the cross wires strung on the east and west ends of the central cell tank. These cross wires were the original alignment fiducials.

XY-translator mounts for the e-beam were installed in the east plug with the source at $z = -161$ cm and the second mount at $z = -279$ cm. The tube was made coaxial to the line of sight just established, and the position of the tube relative to the translator mounts recorded the "zero reference" location.

The various magnets (EBB, EIC, E86, and E180) were energized at a low level (5 to 10%) in continuous mode. The e-beam was then moved so that the electron trajectory was straight and centered in the tube, and position readings were taken for each magnet. The east plug set was then energized with the currents in approximately the same ratio as in normal operation and the "best" tube location determined. The tube was then turned end-for-end, placing the emitter at $z = -279$, and the measurements were repeated.

The tube was then placed in the west plug with the mounts located at $z = +152$ and $z = +278$ cm and the gun at the $+278$ cm position. The magnet axes were then determined for the WIC, W86, and W180 magnets. The WBB was not tested because it had low resistance to ground.

The results of these measurements were used in the magnetic field calculations described in Sec. V.B.

REFERENCE

1. R. L. Wong, L. R. Pedrotti, C. A. Leavitt, A. F. Waugh, A. K. Chargin, and M. O. Calderon, "The TMX Magnet System, Present and Future," in Proc. 8th Symp. Eng. Prob. Fusion Research, San Francisco, 1979 (IEEE, 1979) p. 158; also Lawrence Livermore National Laboratory, Livermore, CA, UCRL-82971 (1979).

V.B MAGNETIC FIELDS IN TMX USING MEASURED COIL LOCATIONS

(E. B. Hooper)

We have calculated magnetic fields in TMX (1 kG) using the coil locations as measured during the period June 6 through June 13, 1980. The coil displacements and angular rotations from alignment are summarized in Table V.B-1.

The only significant uncertainties in these measurements are the following:

- The values of θ_x in the east plug and transition region were measured twice with an e-beam and once (optically) with the cross hairs attached to the coils. The first beam measurement indicated a value large enough to cause a significant effect, even though the rotation measurements indicated a much smaller angle. The result from the cross hairs was used.

- The west baseball and outer C-coil were not measured with the e-beam. However, the cross-hair axis lined up well with the axis of the inner C-coil as measured with the e-beam.

The angles α , β , and γ are the Euler angles. For small rotations,

$$\tan \alpha = \theta_y / \theta_x$$

$$\beta = \theta_x^2 + \theta_y^2^{1/2}$$

$$\gamma = \theta_z - \alpha$$

Results are shown in Figs. V.B-1 through -9. The "magnetic axis" is shown in Fig. V.B-1; the axis is defined as the field line starting from $x = y = z = 0$ (the machine center). Note that between the plug centers (+320 cm) the center line deviates from the $x = y = 0$ line by less than 1 cm.

Figures (V.B-2 through -9) show the magnetic axis defined as $r = 20$ cms at $z = 0$. Each plot shows 12 field lines spaced at 30° at $z = 0$. Straight lines connecting the points have been drawn for ease in observing the surfaces.

The most dramatic effect occurs from the rotation of the east plug about the z -axis by 1° . The resulting rotation can be seen in the figure showing the east gas box (Fig. V.B-2). Because the fan is so narrow there, the rotation causes an offset that is a significant fraction of the plasma width. However, because the entire transition and plug set is rotated, there is no distortion of the surface.

The west coils are not rotated about z . As a result, the surfaces are displaced but not significantly distorted. This can be seen, for example, at the location of the west streaming-plasma gun (Fig. V.B-7).

In all cases, the effects are small. It seems highly unlikely that they could seriously affect the plasma confinement.

Table V.B-1. Coil alignments.

Coil	Axis (cm)	Rotation (degrees)						Displacement		Comments
		θ_x	θ_y	θ_z	α	β	γ	Δx	Δy	
East outer C	-279	0.0	-0.24	1.0	90.0	-0.24	-89.0	0.3	0	Assumed same as east baseball.
East baseball	-279	0.0	-0.24	1.0	90.0	-0.24	-89.0	0.3	0	e-beam 6/12, except θ_x from cross hairs 6/6.
East inner C	-279	0.0	-0.44	1.0	90.0	-0.44	-89.0	0.35	0.37	e-beam 6/12, except θ_x from cross hairs 6/6.
East 86° trans.	-279	-0.15	-0.44	1.0	-108.8	0.46	109.8	0.1	0.65	e-beam 6/12, except θ_x from cross hairs 6/6.
East 180° trans.	-279	-0.15	-0.44	1.0	-108.8	0.46	109.8	0.5	0.32	e-beam 6/12, except θ_x from cross hairs 6/6 and θ_y set same as for E86.
Solenoid		-----								Not measured.
West 180° trans.	152	-1.1	-0.2	0	-169.7	1.12	169.7	0.1	-0.8	e-beam 6/13.
West 86° trans.	152	0.09	-0.55	0	-80.7	0.56	80.7	0.1	0.3	e-beam 6/13.
West inner C	152	0.5	-0.3	0	-31.0	0.58	31.0	0	0.7	e-beam 6/13.
West baseball	320	0.4	0	0	0	0.4	0	0	-0.73	Cross hairs 6/6.
West outer C	320	0.4	0	0	0	0.4	0	0	-0.73	Cross hairs 6/6.

Fig. V.B-1. Mapping of measured TMX field line from $x = 0, y = 0, \text{ and } z = 0$.

Fig. V.B-2. Mapping of 20-cm-radius circle from central cell to east gas box ($z = -235$).

Fig. V.B-3. Mapping of 20-cm-radius circle from central cell to west gas box ($z = +235$ cm).

Fig. V.B-4. Mapping of 20-cm-radius circle from central cell to center of east plug ($z = -318$ cm).

Fig. V.B-5. Mapping of 20-cm-radius circle from central cell to center of west plug ($z = +318$ cm).

Fig. V.B-6. Mapping of 20-cm-radius circle from central cell to streaming-plasma gun location ($z = -420$ cm).

Fig. V.B-7. Mapping of 20-cm-radius circle from central cell to streaming-plasma gun location ($z = +420$ cm).

Fig. V.B-8. Mapping of 20-cm-radius circle from central cell to east end wall ($z = -720$ cm).

Fig. V.B-9. Mapping of 20-cm-radius circle from central cell to west end wall ($z = +720$ cm).

V.C GAS-BOX OPERATION - PARTICLE INPUT AND ENERGY LOSSES

(E. B. Hooper, G. E. Gryczkowski)

We have calculated ion deposition and plasma power losses for gas-box operation of a plasma such as in TMX. The plasma is modeled as a one-dimensional slab. Extensive parameter variations in density, temperatures, and profiles are summarized in this section.

The deposition rates are surprisingly insensitive to plasma parameters in the range of TMX operation. In the limit of absorbing walls, approximately 50% of the incident deuterium nuclei are lost as Franck-Condon and charge-exchange neutrals. Energetic neutrals generated by charge exchange have a mean free path several times greater than the plasma width, and thus charge-exchange neutral deposition is not significant unless the walls are highly reflective. The deposition profile is slightly hollow, but the deposition at the plasma center is within a factor of three of that at the maximum (near the edge).

Uniform deposition in the plasma requires uniform illumination of the plasma by the incident gas. Layout of gas valves, gas diffusers, etc. in the gas box is important.

The energy cost to the plasma for highly reflecting walls can be modeled quite well by $1/2(T_e + T_i) + 25$ eV, averaged over the deposition profile. The first term arises from the energy needed to heat the deposited ion-electron pair, and the second term from the ionization and excitation energy. Possibly, large radiation losses from a cold-plasma edge have not been accurately modeled.

MODEL

The TMX gas-box plasma has been modeled as a slab to determine the trapping of gas, the distribution of deposited ions, energy losses to electrons and to ions, etc. The calculation was done using the CRSC7 code. Molecular deuterium is assumed incident on the plasma, and the processes of ionization, dissociation, and charge exchange are followed through as many generations of neutrals as necessary to evaluate their effects.

The walls of the gas box may be absorbing or either partially or wholly reflecting. For present purposes only, the extreme cases of wholly absorbing and reflecting have been considered.

Examination of magnetic field profiles in the gas-box region (Fig. VC-1) indicates that the field profile is almost independent of the central-cell field. A 1-cm width of the fan corresponds to about 7.7 cm in the plug center. The strength of the field in this region does vary somewhat, as indicated in Fig. V.C-1. To good approximation, therefore, we expect the deposition of plasma to depend on central-cell field only through the plasma properties. Cross-field transport in the gas box, on the other hand, might be significantly stronger for the low central-cell field case.

In most of the calculations described here, we have modeled the plasma density as

$$n = 4 \times 10^{12} \exp [-(x/1.4)^2] \quad (1)$$

The electron and ion temperatures have been given two spatial profiles: Gaussian with width 1.4 cm, and flat (independent of width). The dependence on the magnitude of the temperatures has been examined in detail.

ION DEPOSITION--DEPENDENCE ON PLASMA PARAMETERS

In Fig. V.C-2, we show the net ion deposition rate ($D^+ \text{ cm}^{-3} \cdot \text{s}^{-1}$) profile for the four combinations $T_e, T_i = 50, 100 \text{ eV}$; all have Gaussian profiles. Gas is uniformly incident on the slab from both sides at 1 A/cm^2 of molecules. We see that the deposition is almost independent of the ion temperature; in the remainder of the calculations we keep $T_i = 50 \text{ eV}$. Note that the plasma is almost transparent to atoms of this energy, so that charge-exchange atoms escape with a high probability unless the gas-box walls are highly reflecting.

The peak of the absorption is shifted outward somewhat and the dip of deposition in the center increased at the higher temperature, but the deposition rate is surprisingly insensitive to the electron temperature. Even at 250 eV (not shown), the peak is only $4.7 \times 10^{18} \text{ cm}^{-3} \cdot \text{s}^{-1}$ at 1.45 cm, and the minimum at $z = 0$ is $1.9 \times 10^{18} \text{ cm}^{-3} \cdot \text{s}^{-1}$.

The deposition rate is also insensitive to the plasma density. In Fig. V.C-3, the rate is plotted for a central-cell density of $2 \times 10^{13} \text{ cm}^{-3}$. The peak is higher and at greater x than the corresponding case at $4 \times 10^{12} \text{ cm}^{-3}$, and the minimum is slightly less. Physically, the lack of sensitivity arises because the mean free path for incident molecules is quite short in both cases, so that molecules are broken up at the plasma edge. The mean free path for Franck-Condon neutrals is comparable to the plasma thickness when averaged over the direction of propagation. Thus, near the center of the plasma the

density of Franck-Condon's (from both plasma edges) is down somewhat, but their ionization rate is up for the higher density, so that the deposition rate is only slightly affected.

In the limit of reflecting walls (both particles and energy), the deposition rate is increased (all incident particles are ultimately absorbed) and the center filled in because the energetic reflected particles can reach the plasma center. An example is shown in Fig. V.C-4.

In the limit of a flat electron temperature profile, the deposition rate depends even less on the temperature than for the Gaussian, as shown in Fig. V.C-5. As one would expect, there are considerably more ions deposited on the plasma edge, but in the interior of the plasma the results are much the same as for the Gaussian temperature profile.

• Our first conclusion is that the deposition rate depends only weakly on the plasma and wall parameters in the range of interest. The deposition rate in the center is less than that at the plasma edge by no more than a factor of three.

The net absorption of incident nuclei by the plasma is shown in Fig. V.C-6 for absorbing walls; fully reflecting walls, of course, yield 100%. We see that net absorption depends only weakly on the assumed plasma parameters for $T_e > 100$ eV, with a range of 45 to 65%. Below 100 eV, the absorption drops off, especially for the Gaussian profile. This temperature dependence results from the changing nature of the molecular neutral and molecular ion/plasma interactions. For low-temperature plasmas ($T_e \approx 7$ to 26 eV), electron dissociation of the incoming molecular neutrals dominates, generating two Franck-Condon neutrals per incident molecular neutral. At birth, 50% of the resulting Franck-Condon neutrals are directed towards the wall, but some are ionized before leaving the plasma. At higher plasma energies, electron ionization of the incoming molecular neutrals dominates, and electron dissociative excitation that generates only one Franck-Condon neutral per incident molecular neutral dominates the dissociation of the molecular ions. Thus, a smaller proportion of the incident neutral flux can escape as Franck-Condon neutrals at higher energies; the lower limit being about 30% for the present scenarios. The rest of the particles in the escaping flux are charge-exchange neutrals that are principally generated by plasma ions charge exchanging with the resultant Franck-Condon flux. Thus, the escaping charge-exchange flux is directly proportional to the generation of Franck-Condon neutrals. As a result, for $T_e < 100$ eV the assumption that

half of the incident deuterium nuclei escape as Franck-Condon and charge-exchange neutrals and half are ionized is fairly accurate.

- Our second conclusion, therefore, is that approximately 50% of the incident nuclei are absorbed by the plasma. Of the remainders, some (unknown) fraction will be absorbed after reflection from the gas box walls.

NEUTRAL DENSITY PROFILES

Examples of the neutral density profiles are shown in Figs. V.C-7 and V.C-8. For the case of absorbing walls (Fig. V.C-7) the molecular density dominates the atomic density except near the plasma center where the Franck-Condon are comparable. For walls that are fully reflecting both for atoms and energy, the densities of Franck-Condon and of charge-exchange neutrals are both significantly higher than the molecular densities.

ION DEPOSITION-EFFECT OF NONUNIFORM ILLUMINATION

To illustrate the effect of nonuniform illumination of the plasma, we assumed that gas is incident from only one side. In the results (Fig. V.C-9) we see that the deposition rate shows the asymmetry. The precise drop-off is a function of the molecular and Franck-Condon mean free paths (properly averaged), the density profile, etc.

- Another conclusion is that because the Franck-Condon mean free path is comparable to the plasma size, uniform illumination is important.

ENERGY LOSSES IN GAS BOX

The energy loss by the plasma electrons is defined for present purposes as the sum of the energies of ionization and dissociation of the reacting neutrals, radiation from un-ionized deuterium, and the energy required to heat the electron ($3T_e/2$). The only uncertainty in the calculation is the energy lost to radiation. We have chosen 10 eV/ionization, consistent with calculations that indicate that ionization and excitation require 25 eV at high electron temperatures. The result is shown in Fig. V.C-10; for a flat profile the energy loss can be calculated easily from Fig. V.C-6, but a weighting including spatial effects is required for the Gaussian profile. At temperatures well in excess of 25 eV, the primary energy loss is in heating the new electron. Note, however, that radiation may be greater from the relatively cool plasma edge than assumed here.

The energy loss to the ions is defined as any input to ionization (small), energy carried away by charge exchange to the walls and not returned by reflected particles, and the energy necessary to heat the ions to $3T_i/2$. This loss is plotted in Fig. V.C-11. Note that for the assumed $T_i = 50$ eV, the energy cost of heating the new ions is an appreciable fraction of the plasma energy loss in the gas box. Transport has, of course, not been included.

The energy losses have also been calculated for the limiting case in which the walls are fully reflecting for both particles and energy, (cf Figs. V.C-12 and V.C-13. Power losses are a factor of 1.5 to 2 higher than for absorbing walls, resulting from the greater deposition rates in the plasma.

CONCLUSION

Our final conclusion is that the power losses for gas-box operation of TMX are dominated by the energy required to heat the deposited particles to the energy of the corresponding plasma species.

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Fig. V.C-1. TMX magnetic fields in the gas-box region. Shown are field lines corresponding to 10-cm radius in the end plugs.

Fig. V.C-2. Ion deposition rate for varying electron and ion densities for $n_e = 4 \times 10^{12} \text{ cm}^{-3}$ and absorbing walls.

Fig. V.C-3. Ion deposition rate for $n_e = 2 \times 10^{13} \text{ cm}^{-3}$ and $T_e = T_i = 50 \text{ eV}$ with Gaussian spatial profile and absorbing walls.

Fig. V.C-4. Ion deposition rate for $n_e = 4 \times 10^{12} \text{ cm}^{-3}$ with reflecting walls.

Fig. V.C-5. Ion deposition rate for flat electron and ion temperature profiles for $n_0 = 4 \times 10^{12} \text{ cm}^{-3}$ and absorbing walls.

Fig. V.C-6. Fraction of neutrals absorbed in plasma vs electron temperature for fully absorbing walls.

Fig. V.C-7. Neutral density profiles for absorbing walls.

Fig. V.C-8. Neutral density profiles for reflecting walls.

Fig. V.C-9. Ion deposition rate for one-sided input.

Fig. V.C-10. Ion power loss vs electron temperature for absorbing walls.

Fig. V.C-11. Electron power loss vs electron temperature for absorbing walls.

Fig. V.C-12. Ion power loss vs electron temperature for reflecting walls.

Fig. V.C-13. Electron power loss vs electron temperature for reflecting walls.

V.D PARTICLE STORAGE IN THE GAS-BOX WALLS

(R. P. Drake, M. I. Baskes*, K. L. Wilson*)

SUMMARY

We conclude that during operation of TMX using the gas box, the gas-box walls absorb approximately one deuterium atom for each two atoms ionized in the core of the TMX plasma. These atoms are released from the wall after the plasma shot and before the next shot. This section describes the fluxes striking the wall, the modeling of the wall interactions, our results, and the associated uncertainties. This topic is important because the TMX Upgrade must fuel the central cell using gas boxes.

FLUXES

Three types of fluxes strike the stainless-steel gas-box walls. The D_2 molecules create a gas pressure of about 10^{-3} Torr within the gas box (to equalize the input and the pumping). The resulting flux of order $10^{18} \text{ cm}^{-2} \cdot \text{s}^{-1}$ rapidly establishes an equilibrium at the surface of the gas box wall ($\sim 1 \text{ ms}$). Hence, this flux does not contribute to the storage of deuterium in the wall.

The D_2^+ ions created at the plasma boundary usually dissociate and produce Franck-Condon neutral atoms (2 to 10 eV). We do not know where this boundary is relative to the gas-box slits, and we do not know what happens to the cold D^+ ions remaining at the plasma boundary. The Franck-Condon neutrals are probably reflected from the gas-box wall. However, no data exist at these low energies, and some of these neutral atoms might be stored in the wall.

Finally, for each neutral atom that penetrates the plasma and is ionized, approximately one neutral atom undergoes charge exchange within the plasma. (This is because the rate coefficients are roughly equal for TMX parameters.) The charge-exchange product escapes the plasma and strikes the wall, from which it has about a 50% probability of being reflected. This implies that for each two atoms ionized in the plasma, roughly one atom comes to rest in the wall. We have investigated what happens to these atoms. The key question is whether they are re-released during or after the plasma shot.

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MODEL

The interactions in the wall were modeled using the computer code DIFFUSE.¹ This code is a numerical solution to the diffusion equation in the presence of trapping sites.

The source term for the diffusing hydrogen is taken from Monte Carlo TRIM calculations² of the range profile for a 100-eV Maxwellian energy distribution with a cosine angular incidence. The diffusivity, radiation damage trap concentrations, and trap binding energies are taken from the experimental measurements of Bohdansky et al.³ for deuterium implantation in 304 LN stainless steel at room temperature. The surface recombination boundary condition is for a clean stainless-steel surface.⁴ The DIFFUSE code follows the nonreflected portion of the charge-exchange flux in the wall during repetitive 25-ms discharges and 300-s periods between shots. Fifty discharge cycles were simulated.

RESULTS

Figure V.D-1 shows the results of this investigation. The amount of deuterium stored in the wall is shown both after a shot and before the next shot. We find that, of the $7.5 \times 10^{15} \text{ cm}^{-2}$ 100 eV (Maxwellian) D^0 atoms absorbed in the wall during the shot, $2 \times 10^{15} \text{ cm}^{-2}$ are released during the shot and $5.5 \times 10^{15} \text{ cm}^{-2}$ are released after one shot but before the next. A small amount of deuterium is stored within the wall. Physically, the radiation damage traps and the wall bulk load up with deuterium during the shot, but empty between shots because of the relatively low activation energies of migration (0.6 eV) and detrapping (0.8 eV).

CAVEATS

Although these results create a clear qualitative picture, the quantitative results are uncertain because many effects are not well understood at present. In particular, the code models a clean, oxide-free stainless-steel surface, whereas the gas boxes have a surface oxide. In addition, ion-induced detrapping may contribute to the diffusion of the deuterium, and ion-induced desorption may increase both the rate and character of the desorbed deuterium.

Nevertheless, the calculations do emphasize the importance of plasma-wall interactions on gas-box recycling.

Fig. V.D-1. Results of gas-box-wall simulation.

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V.E GAS PENETRATION
(R. P. Drake and G. E. Gryczkowski)

The total axial loss current observed from the central flux tube of TMX depends upon several processes (Fig. V.E-1), which change when the neutral beams fueling one end plug are turned off. Gas penetration to the core of the central-cell plasma provides the particle source. The axial losses, which are directly measured, depend on classical processes and on the plasma fluctuations, as described in Sec. II.A.

Radial losses are expected due to magnetic drifts. At the core of the plasma in the central-cell, these losses are negligible. The low-energy ions trapped in the end plug (Yushmanov ions) may be lost quickly as suggested by Ryutov, but the maximum losses of this type are usually small compared to axial losses.

AXIAL LOSS: MEASURED BY END-LOSS ANALYZER

RADIAL LOSS: ESTIMATED FROM NEOCLASSICAL THEORY

- LOSSES IN CENTER CELL
- LOSS OF YUSHMANOV IONS IN PLUG

IONIZED SOURCE: ESTIMATED USING COMPUTER CODE

- MULTIPLE CHARGE EXCHANGE PENETRATION
- RADIAL PROFILES AFFECT RESULTS
- WALL REFLECTION IS IMPORTANT
- AFTER EAST PLUG TURNOFF THE SOURCE ON AXIS INCREASES DUE TO MEASURED DECREASE IN ELECTRON TEMPERATURE AND RADIUS

IONIZED NEUTRAL BEAM: NEGLIGIBLE COMPARED TO CENTER-CELL FUELING

Fig. V.E-1. TMX central-flux-tube losses and sources.

The neutral atoms that are ionized at the core of the central-cell plasma must balance the losses. Deuterium gas strikes the plasma boundary but does not penetrate to the core. We have begun to study the fueling of the central-cell plasma using a computer model developed by G. E. Gryczkowski. The neutral atoms ionized at the core of the central-cell plasma are the result of several successive charge-exchange events. The amount of ionization deep within the plasma is sensitive to the plasma densities and temperatures, and also to the probable reflection of neutral atoms by the radial walls of the central-cell vacuum chamber. After one end plug is turned off, the electron temperature is lower and the central-cell plasma is smaller. This enhances the source of ions near the machine axis. The ionized neutral beam current is negligible compared to the ionized neutral current in the central cell.

A comparison of sources and losses in TMX is shown in Fig. V.E-2. The current, normalized to the end-plug midplane, is plotted as a function of central-cell density. These data were obtained by varying the amount of neutral-beam current fueling the end plugs. The plasma fluctuations and the central-cell confinement changed substantially during these measurements. The predicted gas penetration is shown in the limits of no wall reflection and total wall reflection. The observed axial losses lie between these limits. The estimated radial losses are a small correction, but do group the total estimated losses more tightly. After the decay of one end-plug plasma, both the predicted source and the observed losses increase. We are working to refine this model and to obtain better data, including better radial profiles.

Fig. V.E-2. Comparison of central-flux-tube sources and losses in TMX.