UCRL-53120 Summary

Summary of TMX Results
Executive Summary

TMX Group
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PREFACE

This is an executive summary of UCRL-53120, *Summary of TMX Results*, a large and detailed document now in final technical editing. The complete report will be available shortly.

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INTRODUCTION

This report summarizes results from the successful experimental operation of the Tandem Mirror Experiment (TMX) over the period October 1978 through September 1980. The experimental program, summarized by the DOE milestones given in Table 1, had three basic phases: (1) an 8-month checkout period, October 1978 through May 1979, (2) a 6-month initial period of operation, June through November 1979, during which the basic principles of the tandem configuration were demonstrated (i.e., plasma confinement was improved over that of a single-cell mirror), and (3) a 10-month period, December 1979 through September 1980, during which the initial TMX results were corroborated by additional diagnostic measurements and many detailed physics investigations were carried out. This report summarizes the early results, presents results of recent data analysis, and outlines areas of ongoing research and data analysis which will be reported in future journal publications.

The TMX experiments demonstrated the fundamental tandem mirror principles, as summarized in Table 2. Table 3 lists the maximum plasma parameters achieved in TMX. The main result was that TMX generated electrostatic confining potentials that significantly improved central-cell plasma confinement. These data established a new scaling of ion confinement by ambipolar potential in magnetic mirror systems and provided the impetus for the initiation of both TMX Upgrade, a tandem mirror in which potential confinement is increased through the use of thermal barriers, and MFTF-B, a larger tandem mirror that will extend the TMX Upgrade results to thermonuclear temperatures.

TABLE 1. Summary of TMX milestones.

	Milestones	Date achieved	Reference
1.	Begin TMX checkout.	Oct 1978	Direct communication to DOE
2.	Begin plasma-buildup experiments.	Jul 1979	Direct communication to DOE
3.	Determine density and beta of plug and solenoid.	Sep 1979	Direct communication to DOE
4.	Demonstrate electrostatic plugging of solenoid ions in a measured well.	Sep 1979	Direct communication to DOE
5.	Submit draft report evaluating initial TMX performance.	Oct 1979	*Phys. Rev. Letters* 44, 1132 (1980)
6.	Begin neutral-beam heating experiments in solenoid with two beams.	Nov 1979	Section III.E[a]
7.	Submit final report evaluating initial TMX performance.	Jan 1980	UCID-18496
8.	Submit a plan for modification of TMX, based on TMX data, that will address issues most appropriate to MFTF-B.	Jan 1980	Mirror Senior Review Panel
9.	Begin plug-optimization experiments.	May 1980	Section III.G[a]
10.	Submit report on measurements of initial electron-beam experiments in TMX.	May 1980	Section III.G,[a] UCID-18725
11.	Submit report evaluating impurities in TMX including types and origins of impurities.	Oct 1980	Section III.I,[a] UCID-18883
12.	Obtain Thomson-scattering measurements of TMX solenoid electron temperature.	Sep 1980	Section III.A[a]
13.	Initiate procurement of hardware to improve TMX performance.	Aug 1980	Initiation of TMX Upgrade construction
14.	Submit report summarizing TMX results.	Feb 1981	UCRL-53120
15.	Submit report on radial transport of plasma in the solenoid of TMX.	Feb 1981	Section III.F[a]
16.	Submit report on initial TMX central-cell ICRH experiments.	Dec 1980	UCID-18866

[a]Section of this report (UCRL-53120).

TABLE 2. Summary of TMX results.

- **Generated tandem mirror configuration:**
  - —Configuration sustained for full 25-ms shot duration.
  - —Plug microstability maintained with solenoid outflow.
  - —Central-cell MHD stability (40% maximum beta with neutral-beam injection).
- **Demonstrated central-cell electrostatic plugging:**
  - —Measured electrostatic potential well.
  - —Direct evidence by measurements made when one end plug was turned off.
  - —Measured factor-of-9 electrostatic enhancement.
  - —Radial confinement exceeds axial confinement.
- **Improved electron confinement:**
  - —Electron temperature higher than in 2XIIB.
  - —Low density at end wall.
  - —Dominant power loss to end walls.
  - —Low levels of impurities.

TABLE 3. Maximum plasma parameters achieved in TMX with deuterium and a central-cell magnetic field strength of 0.1 T. These parameters were not *achieved simultaneously on the same shot.*

Plug density	4×10^{13} cm^{-3}
Plug ion energy	13 keV
Plug electron temperature	0.26 keV
Plug radius	10 cm
Central-cell density	3×10^{13} cm^{-3}
Central-cell ion energy	0.25 keV
Central-cell radius	30 cm
Plug plasma potential	1 kV
Central-cell confining potential	0.3 kV
Central-cell axial-confinement parameter	10^{11} cm$^{-3}\cdot$s
Electrostatic enhancement in confinement	9
Central-cell beta (0.07 without central-cell neutral-beam injection)	0.40

INITIAL TMX RESULTS

Tandem Mirror Configuration

● One of the expected tandem mirror characteristics verified by TMX was that the density of the plasma in the end plug could be sustained at a higher level than that of the central-cell plasma, and that this produced higher electric potentials in the end plugs than in the central cell. These densities were controlled by varying the end-plug neutral-beam current and the central-cell gas-feed current. The density peaks generate potential peaks, as shown in Fig. 1, which also shows that relatively small end-plug plasmas can electrostatically confine a much larger central-cell plasma.

● The density and temperature of the TMX plasma are within a factor of 2 of those predicted by theoretical codes. Calorimeter measurements showed that most of the neutral-beam power deposited on the axis is carried to the end walls by ions.

● Gross MHD stability and microstability were achieved. Finite-beta plasma was confined in the central cell with minimum-B end-plugs. The outflow of central-cell plasma provided end-plug microstability.

Improved Plasma Confinement

● The TMX end plugs improve confinement of the central-cell plasma by up to a factor of 9 over that which would have been attained if the end-plug plasmas had not been present. Typical enhancements were in the range of 3 to 7 times. Central-cell axial confinement of ions is near that predicted by our theoretical models.

● TMX plasma confinement can be explained by classical Coulomb theoretical models, over a certain range of parameters. However, there must be sufficient warm plasma to stabilize the plugs. If insufficient low-energy plasma flows through the end plug, then fluctuating electric fields develop at the end-plug ion-cyclotron frequency and confinement of central-cell ions is reduced. Theoretical models describing TMX performance over a wide range of operation have been developed on the basis of these experiments.

● A second measure of improvement in the tandem mirror over the single mirror is the electron temperature that can be achieved with a given amount of input neutral-beam power. TMX end plugs achieved electron temperatures up to 260 eV, three to four times higher than the electron temperatures of the similar single-cell mirror machine 2XIIB when operated with comparable neutral-beam input power. Since TMX has such a large central-cell plasma, this electron temperature increase indicates a hundred-fold improvement in electron energy confinement. This improvement arises from the fact that the low-energy plasma required for end-plug microstability is supplied from

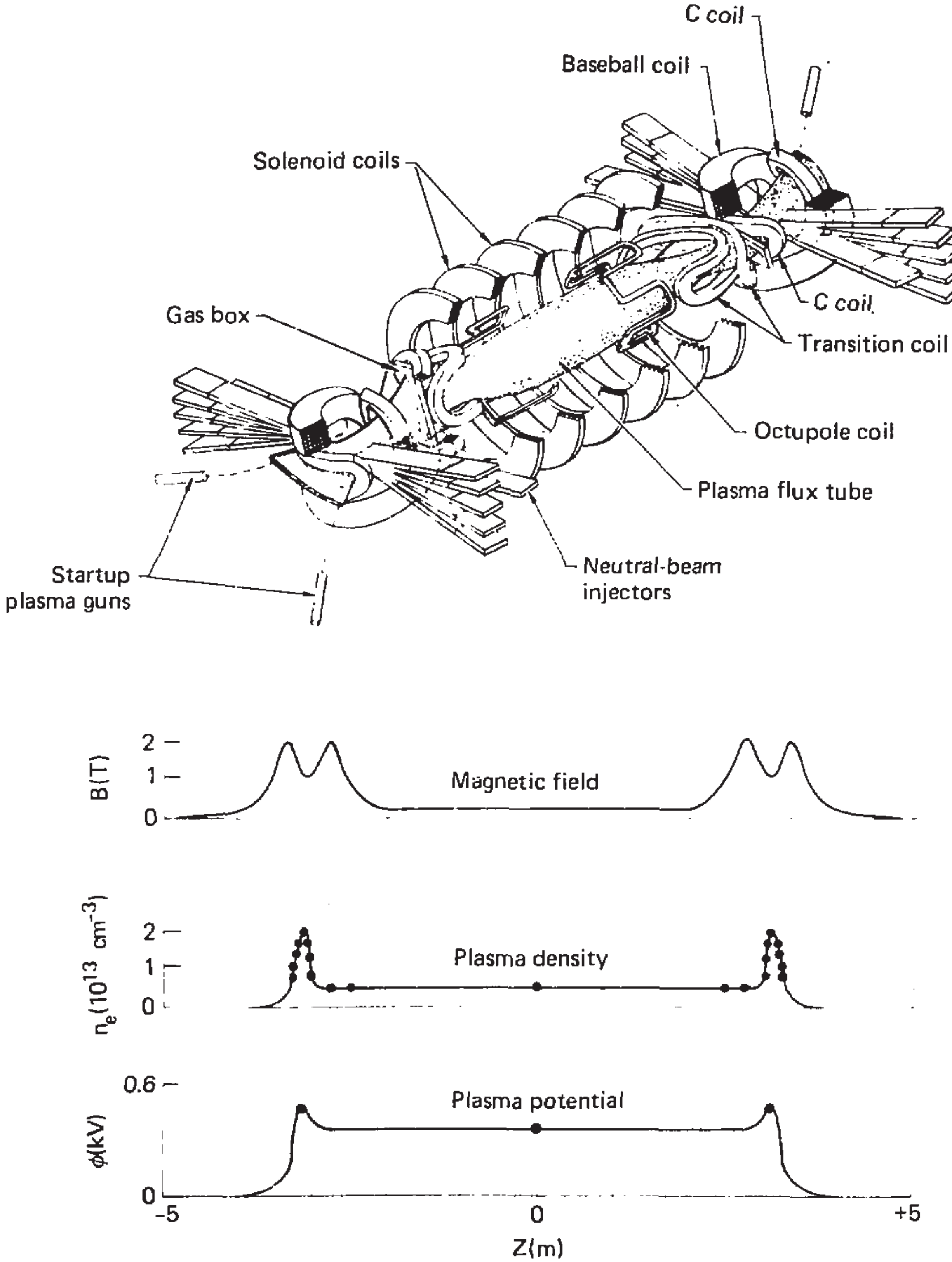

FIG. 1. TMX magnet geometry and measured axial plasma profiles.

the TMX central cell rather than from the ends, as in 2XIIB, thus reducing the electron energy loss to the end walls.

NEW RESULTS PRESENTED IN THIS REPORT

During much of the last period of TMX operation (December 1979 through September 1980), poor vacuum conditions caused lower electron temperatures than had been achieved earlier (although sometimes temperatures above 200 eV were still observed). Therefore, our progress during the later phases of TMX operation was in physics understanding rather than in increasing plasma parameters. This increase in understanding resulted from more extensive diagnostic instrumentation, new data analysis, and improved theoretical understanding. Highlights of these recent results are summarized below.

Tandem Configuration

- Plasma potential measurements carried out as a function of radius have shown that the electrostatic potential well is not just localized near the axis but extends across the central cell. The well-diagnosed plasmas had 150-V well depths, as expected for the measured electron temperature and densities. Other cases had well depths about twice as high.
- End-plug potentials exceeding 1 kV have been generated and maintained in TMX.
- Methods for controlling the radial profiles have been demonstrated. Operation of TMX over a wide range of central-cell gas feeds has shown that the radial density profiles can be changed from peaked on-axis to inverted profiles peaked off-axis. Additional diagnostic channels allowed us to measure these radial density profiles in more detail than was previously possible.

Plasma Confinement

- Under proper operating conditions the confinement of the central-cell plasma is in agreement with the theoretical Coulomb values. The highest confinement parameter achieved was $n\tau = 10^{11}\ \mathrm{cm^{-3}\cdot s}$. When end-plug fluctuation levels are significant, confinement is degraded in agreement with Monte-Carlo calculations. These fluctuations limited the range over which TMX could be operated but did not prevent us from demonstrating the basic features of tandem mirrors.

Power Balance

- We have been able to account for the neutral-beam power input by using multiple diagnostic arrays.
- Near the axis, most of the trapped neutral-beam power is lost axially, indicating good radial confinement. Near the edge, more power is lost radially. Radial arrays of calorimeters on the TMX end wall show that the power is more concentrated on the axis than was previously assumed. Radial end-loss analyzer measurements indicate that this concentration is due to the radial profiles of both the end-loss current and the plasma potential.

Plasma Beta Measurements

- After TMX was shut down, an extensive calibration of the diamagnetic loops was carried out. With this new calibration, we determined that a maximum central-cell beta of 0.4 was achieved with neutral-beam injection.
- This calibration has also enabled us to conclude that the central-cell ion distribution has a non-Maxwellian component, as we had expected, because of ion-cyclotron heating by plug fluctuations.

Radial Transport

- In TMX, radial particle confinement exceeds axial confinement near the axis. Near the edge, radial transport processes are more important.
- Resonant-neoclassical-ion-transport theory is consistent with the experimental measurements, but the measurements cannot resolve factor-of-3 uncertainties in the theory nor can we resolve comparable amounts of ambipolar radial transport.

Radio-Frequency Measurements

- Wavelength and polarization measurements of the end-plug ion-cyclotron fluctuations indicate wave properties more similar to the Alfven ion-cyclotron (AIC) mode than to the drift-cyclotron loss-cone (DCLC) mode. In comparison to 2XIIB, the AIC mode is theoretically more unstable in TMX, while the DCLC mode is less unstable. Theoretically, the AIC mode is expected to be much more stable in the low-ion-beta end plugs of TMX Upgrade and MFTF-B, as is the DCLC mode.

- Turbulent noncoherent central-cell fluctuations extending up to 0.5 MHz, possibly associated with drift waves, have been detected in the central cell. No correlation with plasma confinement has been identified.
- *Coherent low-frequency* 7 kHz ($m = 1$) and 12 kHz ($m = 0$) oscillations have been observed in the central cell. The m = 0 mode is correlated with bursting of end-plug ion-cyclotron fluctuations and thus would not be expected in TMX Upgrade with microstable sloshing-ion end plugs. The m = 1 mode exists at large amplitude near the edge when sufficient central-cell gas input causes large density gradients near the edge. The m = 1 mode can be controlled by modifying central-cell radial profiles by controlled central-cell fueling and heating.

Impurity Studies

- Further analysis continues to indicate remarkably low central-cell impurity levels (0.5%), resulting in less than 10% power loss by impurity radiation. Recent data analysis shows that the lower ionization states of the prevalent oxygen impurity are localized near the edge and the higher ionization states near the axis, as expected.
- High-resolution spectroscopy has provided Doppler-broadening measurements of impurity radiation that corroborate the 100-to-200-eV diamagnetic-loop measurements of central-cell ion temperature.

Sandia Surface-Probe Studies

- Surface probes have been employed to characterize plasma-wall interactions and to determine TMX plasma properties. Passive solid-state probe measurements of particle fluxes and energies at the central-cell walls corroborate other central-cell diagnostic measurements.
- The probes collected the expected number of particles on the end walls. The major component of end losses comes from the central cell. The end-plug contribution is also in agreement with theoretical calculations.

End-Wall Plasma Characteristics

- We have succeeded in decoupling the TMX plasma from the end walls. This was a necessary accomplishment for future higher-temperature machines. A very low density (2×10^9 cm^{-3}) and cool (5 eV) plasma exists near the end wall. This density is four orders of magnitude less and this electron temperature 40 times cooler than the density and electron temperature of the end plug plasmas.
- Secondary electrons emitted from the end wall are detected but the power losses are small, consistent with a model developed for MFTF-B end-wall processes.

ONGOING RESEARCH

The full report, UCRL-53120, describes many major new findings that will subsequently be reported in individual journal publications. Several questions have been raised and are the subject of ongoing research. Many of these questions will be answered by further data analysis and analytic modeling, while others can only be resolved experimentally in the TMX Upgrade, Phaedrus, or other tandem mirror machines. We expect to obtain more quantitative information about power balance, fluctuation studies, and radial transport.

MAJOR TMX PUBLICATIONS

1. F. H. Coensgen, *TMX Major Project Proposal*, Lawrence Livermore National Laboratory, Livermore, CA, LLL-PROP-148 (1977).
2. F. H. Coensgen, C. A. Anderson, T. A. Casper, J. F. Clauser, W. C. Condit, D. L. Correll, W. F. Cummins, J. C. Davis, R. P. Drake, J. H. Foote, A. H. Futch, R. K. Goodman, D. P. Grubb, G. A. Hallock, R. S. Hornady, A. L. Hunt, B. G. Logan, R. H. Munger, W. E. Nexsen, T. C. Simonen, D. R. Slaughter, B. W. Stallard, and O. T. Strand, "Electrostatic Plasma-Confinement Experiments in a Tandem Mirror System," *Phys. Rev. Lett.* **44**, 1132-35 (1980).
3. Papers presented at the session on the TMX experiment at the 21st Annual Meeting of the Division Plasma Physics of the American Physical Society, *Bull Am. Phys. Soc.* **24**, 1017 (1979).
4. D. P. Grubb et al., in *Proc. Intl. Symp. Physics of Open-Ended Fusion Systems, Tsukuba University, Japan 1980*; in preparation.
5. D. E. Baldwin, B. G. Logan, and T. C. Simonen, Eds., *Physics Basis for MFTF-B*, Lawrence Livermore National Laboratory, Livermore, CA, UCID-18496 (1980).
6. T. C. Simonen, C. A. Anderson, T. A. Casper, J. F. Clauser, F. J. Coensgen, W. C. Condit, D. L. Correll, W. F. Cummins, J. C. Davis, R. P. Drake, J. H. Foote, R. J. Fortner, A. H. Futch, R. K. Goodman, D. P. Grubb, E. B. Hooper, R. S. Hornady, A. L. Hunt, C. V. Karmendy, B. G. Logan, R. H. Munger, W. E. Nexsen, W. L. Pickles, P. Poulsen, D. R. Slaughter, B. W. Stallard, G. A. Hallock, and O. T. Strand, "Plasma Confinement Experiments in the TMX Tandem Mirror," in *Proc. Intl. Conf. Plasma Physics and Controlled Nucl. Fusion Research, 8th, Brussels, 1980* (IAEA-CN-38/F-1, Vienna, 1981).
7. R. P. Drake, G. Deis, M. Richardson, and T. C. Simonen, "Gas Control and Wall Conditioning in TMX," *J. Nucl. Mat.* **93/94**, 291 (1980).
8. R. P. Drake, T. A. Casper, J. F. Clauser, F. H. Coensgen, D. L. Correll, W. F. Cummins, J. C. Davis, J. H. Foote, A. H. Futch, R. K. Goodman, D. P. Grubb, R. S. Hornady, W. E. Nexsen, T. C. Simonen, and B. W. Stallard, "The Effect of End-Cell Stability on the Confinement of the Central-Cell Plasma in TMX," UCRL-84558 Rev. 1 (1980); submitted to *Nucl. Fusion*
9. T. D. Rognlien and Y. Matsuda, "Tandem Mirror Confinement in the Presence of Ion Cyclotron Fluctuations," UCRL-84571 (1980); submitted to *Nucl. Fusion*.
10. Papers presented at the session on TMX experiments at the 22nd Annual Meeting of the Division of Plasma Physics of the American Physical Society, *Bull. Am. Phys. Soc.* **25**, 878 (1980).
11. D. L. Correll and R. P. Drake, Eds., *Results of TMX Operations, January-July 1980*, Lawrence Livermore National Laboratory, Livermore, CA, UCID-18803 (1980).
12. T. C. Simonen, "Experimental Progress in Magnetic Mirror Fusion Research," Lawrence Livermore National Laboratory, Livermore, CA, UCRL-85494 (1981); submitted to *Proc. IEEE*.
13. T. C. Simonen, "Comparison of Tandem Mirror Confinement with Single Mirror Experiments," Lawrence Livermore National Laboratory, Livermore, CA, UCRL-85834, (1981); to be submitted to *Nucl. Fusion*.