PREPRINT UCRL- 79749

CONF-771029--16

Lawrence Livermore Laboratory

SYSTEM DESIGN FOR THE NEW TMX MACHINE

A. K. Chargin, M. O. Calderon, L. J. Mooney, and G. E. Vogtlin

October 19, 1977

This paper was submitted for inclusion in the Proceedings of the Seventh Symposium on Engineering Problems of Fusion Research, Knoxville, Tennessee, October 25-28, 1977.

SYSTEM DESIGN FOR THE NEW TMX MACHINE

A. K. Chargin, M. O. Calderon, L. J. Mooney and G. E. Vogtlin

Lawrence Livermore Laboratory, University of California
Livermore, California 94550

Summary

The Tandem Mirror Experiment (TMX) is designed to test the physics of a new approach to Q-enhancement in open confinement systems. In the tandem mirror concept, the ends of a long solenoid are plugged electrostatically by means of ambipolar potential barriers created in two mirror machines or plugs, one at each end of the solenoid. The ambipolar potential in mirror machines develops as a consequence of the higher scattering rate of electrons and the balancing of electron and ion loss rates.

The TMX experiment incorporates very few new engineering developments, but it does involve a new way of combining in an integrated system many previously developed ideas. The engineering task is to design the machine that would provide a proof-of-principle evaluation of the tandem mirror concept as rapidly as possible. The preliminary design was started in September 1976 and was completed by December 1976. It led to a cost estimate of $11 million and a scheduled construction period of 18 months.

Introduction

The tandem mirror concept is a new idea for Q-enhancement of mirror machines. T. K. Fowler and B. G. Logan from Lawrence Livermore Laboratory (LLL) developed the idea at the same time as G. I. Dimov of the Soviet Union.[1,2] An international workshop on Q-enhancement in mirror fusion held at LLL in September 1976 selected the tandem mirror as one of the two most promising approaches to enhancing Q in mirror reactors. A proposal to build the Tandem Mirror Experiment to test the tandem mirror concept[3] was prepared in January 1977 and presented to an ERDA panel in February 1977. Funding for TMX was approved by the beginning of April 1977.

The purpose of TMX is to provide a proof-of-principle evaluation of the tandem mirror concept as rapidly as possible. To accomplish this, the experiment has three main physics objectives:

- To demonstrate the establishment and maintenance of a potential well between two mirror plasmas.
- To develop a scalable magnetic geometry while keeping macroscopic stability at high β.
- To investigate the microstability of the plug-solenoid combination in order to maximize the plug-density/injection-power ratio.

These objectives led to a key set of physics parameters for the experiment (see Table 1). The TMX project is designed to provide an apparatus and facility that will meet the parameter requirements of Table 1 and have sufficient flexibility to meet the three physics objectives listed above. The purpose of this paper is to describe briefly the TMX apparatus and facility together with some of the design trade-offs that were considered in establishing the final configuration.

Table 1. TMX physics parameters.

Parameter	Value
Electron	
Temperature, T_e	0.20 keV
Confining potential, ϕ_e	1.1 keV
Plug	
Density (assumed uniform over V_p), n_p	5×10^{13} cm^{-3}
Average energy, E_p	26 keV
Radius of plasma half-maximum, r_p	7 cm
Central magnetic field, B_p	10 kG
Confinement product, $(n\tau)_p$	3×10^{11} cm$^{-3}\cdot$s
Central cell	
Density (assumed uniform over), n_c	1.2×10^{13} cm^{-3}
Ion temperature, T_c	0.080 keV
Confining ion potential, ϕ_c	0.29 keV
Length, L_c	5.5 m
Radius, r_c	31 cm
Magnetic field, B_c	0.5 kG
Confinement product $(n\tau)_c$	3.1×10^{11} cm$^{-3}\cdot$s

Concept Description

Figure 1 describes schematically the essential elements of the tandem mirror concept. In this scheme, two minimum-$|B|$ mirror machines are connected by a solenoidal section that guides the flux lines through the machine. An idealized flux tube is shown in Fig. 1 below the magnet set. The curve at the bottom of the figure describes the field magnitude profile, which in effect makes three connected mirror machines with the four mirror points.

The essential element of the tandem concept is the plasma potential developed in the end mirror cells or "plugs". With neutral-beam injection in the two end plugs, the hot plasma accumulated in each end develops a strong net positive potential, as in the standard mirror machine. The electrons scatter and escape along the fieldlines from both the plug and the solenoids faster than do the ions because of the difference in mass and velocity. Therefore, the electron density is lower than the ion density throughout the machine. Now the plugs and the solenoid are charged positively with respect to the end walls; this keeps the electron loss rate equal to the ion loss rate. The larger positive charge in each of the end plugs establishes potential barriers that prevent the escape of ions created in the solenoid; electrons are confined by the overall positive potential end to end. As shown in the potential profiles in Fig. 1, the particle density profile follows that of the potential profile. This combination of the elements in a tandem mirror configuration confines plasma better than the standard mirror machine.

In a reactor based on this concept, the fusion power would be produced by the solenoid plasma. This power can be made much larger than the neutral-beam power required to maintain the plugs if the volume of the solenoid is made much larger than the plug volumes.

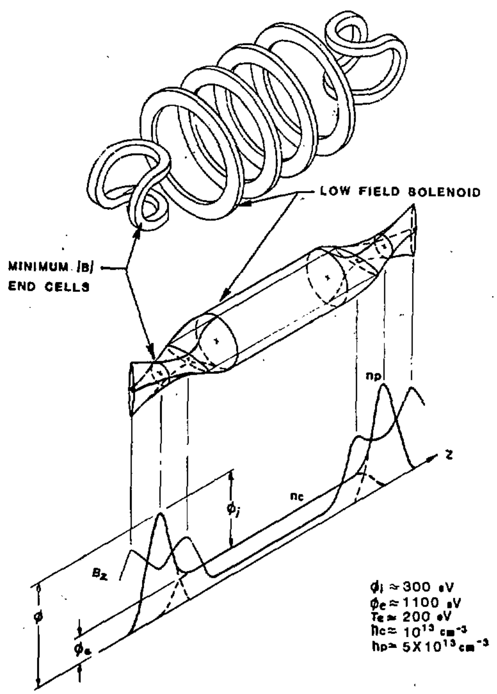

Figure 1. Idealized Tandem Mirror Concept.

TMX Apparatus

The components of the basic TMX apparatus without the vacuum shell are shown in Fig. 2. The flux tube passing through the middle of the machine is shaped by the end-plug magnets, the transition magnets, and the solenoid set. The end plugs are heated by neutral-beam modules clustered in four bundles, two bundles per plug.

A more complete view of the TMX apparatus is shown in Fig. 3. The end tanks provide the vacuum enclosure for the plug magnets and house the pumping surfaces for the scattered gas. The center-cell tank completes the vacuum enclosure and, because of its smaller size, provides for easier diagnostic access to the plasma.

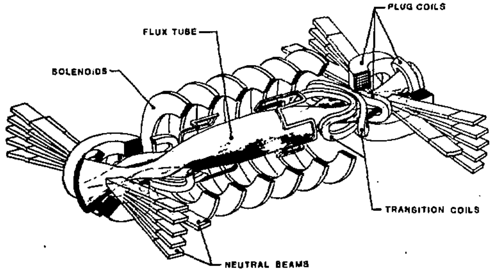

Figure 2. TMX Conceptual Geometry.

The scale of the apparatus is set by the end plugs, which in turn are patterned after 2XIIB.[4] The central-cell parameters are derived from those of the plugs as described in Ref. 3. The minimum size of the plug plasma is determined by the minimum focused dimensions of a single beam, since all beams may be aimed at a single footprint. The size of the plug coil is set by mirror ratio requirements, which dictate a shape resembling a cube-like box, and by the defocused dimensions of a single neutral beam as it passes the coil windings beyond the focal point. The radial access apertures of the plug then tend to be square. Through these apertures, it is possible to aim a number of beams even though the aperture sizes were determined by a single beam. Figure 4 illustrates the beam access possibilities in TMX plugs.

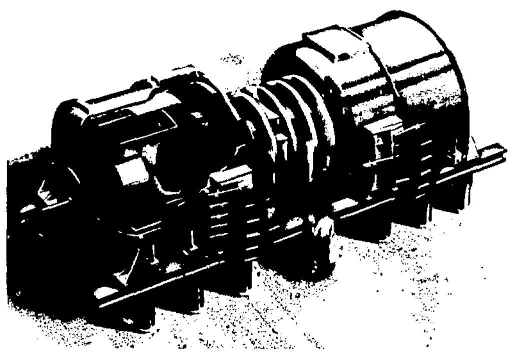

Figure 3. TMX Vacuum Enclosure.

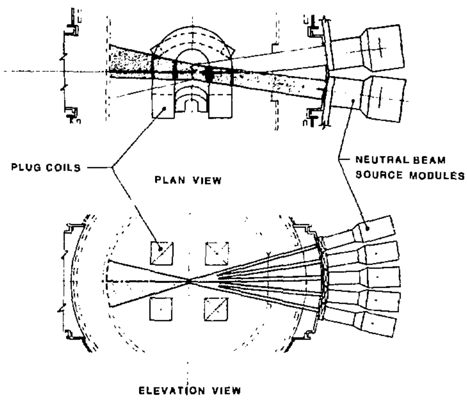

Figure 4. Neutral Beam Access in Plug Magnets.

Although we made an attempt to minimize the magnet size, the plugs could not be built appreciably bigger because the proportional increase in size of the rest of the apparatus would then make it impossible to fit it inside the existing building.

For easy diagnostic access from any direction, the TMX machine will be located over a 9.75 m × 17 m pit. It will be surrounded by concrete shielding for personnel protection from neutron radiation. Figure 5 shows the schematic of much of the facility, including control rooms and structures supporting the neutral-beam power supplies.

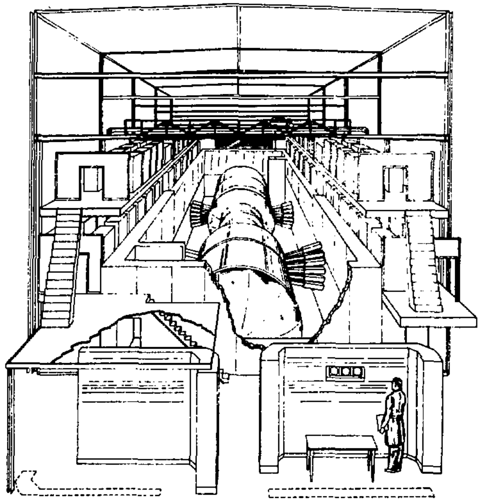

Figure 5. TMX Facility.

Magnet System

Some of the important factors that we considered in the design of the magnet system were

- field strength
- variable mirror ratios
- size
- winding (superconducting or copper)
- power resource limit
- structural integrity
- MHD stability.

The issue of field strength is related to the energy of the injected beams. The highest energy neutral beams that are available for TMX-type application are at the 40-kV energy level. Since the plugs are intended to resemble 2XIIB, 10 kG was a logical number to consider in a TMX point design. From adiabaticity considerations, 40-kV beams and 10-kG plug fields are compatible in a TMX geometry.

The variable mirror ratio was an important issue because the present experimental knowledge of plasma buildup applies to a mirror ratio of 2. In a tandem mirror reactor, due to technological limits of magnet materials, this mirror ratio must be held to a significantly lower value. Present thinking in the tandem reactor holds the plug mirror ratio at 1.07[5,6]; the TMX machine is designed to reach a plug mirror ratio as low as 1.3. This low ratio is obtained by varying the current ratios between the baseball coils and the two plug C-coils (see Fig. 2), the three coils that constitute the plug magnet set.

The size of the magnet set was determined by the required beam access, as already explained in the description of the TMX apparatus. The considerations between superconducting or conventional copper coils included specific circumstances at LLL: the cryoplant for liquid helium (LHe) was available from the Baseball II experiment, and many of the power supplies required to power copper coils were available from Baseball I and 2XIIB experiments. The cost analysis showed that the two ways of building the magnet system would be even at near 14 kG, with copper being cheaper at lower fields. In addition, the power resource limit at the TMX site would only allow powering a conventional plug magnet set to somewhat above 10 kG. In the structural sense, any coil restraints that are applied to a given coil geometry must be clear of any areas that are too close to the plasma. The plug magnet set with its baseball and C-coil combination allows a convenient restraint mechanism.[7]

From MHD stability considerations, the transition coil design is very critical. The field shape of the plug magnet is strongly stable, the field shape of the transition is unstable, and the field shape of the solenoid section is neutral. The transition section has sufficiently bad fieldline curvature to require the design to depend on having the high-pressure plugs stabilize the center cell in the pressure-weighted average. The geometry of the transition coil was optimized to smooth out as much bad fieldline curvature as possible.[8] As shown in Fig. 2, the transition coil set consists of two C-coils and an octupole coil to correct higher-order effects. A summary of the magnet parameters is shown in Table 2.

Table 2. TMX magnet parameters.

Magnet Type - Plug	Baseball plus C-coil pair
- Transition	2 C-coils plus octupole
- Central Cell	Solenoids
Distance between inner mirrors	5.3 m
Distance between plug mirrors	1.1 m
Plug central field	1.0 T
Center-cell field*	0.05 to 0.3 T
Plug mirror ratio, axial*	1.3 to 3.5
Plug mirror ratio, radial* (at 10 cm)	0.98 to 1.04
Maximum plasma radius	
- In plug	0.15 m
- In center cell	0.7 m
Total stored energy	40 MJ

* For some of this range, a field of 1.0 T in the center of the plug can be achieved. The extremes of this range can be attained at somewhat lower plug fields.

Vacuum System

In designing the vacuum enclosure for TMX, we considered three geometries: one long, uniform-diameter tank; two relatively large tanks for plug sections connected with a smaller center-cell tank; and several smaller tanks connected so that each defines a specific magnet, plasma, and injector region. The significant issues that we considered in making the design selection were

- liner surface area
- injector support
- magnet support
- compatibility with facility
- cost
- ease of operation.

The liner surface is the pump for the injected gas. It is geometry-dependent in the sense that the total area required is dependent upon conductances throughout the machine. Our experience with injectors indicates that neutral-beam injectors should be supported on the outer walls and easily accessible for simpler maintenance. The tanks also must provide support for the magnets, which may generate point loads up to 4 tonnes. Any tank design selected must allow for coordination with the remainder of the facility, including power supplies, neutron shielding, pit, and building. A cost consideration involves not just the vacuum tanks, but also the influence of the tank design on the other parts of the experiment. Ease of operation implies relatively quick turnaround for minor machine shutdowns and yet allows for major changes as the experimental results might dictate.

Based on the above considerations, we selected the vacuum enclosure shown in Fig. 3. The small diameter of the center-cell tank allows us to use existing solenoid coils and to provide the diagnostic probes with closer access to the plasma. The plug tanks are internally subdivided into distinct pumping regions by liners. In the injector region, there are two concentric liners separated by limited radial conductance to minimize the gas load into the plasma. The end regions, which intercept the magnetic fieldlines passing through the plasma, are separated from the injector region by liners.

The liners are cooled by liquid nitrogen (LN) with Ti sublimation on the surface. We considered using LHe cryopanels for hydrogen pumping, but rejected that approach because of higher initial cost and longer turnaround time between shutdowns. The TMX injector pulse of 25 ms does not saturate the Ti surface with hydrogen gas; therefore, the main advantage of LHe cryopanels, long-term pumping before saturation, is eliminated. In fact, over the first 10 to 15 ms in the TMX application, the Ti on the LN-cooled surface should have faster pumping speed than LHe cryopanels. In potential future upgrades, it should be possible to lengthen the beam pulse by an interesting amount and still not saturate the Ti surfaces in TMX.[9] The tanks define a volume of 102 m^3 that houses 290 m^2 of Ti on LN-cooled surface and an additional 44 m^2 of Ti on H_2O-cooled surface. The total pumping speed is calculated to be 850 Torr·litres/s.

Injector Highlights

TMX design incorporates three types of injection: neutral beams, streaming plasma, and cold gas. By far, neutral beams present the greatest design challenge. There are sixteen 20-kV and eight 40-kV beams evenly distributed between the two plugs, as shown in Figs. 3 and 4. The 20-kV beam modules are available for TMX from Baseball II and 2XIIB experiments. However, based on the design currently in the prototype test stage, the 40-kV beam modules must be replicated. Each of the modules will be mounted inside a magnetic shield and separated from the vacuum vessel by an isolation valve for easy maintenance. As in 2XIIB, streaming plasma and cold gas will be employed in TMX.[4] The streaming-plasma guns used for startup for generating a target plasma in the plugs are mounted near the end of each plug tank and aligned with a fieldline passing through the plug plasma. The cold-gas box is mounted near the inner plug mirrors and is used for injecting cold gas for plasma stabilization.

Each of the power-supply modules for the neutral-beam injectors consists of four major components: accel, decel, arc, and filament power supplies. As in source modules, the 20-kV power supplies are available from 2XIIB and Baseball II experiments. However, for TMX they must be upgraded to a 25-ms pulse from the present 10-ms capability. The sixteen 20-kV accel supplies will be powered from 2XIIB Bank 6. For the eight 40-kV accel supplies, there is a sufficient number of electrolytic capacitors remaining on 2XIIB. The decel supplies only require additional capacitance to permit 25-ms operation. The previous pulse-forming network (PFN) versions of the arc power supplies are now connected, two in series, and with some additional improvements have been tested to 25 ms.[10] For additional arc power supplies, we are developing a new model using batteries.[11] The battery arc supply should prove to be comparable in cost to the PFN supply, in addition to providing better regulation and longer "on" times. As the arc supplies, those filament supplies available from 2XIIB are of the old ac variety, whereas the new design incorporates batteries. The variety of neutral-beam power supplies presents interesting problems for the control system now being designed.

Cost and Schedule

The construction schedule for TMX is planned for 18 months, beginning April 1, 1977. Up to this point, the milestone schedule as outlined in the TMX Proposal[3] has been maintained. In addition to the TMX Proposal, LLL, ERDA/DMFE, and ERDA/SAN prepared an administrative plan that outlines specific technical, cost, and schedule baselines. A summarized cost estimate is shown in Table 3. The three organizations mentioned above maintain close monitoring of the construction project; during the first six months, no major problems have arisen. The external facility should be completed by January 1978. The tanks and magnets are due for delivery in May 1978, at which time the final assembly of these large components will take place. The neutral-beam transfer from 2XIIB is scheduled to begin in July 1978, and the complete experiment should be ready for debugging operation by October 1, 1978.

Table 3. Initial cost estimate.

	Total Cost (millions of $)
Magnet system	1.4
Vacuum system	1.5
Injection system	2.3
Facility	1.2
Controls	0.5
Diagnostics	1.0
System design and integration	1.0
Administration	0.7
Subtotal	9.6
Contingency	1.8
Total	11.4

Acknowledgments

Any system design as complex as TMX can only be accomplished by the cooperation and hard work of a large group of people. F. H. Coensgen provides the overall project guidance, while D. E. Baldwin, C. C. Damm, T. K. Fowler, B. G. Logan, and T. C. Simonen carry much of the work load in defining physics objectives. This work was performed under the auspices of the U.S. Energy Research and Development Administration under contract No. W-7405-Eng-48.

References

1. T. K. Fowler and B. G. Logan, The Tandem Mirror Reactor, Lawrence Livermore Laboratory Rept. UCRL-78749 (1976); to be published in Comments Plasma Phys.
2. G. I. Dimov, V. V. Zakaidakov, and M. E. Kishinevski, Fiz. Plasmy 2, 597 (1976); also G. I. Dimov, V. V. Zakaidakov, and M. E. Kishinevski, "Open Trap with Ambipolar Mirrors," in 6th Inter. Conf. Plasma Physics and Controlled Nuclear Fusion Research, Berchtesgaden, Fed. Rep. of Germany, 1976 (IAEA, in preparation), Paper C4.
3. F. H. Coensgen, TMX Major Project Proposal, Lawrence Livermore Laboratory, Rept. LLL-Prop-148 (1977).
4. F. H. Coensgen, J. F. Clauser, D. L. Correll, W. F. Cummins, C. Gormezano, B. G. Logan, A. W. Molvik, W. E. Nexsen, T. C. Simonen, B. W. Stallard, and W. C. Turner, "2XIIB Plasma Confinement Experiments," in Proc. 6th Inter. Conf. Plasma Physics and Controlled Nuclear Fusion Research, Berchtesgaden, Fed. Rep. of Germany, 1976 (IAEA, in preparation), Paper CN-35/C1; also Lawrence Livermore Laboratory, Rept. UCRL-78121, Rev. 1 (1976).
5. G. A. Carlson, Parametric Design Study of Tandem Mirror Fusion Reactors, Lawrence Livermore Laboratory, Rept. UCRL-79092 (1977); submitted for presentation at the 23rd Annual Meeting of the American Nuclear Society.
6. W. S. Neef, Jr., Mechanical Design Aspects of a Tandem Mirror Fusion Reactor, Lawrence Livermore Laboatory, Rept. UCRL-79434 (1977); submitted for presentation at the 23rd Annual Meeting of the American Nuclear Society.
7. R. E. Hinkle, M. O. Calderon, A. K. Chargin, F. F. K. Chen, B. S. Denhoy, A. R. Harvey, J. A. Horvath, and J. R. Reed, "TMX Magnets - Mechanical Design," in these Proceedings (1977).
8. F. F. K. Chen, A. K. Chargin, B. S. Denhoy, and A. F. Waugh, "Designing for the Magnetic Field Requirements of the Tandem Mirror Experiment," in these Proceedings (1977).
9. D. P. Atkinson and M. O. Calderon, "The Vacuum System for the Tandem Mirror Experiment," in these Proceedings (1977).
10. G. A. Leavitt, "A Forty Kilovolt, Twenty-Five Millisecond Neutral Beam Power Supply for TMX," in these Proceedings (1977).
11. G. T. Santamaria, "A New Generation of Arc and Arc Filament Power Supplies for Pulsed Neutral Beams," in these Proceedings (1977).