# The LLNL tandem mirror experiment (TMX) upgrade vacuum system

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The tandem mirror experiment (TMX) upgrade is a large, tandem, magnetic-mirror fusion experiment with stringent requirements on base pressure ($10^{-8}$ Torr), low H reflux from the first walls, and peak gas pressure ($5\times10^{-7}$ Torr) due to neutral beam gas during plasma operation. The 225 $m^3$ vacuum vessel is initially evacuated by turbopumps. Cryopumps provide a continuous sink for gases other than helium, deuterium, and hydrogen. The neutral beam system introduces up to 480 l/s of H or D. The hydrogen isotopes are pumped at very high speed by titanium sublimed onto two cylindrical radially separated stainless steel quilted liners with a total surface area of 540 $m^2$. These surfaces (when cooled to about 80 K) provide a pumping speed of $6\times10^7$ l/s for hydrogen. The titanium getter system is programmable and is used for heating as well as gettering. The inner plasma liner can be operated at elevated temperatures to enhance migration of gases away from the surfaces close to the plasma. Glow discharge cleaning is part of the pumpdown procedure. The design features are discussed in conjunction with the operating procedures developed to manage the dynamic vacuum conditions.

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## I. INTRODUCTION

The tandem mirror experiment upgrade is the latest in a series of large, high energy plasma experiments in the Magnetic Fusion Energy Program at Lawrence Livermore National Laboratory.[1] The primary function of the TMX-upgrade vacuum system is to minimize the particle flux across the plasma surface. We have divided the TMX-upgrade vacuum system into two parts, "external" and "internal", for operations management purposes. The subsystems which make up the external vacuum systems (EVS) and the internal vacuum systems (IVS) are listed with a brief description of each in Table I.

The external vacuum system includes all vacuum equipment which can be valved off from the main vacuum vessel of TMX-upgrade. The external equipment provides a base pressure in TMX without the internal vacuum system (IVS) of $3\times10^{-6}$ Torr. The system is composed of standard pumping components and is controlled from a vacuum map in the south control room. It is relatively maintenance-free and provides pumping for the main vessel, diagnostics, and neutral beams. Leak hunting equipment for all of TMX-upgrade is included in this system.

The external vacuum system provides the base pressure of $3\times10^{-6}$ necessary to allow the internal vacuum system to reach $1\times10^{-8}$ Torr. This system also provides pumping of methane and argon which are not pumped effectively by the IVS during physics operation.

The internal vacuum system includes all pumping hardware and pressure gauges which cannot be valved off from the main vacuum vessel. It also includes the main vacuum vessel and glow discharge cleaning. The pumps are Ti gettered liquid nitrogen (LN) cooled liners arranged in two cylindrical coaxial sets, two end fan sections, and a warm plasma liner. The system must provide a base pressure of $1\times10^{-8}$ Torr in the innermost or plasma region of the plugs, central cell, and end fans. During plasma operation the peak gas pressure near to the plasma is held to less than $5\times10^{-7}$ Torr by the liners. $H_2O$, $N_2$, and $O_2$ are pumped in the vacuum regions away from the plasma. Ar and $CH_4$ are not effectively pumped by this system.

In the positive mode of tandem operation the low plug density ($5\times10^{12}$), high electron temperature (1.4 keV,) and longer central cell ion confinement time (15 ms) require low $H^0$ pressures near the plasma boundary (less than $5\times10^{-7}$). High $z$ impurities (C, O, N) can prevent thermal barrier formation. The impurity concentration that can be tolerated is dependent on the plasma configuration.[7]

A summary of the essential characteristics of the TMX-upgrade (described in detail below) is presented in Table II.

## II. VACUUM SYSTEM DESCRIPTION—INTERNAL

### A. General

The mechanical design of the vacuum vessel, the physics vacuum requirements, and the basic analytical methods used to design the system have been published in detail elsewhere.[3,6] We include here a general description of the function of the vacuum system.

Figure 1 shows the TMX-upgrade stainless steel vacuum vessel, the neutral beams as they would be mounted for a positive tandem configuration, the magnets internal to the main vessel, the two cylindrical radially separated stainless steel quilted linears, the diagnostic and ECRH access ports, and the rectangular end fan tanks. The approximate size of the system is shown by the scaled figures of two men. Note that for maintenance access the vessel is built in movable sections that are mounted on tracks. Each of the TMX-upgrade magnets is enclosed in a SS vacuum case which can be differentially pumped to avoid the possibility of leaks from the complicated case welds. The cases are subjected to high stresses by the magnet's weight and the magnetic forces.

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TABLE I. External and internal vacuum systems.

| Subsystems list | Brief description |
|---|---|
| *External vacuum system* | |
| (1) Roughing pumps | External to bldg., connected via 2 two 6 in. lines with 6 roughing pumps each, 1600 CFM total |
| (2) Blowers | 4 each @ 666 CFM |
| (3) Turbomolecular pumps | 2 each @ 1900 l/s $N_2$ |
| (4) Cryopumps | 6 each on 3 ports 1100 l/s Ar and $CH_4$, 2500 l/s $H_2$ |
| (5) Cryoregeneration | 2 each roughing pumps, $N_2$ purge |
| (6) Dry air flush | Dry air trailer permanently installed |
| (7) Diagnostic pumpout | 3 each vacuum carts with turbos |
| (8) Beam pumpout | Auxillary system and pre-pumpdown firing |
| (9) Leak hunting | 4 each residual gas analyzers (RGA) |
| (10) Auxiliary | 10 each carbon vanes @ 10 CFM, 2 each Vac Sorb |
| (11) Controls and readout | Vacuum map-modular commercial |
| (12) Interlocks | 50 each, thermocouple gauges, 16 each ionization gauges, vacuum map |
| (13) Data base interface | Computer driven Camac system |
| *Internal vacuum system* | |
| (1) Liners | 72 each SS quilted, LN cooled, heated by getter wires, individually plumbed, pumpable, Al inner liner panels |
| (2) Getters | $162\times6$ Ta–Ti wire bundles, personnel safe connection, individual voltage regulated power supplies, slow turn on (15 s) |
| (3) Fast ion gauges | 3 each magnetically shielded Baird Alpert gauges + RGA's |
| (4) Moveable RGA's | 2 each, center of plug, nude |
| (5) Reflux gauges | 2 each tunnel type/fast ion gauges |
| (6) Regional ion gauges | 10 each intershot gauges |
| (7) Liner temp sensors | Outlet liner temperatures |
| (8) Readout and control | LN system, getter, all gauges. Intershot log. |
| (9) Interlocks | TC gauges from EVS |
| (10) Data base interface | Via intershot log Camac and computer system |
| (11) Glow discharge | $H_2$ gas, anodes in all regions, exhaust with blowers, hot liners, separate 700 V, 8 A supplies RGA monitor in exhaust |

## B. Vacuum regions

Figure 2 shows schematically the eight separate vacuum regions inside the vacuum vessel. The outer annulus is between the vacuum vessel and the outer liner. Water vapor is collected on the ungettered side of the outer liner when it is chilled to 80 K. The next two inner regions contain both cold and warm Ti gettered surfaces and provide the basic pumping speed for H of $6\times10^7$ l/s. All quilted TMX-upgrade liners are individually plumbed to the LN system so they may be taken out of service and differentially pumped in case a cold leak develops. The neutral beams, ECRH and diagnostics require radial penetrations of all three liners. Those penetrations are the primary conductances between regions. The separate small vacuum region surrounding the actual plasma is provided by a thin aluminum liner which is Ti gettered. For areas which cannot be effectively gettered, ungettered vanadium sheet is being considered. This liner will be warm during plasma operation. The purpose of this liner system is to reduce the reflux of hydrogen charge exchange neutrals to one or less, while limiting the conductance of background H gas and gas from small leaks in the complex outer parts of the machine. The plasma itself acts as a vacuum pump which lowers the pressure in the plasma region during operation. The design criterion for this inner or first wall are still evolving and are discussed in more detail in Ref. 2.

## C. Getters

The Ti getter system for all these liners is extensive and must be precisely controlled to ensure a minimum of three-monolayer coverage just before plasma operation begins. The sticking coefficient for the freshly gettered LN cooled liners is expected to start at 0.6 and fall to 0.3 by the end of the shot.[4,6] The voltage for each getter wire is individually controlled by a programmable power supply.[5] Some power is supplied between shots to keep the getter wires warm. This is done to prevent H pumping and impurity adsorbtion by the wires themselves during the 5 min machine cycle. The getters are also used for heating of the inner plasma liner and of the outer liners during operation of the vacuum system.

## D. Diagnostics

Fast ion gauges and time dependent RGA systems located in eight vacuum regions will record pressures during and between plasma shots. These pressures are a permanent part

TABLE II. Summary of the characteristics of the TMX-upgrade vacuum system.

| Item | Description | | | | |
|---|---|---|---|---|---|
| (1) Vacuum vessel | Consists of 11 separate tanks; 7 cylinders, 2 domes, and 2 rectangular sections.<br>Construction: Nominal 4.06 m diam, 1.27 cm thick shell, 21.7 m long.<br>Material: 304 stainless steel<br>Number of ports: 292<br>Volume:225.2 $m^3$ | | | | |
| (2) Liquid nitrogen liner | Total quantity 72 sections; 40 cylindrical, 12 discs, 20 flat, rectangular<br>Active pumping area: 540 $m^2$ | | | | |
| (3) Titanium getters | 162 getter assemblies, 6 wires per assembly<br>Wire: 85% titanium, 15% tantalum, 0.318 cm diam<br>Expected life per wire: 300–60 s sublimation cycles.<br>Total expected life per getter assembly: 1800 60-s cycles<br>Sublimation cycle: 15 s warm up, 60 s sublimation period at 106 A, 4–5 monolayers per cycle<br>Total length of active getter wire: 274.4 m | | | | |
| | | | Surface area, $m^2$ | | Pumping (l/s) |
| | | | Cold | Warm | speed |
| (4) Internal regions | Totals: | Volume, $m^3$ | 77 K | ~300 K | for hydrogen |
| 1st injector | | 94 | 350 [a] | ... | $3.2 \times 10^7$ |
| 2nd injector | | 80 | 140 | 60 [b] | $2.0 \times 10^7$ |
| Plug plasma | | 9.2 | ... | 15 | $2.6 \times 10^6$ [c] |
| Central cell plasma | | 20 | ... | 32 | $5.2 \times 10^6$ [c] |
| End fan | | 22 | 25 | 6 | $2.6 \times 10^6$ |
| | | 225.2 $m^3$ | 540 $m^2$ | 110 $m^2$ | $6.24 \times 10^7$ |
| (5) External vacuum system 890 l/s @ 100 Torr vessel pumping speed | | | | | |

[a] Cold sticking coefficient = 0.4 for H.
[b] Warm sticking coefficient = 0.03 for H.
[c] Includes pumping effect of plasma itself on region SC = 0.5.

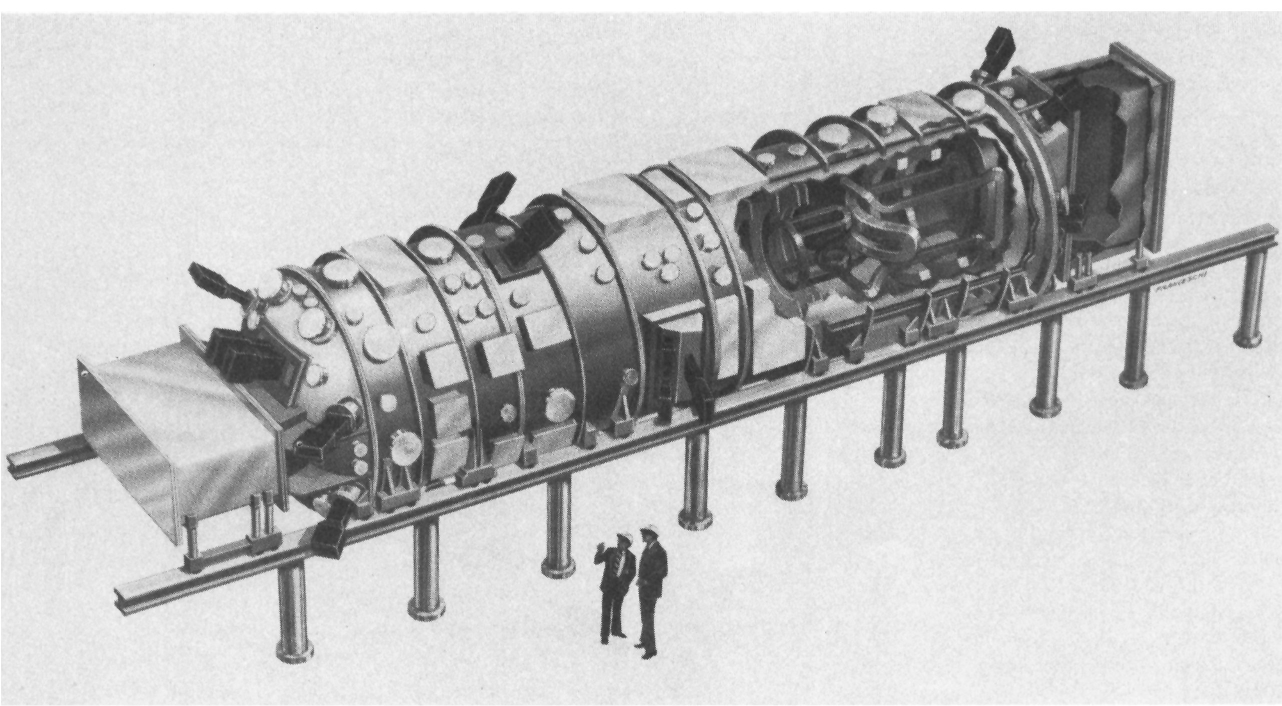

FIG. 1. Functional view of the TMX-upgrade vacuum vessel.

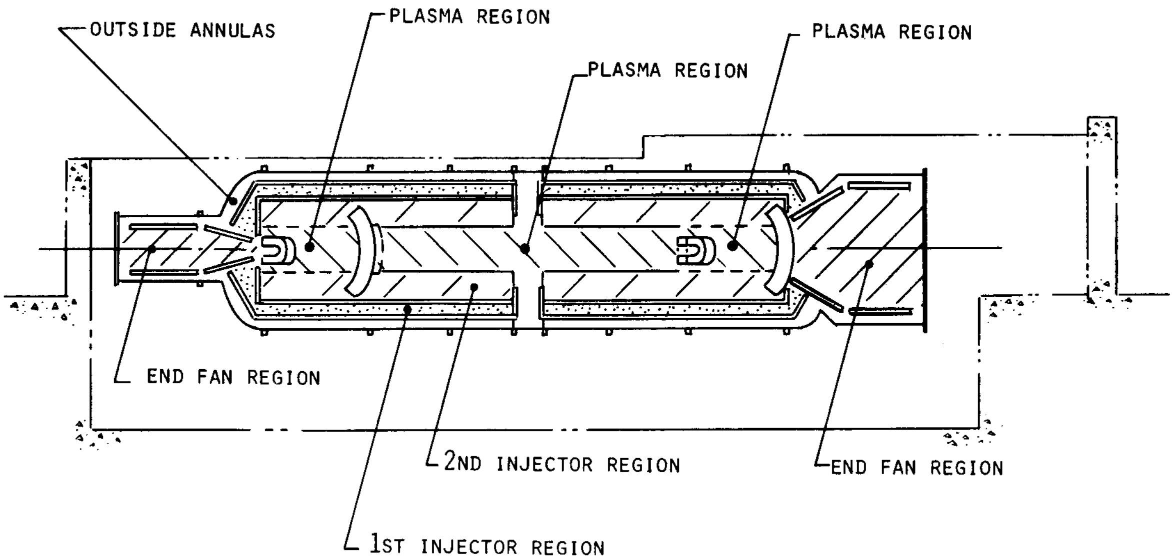


FIG. 2. Schematic of the eight vacuum regions of TMX-upgrade.

TABLE III. TMX-upgrade pumpdown procedure for achieving low base pressures, clean surfaces, and low peak pressures during gettering for TMX-upgrade.

Stage I. Pumpdown
(1) Flush with dry air (remove surface $H_2O$, prevent cloud chamber effect), open all sources and diagnostics which are at air.
(2) Rough main vessel—start pressure (time) recording.
(3) Turn on turbos/blowers—open all sources, all diagnostics.
(4) Use "High-Vac" techniques to fix all leaks.
Proceed to $5 \times 10^{-6}$ Torr
*Assure operation of all machine systems.*
(5) Assure by operating that there are no pulsed gas leaks on magnets or diagnostics.
Cycle magnets to full power-record pressure and RGA.
(6) Bake out *all* getter wire sets.
Hold all wires in a set of 60 A until pressure peaks and reaches a new minimum.
Record final pressure and RGA for each set.
(7) Workup of all N beams with turbopump vacuum.
Record pressures and RGA to indicate N beam dump cleanup.
(8) Replace weak or failed sources and work them up.
Pump new sources before opening to vessel.
Continue until all beams ready for complete physics sequence.
NOTE: Need method for new source cleanup prior to opening to vessel if liners are cold.

Stage II. Cleaning and degassing
(9) Begin glow discharge cleaning with $H_2$.
(Use of getter wires as anodes during GDC is possible. If used perform #10 before #9.)
(10) Turn on all getter wires in 1st set to 60 A to heat liners.
Monitor liner temperatures.
(11) Terminate GDC when impurity exhaust rate is low (8 h).
Record exhaust rate for C,O,N.
(12) Repeat step 6, rebake *all* getter wire sets.
Record final pressure and RGA.
Fire all neutral beams once.
(13) Introduce pure $O_2$ to oxide Ti surfaces (tentative).
(14) Turn on all getter wires in 1st set to 60 A to heat all regions.
Allow pressure to peak and equilibrate.
Record pressure at RGA.
(15) Cycle injector region 1 (outer annulus) at 106 A three times (10 monolayers on liners).
(16) Set getters in outer annulus at 10 A, all other getters at 60 A.

Stage III. Radial migration induced by cooling sequence
(17) Cool outer liners with LN, check for leaks.
Record final pressure and RGA.
($H_2O$ should have moved to outside of outer liner.)
Outer liner is now coldest place in vessel.
Inner liners are still hot.
(18) Open cryopumps.
Will pump $CH_4$ and AR.
Record pressure and RGA.
(19) Set 2nd injector region getters to 10 A leaving outer getters at 10 A and plasma region getters at 60 A.
(20) Cycle 2nd injector region getters 3 times.
Record pressure.
(21) Cool middle liners—check for leaks.
Record pressure.
(22) Set 2nd injector region getters to 10 A.

Stage IV. Final gettering
(23) Set plasma region getters to 10 A and cycle getters three times (10 monolayer minimum).
Record pressure.
(24) Operate full machine plasma shot.
(25) Continue monitoring pressure and RGA for possible leaks.
(26) Start physics sequence.
(Recommend gettering every shot generally.)

of the data base for each shot. These systems utilize computers and are Camac based. Liner outlet temperatures are also recorded. The static and dynamic pressures are considered essential in deciding to proceed with plasma experiments.

## III. EXTERNAL VACUUM SYSTEM

The external vacuum system components, outlined in Table I, are for the most part standard commercial components. I would like to call attention to the role of the cryopumps. The cryopumps will function primarily to remove argon and methane not effectively pumped by the internal vacuum system. The turbopumps are used to handle the pumpdown gas load.

## IV. VACUUM EXPERIMENTS/OPERATIONS

Establishing appropriate vacuum conditions is essential before proceeding with a plasma physics experimental sequence. We track the vacuum conditions through the duration of plasma experiments to accurately identify necessary maintenance or modifications.

The way in which the vacuum system is operated is as important as the capabilities of the system. At this time we consider our operating procedures to constitute a sequence which precedes and then compliments the plasma physics experimental sequence. Table III contains our vacuum operating procedures as of the date of this paper. Throughout the procedure the measurements of pressures and elemental constituents are required to be in the permanent TMX-upgrade data base. The operating procedure calls for pumpdown, followed by cleaning and hot degassing, a radially staged cooldown to provide outward migration of H and impurities, and then final gettering.

## V. SUMMARY

The TMX-upgrade vacuum system and operating procedures are designed to produce low base pressures ($1\times10^{-8}$ Torr) for starting up plasmas and low ($5\times10^{-7}$ Torr) peak pressures near the plasma during operation. The new features of the TMX-upgrade vacuum system are warm low reflux inner plasma liners, careful attention to the handling of neutral beam dumps, stream gun and neutral beam gas, cryopumps to pump argon and methane, hot degassing and glow discharge cleaning, radially staged cool down procedures, careful control of gettering, warm getter wires between shots, and complete recording of vacuum conditions in the plasma physics data base.

## ACKNOWLEDGMENT

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