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THE LLNL TANDEM MIRROR EXPERIMENT (TMX) UPGRADE VACUUM SYSTEM

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INTRODUCTION

The Tandem Mirror Experiment Upgrade (TMX-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 for each in Table 1.

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 3×10^{-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 3×10^{-6} necessary to allow the internal vacuum system to reach 1×10^{-8}. 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 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 1×10^{-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 5×10^{-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 (5×10^{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 5×10^{-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]

VACUUM SYSTEM DESCRIPTION - INTERNAL

General

The mechanical design of the vacuum vessel, the physics vacuum requirements, and the basic analytical methods used for design of the system have been published in detail elsewhere.[3,6] We include here a general description oriented toward 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 liners, the diagnostic and ECRH access ports, and the rectangular end fan tanks. The approximate size of the system is shown through 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 SS vacuum cases which can be differentially pumped to remove 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.

Vacuum Regions - Liners

Figure 2 is a schematic showing the nine 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 6×10^7 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.

Getters

The Ti getter system for all these liners is extensive and must be precisely controlled to ensure a minimum of 3 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 power 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 minute machine cycle. The getters are also used for heating of the inner plasma liner and of the other liners during operation of the vacuum system.

Diagnostics

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

EXTERNAL VACUUM SYSTEM

The external vacuum system components are outlined in Table 1. For the most part they are 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 turbo pumps are used to handle the pumpdown gas load.

SUMMARY OF THE VACUUM SYSTEM CHARACTERISTICS

Table 2 contains a summary of the essential characteristics of the TMX-Upgrade vacuum system.

VACUUM EXPERIMENTS/OPERATIONS

The establishment of 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 preceeds and then compliments the plasma physics experimental sequence. Table 3 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.

SUMMARY

The TMX-Upgrade vacuum system and operating procedures are designed to produce low base pressures (1×10^{-8} torr) for starting up plasmas and low (5×10^{-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.

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Table 1. External and internal vacuum systems.

Subsystems List	Brief Description
External Vacuum System	
1. Roughing Pumps	External to bldg. connected via 2 ea 6" lines 6 ea roughing pumps, 1600 c fm total
2. Blowers	4 ea @ 666CFM
3. Turbo Molecular Pumps	2 ea @ 1900 ℓ/s N_2
4. Cryo Pumps	6 ea on 3 ports 1100 ℓ/s Ar and CH_4, ~500 ℓ/s H_2
5. Cryo Regeneration	2 ea roughing pumps, N_2 purge
6. Dry Air Flush	Dry air trailer permanently installed
7. Diagnostic Pumpout	3 ea vacuum carts with turbos
8. Beam Pump out	Auxillary system and pre-pumpdown firing
9. Leak hunting	5 ea residual gas analysers (RGA)
10. Auxiliary	10 ea carbon vanes @ 10 FM, 2 ea Vac Sorb
11. Controls and readout	Vacuum map-modular commercial
12. Interlocks	50 ea, thermocouple gauges, 16 ea ionization gauges, vac map
13. Data Base Interface	Computer driven Camac system
Internal Vacuum System	
1. Liners	72 ea SS quilted, LN cooled, heated by getter wires, individually plumbed, pumpable, Al inner liner panels
2. Getters	162 x 6 Ta-Ti wire bundles, personnel safe connection, individual voltage regulated power supplies, slow turn on (15 s)
3. Fast Ion Gauges	3 ea magneticaly shielded Baird Alpert gauges + RGA's
4. Moveable RGA's	2 ea, sample impurity conc. center of plug, nude
5. Reflux Gauges	2 ea tunnel type/fast ion gauges
6. Regional Ion Gauges	10 ea 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 sys.
11. Glow Discharge	H_2 gas, anodes in all regions, exhaust with blowers, hot liners, separate 700 v 3 amp supplies RGA monitor in exhaust

Table 2. Summary of the characteristics of the TMX-Upgrade vacuum system.

Item	Description
1. Vacuum vessel	• Consists of eleven separate tanks; seven cylinders, two domes, and two rectangular sections. • Construction: Nominal 4.06 m diameter, 1.27 cm thick shell, 21.7 m long. • Material: 304 stainless steel • Number of ports: 292 • Volume: 225.2 m^3
2. Liquid nitrogen liner	• Total quantity 72 sections; 40 cylindrical, 12 discs, 20 flat, rectangular • Active pumping area: 540 m^2
3. Titanium getters	• 162 getter assemblies, 6 wires per assembly • Wire: 85% titanium - 15% tantalum, 0.318 cm diameter • Expected life per wire: 300 - 60 s sublimation cycles. Total expected life per getter assembly 1800 - 60 s cycles • Sublimation cycle: 15 s warm up, 60 s sublimation period at 106 A, 4-5 monolayers per cycle • Total length of active getter wire: 274.4 m

4. Internal Regions	Totals	Volume, m^3	Surface area, m^2 Cold 77 K	Surface area, m^2 Warm Approx. 300 K	Pumping speed for hydrogen ℓ/s
1st injector		94	350*	-	3.2×10^7
2nd injector		80	140	60**	2.0×10^7
Plug plasma		9.2	-	15	2.6×10^6†
Central cell plasma		20	-	32	5.2×10^6†
End fan		22	25	6	2.6×10^6
		225.2 m^3	540 m^2	110 m^2	6.24×10^7

5. External vacuum system 890 ℓ/s @ 100 torr vessel pumping speed

*Cold sticking coefficient = 0.4 for H
**Warm sticking coefficient = 0.03 for H
†Includes pumping effect of plasma itself on region SC = 0.5

Table 3. TMX-Upgrade pump down procedure for achieving low base pressures clean surfaces and low peak pressures during gettering for TMX-Upgrade

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PUMP DOWN

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 x 1^{-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 at 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 turbo pump vacuum
   Record pressures and RGA to indicate N beam dump clean-up

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 clean-up prior to opening to vessel it liners are cold.

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 hrs)
    Record exhaust rate for C, O, N

12. Repeat step 6, re-bake all getter wire sets
    Record final pressure and RGA
    Fire all neutral beams once

Table 3. (continued)

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 3 times (10 monolayers on liners)

16. Set getters in outer annulus at 10 A all other getters at 60 A

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 cryo pumps
    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 inj reg getters to 10 A

FINAL GETTERING

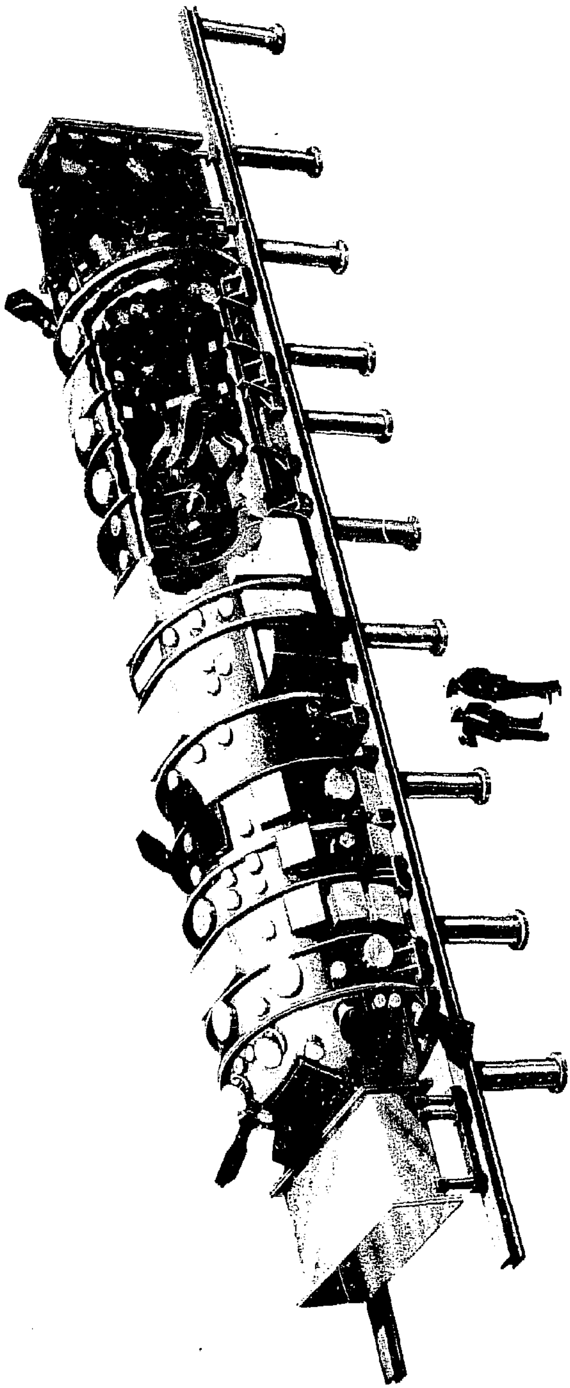
23. Set plasma region getters to 10 A and cycle getters 3 times (10 monolayer minimum)
    Record pressure

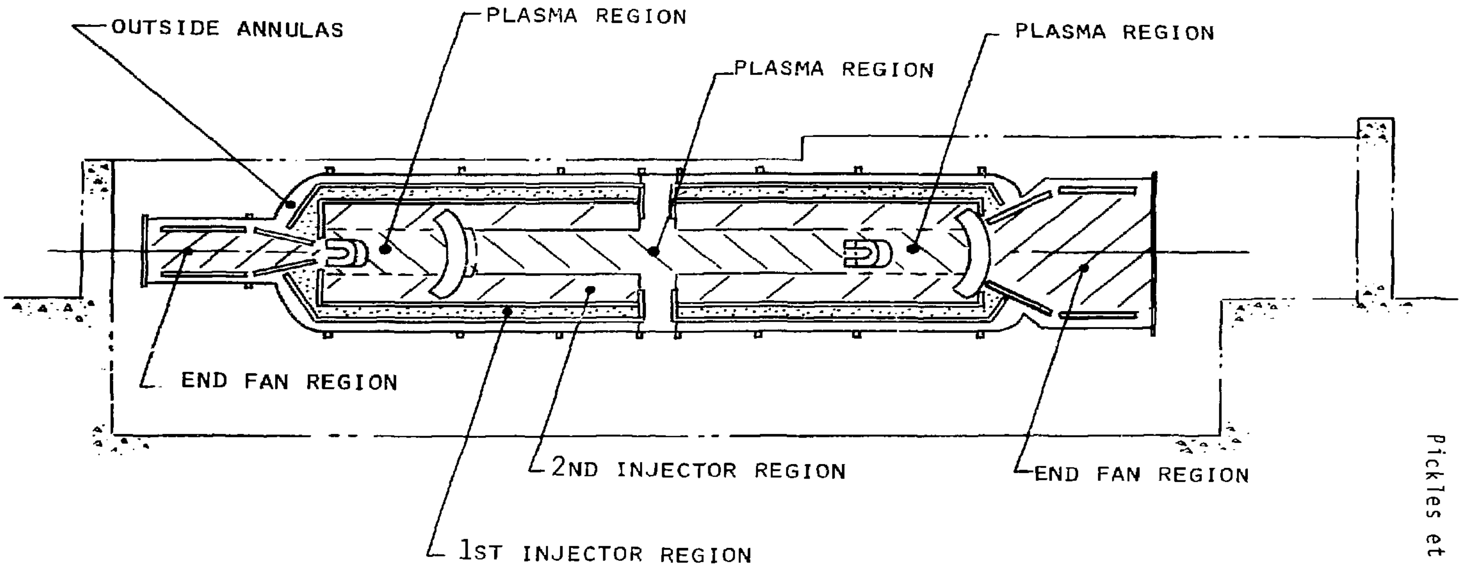
24. Operate full machine plasma shot

25. Continue monitoring pressure and RGA for possible leaks

26. Start physics sequence
    (Recommend gettering every shot generally)

Pickles et al. - Figure 1





Pickles et al. - Figure 2

FIGURE CAPTIONS

Fig. 1. TMX-Upgrade vacuum vessel - functional view.

Fig. 2. Schematic of the eight vacuum regions of TMX-Upgrade.

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