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Construction and Operational Experience of the Tandem Mirror Experiment-Upgrade (TMX-U)

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Abstract

The Tandem Mirror Experiment-Upgrade (TMX-U) incorporates two new features at Lawrence Livermore National Laboratory (LLNL) tandem mirror program, thermal barriers in the end plugs and injection of the neutral beams at several oblique angles. The thermal barriers isolate the electrons in the end plugs from those in the central cell, making it possible to heat them independently with microwaves. In addition, this innovation produces a large potential gradient in the end plugs with lower magnetic fields and lower neutral-beam energies than would be possible in a conventional tandem mirror device. The TMX-U is also designed to test neutral-beam-injection angles as an experimental parameter. We use angles other than 90° to produce a plasma with improved microstability.

The vacuum tanks that house the entire apparatus contain surfaces that pump out cold hydrogen gas. The 540-m^2 surface area in TMX-U is covered with titanium gettering and cooled with liquid nitrogen. These surfaces can pump hydrogen gas at a rate of 6×10^7 litres/s over the neutral-beam-pulse length of 75 ms. The vacuum tanks are 4 m in diameter and 22 m long. In TMX-U, as can be done in any tandem mirror device, we incorporate the neutral beamlines within the main vacuum tank. In this way we save on the cost of the machine and at the same time increase its volume. The large volume helps in the design of the pumping surfaces incorporated within the machine.

The water-cooled copper magnets in TMX-U produce 2-T fields at the magnetic mirrors. The magnet set is 14.2-m long and can accommodate a magnetic-flux bundle diameter of 30 cm in the end plugs and up to 60 cm in the central cell. This magnet set has 24 coils weighing a total of 100 t. The coils are connected in 17 separately controlled circuits, which are energized by 36 MW of primary power.

The neutral-beam power supplies produce 20 MW (total) of accel power in 24 beams, delivering 10 MW of power to the plasma. The beams can be aimed at the plasma in several combinations of angles: 18, 47, 59, 65, 70 and 90°. We can produce another 800 kW of microwave power with four gyrotrons at 28 GHz (ECRH heating). Depending on the transmission system used, between 50 and 85% of the power can be delivered to the plasma. Additionally, we have 200 kW of rf power for heating the central cell (ICRH heating). This power is delivered at the frequency of 2.5 MHz, although the tunable range is from 1 to 30 MHz.

The diagnostics and computer system record 249 plasma-information channels and 233 machine-performance parameters. This information translates into 10 MBytes of data

stored on each experimental shot. The data are stored and calculated by six interconnected mainframe computers with storage capability of 846 MBytes.

In our early experiments with TMX-U we investigated the microstability of the plasma in the new geometry. Later experiments addressed issues associated with generation of thermal barriers in the end plugs.

The machine operates on a four-month cycle of experimentation: one month for modifications and maintenance, one month for workup of the equipment, and two months for data taking.

Introduction

Following the invention of the tandem mirror concept in 1976 by Fowler and Logan[1] in the United States and by Dimov et al.[2] in the USSR, a number of experimental programs were begun to test the concept. Internationally, these programs were in Japan, the GAMMA series of experiments; in the USSR, the AMBAL series; and in the United States, the TMX series initially but later expanded to several others. Presently the tokamak and the tandem mirror concepts form the main-line approach to the U.S. development of fusion energy. The TMX[3] was the first tandem mirror device in the United States. Its construction was completed in October 1978 and the first results confirming the advantages of tandem mirror geometry occurred in July 1979. The TMX was operated through October 1980, when it was disassembled for installation of the next machine. In this presentation, we concentrate on the second experiment in the TMX series, the TMX-U, its construction, operation, and resulting role in the tandem mirror program.

In the original tandem mirror concept, the electrostatic potential of a single mirror cell is used to enhance plasma trapping in a solenoidal magnetic field by installing such a single mirror cell at each end of a relatively long solenoid. Since most of the fusion energy is produced in this solenoidal central cell, the possibility of a relatively simple and accessible fusion-reactor geometry is very good. First proposed by Baldwin and Logan[4], "thermal barrier" is an improvement to the tandem mirror concept. It isolates the electrons in the end cells from those in the central cell, thus allowing independent heating of the end-cell electrons. In this manner, a high electrostatic potential can be maintained, which gives better trapping but at the same time reduces input power demands and simplifies technological requirements.

The TMX-U device incorporates thermal barriers in its design as well as a unique magnetic-field geometry in the end cells which provides improved microstability of the plasma.[5] This improvement occurs because the "sloshing ion" distribution is peaked near the mirrors of the end cell. Therefore, TMX-U is a proof-of-principle machine leading to the major scale-up machine in tandem mirror research, namely, the Mirror Fusion Test Facility (MFTF-B),[6] which will be operational in 1986.

Figure 1 shows the chronological evolution of the TMX sequence of experiments. The TMX sequence represents the testing ground for concepts proposed for the tandem reactor type machines, and even more directly, it is intended to teach us how to run MFTF-B. Not shown in Fig. 1 is another major change to TMX-U, the addition of a 6-T axisymmetric mirror at each end of the axisymmetric portion of the central cell. This axisymmetric mirror is intended to reduce radial losses inherent in quadrupole systems. The coils required to produce this mirror will be added to

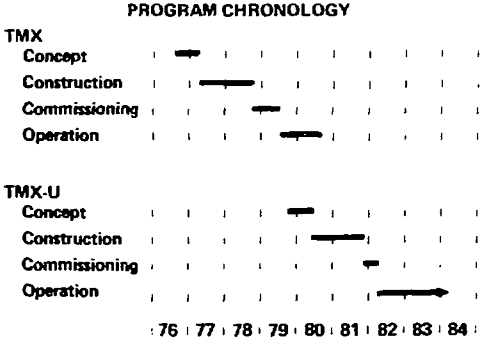

Figure 1. Program history, showing initiation of conceptual design for TMX-U before results from TMX were available.

TMX-U in December 1983. This type of axisymmetric mirror was adopted in the TARA design[7] at Massachusetts Institute of Technology (MIT), United States, and in GAMMA 10[8] at University of Tsukuba, Japan.

Here we describe TMX-U on a subsystem-by-subsystem basis so that its uniqueness and/or similarities with other large fusion machines may be readily apparent.

Vacuum Envelope Design

In the engineering sense, a linear device, such as a tandem mirror machine provides several attractive options for its overall design. Figure 2 shows the evolution of the TMX-U geometry. The conceptual design shown in Fig. 2(a) was considered for TMX, although not adopted. However, such a design has been adopted for the GAMMA 10[8] machine in Japan and for the TARA[7] machine at MIT. Figure 2(b) shows the basic geometry used for TMX. This geometry allows the location of the neutral-beam sources to be at the same focal distance away from the plasma as in Fig. 2(a). In addition, it has the advantage of integral internal volume, which makes it easier to incorportate massive surface pumping while allowing conductances between adjacent surfaces to be at the control of the designer. These advantages are gained in addition of saving 50% in weight and in the cost of the vessels themselves. The required laboratory space, in a plan view, is less by almost a factor of two for tank geometry that is coaxial with the machine axis. In a side view, the required space is similar for the two approaches.

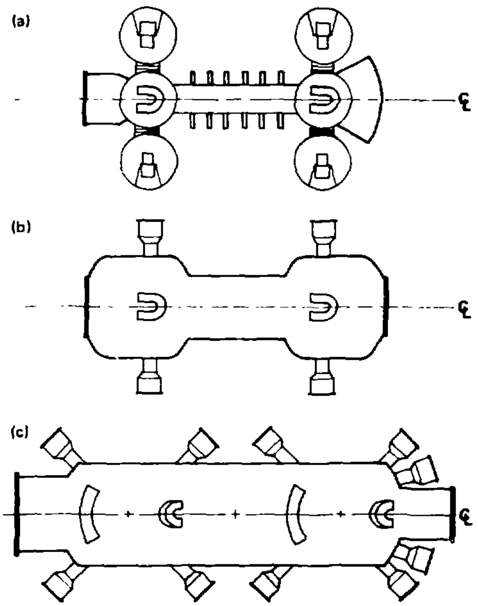

Figure 2. Evolution of TMX-U vacuum-envelope geometry: (a) conceptual design for TMX, (b) final design for TMX, and (c) final design for TMX-U.

Figure 3 illustrates the main advantage of a linear system: full access to the machine, 360° around the axis is allowed. From the original geometry of TMX in Fig. 2(b), the final TMX-U vacuum envelope evolved as in Fig. 2(c). Except for the end walls, this geometry incorporates tanks of uniform diameter throughout.

The vacuum envelope is constructed of seven cylindrical tanks, two domes, and two rectangular sections. The dimensions of interest are: length, 22 m; diameter, 4 m; typical cylindrical wall thickness, 1.3 cm; volume 225 m^3. Together with internal vacuum-system components, the weight of the vacuum vessel is 100 t of the total 250-t machine weight. The domes are constructed from

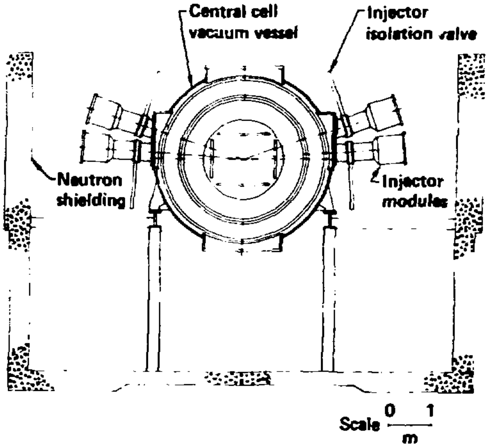

Figure 3. In a linear device, such as TMX-U, machine access can be maintained for 360° around the longitudinal axis.

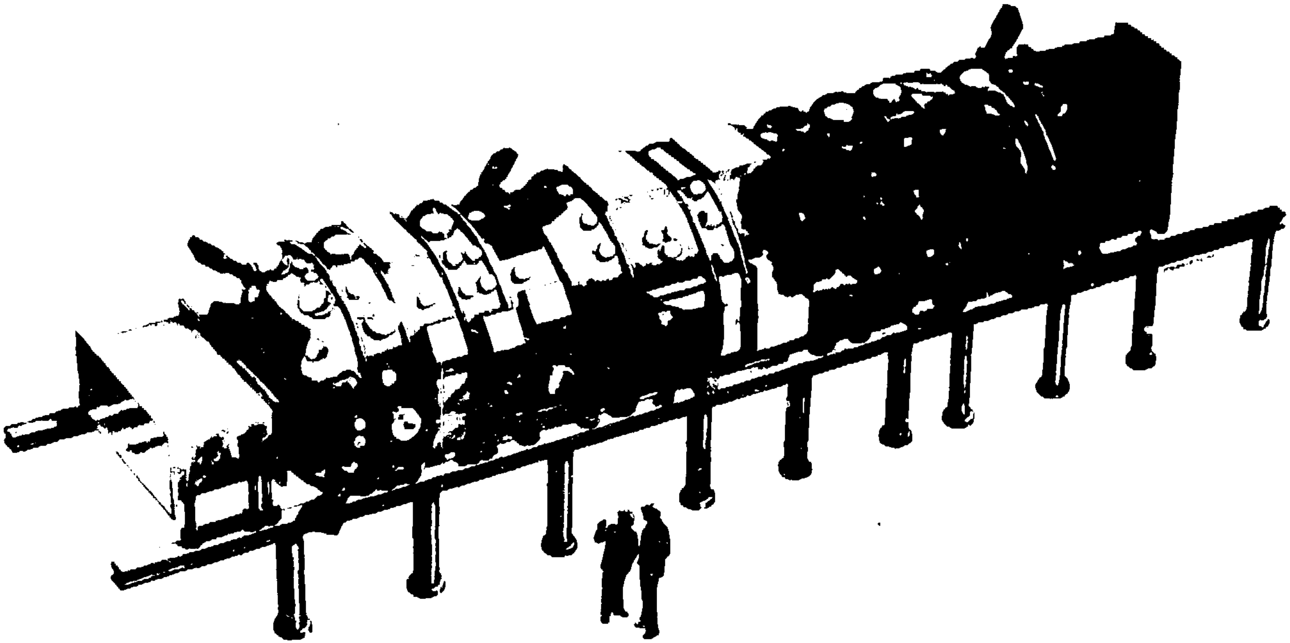

Figure 4. The TMX-U apparatus with cutaway at one end to show the internal components.

ASME torispherical dished heads and a rectangular-box-like shape to match with the end tanks. The structural integrity of this combination, considering the atmospheric pressure load as well as the 50-t axial-magnetic load, was analyzed for buckling, using the newly developed capability of MSC-NASTRAN,[9] a finite-element stress-analysis computer code.

Other vessel sections are designed to ASME Boiler and Pressure Vessel Code. All tank walls are 304 stainless steel, while the majority of flange covers are aluminum.

Figure 4 shows the general arrangement of the machine apparatus. The central-cell tanks are bolted to the longitudinal rails while end tank sections are on wheels to accommodate movement resulting from thermal expansion and to facilitate access in the case of significant machine modifications. Normal machine maintenance access is provided through several 180-cm flange openings. In total there are 300 openings in the tank walls to provide for various connections and access to the outside environment. All flange vacuum seals are made with O-rings. The 4-m-diameter flanges, as well as several other large ones, have double O-rings for pump out between them. This arrangement facilitates leak checking even before the complete tank assembly is at vacuum.

Fast-Surface Pumping

The key element in the design of TMX-U fast-surface pumping is the total amount of gas to be absorbed on the surface before recycling. With 24 neutral beams operating and an average level of gas fueling in the central cell, the total gas load in the machine is 900 Torr.litres. The design goal was to pump this gas for at least 75 ms and maintain H° pressure less than 5×10^{-7} Torr near plasma boundary. With extensive numerical modeling using the computer code DYNAVAC,[10] and analytical modeling of experimental results, we have limited the flow of neutral-beam-thermal gas into the plasma region to 11 Torr.litres/s. With a combined pumping speed for all surfaces of 6×10^7 litres/s, this low flow rate can be obtained because of optimizing internal partitioning of the tank volume and limiting conductances between partitions.

Figure 5 shows the overall internal arrangement of fast-surface pumping panels. The first injector region pumps most of the neutral-beam thermal gas, on 350 m^2 of surface area; the second injector region pumps less gas, on 200 m^2 of surface area, but at lower pressure; and the plasma and end-fan regions pump the least of the neutral-beam thermal gas, on 100 m^2 of surface area, but the pressure is the lowest. However, the gas fuel is added and the wall conditioning is the most critical in these innermost areas, as in any other fusion

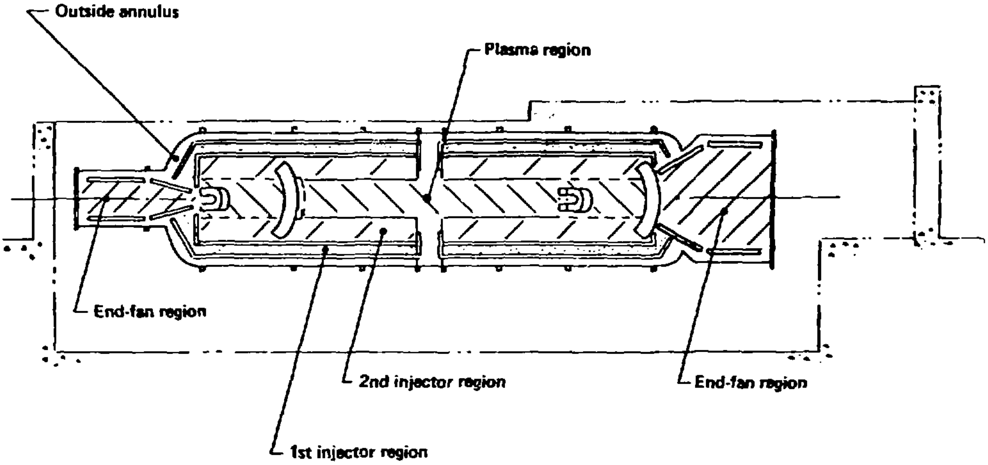

Figure 5. Internal arrangement of fast-surface-pumping panels.

machine. In TMX-U, wall conditioning is accomplished through temperature control of surfaces, glow-discharge cleaning, and titanium gettering.

The internal surfaces surrounding the first injector region (see Fig. 4) are panels at liquid-nitrogen temperature. The outer surface of the second injector region is also at liquid-nitrogen temperature while its inner surface is made of panels at room temperature. Therefore, the plasma region is surrounded with room-temperature walls, including the end walls. The remaining volume in the end-fan region is surrounded with panels at liquid-nitrogen temperature. In total, there are 72 separate panels made of 0.124-cm-thick 316 stainless steel. The panels are made by spot-welding together two such sheets, forming them to appropriate shapes, and pneumatically expanding them to provide volume for liquid-nitrogen flow. The pumping is provided by 162 titanium sublimators, made of 85% titanium-15% tantalum wire 0.317-cm in diameter. A typical sublimator is 180 cm long and contains six wires. This arrangement gives us sublimation capability for 1800 cycles, each 60 s in duration. The average thickness of each new sublimated titanium film is five monolayers. We selected liquid nitrogen surface with titanium sublimation as our pumping method because the other choice considered, liquid helium cryopanels, was more expensive and did not provide faster pumping over a short pulse length.

Magnet System

Because the TMX-U design priority was placed on a large vacuum volume, the magnets had to be located inside the vessel. This means that each magnet is encased in its own vacuum envelope which also acts as a structural restraint. Typical wall thickness of such magnet cases is 1.3 cm of stainless steel, while in a few zones of high magnetic loads the thickness may reach 5 cm.

Figure 6 shows the design used to maintain the electrical integrity of the coil while at the same time maintaining the integrity of the vacuum system. The magnets are built by using square, hollow, water-cooled, copper conductors. The magnet windings and insulation are epoxy-impregnated inside the potting case. The space between the potting and vacuum cases can be pumped out to act as a guard vacuum. In the magnet lead area, the guard vacuum could cause voltage breakdown in the Paschun-curve sense. Careful attention must be given to the design and installation so that either arc paths do not exist or the guard vacuum pressure is controlled. On TMX and TMX-U, such coils have successfully operated at approximately 1000 V and 5000 A.

Each of the considerations in Table 1 was used in selecting the final design. Several hundred cases were iterated through some of the steps in Table 1 before the final design was selected. The primary numerical tools used included a finite-element stress-analysis code as well as several codes relating the physics of plasma stability to magnetic-field shape. The most difficult problem to solve involved the multiple neutral-beam-access angles and the closed particle drifts in the end cell.

As shown in Fig. 7, the design selected consists of five sets of coils: two end-plug sets with five coils each, two transition sets with four coils each, and a central-cell set with 6 coils. The assembled magnet sets weigh 100 t, are 14.2 m long,

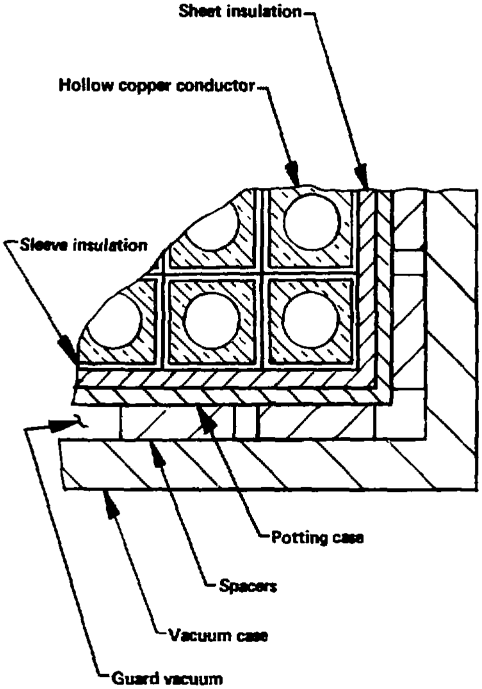

Figure 6. Detail of typical magnet cross section.

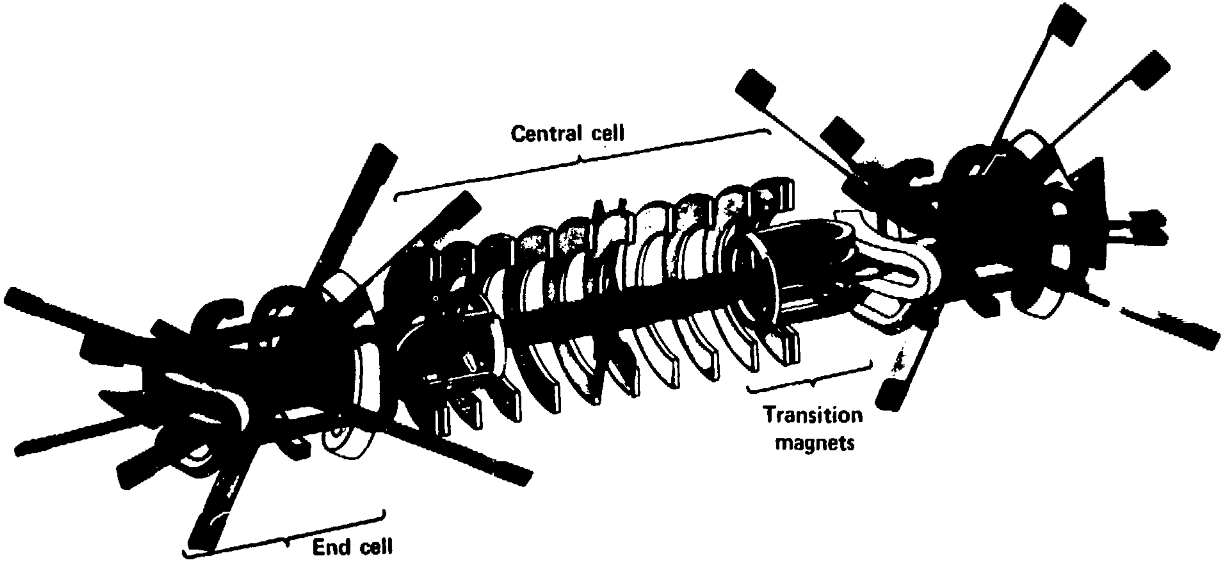

Figure 7. Magnet set with its twenty-four coils.

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and can accommodate a plasma diameter of 60 cm in the central cell and 30 cm in the end plugs. The peak magnetic field in the end plug is 2 T, while at the plug midplane it is 0.5 T. The central cell field can be operated up to 0.3 T. The 24 coils are connected in 17 circuits, which are computer controlled so that a number of magnetic-field configurations can be stored in the computer and selected according to experimental requirements. The ac power input is 36 MW in pulse lengths of 3 s.

Table 1. Magnet design considerations.

Engineering considerations	Physics considerations
Neutral-beam access	Magnetic-field profile and magnitude
ECRH-microwave access	Ellipticity and thickness of the flux-bundle cross section
Diagnostic access	Radial well depth in the end cell (plug)
Coil supports	
Power requirements	Closed particle drift surfaces in the end and central cells
Available space	Adiabaticity in the end cells
	Radial transport in the central cell
	MHD stability: flute interchange
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Neutral-Beam Injection

The TMX-U operates 24 neutral-beam injectors as the main source of power for heating and fueling the plasma. The power delivered per injector is 50 A (accel) at 17 keV in 75-ms pulses. Of the total 20 MW, 10 MW are incident on the plasma. In terms of number of injectors that operate simultaneously, the TMX-U neutral-beam injection is the largest in the world. We use both spherically and cylindrically focused slot extractors with overall aperture size of 7 × 35 cm. The extraction current density is approximately $0.4\ \mathrm{A/cm^2}$ and the gas flow input can be limited to 25 Torr.litres/s.

Since beam-injection angles are an experimental parameter, we have designed the machine to have multiple possible injection angles: 18, 47, 65, and 90° in the end plugs and 59, 70, and 90° in the central cell. This flexibility is possible because of the unique vacuum-system design that incorporates beamline-type pumping within the main vacuum chamber, as described earlier. The neutral-beam source modules operate inside a magnetic shield ranging from 3.6 to 4.5 m away from the plasma. The magnetic shield isolates the source module from the ambient field of 200 to 750 G, depending on the location. Each source module, with its neutralizer, is mounted on an isolation valve to make replacement possible without disturbing the machine.

So as to not degrade the system performance in case of a module failure, we have a maintenance program that keeps a few fully tested modules ready for use on the machine. After a typical machine air cycle, it only takes four days to condition the full 24-injector system so that plasma experiments can begin. We achieve this with the help of a test stand having components identical to those of the main machine. With this test stand, we not only insure the quality of components to be used in the experiment, but we also develop and test hardware and software, making changes relevant to improving system performance. These improvements include impurity reduction by titanium sublimation within the module; gas input reduction by detail characterization of gas valve and arc chamber performance; and reduction of streaming gas by apertures and collisional gas dynamics. Also, since our control system is CAMAC based and is operated through four desk-top computers, we use the test stand to develop software logic, especially that which will be applicable to fully automating the neutral-beam injection.

Electron-Cyclotron-Resonant Heating (ECRH)

The ECRH system is a key element of a tandem mirror device, such as TMX-U, which is designed with tailored potential profiles to enhance plasma confinement. In TMX-U, ECRH is applied at two locations in each of the end plugs: at 1 T for fundamental-mode heating and at 0.5 T for second-harmonic-mode heating. To further tailor the heating pattern in the radial direction, we chose to divide the microwave beam into eight smaller beams. These beams can now be precisely aimed to maximize the energy absorption within the plasma.

The ECRH system consists of four gyrotrons operated at 28 GHz with an output beam in a 63-cm-diameter waveguide and with 200 kW of power for 75 ms. From this waveguide, using an 8-arm mode converter, we convert to a standard WR42 rectangular waveguide that delivers the power to the plasma through a horn. The disadvantage of this system is its low efficiency, 50% overall. Since the initial installation of the rectangular waveguide, we and others have developed large circular components that will enable us to tailor the 63-cm-diameter microwave beam and aim it at the plasma correctly. The new system uses a reflector[11] that converts TE_{01} in the circular waveguide into a linearly polarized Gaussian intensity pattern in the plasma. Based on tests of individual components, we expect the efficiency for the 0.5-T system to be 85% and for the 1-T system to be 75%. One of these systems, for the 0.5-T location, is shown in Fig. 8.

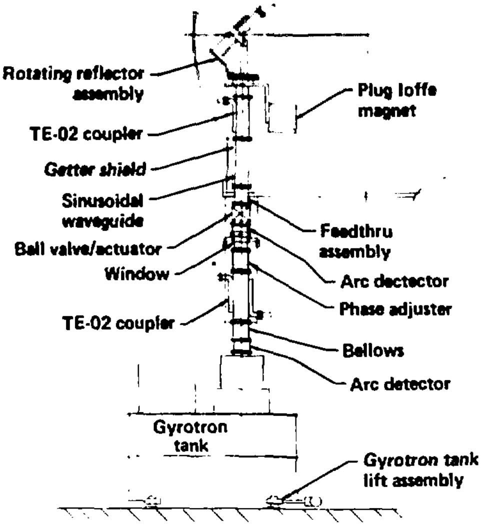

Figure 8. The ECRH transmission system with circular waveguides.

Ion-Cyclotron-Resonant Heating (ICRH)

The ICRH system is capable of delivering 200 kW of rf power to the antenna structure located in the central cell of the machine. The power supply is a modified broadcast transmitter capable of operating in the range of 1 to 30 MHz. Included in the CAMAC-based control is an automatic power foldback capability that regulates output power as a function of antenna-matching performance. Since the antenna impedance is a function of plasma density, the transmitter adjusts itself to maximize the power to the plasma. The antenna sweeps a 110° arc in the plane perpendicular to the machine axis and includes the matching network of vacuum capacitors within the vacuum envelope. Two other 200-kW transmitters, with different antenna elements and operating frequencies, will be installed in the near future.

Diagnostic Instrumentation

The TMX-U machine inherited some of its diagnostics from TMX. However, because of new magnets, general machine configuration changes, ECRH addition, ICRH addition, oblique angle neutral beams, and increase in magnetic-field strength in the central cell, the capabilities of the existing diagnostic system had to be increased both in type of instruments and in their number. In our design approach we differentiate between instruments that monitor plasma performance and those that monitor machine parameters that are relevant to plasma parameters. Figure 9 illustrates the basic set of TMX-U diagnostics and their location with respect to the plasma.

Table 2 lists all plasma diagnostic instruments, a total of 249 separate plasma-information channels, that are used to describe plasma characteristics with parameter values, time resolution, and spacial positions. To produce these characteristics, we take 200,000 to 300,000 data samples at a rate of 1 kHz to 20 MHz, with the majority of them at 50 kHz. The cabling system, as installed,

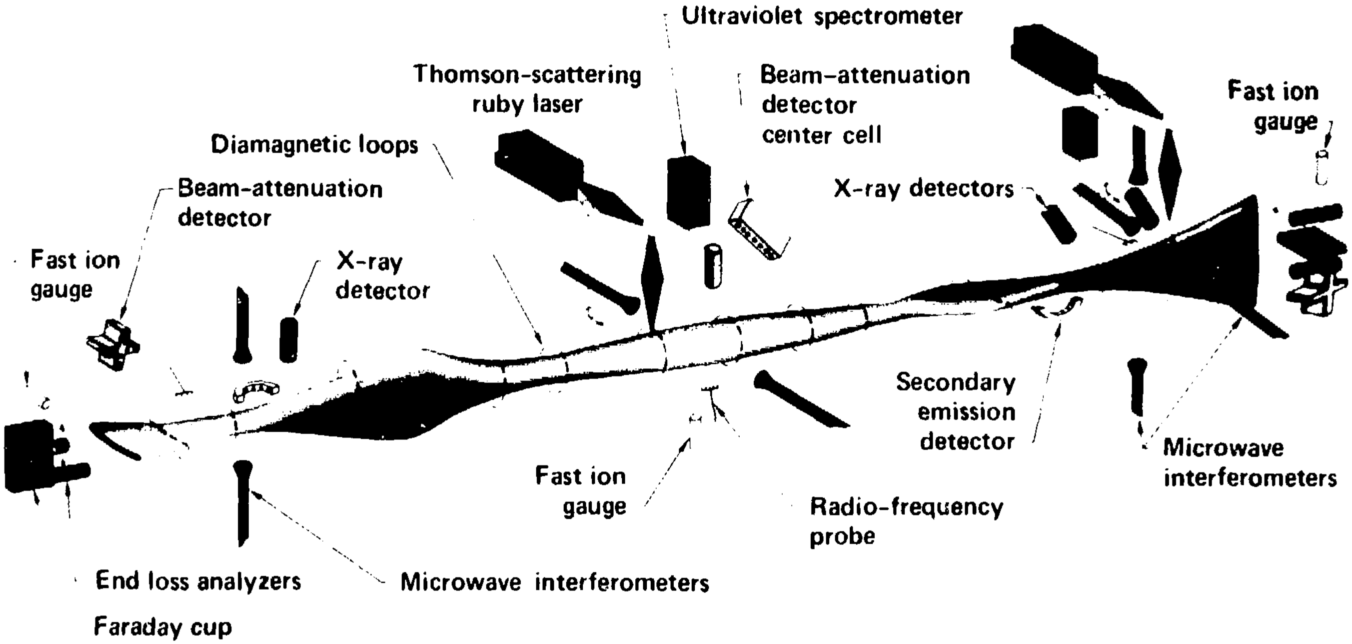

Figure 9. Initial array of instruments used for defining the plasma parameters.

Table 2. Plasma diagnostics instruments.

Diagnostic	No. of plasma information channels[a]
1. Diagnostic timing	6
2. Diamagnetic loops	14
3. Beam-attenuation detectors	51
4. Secondary-emission detectors	26
5. RF probes	21
6. 22 channel EUV monochromator	22
7. Grazing incidence 1024 channel spectrometer	1
8. Normal incidence 1024 channel spectrometer	1
9. X-ray spectrometer	3
10. End-loss analyzer	4
11. Langmuir probe	3
12 Faraday cup	26
13. Net current collectors	26
14. Fast-ion gauges	6
15. Microwave line density	8
16. Microwave-density fluctuations	4
17. Thomson scattering	3
18. Whistler electron-cyclotron emission	1
19. Perpendicular electron-cyclotron emission	1
20. Charge-exchange analyzer	1
21. Bolometers	20
22. Plasma-potential diagnostics	1
Total	249

[a] One plasma information channel is defined as one piece of information about the plasma at a point in space and resolved in time.

Table 3. Machine performance parameters.

Parameter	No. of channels
1. Magnet currents	17
2. Neutral-beam current and voltage	72
3. Neutral-beam current summary	5
4. Neutral-beam secondary-emission detectors	24
5. Streaming guns	8
6. Gas box	22
7. Residual-gas analyzer	4
8. Fast-ion gauges	6
9. Slow-ion gauges	9
10. ECRH	64
11. ICRH	2
Total	233

is capable of transmitting about twice as much data as described above and with enough interconnection flexibility so that data taken at one location on the machine can be transmitted to an almost arbitrary location within the diagnostic room where the CAMAC transient recorders are installed. The additional cable capability facilitates moving a probe from one location on the machine to another and is not there just to increase the number of channels in the future.

Table 3 lists machine-performance parameters, a total of 233 separate channels. These data are collected through transient recorders, the same as plasma diagnostics. However, they are installed in a separate control room where all machine controls are installed. The signals are then routed through to the diagnostic computer. By separating the two types of required information from the machine, we also separate the function of machine control from that of plasma diagnostics, with the connection being made only where necessary to characterize the plasma. To enable the experimental leader to evaluate the experiment status in real time, a summary containing both diagnostic and machine-parameter information is displayed at a separate console.

Diagnostic Computer

The main components of the TMX-U diagnostic computer system are six Hewlett-Packard 21MX computers and eight disc drives. Other components are listed in Table 4. Three of the computers are primarily responsible for acquiring data from the experiment through CAMAC transient recorders. Another two are primarily responsible for outputting data to printers, plotters, monitors, and terminals. The sixth machine is used primarily for code development. All six computers share the data reduction and analysis jobs. Analysis subroutines range from fairly simple scaling

Table 4. Computer system components.

Description	Quantity
CPUs	6
Disk storage	846 MBytes
Input/output channels	164
Magnetic-tape drives	5
Graphics terminals	6
Color TV monitors	5
Printers/plotters	10

and baseline subtraction to very complex fast-Fourier transforms and cross correlations with a number of diagnostics or a number of data shots. The selection of which of the six machines will perform a task is done by a resource-control system so that high-priority results are available immediately while low-priority tasks must be delayed and finally accomplished during interruptions of the experiment operation. The volume of data acquired for each shot is 3 to 4 MBytes, which amounts to 10 MBytes of stored information after preliminary processing.

Operations

The construction of major TMX-U systems was complete in December 1981. After that followed a period of three months for commissioning and checking out the machine subsystems, after which time we produced the initial plasma. Table 5 shows the sequence of experimental runs and follows the pattern of milestones published in the TMX-U proposal.. The first five experimental runs individually established the building block required to achieve the thermal barrier. Run #6, currently underway, is intended to put these building blocks together and to demonstrate the existence of the thermal barrier.

In our operating experience to date, we are establishing a pattern that averages a four-month run duration: one month of installation (at air), one month for commissioning, and two months for data taking. Since many of the envisioned machine additions take a relatively long time to construct, the physics plan and the engineering conceptual design must be started several run cycles ahead of the planned installation. Therefore, the whole program is carefully managed to insure that the flow of experiments runs smoothly and that the hardware is available when needed.

Our operating experience shows little correlation between operational availability of hardware and its conventional or high-technology origin. Rather, it is the experience of the operating personnel with the particular component or subsystem that governs the availability of the hardware to perform. That is, an individual experienced with the difficult high-technology hardware may make it available for a higher fraction of the time than may an inexperienced individual using easy conventional hardware. Exchange of information

Table 5. TMX-U operating history and future operating plans.

Run No.	Date	Modifications or additions	Physics studies
1	December 1981 to February 1982	Construction completed Initial pumpdown made Glow discharge added	Wall preparation technique
2	March 1982	Warm walls added 1 ECRH horn installed	Initial plasma
3	April 1982 to August 1982	ECRH prototype added Replaced Ti sublimator wires	Sloshing ions and microstability ECRH start-up Conventional tandem mode
4	September 1982 to October 1982	Replaced Ti sublimator wire All four gyrotrons installed Pump beams installed	Hot electron production
5	November 1982 to February 1983	ICRH installed Pump beams operational	Modeling MFTF-B type start-up Plug pumping
6	March 1983 to July 1983	Replaced Ti sublimator wires Changed neutral-beam aperture size	Thermal barrier
7	August 1983 to November 1983	Relocation of ECRH horns planned	Negative tandem
8	December 1983	Throttle coil installation planned	Radial transport

and training of operating personnel must be organized with purpose and not occur randomly.

The TMX-U staff consists of technicians, engineers, and scientists of several disciplines. There are a total of 130 persons, half of whom are engaged in operations of the experiment and half in construction of additions and modifications to the machine. With this division of effort, we maintain the ability to construct and test at the rate that keeps up with the rate of invention in tandem mirror physics.

Acknowledgements

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