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THE TMX-U DIAGNOSTIC SYSTEM

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ABSTRACT

Using data from the TMX-U diagnostic system, the production of sloshing ions has already been verified and the formation of electron thermal barriers is presently being investigated on the Tandem Mirror Experiment-Upgrade (TMX-U) at Lawrence Livermore National Laboratory. The TMX-U diagnostics are made up of the earlier TMX complement of diagnostics that determine confinement, microstability, and low-frequency stability, plus diagnostic instrumentation that measures electron parameters associated with mirror-confined electrons. This paper describes the three subsystems within the TMX-U diagnostic system: (1) the diagnostic facility (shot leader console, data cable system, and diagnostic timing system); (2) the individual diagnostic instruments that measure plasma and machine parameters; and (3) the data-acquisition and -analysis computer.

INTRODUCTION

The TMX-U diagnostic system[1] is designed to investigate a complete tandem-mirror thermal-barrier system.[2] The TMX-U facility (see Fig. 1a) comprises five major systems: (1) magnet, (2) vacuum, (3) heating (neutral beams, ECRH, and ICRH), (4) start-up and fueling, and (5) diagnostic. The TMX-U is the first experimental facility designed to test the end-plug configuration that will probably be used in a future tandem-mirror fusion reactor, that is, an end plug with thermal barriers. The purpose of the TMX-U is to confirm the thermal-barrier concept and give us experience in generating and controlling thermal barriers. This experience will be essential when we begin operating the next major test facility in our mirror fusion program, the Mirror Fusion Test Facility (MFTF-B), which is scheduled to be operational in 1986.

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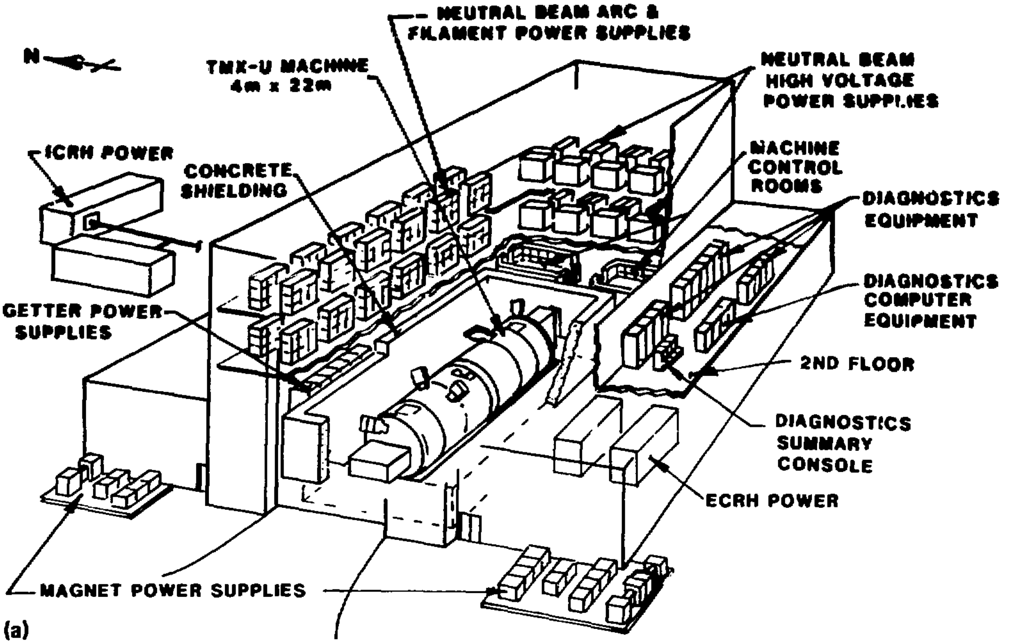
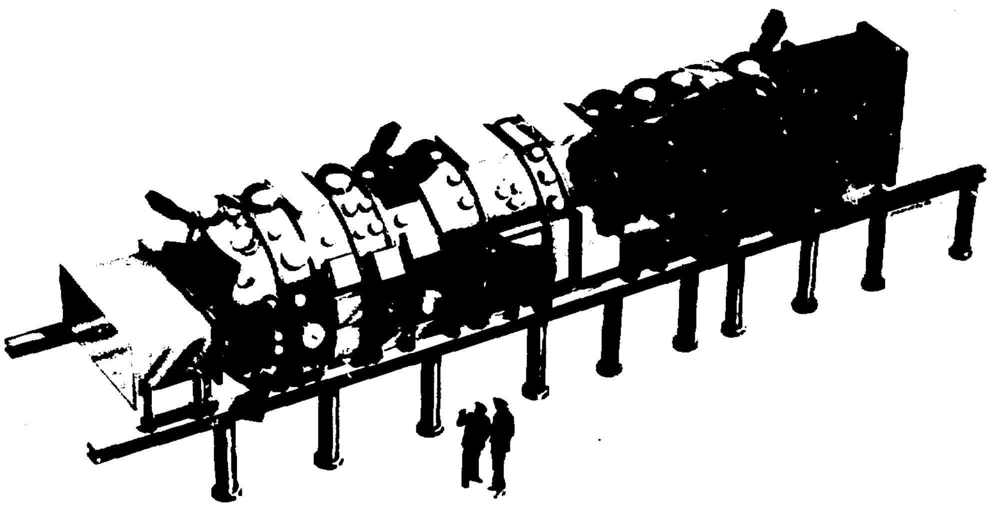


(a)



(b)

Fig. 1. (a) Main components of the TMX-U facility. (b) The TMX-U machine contains improved end-plug magnets, angled neutral-beam sources to produce the sloshing-ion distribution, and microwave sources for experiments in electron-cyclotron resonance heating (ECRH) to produce the thermal barriers that improve plasma confinement.

Figure 1b illustrates the TMX-U end-cell magnet-coil arrangement, the location and orientation of the neutral-atom beams, and the vacuum vessel. The central cell has a magnetic field strength of 0.3 T, and each end-plug magnet set generates a 2-T quadrupole-mirror field having a 4:1 mirror ratio. The design of TMX-U is based on a smaller tandem mirror machine, TMX,[3] that was dismantled before building TMX-U.

A comparison between TMX and TMX-U axial profiles is given in Fig. 2. In TMX, the neutral beams used to heat the plasma entered the end cells of the machine at right angles to the plasma axis. The resulting ions had little axial velocity, so they built up a local density maximum (and consequently a potential maximum) at the midplanes of the two end cells. The TMX was more stable to loss-cone modes than previous mirror machines, but it achieved this stability by continually leaking central-cell ions through the mirrors.[3]

The two major improvements that the TMX-U is designed to test are the use of "sloshing" ions to improve microstability and the production of an electron thermal barrier to improve confinement.

In 1982, the main experimental activity on the TMX-U was the production of sloshing ions.[4] The placement of the neutral-beam injectors, aimed at oblique angles to the end-cell axis, created the sloshing-ion distribution and changed the former end-cell midplane density maxima to minima (with new density maxima at both axial sides of the end-cell midplane). The sloshing-ion distribution was found to be far more stable against both loss-cone and pressure-driven instabilities than the distribution obtained with the TMX. In addition, the plasma-density minimum associated with the sloshing-ion distribution is one of the necessary ingredients for creating the potential minimum of a thermal-barrier end cell.

Mirror-confined electrons--the second ingredient of thermal barriers--have also been produced. The main function of a thermal barrier is to provide thermal insulation for the electrons in the end plug from those in the central cell. The thermal barrier is located at the point where ϕ is at a minimum (see Fig. 2). This depression in the plasma potential serves as an electrostatic-potential barrier for the negatively charged electrons. The end-plug electrons can therefore be heated by means of tuned microwave energy (electron-cyclotron resonance heating, or ECRH) to temperatures greater than that of the central-cell electrons. This, in turn, expedites the end-plug electrons' escape from the plasma, raising the local plasma potential beyond

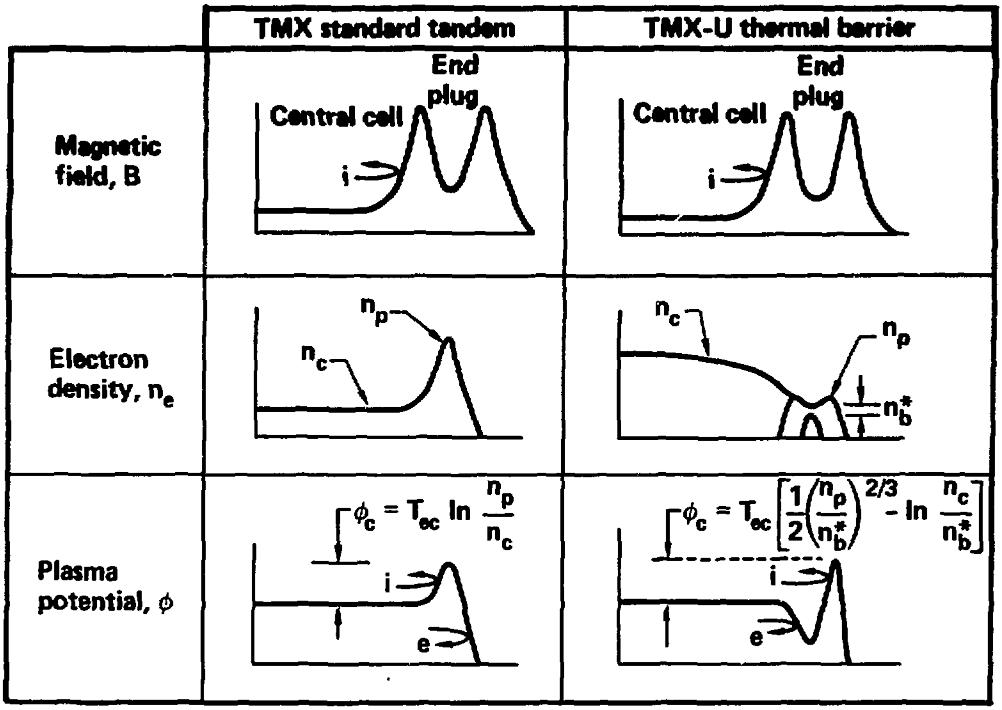


Fig. 2. Axial profiles of B, n_e, and ϕ for standard (TMX) and thermal-barrier (TMX-U) operation of a tandem mirror. The symbols represent the central-cell electron density n_c, the end-cell electron density at the potential peak n_p, the potentially trapped electron density at the end-cell midplane n_b^*, the central-cell electron temperature T_{ec}, and the central-cell ion confining potential ϕ_c.

the values obtained in the TMX. For each operating mode, Fig. 2 indicates the theoretical expression for the central-cell ion potential (ϕ_c). The ion confining potential ϕ_c augments the magnetic-mirror confinement of the central-cell ions by the exponential factor exp (ϕ_c/T_{ic}), where T_{ic} is the temperature of the central-cell ions.

The previous TMX results along with the early sloshing-ion and electron heating data from the TMX-U diagnostic system provide the building blocks for the present thermal-barrier experiments in TMX-U.

DIAGNOSTIC SYSTEM

TMX-U employs diagnostic techniques and instruments similar to those used on TMX[3] plus new equipment to determine electron and ion parameters under thermal-barrier operation. The diagnostic system can be broken down into three subsystems: (1) the diagnostic facility, (2) the individual diagnostic instruments, and (3) the data acquisition and analysis computer.[5]

Diagnostic Facility

The diagnostic facility includes the diagnostic room, the diagnostic summary console ("shot leader" console), the cable system, and the timing system.

- Diagnostic Room. The diagnostic room is located on the second floor of the TMX-U facility (see Fig. 1a). It contains 30 diagnostic racks that house the data acquisition transient recorders as well as any remote process and control electronics. The plasma diagnostic sensors and, when applicable, the front-end process and control electronics are located within the machine or machine vault. CAMAC (computer automated measurement and control) standard equipment modules for control and acquisition are used extensively.

- Diagnostic Summary Console. The diagnostic summary console ("shot leader" console) contains oscilloscopes, video monitors, and a communication system that permit the previous plasma shot and systems status to be evaluated in real time. Most of the transient digitizers have video playback that can be routed to the oscilloscopes mounted in the console via a system of patch cables from the individual diagnostics. The status of the data processing is displayed, including how far the computer processing has proceeded. The console includes a computer control panel so that the various options in the processing can be selected on a shot-by-shot basis. A count-down clock is displayed throughout the diagnostic room so that time to the next shot is known. If necessary, the hardware within the console enables TMX-U to be operated independently of the diagnostic data computer.

- Data Cable System. Twelve diagnostic boxes in the machine vault are connected by rigid conduits to a large signal distribution enclosure adjacent to the diagnostics room. Inside these conduits is a mixture of triax and individually shielded twisted-pair cables that transport signals to the signal distribution enclosure. The signals are routed from the distribution box to the appropriate diagnostic racks using conduit-enclosed cable bundles and isolated patch panels. Care is taken to ensure that the conduits originating in the pit at machine ground are not electrically connected to conduits terminating in the diagnostic racks at rack ground.

- Diagnostic Timing System. The diagnostic timing system provides trigger signals at various times and clock signals of various frequencies for the digital data-recording modules. Phase integrity is maintained by a patch panel arrangement that distributes the triggers and clocks over equal cable lengths.

Diagnostic Instruments

The individual diagnostic instruments, including those under development, are listed in Table 1 along with a brief summary of their primary purposes. Figure 3 shows the positioning of the initial array of plasma diagnostics around the TMX-U plasma flux bundle. Appendix A describes each individual diagnostic and names the principal physicist in charge of the instrument. Many signals from the other machine systems are acquired within the diagnostic data base. These include: magnet currents from the magnet system; vacuum gauges and residual gas analyzers from the vacuum system; neutral beam, ECRH, and ICRH parameters from the heating system; and stream gun signals and neutral-gas manifold pressures from the start-up and fueling system.

Table 1. TMX-U diagnostics.

Diagnostics	Purpose
Beam-attenuation detectors	Barrier and central-cell radial-density profiles
Thomson scattering	Plug and central-cell electron temperature and density
Microwave interferometers	Barrier, mirror-peak, and central-cell electron-line density
End-loss analyzer	On-axis and radial profiles of end-loss current density and plug potential
Extreme ultraviolet system	Barrier and central-cell impurity radiation
Diamagnetic loops	End and central-cell plasma pressure
Net current detectors	Radial profiles of net current to end wall
Faraday cups	Radial profiles of end-loss current density
Langmuir probes	Measure density and electron temperature of radial edge plasma
Electron-cyclotron emission	Detect electron microinstabilities
Charge-exchange analyzer	Ion-energy distribution in plugs
Secondary-emission detectors	Measure end-cell ion angular distribution and radial profile
Fast-ion gauges	Measure transient gas pressure
Radio-frequency probes	Measure ion-cyclotron fluctuations
X-ray diagnostic	Determine electron energy distribution from x-ray spectra
Bolometers[a]	Measure power loss to walls
Microwave scattering[a]	Detect ion microinstabilities
High-resolution extreme ultraviolet[a]	Impurity temperature, evidence of bulk ion heating and plasma rotation
Plasma potential diagnostic[a]	Central-cell potential and radial electric field
Neutron detector[a]	Measure plasma neutron flux

[a]Under operational development.

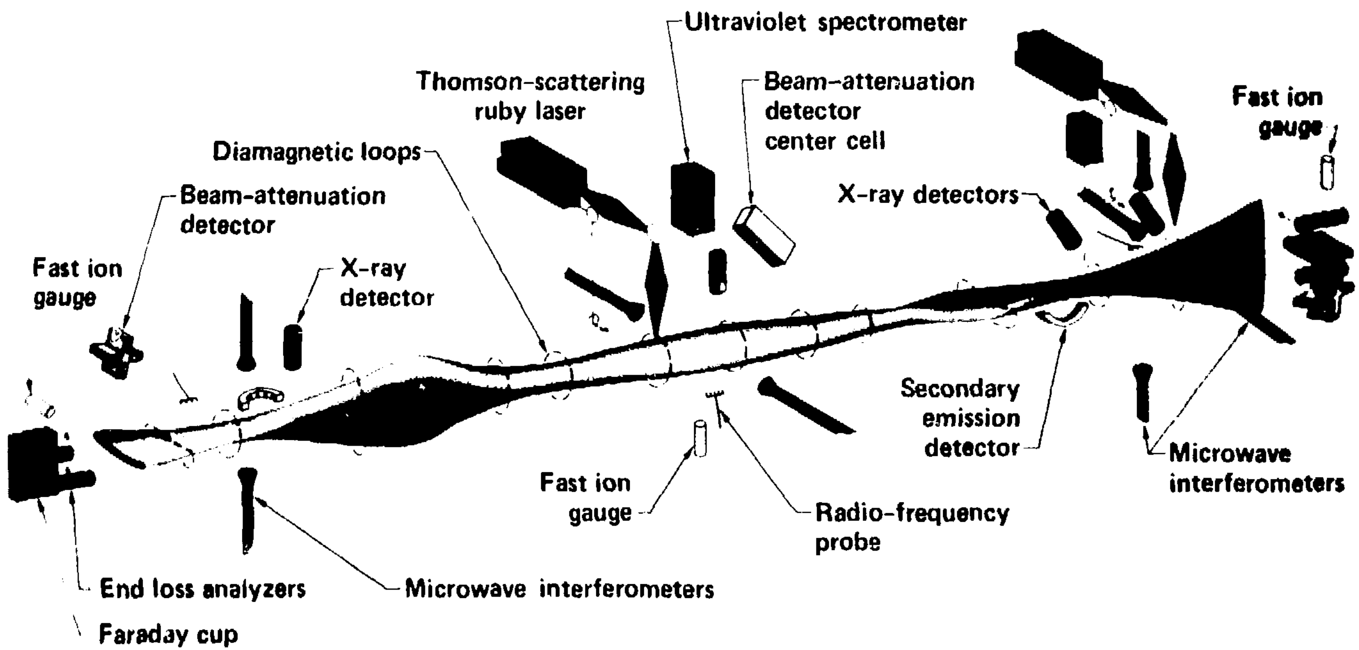


Fig. 3. Initial array of plasma diagnostic equipment used for the experiments on TMX-U (sloshing ions and mirror-confined electrons).

Data Computer

The TMX-U data computer[6] is a subsystem within the diagnostic system. It is a general-purpose system for handling acquisition, processing, archiving, interactive selection and retrieval, and graphical and tabular display of data. It routinely acquires and processes three MBytes of data per shot at an average shot rate of one per 8 min. The computer hardware consists of five central processing units (CPUs) in a multiparallel path with approximately 500 MBytes of disk storage at the central node, upon which all CPUs may read and write. The use of several CPUs in parallel increases computing power, while the use of eight disk drives in parallel increases disk speed. All processing, outputting, and acquisition are performed by program modules that allow serial operations, i.e., the inputs for a given task (program execution) are the output(s) of a previous task or tasks. Tasks for various shots may overlap so that high priority results are immediately available, while low priority results may backlog and catch up during lulls in experiment operation. Figure 4 is a block diagram of the logic for data flow within the TMX-U computer system. Also shown are the possible linkages of a "processor," which is a generic term for a basic program module.

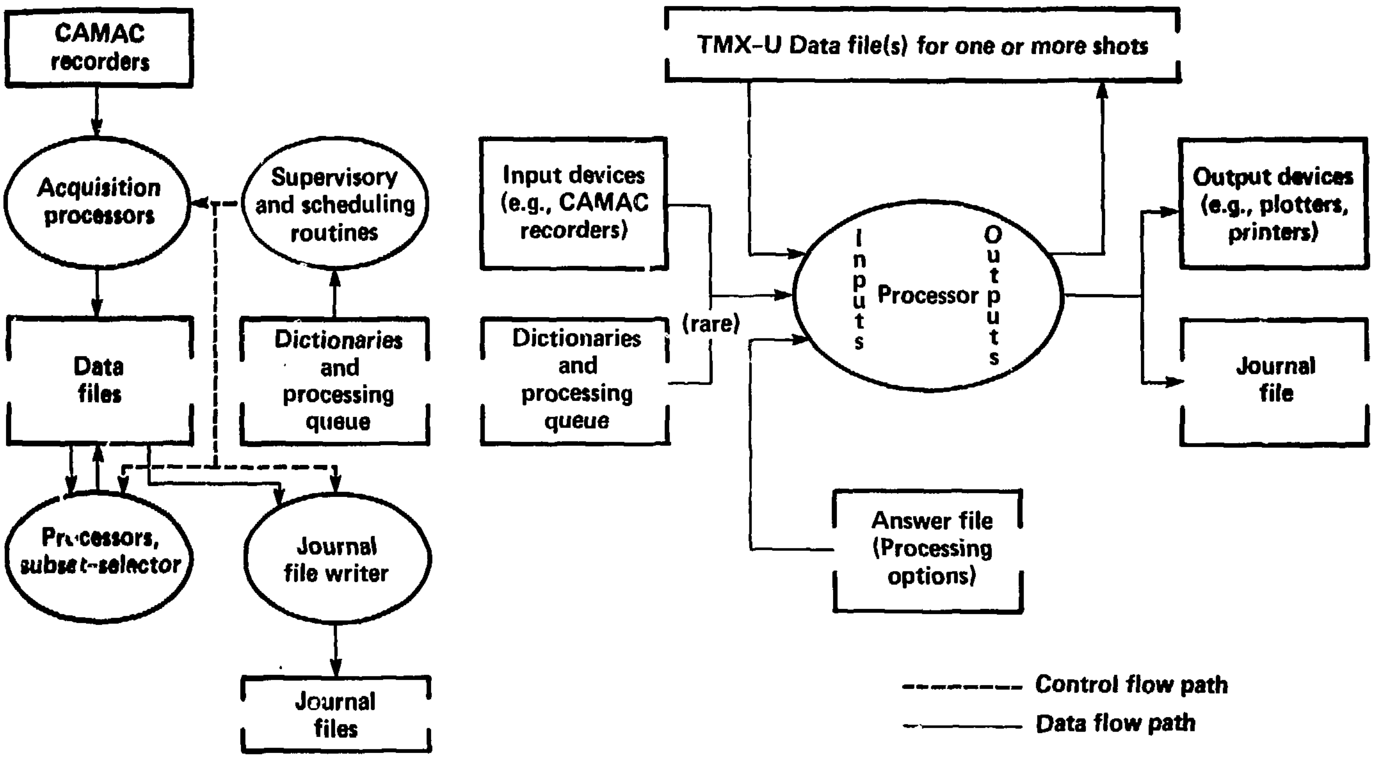


Fig. 4. TMX-U data flow from data recorders to data files, to journal (summary) files with repeated use of processors to perform successive calculations.

Acknowledgment

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APPENDIX A. INDIVIDUAL DIAGNOSTIC INSTRUMENTS

Beam Attenuation Detectors (BAD, J. Foote)

This diagnostic measures the attenuation of a neutral beam in traversing the plasma along 20 different chords through the plasma displaced both axially and radially. Besides the input power, the radius of the plasma and the plasma density distribution are calculated from the array of attenuation data. The BAD detector includes collimating apertures that define the line of sight--chord--through the plasma, a biased cylinder, and a cone-shaped emitter. Neutrals that pass through the collimation apertures and impinge on the cone cause electron emission.

Thomson Scattering System (TSS, R. Goodman)

The TSS determines the electron temperature and density of the plasma by measuring the spectrum of ruby laser light scattered from the electron distribution. The scattered spectrum is determined by the electron energy distribution, each wavelength being the doppler-shifted scattered intensity from each part of the energy spectrum. The initial system implemented on TMX-U determines the electron temperature both at the plug outer density peak and the central cell midplane at one time during the plasma discharge. The Thomson-scattered light is viewed by collection optics at 45^{0} to the beam and focused on a polychromator with 10 ouput channels. Each output channel has a fiber optic transmission line to a photomultiplier tube, which is the actual detector.

Microwave Interfero[illegible] [illegible]tem (MIS, R. Hornady)

This diagnostic inte[illegible]ometrically determines the line density of electrons in the plasma by measuring the phase shift due to the dielectric properties of the plasma of a 140-GHz wave. The receiver uses a 20-W extended interaction oscillator tube (EIO) as a source and a low-power klystron as a local oscillator. The measurement corroborates the BAD data in some regions and is the only technique available for use in other regions (e.g., between the magnets) because the waveguide runs can be installed in tight quarters. The initial microwave receiver system installed on TMX-U supports four simultaneous measurement channels; a set of nine antennas is installed in the vacuum vessel. The position being monitored is changed by moving the waveguide outside the vessel.

End Loss Analyzer (ELA, D. Grubb)

The end loss current spectrum is measured; the ion temperature and plug potential are deduced and compared with other measurements and theoretical predictions. The detector is a retarding-grid electrostatic energy analyzer. The entrance aperture comprises a low transmission mesh that reduces the current in the analyzer to manageable levels, followed by a swept grid and a current collector. The ramp voltage on the repeller grid and the current collected are simultaneously recorded, and the currents/voltage relationship of the plasma is deduced. Four systems are provided, two on each end, one movable, and one fixed in location. The fixed ELAs are close to the central flux tube. The movable detectors traverse the narrow width of the plasma cross section and are used to perform radial scans in order to determine plasma properties as a function of radius.

Extreme Ultraviolet System (EUV, S. Allen, LLNL, and T. Yu, Johns Hopkins University)

This diagnostic uses an absolutely calibrated multichord monochromator to examine the intensity of impurity radiation in the wavelength range from 300 to 1200 A. From the line radiation measurements, quantities bearing on power balance and impurity density can be deduced. Also, certain lines are monitored during each experimental series to establish that no unusual machine conditions arise, e.g., nitrogen density changes implying a vacuum pulse leak. By intentionally injecting impurities, diffusion and transport rates can be studied. The instrument is a 22-spacial-channel 0.4-m normal-incidence grating monochromator. Wavelength is remotely selected. The detectors are strip-current collectors behind a chevron microchannel plate.

Diamagnetic Loops (DL, W. Nexsen)

This diagnostic measures the magnetic flux forced out by the plasma, from which the ion-temperature density product is estimated. An array of 14 Faraday-shielded, single-turn loops is placed along the length of TMX-U. Three coils in each plug are provided. Eight coils are positioned along the central cell. The signal induced in each loop has subtracted from it the contribution due to magnet current ripple. To produce signals equal to the diamagnetic loop signal in the absence of a plasma, the power supply currents are monitored and filtered with a time constant the same as the transient soak in time in the parasitic conductors (vacuum tank, coil cases, etc.).

Net Current Collectors/Faraday Cups/Langmuir Probes (NCC/FC/LP, E. Hooper, LLNL, M. Flammer, Univ. of Calif. at Davis, W. Hsu, Sandia National Laboratory)

The various sensors in this system determine the nature of the TMX-U plasma at its interfaces with end-walls, gas boxes, or vacuum. On the end walls, net current collectors and Faraday cups determine end-loss current distribution. Edge plasma density and temperature are determined by swept Langmuir probes. Each Faraday cup has a grounded chamber with a pinhole aperture, an electron suppressor (also with a pinhole aperture), and a biased Faraday cup. Each successive aperture is larger than the one in front of it so that the exact alignment is not particularly critical. The Faraday cup is biased negatively and the signal is coupled out through a high voltage-blocking capacitor. The net current collector is a small electrode flush to the wall. The net current that flows is monitored by a low impedance system (so that the electrode is always close to ground potential).

Secondary Electron Detectors (SED, D. Correll and, in the early stages, T. Orzechowski)

The detectors in this diagnostic measure the charge-exchange neutral flux emitted from the plasma by generating a current proportional to the incident neutral flux through emission of secondary electrons from a copper surface in the detectors. A collimated array of SEDs in each plug is arranged to measure the angular distribution of the charge-exchange flux. This allows the sloshing ion distribution to be identified. The sensors are cone-shaped emitters inside a shielded enclosure with a collimating aperture that provides for a detection cone of an approximately 12^{0} included angle. The cone is biased so that secondary electrons are driven to the surrounding shield. An array of detectors is mounted on an arc-shaped beam in the east and west plugs with a 90-cm radius of curvature.

Fast Ion Gauges (FIG, W. Pickles)

A set of five fast Bayard-Alpert vacuum gauge control chassis is provided so that pressure changes in various regions of the TMX-U vacuum vessel can be measured on fast-time scales compared to the plasma duration.

Radio Frequency Probes System (RFP, T. Casper, LLNL, and L. Berzins, Univ. of Calif., Davis)

This diagnostic measures fluctuations in the plasma's electric and magnetic fields. From the frequency information and signal amplitude, the level of unstable waves and their physical nature can be deduced. This system has 29 probes, 9 probes for magnetic fluctuations and 20 high-input impedance electron field probes.

X-Ray Diagnostics (XRD, P. Poulsen and J. Clauser, LLNL, and B. Failor, Univ. of Calif., Davis)

These detectors determine the electron temperature by measuring the electron Bremsstrahlung spectrum. The basic detector unit is a germanium solid-state detector with a filter to remove the low energy end of the x-ray spectrum. The detectors are used in a pulse-counting mode with attention given to obtaining maximum count rate for good statistics.

Electron-Cyclotron Emission (ECE, R. James and C. Lasnier, Univ. of Maryland)

This diagnostic measures the short wavelength electron emission spectrum from the plug region. Electron-cyclotron emission from the hot electrons generated by ECRH in the east end cell is sampled by a high gain dish antenna attached to the east end wall. From this spectrum, electron instabilities in the high-frequency range can be detected.

Charge-Exchange Analyzer (CXA, W. Nexsen, LLNL, and M. Carter, Univ. of Calif, Davis)

To measure the energy distribution of the charge-exchange flux from the plasma, a CXA diagnostic is used. The energy distribution of the charge-exchange flux is representative of the plasma ion distribution. In the initial diagnostic set, the "burden-of-proof" for the creation of a sloshing ion distribution in the plug rested on the SED diagnostic, which measured the angular distribution of total charge-exchange flux. From the CXA data the mean ion energy and charge-exchange power loss are calculated.

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