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MACHINE AND PLASMA DIAGNOSTIC INSTRUMENTATION SYSTEMS FOR THE TANDEM MIRROR EXPERIMENT UPGRADE*

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Summary

To evaluate performance of a second generation Tandem Mirror Machine, an extensive instrumentation system is being designed and installed as part of the major device fabrication. Of these systems, the diagnostic systems listed in Table I acquire data related to plasma parameters. The systems listed will be operational during the start-up phase of the TMX Upgrade machine and provide bench marks for future performance data. In addition to plasma diagnostic instrumentation, machine parameter monitoring systems will be installed prior to machine operation. Simultaneous recording of machine parameters will permit evaluation of plasma parameters sensitive to machine conditions.

To support the above instrumentation a timing system and a diagnostic-cable plant system will be installed prior to machine operations. Careful use of the above systems will permit accurate cross correlation of data recorded by the numerous data recorders. The following text outlines the implementation details for each system mentioned above.

I. Facilities

The plasma diagnostics and machine instrumentation components are located in the three main areas shown in Figure 1. Located within the machine and/or machine vault are all the plasma diagnostic sensors and some front-end process and control electronics. Housed in an upper level diagnostic room are 30 diagnostic racks containing the remaining remote process and control electronics and data acquisition transient recorders. Another eight racks house the data acquisition and processing computer system. Four short racks in the center of the room form the shot leader diagnostic and machine monitor console. Contained in this console are s... displays, and a communication system that permits the experimental leader to evaluate systems status in real time.

II. Data Cable System

Diagnostic data and control signals are transported between the machine vault and the thirty instrumentation racks by an extensive diagnostic 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 a mixture of triax and individually shielded, twisted pair cable transport pit sensor signals to this signal distribution enclosure.

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 insure that conduits originating in the pit are not electrically connected to conduits terminating in the diagnostic racks. Grounding philosophies and techniques used for this installation are similar to those employed in implementing the Beta II diagnostic system.[1]

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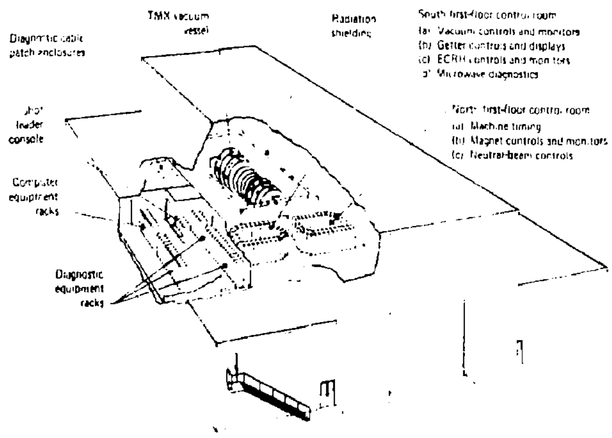

Fig. 1. Layout of the TMX Upgrade Experimental Facility.

III. Diagnostic Timing System

The diagnostic timing system is housed in two racks in the upstairs diagnostic room. All trigger and clock signals for the diagnotic and machine parameter instrumentation are generated with the high resolution diagnostic timing system.[2] The diagnostic timing system is coupled to the machine timing system by a -500 millisecond trigger generated by the machine timing system. The machine trigger is regenerated and distributed to five digital delays which, in turn, generate five high-resolution diagnostic triggers. Details of the timing system are outlined in an accompanying paper. Since all the timing hardware is either CAMAC or Nim modules, expansion or modification can be easily achieved.

IV. Secondary Emission Detector

The secondary emission detector system measures the neutral-particle flux generated by charge exchange and escaping from various regions of the plasma.[3]

Two arrays of detectors will be installed to measure the angular distribution of charge-exchange flux. Data from the arrays will be used to investigate the "sloshing" ion distribution in each plug region. *All detectors used in this diagnostic have a* cylindrical geometry with collimating apertures that limit the detectors field of view to 12°. Fifteen detectors will be mounted on an arc-shaped support and view the east plug barrier (5-kG plasma) region from a 90-cm radius. Six identical detectors will be located in the west plug. Four similar discrete units will be located around the central-cell midplane. These detectors will look directly at the central-cell plasma and provide information concerning radial loss symmetry.

Signals from all detectors are transported over shielded twisted pair cables that terminate in a distribution box where individual batteries in series with 10-kΩ resistors will provide detector bias. The signal across the resistor is recorded by a transient recorder. The cable capacitance and termination resistor set the signal bandwidth at about 10 kHz. Thus, no aliasing problems should occur when recording data at 50 kHz.

V. Beam Attenuation Detectors

The beam attenuation detector (BAD) system uses secondary emission detectors to measure the neutral beam current passing through the plasma.[4] Using data taken with and without the presence of a machine plasma, input power to the plasma and plasma line density can be estimated. Since the neutral beam diameter is about the same size as the plasma, an array of detectors on a neutral beam provides information on the plasma geometry.

The BAD systems to be used on the TMX upgrade will consist of seven individual detectors and two arrays composed of 24 detectors. The two arrays will be mounted in the plug regions and provide data concerning the 5-kG plasma region. The seven single-channel detectors provide central-cell plasma data.

The current signals from the secondary-emission detectors are amplified by high-gain transresistance amplifiers located close to the sensors. The output from the amplifiers is sent through shielded-twisted pair cable to transient recorders in the diagnostic area. The very high amplifier gains limit the overall system bandwidth to 8 kHz. Digitizing rates will be set to 50 kHz using a standard clock frequency.

VI. Thomson Scattering

Two Thomson scattering systems are used to determine the electron temperature and density of the plasma in the machine central cell and east plug barrier region. The electron energy distribution is determined by measuring the scattered spectrum of ruby-laser light as it passes through the plasma.[3] From the absolute level of the Doppler light returned to the detectors the electron density is also estimated.

The Thomson scattering systems consist of numerous subsystems.[4] A single-pulse ruby laser provides the light source for a single temporal measurement during the plasma cycle. The laser beam transport and laser input arm contain the optics necessary to transport the laser into the plasma. A laser beam dump absorbs the laser energy after it passes through the plasma and provides the mechanism neces- sary to minimize back-scattered laser light. A view tube collects the Doppler-broadened light scattered by plasma electrons and delivers it to a distribution box. The distribution box distributes the scattered light associated with a unique plasma volume to the input of a polychromator. Ten spectral outputs of the polychromator are coupled into a bank of the photomultiplier tubes by fiber optics bundles. The tube output signals are transported to a remote data monitor and recording system. Also, located in the diagnostic room is the laser timing system and auto-calibration control electronics. The calibration sources are located in the distribution box and enable periodic calibration of the detection system.

The central-cell and east-plug viewing angles *are 49° and 45° from beam orthogonal. The dis*tribution box designs permit each system to monitor three radial positions perpendicular to the machine center line.

VII. Diamagnetic Loops

This system measures the plasma diamagnetism from which estimates of ion temperature and density can be made. Fourteen, Faraday shielded, single-turn loops will circle the plasma at various points of interest. Each plug contains three coils: one positioned near the plug midplane point and one each at the inner and outer 10-kG points. The remaining eight coils are positioned along the central cell with six coils east and two coils west of the machine midplane.

The signal induced in each loop is transported to the diagnostic recording area by shielded-twisted pair cables. The plasma signals are enhanced by subtraction of the magnetic current ripple components using multichannel ripple reduction amplifiers. Using Rogowski loops to monitor the individual magnet currents, a signal very close to the ripple components in various loops is generated. Putting both signals through a difference amplifier produces the enhanced plasma signals. Data recording is achieved using 50-kHz transmit recorders.

VIII. Radio-Frequency Probes

The rf probe system is used to measure electromagnetic field emissions from the confined plasma. Using frequency and amplitude measurements obtained from numerous probes, the plasma confinement instabilities can be evaluated.

Initial systems implementation consists of four probes, each containing numerous elements. In the central-cell region a probe containing six small electrostatic antennas and two magnetic loops will be used. In the east plug two probe positions are available to study emissions in the 5-kG plasma region. One probe with five antennas and one probe with three orthogonal magnetic loops will be used in this region. The east plug (10-kG plasma region) will be studied using two access positions and a five-tip antenna probe. The west-plug 5-kG point will be studied by a probe that can be inserted through either of two access ports.

Signals from the probes are taken to the diagnostic area over 100 meters of coax cable. The long cable runs limit system bandwidth to about 10 MHz. The signal processing electronics employs various rf amplifiers, filters, envelope detectors, and heterodyne detectors. The 20-channel electronic acquisition hardware is a combination of high-speed and low speed digitizers. Data acquisition rates will vary from 50 MHz to 5 kHz depending on experimental requirements. The diagnostic timing system assures the phase stability of the recorded data.

IX. Fast Ion Gauges

This diagnostic monitors pressure changes during plasma cycles, in various regions of the vacuum vessel on time scales short compared to plasma duration. Three nude Bayard-Alpert gauges, housed in magnetically shielded enclosures, are mounted on the vacuum vessel. One unit is mounted on each of the machine end fans. A third unit is mounted on the machine central cell. Gauge controls and signal pro- cessing electronics are located in the machine vault near each unit. The electronics supports all the functions normally provided by standard gauge control electronics, (out gassing, over pressure shutdown, and emission regulation). The collector current, which is proportional to pressure, is ampli- fied using a wide dynamic range operational amplifier. In order to cover the three decades of dynamic range, a high and low-range analogue output is provided. By manually changing the emission current, the range of the instrument can be made to cover any three decades within a 10^{-4} to 10^{-8} torr. pressure window.

X. Microwave Interferometer

The microwave interferometer system will be used to measure plasma line densities in various regions of the TMX-Upgrade machine. Line density is calculated from the phase shift induced in a 140-GHz microwave beam that has passed through the plasma.

The initial microwave system contains antennas at the east and west 5-kG point, the east plug 10-kG point, and in the machine central cell. Waveguides, from the various antennas in the machine, run through the shielding wall and to the first floor, south control room racks. Contained within these racks are the sources, receivers and data acquisition hardware.

Four double-down conversion microwave receiver systems will be installed prior to the first plasma experiments. A digital-logic phase comparator generates four analog phase signals that are sampled by a CAMAC transient data recorder. Data from this recorder is transferred to the data-base computer over optically isolated digital cables.

XI. End-Loss Analyzer

The four end-loss analyzers used on the Tandem Mirror Experiment (TMX) will be used on TMX Upgrade. These sensors provide information on the end-loss current spectrum, the ion temperature, plug potential, and the central-cell confinement product.[3] The detector is a retarding-grid electrostatic energy analyzer. The entrance aperture is a low-transmission metal mesh that attenuates the end-loss flux to useable levels. Behind the mesh is a positive, high-voltage swept-ion repeller grid and negative-biased secondary-electron suppression grid. At the rear of the detector is a current collecting plate.

Signals from the current collectors and control electronics are passed to the diagnostic recording area using shielded-twisted pair cable. Because the collector current measurements must be referenced to machine ground, differential amplifiers are required for each detector. The output of the amplifiers are recorded with 50-kHz data digitizers.

The high voltage for the swept grid is generated by a high-voltage amplifier driven by a gateable function generator. Cable capacitance and amplifier output limits voltage slew rates to 4×10^{6} V/sec or less. Also the maximum peak voltage presently obtainable is less than 2 kV. Each sweep voltage is monitored using a high-voltage divider, line driver and transient recorders.

On the TMX Upgrade two detectors will be located in each of the end-fan tanks. A rigidly-mounted unit in each fan tank is centrally located to provide information about the central plasma. Also in each end-fan tank is a moveable unit. Radial scans across the narrow width of the end-fan plasmas will provide data concerning plasma properties as a function of radius.

XII. Extreme Ultraviolet System

The extreme ultraviolet diagnostic system utilizes an absolutely calibrated, 0.4-m, normal-incidence, grating monochromator to examine the intensity of impurity radiation in the wavelength range 300 Å to 1200 Å. The instrument spatially resolves twenty-two radial positions with a time resolution of 1 to 2 msec.[3] From line radiation measurements, quanti- ties related to power balance and impurity density can be deduced. In particular, nitrogen density changes can be monitored and possibly reveal dynamic vacuum leaks. Also injection of impurities can pro- vide useful data concerning diffusion and transport rates within the TMX plasma.

During the initial phase of machine operation a single 22-channel unit will be installed. Two mounting fixtures have been provided for viewing the plasma. Viewports have been assigned so these mounting fixtures can be used at both 5-kG points, both 10-kG points, and one central-cell position.

During a machine cycle, pulses from strip-current collectors, located behind a chevron microchannel plate, are amplified, shaped, and transmitted to scalers located in the remote diagnostic room. Signal transport is over twenty-two RG-174 shielded cables. In the diagnostic area each scaler count is passed directly into a CAMAC dual-port memory. A desk-top computer is interfaced into the system to provide local data reduction. Data is also acquired by the larger data base computer system.

XIII. Langmuir Probes-Faraday Cups

This diagnostic provides information concerning the nature of the end-fan plasma at the end-wall interface region. End loss current distributions are determined using an array of net current collectors and Faraday cups. Information obtained using these detectors will supplement data obtained with the end-loss analyzers.

This system requires installation of 13 Faraday cups and 13 current collectors in each end-fan tank of the TMX machine. Each Faraday cup is enclosed in a grounded chamber with a pinhole entrance aperture. Located between the entrance aperture and cup is an electron suppressor plate with a larger pinhole. The electron suppressor plates for all detectors are connected together and then biased negatively with a high-voltage supply. To collect ions the detector cup is also biased negatively with a magnitude less than that of the suppression plate. Bias for each cup is achieved using multilple high-voltage bias capacitors and a single high-voltage supply. Detector cup signals are coupled out through a high-voltage blocking capacitor and passed through anti-aliasing filters prior to amplification and digital recording. Digital sampling rates for these detectors will be set at 50 kHz for initial measurements.

The net current collectors are small disk electrodes that are flush with, but isolated from, the machine wall. The detectors are connected to the machine wall by a low-value resistor in order to keep the electrode close to machine ground potential. Monitoring the potential developed across the resistor determines the net plasma current incident on the electrode. Because of the low signal levels and machine ground reference these signals are amplified by differential amplifiers and then passed through 2.5 kHz low-pass filters prior to recording. Digital recording rates for this system are set at 5 kHz.

XIV. X-Ray Diagnostics

The x-ray detection system will measure the electron Bremsstrahlung spectrum emitted from the plasma. From these spectral measurements estimates of the electron temperature in TMX-upgrade can be generated. Bremsstrahlung measurements will be made using solid-state detectors and pulse-height analysis electronics.

Mechanical shielding, collimating and filter hardware is being built to monitor five areas of the machine. Only three systems will be instrumented and operational during the fall of 1981. One plug region will contain a spectrometer capable of measuring Bremsstrahlung from electrons with energies in the range of 300 to 1500 eV. The east and west plug thermal barrier will each contain spectrometers capable of measuring 50-keV Bremsstrahlung.

The lower energy spectrometer utilizes a liquid nitrogen-cooled lithium-drifted silicon detector and associated low-noise preamplifier. The output of the detector is amplified and sent to the remote diagnostic area using triax cable. In the diagnostic room the signal is digitized by a A/D converter located in a CAMAC crate. The digital signal out of the A/D converter is stored in a histogramming memory using a CAMAC data router. Data from each shot may be accessed and stored by either a local desk-top computer or the main data acquisition computer. The system arrangement is identical for the two thermal barrier spectrometers except germanium detectors are used to accommodate the higher energy spectrum.

Using the above equipment, energy spectra should be obtainable with sample times as short as two milliseconds. Thus, up to 40 time resolved spectra could be available during one plasma cycle. Using tandem A/D converters the data rate could be increased and better time resolution achieved.

XV. Machine Parameters

A machine monitor system will be installed. Numerous multichannel CAMAC transient digitizers will be used to monitor signals from: 1) seventeen magnetic current sensors; 2) two each, stream-gun voltage and current sensors; 3) twenty-four neutral-beam acel voltage and current sources; 4) eight slow vacuum gauges; and 5) four input gas-manifold pressure transducers. The magnet currents, and neutral-beam data recorders will be triggered at zero time and acquire data at a 5-kHz rate. The recorder allocated for the gas injection monitoring will be triggered just prior to zero time and the sample rate will be set to cover the full pressure cycle that could approach one second. The recorder monitoring the stream guns will be triggered just prior to zero time and sample at a 100-kHz rate. The eight-gauge vacuum-condition monitoring system will continually monitor the machine gas pressure using Bayard-Alpert gauges located within the machine vessel. A BCD output is provided by the electronics unit associated with each gauge. The eight BCD outputs are periodically stored in a CAMAC dual-port memory using a specially designed digital data multiplexer. Data acquisition rates are controlled by a dedicated programmable clock. Periodically, the data stored in the 32-K dual-port memory is archived by the TMX computer system.

A desk-top computer, which presents a status menu, monitors the getter status. After the menu is manually updated, the data is transferred to a dual-port memory where it is available to the TMX data acquisition computer. In a like manner other machine status information is entered into the facility data base.

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