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MTX DIAGNOSTIC AND AUXILIARY SYSTEMS FOR CONFINEMENT, TRANSPORT, AND PLASMA PHYSICS STUDIES

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INTRODUCTION

This note describes the diagnostics and auxiliary systems on the Microwave Tokamak Experiment (MTX) for confinement, transport, and other plasma physics studies. It is intended as a reference on the installed and planned hardware on the machine for those who need more familiarity with this equipment. Combined with the tokamak itself, these systems define the opportunities and capabilities for experiments in the MTX facility.

We also illustrate how these instruments and equipment are to be used in carrying out the MTX Operations Plan. Near term goals for MTX are focussed on the absorption and heating by the microwave beam from the FEL, but the Plan also includes using the facility to study fundamental phenomena in the plasma, to control MHD activity, and to drive current noninductively.

The auxiliary systems on (or available for) MTX are:

- 140-250 GHz free-electron laser (2 MW)
- 4.6 GHz lower hybrid system (2 MW)
- Pellet injector (4 shot)
- Compact torus injector for fueling

A wide variety of diagnostics are installed on or planned for MTX as listed in Table 1. In addition to most of the standard tokamak diagnostic instruments, these provide profile measurements of plasma quantities, fast electron temperature and density measurements, and significant fluctuation measurement capability.

Table 1. Diagnostic capability on (or planned for) MTX

Diagnostic	Measurement
Magnetic loops	Plasma fields, currents, etc.
Mirnov loops	Magnetic fluctuations
Far infrared interferometer	Density (with UCLA)
ECE interferometer	Electron temperature
Thomson Scattering	Electron temperature, density
Soft x-ray array	X-ray emission
Soft x-ray fast detectors	X-ray emission (μsec response) (JAERI)
Limiter xray	Run-away electrons
Bolometer array	Power emission
Visible bremsstrahlung	Z_{eff} profile
Fast ion gage/RGA	Gas
Neutron detectors (fast)	Ion temperature (JAERI)
SPRED spectrometer	Impurities
Magnetic loops (fast)	Plasma response to FEL
Microwave calorimeter	Plasma transmission
Microwave detectors	Power (incident, reflected, transmitted)
Limiter camera	Limiter heating
ECE polychrometer (fast)	Electron emission (μsec) (U. Maryland)
ECE hetrodyne system (fast)	Electron emission in high field direction (μsec) (JAERI)
X-ray spectrometer	Ion temperature (proposed)
Infrared scattering (forward)	Density fluctuations; uses FIR interferometer
Infrared scattering	Fluctuations (development with JAERI)
Reflectrometry	Radial density fluctuation correlations (developmental)
ECE fluctuations	Electron temperature fluctuations (proposed with U. Maryland)
Charge-exchange analyzer	Ion temperature (schedual depends on resources)
FIR polarimetry	Current profile (developmental with UCLA)
Zeeman polarimetry	Current profile (testing at GA)
Hard x-ray systems	Xrays from energetic electrons (available from TMX)
Microwave electric field	Wave penetration (developmental with JAERI, Hiroshima)

AUXILIARY SYSTEMS ON MTX

The auxiliary systems listed above add substantially to the flexibility of the MTX facility. These systems can be applied to studies of transport, current drive, stability control, and other plasma phenomena.

Free-Electron Laser (FEL)

The FEL is a new, high power source of microwaves for heating plasmas. Because of its tunability and its high frequency operating range, it allows heating at high magnetic fields and densities, and at the second harmonic for 4.5 T operation. Later upgrades could push the frequency to 500-600 GHz.

The electron beam for the FEL is generated by the ETA-II linear induction accelerator, capable of delivering 70 ns pulses, 3000 A electrons at up to 10 MeV. High average power will be provided by 5 kHz repetition of the pulses.

The initial microwaves will be generated in the ELF wiggler. Single pulses at 140 GHz, 20 ns with a peak power of 2-3 GW will be used in absorption experiments. Following replacement of ELF with the IMP wiggler, a 10 ms, 5 kHz burst of 35 ns microwave pulses at 140 GHz will be used for heating and other experiments. This will then be upgraded to 250 GHz, 50 ns pulse bursts and then to 0.5 second burst operation.

Lower hybrid

2 MW of lower hybrid power at 4.6 GHz was loaned to LLNL by MIT when the tokamak was moved. The microwaves are generated by 8 cw klystrons with 250 kW each. The equipment includes transmission lines and antennas consisting of 4x4 arrays of waveguides 0.8cm by 5.75 cm. The waveguides are constructed of stainless steel and have internally brazed BeO windows 12 cm from the waveguide ends. Microwaves are launched vertically in phase; the horizontal waveguide-to-waveguide phase is controlled externally. Up to 50 kW per port were injected at MIT.

Pellet injector

A 4 pellet pneumatic injector will be available starting in October, 1989. This is a rebuild of that used on PLT and TEXT. Hydrogen or deuterium pellets can be injected with sizes ranging from 0.75 mm diameter by 1.5 mm length to 1.6

mm diameter by 2.3 mm length at a velocity of 1 km/s. Barrels for other pellet sizes can be easily installed. The velocity can be upgraded to about 1.3 km/s by upgrading the propellent valves. Timing of the 4 pellets can be independently controlled.

Compact torus

Theoretical analysis has suggested that compact torus (CT) injection is a possible means of fueling reactor-grade plasmas. Experience with the acceleration of CT's is available from the RACE experiment at LLNL, where 0.5 mg CT's have been accelerated to 400 km/s and smaller CT's to over 2500 km/s. Preliminary designs exist for injectors which could be installed on MTX. Trapped magnetic fields of 10 T are planned for penetration of the 10 T tokamak field and plasma densities of 10^{19}-10^{20} m^{-3} to provide adaquate fuelling. The muzzle diameter of the proposed gun is 4 cm to allow for injection through an MTX port.

DIAGNOSTIC CAPABILITY ON MTX

The experiments planned for MTX have stimulated the development and/or installation of high performance diagnostics. Although the prime motivation for many of these diagnostics is the study of the FEL interaction, they provide new opportunities to study transport and other plasma phenomena. In addition, several new diagnostics are planned which will aid in these studies. The MTX diagnostic capability, coupled with the unique heating and current drive capabilities of the FEL-generated microwaves can be exploited to provide significant new data on energy transport in tokamaks.

An extensive set of diagnostics were used on Alcator-C at MIT in their studies of transport and other tokamak phenomena. Of particular importance to MIT's study of transport was the ability to determine the energy content of the plasma from measurements of n(r), $T_e(r)$ and $T_i(r)$. (In most of the work only $T_i(0)$ was measured. The data was fit using T_i profiles assuming that the ion transport coefficients scaled as anomalous multipliers times neoclassical. At high density the strong coupling of ions and electrons make this assumption reasonable.) An integration of the local energy content over the plasma volume was combined with the known energy inputs to determine energy confinement time. Bolometer measurements, supplemented by spectroscopy and measurements of Z_{eff}, determined the radiation characteristics. Density fluctuations were studied in a series of experiments using CO_2 lasers. Measurements at sufficiently low density that electrons and ions were partially decoupled demonstrated anomalous ion transport; they speculated that the anomally was due to the ion-temperature gradient (η_i) mode. This identification was supported by pellet injection experiments in which the anomaly disappeared in the presence of a steep density gradient.

Further transport information was obtained from impurity injection experiments. Results were in qualitative agreement with neoclassical predictions.

The MTX diagnostic capability listed in Table 1 is discussed briefly here, organized according to the parameter to be measured. This discussion focuses particularly on those features of the diagnostics applicable to transport studies.

<u>Density</u>

1. INTERFEROMETER. The far infra-red interferometer installed on MTX was developed in collaboration with Luhmann and Peebles at UCLA and takes advantage of advances in technology since the original Alcator system. The new instrument has 3-times as many chords (16 total) than the one at MIT, is less sensitive to vibrations, and provides line density directly rather than using fringes to determine density.

This added spatial information will provide a more accurate measurement of the density gradient than previously available resulting in an increase in the accuracy of local measurements of the thermal diffusivities (χ_e, χ_i).

2. THOMSON SCATTERING. The MTX Thomson scattering uses a single-pulse ruby laser to measure scattering at a single point. The spatial and time points may be moved between MTX discharges.

Density fluctuations

1. SCATTERING. As part of the JAERI collaboration, a diagnostic will be constructed to scatter laser radiation from density fluctuations, yielding wave vector spectra. Analysis is presently underway to determine the best scattering wavelength given the constraints of plasma parameters and geometry. MIT experiments were done at 10μm using a CO_2 laser in collaboration with Bell Laboratory.

2. REFLECTROMETRY. Equipment for exploratory tests of a two-frequency reflectrometer to measure radial density correlations in the plasma core is available. This is a measurement which MFAC Panel 22 identified as critical to understanding transport. If tests are successful, the initial equipment will be used in near term studies, and a new instrument designed and constructed for the longer term.

Electron Temperature

1. THOMSON SCATTERING. As mentioned above, the Thomson scattering can measure T_e at a single point/single time. In this mode it will act to calibrate the ECE instruments discussed below.

The MTX system provides the ability to measure the distribution function at energies $\gg T_e$. This capability was developed to study the electron tail predicted to form during heating by the FEL/ECRH microwaves.

2. ELECTRON CYCLOTRON EMISSION (ECE) - Michelson interferometer. (On loan from GA.) This instrument provides a time-averaged measurement (15 ms) of the electron temperature profile and is equivalent to similar measurements on Alcator C. A low loss dielectric transmission line is used from the tokamak to the interferometer and provides the high sensitivity required for calculating energy confinement times.

3. ELECTRON CYCLOTRON EMISSION (ECE) - polychrometer. (University of Maryland, Boyd and Ellis.) This instrument will provide a time response (≤1 μs), sufficiently fast to evaluate emission from the electrons heated by the FEL. To provide faster time response than the indium-antimonide detectors, the University of Maryland is working with the University of Illinois (Stillman) to evaluate cryogenic gallium arsenide detectors. The fast time

response of this instrument will be important for transport studies. For example, a study of energy loss during the thermal dump phase of disruptions is planned for early FY90 while the FEL is being modified by the installation of the IMP wiggler. The milestone for installing this instrument on MTX is January, 1990.

4. ELECTRON CYCLOTRON EMISSION (ECE) - Fabre-Perot. (Collaboration with the University of Maryland.) Two to four channels of single-frequency Fabre-Perot interferometers will be installed this summer to provide a near term measurement of the emission from energetic electrons.

5. ELECTRON CYCLOTRON EMISSION (ECE) - heterodyne system. - (JAERI) A heterodyne instrument will be installed to measure the emission towards the inside of the tokamak. These measurements will be fast, thus providing a measurement of emission from the hot electrons produced during an FEL pulse. By looking from the interior, second harmonic emission can be measured which would be re-absorbed by the plasma in emission to the outside.

Electron temperature fluctuations

1. ENERGETIC X-RAY DIAGNOSTIC. Energetic electrons should be a good marker to track electrostatic turbulence, especially of trapped-electron modes. If analysis supports this application, energetic xrays (and other diagnostics) will be used to measure the energetic electron response to the fluctuating fields. Studies are underway to determine the best instrument for this measurement.

2. ELECTRON CYCLOTRON EMISSION (ECE) - electron temperature fluctuations. The University of Maryland has proposed to construct an instrument to measure electron temperature fluctuations. This effort will require a substantial advance in the state-of-the-art in measurements of emission from plasmas. Temperature fluctuation measurements are a critical missing part of the data base needed for understanding transport.

Ion temperature

1. NEUTRON YIELD DETECTORS. JAERI has installed a set of neutron detectors on MTX as part of the collaboration with Japan. The measurements will be

made by two external systems, each with 6 detectors (He^3, BF_3, and U^{235}) to provide sensitivity from <10^9 neutrons/second total emission to >10^{14} neutrons/second. This data will yield the central ion temperature in the tokamak, and is sensitive to $T_i > 0.5$ keV. MIT used similar data to constrain the ion energy confinement time in their analysis of total energy confinement.

2. Charge-exchange analyzer. Charge-exchange equipment exists from the TMX (mirror) experiment which can be adapted to MTX. This would yield the ion temperature profile in the entire plasma for densities < 2×10^{20} m^{-3} and in the outer part of the plasma for higher densities. This data is important for the evaluation of ion-thermal transport coefficients. The schedule for the equipment to be converted for MTX and installed is dependent on funding.

3. X-RAY DOPPLER -BROADENING SPECTROMETER. A spectrometer to measure the Doppler-broadening of impurity (titanium, molybdenum) lines to yield the ion temperature in the plasma core has been designed. Construction is planned for FY90.

Ion temperature fluctuations

1. NEUTRON FAST (FLUCTUATION) DETECTOR. JAERI is installing a fast (10 μs) scintillation detector. This will be used to measure fast events in the plasma, and will be used in an attempt to determine fluctuations in the core ion temperature. It will also provide information on ion heating following the FEL microwave pulses and on the thermal quench phase of disruptions.

Current/poloidal field profiles

1. FAR INFRA-RED POLARIMETER. (UCLA collaboration with Luhmann and Peebles) The interferometer has been constructed for adaptation to measure the poloidal field profile (and thus current density) in the tokamak by polarization rotation. This profile is critical for determining the plasma equilibrium characteristics for transport analysis. The polarimetry is estimated to be sensitive at densities ≥10^{20} m^{-3}, characteristic of MTX plasmas.

2. ZEEMAN ROTATION POLARIMETRY. The LLNL effort on DIIID is attempting measurements of polarization rotation using Zeeman rotation of impurity

lines. This measurement should work at densities $\leq 10^{20}$ m^{-3}, and is thus complementary to the FIR measurement. A decision to implement this on MTX will be made following results on DIIID.

Magnetic field fluctuations

1. MAGNETIC LOOPS. An extensive magnetic loop system was installed at MIT. This includes two sets of Mirnov loops to study low mode-number MHD fluctuations. Saddle loops will determine the level of locked mode activity, a topic not explored on Alcator C.

2. FAST MAGNETIC LOOPS. Fast loops are being installed in a collaboration with GA (Taylor). These loops will be used to monitor the deposition of energy from the FEL microwaves. Also, high frequency MHD activity will be evaluated in conjunction with transport studies.

Impurity measurements

1. VISIBLE BREMSSTRAHLUNG (Z_{eff}). A 15 chord visible bremsstrahlung system is installed on the machine. It will yield accurate profile data on Z_{eff}, important for transport analysis. The system has a fast time response and will yield measurements of fluctuations in $n^2 Z_{eff}/T_e^{1/2}$. These measurements will be combined with other diagnostics to characterize the fluctuations in MTX.

2. SPRED SPECTROMETER. The SPRED spectrometer, installed on MTX, is a survey instrument to determine the impurity species in the discharge.

3. FAST ION GAGES/RESIDUAL GAS ANALYZER. These instruments are installed on the machine to provide measurements of the gas pressure and impurities during and just after discharges.

X-ray measurements

1. MULTICHORD ARRAY. A 16 chord array from MIT is being used to determine the spatial profile of soft x-ray emission. Additional arrays can easily be installed, as was done at MIT, to provide more views of the plasma. For particular experiments, sufficient chords can be installed for fast

tomographic measurements of emission. The emission may be modulated, for example, by sawtooth activity. These arrays will be used during heat-pulse measurements of transport coefficients.

2. FAST SOFT X-RAY SYSTEM. JAERI has installed a fast x-ray system to study the energetic tail predicted for the FEL microwave heating. Tests using the initial system will be expanded to a multichord system with energy resolution provided by absorbers. Fast events involving energetic electrons, e.g. during disruptions or affecting transport, will be studied using this system.

3. HARD X-RAY MONITOR. X-ray emission due to runaways are monitored with a scintillator system.

4. *HARD X-RAY SYSTEMS. Several systems are available from TMX-U (mirror* machine). These include pulse-height analysis for energies from <10 keV to MeV. For studies of the transport of energetic electrons, proposed to determine turbulent levels due to trapped electron modes, we plan to adapt one of these systems.

Power balance

1. BOLOMETER ARRAY. A multichannel bolometer array from MIT has been installed to measure radiation and charge-exchange losses from the plasma. This data is required as part of the analysis of energy balance in the plasma.

2. LIMITER HEATING. This will be measured by an infra-red camera. It is part of the power balance measurement.

Microwave electric field

1. FORBIDDEN LINE EMISSION DIAGNOSTIC. (A collaboration with JAERI, University of Hiroshima, and University of California at Davis.) In this measurement, the Stark effect couples forbidden and permitted transitions, e.g. in a small helium beam. The result is a measurement of the microwave electric field in the plasma. The diagnostic will be used to map the microwave field, thus determining directly the effects of absorption, penetration, and scattering on the injected microwaves. Installation on MTX is planned for FY91.

Microwave diagnostics

1. CALORIMETER. A microwave calorimeter is being installed in MTX to measure the transmitted power profile at the inside wall of the tokamak. This measurement is critical to the evaluation of the absorption of microwaves from the FEL.

2. HIGH-AVERAGE POWER CALORIMETER. A calorimeter capable of measuring the full energy during 0.5 s, 2 MW average power operation is being installed by JAERI on MTX.

2. TRANSMITTED POWER MONITOR. A waveguide on the inside wall will monitor the power transmitted through the plasma. This will yield information on any time variation of the transmission with high temporal resolution.

3. INCIDENT POWER. This will be measured during experiments by a waveguide in the last mirror of the transport system. Measurement of the total incident power will be made from scattering from a grid in the "JAERI microwave diagnostic box" at the tokamak entrance.

4. REFLECTED POWER. This will be measured by a waveguide in the last mirror of the transport system. Measurement of the reflected power will also be made by scattering from a grid in the "JAERI microwave diagnostic box" at the tokamak entrance.

5. MICROWAVE BEAM PROFILE. The incident, 2-dimensional profile will be measured by scanning waveguide probes in the JAERI diagnostic box.

APPLICATIONS OF THE AUXILIARY SYSTEMS AND DIGANOSTICS

MTX can be used for confinement and transport experiments on high magnetic field - large aspect ratio plasmas ($B \leq 12$ T, $3.9 < A < 5.3$). Operation in such regimes could have a high impact in improving tokamaks. This was a finding of the Tokamak Improvement Concept Workshop held at UCLA on May 25, 1989. Auxiliary heating allows us to perturb plasma conditions during confinement studies, and pellet injection will give peaked density profiles for reducing η_i modes. Comparison with flatter density profiles will be made.

Many of the diagnostics installed on the experiment will give information on transport phenomena, in many cases because their fast time response permits exploration of fluctuation phenomena. In addition, several new diagnostics are planned to explore these fluctuations directly. This document gives special attention to that diagnostic capability.

The FEL produces short (50 ns) pulses of microwaves which are propagated to the tokamak by a quasioptical system. The deposition profile of the microwaves can be controlled by beam focusing and aiming at the final mirror in the transport system. The effect of the heating profile on confinement will be explored in a controlled manner. An example of a poorly understood effect is the observation in the T-10 tokamak of the lack of sensitivity to heating location inside the q=2 surface. Alternatively, in MTX the heating profile can be tailored to approximate ohmic to see if this recovers the ohmic confinement time.

Fueling will be done by gas-feed, pellet injection, and (proposed) by compact torus injection. Pellets will generate peaked density profiles; the combined sensitivity to heating and density profiles will be evaluated. Compact tori may provide a completely new means of fueling which will need to be evaluated for their affect on confinement. Diagnostics are planned that relate these measurements to fluctuation phenomena.

Current profiles can be controlled by lower-hybrid (LH) current drive. A particularly interesting experiment would be to drive current in the outer plasma regions by LH, broadening the profile to establish second stability, and heating by ECRH in the center to increase β_p. Stability and transport would be evaluated in this regime. A 2 MW lower-hybrid system is available for installation if these studies are carried out. The LH system can also be combined with ECH current drive when FEL power is launched with $k_{\parallel} \neq 0$.

The FEL microwave pulses lend themselves naturally to heat-pulse experiments in all of the above scenarios. Measurement of the broadening and flow of the heat pulses is planned to provide information on local confinement.

For some heating modes in MTX, energetic electrons will be generated locally; these electrons can act as a "tag" for the background turbulence. Tracking them by x-ray or synchrotron emission will provide measurements of turbulent spectra and correlation lengths.

The diagnostic capabilities have been extended in some areas over those available on Alcator C at MIT. The expansions are of two types: (1) New developments in the technology that provide more radial channels of data at higher accuracy, thus yielding a more accurate description of the plasma, and (2) Diagnostics with higher speed and/or improved capability to quantify fast processes in the plasma including fluctuation spectra and other processes which may influence confinement.

As discussed above, many of the diagnostics on MTX yield good spatial information: interferometer (density) - 16 channels; ECE (electron temperature) - 1 cm resolution; bolometry (Z_{eff}) - 15 channels; soft xrays - 16 channels. Upgrades to ion temperature profile data await priority decisions for funds.

Because of needs for diagnosing the FEL heating, diagnostics with fast time responses are being used in the experiments. The interferometer has a maximum response time ~ 1 μs. This capability will be used to measure forward scattering spectra from density fluctuations, and the large number of channels will yield good spatial resolution. The ECE polychrometer being built by Maryland for MTX also has a response ~ 1 μs, and an upgrade to gallium arsenide detectors is being considered. A fast soft x-ray system installed through the collaboration with JAERI will provide ~0.1 μs time response at high sensitivity. Fast magnetic loops, designed in collaboration with GA, will measure magnetic perturbations at times « 1 μs.

In addition, several instruments are planned to study fluctuations directly. JAERI is collaborating with MTX to design and install an infra-red scattering diagnostic. Reflectrometry is being evaluated for measuring the radial correlation functions of density fluctuations in the important range spanning the gradient length to the short wavelengths normally available from scattering diagnostics. A new diagnostic for measuring electron temperature fluctuations has been proposed in collaboration with Maryland.