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Microwave Tokamak Experiment: An Overview of the Construction and Checkout Phase

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Abstract

At Lawrence Livermore National Laboratory (LLNL) we constructed and presently operate the Microwave Tokamak Experiment (MTX) to demonstrate the feasibility of using microwave pulses produced from a free electron laser (FEL) to provide electron cyclotron heating (ECH) for use in tokamaks, particularly high-field machines. The MTX consists primarily of the ALCATOR C tokamak and power supplies that were documented and disassembled at the Massachusetts Institute of Technology (MIT) and shipped to LLNL in April 1987. We made many additions, including a new primary power system from the Magnetic Fusion Test Facility (MFTF) substation, a new commutation system, a substantially upgraded seismic support system for earthquake loading, a fast controls system for use with the FEL, a new data-acquisition system, and a new vault facility. We checked out these systems and put them into operation in October 1988; we achieved the first plasma in November 1988.

We have also constructed and installed the microwave transmission system and the local microwave system to be used with the FEL. These systems transmit the microwaves to MTX quasi-optically through an evacuated tube. The ongoing plasma operations, both with and without FEL heating, are described in a companion paper.¹

Introduction

LLNL, as part of the Strategic Defense Initiative, has been the major developer of FELs driven by linear induction-accelerated electron beams. The demonstration of microwave production by an FEL in 1986 led us to propose the MTX in July 1986 (Ref. 2). MTX was funded in April 1987. The major device fabrication was completed in September 1988, and the first plasma was obtained in November 1988.

MTX has two main purposes: (1) to demonstrate the technology and physics of plasma heating with a microwave FEL and (2) to explore current drive and other ECH applications in a tokamak. ECH applications have resulted in improved stability and confinement in tokamaks, and these improvements are well documented. In the past, microwaves that have been used for ECH in magnetic fusion machines have been produced by gyrotrons at frequencies up to 60 GHz and continuous-duty power levels of a few hundred kilowatts. The current state of the art has produced gyrotrons that operate at 140 GHz with 20-ms pulses at output powers of 400 kW. Further development of higher-frequency and higher-power gyrotrons is needed for future magnetic fusion devices, but this is difficult due to the high heat loads associated with these power levels and the small wavelengths (1 mm at 250 GHz). See Ref. 2 for a more complete description of the physics.

MTX has coupled the Experimental Test Accelerator II (ETA II) with the Electron Laser Facility II (ELF II) to what was formerly the ALCATOR C tokamak from MIT. (The use of existing machines enabled us to produce physics results more quickly, with a cost savings.) ETA II/ELF II is designed to produce 2-GW microwaves in 50-ns pulses, at a repetition rate of 5 kHz for half a second, for an average power of 2 MW at frequencies of 140 and 250 GHz.

MTX Major Device Fabrication

MTX is located at LLNL in Building 431, in an area previously used for MFTF-B, next to the ETA II facility. The overall experimental facility is shown in Fig. 1.

The tokamak is located inside a new experimental vault. The microwaves produced in the FEL are transmitted to, and launched into, the tokamak by the microwave transmission system. The control room and the local data-acquisition system are located on the second floor, to the north of the experimental vault.

Tokamak Systems

The construction phase of our project began when we traveled to MIT, where we documented, disassembled, packaged, and shipped the tokamak and power supplies to LLNL (shipping required 14 trucks). This job is fully described in Ref. 3. We then modified the tokamak support system to raise the machine to a centerline height of 10 ft, which provides better diagnostic access under the machine, and we upgraded the complete support system to handle seismic loads. Next, we examined the toroidal field magnet restraining clamps and Belleville washers (which provide inward clamping for individual bitter plates); we changed the threads to eliminate thread failures and replaced broken Belleville washers.

We continued to modify the equipment:

- Rebuilt the main transformer ohmic heating coil because arcing had occurred during operation at MIT.
- Rebuilt the fiberglass cryostat that provides thermal insulation for the liquid-nitrogen-cooled magnets.
- Modified the MFTF-B liquid nitrogen system to provide liquid nitrogen to the recirculating system obtained from MIT.
- Installed a new vacuum system on the tokamak.
- Reinstalled the MIT discharge cleaning system, together with a new gas fueling system.

Figure 1. The Microwave Tokamak Experiment (MTX) is located in Building 431, close to the Experimental Test Accelerator II.

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Facilities and Grounding

After a new concrete floor was poured that provided cable and diagnostic access ducts to a sunken area under the tokamak, we constructed a new 1-ft-thick concrete shield wall around the 41-by-44-ft experimental area. We added cable trays, cooling water, compressed air, ac power, and communications.

We took care to maintain the overall grounding plan.⁴ All of the walls and the floor, including all attached hardware, are connected to a single ground plane. The reinforcing steel in each of the concrete sections is isolated from every other section. None of the facilities has electrical connections from one section to another; we did this to minimize eddy currents that can be induced during commutation of the ohmic heating magnets. All individual ground planes are connected to a single-point ground located in the center of the vault. We also constructed new platforms in the MFTF-B vault to house the ohmic heating power supplies and the commutation equipment.

Magnet Power System

At MIT, the primary ac power for the magnet power system was provided by a motor generator set. At LLNL, we used the MFTF-B substation (230 kV, 250 MW) to provide the primary ac power because this substation is tied to a very stiff part of the California power grid. In underground ducts and overhead cable trays we installed new ac feeder cables from the substation to Building 431. We installed new switchgear in the substation, in addition to a second set of switchgear at Building 431, which was used to de-energize the power supplies between shots. The toroidal power supplies will provide 120 kA for the 12-tesla tokamak runs or 70 kA for the 5-tesla runs. The installation of the magnet power system is described in Ref. 5.

Using parts of the MIT bus structure, we constructed new dc bus systems for the toroidal and ohmic heating power systems.

The ohmic heating power supplies provide a current swing in the ohmic heating magnets from +20 kA to -20 kA, half the total capability that was available at MIT. We designed and built a new ohmic heating commutation system, using the commutation resistor from MIT; this is described in Ref. 6.

Data Acquisition and Control Systems

This is a new system that was under development at LLNL for use on any of the magnetic fusion experiments. The hardware includes a DEC VAX cluster (with an 8200 and an 8600), HP workstations, and HP desktop computers, all interfaced with CAMAC crates. We are using commercial software in addition to packages from MIT, Oak Ridge National Laboratory (ORNL), and LLNL.

The plasma diagnostic data from MTX is acquired by this expandable, distributed, multi-vendor computer network. The front-end equipment in Building 431 is linked to the Magnetic Fusion Energy (MFE) computer center in Building 543 via fiber optics. From there, the data can be viewed or analyzed from any terminal in the MFE area. The data can be transferred to the National Magnetic Fusion Energy Computer Center for additional analysis. This system is described in more detail in a companion paper.⁷

The instrumentation and control system uses many of the components from MIT, with substantial rework, and incorporates the new LLNL magnet-temperature monitors, ac switchgear controls, personnel interlock system, communications system, and fast timing system.⁸

Plasma Diagnostics

The plasma diagnostics on MTX are listed in Table 1. The mechanical portions of the soft x-ray array and the bolometers were obtained from MIT as part of ALCATOR C. All of the other diagnostics are new or reconstructed from diagnostics used on either the Tandem Mirror Experiment Upgrade (TMX-U) or from MFTF-B.

TABLE 1
MTX DIAGNOSTICS LIST

Diagnostic	Measurement	Instrument Description
In Place		
FIR interferometer	$n(r)$	15 radial chords
Electron cyclotron emission	$T_e(r)$	Michelson interferometer
Magnetic loops	I_p , V-loop, MHD beta-p	58 loops on MTX
EUV SPRED spectrometer	Impurities	100-1000 angstrom range
Soft x-ray array	T_e , sawteeth	16-channel PIN diode array
Imitator x-ray	Electron tail, disruptions	Single NaI detector
Visible Bremsstrahlung	Z_{eff} , n_e , plasma position	15-channel photomultipliers
Bolometers	Energy confinement	16-channel array
Plasma camera	Plasma position, H_α	16-ms-resolution video
Fast ion gauge & RGA	Gas pressure, impurities	
Thomson scattering	$T_e(r)$, $n_e(r)$	Single-pulse ruby laser
H α alpha detectors	H_α breakdown	Fiber and photomultiplier
JAERI fast soft x-ray	FEL hot electrons	Fast-time-response diodes
JAERI neutron	Ion temp., fusion products	Fast and slow time response
Fast loops	FEL hot electrons	Small loops inside torus
Microwave detectors	For, ref, trans FEL power	Receiver, photon drag det
Calorimeter	FEL profile inside tokamak	48 thermistor channels
Future Instruments		
FIR scattering	Fluctuations, transport	JAERI collaboration
FIR polarimetry	Plasma current profiles	Add on to interferometer
X-ray spectrometer	Ion temperature	Curved crystal spectrometer
Fast ECE polychromator	$T_e(r)$ during FEL	U. of Maryland instrument
Fast Fabry-Perot ECE	T_e at two loc. during FEL	Split signal from Michelson
Fast ECE radiometer	Inside view of hot electrons	JAERI instrument

The Thomson scattering system was constructed from components from the TMAX-U system, with a new laser table, spatial filter, input optics, new viewing optics, and alignment system. The far infrared interferometer (FIR) uses a CO₂ laser-driven far infrared laser purchased for MFIF-B. The FIR optical tower⁹ is built with composite fiberglass and custom-formed stainless steel channels; it is configured to minimize the induced eddy currents in the metal portion. This is done to maintain the relative position of the fiberglass optical tables above and below the machine to within 0.0001 in. A number of diagnostics are provided through the DOE/LLNL-Japan Atomic Energy Research Institute (JAERI) collaboration. These include the fast soft x-ray array and the high power microwave dump. A complete description of the diagnostic system is given in Ref. 10.

Program Management

MTX is divided into seven main areas of work: tokamak systems, magnet power, data acquisition, controls and instrumentation, diagnostics, facilities, and program management. We made detailed cost and schedule estimates for each of the subsystems, based on the overall financial constraints. From these, we set the overall project budget and major milestones. The critical paths for construction were the magnet power subsystem and the facility, and the installation of the tokamak systems.

Our method for managing the major device fabrication of the MTX project was goal-oriented and milestone-driven. Within the main work breakdown structure, we developed detailed work breakdowns, together with applicable requirements. We made detailed cost and schedule estimates for each subsystem, and we monitored the progress of each subsystem against those projections of assigned major project milestones to each of the major subsystems and reported these to the Department of Energy.

Because of financial limitations, we kept upgrades to a minimum to any system, and we made great efforts to use existing equipment available in the magnetic fusion community. We used equipment from TMAX-U, MFIF-B, ALCATOR C, Doublet III-D (DIII-D), and a pellet injector that had been used on the Princeton Large Torus (PLT) and Texas Experimental Tokamak (TEXT). The only task in the proposal we did not complete was installation of the lower hybrid heating system; we had to drop this because of budget cuts.

We monitored the design of the various systems in preliminary and final design reviews. A more complete description of the

TABLE 2.
MAJOR DEVICE FABRICATION TOTAL COSTS

Subsystem	Costs (k\$)		
	FY87	FY88	Total
1.0 Tokamak systems	430	444	874
2.0 Magnet power	854	1,933	2,787
3.0 Lower hybrid heating	37	175	212
4.0 Program management	58	1,204	1,262
5.0 Data acquisition	27	38	65
6.0 Controls & instrumentation	38	267	305
7.0 Diagnostics	121	1,286	1,407
8.0 Facilities	651	81	732
9.0 System testing	0	0	0
Administrative overhead	244	712	956
Total	2,460	6,140	8,600

program management is given in Ref. 11. The major device fabrication costs are shown in Table 2.

ELF II and Microwave Transmission System

While the initial ohmic heating operation of the tokamak was under way, we completed installation of the ETA II wiggler (ELF II) and the microwave transmission system. This connection (shown in Fig. 1) completed the hardware required for the phase I FEL heated-plasma experiments.

The microwave transmission system uses a 20-in.-diameter evacuated tube and a series of metal mirrors to transmit the microwave pulses in a quasi-optical mode from the ELF II into the tokamak. The microwave transmission system is shown in detail in Fig. 2. The microwaves amplified by the FEL action in the wiggler are broadcast from the end of the wiggler in an antenna pattern that is captured by the first turning mirror.

This first mirror focuses the microwaves and samples the amount of both forward and reflected power incident on it. On mirror 4, the microwave beam is focused down to fit through the 4- by 30-cm slot to hit the plasma. Typical transmission efficiencies are in the range of 87% of the microwave produced by the wiggler, with most of the losses occurring on the first mirror. Testing of the

Figure 2. The microwave transmission system ties ETA-II/ELF-II to MTX.

FEL is done by swinging a movable mirror into the path of the microwaves as they exit the wiggler, and diverting them into the load tank, where they are monitored for power, frequency, and mode.

The alignment of the transmission system is done with a laser that is aligned to the centerline of the wiggler using linear-effect photo diodes. The laser is then shot through the system, where it is reflected off the mirrors. The position of the laser is monitored by insertable probes at various mirrors and immediately in front of the tokamak slot. Many fast microwave diagnostics are located between mirror box 4 and the tokamak. These are described in detail in Refs. 1 and 12.

Completion

The MDF installation was completed in July 1988. The Engineering System Test—the last MDF activity—was completed on schedule in September 1988.

Checkout

In September 1988 all individual systems had been operated to their required ratings. The magnet system had been operated to toroidal fields of 9 tesla (120 kA from the toroidal power supplies); the ohmic heating coils had been operated to their rated 17 kA; and all plasma positioning coils had been run to their rated currents. The vacuum system had been baked, discharge-cleaned, and operated to obtain vacuums to 10^{-8} Torr.

The controls and instrumentation system had been used during the tests of the magnet system; the data acquisition system had acquired the various magnet currents and the diagnostics data. The MDF cost was \$8.6 million. Breakdown of the cost by subsystem is given in Table 2.

As stated before, the first plasma was obtained in November 1988. A companion paper describes the operation of MTX since that time and the operation of MTX with FEL.¹

New Construction

We are constructing a pellet injector with parts of the old PLT pellet injector used on TEXT. We have incorporated into this injector the new "pipe gun" design from the Pellet Injector Group at Oak Ridge National Laboratory. It is a 4-shot injector, capable of shooting pellets ranging from 0.75 to 1.55 mm in diameter. This pellet injector should be ready to start shooting pellets in October 1989. It will be installed on the tokamak for pellet-fueled experiments starting in November 1989, after the present FEL experiments have been completed.

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