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First Year of Operation and Future Plans

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MICROWAVE TOKAMAK EXPERIMENT (MTX)
FIRST YEAR OF OPERATION AND FUTURE PLANS*

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Abstract

The Microwave Tokamak Experiment (MTX) at Lawrence Livermore National Laboratory (LLNL) began plasma operations in November 1988, and our main goal is the study of electron-cyclotron heating (ECH) in plasma discharges. The MTX tokamak was relocated from the Massachusetts Institute of Technology (MIT), and we have re-created plasma parameters that are similar to those generated while the tokamak was at MIT. After stable ohmic operation was achieved, single-pulse FEL heating experiments began. During this phase, the FEL operated at low power levels on the way to its ultimate goal of 2 GW and 140 GHz with a 30-ns pulse length. We have developed a number of new diagnostics to measure these fast FEL pulses and the resulting plasma effects.

In this paper, we present results that show the correlation of MTX data with MIT data, some of the operational modifications and procedures used, results to date from preliminary tokamak operations with the FEL, and our near-term operational plans.

Introduction

LLNL's MTX experiment, shown schematically in Fig. 1, joins two technologies: tokamak fusion technology and free-electron laser (FEL) technology. In order to combine the two in the most cost-effective way possible, this tokamak, which was originally designed and operated at MIT under the name ALCATOR-C, and most of its equipment were relocated to LLNL in April 1987.¹ By moving the tokamak to LLNL, researchers can combine a high-field, high-density tokamak plasmas with the FEL technology available here. This provides a means for studying a unique approach to microwave heating, in powers and frequencies that are otherwise unavailable in a single device, that could be applicable to future tokamaks.

The first plasma was obtained in November 1988, and since that time, we mostly have been learning how to operate the system and to reproduce the plasma conditions that were obtained while it was at MIT. Recently, we have been using this base ohmic-heated plasma as the target for the FEL heating experiments.

Additions and Modifications

The tokamak support system used at MIT had to be modified at LLNL for MTX use because of seismic (earthquake) requirements. This included upgrading the epoxy-impregnated (G-10) supports coming out of the side of the machine (see Fig. 1), and changing the support connections at the concrete.¹ In addition, during this upgrading, we raised the tokamak's centerline from 264 cm above the floor (as it was at MIT) to 335 cm for easier diagnostic and personnel access. Also, for seismic reasons, the toroidal bus connection to the tokamak was changed from the rigid MIT configuration to two sets of flexible braids. Because we had to fit the braids into a tight space, we

provided each set with an active, liquid-nitrogen spray that reduces their resistance by a factor of 7, thus permitting an equivalent reduction in size.

Upon disassembling the tokamak, we found numerous signs of arcing in the winding of the ohmic-heating transformer. Since the arcing appeared to have occurred intermittently and at low energy levels, we believe that it occurred during discharge cleaning, when the winding was at maximum voltage (20 kV peak-to-peak). To prevent further arcing, we replaced some inner-winding insulator plates and made mechanical changes to the conductor plates to increase the electrical path length between them.

The toroidal field (TF) magnet is a torus-shaped Bitter coil, held together by a pair of tension rings, against which 60 compression members bear inward on individual, tapered, conductor plates. Because the threads of the nut plates and bolts that transfer load from the tension rings to the compression members had a long history of stripping, we changed them from fine to coarse threads.

The main power source for MIT's ALCATOR-C experiment was a 225-MVA, motor-driven alternator. Because LLNL has a strong utility system and a previously installed, dedicated, 230-kV power line, the MTX power supplies are now

Figure 1. The Microwave Tokamak Experiment (MTX) layout.

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fed directly from the power grid. Safety policy requires that the ac feed be positively killed between operational cycles to ensure safety of operational personnel during inspections and adjustments between shots. This was accomplished at MIT by killing the alternator field between cycles. At MTX, it is accomplished by physically opening the circuit breaker that feeds each supply.²

The MTX ohmic-heating system uses a 20-kA power supply to break down the plasma and initiate the current pulse, and another 20-kA power supply to drive the current in the other direction and sustain the plasma. (At MIT, this full-current swing capability was 40 kA instead of 20 kA.) Because the circuit that commutates the current in the ohmic-heating system to initiate the plasma was retained at MIT for use on their new tokamak (C-MOD), a new system³ was built at LLNL.

The data-acquisition system supplied by LLNL consists of standard computer-automated measurement and control (CAMAC) modules, which can be connected either via a fiber-optic serial highway to a VAX 8200 or to desktop microcomputers. Another computer, which is shared with other LLNL users, is available for data analysis and plotting, and it is also our line to the magnetic fusion energy (MFE) network. We are using the MIT Data Acquisition System (MD5) to acquire the data from the CAMAC modules.

Operations with Ohmic-Heated Plasma

Plasma operations started at MTX in November 1988. We spent much of the first few months trouble-shooting equipment problems and learning how to operate the power supplies reliably. We experienced a failure with one of the ohmic-heating supplies, which caused us to operate at lower plasma currents and durations, but by June 1989, after conquering this and other problems, we were running the tokamak with reliable, full-duration plasmas in hydrogen and deuterium.

Plasma parameters for the MTX experiment are shown in Table 1. A typical physics shot is shown in Fig. 2. The parameters shown in this figure are similar to those obtained at MIT² under a similar 20-kA-capability, ohmic-heating operation. Most of the MTX runs (including Fig. 2) have been at a toroidal field of 5 T in preparation for the FEL experiments at 140 GHz, but the machine has been operated equally well at 8 T.

TABLE 1
PLASMA PARAMETERS

	Nominal	Range
Minor radius (cm)	16.5	10-17
Major radius (cm)	64	58-71
Toroidal field (T)	5	5-10
Plasma current (kA)	300	200-400
Line avg. density (10^{14} cm^{-3})	2	0.5-3
Electron temp. (keV)	0.6	0.6-1.2
Shot length (s)	0.4	0.2-0.5

Free-Electron Laser

The FEL amplifier consists of an induction linear accelerator (ETA II) and a series of alternating-direction, dipole magnetic fields (i.e., a wiggler).⁶ As the electron beam from the accelerator passes through the wiggler, it resonantly interacts with waves and amplifies them. The waves that it amplifies in this case are microwaves input from the master oscillator (see Fig. 3). In the MTX configuration, the wiggler provides approximately 80 dB of amplification to the master oscillator signal, generating a power of 8 GW. The actual microwave output at this power has a duration of approximately 50 ns.

The microwave transmission to the MTX vessel is accomplished by a quasi-optical transmission line (see Fig. 1). This consists of a 50-cm-diameter evacuated pipe with four focusing mirrors. Over the 35-m line, about 92% of the

Figure 2. Typical plasma parameters, demonstrating the similarities between ALCATOR-C and MTX operations: (a) plasma current, (b) horizontal position, (c) vertical position, (d) density, and (e) soft x-ray.

microwave power will be transmitted to the plasma, with the remaining power being lost at the mirrors. At each of these mirrors, the beam is about 17 cm in diameter, but must be focused to pass through a port into the tokamak, which is 4 cm wide and 30 cm high.

The microwave generation to the MTX tokamak will occur in three distinct phases. The first phase will be a 140-GHz, 2-GW, 30-ns pulse at 1/2 Hz. This rate will give us an ample supply of microwaves to test our diagnostics, but only one pulse will occur during actual plasma operations. This is an interim solution that will use the existing wiggler structure and its power

Figure 3. Simplified schematic, depicting the operation of the free-electron laser (FEL) used for MTX heating experiments.

supplies and will allow us to test the various diagnostics that will be used during microwave experiments.

The second phase will be a 140-GHz, 8-GW, 50-ns pulse at a 5-kHz repetition rate. This mode will require the installation of a new wiggler, upgraded power supplies, and a new, higher-power master oscillator. This oscillator—a 400-kW, 140-GHz gyrotron—will replace the 200-W, 140-GHz, extended-interaction oscillator (EIO). This mode will enable us to conduct heating experiments with an average power of 2 MW into a 5-T target plasma. We expect this step to be ready for operation in the last quarter of FY 1990.

The final phase will be to change the master oscillator to a 25-kW, 250-GHz gyrotron. This mode will enable us to conduct the final set of 2-MW heating experiments into a 9-T target plasma. This phase is planned for the middle of FY 1991, finances permitting.

FEL Diagnostics

Several diagnostics were specially designed to detect fast microwave pulses between the final injection mirror and the tokamak (see Fig. 4). The first of these is a calorimeter,⁷ which uses SiC tiles instrumented with thermistors mounted on the inside wall of the tokamak to detect the absorption of microwaves from the FEI by measuring the power profile on the tiles, with and without a plasma. The difference between these two measurements is the power absorbed by the plasma. Also, a small horn has been installed through a hole in the calorimeter to measure the transmitted power at one location with high temporal resolution.

Forward and reflected power are each measured two different ways. In the first method, two orthogonal waveguides, one for each of the two modes, are located in the last mirror of the transport system and are aligned to detect either the forward or reflected power. A microwave receiver is used at the end of each waveguide to detect the coupled power. In the second method, a beam-splitting grid is lowered into the beam. Approximately 2% of the beam is reflected into the optics and coupled to a photon drag detector to determine the forward power (see Fig. 5). Any beam that is reflected back is incident on

Figure 4. Overall view of the area between the last beam-focusing mirror and the MTX vacuum vessel, showing the fast microwave diagnostics.

Figure 5. Isometric view of the beam-splitting grid, which reflects the beam into the forward and reflected microwave-power diagnostics.

the grid in the opposite direction and is reflected into the reflected-power detector.

Presently, the only operational diagnostic is the transmitted-power monitor. All the other diagnostics are being installed, but we plan to have them operating shortly.

Tokamak Operation with the FEL Beamline

The crux of the FEL experiments is to first obtain a plasma with the tokamak open to the microwave transport system. The scenario for this group of experiments is to open the gate valve between the beamline and the tokamak 10 s before plasma initiation. This is done without the FEL, but just as if the FEL were operating. An initial problem with this mode of operation was that, because the walls of the vacuum vessel are maintained at -60°C , they become a cold trap for the beamline when the valve is opened. This problem stemmed from the fact that the FEL can run with a vacuum of 10^{-5} torr, and the tokamak runs with a vacuum of 10^{-8} torr. Because of this, it is extremely difficult to make the FEL system work to the same vacuum standards as the tokamak. The FEL vacuum still needs some work, but it is working better than it did, and it does not keep the system from operating.

Another problem that had to be solved under this combined operation was the tokamak static-fill pressure. The fill pressure for ohmic operation is 3×10^{-5} torr. A 5000-L/s turbopump is located very close to the port to the tokamak to maintain the vacuum in the beamline prior to its being opened to the tokamak. When the gate valve opened, the beam-line turbopump would pump out the fill gas. With experimentation, we found that the fill pressure had to be 2×10^{-4} torr prior to opening the gate valve so that, at plasma initiation, the pressure would be down to 3×10^{-5} torr.

Once the vacuum and fill-pressure problems were solved, the results were similar to those of Fig 2 for simple ohmic-heating operations.

FEI, Results to Date

Currently, the FEL is in the early stage of operation. Low-power pulses (~10 MW, 5 ns in duration) are being produced so that accelerator alignment and tuning can be done before ramping up to full power. These early pulses were sent over to the tokamak, where they were detected on the back wall with a microwave receiver, as shown in Figs 6 and 7. These tests verified that the microwave quasi optical transmission system was working correctly. The plasmas upon which this beam was incident have not shown any changes caused by the FEL. It is hoped that in the next month (when the power is increased and the new diagnostics will be ready), microwave absorption will be present even under this single-pulse operation.

Figure 6. Internal view of the MTX vacuum vessel, showing the FEL beam incident on the calorimeter and transmitted-power diagnostics.

Figure 7. Data showing the power from one of the first FEL single-pulse experiments, as measured by the transmitted-power monitor.

Near-Term Plans

As stated earlier, the first priority at MTX is to get the single- and multi-pulse, 140-GHz FEL experiments under way. Now that we have an operational tokamak, however, some other experiments are planned. The first is to use the 400-kW, 140-GHz, master oscillator gyrotron as a direct input to the tokamak. The gyrotron will use the same quasi-optic transport system used by the FEL. This is accomplished by rerouting the gyrotron output waveguide from the FEL input to the transport system (see Fig. 8). Mirror box #2 of the transport system is then rotated to allow microwave launching from the top rather than the bottom.

Figure 8. The use of the master oscillator for the FEL as a direct input into the MTX. Note that the output waveguide for the master oscillator is redirected toward mirror box 5, and mirror box 2 is rotated 180°.

Another addition (under construction) is a four-pellet pneumatic injector. This is a rebuild of that used on the Princeton and Texas fusion experiments (PLT and TEXT). Hydrogen and deuterium pellets can be injected at 1 km/s, with sizes ranging from .75 mm in diam $\times$ 1.5 mm long to 1.6 mm in diam $\times$ 2.3 mm long. The pellets will generate peaked density profiles so that the combined sensitivity to heating and density profiles can be evaluated.

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