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MICROWAVE SYSTEM FOR THE MICROWAVE TOKAMAK EXPERIMENT (MTX)

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Abstract

The microwave system for the Microwave Tokamak Experiment (MTX) will include part of the Lower Hybrid Heating (LHH) system used at Massachusetts Institute of Technology (MIT) on the Alcator machine and the new Free Electron Laser (FEL) microwave system being developed at LLNL. The LHH system for MTX will be two carts of four klystrons, each with a nominal total power of 2.1 MW at 4.6 GHz. The FEL system will deliver 2-MW average power at 250 GHz. 50 ns pulses every 200 μs of 8 gigawatt peak power will deliver the 2-MW average power.

This paper will present both the LHH system from MIT and the FEL transmission system, which includes the master oscillator, launch into the FEL, mirrors, and transport system into the MTX. The microwave transmission system, microwave beam diagnostics, present design status, and other related issues will be presented.

The MTX joins two devices, ETA-II and Alcator-C, through a beamline. Figure 1 shows the existing ETA-II facility and the new MTX facility, which houses the former MIT Alcator-C machine.

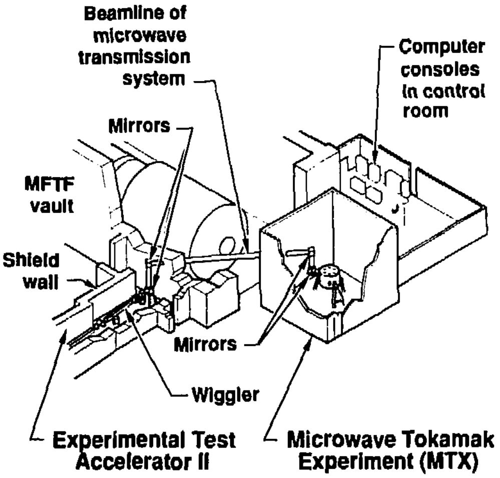

Figure 1 The MTX and ETA-II facility.

Lower Hybrid Heating System

LLNL moved one-half of the existing Alcator-C LHH capability from MIT to Livermore. Eight klystron tubes give a total system rf output power of 2.1 MW as measured at the klystron windows. The LHH system proposed by LLNL is shown in Fig. 2.

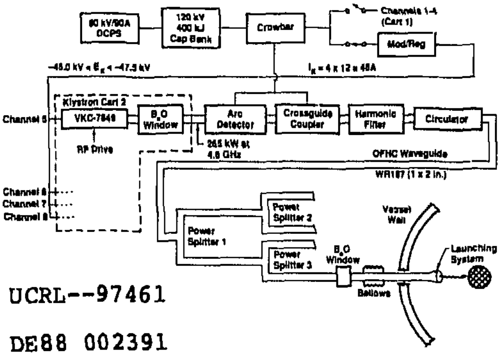

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Figure 2 The block diagram of the MTX Lower Hybrid Heating System,.

Klystrons

The LHH system is based on the operation of Varian Associates model VKC-7849 klystron amplifiers, each with a center frequency of 4.6 GHz and an instantaneous bandwidth of 20 MHz. Rated output power per tube is 265 kW (CW). The tubes are substantially overrated for the LLNL Alcator-C application.

Klystron Carts

Two of the existing klystron "carts" will be installed in a strategic position near the shielded LLNL Alcator-C vault. Each cart will house four klystron tubes and their associated magnet assemblies.

Klystron Power Supplies

For maximum rf output power, each of the LHH klystrons requires an operating cathode voltage between -46.0 to -47.5 kV at an average beam current of 12.0 A (12.5 A maximum). LLNL will provide high-voltage dc power to the klystrons by using two modulator/regulators from the electron-cyclotron resonance heating (ECRH) on the Mirror Fusion Test Facility (MFTF-B) (four klystron tubes per channel).

Unregulated dc input to the two modulator/regulators will be provided from a 90 kV/90 A outdoor power supply. An existing 400 kJ/120 kV capacitor bank will provide high-voltage filtering and transient compensation. Existing high-voltage disconnect switches will allow us to troubleshoot each modulator and its associated klystron cart, independent of the other half of the system.

Each modulator/regulator incorporates a BBC CQK-200-4 superpower tetrode capable of 1.0 MW (CW) anode dissipation and a cooling system design for 10% duty (100-kW average) operation.

Klystron heater-filament supplies (12 A at 12 V/tube) from MIT are an integral part of the klystron cart assemblies. These supplies require 480-V ac input to isolation transformer primaries that will feed full-wave bridge rectifiers to produce dc filament-power floating at cathode potential.

Power supplies for the klystron magnets will be reinstalled near the klystron carts. These supplies (one per klystron) were manufactured by Universal Voltronics Corporation. Each current-regulated supply can produce dc current of 30 A (nominal) between 40 and 65 V. The 480-V ac input power for these supplies will be provided from the cabinet that provides primary power to the klystron filament transformer primaries.

To maintain klystron vacuum, the MIT vac-ion pump power supplies were installed in appropriate locations. These supplies will be interlocked so that in the event of arcing internal to a klystron, high-voltage dc power will be interrupted until the recovery of vacuum is achieved.

Klystron RF Input System

Saturated rf input power per klystron is 1.0 W and will be obtained from existing GASFET phase-locked amplifiers manufactured by California Microwave, Inc. These amplifiers are used to power two traveling-wave-tube (TWT) amplifiers (one per klystron cart). The output of each TWT is passed through a four-way power divider to four adjustable phase shifters before input to the klystrons. All rf drive circuitry is mounted in a standard 19-in.-wide rack.

Waveguide Transmission System

The rf output power of each klystron will be transported to the Alcator-C torus by the MIT fundamental-mode TE-01 waveguide system based on OFHC WR-187, C-band (RG-49U) components. The output flange interfaces to an rf transmission system, which consists of an arc detector, a reverse rf crossguide coupler, a harmonic filter, an rf circulator (20-dB isolation), and a four-way power splitter. Both the arc detector and the reverse rf coupler are interlocked to the high-voltage cathode-power-supply crowbar to prevent damage to the klystron in the event of high power reflection, which may occur during plasma disruption. The harmonic filter and the circulator present very low insertion disruption. Near the torus, each klystron rf output is divided by four-way power splitters and passed through half-wavelength BeO windows. Four bellows assemblies provide the necessary vacuum isolation between the windows and the Alcator-C LHH ports. The rf power is launched into the plasma by waveguide horns. During system conditioning or tune-up, waveguides will be terminated with 200-kW dummy loads, which will be positioned at the rf circulator output.

Controls and Monitors

The LHH system will use the proven MFTF-B ECRH local-control system. Modifications to local control software will chiefly include changes to interlock setpoints and waveform acquisition requirements. Protective circuitry for the klystrons is similar to that used for the MFTF-B ECRH gyrotrons. Interlocked parameters will include cathode voltage/current, magnet current, body current, coolant pressures/flows/temperatures, and reverse rf power. Information to be archived after each physics shot will include forward and reflected rf per channel and phase data.

Free Electron Laser

The MTX FEL microwave system will provide approximately 8-GW peak and 2-MW average power at 250 GHz to the MTX plasma. The power input to the plasma will be used for ECRH initially, but could be used in future plasma-current drive experiments. The microwave system consists of the ETA-II FEL, wiggler feed system, master oscillator and its associated hardware, a quasioptic microwave transmission system from the FEL output to MTX, and microwave diagnostics (Fig. 3).

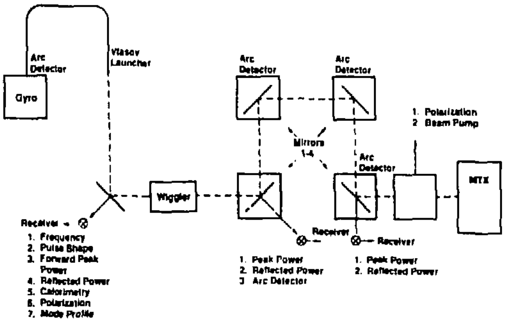

Figure 3 The Free Electron Laser system for MTX.

The FEL amplifier consists of the ETA-II accelerator and its wiggler. It will provide approximately 80 dB (8 GW maximum) of amplification to the master oscillator signal. The ETA-II relativistic electron beam and the master oscillator signal are injected colinearly into the wiggler, which will have energies exceeding 7 MeV at currents greater than 3 kA. The beam pulse duration will be 50 ns at a 5 kHz repetition rate for up to 30 s. The wiggler will be 5m in length and have an 8-cm wiggle period with a maximum transverse wiggler field of 5 kG. Accelerator and wiggler parameters are summarized in Tables 1 and 2.

Table 1 ETA-II Accelerator Parameters

Beam Energy	7 Mev
Current	3.0 kA
Pulse length	50 ns
Repetition rate	5 kHz max.
Beam pulse energy	1500 J/pulse

Table 2 Wiggler Parameters

Wiggler period	10 cm
Wiggler field, max.	5 kG
Wiggler length	5 m

Master Oscillator

The master oscillator used to drive the ETA-II wiggler will be a Varian model VGT-8014 140-GHz gyrotron, which will be reconfigured to operate at a second harmonic (250 GHz). The maximum output power will be greater than 10 kW at 250 gHz, in a TE11,2 (whispering gallery) mode. The gyrotron output pulse length will be 7 μs and will bracket each accelerator beam pulse as shown in Fig. 4. The trigger signal for each master oscillator pulse will be generated by the accelerator timing system to ensure proper bracketing of the beam pulse within the master oscillator pulse. Gyrotron parameters are summarized in Table 3.

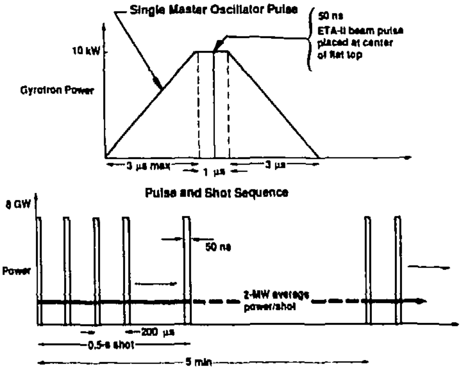

Figure 4 The Master Oscillator Pulse and the entire FEL microwave shot sequence showing timing and pwer levels.

Table 3 Gyrotron Parameters

Output power	10 kW max.
Output mode	TE11,2
Pulse duration	7 µs
Repetition rate	5 kHz max.
Cathode voltage	-50 kV max.
Cathode current	3.5 amps max.
Anode voltage	30 kV max.
Anode current	30 mA max.
Filament voltage	15 vac max.
Filament current	15 aac max.

Gyrotron Output System and Wiggler Feed

The gyrotron output system transports and mode converts an oscillator output RF pulse to the ETA-II wiggler input. The nominal TE11,2 gyrotron output is converted to a TE0,1 mode with a Vlasov launcher located at the end of the gyrotron output waveguide. The launcher output beam is then transported quasioptically to the wiggler feed section.

The wiggler feed is only conceptual at this time, but the baseline design feed would inject the microwave beam colinearly with the electron beam after the achromatic jog. The quasioptical transport system would focus the microwave beam so it couples directly into the wiggler input waveguide. Other feed techniques under consideration are a miter-bend reflector placed inside the electron beam tube before the wiggler input, and a side coupler. Both options would eliminate the need for an achromatic jog in the electron beam tube. Nominal insertion loss for all options under consideration is 10 dB.

Gyrotron High Voltage Power Supply

The output characteristics are a function of the relationship between cathode voltage, anode voltage, filament current, and magnetic field. While holding cathode voltage, filament current, and the magnetic field constant, the output power of the gyrotron can be adjusted between zero and full power by adjusting the anode voltage applied to the tube. The high-voltage supply used to power the gyrotron will be capable of such operation and will meet the minimum specifications outlined in Table 4.

Table 4 Power Supply Specifications

Cathode voltage	0-50 kV neg.
Cathode current	5 A max.
Voltage regulation	+/- 0.1%
Anode voltage	0-30 kV w.r.t cathode
Anode current	100 mA max.
Voltage regulation	+/- 0.1%
Filament voltage	0-15 vac at cathode potentiometer
Filament current	15 aac
Pulse duration	7 µs
Repetition rate	5 kHz max

Microwave Transmission System

The microwave transmission system shown in Fig. 3 quasioptically transports the high-power output of the FEL amplifier to the MTX plasma. The transmission system consists of four ellipsoidal mirrors each approximately 17 in. by 23 in. in diameter contained within an evacuated stainless steel tube with a 20-in. outside diameter.

The transmission efficiency for the system depends on mirror alignment but should exceed 90% for the dominant TE0,1 mode. The polarity of the microwave beam also will be preserved during transport.

Mirror alignment scenarios may involve one or more low-power alignment lasers. Lasers would be reflected through the system, and each mirror adjusted in succession until the system can transport the beams from the FEL output to the MTX vessel entrance.

Alignment

Two visible alignment schemes have been proposed. The first uses two laser beams, one of which may be a diffuse beam. The second used a Gaussian beam simulator to model the entire microwave beam transported through the mirror system. Neither requires modification to the microwave transport system. The expected sources of error that would degrade transmission during this alignment will be from vacuum forces, temperature variations, and vibrations. Bellows isolation, stiffened supports, and operational experience will be used to resolve misalignments. Misalignments in all rotations and translation were easily within the attainable limits needed to ensure the beam passes successfully through the beamline and into the narrow Alcator-C port. Initial alignment will be done manually at normal air pressure. This initial alignment will take into account deflections caused by temperature changes and vacuum forces.

The microwave beam shape and position at the MTX plasma is controlled with both the mirror shape and mirror alignment. Different beam shapes at the plasma

Optics

The microwave beam optics will transmit the 250-Ghz FEL microwave pulses over the 33 m from the wiggler to the MTX. The position for the "waist" of the beam was varied to capture the maximum power possible while focusing the power through the Alcator-C port. Each mirror is kinematically mounted at 3 points that are externally adjustable from the vacuum system. They are presently designed to accommodate manual or remote adjustment devices. Manual adjustment is planned for the initial startup. Each mirror is removable from its vacuum flange, and the flange has additional ports for diagnostics and access. Side ports on the mirror box allow visual inspection and diagnostic access.

The optics design traced the microwave from the output of the ETA-II FEL wiggler through the distances established by the existing facility, into the final focus at one of the large Alcator-C ports. Optical arc detectors mounted at each turning mirror will shut off the master oscillator if a breakdown occurs.

Vacuum

The beamline will be a 20-in.-diameter stainless steel vacuum vessel. Prefabrications will use conflat type copper gaskets for flanges up to 16 1/2 in. in diameter and Helicoflex for larger sizes. Mirror boxes, flanges, mirror pedestals, and supports will be assembled into the vacuum beamline by using vacuum welding where necessary. The vacuum requirement of the ETA-II wiggler is 5×10^{-8} Torr. A general equivalent circuit analysis of the entire beamline with pumps and conductances showed that a transient pulse of 500 ms needed additional conductance limitations at the waist of the beam or an increase in the speed of the pump before Mirror Box 3.

Microwave Diagnostics

Various microwave diagnostics to measure peak and average power, beam polarization and shape, and frequency will be located throughout the transmission system and at the input into the MTX vessel. Limited power dummy loads are planned for both the wiggler output and transmission system output. These loads will handle a limited number (50-100) of full-power 50-ns pulses at the 5-kHz repetition rate. The microwave beam will be deflected into these loads by retractable mirrors located at the FEL output and before the entrance into the MTX vessel.

Design Status and Future Plans

The contract for converting the VGT-8014 gyrotron tube was awarded to Varian Associates in Palo Alto, California. Design will begin in October 1987 with an expected completion date of July 1988. The contract for the gyrotron high-voltage supply was awarded to ORAM High Voltage Systems in Houston, Texas. The supply will be shipped to LLNL in February 1988.

Final design reviews have been held for the microwave transmission system and the vacuum system. Final fabrication drawings and parts lists will be complete in January 1988. The fabrication of the transmission system will begin in late FY88. The final mirror design cannot be completed until all system dimensions are fixed. Optics codes have been run for worst-case configurations to verify design feasibilities.

Designs of the microwave diagnostics, wiggler feed, and gyrotron output systems are in the preliminary stages. These systems are being designed as a cooperative effort between the ETA-II microwave group, the MTX microwave group, and TRW in Redondo Beach, California, to avoid duplicating work.

The ETA-II accelerator is being constructed and the expected date for completion of the FEL amplifier is June 1989. Expected date for completion of the microwave system is late FY89.

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