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MILLIMETER WAVE TOKAMAK HEATING AND CURRENT DRIVE
WITH A HIGH POWER FREE ELECTRON LASER

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MASTER

INTRODUCTION

Recent experiments¹ on microwave generation using a free electron laser (FEL) have shown this to be an efficient way to generate millimeter wave power in short, intense pulses. As depicted schematically in Fig. 1, the technologies used in these experiments are induction linear accelerators and high magnetic field strength wigglers to amplify waves from a master oscillator. Concurrently, high repetition rate pulsed power supplies for induction linacs have been developed^{2,3}. These supplies make it possible to generate high average powers, at the megawatt level and higher for millimeter waves. These events have renewed interest in the magnetic fusion community in electron cyclotron heating (ECH) and current drive, since this technology promises to produce the required power economically and at any frequency envisaged by machine designers. Overall efficiencies of power absorption in the plasma from power drawn off the line are expected to be in the range of 25 - 35 %.

There are significant advantages in using ECH relative to other auxiliary power schemes. No launching structures are required near the plasma, penetrations of the vessel are small owing to the high average power flux, the waves do not perturb the plasma edge, nor are the significantly perturbed by them, efficient single pass absorption is expected, and the power can be localized, perhaps to the benefit of plasma stability and confinement. Short pulse FEL's (50 ns, typically) have the further advantage of avoiding breakdown in the waveguide or machine ports, even at pressures of 10^{-5} Torr.

To demonstrate this technology, and to explore heating and ECH current drive (ECD) applications in tokamaks, an experimental facility is being assembled. It uses the Alcator C tokamak, shipped from MIT to LLNL for that purpose, and an experimental test accelerator (ETA-II) being constructed⁴ at LLNL for beam research. This facility, called the Microwave Tokamak Experiment (MTX), is shown in Fig. 2 while the floor plan of ETA-II is shown in Fig. 3. The major parameters of the tokamak for ohmic heating operations are listed in Table 1. With the ECH system we expect⁵ to increase the central electron temperature to over 3 keV at a line averaged density of $2 \times 10^{14} \text{ cm}^{-3}$.

Auxiliary systems for MTX include 2 MW of ECH at 250 GHz from a free electron laser (FEL), 2 MW of lower hybrid (LH) waves at 4.6 GHz, and a pellet injector originally built for Alcator C. The maximum line averaged density obtainable with gas fueling, $6 \times 10^{13} \text{ B(T) cm}^{-3}$, can be increased about 30% with pellet fueling and the density profile can be changed. With pellets and ECH, important confinement experiments can be carried out under conditions of central heating and central fueling.

TABLE 1. TOKAMAK PARAMETERS FOR MTX

Major Radius	0.64 m
Minor Radius	0.165 m
Magnetic Field	12 T
Plasma Current	250 - 500 kA
Central Ion Temperature	1 - 1.8 keV
Central Electron Temperature	1 - 2.5 keV
Peak Electron Density (units of 10^{14} cm^{-3})	0.1 - 10

THE MICROWAVE SYSTEM

The MTX microwave system components include the FEL amplifier, a 10 kW gyrotron driver source, and a 32 m long quasi-optical transmission system (see Fig. 4) with 4 mirrors. The FEL uses a relativistic E-beam from the ETA-II induction linac to amplify the microwave signal in the wiggler. Design parameters for the accelerator, wiggler, and microwave system are given in Table 2, and a layout of the wiggler region is given in Fig. 5. The beam is transported from the end of the accelerator and passes through an achromatic jog to permit line-of-sight launching of the signal from the master oscillator. E-beam dumps ahead of the wiggler, for beam alignment and operation without the FEL, and after the wiggler are provided. A mirror for diagnostics purposes will be inserted in the microwave output section ahead of the first mirror in the transmission system.

TABLE 2. MTX MICROWAVE SYSTEM

Frequency	250 GHz
Peak Power	8 GW
Average Power	2 MW
Pulse Length	50 ns
Pulse Repetition Rate	5 kHz
Accelerator Current	3 kA
Accelerator Energy	8.5 MeV
Wiggler Field	0.55 T
Wiggler Length	5 m
Wiggler Period	8 cm

Predictions of the microwave performance of the FEL have been made by Jong⁶ using the FRED code^{7,8} developed at LLNL. At 8.5 MeV and 3 kA in the electron beam, the code predicts that the power in the TE₀₁ rectangular waveguide mode is 10.6 GW (99% of the total), an extraction efficiency of 42%. At 7 MeV and a lower peak wiggler field (0.45 T rather than 0.55 T), the prediction is 10 GW at 48% efficiency. Our goal for MTX is 8 GW, leaving some margin in practice.

The codes assume a 50 W input power, well above the anticipated noise level on the beam, in calculating the power level in the wiggler. A multifrequency code called GINGER⁹ was used to calculate the output at all frequencies within the bandpass of the FEL to determine the noise level. The FEL operates in the collective (Raman) regime, so the frequency for maximum gain differs from the synchronism frequency. Thus, to prevent growth of the noise to levels greater than the signal, the wiggler field is lowered slightly in the first 2 m to amplify the signal at maximum gain. Then, by raising the wiggler field slightly, the beam and signal are brought into synchronism to trap electrons in a ponderomotive well as is necessary for high extraction efficiency in the tapered section of the wiggler.

To have 50 W of power at the entrance of the wiggler in the proper mode requires substantially more power in the master oscillator for the FEL. We have conservatively chosen a 10 kW second harmonic gyrotron operating in a TE_{11,2} mode. Considerable power is lost to higher order modes in the transmission system between the gyrotron and wiggler, but we expect to couple at least 300 W onto the beam in the proper mode. Despite there being a mode mixture at the input, the interaction throughout the wiggler selects only the TE₀₁ mode if the FEL is properly designed.

One of the interesting properties of the FEL is its tunability. The gain-bandwidth curve measured¹⁰ at 35 GHz in the experiments at LLNL show the 1 dB power points at $\pm 12\%$, so that with only a tunable driver source one could tune through resonances covering half the plasma diameter at fixed field. Further tunability is available through changes in the wiggler field or beam energy, as shown by the curves in Fig. 6, according to the synchronism condition. For these curves a 9.8 cm wiggler wavelength and a 3×10 cm rectangular waveguide structure in the wiggler were assumed.

The transmission system being designed¹¹ for MTX uses 4 mirrors that maintain the horizontal polarization of the signal after it leaves the wiggler. At the tokamak the wave is therefore launched in the ordinary mode (neglecting the small angle of the magnetic field due to the poloidal field). Just after leaving the wiggler, the microwave beam must be deflected to the right to steer it towards the tokamak, so to maintain polarization it must be deflected to the right a second time, with the same angle, before passing through the port to the plasma. We expect the transmission system to pass 92 % of the power from the wiggler output to the plasma. About 4 % is lost in illuminating the first mirror, while the rest is lost to spillover at the various mirrors. At the tokamak port, which is 22 cm deep and 4 cm wide, 99 % of the power will be contained within 3 cm, leaving 1 cm for errors in alignment. At the center of the plasma we plan to have spot sizes of the microwave beam ranging from 3 cm $\times$ 3 cm to 3 cm $\times$ 8 cm.

PROPAGATION AND ABSORPTION

The use of intense pulses for plasma heating at the electron cyclotron frequency raises two critical issues that have both been addressed for MTX and for future fusion devices in general. These are the ability to

propagate the power to the resonant layer without encountering non-linear processes that would reflect, disperse, or absorb the wave enroute, and the ability to absorb the wave locally at the cyclotron resonance. The first of these issues was treated thoroughly by Porkolab and Cohen¹² while the latter was dealt with by Nevins, Rognlien, and Cohen¹³.

In summary, above a critical density of about $2 \times 10^{14} \text{ cm}^{-3}$ all the power should be absorbed in the ordinary mode, and non-linear effects should not hinder propagation. Raman and Brillouin backscatter, the oscillating two stream and parametric decay instabilities, pondermotive forces, and filamentation processes were all assessed. For the heating calculation, non-linear perturbations of the electron orbits were important, and lead to an increase in thickness of the absorption layer and a decrease in the opacity. For MTX both the thickness and the density for full absorption increased by about a factor of 3 over the linear theory.

The experiments in MTX are unique in their high power density and frequency of operation. This uniqueness follows partly from the FEL technology (allowing higher frequencies) and partly from the small volume of Alcator C. As shown in Fig. 7, MTX experiments will differ substantially in their regime of operation from other ECH experiments in the world.

Our goal in the heating experiments, beyond demonstrating the FEL technology for fusion, is to improve and understand plasma confinement in the auxiliary heated regime using ECH. We plan to measure the energy containment time and thermal diffusivity of the electrons as a function of ECH power and radial location of the power deposition. We will also explore the effect of heating with peaked electron density profiles provided by pellet fueling. Our expectations for increasing the electron temperature over their ohmic values are given in Fig. 8 as taken from Bonoli¹⁴.

CURRENT DRIVE

Unlike other current drive schemes, ECH waves do not directly impart momentum to particles in the toroidal direction. Rather, as proposed by Fisch and Boozer¹⁵, the waves increase the perpendicular energy of the electrons and alter their collisionality. This hole in velocity space is filled by neighboring electrons on the electron collision time scale using the original electron velocity. If the ECH wave were a short pulse (50 ns) then this current would appear on a longer time scale. It would persist on an even longer time scale, given by the electron collision time using its new electron velocity, as the new distribution equilibrates with the ions. The current drive efficiency, defined as the product of density, major radius, and current divided by power, is then proportional to the product of the original and final electron velocities. For good efficiency one must resonate with electrons in the tail of the distribution and heat them to high velocities.

In MTX, we will simulate the large population of 50 keV electrons that one might expect in a reactor by creating that population with a LH wave system (we expect 1 MW to be absorbed). Given the electron distribution

expected using that source, Nevins and Porkolab¹⁶ predict that up to 400 kA of current might be driven with the combined ECH and LH systems at a density of 10^{14} cm^{-3} . About 40 % of this current comes from the LH system, so its use substantially improves the current drive efficiency of the ECH system over that expected without an assist.

Another interesting current drive scheme, one that relies on non-linear wave interactions such as are possible only with FEL's, was first suggested by Cohen¹⁷. This beat-wave scheme would launch two intense pulsed sources into the plasma and produce a beat wave that in turn gives momentum to electrons, thereby driving current. One realization of that idea, shown in Fig. 9, is being examined in detail for MTX. The second source, having a lower frequency and an intensity perhaps as low as a few percent of the primary source, differs in frequency from the first by the plasma frequency. Parameters are picked so that the two modes of propagation (each combinations of right and left circularly polarized waves) differ in their wavenumber so that the phase velocity of the beat wave is at 3-4 times the electron thermal velocity. At that velocity Cohen¹⁸ finds that the wave momentum is given entirely to the electrons, since Landau damping and wave-particle trapping are strong and there are enough particles in that part of the distribution to damp the wave.

This scheme is potentially a very high efficiency one for fusion reactors, one that could be tested in MTX (where the efficiency will be modest) with the addition of a second source of intense pulses. Further analysis, including ray tracing to determine the extent of the interaction region, and treating spatial gradients in field and density, is in progress. From these preliminary results it appears that one can achieve 100% of the quantum efficiency (here, the ratio of the plasma frequency to the highest frequency source) of conversion to parallel electron momentum over the interaction region in MTX. Preliminary estimates show that 150 - 200 kA of current may be driven in MTX with 2 MW of ECH.

OTHER EXPERIMENTS

Several other uses of the MTX facility have been considered. These include the use of a tunable driver source to track changes in specific locations within the plasma (such as rational-q surfaces, where $2\pi q$ is the inverse of the rotational transform). For example, ECH or ECD at the $q=2$ surface may prevent the growth of magnetic islands that lead to plasma disruptions. Or, as proposed by Rutherford¹⁹, ECD at the $q=1$ surface could be used to prevent growth of the magnetic islands that lead to sawtooth behavior when q is less than unity at the center of the plasma. Operation in this regime (higher plasma current for a given set of machine parameters) should lead to improved performance over that at higher q operation.

More generally, using the localization possible with ECH, one can imagine that the power deposition profile can be tailored to maximize the energy confinement time. This could be done by sweeping the frequency on a time scale shorter than the fastest transport time in the plasma. In

principle one could match the profile that obtains when ohmic heating alone is applied. It would be interesting to determine whether or not this eliminates the confinement degradation usually found on the application of auxiliary power.

If the ETA-II accelerator could be extended in performance to about 10 MeV, then it would be possible to operate the FEL at frequencies up to 500 GHz. This would allow heating at second harmonic at 9 T, using the extraordinary mode launched from the outside of the plasma. The plasma dielectric constant for peak absorption at the second harmonic is about twice that for fundamental heating. So, since the dielectric constant is proportional to the plasma β (ratio of plasma to magnetic pressure) and inversely proportional to temperature, second harmonic waves allow heating at higher β for a given temperature. While there are no current plans for an accelerator upgrade, this demonstration in MTX could be important to the Compact Ignition Tokamak (CIT), now being designed. The addition of 10 MW of ECH at second harmonic frequencies in CIT (about 600 GHz) is being contemplated, an addition that both provides a backup to the baseline ion cyclotron heating scheme and a new opportunity for enhancing the machine performance.

CONCLUSIONS

A new technology for plasma heating and current drive has been developed and will be used in the MTX. This opens up the high-field, high-density plasma regime for ECH. If successful these experiments will lead to important reactor applications and provide additional means for plasma heating and control. Among the most exciting prospects is the demonstration of an efficient current drive scheme to allow steady state operation of tokamaks.

FIGURE CAPTIONS

Figure 1. Component technologies for a high power Free-Electron Laser

Figure 2. Layout of the MTX facility, showing the former Alcator C tokamak in a shielded vault, the end of the ETA-II accelerator, the wiggler for amplifying microwaves, and a quasi-optical transmission system.

Figure 3. A ground-level floor plan for the ETA-II accelerator and wiggler for microwave generation in MTX.

Figure 4. The MTX microwave transmission system, consisting of 4 mirrors to transport and focus the 250 GHz beam into the tokamak port, and an evacuated 20 inch diameter pipe to enclose the beam. The distance from mirror 2 to mirror 3 is about 20 m, while the overall distance from the output of the wiggler to the tokamak port is about 32 m.

Figure 5. Beam transport and wiggler region of the MTX microwave system, showing an achromatic jog for line-of-sight delivery of the driver signal, 5

meter wiggler, diagnostic turn-out mirror and microwave diagnostics, and the first mirror box in the transmission system.

Figure 6. Synchronism condition between waves in a rectangular guide and a relativistic beam, showing the tunability of FEL's with beam energy and wiggler field strength.

Figure 7. Parameter regime for various planned, proposed, or existing plasma experiments using ECH sources. The uniqueness of the MTX source and facility to reach high plasma densities and to heat with large microwave power densities is evident.

Figure 8. Expected increase in electron temperature in MTX as a function of microwave power for two different operating regimes. The initial central electron temperature at the higher density is about 1.4 keV, and 1.7 keV at the lower density. The maximum central electron temperature expected in MTX with the ECH system and pellet injector is over 3 keV.

Figure 9. A scheme to launch two intense waves to make a plasma wave for current drive in the tokamak. The beat-wave scheme may be a very efficient current drive method for reactors.

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Component technologies for a high power Free-Electron Laser

Microwave Tokamak Experiment (MTX)

ETA II — ground-level floor plan

MTX microwave transmission system

MTX FEL systems wiggler layout

Tunability of waveguided FEL

ECH - Tokamak Experiments

Temperature increase with ECH power

Beat wave current drive