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Microwave Free-Electron Laser Applications for Electron Cyclotron Heating of Plasmas

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ABSTRACT

Millimeter wave power may be the ideal source of heat for a plasma, but advances in technology are needed to meet requirements of next generation fusion devices. Free electron lasers (FEL) are one candidate for such sources, and this paper reviews the progress, issues of physics and technology, and potential benefits for fusion from these devices.

1. INTRODUCTION

Plasmas confined by magnetic fields must be heated to temperatures of 5-10 keV for ignition and burn, a task requiring auxiliary power in both the tokamak and stellarator approaches to fusion. Given the plasma volumes and energy confinement times of such devices this requires tens of megawatts of power. One currently has a choice of neutral particle beams, radio frequency (rf) sources in the 100 MHz range to heat ions, or microwaves in the lower hybrid range of frequencies of 2-8 GHz. If economical sources of power in the electron cyclotron (EC) range of frequencies, 200-300 GHz (or higher), were available these would likely be the sources of choice.

Waves at EC frequencies are desirable in fusion reactors since they require the smallest penetration of the blanket surrounding the fusion core where power and tritium are produced. Bringing the power into the machine through a final turning mirror allows easy shielding of the sources and minimum penetration of neutrons into the cell housing the machine. Antennas or launching structures for both rf and lower hybrid waves require intimate plasma contact for efficient coupling to the appropriate waves in the plasma. This coupling is sensitive to perturbations in the edge plasma, and the plasma can in turn erode material from the structures that introduce unwanted impurities into the plasma. Waves at EC frequencies do not require a structure at the plasma boundary, and they continue across the plasma boundary without perturbation to or from the plasma.

From a physics perspective, localized and complete absorption by the electrons can be achieved, and the location of the resonance accurately controlled. These features follow from the fact that the wave packet that is launched can be tightly focused, and the high absorption coefficients (typical of this resonant interaction) mean the waves absorb in a very short radial distance. Control of MH D instabilities for example depends on accurate, local deposition of the microwave power. Since the resonance location is controlled by the magnetic field, which in a tokamak decreases inversely with radius, a tunable source allows greater flexibility in picking arbitrary locations for power absorption. Without tunability one is left to vary the magnetic field to match the available source frequency, or to launch off-perpendicular to introduce a Doppler shift. In either case, operational constraints are introduced if the source is not tunable.

These desirable features of microwave sources are somewhat independent of the nature of the source, whether it be a microwave tube or a FEL. For example, both gyrotrons and FEL's that achieve high average power through high repetition rates give a power flux of about 100 kW/cm*2, allowing small penetrations through the reactor. Also, many of the physics applications are independent of the pulsed or steady nature of the sources. In some instances however the FEL is different and there can be either an advantage or disadvantage depending on the issue in question. These issues have been studied[1] and are briefly reviewed here in the physics section.

Only recently have FEL's been considered as challengers to gyrotrons as a source of microwaves for fusion. This emergence is traceable to several factors; the recent demonstrations[2,3] that millimeter waves can be efficiently produced from induction FEL's, that the high repetition rate components[4] to drive these accelerators are now available, that FEL's come naturally in large unit power sizes, and that high power can be produced at any frequency needed for fusion applications can be produced.

2. PYHSICS APPLICATIONS

Since the microwave FEL can potentially produce large unit power it will be ideal for heating applications if the cost is acceptable. For typical next step devices the total power required might be in the 20 - 50 MW range, with frequencies of 150 - 300 GHz if fundamental resonance is used. In the Compact Ignition Tokamak (CIT) under design at Princeton a microwave heating system at about 300 GHz is being considered. System designs using both gyrotrons[5] and FEL's [6] have been done.

The availability of sources at twice the above frequencies could easily change these "requirements" in order to use second harmonic waves that allow higher density operation and shorten the absorption depths. From the outside of a tokamak, one can launch either an ordinary mode (rf electric field parallel to the tokamak magnetic field) at the fundamental frequency, or an extra-ordinary mode (rf electric field perpendicular to the tokamak field) at the second harmonic. The absorption is substantially better for the X-mode than for the O-mode, so that complete absorption occurs at much lower density for the former than for the latter. Also, there is better localization (less refraction) for the X-mode at a given density. For frequencies above 300 GHz, corresponding to second harmonic operation, the FEL option may prove to be the only technically feasible one.

It was recognized very early that the intense short pulses generated by FEL's could introduce nonlinear plasma physics issues. These include absorption based on relativistic detuning, parametric effects that could lead to backscatter of the wave, and possible filamentation of the wave leading to reduced absorption or burn-through. Tests in MTX (the Microwave Tokamak Experiment at LLNL) of these nonlinear physics issues[7] will determine the feasibility of FEL's for these applications.

Having a source of intense microwave pulses has stimulated thought on innovative uses for them. Several ideas have been generated[8], all related to inducing plasma current with these waves. Since intense waves trap particles in phase space buckets, appropriate aiming of the wave packet into the tokamak can lead to the acceleration of plasma electrons. The process is similar to that in a synchrotron accelerator, or the inverse of the trapping process in a tapered wiggler. This process can be efficient for plasma current drive. Another scheme requires such large amplitude rf fields from the FEL pulse that the buckets overlap in phase space and the particle motion becomes stochastic. Then, particles can diffuse up in energy to values large compared to their initial energy. This reduces the collisionality of the particles so their slowing down time is long and the current persists. This also means the scheme is efficient (number of watts to produce an ampere in appropriately normalized units).

A third scheme proposed by Cohen[9] uses two FEL's, one of them at low power, to generate an in situ beat wave in the plasma that traps electrons and gives wave momentum to them. This is again a fairly efficient scheme for driving current non-inductively in a plasma. Finally, a scheme related in both physics and technology to the above ideas uses an induction linac to generate intense beam pulses of a few MeV for a relativistic klystron[10]. Intense electromagnetic waves in the 10 GHz range can be produced. For fusion applications, pulses of about 1 GW can be used to "burn through" the plasma to its core, where the waves can damp on electrons, thus driving current[8]. At low power levels these "lower hybrid frequency" waves damp on the edge plasma and do not penetrate. The Landau damping process responsible for this damping is defeated by altering the plasma electron distribution function in a way that allows penetration. The nonlinear alteration requires the high peak power levels quoted here. All of the above current drive applications await experimental verification, a step that first requires the high average power operation of FEL's or the relativistic klystron.

There are additional applications for EC wave sources that have been explored experimentaly[11], but much more work remains to determine their potential. These include stabilization of MHD instabilities, assist in plasma startup, and plasma profile control. Many of these provide the rationale[12] for an EC system on the International Thermonuclear Experimental Reactor (ITER).

Two phenomena, sawteeth oscillations and disruptions, are dominant MHD activities in tokamaks that can limit performance. The MHD activity is initiated on surfaces where the magnetic field lines close on themselves after a few (depending on the phenomena in question) transits around the torus. There are two surfaces in particular, the q=1 and q=2 surfaces, where sawteeth and disruption activity respectively begin. Here, "q" is the number of transits for field closure. If there is sufficient plasma current there is a q=1 surface in the core of the plasma. Inside of this surface there is a rapid spreading of heat when the sawtooth "crash" occurs. The core temperature drops significantly, and in a burning plasma this would rapidly reduce the fusion output. Following the crash the temperature and current again build up to the next crash, and the process repeats itself. Disruptions initiate from the q=2 surface, which is closer to the edge of the plasma. A disruption results in a sudden loss of energy, and then current, from the plasma. When the current drops it appears in the vacuum vessel walls (to conserve flux), and the force of these wall currents tends to crush the vessel around the plasma. Aside from losing control of the plasma, disruptions can severely damage the vessel, so one must design accordingly. Operations are always carried out in a way that avoids parameter space in which disruptions are likely.

Since FEL's are tunable, they would offer new possibilities for control of these MHD effects. In experiments to date the frequencies have been fixed and the magnetic field or plasma current is varied so as to co-locate the absorption layer and the appropriate MHD surface. However, on current diffusion time scales one can expect the q=1,2 surfaces to move, so to follow them by adjusting the frequency, perhaps by feedback control, would be advantageous. One can influence the MHD stability either by locally heating around these surfaces, or by driving currents in the plasma with EC waves at these surfaces. In the first case, the added heat lowers the plasma resistivity locally, so that more ohmic current flows at the absorption layer.

Another interesting use of EC waves is to assist in plasma startup. One can preionize the plasma to assist in breakdown, and also heat the plasma directly during the current ramp-up to save transformer volt-seconds and prolong the current pulse. An important goal is to lower the design voltage imposed on the plasma to initiate startup. Since a thicker vacuum vessel will reduce the applied loop voltage to the plasma for a given flux change in the ohmic heating transformer, and since a thick shell is structurally desired, one would like to be able to startup with less loop voltage than is now customary to reap this benefit. This application is not specific to FEL's, but if the source were tunable the resonance location could be optimized during startup for this purpose, then changed to optimize the heating profile during ramp-up, and finally used for MHD control by initiating feedback control around the rational q surface of choice.

3. MICROWAVE FEL PROGRESS

The proposed use of microwave FEL's for fusion[13] followed successful experiments at LLNL[2-4] to produce microwaves at high efficiency (35-40% at 35 GHz), and to demonstrate that high repetition rate driver technology for these accelerators is available. The experiments also showed tunability on a slow time scale by operating the same system at 35 and 140 GHz with a simple change in beam voltage, and showed that the bandwidth of the FEL amplifier is sufficiently wide as to allow rapid tunability over 10-20% with a tunable driver source. The MTX experiment was designed to test this new technology, to explore the nonlinear physics issues described earlier, and experimentally to study the various applications listed above.

Experiments in MTX are planned in several phases, starting with single pulse operation as dictated by the available wiggler. Initial experiments in this phase, with a beam energy of about 6 MeV and at a frequency of 140 GHz have been reported[14]. Microwave pulses of about 150 MW were produced with an untapered wiggler, and up to 400 MW with a quick attempt at tapering (see Fig.1). The goals for this phase are to produce 1-2 GW pulses for transmission and absorption in the plasma. With a new wiggler nearly completed (the Intense Microwave Prototype, or IMP) experiments with a string of pulses at rep rates up to 5 kHz are planned, initially at 140 GHz. With an increase in beam energy to 9-10 MeV in the final phase, the frequency will be raised to 250 GHz. When a 20 MW power supply for the accelerator is added, the burst of pulses will be extended to several seconds, or longer with modest changes to the cooling of certain components. Current plans are to complete this program in the next several years.

In preliminary transmission experiments[15] the wave transmission through the plasma at this 150 MW level showed the expected attenuation as a function of density, as shown in Fig. 2. The transmitted signal in Fig. 2 goes to zero when the critical density (wave frequency equal to the plasma frequency) is reached, as expected from theory. The exact shape of this curve with density is determined by both refraction and absorption, and further analysis is being done to compare theory and experiment. In particular, a similar measurement was made when the tokamak field was raised so as to remove the resonance zone from the plasma, leaving only refraction and cutoff to influence the curve. This data is being compared with linear absorption theory, since nonlinear effects should only be observable above 500 MW. If the absorption were nonlinear the result would be to slightly increase the transmitted power at all densities up to cutoff.

Designs for a 280 GHz, 10 MW FEL to be used to heat the CIT have been completed[6], and these are based on the technology to be demonstrated on MTX. The repetition rate was increased a factor of two, the beam energy raised about 40%, and the pulse length increased from 50 to 70 ns in comparison with the MTX system. One option in this design is to build an extra wiggler and switch the beam between them, either on alternate pulses or on any other arbitrary schedule. This arrangement, shown in Fig. 3, allows two different frequencies of operation with the power ratio determined by the switching schedule. Thus, two different applications could "simultaneously" be accommodated with this setup.

4. CONCLUSIONS

High power millimeter wave source development for fusion is still in the early stages, but applications that have the potential to improve the performance and operation of plasmas have been identified. Some of these applications are unique to high peak power FEL's based on the induction linac. Others will benefit substantially from the flexibility of such FEL's, in particular from the tunability. The large unit sizes natural to the FEL, the inherent low wall loading from the beam and rf heat sources, and the unlimited frequency choices all combine to make this an interesting option for fusion.

With further development and physics tests the potential of this approach should be known in the next several years.

5. ACKNOWLEDGMENTS

Considerable effort on the part of the MTX and Beam Research groups ws required to produce the first results of microwave FEL pulses in the tokamak, and the author is indebted to them. Initial FEL results (Fig. 1) from 140 GHz operations were provided by Bill Turner, Al Throop, Ted Scharlemann, and Ray Jong, while Bick Hooper and Steve Allen provided the information on plasma transmission (Fig. 2) in MTX. The work was supported by Lawrence Livermore National Laboratory under the auspices of the U.S. DOE under contract W-7405-ENG-48.

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Figure Captions

1. (a) A gain curve at 140 GHz for the wiggler used in MTX experiments, and (b) a sequence of FEL pulses up to 400 MW generated by tapering the last meter of the wiggler.

2. Power transmitted through the MTX plasma at 5 T, normalized to incident power, showing the expected cutoff at the plasma frequency. (Courtesy E.B. Hooper and S.A. Allen, LLNL).

3. Use of a pair of wigglers on a single accelerator to enhance the flexibility of the FEL. (Courtesy R. Jong and R. Stone, LLNL).

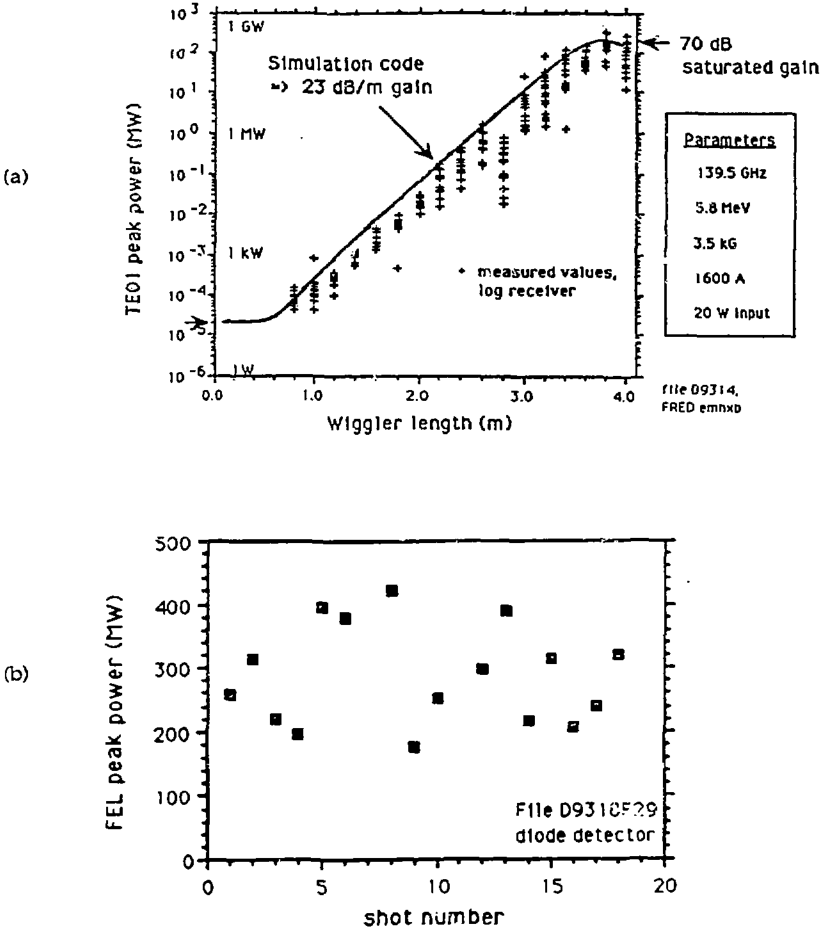
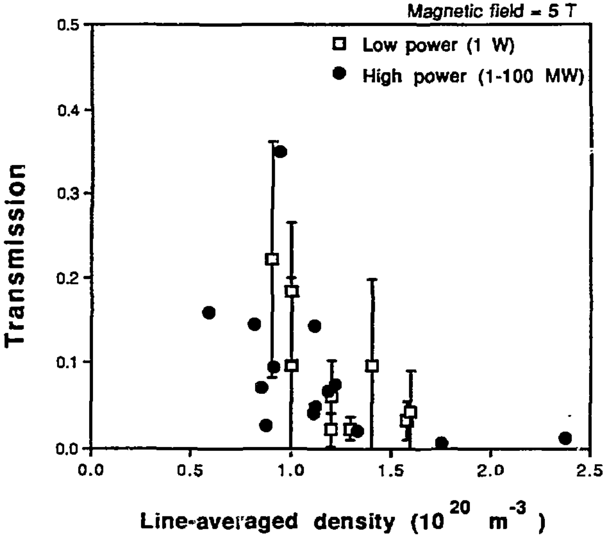

(a)
TE01 peak power (MW)
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
1 GW
1 MW
1 kW
1W
Simulation code
=> 23 dB/m gain
70 dB
saturated gain
+ measured values,
log receiver
Parameters
139.5 GHz
5.8 MeV
3.5 kG
1600 A
20 W input
0.0
1.0
2.0
3.0
4.0
Wiggler length (m)
File 09314,
FRED emnxb
(b)
FEL peak power (MW)
500
400
300
200
100
0
0
5
10
15
20
shot number
File D9310529
diode detector

Fig. !



Magnetic field = 5 T
□ Low power (1 W)
● High power (1-100 MW)
Transmission
0.0
0.1
0.2
0.3
0.4
0.5
0.0
0.5
1.0
1.5
2.0
2.5
Line-averaged density (10^{20} m^{-3})

Fig. 2

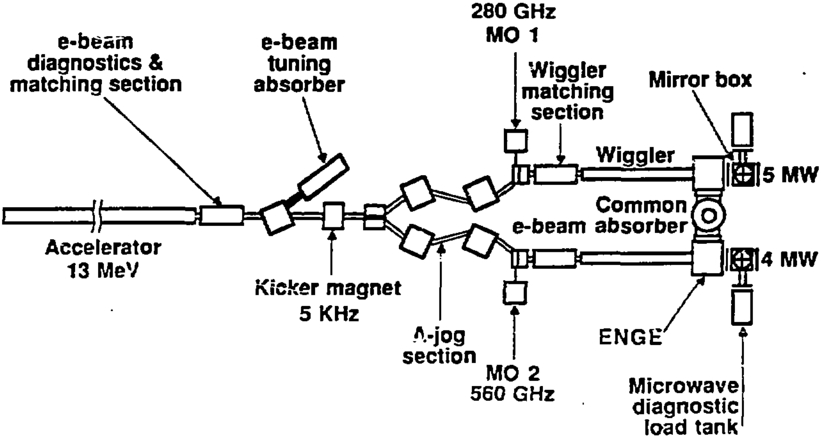

e-beam diagnostics & matching section
e-beam tuning absorber
280 GHz MO 1
Wiggler matching section
Mirror box
Wiggler
5 MW
Common e-beam absorber
4 MW
Accelerator 13 MeV
Kicker magnet 5 KHz
Λ-jog section
MO 2 560 GHz
ENGE
Microwave diagnostic load tank

Fig. 3