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UCID- 18486

MICROWAVE HEATING OF HOT, OVERDENSE PLASMAS

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MASTER

December 4, 1979

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Livermore
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Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore Laboratory under Contract W-7405-Eng-48.

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MICROWAVE HEATING OF HOT, OVERDENSE PLASMAS

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ABSTRACT

Calculations were made of the heating of hot (~ 5 keV), overdense (10^8 critical density) deuterium plasmas by 1 cm microwaves with an incident power of $5 \cdot 10^{16}$ watts/cm². The code OREMP (written by K. Estabrook) was used. Previous calculations by Estabrook⁽¹⁾ at 10^4 critical density showed about a 1% absorption rate of the incident flux, with about 50% of the absorbed energy converted into pulses of hot ions moving radially inward. At the higher density a realistic ion mass was possible, and resulted in a smaller heating rate ($\sim 3\%$ at $T = 5$ keV) but a higher proportion of the energy ($>90\%$) going to ion pulses. These pulses had energies (~ 50 keV) which are very favorable for thermonuclear reactions. The low absorption rate is not a serious problem if the unloaded Q of the microwave cavity is high (10^3 - 10^4).

Dependence of the heating rate on the plasma temperature and the drift velocity of the surface was also studied. The power absorption is found to vary approximately as $T^{1/2}$.

The effect of α particles produced by fusion reactions was briefly studied. These particles will be trapped near the pellet by the potential well set up after a few charged particles escape. Calculations show that it is possible for the α particles to lose a substantial portion of their energy to the electrostatic field in a few reflections. This energy will either go back into the plasma or can pump up the microwave field. A one-dimensional code cannot calculate this pumping

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properly, however, because the effective antenna dimensions are not correct. It appears that the electrostatic field of the α particles will also enhance the overall heating rate, but estimates show that this will probably not be a substantial increase at the field strengths of interest.

INTRODUCTION

The aim of the MAESTRO project is to induce controlled fusion by heating a pellet with very high power microwaves.⁽²⁾ The microwaves could be produced by a relativistic magnetron --- a device with very high efficiency (typically 40%, possibly 80%) in converting an electric pulse to a microwave beam. A major conceptual difference between the use of microwaves rather than lasers or particle beams is that microwaves can be contained in a high Q resonant cavity, and can thus irradiate the pellet for many r.f. cycles. Thus the energy need not be absorbed at once, but can heat the pellet gradually. The pellet will not implode, but will "cook" slowly in a "microwave oven". The plasma surface is stable if the wavelength of the microwaves is longer than the pellet radius.⁽³⁾

PHYSICAL REGIME FOR A MAESTRO PELLETT

MAESTRO requires very high field strengths and high plasma temperatures to operate. The plasma corona would typically be at densities $n \sim 10^{21} \text{ cm}^{-3}$. With typical wavelengths in the 1 cm range, this corresponds to $\omega_{pe} \sim 10^4 \omega_{em}$, or $n \sim 10^8 n_{\text{critical}}$. The microwave fields need to have $B_{em} \sim 10^7$ gauss, so the incident power $P_{em} \sim 10^{16} \text{ watts/cm}^2$. To reach break-even probably requires the total microwave power $E_{em} \sim 10^6$ joule. Typical corona temperatures will be mainly in the range $T \sim 1\text{-}10 \text{ keV}$ for most of the reaction time.

It is difficult to calculate the heating rate of such a corona because its density is so high. The time step is limited by the plasma period, and here even one r.f. cycle is 10^4 plasma periods. In 1976 Estabrook made a test calculation at a lower density using his code OREMP, a one-dimensional particle simulation code with self-consistent electromagnetic fields. The plasma is modeled as a slab with normally incident microwave fields. The particle mover uses cloud-in-cell interpolation and the field solver uses explicit time-centered differencing.

The particle moving subroutines were hand coded in assembly language, making OREMP one of the fastest plasma codes at LLL.

The 1976 calculation used $\lambda = 1$ cm, $n = 10^4$ critical ($1.1 \cdot 10^{17}$ cm $^{-3}$). The peak B field was $1.4 \cdot 10^5$ gauss (in approximate equilibrium with the plasma at a temperature of 5 keV). The temperature of 5 keV is a typical one, as shown by Vidal's burn calculations.⁽⁴⁾ The ion mass was taken to be 100 electron masses. Since here $\omega_{pe} = 10^2 \omega_{em}$, this will give $\omega_{pi} = 10^2 \omega_{em}$. One cannot here use a much higher ion mass and still try to maintain the condition $\omega_{pi} \gg \omega_{em}$.

Estabrook found an absorption of about 1% of the incident Poynting flux. An important result was that the energy was converted into pulses of hot ions moving radially inward. The energy was about evenly divided between ions and electrons. These results agreed fairly well with Ensley's analytic calculations and White's ORBIT code.⁽⁵⁾

Plasma Heating Mechanisms

Ensley has devised several mechanisms which can contribute to absorption of microwave energy by a plasma. They are electron drift heating, field pressure heating, and field reversal heating.

Electron drift heating results from the fact that electrons moving in the crossed fields E_x (longitudinal charge separation field) and B_z (transverse microwave field) experience a net drift velocity v_y parallel to the microwave field E_y (Figure 2). There is thus a net $F \cdot v$ work done on the electrons. There is an overall gain in energy because electrons moving opposite the field will lose at most energy kT , while electrons moving parallel to the field can gain several kT .

Field pressure heating results from the fact that the plasma surface expands and contracts as the field oscillates and the field pressure $B^2/8\pi$ varies. Thus the field does $F \cdot v$ work on the moving ions.

Again the particles which gain energy will gain more than those which lose energy.

Field reversal heating results when B_z and then E_x go through zero (Figure 1) and the electrons are momentarily free to expand away from the corona surface. As the field reverses and E_x increases again, the electrons find themselves at regions of high potential and are accelerated back into the plasma, picking up many kT in the process. However, only a small fraction of the electrons appear to undergo this process. The combined effect of all three processes is greater than the linear sum. This is because the ions will have a higher inward velocity initially, and then more work will be done on them by the field pressure term. All three effects are observed in the code calculations, but it is difficult to separate the contributions of the different terms.

The exact mechanism by which the electron energy is coupled into the ion pulses is not yet clear, but Ensley suggests that it is through means of electron plasma oscillations, which are visible in the plot of E_x (Figure 3).

Calculations of High Density Plasmas

The difficulty in running OREMP at the realistic density of 10^8 critical was a problem of running time and numerical error. The time step is limited by the Courant limit for the electromagnetic field, proportional to Δx^{-1} . Numerical accuracy requires $\Delta x < 2 \cdot \lambda_D$, the Debye length, which is proportional to $n^{1/2}$. So the execution time for a given number of r.f. cycles increases as $n^{1/2}$ (for a region of a fixed number of λ_D). Since the 1976 run took several hours, it seemed prohibitive to run at 10^4 higher density. Also there was a question that the numerical self-heating error could become large at higher densities unless one increased the number of particles even further.

We found that the run time could be substantially decreased without unacceptable loss of accuracy. The savings was accomplished by increasing the cell size Δx to $1.9 \lambda_D$, reducing the total plasma thickness L to $318 \lambda_D$, and reducing the number of particles N per λ_D to 9.4. The total number of particles was 3000 and $\omega_{pe} \Delta t = .375$. This produced an overall factor of 25 increase in speed (a final time of 4.6 hours to run 2 r.f. cycles at $n = 10^8$ critical). It was also not necessary to run for as many cycles to estimate the average heating rate. When a run was made with equivalent parameters at 10^4 critical, it agreed to Estabrook's answers to about 20% in the total heating rate. An examination of the sources of error in the initial run showed that self-heating error (estimated from a study by Peiravi and Birdsall⁽⁶⁾) was negligible at these parameters. The total error in the heating rate was about $\pm 5\%$. This was probably due to finite difference errors in the solution of the electromagnetic fields which would not increase if $\Delta t/T_{em}$ became smaller. Self heating errors could be kept within bounds by the larger Δx and by adding a smoothing term to E_x .

It was then possible to make a calculation with $n = 10^8$ critical density ($1.1 \cdot 10^{21} \text{ cm}^{-3}$), $\lambda = 1 \text{ cm}$, $T = 5 \text{ keV}$, $B = 2 \cdot 10^7 \text{ gauss}$ ($P = 5 \cdot 10^{16} \text{ watts/cm}^2$). For this run the realistic deuteron mass of 3672 electron masses was used. This had a significant effect. It appears that the heating rate scales roughly as $M_i^{-1/2}$. The calculated absorption was then approximately 0.3% of the Poynting flux (Figure 4). This reduction does not reduce the burn efficiency of the pellet if the unloaded Q of the cavity is high ($\sim 10^4$). For cold copper cavities at resonance a Q of $> 10^5$ is not difficult to achieve. Ensley's calculations indicate that even with the intense microwave energy in the cavity, a Q of 10^4 is obtainable.

An important new result is that as the density (and thus ω_{pi}/ω_{em}) increases, the fraction of the energy given to the ions increases, and at $n = 10^8$ critical well over 90% of the absorbed energy is converted into hot ion pulses. (Figures 4, 5)

Effect of Corona Temperature on Absorption Rate

Ensley predicted that the absorbed power should vary with the electron temperature as

$$(1) \quad \frac{P_{\text{absorbed}}}{P_{\text{input}}} \propto T_e^{1/2}$$

We found a dependence on both electron and ion temperatures, roughly fitted by

$$(2) \quad \frac{P_{\text{absorbed}}}{P_{\text{input}}} = 1.3 \cdot 10^{-3} T_e^{(a)} T_i^{(b)}$$

$$a = .2 \quad (\text{temperatures in keV})$$

$$b = .3$$

so if $T_e = T_i = T$ the absorption does vary as $T^{1/2}$.

The mean velocity of the accelerated ions has a similar dependence, i.e.

$$(3) \quad \frac{\bar{v}_{\text{ion}}}{c} = 3 \cdot 10^{-3} T_e^{(a)} T_i^{(b)}$$

with the same a and b as above.

Thus for $T = 5$ keV, the ion energies are about 50 keV, which is a good energy for D-T thermonuclear reactions. (Figure 6)

At low temperatures (a few hundred eV) the absorption dependence is different, roughly

$$(4) \quad \frac{P_{\text{absorbed}}}{P_{\text{input}}} \propto T^{-1} \quad (T_e = T_i = T)$$

with most of the energy going to the electrons. This may result from resonance absorption by electrons whose velocities are low enough so they can spend long fractions of a cycle in the skin region. (We have not included ohmic collisional heating, which also becomes large at low temperatures.) The conclusion is that the pellet should heat to several hundred eV rapidly. Although most of this energy goes to the electrons, only a small fraction of the total microwave power is involved in this portion of the absorption.

Effect of Drift Velocity on Absorption Rate

As the pellet heats up and expands, the surface velocity can become comparable to the thermal velocity. This can change the absorption substantially. As a simple model we can assume that each ion which is accelerated receives an incremental velocity Δv independent of its initial velocity. Then when the corona expands the heating will be reduced, for

$$(5) \quad \frac{P_{\text{absorbed}}}{P_{\text{input}}} = 1 - 2 \frac{V_{\text{drift}}}{\Delta v}$$

(where outward velocity > 0)

Loss of energy to the field brakes the expansion. However even with a net loss of energy to the field one can still have an inward pulse generated from the inward moving tail of the thermal distribution.

Effect of Trapping of Alpha Particles

Ensley has proposed the possibility that a "nuclear maser" effect could occur resulting from emission of the 3.5 MeV particles from DT nuclear reactions. After a small number of these particles escape, the charge on the pellet sets up a potential barrier which traps and reflects subsequent α 's back into the pellet. Collisional losses in the core are

very slow for particles of such energies, and most of their energy could be transferred to the charge separation field.

We attempted to model an aspect of this trapping process by modifying CREMP to inject fast ions out of the plasma at specified time intervals. When they are reflected by the potential barrier back into the plasma they are held at the boundary for a time to simulate transit through the core.

These calculations demonstrated trapping of α 's by the electric potential and also showed a gradual loss of energy to the charge separation field. The loss was roughly 10% per reflection. For a typical pellet size (say .2 cm diameter) the characteristic time to lose most of the α energy is thus $\sim 10^2$ r.f. cycles, which is fairly small compared to the total burn time of $\sim 10^3$ cycles.

Since the charge separation layer is oscillating in the same mode as the driving microwave fields, this energy could be reradiated back into the microwaves, thus continuing the reaction for longer times. However we cannot calculate this process correctly with a one dimensional code because of the length scales involved. The energy loss of an oscillating dipole layer goes as

$$(6) \quad \dot{E}/E \propto (a/\lambda)^3$$

Where a is the effective antenna size, here the width of the charge separation layer, $\ll \lambda$. A pellet with an oscillating space charge layer acts as an antenna whose size is the order of the pellet size, which can be of order λ .

These code calculations also indicated that the presence of the space charge layer set up by the α 's can increase the absorption of energy by the corona. This is probably due to enhancement of field reversal heating. As soon as the confining magnetic field turns off, the electrons in the skin move outward to neutralize the space charge of α 's lying outside the corona surface. For low densities factors of 2 or 3 increase in the net heating rate were seen. We can estimate what sort of increase would be possible in a real situation. The energy picked up by an electron is approximately

$$(7) \quad \Delta E \sim e E_r \delta r$$

where E_r is a typical value of the charge separation field and δr is the distance the electrons travel, which is approximately to the location of the α 's. We can estimate δr if we assume a uniform distribution of α particles through a sphere of radius $r_0 + \delta r$, where r_0 is the pellet radius, and we can assume $r_0 \gg \delta r$. If δr is the distance for which the α kinetic energy is equal to the potential energy, then

$$(8) \quad \delta r \sim \left(\frac{E_0 r_0^3}{1.5 n q^2} \right)^{1/2}$$

where $E_0 = 3.5 \text{ MeV} = 6 \cdot 10^{-6} \text{ erg}$

$$q = 2e$$

$$n = \text{number of } \alpha\text{'s emitted.}$$

The number of α 's outside the plasma, n_1 is

$$(9) \quad n_1 \sim 3n\delta r/r_0 = \left(\frac{6nE_0 r_0}{q^2} \right)^{1/2}$$

For breakeven at 10^5 joules, $n \sim 3 \cdot 10^{17}$. If $r_0 \sim .2$ cm, $\delta r \sim 3 \cdot 10^{-4}$ cm, $B \sim 10^7$, $E_r \sim 10^7$, $\Delta E_{\text{tot}} \sim n_1 e E_r \delta r \sim 3 \cdot 10^2 E_r$ ergs $\sim 3 \cdot 10^{12}$ joules per half cycle, or $\sim 2 \cdot 10^{13}$ watts ($\lambda=1$). This is about 0.1% of the incident flux.

Thus it seems unlikely that the effect of the space charge layer will substantially increase the absorption rate at densities of interest.

Conclusions

The results of these calculations indicate that the MAESTRO project seems to be a quite viable method for the production of fusion power. The major problems seem to be production and transport of the very high levels of microwave energy needed, and maintaining a high Q cavity while containing intense fields. More calculations need to be made of the burn process. The "nuclear maser" idea is still speculative and probably requires a new, 2d code to solve it. It would also be very valuable to study 2d calculations of the absorption process and the burn reaction to learn if any substantial changes will occur to the 1d results.

KRE:lk

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Figure Captions

Results shown for the following parameters:

$$\lambda = 1 \text{ cm}$$

$$n = 1.1 \cdot 10^{21} \text{ cm}^{-3} (10^8 \text{ critical})$$

$$\omega_{pe}/\omega_{em} = 10^4$$

$$\lambda_{\text{Debye}} = 1.6 \cdot 10^{-6} \text{ cm}$$

$$T = 5 \text{ keV}$$

$$P_{\text{incident}} = 5 \cdot 10^{16} \text{ watts/cm}^2$$

$$B_{\text{peak}} = 2 \cdot 10^7 \text{ gauss}$$

$$m_i/m_e = 3672 \text{ (deuteron)}$$

$$n_e = n_i = 3000 \text{ (simulation particles)}$$

$$L/\lambda_D = 318 \text{ (} L = 5 \cdot 10^{-4} \text{ cm = simulation thickness)}$$

$$\Delta x = 3 \cdot 10^{-6} \text{ cm} = 1.9 \lambda_D$$

$$N/\Delta x = 9.4 \text{ (electrons/cell)}$$

$$\omega_{pe} \Delta t = .375$$

$$t_{\text{max}} = 2 \text{ r.f. cycles}$$

(required about 4.6 hours computer time on CDC 7600)

Figure 1. Charge separation field (E_x) and transverse microwave field (B_z) as functions of time, showing field reversal as B_z goes through zero.

Figure 2. Electron phase space V_y/C versus x showing electron drift in the crossed E_x and B_z fields, at $t = 0.75$ cycles.

Figure 3. (a) B_z versus x at $t = 0.75$.

(b) E_x versus x at $t = 0.75$. The plot has been smoothed. The oscillations probably represent actual plasma oscillations rather than numerical noise.

- Figure 4. (a) Energy absorbed versus time.
(b) Energy absorbed/Energy incident.
(c) Energy versus time for each species. Note that the ions absorb almost all the energy. (The energy drops when ions are lost through the right hand boundary.)

Figure 5. Ion phase space V_x/C versus x . ($t = .75$) Notice the well-defined pulse of ions moving inward.

Figure 6. Ion velocity distribution at $t = .75$. The accelerated pulse is roughly Maxwellian and has an average energy of about 50 keV.

FIGURE 1

LAWRENCE LIVERMORE LABORATORY 17:08:505 02/13/79 13:18:485 02/14/79
 TE (KEV) = 5.00 TE/TI = 1.0 LASER = 5.00E+16W/CM**2 DEN** TO * IN 0.0 *0
 TIME = 0.75 LASER CYCLES ELECTRONS X-VY INITIAL TE = 5.0 KEV
 LASER POWER=5.0E+16 WATTS/CM**2 MI/ME = 3672.
 IYI**2/P2*HDE*NELECTRONS = 3.051 KEV

0.1
 0.2
 0.3
 0.4
 0.5
 0.6
 0.7
 0.8
 0.9
 1.0
 1.1
 1.2
 1.3
 1.4
 1.5
 1.6

FIGURE 2

FIGURE 3a

FIGURE 3b

LAWRENCE LIVERMORE LABORATORY 17:08:505 02/13/79 17:26:565 02/15/79
 TE (KEV) = 5.00 TE/TI = 1.0 LASER = 5.00E+16W/CM**2 DEN** TO * IN 0.0 AD
 KEN EPPLEY BOX Y26 L-18 X24662

FIGURE 4a

LAWRENCE LIVERMORE LABORATORY 17:09:505 02/13/79 17:26:565 02/15/79
 TE(KEV)= 5.00 TE/TI= 1.0 LASER= 5.00E+16W/CM**2 DEN** TO IN 0.0 AD
 KEN EXPLEY BOX V26 L-18 X24662

FIGURE 4b

LAWRENCE LIVERMORE LABORATORY 17:08:505 02/13/79 17:26:575 02/15/79
 TE1(KEV) = 5.00 TE/TI = 1.0 LASER = 5.00E+16M/CH*2 DEN = . TO . IN 0.0 10
 KEN EPPLBY BOX 726 L-1P XE4662

ADD X,Y ENERGIES OF SPECIES TO GET TEMPERATURES

FIGURE 4c

LAWRENCE LIVERMORE LABORATORY 17:08:505 02/13/79 13:18:505 02/14/79
 TE(KEV) = 5.00 TE/TI = 1.0 LASER = 5.00E+16W/CM**2 DEN=* TO * IN 0.0 *0
 KEN EPPLLEY BOX V26 L-18 X24662

THE = 0.75 LASER CYCLES LONG X-VX INITIAL TE = 5.0 KEV
 LASER POWER=5.0E+16 WATTS/CM**2 MI/NE = 3672.
 IPX**2/(2.*NIDE*NIONS)=13.618 KEV

FIGURE 5

LAURENCE LIVERMORE LABORATORY 17:08:505 02/13/79 13:18:515 02/14/79
 MPX**2/(2.*HDE*NION5)=13.618 KEV
 TE(KEV)= 5.00 TE/TI= 1.0 LASER= 5.00E+16A/CM**2 DENS*. TO *. IN 0.0 A0
 KEN EMPLEY BOX V25 L-1B XPM662

TIME = 0.75 LASER CYCLES ION FIVX/C) INTEGRATED OVER X SPACE

FIGURE 6