The behavior near resonance is modified due to cyclotron damping, but otherwise the exact solutions follow the approximate solutions closely.

For heating of plasmas using the fast-wave cavity resonance at the first harmonic of the ion-cyclotron frequency, we find for fusion plasmas that the cavity modes will probably not be resolvable and that mode conversion and tunneling will modify greatly the cavity-mode structure. These effects should be small in present machines unless high-density operation is investigated, but large in fusion devices. We find both effects to have exactly the same parameter dependence, so that if the modes are resolvable, tunneling will presumably be highly efficient and the usual cavity-mode structure will be observed, whereas if the modes begin to overlap, the mode structure changes, the modes become untrackable, and the antenna coupling changes.

For higher harmonics, the situation improves, so that at the second or third harmonic the modes may be resolvable because they are narrowed by a factor of the order of $(10\beta_i)$ and the tunneling distance is reduced by the same factor; the reduction factor is proportional to $(10\beta_i)^2$ for the third harmonic. It thus appears we must move to higher harmonics for cavity-resonance heating of fusion plasmas.

[1]J. Adam *et al.*, in *Proceedings of the Fifth International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Tokyo, Japan, 1974* (International Atomic Energy Agency, Vienna, Austria, 1975).

[2]D. G. Swanson, Bull. Am. Phys. Soc. 18, 1281 (1973), and 19, 734 (1974).

[3]J. Adam and H. Takahashi, Bull. Am. Phys. Soc. 19, 734 (1974).

[4]D. G. Swanson, to be published.

[5]F. W. Perkins *et al.*, in *Proceedings of the Third International Symposium on Toroidal Plasma Confinement, Garching, Germany, 1973* (Max-Planck-Institut für Plasmaphysik, Garching, Germany, 1973); and F. W. Perkins, in *Proceedings of the Symposium on Plasma Heating and Injection, Varenna, Italy, 1972* (Editrice Compositori, Bologna, 1973).

[6]D. G. Swanson, Phys. Fluids 10, 428 (1967).

[7]L. Hedrick, B. D. Fried, and J. W. McCune, Bull. Am. Phys. Soc. 13, 310 (1968).

[8]G. L. Kulcinski and R. W. Conn, in *Proceedings of the First Topical Meeting on the Technology of Controlled Nuclear Fusion, San Diego, California, 1974,* edited by G. R. Hopkins and B. Yalof, CONF-740 402 (U.S. Atomic Energy Commission, Oak Ridge, Tenn., 1974), Vol. 1, p. 38.

[9]E. Bertolini *et al.*, in *Proceedings of the First Topical Meeting on the Technology of Controlled Nuclear Fusion, San Diego, California, 1974,* edited by G. R. Hopkins and B. Yalof, CONF-740 402 (U.S. Atomic Energy Commission, Oak Ridge, Tenn., 1974), Vol. 1, p. 21.

[10]R. R. Weynants, Phys. Rev. Lett. 33, 78 (1974).

Preheat Effects on Microballoon Laser-Fusion Implosions[*]

G. S. Fraley and R. J. Mason
Theoretical Division, Los Alamos Scientific Laboratory, Los Alamos, New Mexico 87544
(Received 2 June 1975)

Nonequilibrium hydro-burn simulations of early laser-driven-compression experiments indicate that low-energy photons from the vicinity of the ablation surface are preheating the microballoon pushers, thereby severely limiting the compression achieved (similar degradation may result from 1–4% energy deposition by superthermal electrons). This implies an 8- to 27-fold increase in the energy requirements for breakeven, unless radiative preheat can be drastically reduced by, say, the use of composite ablator pushers.

Theory[1] predicts that shells can be compressed to many times solid density by laser-driven ablative implosions. In an ablative implosion only the exterior of the shell is heated. The shell is shocked, compressed, and driven towards the origin by the reaction force to material streaming off. DT fuel inside the shell can thus be brought to densities and temperatures favoring thermonuclear burn.[2] When a low level of preheat is introduced, the shocks are weakened, the back-pressure is increased, and the degree of shell and fuel convergence is reduced. Under extreme preheat, the entire shell is raised to high temperatures and pressures before any shocks can cross. It simply expands at both its surfaces, compressing the fuel within, but only to minimal densities.

Laser-fusion experiments have been reported[3-5] which have produced x-ray pinhole pictures as proof of compression, and from 10^4 to 10^7 neutrons.[3,5] In this paper we report the results of calculations which indicate that the phenomenology in these experiments is dominated by radiative and, perhaps, superthermal-electron preheat. This suggests that, for breakeven with simple scaled versions of the reported targets and pulse shapes, energies well in excess of 10 kJ may be required.

At least three mechanisms are available to heat the pusher shell: (a) classical electron thermal conduction, (b) radiative redeposition, and (c) superthermal-electron transport. The classical conduction is always present, modified, of course, by flux limitation[6] as influenced by anomalous effects from ion and magnetic field fluctuations. If excessive energy is deposited in the thermal electrons during an implosion, i.e., typically more than 1 J/ng, then the classical conduction wave will "burn through" the shell, leading to the expanding pusher behavior. This condition is readily avoided, however, with proper pulse shaping.

Radiative preheat arises from the reabsorption of bremsstrahlung, recombination- and line-radiation photons produced near the ablation surface where the plasma electrons are typically from 300 to 500 eV. The thickness of the microballoon walls is comparable to the range of such low-energy photons so that a portion of this radiation is redeposited deep in the shells with significant consequence, as we shall demonstrate.

Superthermal electrons are generated when various thresholds for absorptive instability are exceeded. Resonant absorption,[7] for example, readily furnishes 100-keV electrons at 10^{16}-W/cm^2 1.06-μm light intensities. At the lower ~10^{15}-W/cm^2 intensities appropriate to the experiments,[3-5] the energy deposited by superthermals still remains an uncertainty.

Our calculations have been done with the nonequilibrium and 3-T codes described in Ref. 2. Free-bound and line-radiation effects are included in the Monte Carlo, frequency-group nonequilibrium calculations.[8] The nonequilibrium code has been run with the radiation "on" and "off" (no photons generated) to probe the radiative preheat dependency. The 3-T calculations diffuse bremsstrahlung in an assumed Planckian by Rosseland mean opacities; they agree generally with the multigroup radiation-off predictions. In the two codes it is assumed that the superthermal electrons deposit their energy in proportion to the local mass at a constant rate over the length of the pulse. This procedure provides an approximate picture of the effects of long-range energy transport by the electrons.

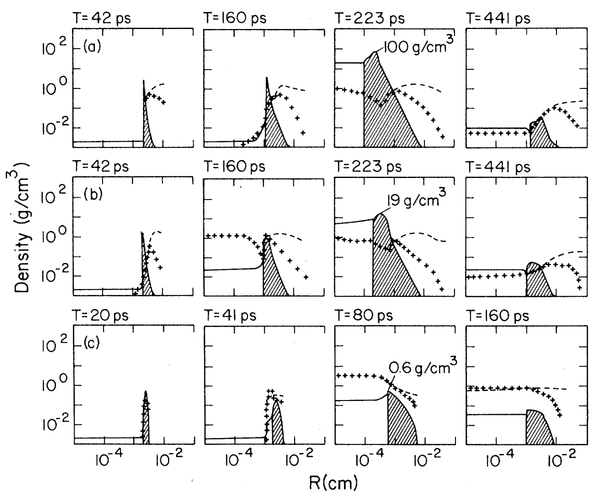

FIG. 1. Implosion of a 52-μm DT-filled microballoon: (a) radiation off and no superthermals—pure ablative implosion; (b) radiation on and no superthermals—mixed-mode implosion; and (c) 100% deposition by superthermals and radiation on—pure expanding pusher. The solid line is ρ (in grams per cubic centimeter), the pluses represent T_i, and the dashes represent T_e, both in kiloelectron volts. Glass is cross-hatched.

Figure 1 characterizes the general implosion phenomenology that we calculate with the nonequilibrium code for a typical microballoon target shot by KMS Fusion under its contract with the U. S. Energy Research and Development Administration[9] (ERDA) (shot 110A). The target diameter was 52 μm and the wall thickness was 1.1 μm. The DT (18–13 mix) was at 10 atm. The pulse was square, nominally 240 psec long, and it delivered 4.9 J to the microballoon. Experimentally, 2.5×10^5 neutrons were obtained from this target. Specifics of its calculated performance are recorded in Table I.

The top four frames of Fig. 1 (part a) are for the radiation off and no superthermals. The implosion is purely ablative. The tamper goes to a maximum density $\rho_t = 100$ g/cm^3, when the fuel is at an average density $\rho_f = 21$ g/cm^3. The maximum compression of the system, as measured by $\langle \rho R\rangle_{\rm tot} = \int \rho_t\, dR + \int \rho_f\, dR$, is 1.5×10^{-2} g/cm^2. The next sequence (b) is for radiation on and no superthermals. The preheat drops the maximum tamper density to 19 g/cm^3 and $\langle \rho R\rangle_{\rm tot}$ to 7.0×10^{-3} g/cm^3. The fuel $\langle \rho R\rangle_f = \int \rho_f\, dR$ is also down by about a factor of 2. The predicted number of neutrons drops from 5.4×10^6 to 5.0×10^5. If we assume that 4% of the energy was delivered in superthermals, the implosion is similar to (b),

TABLE I. Performance of the 52-μm microballoon; radiative and superthermal preheat.

Property	No rad no sup	Rad no sup	Rad 4% sup	Rad 100% sup
T_{if}, T_{ef} (keV)	1.0, 0.9	0.7, 0.55	0.7, 0.65	3.7, 1.2
ρ_f (g/cm^3)	21.0	7.0	1.6	0.2
ρ_t (g/cm^3)	100.0	19.0	3.0	0.5
$\langle \rho R \rangle_{tot}$ (g/cm^2)	1.5×10^{-2}	7.0×10^{-3}	2.5×10^{-3}	3.0×10^{-4}
$\langle \rho R \rangle_f$ (g/cm^2)	2.5×10^{-3}	1.2×10^{-3}	4.5×10^{-4}	1.7×10^{-4}
Neutrons	5.4×10^6	5.0×10^5	7.0×10^4	8.2×10^7

but ρ_t drops further to 3 g/cm^3. Finally, with 100% of the deposition through superthermals, we get (c). The tamper drops from its solid value (2.2 g/cm^3) and recompresses at maximum convergence to only 0.6 g/cm^3. The expanding tamper shock heats the fuel to 3.7 keV, so that the predicted neutron output rises to 8.2×10^7. The $\langle \rho R \rangle_f$ obtained in this implosion mode is so low, however, that superthermal ion loss[10] should substantially lower the actual yield.

Thus, our codes indicate that, in a typical current microballoon experiment, radiative preheat is responsible for a fivefold reduction in tamper density and a twofold reduction in $\langle \rho R \rangle_{tot}$—below the values anticipated for a purely ablative implosion. Additional reductions of nearly equal magnitude can derive from a low level of energy deposition by long-range superthermal electrons.

Figure 2 plots the 3-T-model's predictions for the 52-μm-diam microballoon as a function of the fraction of energy in superthermals, $f_s = \epsilon_s/(\epsilon_s + \epsilon_{th})$; ϵ_{th} is the classical energy deposition in thermal electrons. With 0.1% superthermals we recover $\rho_t = 100$ g/cm^3 and $\langle \rho R \rangle_{tot} = 1.5\times10^{-2}$ g/cm^2 (the 3-T code overlooks the line- and recombination-radiation preheat effects). Only 1% of the energy deposition by superthermals is required for a threefold reduction in the peak tamper density.

Energy needs scale roughly as the mass m of a given aspect-ratio shell. Comparable shell temperatures and collapse velocities are thereby achieved, the shell radii and pulse length then scale as $m^{1/3}$, and the laser intensity at the critical surface becomes mass independent. The 52-μm balloon has a mass of 21 ng. Scaling it up to a 7.5-μg shell requires 1.75 kJ delivered in a 1.7-nsec (square) pulse. The bigger shell has a 7.1-μm wall thickness. With the radiation off this scaled pellet compresses to $\langle \rho R \rangle_{tot} = 0.15$ g/cm^2; with it on $\langle \rho R \rangle_{tot} = 0.058$. This is a 2.6-fold reduction despite the thicker wall. Scaling further to 428 μg requires 100 kJ of deposition over 6.5 nsec. Still, $\langle \rho R \rangle_{tot}$ drops from 0.62 to 0.34 g/cm^2 and ρ_t goes from 190 to 50 g/cm^3, when the multigroup transport is introduced.

The preheat degradation persists beyond the 100-kJ range. We find, however, that replacement of the outer 40% of the glass by a low-Z ablator material (Be) can improve the compression substantially (for the 100-kJ pellet $\rho_t = 160$ g/cm^3, $\langle \rho R \rangle_{tot} = 0.52$) by minimizing the output of line and recombination radiation that leads to

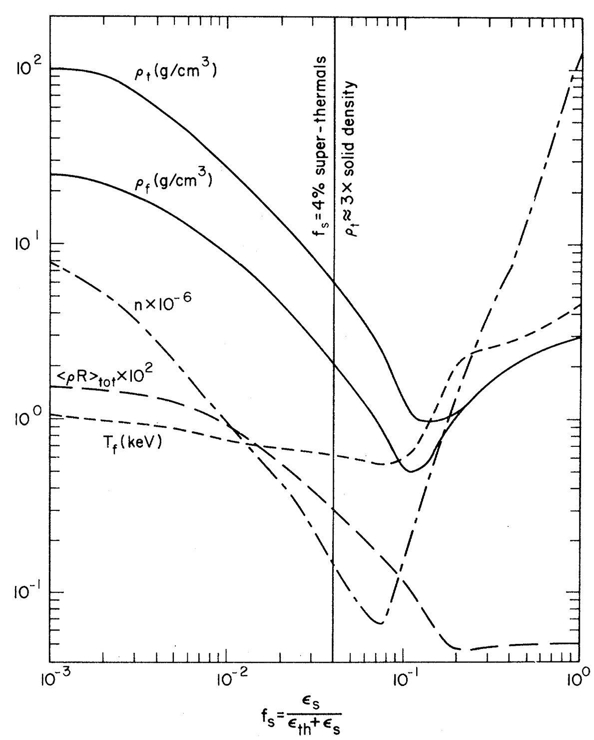

FIG. 2. Implosion characteristics of the 52-μm target as a function of the fractional energy deposition by superthermals f_s.

preheat.

The effective use of pulse shaping and cryogenics will be needed to achieve breakeven at minimal input energies. The DT must be frozen uniformly to the inside of the microballoons, and the shell must resist instabilities under time-tailored laser pulses. Our 3-T calculations indicate[11] that breakeven should be possible (ignoring preheat) with 3.5 kJ delivered in a $\dot{\epsilon} \sim t^3$ pulse over 1.4 nsec to a 6.7-μg homogeneous glass microballoon, 470 μm in diameter, containing a 270-ng DT-ice liner. A peak $\langle \rho R \rangle_{tot}$ of 0.64 g/cm^2 is calculated for this target. If radiative preheat is assumed to cause no greater difficulty than to degrade $\langle \rho R \rangle_{tot}$ by the twofold to threefold factor discussed, then, since $m \sim \langle \rho R \rangle^3$ with fixed shell density, to recover the lost compression we need only scale the pellet mass by a factor of 8 to 27. Breakeven with no low-Z ablator then lies between 28 and 94 kJ. A complication, however, is that in the KMS Fusion–ERDA experiments it appeared that ablation-front, Taylor-like instabilities prohibited even linear ramp pulse shaping. This has been attributed to the low transverse thermal conductivity of the glass.[9]

A multigroup photonics treatment is clearly essential for the proper modeling of current and forseeable laser-implosion experiments. We have shown that the breakeven energy needs of microballoon targets will be significantly higher than the optimistic predictions of earlier 3-T calculations, unless radiative preheat is markedly reduced. To this end we suggest that an outer fraction of the pusher mass should be converted to low-Z material, e.g., beryllium, to minimize the generation of radiation. This may also stabilize the ablation surface, by enhancing transverse conduction, thus permitting effective pulse shaping. The retention of an inner high-Z portion of the pusher has advantages, structurally, hydrodynamically,[11] and as a superthermal-electron shield.[12] However, for the suppression of flow instabilities, it may be necessary to make the entire pusher out of low-Z material.

Added note.—An analogous pusher-preheat problem exists for electron-beam fusion targets.[13] This also leads to larger energy requirements for breakeven, although the mechanism for photon production is the direct deposition of relativistic electrons.

*Work performed under the auspices of the U. S. Energy Research and Development Administration.

[1]J. Nuckolls, L. Wood, A. Theissen, and G. Zimmermann, Nature (London) 239, 139 (1972); J. S. Clarke, H. N. Fisher, and R. J. Mason, Phys. Rev. Lett. 30, 89, 249 (1973); K. Brueckner, IEEE Trans. Plasma Sci. 13, 1 (1973).

[2]G. S. Fraley, E. J Linnebur, R. J. Mason, and R. L. Morse, Phys. Fluids 17, 474 (1974); R. J. Mason and R. L. Morse, Phys. Fluids 18, 814 (1975).

[3]G. Charatis *et al.*, in *Proceedings of the Fifth International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Tokyo, Japan, 1974* (International Atomic Energy Agency, Vienna, Austria, 1975); P. M. Cambell, G. Charatis, and G. Montry, Phys. Rev. Lett. 34, 74 (1975).

[4]G. McCall and R. L. Morse, Laser Focus 10, 40 (1974).

[5]G. H. McCall, R. P. Godwin, and D. V. Giovanelli, in Proceedings of the IEEE International Conference on Plasma Science, Ann Arbor, Michigan, 14–16 May 1975 (to be published), 4A1; J. F. Holzrichter, H. G. Ahlstrom, E. Storm, and J. Swain, *ibid.*, 4A7.

[6]R. C. Malone, R. L. McCrory, and R. L. Morse, Phys. Rev. Lett. 34, 721 (1975).

[7]D. W. Forslund, J. M. Kindel, K. Lee, E. Lindman, and R. L. Morse, Phys. Rev. A 11, 679 (1975).

[8]G. S. Fraley, LASL Report No. LA-4592, 1971 (unpublished).

[9]KMS Fusion, Inc., Ann Arbor, Michigan, Report No. U323, 1975 (unpublished).

[10]D B. Henderson, Phys. Rev. Lett. 33, 1142 (1974).

[11]R. J. Mason, to be published.

[12]R. L. Morse and C. W. Nielson, Phys. Fluids 16, 909 (1973), see p. 912.

[13]M. J. Clauser, Phys. Rev. Lett. 34, 570 (1975).