High-Density Effects on Thermonuclear Ignition for Inertially Confined Fusion

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Alpha particles (3.5 MeV) from the deuterium-tritium reaction have been calculated to reflect from a high-Z, Fermi-degenerate shell surrounding the fuel of inertial fusion targets. This leads to a reduction in the minimum fuel ρR (density-radius product) needed to sustain a thermonuclear burn, and possibly to a reduction of the minimum input energy required to achieve thermonuclear ignition.

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Properties of the high-density matter anticipated for inertially confined fusion have been exploited to reduce the minimum ρR (density-radius product) needed for thermonuclear ignition. The parameter ρR (at a fixed temperature) determines the fractional energy deposition in the fuel by 3.5-MeV α particles produced in the DT (deuterium-tritium) reaction, i.e., using $dE/dx \propto \rho$, we have $\Delta E \propto \rho R$. Such deposition is necessary for sustaining the thermonuclear burn by compensating for radiative energy losses. Values of ρR larger than ~ 0.3 g/cm^2 are required.[1] The new result discussed here is that these α particles can be reflected by a high-Z, Fermi-degenerate shell (tamper) surrounding the fuel at ignition conditions, and thus increase the amount of energy deposition in the fuel. Consequently, the minimum fuel ρR and possibly the minimum input energy needed for thermonuclear ignition of tamped targets can be reduced.

The amount of energy reflection is determined by competition between energy loss to electrons and Coulomb scattering by ions in the tamper. At the onset of thermonuclear burn, the tamper should be Fermi degenerate for minimum ignition requirements. Since only electrons near the Fermi surface can contribute to particle slowing down, the energy loss will be less than expected classically, and the relative amount of scattering will be enhanced.

More quantitatively, energy reflection will depend on the ratio of mean free paths for 90° scattering λ_R and for energy loss λ_E. The scattering term is dominated by small-angle collisions with ions and is given by[2]

$$1/\lambda_R = Zn_e \pi (ze^2/E)^2 \ln(b_{\max}/b_{\min}), \tag{1}$$

where E and z are the α-particle energy and charge; Z and n_e are the nuclear charge of plasma ions and the electron density; $b_{\min}$ is the minimum impact parameter zZe^2/E, and $b_{\max}$ is the largest impact parameter which should be the ion-sphere radius $(\frac{4}{3}\pi n_i)^{-1/3}$ under these conditions. For energy loss, the mean free path was approximated by treating all electrons, both bound and free as a uniform, semidegenerate electron gas. Using $\lambda_E = E/(\partial E/\partial x)$, we have[3]

$$1/\lambda_E = n_e T^{-3/2} E^{-1/2} z^2 e^4 (\pi m/M)^{1/2} \tfrac{8}{3} \times \left[\frac{\sqrt{\pi}}{2F_{1/2}(\eta)} \frac{1}{\exp(-\eta)+1}\right] \ln\Lambda_{\mathrm{RPA}}. \tag{2}$$

Here m and M are the electron and α-particle masses, T the electron temperature, η the degeneracy parameter for the electron gas, and $F_{1/2}(\eta)$ is the usual Fermi-Dirac integral. The Coulomb logarithm is approximately

$$\ln\Lambda_{\mathrm{RPA}} \equiv \tfrac{1}{2}[\ln(1+\Lambda^2) - 1],$$

where

$$\Lambda \approx 12 m T \lambda_{\mathrm{D}}^2 [0.37 + (T_{\mathrm{F}}/T)^2]^{1/2}/\hbar^2,$$

and where λ_{D} is the Debye length $(T/4\pi n_e e^2)$ and T_{F} is the Fermi temperature $(\frac{2}{3}\eta T)$. The quantity in brackets in Eq. (2) is 1 in the classical limit and becomes $T^{3/2}/\eta_e$ at high electron degeneracy. Hence, for highly degenerate matter Eq. (2) is independent of density and temperature (except for $\ln\Lambda$), and the ratio of mean free paths varies as

$$\lambda_R/\lambda_E \propto 1/\eta_e. \tag{3}$$

As a result, the ratio will be small at sufficiently high density, implying that α-particle scattering (reflection) will dominate energy loss.

To find the density needed for reflection, the following test problem was solved. A deuterium-tritium sphere was set at $T = 10$ keV, $n_e = 5\times10^{26}$ cm^3 and $\rho R = 0.3$ g/cm^2. This was surrounded by a gold shell ($Z = 79$) at 1 keV whose density was varied. (Such target configurations were discussed in Ref. 1). To determine how the energy reflection depends on tamper density, the Fokker-Planck equation was solved for the α-particle transport. The P_1 approximation[4] was used, yielding the following equations:

$$\left(\frac{\partial}{\partial r}+\frac{2}{r}\right)J=\frac{\partial}{\partial E}\left(\frac{\varphi E}{\lambda_E}\right),$$

$$\frac{1}{3}\frac{\partial}{\partial r}\varphi=-\frac{J}{\lambda_R}\left(\frac{JE}{\lambda_E}\right).$$

Here $\varphi = vn_\alpha$ and J is the α-particle current per unit area. Often the term $\partial J/\partial E$ is neglected.[4] It was kept in the present calculation to preserve the direction of particles as they lose energy. For an untamped DT sphere, the P_1 approximation gave energy deposition results within 2% of a more exact calculation which transported the α particles along straight-line paths through the fuel. For the tamped target, a flux limiter was used at the interface to prevent transport faster than the free-streaming limit.[4] This procedure correctly produces the two limits of diffusion and free streaming in the tamper, and should be sufficiently accurate to demonstrate the conditions needed to reflect α particles back into the fuel.

Results of this calculation are shown in Fig. 1. Plotted is the fraction of all the α-particle energy (produced throughout the fuel) which is deposited back into the fuel. The effect of reflection becomes apparent as the electron density in the gold shell exceeds 10^{27} cm^{-3}. At 5×10^{27} e/cm^3, energy deposition in the fuel has increased by 25%. The maximum electron density in gold permitted by pressure equilibration with the fuel in this example is about 5×10^{27} cm^{-3} from the Thomas-Fermi equation of state.

An important question is whether the α particles will be reflected in a time which is short compared to the thermonuclear burn time. This can be estimated as follows: The time for energy reflection τ_R must be shorter than the energy-loss time $\tau_E = \int dE(\partial E/\partial t)^{-1}$. By the definition of λ_E above, the slow-down rate dE/dt is vE/λ_E. Evaluating Eq. (2) for tamper conditions $n_e = 5\times10^{27}$ cm^{-3} and $T = 1$ keV, yields $\partial E/\partial t = -E\times5\times10^{13}$ sec^{-1} with the result that the time for losing 99% of the α-particle energy is 10^{-13} sec. Since the burn time[5] is about 5×10^{-12} sec, reflection will be effecitvely instantaneous.

The size of the gold tamper needed for reflection is shown in Fig. 2. For these results, the tamper electron density was set at 5×10^{27} cm^{-3}, and its ρR was varied. (Fuel conditions remained the same as in Fig. 1). As seen, almost all the reflection occurs with a tamper ρR of 0.1 g/cm^2. This is much smaller than the values of ρR (~1g/cm^2) needed for energy breakeven.[1] (A tamper would be required, independent of α-particle reflection. Its ρR here determines the confinement

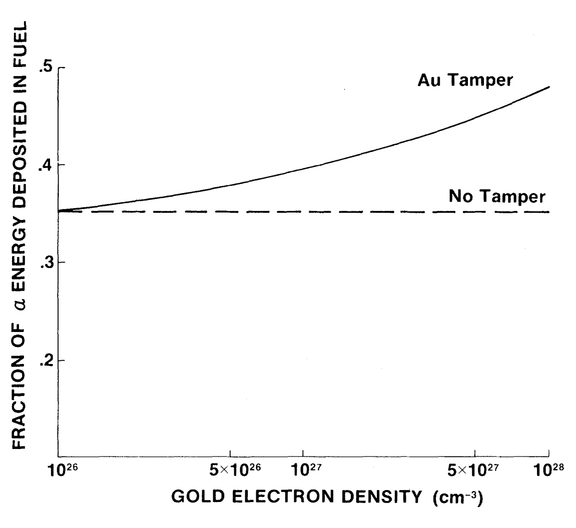

FIG. 1. Fraction of α-particle energy deposited in the fuel as a function of density in the gold tamper. (Fuel: $T = 10$ keV, $n_e = 5\times10^{26}$ cm^{-3}, $\rho R = 0.3$ g/cm^2. Tamper: $T = 1$ keV).

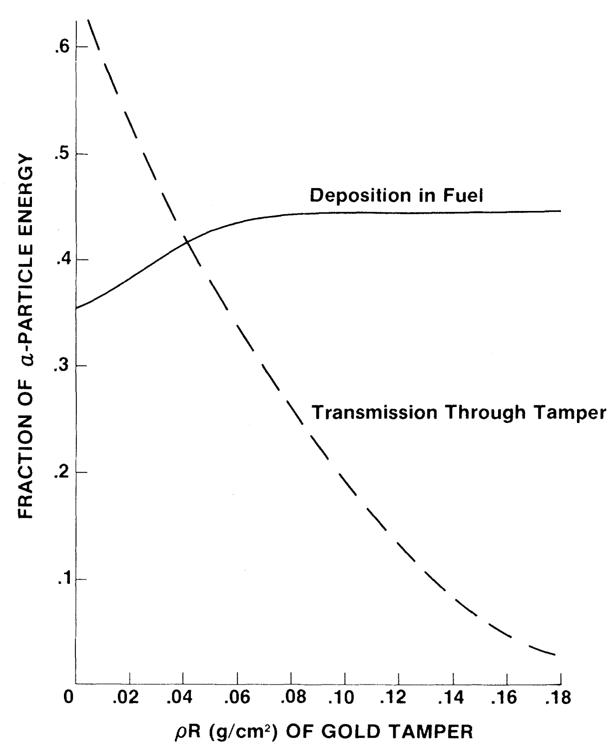

FIG. 2. Fraction of α-particle energy deposited in the fuel and transmitted through the tamper as a function of ρR in the tamper ($T = 1$ keV, $n_e = 5\times10^{27}$ cm^{-3}).

time of the fuel and consequently the time for thermonuclear burn).

The fraction of α-particle energy transmitted through the tamper is also shown in Fig. 2. Such transmission could be important for double-shell target designs which require the thermonuclear burn to propagate from one DT-fuel region to another, across a high-Z shell. (The fraction of energy in Fig. 2 which was not deposited or transmitted was absorbed by the tamper). If electron degeneracy had not been considered, then, for these conditions, there would have been essentially no reflection and no transmission. All α particles escaping the fuel would have deposited their energy in the tamper.

As a final point, the reduction in ρR needed for thermonuclear ignition is shown in Fig. 3. Again, the gold tamper was set with $n_e = 5\times10^{27}$ cm^{-3}, but now the ρR of the fuel was changed. The results show that if the bare fuel ignites at $\rho R = 0.3$ g/cm^2, then, for the same fractional energy deposition, it should ignite at $\rho R = 0.22$ g/cm^2 with the gold tamper—a reduction of 25% in ρR. This reduction represents a lower bound, for if the tamper heats up, then reflection will begin to increase classically as $T^{3/2}$. Similarly, there will

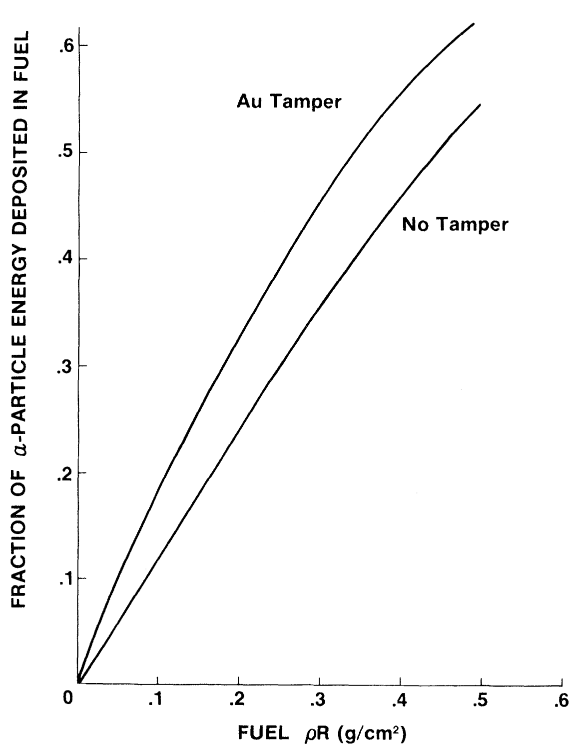

FIG. 3. Fraction of α-particle energy deposited in the fuel for tamped and untamped pellets. (Tamper conditions $T = 1$ keV, $n_e = 5\times10^{27}$ cm^{-3}).

be an increase in transmission through the tamper. Although the Fermi-degenerate state represents a lower limit on reflection, it still gives a result considerably larger than expected classically at these conditions.

The results discussed here demonstrate that in principle, mega-electron-volt α-particle reflection can occur at conditions anticipated for inertial fusion. This effect would not have been seen in past calculations that included the possibility of reflection, but not the contribution of electron degeneracy. With no degeneracy corrections, the results would be the same as the "no tamper" curves in Figs. 1 and 3. Of course, the model used here for the compressed target was highly simplified. A complete implosion calculation would not show a sharp discontinuity at the temper-fuel interface but would have time-varying temperature and density gradients. Thus, the exact contribution from α-particle reflection will depend on details of the particular target design.

For reflection to become important, the above estimates require electron densities in the tamper greater than 10^{27} cm^{-3}. (Neglected effects such as large-angle scattering and the binding energy of gold electrons will reduce this estimate.) In principle, such densities can be achieved by laser compression. The fuel density used was the optimum suggested in Ref. 6. In practice, however, the compression will be limited by preheat from superthermal electrons, hydrodynamic instability, etc., so that present-day estimates place the maximum tamper electron density at less than 10^{27} cm^{-3}. However, suprathermal electrons are only a problem for laser fusion and not for ion beam fusion. Further, suprathermal-electron preheat in laser fusion can possibly be eliminated (or greatly reduced) by use of shorter-wavelength lasers. (An active effort is aimed at tripling the frequency of Nd-glass lasers). Regarding hydrodynamic instabilities during the implosion, their magnitude is still an open question that awaits the development of more accurate computer codes. At present, high-density compressions (fuel density $\sim 10^4\times$ liquid DT density) cannot be ruled out.

If tamper densities of $\sim 5\times10^{27}$ e/cm^3 can be achieved, then the significance of the 25% reduction obtained for fuel ρR is that it corresponds to almost a 50% reduction in mass of the compressed target. [The mass will vary as $(\rho R)^2$ for fixed ρ since typically most of the mass M is concentrated in the tamper, i.e., $M \propto (\rho R)^2(\rho_T\Delta R)/$

ρ^2, where ρ_T and ΔR are the density and thickness of the tamper]. Even though the shell should be Fermi degenerate (to minimize the energy of compression) no additional energy penalty is paid to reach such densities because the increased degeneracy energy from compression is well balanced by the decrease in material needed to attain a specific $\rho_T \Delta R$. (It is $\rho_T \Delta R$ of the tamper rather than its mass which determines the energy gain of the target[1]). Since in many target designs, the input energy varies as the compressed mass, α-particle reflection could lead to a substantial reduction in the driver energy needed to achieve thermonuclear ignition.

These arguments apply mainly to the small targets that are designed to demonstrate the feasibility of inertially confined fusion by reaching near-breakeven conditions, and not to high-gain, reactor-grade designs. It should be emphasized that α-particle reflection is only one of many mechanisms that will affect ignition, and which need further study. Others presently under investigation include: (1) reduction in thermal conduction to the tamper by intentionally seeding the fuel with high-Z ions, (2) large contamination of the fuel by high-Z tamper ions due to hydrodynamic instabilities, and (3) preheat of the fuel resulting from an incomplete understanding of energy transport in the design of the target. Of these, only high-Z seeding and α-particle reflection can relax the constraints needed for thermonuclear ignition.

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Convective Plasma Loss Caused by an Ion-Cyclotron rf Field and Its Elimination by Mode Control

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This paper reports experimental evidence that a convective loss occurs in a low-density plasma subjected to the ion-cyclotron rf field of $m = \pm 1$ azimuthal mode which is conventionally employed. By utilization of an $m = +1$ circularly polarized rf field produced with a multiphase rf source, the convective plasma loss is eliminated, which results in an improvement in heating efficiency by more than 70%.

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Radio frequency heating has now been recognized as one of the most promising methods for direct heating of ions in a fusion plasma. In conjunction with heating, however, there has been observed anomalous loss of the plasma due to rf-enhanced turbulence.[1,2] Recently, Wong and Bellan[3] reported the enhancement of drift waves by electric fields near the lower hybrid frequency, which results in modification of density profile. The effect of ponderomotive force also becomes important when the excursion velocity of particles in rf fields exceeds the thermal velocity. It is thus desirable not only to achieve higher heating efficiency but to reduce enhanced plasma loss during rf heating.

In this Letter, we wish to present the experimental evidence that an rf field of $m = \pm 1$ azimuthal mode, which is conventionally used in ion-cyclotron rf (ICRF) heating, produces convective cross-field plasma loss. By utilizing the $m = \pm 1$