Simulation of target burning and dispersal in inertial fusion

S. I. Anisimov and A. M. Oparin
Landau Institute of Theoretical Physics, Russian Academy of Sciences, 117334 Moscow, Russia
Max-Planck-Institut für Quantenoptik, D-8046 Garching, FRG

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A kinetic equation describing the interaction of the high-energy products of fusion reactions with the plasma is solved for a collisional plasma by the particle-in-cell method. This method has been used in a program which simulates the burning and dispersal of targets in inertial controlled fusion. The calculation method is illustrated.

Theoretical analysis of various approaches to inertial fusion includes calculating the energy which is released in the target by fusion reactions. Such calculations are complicated by the circumstance that the target plasma is highly nonuniform and varies rapidly in time. The mean free path of the fast charged particles produced in the fusion reactions is often comparable to the target radius, while the neutron range is usually much larger than the target. The nonlocal nature of the energy release is usually dealt with by adopting some approximation or other for the fast-particle transport equation. Examples of such calculations were published in the 1970s (e.g., Refs. 1 and 2). It was shown there that the parameters which primarily determine the extent to which the fuel is burned and the fusion yield are the quantity $\langle \rho R \rangle = \int \rho dR$ and the ion temperature T_i at the time of maximum compression. Fraley *et al.*[2] proposed a simple formula for estimating the fraction of the fuel which has burned (for the DT reaction and for a spherical target):

$$f = \langle \rho R \rangle / (\langle \rho R \rangle + 6.3). \tag{1}$$

This formula came to be adopted widely. According to Ref. 2, the range of applicability of (1) is set by the inequalities

$$\langle \rho R \rangle > 1, \quad 20 \text{ keV} < T_i < 70 \text{ keV}. \tag{2}$$

Although this region has yet to be reached in laboratory experiments, the simplicity of expression (1) has frequently led people to use it outside this region.

The calculations of the energy release by Fraley *et al.*[2] were based on an approximate description of the α-particle kinetics. They used a greatly simplified model of the interaction of a monoenergetic ion beam with a plasma.[3,4] We can get an idea of the accuracy of that approximation by looking at the results of Ref. 5, where calculations were carried out on the stopping of α particles in a homogeneous plasma by solving a kinetic equation and also by using the approximation of a monoenergetic beam. The accuracy of the approximate calculation falls off rapidly with decreasing energy of the α particles. As a result, the error in the energy transferred to ions (the interaction with

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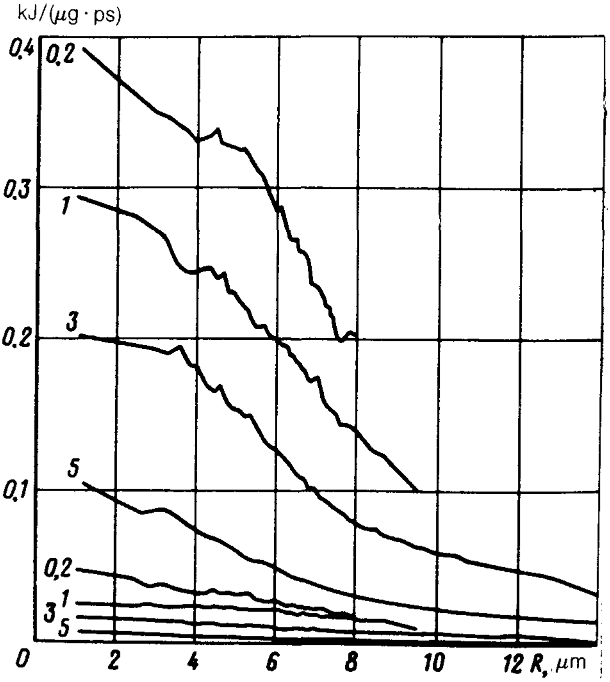

FIG. 1. Radial profiles of the total power transferred to the plasma and of the power transferred to the ions (lower curves) in the target at various times (the curve labels are the times, in picoseconds).

the ions occurs for the most part at the end of the range) can exceed 100%. Since the hydrodynamics of the target dispersal depends strongly on the distribution of energy among the plasma components, it is necessary to solve kinetic equations for the fast particles in order to find a correct picture of the dispersal.

An extremely powerful method for solving problems of this sort is the particle-in-cell method developed for a collisional plasma by Ivanov and Shvets.[6–9] This method was used in Refs. 5, 6, and 10 to study the collisional kinetics of impurity particles in a moving plasma. The method involves replacing the kinetic equation for the group of fast ions by an equivalent system of equations of motion for model finite-size particles. For a system with a Coulomb interaction, these equations have the form of Langevin equations,

$$dv_i^\alpha/dt = h_i^\alpha(v^\alpha) + g_{ik}^\alpha(v^\alpha)\xi_k(t), \tag{3}$$

where the index α specifies the particle species; $i,k = 1,2,3$; ξ_k is a white-noise vector; and $h_i(v)$ and $g_{ik}(v)$ are functions which were found in Ref. 6 for the Fokker–Planck collision term. The first term on the right side of (3) describes the stopping of particles, and the second describes a diffusion in velocity space.

In our model, the motion of the bulk of the plasma is described by hydrodynamic equations, which are solved numerically in the Lagrange representation for a spheri-

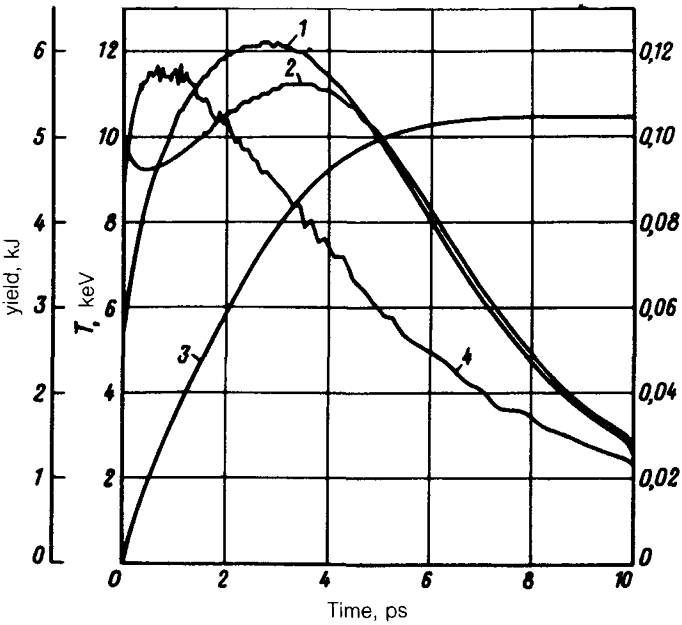

FIG. 2. Time evolution of (*1*) the electron temperature, (*2*) the ion temperature, (*3*) the total energy yield, and (*4*) the ratio of the power transferred to ions to the total power transferred to the plasma.

cally symmetric, time-varying motion. On each time step, and for each Lagrange zone in the local density and the temperature, the number of fast particles generated by reactions is determined. The interaction of these particles with the bulk of the plasma is modeled by solving a system of 3D Langevin equations for a proportionate number of finite-size particles. For each Lagrange zone, the energy and momentum transferred by the fast particles to the bulk of the plasma are calculated and then substituted into the hydrodynamic equations. The program then moves on to the next time step.

Figures 1–3 illustrate calculations by this method, for the burning and dispersal of a uniformly compressed DT sphere with a mass of 1 μg. Figure 1 shows radial profiles of the energy release at various times. These calculations were carried out for an initial density of 500 g/cm^3 and for an initial ion temperature of 10 keV. The four lower curves show the energy transferred by fast particles to the ion subsystem. Under the conditions assumed, this energy is small in comparison with the total energy transferred.

Figure 2 shows the time evolution of the electron and ion temperatures at the center of the target. The target parameters here are the same as in Fig. 1; the electron temperature is 5 keV. Since the energy released in the ion subsystem is comparatively small, the ion temperature initially decreases slightly because of the expansion of the plasma. The temperature T_i then begins to rise because of an energy transfer between ions and electrons. About 3 ps after the beginning of the dispersal, the energy release

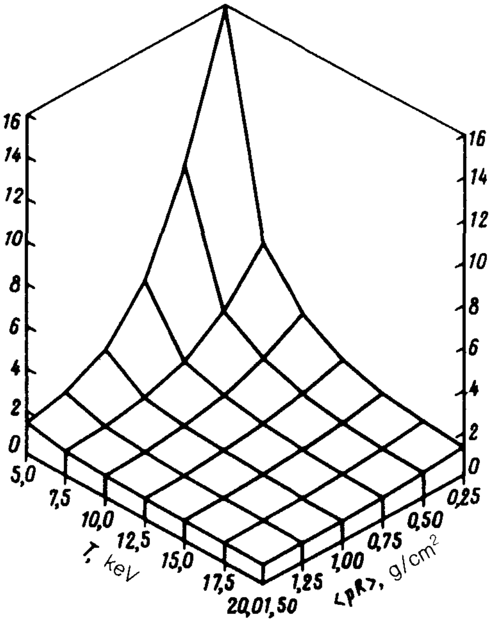

FIG. 3. Ratio of the fusion yield calculated from expression (1) to that calculated in the present study versus the parameter $\langle \rho R \rangle$ and the ion temperature.

has decreased to the point that the heating due to the reaction is offset by the cooling due to the plasma expansion. Thereafter, T_e and T_i fall off monotonically, remaining nearly equal.

Figure 2 also shows the time evolution of the total energy release in the target (curve *3*). By 4 ps the burning has essentially ended; i.e., the burn time is about half the scale time of the expansion, R/c_s, calculated from the initial values of the target parameters.

Curve *4* in Fig. 2 shows the time evolution of the ratio of the power transferred by fast particles to the plasma ions, on the one hand, to the total power transferred, on the other. The ion fraction is about 10% in the stage of rapid burning and falls off to $\simeq$ 2% during the expansion.

Figure 3 shows the ratio of the fusion yield estimated from expression (1) to the same quantity as found from the calculations by the model described above. We see that expression (1) is fairly accurate ($\simeq$ 20–30%) in the region defined by inequalities (2). At a temperature $\simeq$ 5 keV and at the value $\langle \rho R \rangle \simeq 0.5$, however, expression (1) overestimates the fusion yield by more than an order of magnitude.

The results reported above correspond to a uniformly compressed and heated target. For such targets, the rate of energy release during the fusion burn falls off monotonically with distance from the center. In the case of central (spark) ignition, the situation is quite different. The rate of energy release may reach a maximum at a certain distance from the center of the target; if so, a converging compressional wave forms, and there are a repeated collapse and a heating of the central part of the target. With conditions chosen correctly, this repeated collapse could be exploited to reduce the ignition energy.

The method described here can deal rigorously with effects of the nonlocal nature of the energy release during the fusion burning of microtargets. Calculations on the burn and dispersal of very simple uniform targets confirm that approximate expression (1) is satisfactorily accurate when conditions (2) hold. These calculations also show that expression (1) should not be used outside the intervals in (2).

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