ELSEVIER Nuclear Instruments and Methods in Physics Research A 464 (2001) 192–195

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

www.elsevier.nl/locate/nima

Magnetized cylindrical targets for heavy ion fusion☆

A.J. Kemp[a,]*, M. Basko[b], J. Meyer-ter-Vehn[a]

[a] *Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, 85748 Garching, Germany*
[b] *Institute for Theoretical and Experimental Physics, B. Cheremushkinskaya 25, 117259 Moscow, Russia*

Abstract

Ignition conditions for magnetized cylindrical fusion targets are investigated by means of one-dimensional hydrodynamic calculations. Of particular interest is the effect of a tamper surrounding the fuel at the time of stagnation. The key assumption in this paper is that the targets are magnetically insulated, i.e. electronic and ionic heat conduction as well as the diffusion of 3.5 MeV alpha particles are suppressed. It is found that magnetically insulated targets can be ignited at significantly reduced values of the fuel ρR, but, in contrast to conventional fusion targets, the value of the fuel ρR at ignition depends on the fuel mass as well as on the tamper entropy. © 2001 Elsevier Science B.V. All rights reserved.

PACS: 52.58.Hm; 52.30.Jb

Keywords: Magnetized fuel; Ignition threshold

1. Introduction

Magnetized target fusion (MTF) stands for inertial confinement fusion (ICF) with an additional magnetic field; it has been discussed mostly in the context of spherically symmetric implosions [1,2]. The recent interest in cylindrical configurations [3–5] arises in the context of heavy ion beam fusion, where a cylindrical geometry is the natural choice in view of the cylindrical geometry of the beam. A major drawback of this geometry is that, under similar constraints on symmetry and stability, cylindrical implosions are less efficient than spherical ones [4]. Hence they result in lower ρR values at stagnation.

However, this would be acceptable as long as the fuel can be ignited. Once ignition is achieved, the benefit is a significant reduction of the required driver power [5], compared to the usual ICF. A natural way to reduce energy losses out of the fuel is to apply an external magnetic field in the target, in axial or azimuthal direction. In particular, it has been shown [5] that ignition can be achieved at significantly reduced ρR values if the gyroradius of the 3.5 MeV alpha particles in the magnetic field is of the same order as the fuel radius at stagnation, always on the assumption that the fuel is sufficiently confined.

In this article, we therefore examine the role of the confinement for tamped fuel volumes at low ρR. We assume the fuel plasma to be magnetically insulated, which means that heat conduction losses as well as diffusion of alpha particles are suppressed along the radial direction. Our main

---

☆Reference No. WP.I-06.

*Corresponding author.

E-mail address: kemp@mpq.mpg.de (A.J. Kemp).

PII: S 0 1 6 8 - 9 0 0 2 (0 1) 0 0 0 3 2 - 8

conclusion is that the fuel ρR necessary for ignition depends both on the fuel mass and the tamper entropy. Below, we present the results of one-dimensional computer simulations of pre-assembled fuel–tamper configurations. Similar configurations have been widely studied for non-magnetized targets in a spherical geometry [6]. Here, we reconsider this matter for magnetized cylindrical targets to assess their potential for ICF.

2. Basic assumptions and initial configuration

Since the fuel ignition occurs approximately when the target implosion has come to a halt, one can, as a first step, investigate the basic properties of the ignition process by starting at the time of stagnation. Such a configuration consists of a hot DT fuel volume surrounded by a layer of dense tamper material to provide inertial confinement to the fuel. The tamper thickness is characterized by the ratio ξ_t of the outer tamper radius to the outer fuel boundary at stagnation. In order to account for different heating situations, we vary T_t in the range 1–100 eV. We assume that at stagnation the pressure is constant throughout the compressed core [7] and that the profiles of density and temperature are uniform in fuel and tamper layer. This simplifying assumption reproduces the main physical aspects of realistic targets at stagnation, as expected from one-dimensional simulations of cylindrical implosions.

The limit of magnetically insulated targets, as defined above, is adequate if the collision frequency of alpha particles and electrons is small compared to the cyclotron frequency of the alpha particles in the magnetic field. The energy relaxation time between alpha particles and electrons is not affected by the magnetic field [8,9]. Since there is a wide range of fuel parameters where the effects of magnetic field pressure on the plasma dynamics can be neglected, we can perform purely hydrodynamic, rather than full MHD simulations.

The fuel is described in terms of its stagnation temperature T_0, the fuel confinement parameter (ρR) and the fuel mass per unit length $m = \pi\rho R^2$. Its initial temperature T_0 can be chosen at any reasonable margin of about a factor 1.5–2 above the lower limit for the ignition temperature of ICF targets, which is at approximately 4.5 keV [10]. We have selected our working point at $T_0 = 7$ keV, but the final results of this paper are not selective to the exact number. Results will be plotted as functions of ρR and m.

3. Results

The simulations described below were performed with the Lagrangean, one-dimensional hydrodynamics code DEIRA [8], featuring three temperatures for electrons, ions and radiation, real matter equation of state and opacity tables, and thermonuclear reactions. Non-local deposition of fast alpha particles in the fuel is modeled by a diffusion equation [8,9]. In order to account for magnetic insulation of the target in the sense discussed in Section 2, the diffusion coefficient for fast alpha particles and coefficients for both ionic and electronic heat conduction are set to zero in the code.

The role of the tamper is to provide inertial confinement to the hot fuel in order to allow considerable burn-up before the configuration explodes. While growing tamper thickness ξ_t improves the inertial confinement, it also influences the efficiency of the configuration. After reaching a maximum at approximately $\xi_t = 1.8$, the fraction of burnt fuel saturates and the efficiency drops. As an optimum working point, we have chosen $\xi_t = 1.7$.

In contrast to non-magnetized ICF targets, where one observes a marked increase of the fuel burn fraction when the fuel ρR exceeds the alpha stopping range of approximately 0.3 g/cm^2, the fuel burn fraction in magnetically insulated targets increases gradually with the fuel ρR; this is caused by the complete redeposition of alpha particles in the fuel, even for low values of the fuel ρR. Fig. 1 shows the peak fuel temperature reached in various target explosions as a function of the initial fuel ρR. Each point in the plot represents an individual history of a target evolution with given initial values of fuel mass m and ρR; the curves connect points of constant fuel mass. Targets are called "ignited" if the peak fuel temperature

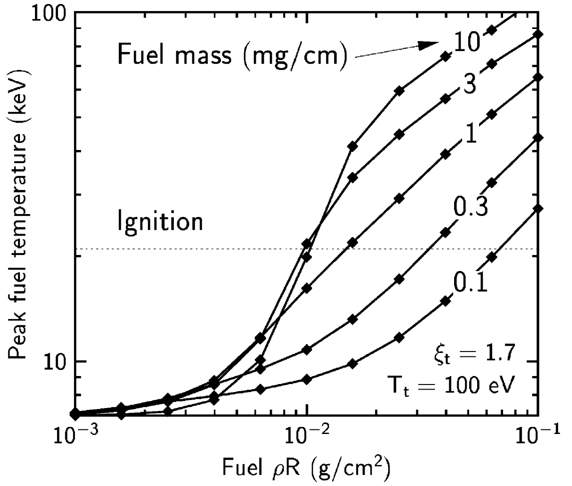

Fig. 1. Peak fuel temperature during target disintegration vs. the initial fuel ρR, for targets with various fuel masses m. The ignition threshold is indicated by the horizontal line.

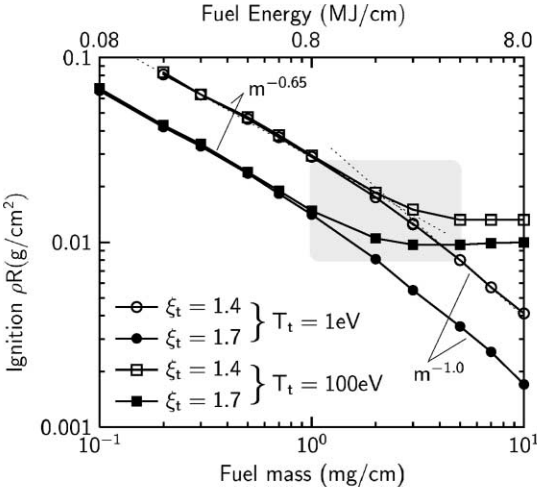

Fig. 2. Ignition ρR vs. fuel mass for different choices of thickness ξ_t and initial temperature T_t of the tamper. The ignition scalings for two values of the fuel mass are indicated by dotted lines. For the shaded area, see Section 4.

during disintegration exceeds 21 keV, i.e. if the fuel temperature rises at least to three times the initial value of $T_0 = 7$ keV, corresponding to a fuel burn fraction of the order of ten percent. Here, we need such a definition since there is no clear ignition "cliff", as in the case of the non-magnetized targets. This definition is consistent with the ignition threshold of non-magnetized targets.

The dependence of the ρR ignition threshold on the fuel mass is shown explicitly in Fig. 2. Various curves are presented for different values of the tamper parameters in order to account for different implosion histories. The ignition threshold ρR scales with the fuel mass $(\rho R)_{\text{ign}} \propto m^{-\kappa}$, where $0.65 \leqslant \kappa \leqslant 1.0$, depending on the fuel mass as indicated on Fig. 2. It turns out that the position of the ignition threshold ρR for large fuel masses $m \geqslant 1.0$ mg/cm depends on the tamper entropy. For tampers with $T_t \approx 100$ eV, it remains above 0.01 g/cm^2. For cold tampers, however, it can drop significantly below this value. Also shown in Fig. 2 is the dependence on the tamper thickness ξ_t. The ignition ρR of targets with a thin ($\xi_t = 1.4$) and those with a large ($\xi_t = 1.7$) tamper differs by about a factor of two. The simulation results presented above can be understood in terms of equation of state properties of the tamper. This will be discussed in Ref. [11].

4. Summary and conclusions

We have investigated ignition conditions for magnetically insulated cylindrical fusion targets by examining assembled fuel–tamper configurations at the time of stagnation. This has been done by means of one-dimensional hydrodynamic simulations, where the effects of heat conduction and the diffusion of alpha particles have been ignored. We have found that under these assumptions, ignition occurs only when a minimum fuel ρR is reached at stagnation. The minimum ρR for fuel ignition depends on the fuel mass as well as on the tamper entropy. This result can serve as a guideline in the vast parameter space, when designing cylindrical MTF targets that should ignite in the hydro-mode.

A possible window for MTF operation with heavy ion beams is indicated by the shaded area in Fig. 2. The boundaries have been selected such that the lowest possible $(\rho R)_{\text{ign}}$ is obtained at fuel energies of a few MJ/cm, which may be available from future heavy ion drivers. The window corresponds to fuel radii up to 1 mm and pressures below 10 Gbar. Compared to non-magnetized ICF targets, magnetic insulation of cylindrical DT targets allows to reduce the ignition ρR threshold by a factor of 10–30, depending on the implosion history. Since the driver power necessary for breakeven in cylindrical ICF targets scales as [5] $P_{\mathrm{dr}} \propto (\rho R)^2_{\mathrm{ign}}$, this leads to a significant reduction in the required driver power for heavy ion beam driven, magnetized cylindrical targets in the MTF ignition mode.

In this paper, we have not considered how the assembled fuel–tamper configurations can be reached by target implosions. Neither have we considered losses through the ends of the cylindrical configuration, see [5], nor the questions of symmetry and stability. These questions, together with a more realistic implementation of the magnetic field, will have to be addressed in future investigations

References

[1] I. Lindemuth, R. Kirkpatrick, 23 (1983) 263.
[2] R. Kirkpatrick, I. Lindemuth, M. Ward, 27 (1995) 201.
[3] M. Churazov, B. Sharkov, E. Zabrodina, 32 (1996) 577.
[4] M. Basko, CEA Report EUR-CEA-FC-1645, 1998.
[5] M. Basko, A. Kemp, J. Meyer-ter-Vehn, Nuclear Fusion 40 (2000) 59.
[6] S. Atzeni, Jpn. J. Appl. Phys. 34 (1995) 1980.
[7] J. Meyer-ter-Vehn, Nuclear Fusion 22 (1982) 561.
[8] M. Basko, DEIRA-3. 1-D 3-T Hydrodynamic Code for Simulating ICF Targets driven by Beams of Fast Ions, 1994.
[9] M. Liberman, A. Velikovich, J. Plasma Phys. 31 (1984) 369.
[10] J. Lindl, in: A. Caruso, E. Sindoni (Eds.), International School of Plasma Physics Piero Caldirola: Inertial Confinement Fusion, p. 617, 1988.
[11] A. Kemp, M. Basko, J. Meyer-ter-Vehn, Ignition condition for magnetically insulated tampered ICF targets …, Nuclear Fusion 41 (2001), in press.