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GAIN SCALING LAWS FOR HIF

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ABSTRACT

The relationship between target gain (thermonuclear energy-released/ion energy incident) and such factors as the total ion energy, the ion beam radius, the ion range, the ion power, the beam geometry, and the released target debris are critical in assessing the feasibility of a particular heavy ion inertial confinement fusion reactor concept.

Scaling relationships that allow target gain to be calculated from the target hydrodynamic coupling efficiency (η), the target radius (R), and the ion energy incident on the target (E_i) are presented. These relations include scaling laws for the required peak power and ion energy, the fuel fractional burnup, and the fraction of energy released in charged particles and x-rays as a function of r, η, and E_i. Relations have been developed for two single-shell target concepts, one requiring two-sided and the other symmetric ion illumination.

INTRODUCTION

There are many factors that impact the design of a heavy ion fusion reactor facility. The length of the linear accelerator and its cost is a function of the ion charge state, the ion current, and the ion kinetic energy. The number of beam lines and their geometrical orientation around the reactor chamber depends on the target illumination and power requirement. The total ion energy required to ignite the target depends on the beam waist size and the ion kinetic energy. The size and type of reactor chamber depends on the thermonuclear energy released and the partitioning of this energy in x-rays, charged particles, and neutrons. The purpose of this paper is to present scaling relations between target, driver, and reactor parameters.

Curves that give target gain as a function of ion beam energy and the parameter $r_i^{3/2} x$ (r_i is the beam radius and x the range) have been published by Bangerter et al.[1] and Lindl and Mark.[2] Scaling relations have also been published.[3-6] These relations have helped improve our understanding of the gain curves by illustrating how parameters such as the cold fuel isentrope (ξ) (the temperature of the cold fuel at ignition) and the hydrodynamic coupling efficiency (η) (energy in the fuel at ignition/ion energy absorbed) impact gain. However, scaling relations for a particular target concept have not been published; so, the scaling for such parameters as illumination geometry, fuel mass, and target thermonuclear debris have remained unknown.

In this paper scaling relationships that allow target gain to be calculated from the target hydrodynamic coupling efficiency (η), the target radius (R), and the ion energy incident on the target (E_i) are presented. These relations include scaling laws for the required peak power and ion energy, the fuel fractional burnup, and the fraction of energy released in charged particles and x-rays as a function of r, η, and E. Relations have been developed for two single-shell target concepts, one requiring two-sided and the other symmetric ion illumination.

ION ENERGY AND POWER RELATIONS

The power requirement will depend on the amount of mass to be accelerated. It is proportional to the product of R^2 and the ion range x (g/cm^2); so, the ion energy absorbed E_i is

$$\eta E_i \propto R^2 \Delta t \qquad (1)$$

where Δt is the time of the main power pulse and η is the efficiency of coupling ion energy to the capsule. Notice that η contains both the efficiency of coupling ion energy to the pusher and fuel kinetic energy, and the efficiency of coupling this kinetic energy to the fuel at ignition. Also we have assumed that the energy incident and the energy absorbed are the same. As yet no experimental evidence suggests otherwise.

We have studied the optimal gain as a function of the capsule radius and the cold fuel isentrope ξ that denotes deviation from complete degeneracy, and have found that the maximum velocity v associated with the optimum gain scales as:

$$v \propto (\xi/R)^{1/4}. \qquad (2)$$

The Δt will depend on the target collapse time so,

$$\Delta t \propto R/v. \qquad (3)$$

Combining Eqs. (1), (2), and (3) gives the scaling relation we wanted. We have

$$E_i \propto R^{13/4}/(\xi^{1/4}\eta). \qquad (4)$$

The power P can then be expressed as:

$$P \propto R^2/\eta. \qquad (5)$$

CAPSULE ENERGETICS

Our model of capsule energetics uses many of the ideas discussed by Meyer-ter-Veh[3] and Rosen[4], and has features first presented by Kidder[5] and Bodner.[6] Consider the ignition conditions for a capsule with radius R -- the distance from capsule center to the outer surface of the ablator, and a convergence ratio $\gamma \equiv R/R_f$ -- R_f is the fuel radius at ignition. We divide the fuel into a hot ignition region that can be described by an ideal gas and a highly compressed, low entropy region described as a degenerate electron plasma with the pressure:

$$p_c = 2.3\times10^{12}\xi\rho_c^{5/3} \qquad (6)$$

in cgs units. As before the parameter ξ denotes the deviation from complete degeneracy and labels different isentropes.

The thermonuclear energy is

$$E = q_{DT}M_f\theta \qquad (7)$$

where the specific DT fusion energy $q_{DT} = 3.34\times10^{11}$ J/g, the total fuel mass $M_f = M_s + M_c$, and the fraction of burned fuel

$$\theta = H_f/(H_b + H_f) \qquad (8)$$

where $H_f = \rho_s R_s + \rho_c R_c$. The R_s and ρ_s and the R_c and ρ_c are the hot and cold fuel radius and density, respectively. The H_b is a constant that depends on the amount of fuel tamping and the fuel reaction rate. For our concepts H_b is approximately 3.

To find scaling relations, we use the fact that for high-gain targets the fuel ρr is greater than 1.[3,4] This allows us to write the approximate expressions:

$$E_f \propto p_c R_f^3, \qquad (9)$$

$$\rho_c R_c \propto M_c/R_f^2, \text{ and} \tag{10}$$

$$E = q_{DT} M_c \theta \tag{11}$$

where $\theta = \rho_c R_c/(3.2 + \rho_c R_c)$ and $E_f = \eta E_i$. We also have

$$M_c \propto (R_f^2 E_f/\xi)^{3/5}. \tag{12}$$

These ideas were used to write a simple code to study gain as a function of γ. We found that the value of γ that gave maximum gain was proportional to $R^{-1/2}$, a relation also found by Rosen.[4] With this relation for γ, Eq. (12) becomes

$$M_c \propto (R^3 E_f/\xi)^{3/5}, \text{ and} \tag{13}$$

$$\rho_c R_c \propto (E_f/\xi)/R^{6/5}. \tag{14}$$

SCALING LAWS

The previous sections give most of the information needed to determine gain as a function of the relevant target and ion beam parameters. For example, combining Eqs. (9), (10), (11), (13), and (14) gives the yield as a function of R, E_i, η, and ξ. Thus, the gain can be written as

$$G = C_1 \{ R^3 \eta E_{ion}/\xi \}^{3/5} \theta/E_i \tag{15}$$

where $\theta = \rho r/(3.2 + \rho r)$ and

$$\rho r = C_2 \{ \eta E_i/\xi \}^{3/5}/R^{6/5} \text{ (g/cm}^2\text{)}. \tag{16}$$

From Eqs. (4) and (5) we also have

$$E_i = C_3 R^{13/4}/(\xi^{1/4} \eta) \text{ (MJ), and} \tag{17}$$

$$P = C_4 R^2/\eta \text{ (TW)}. \tag{18}$$

We have found the constant coefficients and η values for two target concepts. Concept A requires two-sided ion irradiation and concept B symmetric illumination. The η values and their associated constant coefficients were determined from target calculations and analytical models of the target coupling physics and include symmetry contsraints. For a discussion of symmetry issues for direct drive targets see Ref. 7. The values of η are given in graphical form that is curves of η versus target radius for different values of the ion range. The values of η as a function of r (cm) and x (g/cm^2) for concepts A and B are shown in Figs. 1 and 2, respectively. Target calculations suggest that the fuel isentrope ξ is a function of R. A very approximate expression for ξ is

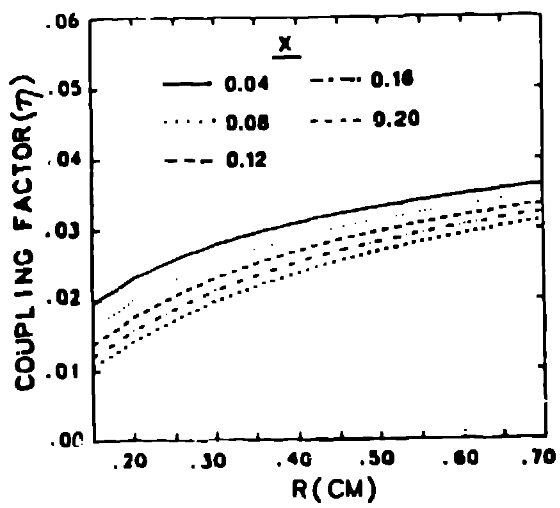

Fig. 1. Hydrodynamic coupling efficiency η as a function of R (cm) and x (g/cm^2) for concept A.

$$\xi \approx 1.0 + (C_5/R)^2 . \tag{19}$$

This is a very approximate relation because our calculations have shown the functional form to depend on the preheat allowed, the stability criteria, and the pusher and ablator materials. The constant coefficients C_1 - C_5 for concept A are 5.9x10^4, 3.9, 11.6, 205, and 0.28. The corresponding coefficients for concept B are 3.2x10^4, 6.0, 3.44, 73.4, and 0.54. These scaling relations are valid for incident ion energies from 1 to 20 MJ and for ion ranges from 0.035 to 0.2 g/cm^2. They were determined in such a way as to consistent with the best estimate gain curves published earlier.[1-2]

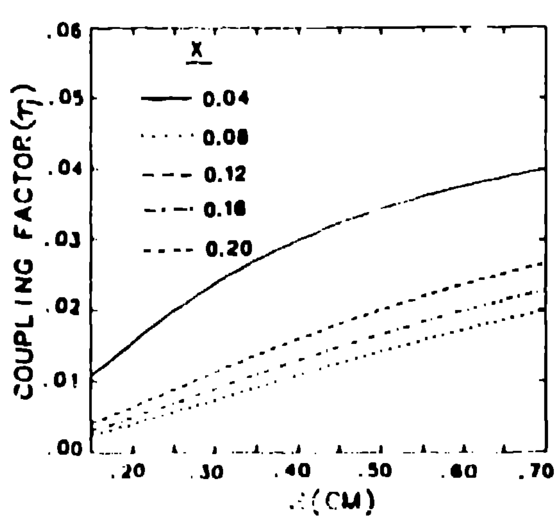

Fig. 2. Hydrodynamic coupling efficiency η as a function of R (cm) and x (g/cm^2) for concept B.

A COMPARISON WITH PREVIOUS WORK AND A RELATION FOR THE DEBRIS NEUTRON FRACTION

Because most of the capsule energetics was based on previous scaling studies of gain and is most directly related to that of Meyer-ter-Veh,[3] we make a comparison with his results. We find that our ρr scaling can be written

$$\rho r \propto (\eta E_i)^y / \xi^z \qquad (20)$$

where $y = 3/13$ and $z = 0.6$. The Meyer-ter-veh result gave $y = 0.2$ and $z = 0.6$. Equation (20) was found by combining Eqs. (16) and (17) and ignoring the ξ dependence in Eq. (17). If we ignore the velocity dependence on capsule radius, the y values become equivalent and equal to 0.2.

Comparisons with the gain scaling are slightly more difficult. If we approximate the burn fraction θ with the expression[3-4]

$$\theta = (\rho r / 12.8)^{1/2}, \qquad (21)$$

we can write θ as

$$\theta \propto (\eta E_i)^{3/26} / \xi^{3/10}. \qquad (22)$$

Then, the gain is approximately

$$G \propto (\eta E_i)^w / \xi^p \qquad (23)$$

where $w = 7/26$ and $p = 0.9$. The Meyer-ter-Veh result gave $w = 0.3$ and $z = 0.9$. Again, if we ignore the velocity dependence on radius, the w's become equivalent and equal to 0.3.

Besides the gain, yield, power and energy, the fuel mass and neutron debris fraction can be estimated. From the target yield (the product of E_{ion} and G) and the fuel burnup fraction, the fuel mass is determined. The neutron fraction of the yield N can be estimated from the fuel ρr value. The fraction is[8]

$$N = 0.8 - 0.04 \rho r. \qquad (24)$$

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