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FUSION SYSTEMS STUDIES

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Abstract

Some of the target information required for reactor and systems studies is not readily available. In this paper we attempt to improve this situation by developing simple target models that give estimates of DT fuel mass, the masses of other target constituents, the DT burn fraction, and the fraction of energy in neutrons.

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In order to perform reasonable systems and reactor studies for ion beam fusion the following target information is required:

1. Target gain. For ion targets the gain is a function of at least three variables. These variables are normally chosen to be driver energy (E), ion focal spot radius (r), and ion range (R). See for example reference 1, which gives gain as a function of these variables.
2. Peak power and pulse length. The peak power as a function of E, r, and R is also given in reference 1. For the targets described in reference 1 the pulse length can be obtained by dividing the input energy by the power to obtain a time τ . The full-width-half-maximum of the main power pulse is approximately 0.5τ . The total pulse length is about 2.5τ for single-shell targets and 1.25τ for double-shell targets.
3. Masses of various target materials.
4. Target output spectra for neutrons, photons, and charged and neutral particles. For some purposes the single number, fraction of energy in neutrons (f_n), may suffice.

The third and fourth categories of information are not readily available in a form that is convenient and useful for reactor and systems studies. Fortunately simple models can be used to obtain the information required. In order to obtain the masses of various materials we adopt a simplified version of the model of Meyer-ter-Vehn² (MTV).

In this model the ρr of the spark is set to

$$H_s = \rho_s R_s = 0.4 \text{ g/cm}^2.$$

By specifying R_s one can calculate ρ_s and the mass of the spark M_s . The pressure in the spark (p) is given by an ideal gas equation of state where the spark temperature is chosen to be 5 keV which is approximately the ignition temperature for DT. We use $7.68 \times 10^{14} \rho T$ dyne/cm² where ρ is in g/cm² and T is in keV. The MTV model assumes that the pressure in the bulk of the fuel (the "cold" fuel) is equal to the pressure in the spark. If the cold fuel is described as a degenerate electron gas, the pressure is given by

$$p = 2.3 \times 10^{12} \alpha \rho_c^{5/3} \text{ (cgs units)}$$

where α is a parameter that denotes the deviation from complete degeneracy and ρ_c is the density of the cold fuel. If one specifies α one can calculate the radius of the cold fuel R_c as a function of the cold fuel mass M_c using the relation

$$M_c = \frac{4\pi}{3} \rho_c (R_c^3 - R_s^3).$$

The total ρr of the fuel H_F is given by

$$H_F = 0.4 + \rho_c (R_c - R_s)$$

The burn efficiency ϕ is given by $\phi = H_F / (H_B + H_F)$ where H_B is 6-7 g/cm². The yield of the target is then given by

$$Y = 334 \phi (M_s + M_c)$$

where Y is in MJ and mass is in mg. Meyer-ter-Vehn uses $R_s = 75 \mu\text{m}$ and $\alpha = 3$ to match typical gain curves. We have used $R_s = 70 \mu\text{m}$, $\alpha = 2$ and $H_B = 6 \text{ g/cm}^2$ to obtain the table given below.

YIELD (MJ)	MASS (mg)	H_F (g/cm ²)
1.7	0.082	0.400
7.6	0.237	0.639
12.8	0.335	0.778
23.3	0.494	0.988
44.7	0.753	1.298
88.0	1.174	1.737
174.2	1.861	2.335
340.7	2.980	3.122
653.4	4.802	4.124
1225.	7.771	5.367
2249.	12.61	6.882

We have thus succeeded in obtaining fuel mass and H_F , as a function of target yield. We can now use target yield from typical gain curves to estimate these parameters independent of the details of target design. However, specification of the masses of other materials in the target requires additional assumptions.

Targets similar to the design of Bangerter and Meeker³ and the HIBALL design⁴ provide some guidance. In the Bangerter-Meeker target the masses are 72.1 mg Pb, 16.8 mg plastic and 1.00 mg DT. The mass ratios for the HIBALL-II target are very similar. However, the plastic in the Bangerter-Meeker target has been replaced by lithium. Thus, it appears that any moderately low-Z material is acceptable. Possible candidates could include hydrogen isotopes, lithium, beryllium, boron, carbon, and compounds of these elements. Glasses containing silicon and oxygen may also be useful. Within order-of-magnitude accuracy it would appear reasonable to assume that the lead mass is ~ 100 times the DT mass, and the mass of the other low-Z materials is ~ 15 times the DT mass. However, one should note that if seeded DT is used for the low-Z

absorber material, the DT flow rate would be substantially larger than for plastic or lithium. It might be interesting to systems designers to see if this matters by varying the DT mass flow rate from about 0.5 to 15 times the value given by the simple model. Incidentally, targets with a seeded DT absorber roughly correspond to the "bare drop" or "bare shell" targets sometimes proposed for laser fusion.

The fraction of energy in neutrons can also be obtained from a simple model. Assume that the nuclear reaction length for neutrons in DT is about 5 g/cm^2 and that roughly 1/4 of the neutron energy is lost per reaction. The fraction of neutrons escaping without reacting is approximately $\exp(-H_F/5)$ so that, ignoring multiple reactions, the fraction of neutron energy escaping is $\exp(-H_F/5) + 0.75 [1 - \exp(-H_F/5)]$ or to first order $1 - 0.05 H_F$. Since neutrons are produced with about 80% of the total energy,

$$f_n \approx 0.8 (1 - 0.05 H_F)$$

In conclusion we have derived several simple relationships for use in systems studies involving ion beam drivers.

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