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UKAEA RESEARCH GROUP

Report

SOME REACTOR IMPLICATIONS OF LASER (OR RELATIVISTIC BEAM) FUSION

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SOME REACTOR IMPLICATIONS OF LASER (OR RELATIVISTIC BEAM) FUSION

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ABSTRACT

The thermal stability of tamped cryogenic DT spherical-shell targets was considered: it was shown that both black-body radiation and the ambient vapour pressure within the inner-most wall of an operational reactor could significantly modify the geometry of some types of target during their transit from the exterior to the centre of the reaction chamber. A "check-list" of some inertial-confinement reactor topics meriting examination by the Advisory Group was also suggested.

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INTRODUCTION

Some technological implications of the use of homogeneous, spherical, pure DT targets for laser-ignited inertially-confined thermonuclear reactor applications have been discussed previously. The fractional mass-loss of such pellets due to sublimation in transit from a cryogenic "pellet factory" to the centre of the reactor vessel can be kept quite small, i.e. $\leq 3\%$, assuming pellet radii of order $10^{-2} - 10^{-1}$ cm, working temperatures within the reactor vessel of $\lesssim 1000$ K, ambient Li vapour pressures $\lesssim 1$ Torr, and pellet injection velocities between $1 - 10^{3}$ m/sec.(1) (Note, however, that the effects on pellet trajectory and implosion symmetry of any departure from sphericity during in-transit evaporation of the micro-crystalline target(2) were not considered in Reference 1).

The present paper examines the implications of using spherical, inhomogeneous, cryogenic <u>shell</u> targets of the general type discussed in References 3 - 7 in a similar reactor environment. (Such targets pose a less difficult challenge to the laser designer since the laser pulse can rise almost linearly, to a lower peak power(3-5). The lower incident target intensity also alleviates heat-transport problems at the critical surface.) Because of the very wide range of target designs which have been discussed in the literature, the discussion will be restricted to two specific target designs in order to illustrate fundamental principles with a minimum of quantitative numerical detail.

TYPICAL MULTI-SHELL TARGETS

Consider targets categorized as "Type IV" in Reference 5. Thermonuclear fuel is deposited on the inner spherical wall of a high Z shell, having inner and outer radii of R_2 and R_3 respectively. The fuel, having a well-defined inner radius R_1 may be cryogenic DT or a chemical compound such as lithium hydride. Table I summarises characteristic dimensions of two targets, A and B, inferred from the texts of References 5 and 6, respectively.

TABLE I - Typical "Shell" Targets

	TARGET "A"	TARGET "B"
Reference	(5)	(6)
R_3 (μm)	484	1000
$R_3 - R_2$ (μm)	~ 3.4 (High Z)	~ 40 (Pb or Au)
$R_2 - R_1$ (μm)	~ 15.9 (Solid DT)	~ 56 (Solid DT)
Laser Input	100 kJ	1 MJ
Laser Pulse duration (τ_1)	3.5×10^{-9} s (Gaussian FWHM)	10^{-7} s (Triangular)
Thermonuclear O/P	< 10MJ? (See Ref.7)	1000MJ
Reactor Wall Radius	~ 1m	~ 5m
τ_t	~ 3.3ms	~ 16.6ms

As discussed in Reference 1, it seems more convenient to fabricate the pellet outside the heated structure of the reactor, and then to insert it (at high velocity) to the centre of the reaction-chamber. We shall conservatively assume that velocities of order 3×10^2 m/sec are practicable, noting that velocities approaching 10^4 m/sec would imply energies of order 1 eV per particle (i.e. far exceeding the DT binding energy) and a target movement exceeding 3% of its diameter during the time of irradiation (τ_1). The times τ_t listed in Table I thus represent reasonable estimates of the transit times to the centre of reactor chambers having inner (vacuum) wall radii of approximately 1 and 5m, respectively.

EFFECT OF REACTOR ENVIRONMENT ON TARGET

The ambient temperature (θ_R) in the reactor is likely to lie within the range 560 - 1000 K, irrespective of details of the reactor design (eg. lithium blanket or "dry wall" designs). Thus the black-body radiation intensity incident on a cryogenic target is of order $\lesssim 5.7$ W/cm^2. A comparable heat flux will be produced by any vaporized lithium (or other gas) having a pressure (P_{Li}) $\gtrsim 4$ Torr. These are the principal heat loads incident on the target; heating due to tritium β-decay is by comparison completely negligible. What would be the consequence of complete absorption ($\beta = 1$) of a 5.7 W/cm^2

heat load on the outer surface of the pellet?

One-dimensional thermal diffusion calculations are adequate for these thin-shell (high aspect ratio) targets, and some characteristic thermal penetration depths are listed in Table II, for typical target materials. Here,

$$\Delta Z = 0.68\sqrt{\kappa\,\tau_t} \qquad (1)$$

where κ is the thermal diffusivity of the material.

TABLE II - Approximate thermal penetration depths

MATERIAL	ΔZ	
	τ_t = 3.3ms (Target A)	τ_t = 16.6ms (Target B)
Solid (normal) H_2	400 µm	900 µm
Glass	23 µm	51 µm
Au	900 µm	2000 µm

Comparison of Table II and Table I shows that during a transit time of several milliseconds any temperature rise on the outer surface of the pellet will be rapidly conducted to the interior; indeed, temperature gradients of less than 0.4° C are required to conduct a heat flux of 5.7 W/cm^2 through the shell materials of either Target A or B. The initial temperature rise of the solid DT is thus of order

$$\frac{dT}{dt} = (\beta\,\sigma\,\theta^4 + 0.25\,P_{Li}\cdot\bar{C}_{Li})\,([R_2 - R_1][S_{DT}\rho_{DT}] + [R_3 - R_2][S_Z\rho_Z])^{-1} \qquad (2)$$

where σ is Stephan's constant and S and ρ are the specific heat and density of the respective shell materials. This temperature rise is sufficiently rapid to melt the DT in either target. Numerical summation of the energy needed to melt solid H_2, raise it to its boiling point and subsequently vaporize the liquid indicates that for either target over 10% of the cryogenic shell will evaporate; comparable numbers could be expected for DT, for which less cryogenic data has been published.

Whether the black-body spectrum is fully absorbed by the pellet will, of course, depend on its detailed design; it is often assumed, for example, that a low Z (and therefore partially-absorbing) outer ablative layer may be used to provide conductive "smoothing" of any non-uniformity of the incident laser pulse. The main purpose of the present note is to stress the significant impact the reactor environment could have on cryogenic target stability and design. As a specific example, Rudakov discussed at this meeting the possibility of a 10^{10} - 10^{11} J thermonuclear output pulse being absorbed in 1 tonne of Li blanket; his duty cycle of one pulse every 10 seconds implies exceptional (and energy-consuming) pumping requirements if the ambient vapour pressure is to be held below 4 Torr.

CONCLUSION

Six questions summarize these and other reactor-related issues, which it would seem profitable to discuss at this Advisory Group.

(1) A thermonuclear gain Q (fusion output/laser input) of 1000 was predicted in Reference 6 for a laser input energy of 1MJ, compared to gains of order 100 discussed in American work (7,8). The probable magnitude of Q determines the credibility of inertial-confinement approaches to civil power production; what are thought to be the major physics uncertainties in these various calculations?

(2) Apart from the relaxation of the laser-efficiency requirement, what are the benefits of a fission-fusion hybrid?

(3) What is the maximum credible benefit to be derived from a successful nuclear-pumped laser development?

(4) Does direct H_2 or CH_4 fuel production (via 14MeV neutrons), rather than electricity production via a conventional thermal cycle, significantly affect the economics of inertial-confinement?

(5) Can double (high Z shell) cryogenic targets (classified "Type V" in Ref. 5) actually be made with reasonable symmetry, and at realistic cost?

(6) Are cryogenic shell targets credible for high-repetition-rate reactor operation? (If not, what thermonuclear gains are predicted using chemically-bound, higher $\bar{Z}$, thermonuclear fuel?)

(Note that the gas filled targets discussed by Jonas and others, classification "Type III" of Reference 5, are thermally stable to the reactor environment, but are claimed to require highly-shaped heating pulses for maximum thermonuclear output (6)).

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