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LASERS AND THE REACTOR IGNITION PROBLEM

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LASERS AND THE REACTOR IGNITION PROBLEM

by

I.J. SPALDING

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ABSTRACT

Some published estimates of the laser energy (W_0) required to heat an inertially-confined D-T target in a pulsed-fusion reactor are summarised. Assuming a thermal efficiency of ⅓ and a laser heating efficiency (target energy/laser pumping energy) of 100%, most of these estimates of W_0 range between 10 and 1000 MJ, depending on the various assumptions which are made about the degree of solid state target compression, the possibility of target tamping, and the required reactor power gain. Any energy gain due to fusion reactions in material other than the target is omitted in these calculations. These estimates of W_0 are then compared with the maximum fusion outputs which can be handled with and without damage to the structure and the low permissible cost of replacing damaged components is stressed.

The possibility of using non-linear absorption of repetitively-pulsed CO_2 lasers to start-up a steady-state stellarator reactor which is fuelled by D-T pellet injection and has an output of ~ 10 GW(E) is then discussed. It is shown that laser energies as low as 80 kJ may be feasible and possible advantages and difficulties of such a hybrid inertial/magnetic confinement approach are outlined.

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CONTENTS

1. INTRODUCTION

There have recently been an increasing number of papers examining technological and economic implications of the various possible approaches to controlled thermonuclear fusion$^{(1-3)}$. Although highly simplified theoretical models of physical processes are usually involved, such studies have often served to high-light the most promising approaches, and to define the physical problems most urgently needing solution. The detailed quantitative conclusions, being subject to economic or technological constraints which may change with time, must be treated with some caution. Nevertheless, many of these constraints, such as the maximum heat loading due to fusion products which can be permitted at the vacuum wall of the reactor, the maximum electrical output which it is convenient to generate at one locality, and the maximum permissible capital cost per kilowatt generated, are unlikely to change rapidly over one or two decades.

Section 2 of this paper presents a brief survey of laser heating possibilities, and Section 3 then examines in rather more detail the possibility and implications of using the highly efficient CO_2 molecular gas laser for igniting an α-particle heated toroidal reactor, such as a steady-state stellarator.

2. SOME LASER-HEATING POSSIBILITIES

2.1 Inertial Confinement of Untamped D-T Pellets

Assume that a D-T plasma of density n, radius r, and temperature $T \ll 10^4$ eV can be raised instantaneously to a temperature $T \sim 10^4$ eV. The plasma expands freely with a velocity $V_s \sim \sqrt{2kT/M}$, with a lifetime of order $\tau \sim r/V_s$, so that equilibrium, MHD and micro stability problems are avoided. To obtain a net energy yield in a typical pulsed reactor it is necessary that the Lawson product should be exceeded$^{(4)}$, thus:

$$n_0\tau \geqslant \varepsilon_p^{-1} 10^{14} \qquad \ldots (1)$$

where ε_p is the efficiency of conversion of the heating source energy into plasma energy W_p, and the thermal efficiency is assumed to be ⅓. An order of magnitude estimate of the minimum input energy W_p is readily derived by combining Eq.(1) with the conditions

$$T \sim 10^4 \text{ eV}, \qquad \tau \sim r/V_s \qquad \ldots (2)$$

Since W_p scales as n_0^{-2} the smallest systems will operate near the solid-state density $n_s \sim 4 \times 10^{22}$ cm^{-3}. Allowing for reductions in density and temperature during expansion, and putting $\varepsilon_p \sim ⅓$, the minimum 'break-even' energy W_p is calculated to be of the order 1000 MJ for $n_0 \sim n_s$. This energy must be deposited in a time less than a few nanoseconds. Unless non-linear effects permitted the use of CO_2 lasers, ε_p is likely to be very much less than ⅓ and the fusion output of the device would have an energy equivalent in excess of 1 ton of TNT (i.e. > 10^{10}J). Linhart$^{(4)}$ estimates that explosions having energies up to 1 k ton of TNT can be contained in suitable cavities, but the maximum permitted cost of replacing components between shots places a very severe economic constraint on such an approach$^{(6)}$.

Fraas$^{(7)}$ has estimated that a hollow cylinder of rotating fluid Li, containing externally injected gas bubbles, is capable of containing an energy of the order 500 MJ without damage. The bubbles are able to absorb a large fraction of the shock energy, whilst the Li absorbs fusion neutrons, breeds tritium, and serves as an energy exchanger in a conventional heat cycle. There are, therefore, good reasons for investigating any method by which the 'break-even' input energy could be lowered to $W_p \lesssim 50$ MJ.

2.2 Confinement of Tamped D-T Pellets

Linhart, in Appendix II of Ref.(4), discusses methods by which a relatively small energy W_0 might be used to trigger a fusion energy release from a larger fusionable reservoir. Table 1 summarises some of his assumptions and conclusions. For time scales consistent with input intensities of reactor interest ($\sim 10^{18}$W cm^{-2}), it is thought that electron heat conduction can be a sufficiently powerful mechanism for propagation of the trigger. There is little published data on the subject of fusion reactions in solids and so it is difficult to estimate whether the fulfilment of the trigger conditions will lead to an appreciable combustion of D-T fuel in contact with the trigger. The trigger energy may be reduced to $W_0 \sim 40$ MJ by precompression - perhaps by the use of a laser-generated shock.

W_0 could be lowered still further if it were possible to use a high Z tamp to enhance the inertial confinement time. The practical complications associated with this approach are discussed by Eden and Saunders(6), and by Linhart(4).

Both enhanced radiation and conduction losses to the tamp must be avoided; moreover, plasma losses are inevitable through the holes which must be left in the tamp for the laser beam input. Magnetic fields of the order 10 MG can be used to reduce the conduction losses, but the technological complications associated with the required liner implosions are formidable. Current laser capabilities, various estimates of laser inputs required to generate inertially-confined plasmas of reactor interest, and practical limitations on the useful output are shown schematically in Figure 1. It should be noted that present laser capabilities are well removed (by a factor $\sim 10^4$) from the most optimistic estimates of W_0; the variation in the minimum value of W_0 reflects varying assessments of the difficulty of tamping, and of the overall laser efficiency ε_p likely to be achieved in a working reactor(8,9).

Linhart(4) also reviews two other techniques for producing high power and energy densities and concludes that although there is currently less technological know-how concerning micro-projectile and electron beams, they may holds more promise as fusion triggers. Energy outputs already achieved in some high energy-density electron beam and laser sources are summarised in Table 2.

2.3 Laser Heating of Magnetically Confined Plasmas

The high continuous powers already achieved for the CO_2 laser (Laser 4 of Table 2) and the high peak powers which are now technically possible for pulsed near-atmospheric CO_2 lasers(10,11), raises the possibility of heating magnetically confined plasmas using long-wavelength laser radiation. Some potential fusion advantages of such lasers are the following:

(i) Efficient absorption is possible at lower plasma densities ($10^{17} - 10^{19}$ cm^{-3}) than in the visible region of the spectrum. (Absorption will be discussed in greater detail in Section 2.3.1).

(ii) At the lower end of this density range (i.e. near 10^{17} cm^{-3}), steady state magnetic confinement at thermonuclear temperatures is possible.

(iii) The quantum efficiency of the CO_2 laser is very high, being 45% at 9·6μ and 40% at 10·6μ; the electrical efficiencies actually achieved are also uniquely high, being commonly in the range 5-25%.

2.3.1 Absorption

When $\omega > \omega_p$, and $\nu_{ei}^2 \ll (\omega^2 - \omega_p^2)$, the classical absorption length ℓ_c is given by

$$\ell_c \sim \frac{1{\cdot}5 \times 10^5 T_e^{3/2} \omega^2}{n^2 \bar{z}} \text{ (cm)} \qquad \ldots (3)$$

where

$$\bar{z} = \frac{\Sigma n_i z^2}{\Sigma n_i z} ,$$

T_e is the electron temperature (eV) and n_e the electron density per cm^3.

At sufficiently high power intensities P(watts cm^{-2}) it may become possible to excite instabilities which enhance the high frequency resistivity of the plasma at one of its characteristic frequencies, leading to an anomalous heating effect. Several possibilities have been discussed in the literature:

(i) A low frequency 'thermal instability'(12).
Kaw and Dawson conclude that this instability will not be excited in a fully ionized plasma, although it may be of importance during the initial ionization of the gas.

(ii) A two-stream instability(13) giving a strongly enhanced resistivity at frequencies

$$\omega^2 \lesssim \omega_{pe}^2 + k v_e^2 \qquad \ldots (4)$$

when $T_e > T_i$ and the laser flux exceeds a threshold intensity

$$P_{KD} \geqslant 10^{-16} \left(\frac{n^3}{T} \right)^{1/2} \text{ (watts cm}^{-2}\text{)} \qquad \ldots (5)$$

The anomalous absorption length is

$$\ell_{KD} = 3 \times 10^{-2} \, (Tn^{1/2}/P) \text{ (cm)} \qquad \ldots (6)$$

and the instability is predicted by Kaw and Dawson(13) to give a marked increase in absorption for over-dense plasmas, near the point where the laser beam is reflected.

(iii) A parametic instability has been discussed by Dubois and Goldman(14) for $\omega \sim \omega_{pe}$; the threshold intensity is

$$P_{DG} \geqslant 10^{-10} nT \text{ (watts cm}^{-2}\text{)} \qquad \ldots (7)$$

but there are restrictions on the inhomogeneity of the plasma and of the spectral structure of the laser line.

(iv) Jackson(15) discusses an instability at $\omega \sim 2\omega_{pe}$ having a threshold

$$P_J \geqslant 6 \times 10^{-5} \, n \text{(watts cm}^{-2}\text{)} \qquad \ldots (8)$$

(v) Instabilities can be excited by tuning two lasers of slightly different frequency (ω_1, ω_2) so that their beat frequency resonates at a plasma or cyclotron frequency(16,17). However, it seems unlikely that this would permit strong absorption in an under-dense $(\omega_1, \omega_2 \gg \omega_p)$ plasma for the following reason: appreciable absorption is only possible if multiple scattering occurs, since only a fraction $\left(\frac{\omega_p}{\omega_1} \right)$ of the photon energy is lost in a single scattering process. Only those instabilities which produce small-angle forward scattering therefore remain in resonance(18).

It should be noted that some of the resonances discussed above can be destroyed by sufficiently strong density inhomogeneities(17), but that other-mode coupling possibilities then arise. There has been very little experimental work to substantiate any of these theories.

2.3.2 CO_2 heating of magnetically confined plasmas

Table 3 lists the major parameters of 'economic' toroidal reactor concepts currently being examined at Culham. (In the light of present experimental trends it is assumed for the present calculations that a containment time of $\sim 10^2$ Bohm times can be achieved). Table 4 lists absorption lengths for a variety of thermonuclear plasma conditions. At toroidal densities $n \sim 3 \times 10^{14}$ cm^{-3}, the classical absorption length appears too long to permit efficient continuous (or pulsed) heating, even using a multi-path optical cavity and high-reflectivity cryogenic mirrors. (Moreover, refraction effects would be difficult to overcome). At wavelengths $\lambda \sim 200\mu$ and densities $n \sim 3 \times 10^{15}$ cm^{-3} classical absorption does become significantly stronger; however, thermal population of the lower level of any hypothetical fluid laser would almost certainly be expected to reduce the efficiency of such a device to an unacceptably low level.

Another possibility is to heat a linear high-β device, at densities near 10^{17} cm^{-3}. Such an approach seems to lead to many of the practical and economic difficulties of linear θ-pinch or cusp operation detailed in Ref.(2).

A final possibility, and the one which may prove most promising, is to heat an inertially confined plasma at a density $n \sim 10^{19}$ cm^{-3}. At these densities $\omega \sim \omega_p$ and so the non-linear effects detailed in Section 2.3.1 may permit efficient single-pass coupling of the laser energy into the plasma. The size of the target ($\beta > 1$) plasma can be conveniently adjusted to permit expansion within the toroidal field to a density at which trapping might be expected.

In Section 3 we shall show that the long confinement time characteristic of the toroidal system permits repetitive pulsing of the laser, with a very significant reduction in the lasing volume and energy required. Moreover, in an α-heated toroidal reactor the efficiency of the laser is not a primary constraint in the design, although it may well be the most important single factor influencing the capital cost of the heating system.

3. PULSED CO_2 HEATING OF HYPOTHETICAL TOROIDAL REACTOR

Approximately 700 MJ is required to heat the stellarator reactor of Table 3 to ignition temperature. The precise rate at which this energy must be supplied depends on the detailed scaling of the particle and energy loss times. For example, Wort(19a) follows the (intermediate-regime) Galeev-Sagdeev scaling to show that (at constant density) the start-up power should exceed 70 MW (only), with an ignition temperature (at $n = 3 \times 10^{14} cm^{-3}$) of $\sim 6{\cdot}4$ keV (see Fig.2). We shall assume that the stellarator is to be re-fuelled by D-T ice injection, and that laser heating is to be compared with the present (preferred) alternatives of

(i) neutral injection (via ion-source or Hall acelerator) or

(ii) transit-time magnetic pumping

A fairly detailed example of a possible approach is presented tentatively below. Such an approach may also be applicable to other toroidal devices; however, the primary purpose of the present paper is qualitative rather than quantitative. We wish to establish whether any broad principles are likely to preclude lasers as a toroidal heating possibility.

In particular:

(i) What is the probable heating efficiency?

(ii) Does the laser volume exceed the contained plasma volume?

(iii) Is the capital cost of capacitors etc. excessive?

(iv) Does the transit-time of light present a significant design constraint in the laser?

3.1 Repetitively Pulsed Laser

A possible repetitively-pulsed CO_2 laser array is detailed in Table 5. It is assumed that each laser is coupled with an appropriate D-T pellet injector and that ablation, plus a laser pre-pulse if necessary, has expanded the plasma into an easily-hit volume of a few cm^3.

3.1.1 Probable heating efficiency

Table 4 indicates $\ell_c \sim 50$ cm when $n \sim 10^{19}$ cm^{-3} and $T \sim 10^4$ eV. The Kaw-Dawson threshold intensity is $P \sim 3 \times 10^{10}$ watts cm^{-2} and so non-linear absorption (Eqn.6) should be significantly enhanced for $P \sim 5 \times 10^{12}$ W cm^{-2}. Clearly the whole range of physical processes, including the possibilities of refraction and self-focusing, need to be examined self-consistently, but the possibility of a net CO_2 heating efficiency exceeding $\varepsilon_p = 10\%$ in a multi-pass cavity is not, a priori, impossible.

3.1.2 Probable laser volume

Table 6 compares the energy density in a stellarator reactor plasma with that already available from a variety of lasers. Assuming a CO_2 laser repetition rate of 100 Hz for 10 seconds, (i.e. a total of $N = 10^3$ pulses) the lasing volume can certainly be less than the plasma volume.

3.1.3 Laser capital cost

The major cost of the CO_2 laser would most probably lie in the relatively fast capacitor bank of $(800/N\varepsilon_p)$MJ energy storage. For start-up, these capacitors do not need to have an excessively long life; assuming a cost of £50,000/MJ(20), we arrive at a capital cost per kilowatt of electrical power generated of £$(4/N\varepsilon_p)$ per kW(E). This figure (~ 0·04 £/kWE) is considerably less than the value of £4/kW(E) assigned by Carruthers et al(3) for the reactor vessel and blanket. Assuming that ~ £4/kW(E) is also available for heating equipment, there is a good margin for the slow (10 second) power supply and pellet injectors.

3.1.4 The light transit-time criterion

The transit-time of light does not appear to be a significant design constraint for the laser parameters outlined in Table 5.

4. SUMMARY AND CONCLUSIONS

Inertially confined plasmas have the attraction that equilibrium, MHD stability, and microinstability problems associated with magnetic confinement can be avoided. Published estimates of the laser energy W_o required to trigger an inertially - confined power-producing fusion reactor have been briefly reviewed. The estimates of W_o vary widely, from below 10 MJ up to 1000 MJ depending on detailed assumptions concerning actual power gain, over-all laser heating efficiency, degree of target compression above solid state densities(8), degree of tamping and the physics of fusion reactions in solids(4,21). The laser pulse should not exceed a few nanoseconds in duration, and target densities exceeding 4×10^{22} cm^{-3} are envisaged. Only if W_o lies at the lower end of the energy range is it possible to contain the fusion products without mechanical damage; the permissible cost of replacing components is quite low(6).

The mechanical strength of materials limits the quasi-steady magnetic confinement of themonuclear plasmas to densities $n \lesssim 10^{17}\ \mathrm{cm}^{-3}$. (Linhart(4) discusses the implications of exceeding the limit by using impulsively generated magnetic fields). Multi-pass laser heating by classical absorption at $n \sim 10^{17}\ \mathrm{cm}^{-3}$ may be conceivable in a linear, high-β system, but such an approach leads to many of the technological and economic difficulties discussed in Ref.(2). The possibility of efficient laser heating of significantly lower plasma densities magnetically confined in toroidal devices appears very remote. Stimulated by Kaw and Dawson's papers on non-linear absorption we have therefore considered the possibility of using a CO_2 laser to heat inertially confined plasmas produced by pellet-injection into a steady-state stellarator(19b). One envisages several lasers spaced around the circumference of the device, energizing a succession of pellets during the ignition time. It is assumed that the high-β plasma so produced expands and is trapped in a time short compared to the magnetic confinement time of the resulting $\beta \sim 5\%$ plasma.

The advantage of such a (hybrid) scheme is that the output of any individual laser may be reduced to values as low as 80 kJ, a figure which is considerably lower than the trigger energies normally quoted for purely inertial confinement. Lasers of the required output may already be technically feasible. A low heating efficiency can be tolerated for igniting a steady-state reactor; however, the efficiency of the CO_2 laser system could be quite high, and this fact permits an optmistic assessment of the possible capital cost of the laser equipment. Some of the more important problems affecting the success of such a scheme are the following:

(i) The D-T pellet injection problem. (Ablation controls the minimum size of pellet which it is technologically feasible to inject into the core of the reactor. This constraint will affect the number of lasers and their rate of firing in any optimised design.)

(ii) The actual (rather than assumed) scaling of particle and energy confinement times in the reactor.

(iii) The efficiency of energy absorption (i.e. accuracy of the non-linear theories etc.).

We discussed only the last of these problems in Section 3.

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REFERENCES

(1) Proceedings of the B.N.E.S. Conference on Nuclear Fusion Reactors, Culham Laboratory, 1969. (London, B.N.E.S., 1970).

(2) SPALDING, I.J. Nucl. Fusion 8, 161 (1969).

(3) CARRUTHERS, R. et al. Culham Laboratory Report CLM-R 85 (1967).

(4) LINHART, J.G. Nucl. Fusion 10, 211, (1970).

(5) HAUGHT, A.F. et al. United Aircraft Corporation Research Laboratories Report NYO 3578-11 (1969).

(6) EDEN, M.J. and SAUNDERS, P.A.H. Culham Laboratory Preprint CLM-P 226 (1969).

(7) FRAAS, A.P. ORNL (1969) (Unpublished).

(8) HORA, H. and PFIRSCH, D. 6th Int. Quantum Elect. Conferencen, Kyoto, Japan, August 1970, paper 2.2

(9) BASOV, N.G. and KROKHIN, O.N. Vest. Ak. Nauk SSR 40, 55 (1970).

(10) HILL, A.E. App. Phys. Lett 12, 324 (1968).

(11) BEAULIEU, A.J. 6th Int. Quantum Elect. Conference, Kyoto, Japan, August 1970, paper 18.7

(12) KAW, P. and DAWSON, J. Phys. Fluids 12, 2586, (1969).

(13) DAWSON, J. et al. Phys. Rev. Lett 24, 987 (1970).

(14) DUBOIS, D.F. and GOLDMAN, M.V. Phys. Rev. 164, 207 (1967).

(15) JACKSON, E.A. Phys. Rev. 153, 235 (1967).

(15) KROLL, N.M. et al Phys. Rev. Lett 13, 83 (1964).

(17) MONTGOMERY, D., Physica 31, 693 (1965).

(18) BORNATICI, M. et al. Phys. Fluids 12, 2362 (1969).

(19) (a) WORT, D.J.H. Culham Heating & Injection Study Group Report (Feb 1970) (unpublished)
(b) SPALDING, I.J. ibid (Appendix 3).

(20) JAMES, T.E. et al. Reference (1), paper 3.6

(21) BASOV, N.G. and KROKHIN, O.N. Proc. 3rd Int. Quantum Elect Conf. Paris, 1963. Paris, Dunod, 1964, vol.2, p.1373.

TABLE 1

LINHART TRIGGER CRITERION IN D-T MEDIUM

UNTAMPED

TRIGGER ENERGY $W_0 > 700 \left(\frac{n_s}{n_0}\right)^2$ MJ ... (1) (OPTIMISTIC)

N.B.

Eq.(1) is optimistic because the following processes (listed in order of importance) are neglected:

(a) heat conduction ahead of shock.

(b) ^{4}He energy deposition outside fusion zone.

(c) $T_i < T_e$.

(d) departure from self-similar distribution.

(e) undeveloped tail of Maxwellian ion-distribution.

(f) radiation losses.

Linhart estimates the importance of these effects and deduces the 'more realistic' value:

$$W_0 = 1000 \left(\frac{n_s}{n_0}\right)^2 \text{ MJ} \qquad \text{... (2)}$$

and target radius

$$r_0 = 0{\cdot}75 \left(\frac{n_s}{n_0}\right) \text{ cm} \qquad \text{... (3)}$$

TABLE 2

CURRENT HIGH-ENERGY DENSITY SOURCES

Source	Energy (W)	Duration (τ)
1. Pulsed Nd laser	~ 1000 J	~ 10^{-9} sec
	~ 50 J	~ 2×10^{-12} sec
2. Electron Beam (1 MA, 10 MV, 0·1 cm^2) (Physics Today, <u>22</u>, 67, 1969)	1 MJ	10^{-7} sec
3. Pulsed CO_2 laser (Beaulieu, Ref.(11)	~ 10 J	~ 10^{-7} sec
4. CW CO_2 laser (Avco, Physics Today, <u>23</u> (7) 55, July 1970)	600 kJ	(over 10 seconds)

TABLE 3

'ECONOMIC REACTOR' TARGETS (CULHAM STUDY)

	STELLARATOR	TOKAMAK/DIFFUSE PINCH
PLASMA RADIUS	1·5 m	1·0 m
MAJOR RADIUS	15 m	7 m
PLASMA DENSITY	3×10^{14} cm^{-3}	3×10^{14} cm^{-3}
APPROXIMATE IGNITION TEMPERATURE	6·4 keV (Galeev-Sagdeev)	10 keV
TOTAL NUMBER OF IONS	2×10^{23}	4×10^{22}
PLASMA ENERGY CONTENT	~ 700 MJ	~ 150 MJ
CONTAINMENT TIME	~ 1 sec	~ 1 sec
β	4-7%	

N.B.

1. MAXIMUM "ECONOMIC" COST OF REACTOR VESSEL AND BLANKET ~ £4 per kW(E) (Ref.(3)).
2. MAXIMUM CAPITAL COST OF HEATING EQUIPMENT/kW OF EFFECTIVE HEATING POWER
   - (a) Stellarator: ~ £400/kW Alpha particle heating
   - (b) Closed line: ~ £40/kW
   - (c) Mirror: £8/kW.
3. POSSIBLE STELLARATOR REACTOR HEATING TECHNIQUES.
   - (a) High Energy Neutral Injection (Ion source or Hall Accelerator)
   - (b) Transit Time Magnetic Pumping
   - (c) Non-linear laser heating??

TABLE 4

TYPICAL ABSORPTION LENGTHS (L) IN A THERMONUCLEAR PLASMA (T ~ 10^4 eV)

	n_e(cm^{-3})	λ(μm)	L(cm)	Mechanism
(1)	3×10^{14}	10	5×10^{10}	(classical)
(2)	3×10^{15}	200	1×10^{6}	(classical)
(3)	10^{17}	10	5×10^{5}	(classical)
(4)	~ 10^{19}	10	50	(classical)
(5)	~ 10^{19}	10	~ 3	Non linear (Kaw-Dawson) at $P = 3 \times 10^{11}$ W/cm^{-2} (i.e. × 10 threshold).

TABLE 5

Repetitive Stellarator Injection

Assume:

(1) Energy input 80 MJ $\sec^{-1}$ for 10 seconds

(2) 10 lasers around perimeter firing at $R = 100$ Hz.

Therefore:

(3) Each pellet contains $(2 \times 10^{23}) \times (10^{-4})$ particles.

i.e. pellet diameter $\sim 0{\cdot}1$ cm

Hence target plasma radius ($n = 10^{19}$ cm^{-3}) $r_0 \sim 0{\cdot}8$ cm (spherical)

Plasma radius ($n = 3 \times 10^{14}$ cm^{-3}) < 25 cm.

(4) Laser pulse length to heat inertially confined plasma of radius r_0.

$\tau \sim r_0/v_s < 8$ ns.

Equivalent length of light pulse < 240 cm

(5) Laser output = 80 kG; Laser power = 10^4 GW.

$P \sim 5 \times 10^{12}$ W cm^{-2}.

Assume:

(6) CO_2 laser gives 5 J/litre, $\therefore$ volume = 16,000 litres.

$\therefore$ Amplifier cross section $\sim 7 \times 10^4$ cm^2 (50 cm × 13 m ?)

(7) Transverse gas flow in laser should exceed

$$\frac{50\ \text{cm}}{10^{-2}\sec}, \text{ i.e. } v_\perp > 5 \times 10^3\ \text{cm}\ \sec^{-1} .$$

TABLE 6

COMPARISON OF PLASMA VOLUME AND LASER VOLUME

The plasma energy density and laser storage energy density are compared below:

REACTOR PLASMA		
1.	Plasma energy/cm^3 required for ignition of Stellarator ($\tau < 1$ sec)	600–1000 mJ cm^{-3}
SOLID STATE LASER		
2.	Photon energy/cm^3 from Nd glass rod (per second)	$\sim$ 300 mJ cm^{-3}
3.	Photon energy/cm^3 averaged over pumping cavity of Nd laser	$\sim$ 30 mJ cm^{-3}
MOLECULAR GAS LASER		
4.	Maximum photon energy/cm^3 available from pulsed atmospheric (10% CO_2) laser	$\sim$ 50 mJ cm^{-3}
5.	Pulsed CO_2 laser (actual)	$\sim$ 5 mJ cm^{-3}

N.B. Gas recirculation permits high repetition rates R ($\gg 1$ Hz), with consequent reduction in required laser volume by a factor $\geqslant$ R.

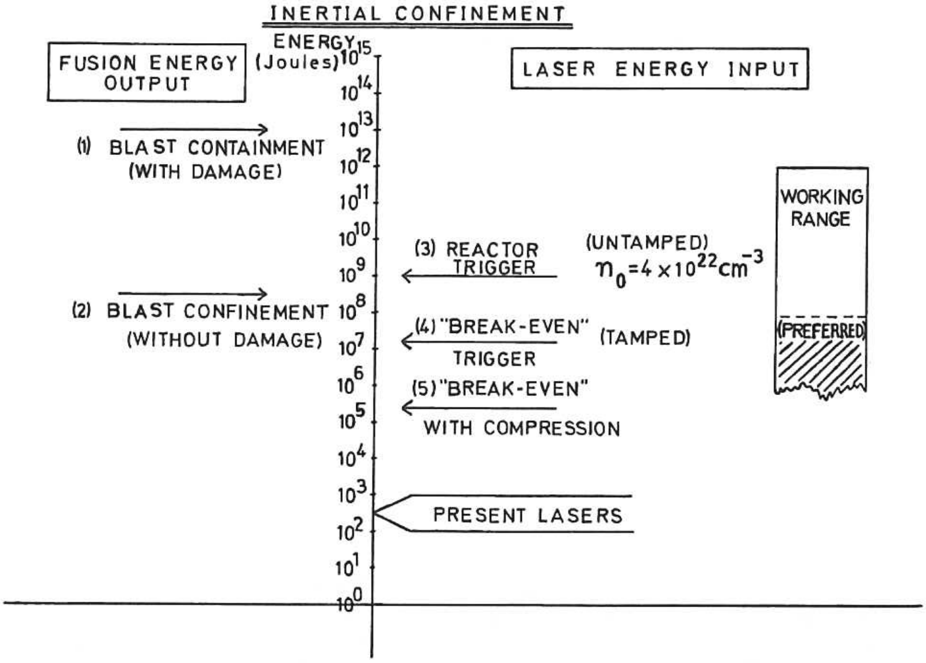

Fig.1 (1) Herlach & Knoepfel LGI 63/23 (Frascati)
(2) Fraas ORNL (1969)
(3) Linhart, Nuclear Fusion 10, 211 (1970) (Also Haught, Dawson, Saunders.)
(4) Lubin, to be published
(5) Hora & Pfirsch Kyoto Paper 2.2 (1970); Basov & Krokhin Vestnik Akademii Nauk SSSR 40, 55 (1970).

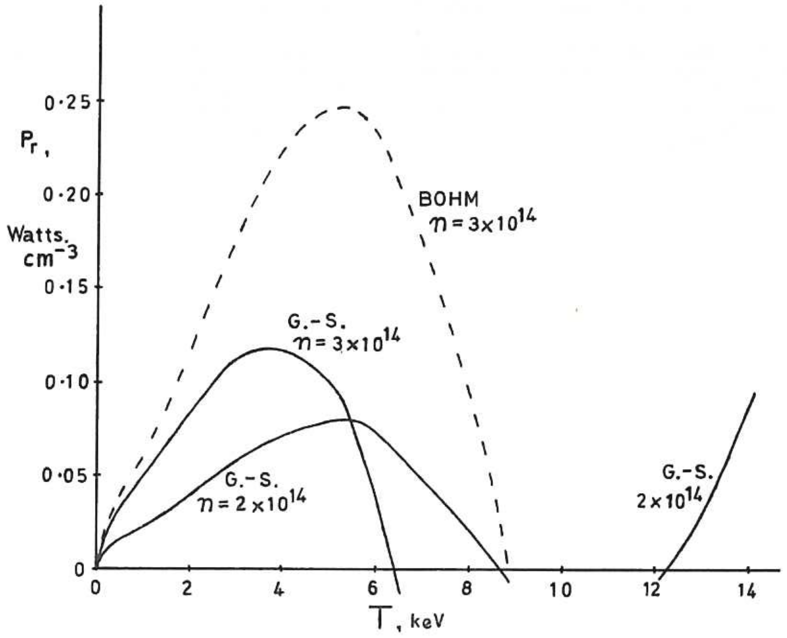

Fig.2 Power required (watts cm^{-3}) to maintain plasma at given temperature (keV) in R85 reactor, assuming Galeev-Sagdeev diffusion (solid curves) and Bohm (dashed curve)

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