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Physics and prospects of inertial confinement fusion

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Abstract. Some key physical aspects of the inertial confinement fusion (ICF) are discussed. The minimum scale of ICF microexplosions is determined by the ability to implode spherical shells with high radial convergence ratios C_R and high initial aspect ratios A_{R0}. The attainable values of C_R are limited by large-scale drive asymmetries, while the values of A_{R0} are constrained by the Rayleigh-Taylor instability. Under the indirect drive approach to ICF, it is easier to achieve the required uniformity of the drive pressure, but the penalty is a factor 4–5 reduction of the target energy gain as compared to the direct drive option. Spark ignition is a crucial issue for indirect drive targets (at least for those to be used in power reactors), while the targets driven directly by heavy ion beams could, in principle, utilize a less demanding volume ignition scheme.

1. Introduction

Inertially confined controlled fusion occurs when a small capsule containing a tiny amount of deuterium-tritium (DT) fuel undergoes a thermonuclear explosion. In a successful microexplosion, a substantial fraction of the initial DT mass (some 30–60%) must be depleted before the fuel is dispersed by enormous pressure generated in the explosion. For decades, the research in inertial confinement fusion (ICF) has been focused on achieving a successful ignition for

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the smallest DT mass possible.

The principal objective of the controlled nuclear fusion is a thermonuclear power station. If based on ICF, the microexplosions of DT pellets in a reactor chamber of such a station must follow one another at a frequency 1–10 times per second. It is quite conceivable however that an ICF power station will never be built, and thermonuclear microexplosions will be carried out individually in a laboratory facility (that such a facility can be built is now hardly doubted) with no (or very little) net energy gain. But even then an ICF laboratory facility will be so rich in applications – and especially so as the world is moving towards a comprehensive ban on the underground nuclear tests – that it will fully justify all the efforts and resources spent on ICF research. Below, I discuss some of the key aspects of the ICF physics and try to outline what has been achieved and what remains to be done with respect to each of these aspects.

2. Drivers for ICF and target energy gain

To ignite the DT fuel in a fusion capsule, a certain amount of driving energy must be delivered onto it. I will refer mainly to two (in some sense opposite) types of ICF drivers: lasers, which generate beams of massless neutral particles – photons, and accelerators of heavy ions, which generate beams of massive charged particles. Despite a steady progress in their development, light-ion drivers appear less promising than the heavy-ion ones because relatively higher beam currents severely aggravate the problems of beam transport and final focusing. Up to now, the experiments with ICF targets have been conducted by using mainly the laser drivers. The performance of ICF targets driven by heavy ion beams has been analyzed only theoretically.

Assuming that the ultimate goal is a thermonuclear power station, the driver efficiency η_{dr} and the target energy gain G, defined as the ratio of the thermonuclear yield in the capsule explosion to the drive energy delivered on the target, must satisfy the condition

$$\eta_{dr} G \gtrsim 10. \tag{1}$$

The efficiency of currently operating Nd glass lasers, used in ICF experiments, is $\eta_{dr} \lesssim 1\%$ [1], which practically excludes them as potential drivers for power reactors. For lasers to be a viable driver option for commercial reactors, a new generation of powerful lasers with $\eta_{dr} \simeq$ 5–10% has to be developed. If successful, such lasers will require targets with $G \gtrsim$ 100–200.

In contrast, the efficiency of heavy ion accelerators – even with the currently available technology – is $\eta_{dr} \simeq 25\%$ [2], which lowers the limit on the target energy gain down to $G \gtrsim 40$. In combination with high repetition rate, this is the main reason why heavy ion drive is considered as the most promising option for thermonuclear power generation. However, when compared with lasers, the ion beams are more difficult to focus on a small area and to compress into short pulses with duration $\lesssim 10$ ns.

3. Ignition criterion and fuel compression

To ignite the DT fuel, its temperature (at least in the spark region) must be raised to $T \gtrsim 5$ keV; to ensure a sizable burn-up fraction, a column density

$$\langle \rho R \rangle_m \gtrsim 2\text{–}3 \text{ g cm}^{-2} \tag{2}$$

must be reached in the fuel volume. Condition (2) implies that, if we want to ignite a mass M of DT, we must compress it to a density

$$\rho_m = \left[\frac{4\pi}{3} \frac{\langle \rho R \rangle_m^3}{M} \right]^{1/2} \approx 200\text{–}300 \text{ g cm}^{-3} \left(\frac{1 \text{ mg}}{M} \right)^{1/2} . \tag{3}$$

Hence, the minimum scale of thermonuclear microexplosions is determined by our ability to compress matter to very high densities.

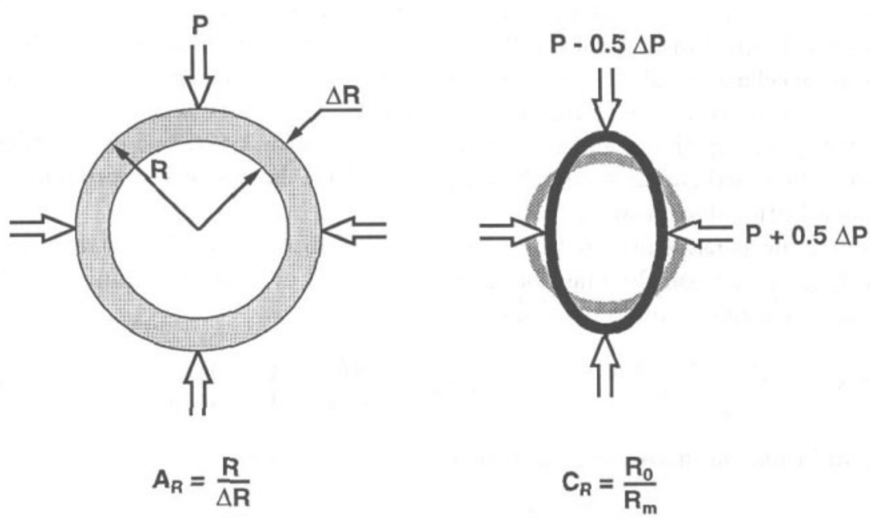

Figure 1. Basic features of DT fuel compression.

Any spherical implosion to a high density is inevitably distorted by the non-uniformity of the drive and imperfections of target fabrication, amplified by the Rayleigh-Taylor (RT) instability. On a large angular scale (low Legendre modes $l \lesssim 4$), the drive asymmetries play a dominant role and the RT amplification is not important. If we assume that a pressure perturbation $\pm\frac{1}{2}\Delta P$ in the $l = 2$

mode (see figure 1) should result in no larger than $\mp\frac{1}{2}R_m$ distortions of the fuel radius R_m at ignition, we conclude that the fuel convergence ratio is limited to

$$C_R \lesssim \frac{P}{\Delta P}. \tag{4}$$

For a peak-to-valley amplitude $\Delta P/P = 2\%$ we obtain $C_R \lesssim 50$. A more realistic value that has already been achieved in both the direct [3] and indirect [4] drive experiments will probably be $C_R \approx 30$.

For a given upper limit on the drive pressure P, it is advantageous to implode a thin shell rather than a solid sphere of DT (see figure 1). But even for a perfrectly uniform drive pressure, the implosion of a thin shell is limited by the RT growth of small short-wavelength perturbations. Both experiments and numerical simulations [5,6] demonstrate that even when only natural-noise initial disturbances are present, the mixing layer advances into the heavier fluid as

$$h_1(t) = 0.07\, A_{12}\, gt^2. \tag{5}$$

With the Atwood number A_{12} typically close to 1, equation (5) implies that an accelerated shell can travel only about 7 its inflight thicknesses before being disrupted by the RT instability. Ablative stabilization increases this number by a factor of 3–4 [7]. Since capsule shells are accelerated typically over about one half of their initial radius, their inflight aspect ratios are limited to $A_R \lesssim 40$–60. Because accelerating shells are compressed by about a factor 4 as compared to their initial state, the initial aspect ratios should not exceed $A_{R0} \approx 10$–15. (Strictly speaking, this argument applies to the ablator layer; but in optimized capsules the plastic ablator and the liquid (solid) DT layers have approximately the same initial thicknesses.)

Given the constraints on the convergence ratio C_R and the initial aspect ratio A_{R0}, we can use the mass balance equation to evaluate the minimum DT mass for a successful microexplosion:

$$M \gtrsim \frac{4\pi}{3} \frac{(\langle\rho R\rangle_m)^3}{\rho_0^2} \left(\frac{A_{R0}}{3}\right)^2 \frac{1}{C_R^6} = 80\ \mu\text{g} \left(\frac{\langle\rho R\rangle_m}{3\ \text{g cm}^{-2}}\right)^3 \left(\frac{A_{R0}}{15}\right)^2 \left(\frac{30}{C_R}\right)^6. \tag{6}$$

If, in addition, we invoke the equation of energy balance

$$\frac{4\pi}{3} R_0^3\, P = 4\pi R_0^2\, \Delta R_0\, \rho_0\, \epsilon_m, \tag{7}$$

where

$$\epsilon_m = 3.27 \times 10^{12}\ \text{erg g}^{-1}\ \alpha_F\, \rho_m^{2/3} \tag{8}$$

is the specific energy of compressed fuel and α_F is the ratio of the total DT pressure to the degenerate Fermi pressure, we obtain a lower bound on the drive pressure,

$$P \gtrsim 70\ \text{Mbar} \left(\frac{\alpha_F}{4}\right) \left(\frac{15}{A_{R0}}\right)^{5/3} \left(\frac{C_R}{30}\right)^2, \tag{9}$$

and on the energy investment into the fuel,

$$E \gtrsim 10 \text{ kJ} \left(\frac{\alpha_F}{4}\right) \left(\frac{\langle\rho R\rangle_m}{3 \text{ g cm}^{-2}}\right)^3 \left(\frac{A_{R0}}{15}\right)^{4/3} \left(\frac{30}{C_R}\right)^4. \qquad (10)$$

When combined with the laser-fuel coupling efficiency $\eta_{lf} \simeq 2\%$ for indirect, and $\eta_{lf} \simeq 10\%$ for direct drive targets (see section 5 below), this simple estimate gives a good idea why a laser with an output energy $E_l \gtrsim 0.5$–1 MJ ($E_l \gtrsim 100$–200 kJ) is needed for an ICF microfusion facility under the indirect (direct) drive approach. For comparison, note that the indirect-drive implosion experiments have been conducted so far with the $E_l = 30$–50 kJ NOVA [4] and $E_l = 6$–10 kJ GEKKO-XII [3] lasers, while the direct-drive experiments — mostly with the $E_l = 1.5$–2 kJ OMEGA [1] laser.

4. Spark ignition versus volume ignition

The fusion energy deposition by alpha-particles exceeds the bremsstrahlung energy losses from the DT fuel at $T > 5$ keV. It does not however mean that the entire fuel must be heated to this temperature to obtain ignition. It is sufficient to create a hot spot (thermonuclear spark) with $T > 5$ keV and $\langle\rho R\rangle \simeq 0.3$ g cm^{-2}, which initiates a self-sustaining burn wave propagating into the cold fuel layers (see figure 2).

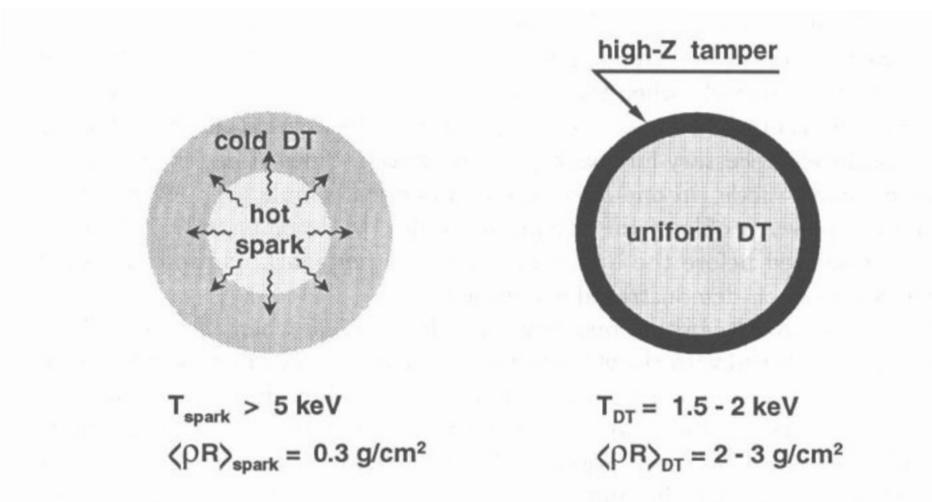

Figure 2. Compressed fuel configurations that correspond respectively to spark and volume ignition modes.

Clearly, spark ignition is energetically more economical than the volume ignition, where the entire fuel mass must be heated to a high temperature. The advantage, however, turns out to be not very big when two modes of ignition are compared under the assumptions that (a) the pressure is uniform over the fuel volume at the time of stagnation, and (b) the DT fuel is surrounded by a high-Z tamper in the case of volume ignition (see figure 2). Under such conditions, the best spark ignition configuration exhibits only about a factor 2 higher energy gain (for DT masses $M < 10$ mg) than the best configuration with volume ignition. In reality, the advantage of the spark ignition may be somewhat higher because the pressure in the cold fuel is somewhat lower than in the hot spot.

Relatively high gains of uniformly igniting DT microspheres are due to the fact that a high-Z tamper around the fuel is opaque for the bremsstrahlung radiation and locks it inside the DT volume. With the bremsstrahlung energy losses strongly suppressed, the DT fuel ignites at $T \simeq 1.5$–2 keV rather than at $T = 5$ keV. In addition, the inertia of the massive tamper provides an extra confinement, which also leads to lower ignition temperatures. A major problem for this scheme arises from the RT instability of the fuel-tamper interface during the deceleration phase: the resulting mixing of the tamper material into the fuel may prove this ignition mode to be unpractical. As for now, no comprehensive study of this issue has been published yet.

Spark ignition is a key aspect of the indirect drive option for a power reactor. Without it, the target energy gains may never reach the power-plant threshold $G = 40$ even for the heavy ion drive. To obtain spark ignition, the bulk of the DT fuel must be compressed along a low adiabat, avoiding strong shocks. Usually, this is achieved by carefully tailoring the power of the driving pulse to rise gradually from a low prepulse to the high main-pulse level. A central hot spot is created naturally when the first shock passes through a low-density DT vapour in the central cavity of the fusion capsule. However, the pulse shaping is not absolutely necessary for spark ignition: certain types of heavy ion targets ignite via spark mode (in one-dimensional numerical simulations) even with a rectangular power profile of the driving pulse [9,11]. Unfortunately, it has not yet been disclosed before the broad audience whether spark ignition in proper sense has ever been demonstrated experimentally.

In contrast, spark ignition becomes much less critical when the direct drive approach is combined with the efficient heavy ion driver. The more so that, with heavy ion drive, it is generally more difficult to reach high implosion velocities required for spark ignition. One-dimensional energy gains $G \simeq 100$–200 have been calculated for heavy ion targets with volume ignition under the conditions of perfectly symmetrical illumination and with the RT instability ignored [9]. However, it is not clear so far whether it will be possible to design an ion focusing system with a sufficient symmetry of target irradiation, and how strongly will the performance of such targets be downgraded by the RT instability.

5. Direct drive versus indirect drive

A straightforward way to implode the fusion capsule is to deposit the drive energy directly in its outer layer – the ablator in laser driven targets, the absorber in heavy ion targets. In this case, however, any non-uniformity in the incident energy flux is transformed into an almost equally strong non-uniformity of the drive pressure. Some 50 to 100 uniformly spaced and accurately tuned beams may be needed to keep $\Delta P/P \lesssim 2\%$. Also, the brightness profile of each beam must be smooth enough, which is not easy to achieve with a highly coherent laser light.

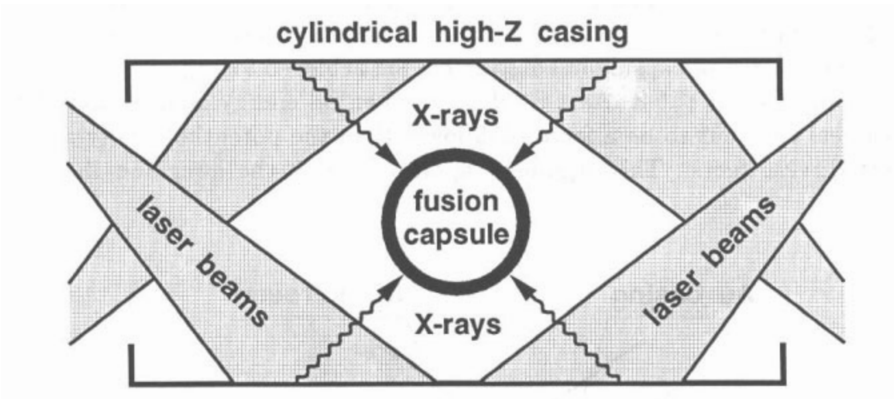

Figure 3. Hohlraum target for indirect laser drive.

The required uniformity of the drive pressure is considerably easier to achieve by using indirect drive, where the laser (ion) energy is converted into an intense field of thermal X-rays inside a cavity (hohlraum), and the X-rays drive the implosion of the fusion capsule. A sketch of an indirect drive target used in laser ICF experiments [10] is shown in figure 3. To minimize the radiation losses from the hohlraum, the cavity walls are made of a high-Z material. The geometry of the hohlraum and the beam configuration are arranged in such a way as to eliminate the lowest $l = 1$ and $l = 2$ Legendre modes in the non-uniformity of the ablation pressure on the fusion capsule. The higher modes are suppressed by radiative symmetrization inside the hohlraum.

An additional stage of energy conversion in indirect drive targets is the main cause of their lower overall efficiency as compared to direct drive targets. For a rough comparison, we can assume that the energy gain of a direct drive target G_{dir} is about equal to the energy gain of the fusion capsule inside an indirect drive target estimated with respect to the absorbed energy of X-rays. Then

$$G_{ind} = \eta_x \eta_t G_{dir}, \tag{11}$$

where $\eta_x = 0.7$–0.8 [4] is the efficiency of conversion into X-rays, and η_t is the fraction of the X-ray energy absorbed by the capsule. We can evaluate η_t as

$$\eta_t = \frac{S_{caps}F_{caps}}{S_{caps}F_{caps} + S_{case}F_{case}}, \tag{12}$$

where S_{caps} and S_{case} are the areas of the capsule and casing surfaces, and F_{caps} and F_{case} are the X-ray energy fluxes absorbed by these surfaces. For a carbon (plastic) capsule ablator and a gold casing irradiated by thermal X-rays with $T_x = 250$–300 eV, the ratio $F_{caps}/F_{case} \approx 5$. It appears hardly realistic that a sufficient symmetry of capsule irradiation can be achieved for $S_{case}/S_{caps} < 10$, which implies that $\eta_t \lesssim 0.3$. As a result, the potential energy gains of indirect drive targets turn out to be a factor 4–5 lower than the potential energy gains of direct drive targets. This argument applies to both the laser and the ion drive.

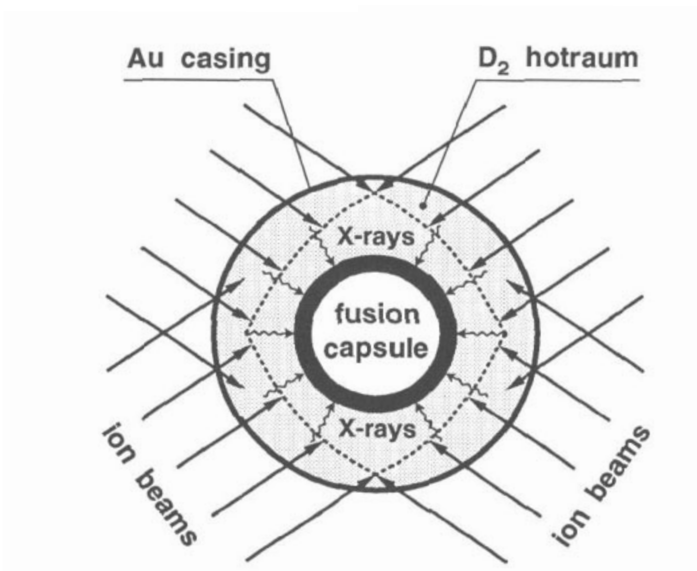

Figure 4. Hotraum target for indirect heavy ion drive.

Several concepts of direct and indirect drive targets for heavy ion fusion have been discussed in literature, but none of them has been tested experimentally. Figure 4 shows a recently proposed "hotraum" target [11], where the hohlraum is filled with deuterium at initial density $\simeq 0.1$ g cm^{-3}. Deuterium is transparent to X-rays with $T_x = 200$–300 eV, but absorbs the final energy portion of irradiating 6 GeV bismuth ions. The initial target configuration – in contrast to that shown in figure 3 – is perfectly spherical, which would make it much easier to inject such targets into a reactor chamber at a frequency 1–10 times per second. The energy gains calculated for this type of target with one-dimensional code fall in the range $G = 50 - 80$.

6. Conclusion

Substantial progress in experiments with indirectly driven targets, reported recently from Lawrence Livermore National Laboratory [12], leaves little doubt that ignition and moderate gain can be achieved along this direction when the Nova Upgrade laser with an output energy $E_l = 1.5$–2 MJ becomes operational. More uncertain is whether indirect drive targets will ever be able to demonstrate energy gains $G \approx 100$ with the input energy $E_l \lesssim 10$ MJ [13]. Significant steps forward have been made also along the direct laser drive approach [1,3]. However, one more step is needed – such as the OMEGA Upgrade facility with $E_l = 30$ kJ in 60 uniformly spaced beams [1] – before it will be possible to assess the feasibility of ignition and high gain in direct drive laser targets. In what concerns heavy ion drive, the basic programme of ICF target experiments is still to be formulated.

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