BULLETIN OF THE POLISH ACADEMY OF SCIENCES
TECHNICAL SCIENCES, Vol. 60, No. 4, 2012
DOI: 10.2478/v10175-012-0084-8

Laser nuclear fusion: current status, challenges and prospect

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Abstract. In 2009, in Lawrence Livermore National Laboratory, USA, National Ignition Facility (NIF) – the largest thermonuclear fusion device ever made was launched. Its main part is a multi-beam laser whose energy in nanosecond pulse exceeds 1MJ (10^6 J). Its task is to compress DT fuel to the density over a few thousand times higher than that of solid-state DT and heat it to 100 millions of K degrees. In this case, the process of fuel compression and heating is realized in an indirect way – laser radiation (in UV range) is converted in the so-called hohlraum (1 cm cylinder with a spherical DT pellet inside) into very intense soft X radiation symmetrically illuminating DT pellet. For the first time ever, the fusion device's energetic parameters are sufficient for the achieving the ignition and self-sustained burn of thermonuclear fuel on a scale allowing for the generation of energy far bigger than that delivered to the fuel.

The main purpose of the current experimental campaign on NIF is bringing about, within the next two-three years, a controlled thermonuclear 'big bang' in which the fusion energy will exceed the energy delivered by the laser at least ten times. The expected 'big bang' would be the culmination of fifty years of international efforts aiming at demonstrating both physical and technical feasibility of generating, in a controlled way, the energy from nuclear fusion in inertial confined plasma and would pave the way for practical realization of the laser-driven thermonuclear reactor.

This paper briefly reviews the basic current concepts of laser fusion and main problems and challenges facing the research community dealing with this field. In particular, the conventional, central hot spot ignition approach to laser fusion is discussed together with the more recent ones – fast ignition, shock ignition and impact ignition fusion. The research projects directed towards building an experimental laser-driven thermonuclear reactor are presented as well.

Key words: laser, plasma, inertial fusion, laser acceleration.

1. Introduction

Nuclear fusion is one of the most promising and forward-looking directions in search of new sources of energy. The main advantages of fusion energy, as opposed to the energy sources using fossil resources or the nuclear energy using a heavy nuclei fission reaction, are as follows: (a) practically unlimited resources of raw materials (deuterium from sea water and lithium for the production of tritium – in the crust of the earth), (b) energy produced is "clean" (it does not emit greenhouse gases and there is no long-lived radio-active waste), (c) fusion power plant is safe (there is no possibility of uncontrolled "nuclear explosion"). As opposed to the so-called renewable energy sources (solar, wind, etc.), the energy production using nuclear fusion is incomparably more efficient.

The fusion reaction of nuclei of hydrogen isotopes, namely deuterium (^{2}H or D) and tritium (^{3}H or T) is the core of fusion energy (although other less efficient reactions are taken into consideration as well). As a result of this reaction, helium nucleus (^{4}He) and a neutron are produced and energy of 17.6 MeV is emitted (including 14.1 MeV of the neutron energy), much higher then the initial energy of deuterium and tritium. In order the reaction efficiency was high and energy production in a macroscopic scale was possible, the energy of colliding nuclei of deuterium and tritium must be high enough (to overcome the electrostatic repulsion between nuclei), and those reactions should take place in sufficiently large amounts and under appropriate conditions. The environment in which those conditions may be close to optimal is deuterium-tritium (DT) plasma of temperature $\sim$ 10 keV ($\sim$ 100 millions of Kelvin degrees) and of appropriate density and volume. If such plasma can be generated, the main problem is to confine it in time to let the substantial amount of DT fuel "react". In space conditions, high-temperature hydrogen plasma is confined by gravitational forces (in the Sun and other stars). In terrestrial conditions, the confinement of hot plasma is possible either by a strong magnetic field or inertial forces. In the first case we are talking about magnetic confinement fusion (MCF), and in the second one – about inertial confinement fusion (ICF) or inertial fusion.

The inertial fusion with a high energy gain was demonstrated (in the form of a hydrogen bomb) almost 60 years ago. Unfortunately, the solution used in this case (nuclear fission explosion as a driver of DT fusion) is not suitable to be implemented in case of the controlled and "clean" fusion energy production. The driver in the case of the controlled inertial fusion is now a laser, and laser fusion right now is a synonym for inertial fusion.

This paper briefly reviews the basic current concepts of laser fusion and main problems and challenges facing the research community dealing with this field. In particular, the conventional, central hot spot ignition approach to laser fusion is discussed together with the more recent ones – fast ignition, shock ignition and impact ignition fusion. The research projects directed towards building an experimental laser-driven thermonuclear reactor are presented as well.

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2. Basic concepts of laser fusion

In the conventional approach to the laser fusion, as proposed in the early 70s [1], a spherical target containing DT fuel is symmetrically illuminated by many beams of a nanosecond laser or X-rays generated by this laser, as a result of which rapidly expanding plasma is produced on the target's surface. The momentum of the expanding plasma is balanced by the momentum of the inner part of the target, which leads to the implosion of the target and the fuel compression. The decrease of volume of the imploding target is accompanied by the increase of the temperature inside of it (the process is roughly of isobaric character) and the increase of the fuel density. At sufficient reduction in volume, the temperature in the centre of properly designed target rises to very high values ($\sim$10 keV). A "hot spot" is formed which allows the self-ignition of the fuel (the situation here is analogous to the diesel engine). Such kind of the fuel ignition is referred to as central ignition (CI) or central hot spot ignition (CHSI). In order the energy produced in the fusion reactions, E_{fuz}, was higher than the energy of the laser, E_{las}, (the energy gain G = $E_{fus}/E_{las} > 1$) the density of the compressed fuel should be very high (over 1000 times the density of a solid DT) and its mass should exceed a certain critical value ($\sim$ mg). Achieving such extremely high temperatures and densities of the DT fuel with supercritical mass using CHSI approach requires the nanosecond laser ($\sim$10ns) with very high energy ($E_{las} \geq$ 1MJ = 10^6J), extremely high symmetry of the target's illumination and meeting several other technically difficult conditions [2] (see below). To reduce these requirements, several alternative ways to ignite the fuel have been proposed. They include:

- fast ignition (FI) [3]; in this approach the ignition of the DT fuel, initially compressed with a multi-beam laser to the density of $\sim$1000 densities of the solid DT, is done as a result of its very rapid heating (over $\sim$10–20ps) by a very intense (intensity I $\sim 10^{20}$ W/cm^2) flux of particles (electrons or ions) [4–6] (in this case the situation is analogous to that in a petrol engine where the ignition of the compressed fuel is initiated with a spark from the spark plug);
- shock ignition (SI) [7]; in this case the "ignitor" is a strong, converging shock wave generated in the DT target in the final stage of its compression with the most intense final part of appropriately shaped laser pulse compressing the fuel (in fact, it is an intermediate variant between the fast ignition made by the outer energy source and CHSI variant discussed earlier);
- impact ignition (II) [8, 9], in which a rapid heating of the compressed fuel is the result of the impact of a microprojectile of m $\sim 10^{-6}$–10^{-4}g accelerated to the velocity of $>$ 1000 km/s.

All these advanced concepts promise higher energy gain G with laser energy much lower than in the case of CHSI. However, independently of the ignition scheme, to achieve ignition and energy gain some basic conditions for parameters of the compressed DT fuel have to be fulfilled. They concern the ion temperature T, the density ρ_f and the areal mass density (the "confinement parameter") $\rho_f r_f$ of the fuel [2] (r_f is the compressed fuel radius). The temperature should be roughly in the range $\sim$10–100 keV as below 10 keV the rate of D – T reaction is much lower than that at the optimum T $\sim$30 keV. Minimum values for ρ_f and $\rho_f r_f$ can be derived from the assumption that permissible mass of DT fuel (limited by the permissible explosion energy of $\sim$1 GJ) is limited to $m_0 \sim 10$ mg:

$$m_f = (4\pi/3)\rho_f r_f^3 < m_0, \tag{1}$$

and that the burn fraction ϕ (it defines this part of the fuel which is actually consumed) is higher than some practically useful value ϕ_0 [2]:

$$\phi = \frac{\rho_f r_f}{\rho_f r_f + H_B} > \phi_0, \tag{2}$$

where H_B(T) is the co called burn parameter – a slowly varying function of the ion temperature equal $\sim$7 g/cm^2 at T$\sim$30 keV [2].

Assuming $m_f = 10$ mg, $H_B = 7$ g/cm^2 and $\phi_0 = 0.2$, we arrive at:

$$\rho_f > 200 \text{ g/cm}^3, \tag{3}$$

$$\rho_f r_f > 2 \text{ g/cm}^2. \tag{4}$$

It should be noted, however, that the hot spot areal density can be much lower than that determined by (4): $\rho_{hs} r_{hs} \approx 0.2$–0.4 g/cm^2 [2] though the hot spot density should be high and the temperature T_{hs} must be $\sim$10 keV.

3. Central hot spot ignition scheme

As it was explained in Sec. 2, in the CHSI option of laser fusion self-ignition of nuclear fuel takes place in the centre of a spherical DT pellet due to roughly isobaric compression of the pellet to very high densities ($\rho_f >$ 1000 densities of solid DT). Particular stages of the CHSI fusion are shown in Fig. 1: a) laser beams or laser-produced X-rays rapidly heat the surface of the fusion pellet, forming plasma expanding outwards with a high velocity ($\sim 10^8$ cm/s), b) due to the rocket-like blow-off of the hot plasma a strong converging shock wave is formed near the plasma ablation surface which compresses DT fuel inside the pellet, c) during the final stage of the pellet implosion the fuel density reaches very high value and the temperature in the pellet centre (at hot spot) attains $\sim$10 keV and the hot spot is ignited, d) thermonuclear burn spreads rapidly through the compressed high-density fuel, yielding many times the input laser energy.

CHSI can be realized both in the direct-drive and indirect-drive scheme – Fig. 2. In the first one, many (tens), ultraviolet nanosecond laser beams symmetrically irradiate the fusion pellet directly (Fig. 2a). In the second one, the pellet is placed in a small ($\sim$1 cm) cylinder, called hohlraum, made of high-Z metal (Au, U or some high-Z metals mix) (Fig. 2b). The laser beams irradiate the inner side of the hohlraum, heating it to produce hot plasma which radiates mostly thermal soft X-rays. The X-rays from this plasma are then absorbed by the target surface, imploding it in the same way as if it had been hit with the laser beams directly. The absorption of thermal X-rays by the target is more efficient than the direct absorption of laser light, however, the hohlraum also takes up considerable energy to heat on their own thus significantly reducing the overall efficiency of laser-to-target energy transfer.

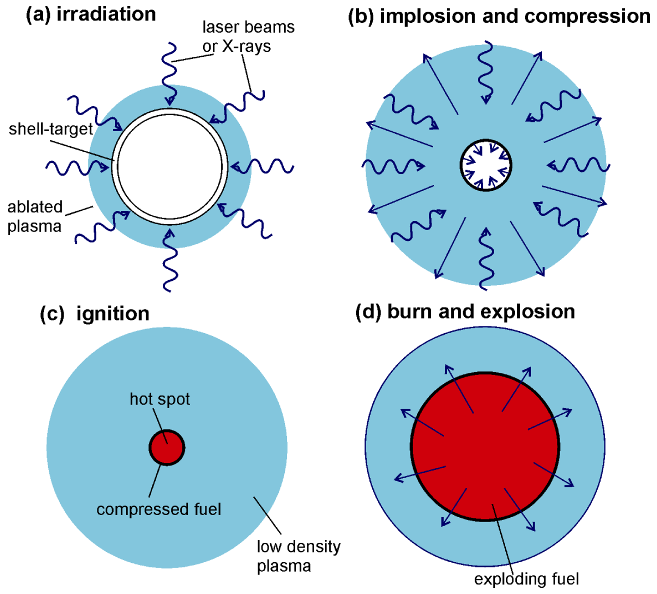


Fig. 1. Scheme of stages of laser fusion (see the text)

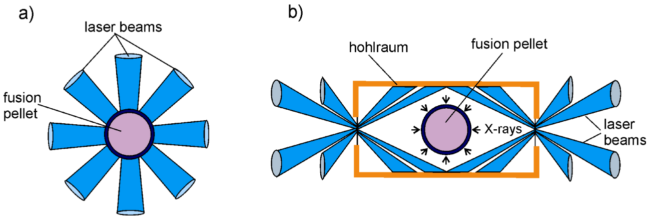


Fig. 2. The direct-drive (a) and indirect-drive (b) schemes of laser fusion

The main challenges for the direct-drive and indirect-drive CHSI fusion are basically the same. They include: achieving high laser-fuel energy transfer efficiency, controlling symmetry of the imploding fuel, preventing pre-heating of the fuel by hot electrons and X-rays, preventing premature mixing of hot and cool fuel by hydrodynamic (mostly Rayleigh-Taylor (RT)) instabilities, and the formation of a "tight" shockwave convergence at the compressed fuel center. To meet these requirements, short-wavelength radiation must be used to compress the fuel, the pellet must be made with extremely high precision and sphericity with aberrations of no more than a few micrometres over its surface (both inner and outer), the laser (X-ray) beams must be extremely precise and the beams must arrive at the same time at all points on the pellet.

The advantage of the indirect-drive scheme is more stable and more symmetric implosion (irradiation of the pellet by thermal radiation in the hohlraum is more homogeneous than by many laser beams) as well as higher ablation pressure (due to shorter wavelength of X-rays), therefore lower energy absorbed in the pellet is required to compress the fuel. However, due to lower overall energetic efficiency of this scheme usually higher input laser energy is needed here for fusion ignition than in the case of direct-drive scheme. Anyway, for both schemes this energy is an order of 1MJ.

At present, only one laser facility produces laser energy above 1 MJ and is able to meet requirements for fusion ignition and energy gain. This is the National Ignition Facility (NIF) launched at Lawrence Livermore National Laboratory in USA in 2009 [10]. In the advanced stage of construction is also the megajoule laser facility LMJ in France which is predicted to be launched in 2014 [11]. Both NIF and LMJ are designed to achieve ignition and energy gain G∼10 using the indirect-drive CHSI scheme.

National Ignition Facility. The principal goal of NIF (Fig. 3) is to achieve ignition of a DT fuel pellet and provide access to high-energy-density physics regimes needed for experiments related to national security, fusion energy, and frontier scientific exploration in such fields as astrophysics, nuclear physics, and material science. To reach this goal, the National Ignition Campaign (NIC) was established in an aim to perform credible experimental campaigns on NIF and demonstrate, within a few years, a reliable and repeatable fusion ignition source. The first stage of NIC is focused on refining detailed requirements on targets, laser and diagnostics to optimise the compression and ignition process and to balance a risk.

The laser beams in NIF begin with nanojoule pulses from a solid-state laser (Fig. 3). The precisely shaped ∼15 ns pulses are divided into 48 beams and passed through preamplifiers. Those beams are subsequently divided further into a total of 192 beams, each about 40 cm square in profile, that pass six times through Nd:glass amplifiers, ultimately achieving a total of 4 MJ of 1051 nm laser light. These 192 beams are transported in sets of four "quads" to a target chamber, at which KDP crystal sheets convert the 1051 nm (1ω) light first to 526 nm (2ω) light, then in a second KDP crystal to 1.8 MJ of 351 nm (3ω) light. This ultraviolet light beams then enter a 10 m diameter target chamber, where the beams are focused onto the inner wall of a hohlraum, that houses the DT spherical pellet (Fig. 4). The laser light produces X-rays inside the hohlraum that ablate the shell of the pellet, which then heats and compresses the DT fuel to the temperature of ∼10 keV and density of several hundred gcm^{-3}, which should produce ignition. Under these conditions, the DT fuel in the pellet should burn to produce more than 10 MJ of energy within 10–100 ps.

Over two-year experimental and numerical efforts within NIC have resulted in significant improvements in the NIF laser parameters (e.g. increase in UV laser energy from 1.1 MJ to 1.7 MJ), the hohlraum X-rays parameters [12, 13], symmetry [14] and velocity [15] of the pellet implosion as well as in parameters of the compressed fuel [16]. In particular, in the first implosion experiment with cryogenic (0.17 mg) DT fuel, performed with 192 UV laser beams of total energy of 1.6 MJ, extremely high compressed fuel parameters were achieved [16]: the fuel density $\rho_f \approx 600$ g/cm^3 (more than 2000 of the solid DT density), the fuel areal density $\rho_f r_f \approx 1$ g/cm^2 and the average ion temperature of the fuel T ≈ 3.5 keV, and, as a result, 10^{15} fusion neutrons were produced. Although these parameters are still lower than required for ignition and significant energy gain, it is believed that this goal is to be reached within next two years. If achieved, the ignition and energy gain on NIF would be a major step towards demonstrating the feasibility of energy production from fusion and would likely open the door for building an experimental laser-driven fusion reactor. It would also be highly stimulating for the development of advanced laser fusion concepts described in the next section.

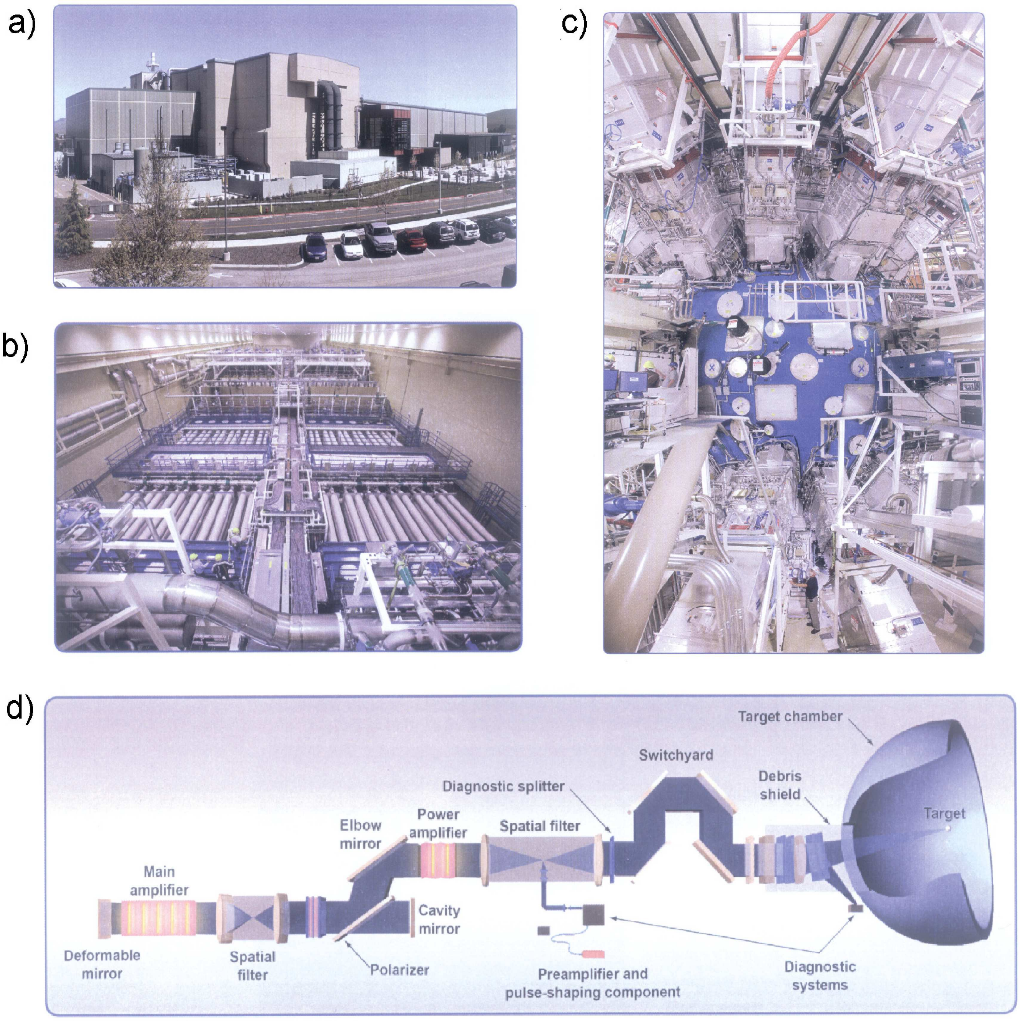


Fig. 3. National Ignition Facility: a) the NIF building, b) the laser bay, c) the vacuum chamber with diagnostics, d) scheme of the laser

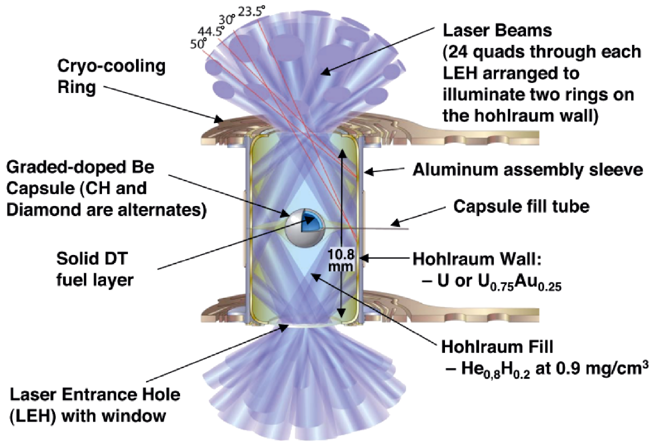


Fig. 4. The hohlraum target used for indirect-drive CHSI fusion at NIF

4. Advanced laser fusion concepts

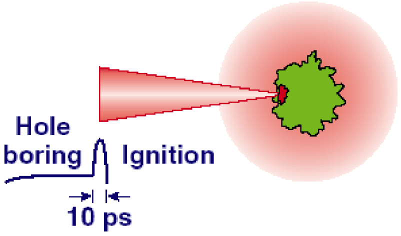
4.1. Fast ignition. Fast ignition (FI) [3–6] is a novel approach to laser fusion which differs from the conventional CHSI fusion in using separate drivers for compression and ignition of the hydrogen fuel. In this approach, the fuel pre-compressed by a long-pulse (ns) driver (laser beams, X-rays) is ignited by a short-pulse (ps) ultra-intense ($\sim 10^{20}$ W/cm^2) particle beam. FI has some significant potential advantages over the conventional laser fusion: higher gain, lower overall driver energy, the reduction in symmetry requirements, and flexibility in compression drivers. The price to be paid is the need for efficient production and coupling to the fuel of a particle beam of extreme parameters.

FI requires that a small part ($\sim 10^{-5}$ g) of DT fuel compressed to about 1000 times the solid density ($\rho_f > 200$ g/cm^3) is heated by an external ignitor to temperature

$\sim$10 keV. If the volume of the compressed fuel is sufficiently large (the confinement parameter $\rho_f r_f > 2$ g/cm^2), a thermonuclear burn wave ignited in the hot spot propagates through the fuel and thus energy is produced. To compress the fuel, both direct-drive and indirect-drive approaches can be used. In the second approach, the X-rays can be produced by a laser, by a heavy ion beam from an accelerator, or by a Z-pinch [2]. As an ignitor, a fast electron, proton, or light ion beams [3–6] driven by a short-pulse (ps) PW laser can be used though conventionally accelerated heavy ion beams [17] are considered as well.

In the original FI scheme of Tabak et al. [3] the ultra-intense $\sim$10-ps laser pulse penetrates close to the dense fuel through a channel bored in the surrounding plasma by light pressure of a preceding $\sim$100-ps laser pulse (Fig. 5a) The relativistic (MeV) electron beam produced at the interaction of the ultra-intense pulse with the critical surface of the dense plasma core ignites the fuel. A crucial issue for this scheme is the effective formation of the channel and transport the ultra-intense pulse through it.

a) channeling FI concept



b) cone-in-shell FI concept

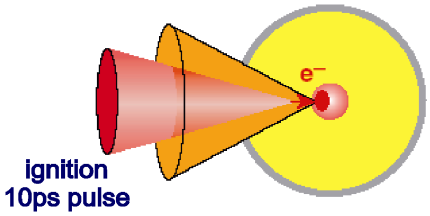


Fig. 5. Two basic concepts of fast ignition: a) the original concept of Tabak et al., which uses hole-boring and ignition pulses, b) the cone-in-shell concept using a single picosecond pulse penetrating close to the dense fuel core through a hollow cone

More recently proposed, an alternative FI concept uses a hollow high-Z cone inserted into a standard spherical shell target [18, 19] (Fig. 5b). The cone provides an open path for the ultra-intense laser beam and allows the beam to be focused inside the cone and to generate fast electrons at its tip, very close to the dense plasma produced by the cone-guided implosion. A variant of the cone scheme uses a thin foil target, placed in the cone in some distance from the cone tip, to generate proton (ion) beam igniting the compressed fuel [4–6]. The cone concept makes transport of the ignition laser beam toward the dense fuel core easier, but – on the other hand – it complicates the target structure and disturbs spherical symmetry of implosion.

The first integrated (compression + heating) FI-related experiment was performed by Japan /UK team [19]. They used the Gekko XII nanosecond laser (9 beams/2.5 kJ/0.53 μm) for CD shell implosion in cone-guided geometry and the PW laser (300 J/0.5 ps) for fast plasma heating. It was found that the neutron yield increased by 1000 times (from 10^4 to 10^7) due to the PW laser heating and the PW laser-thermal plasma coupling efficiency approached 20–30%. It was also inferred that the cone does not substantially degrade the target implosion. This breakthrough experiment provided a strong support for the FI concept and stimulated worldwide FI research.

General requirements for the fast ignitor were determined by a series of 2D numerical hydrodynamic simulation in [20]. Optimal values of the ignitor beam energy E_{ig} and intensity I_{ig} to be delivered to the fuel and corresponding optimal pulse duration τ_{ig} and beam radius r_{ig} were parameterized as a function of the fuel density:

$$E_{ig} = E_{opt} = 18\left(\frac{\rho_f}{300\ \text{g/cm}^3}\right)^{-1.85}\ \text{kJ}, \tag{5}$$

$$I_{ig} = I_{opt} = 6.8\times 10^{19}\left(\frac{\rho_f}{300\ \text{g/cm}^3}\right)^{0.95}\ \text{W/cm}^2, \tag{6}$$

$$\tau_{ig} = \tau_{opt} = 21\left(\frac{\rho_f}{300\ \text{g/cm}^3}\right)^{-0.85}\ \text{ps} \tag{7}$$

$$r_{ig} = r_{opt} = 20\left(\frac{\rho_f}{300\ \text{g/cm}^3}\right)^{-0.97}\ \mu\text{m}. \tag{8}$$

The formula (5) shows that the required ignitor energy decreases fairly rapidly when the fuel density increases. However, the higher ρ_f, the higher the demands for the compression driver. As a compromise, the value $\rho \approx 300$ g/cm^3 is usually accepted. For such density, the ignitor parameters are as follows:

$$\begin{gathered} E_{ig} \approx 17\ \text{kJ}, \qquad I_{ig} \approx 7\times 10^{19}\ \text{W/cm}^2, \\ \tau_{ig} \approx 20\ \text{ps}, \qquad r_{ig} \approx 20\ \mu\text{m}. \end{gathered} \tag{9}$$

These parameters are extremely demanding and cannot be achieved with a conventional particle accelerator. The only way to produce such ultra-intense particle beams seems to be the use of laser acceleration [4–6, 21].

The equations (5)–(9) specify required parameters of the ignitor (a particle beam) “delivered” to the fuel (to the hot spot). To determine required parameters of the ignitor driver, e.g. laser, we must introduce some coupling factors. The most important one, determining practical feasibility of FI, is the quantity $\eta_E = \dfrac{E_{ig}}{E_L^{ig}}$, defined as a ratio of the energy deposited to the fuel by the ignitor (particle beam) and the energy of the ignitor driver E_L^{ig}. This “total” energy conversion efficiency can be written down in the form:

$$\eta_E = \eta_{prod} \times \eta_{transp} \times \eta_{dep} \tag{10}$$

which reflects three main stages of the ignitor driver-fuel interaction. Here, η_{prod} is the energetic efficiency of particle beam production at the source, η_{transp} is the efficiency of the beam transport from the source to the dense fuel, and η_{dep}

is the efficiency of the beam energy deposition to the dense fuel (to the hot spot). Both η_E and the particular efficiencies defined above substantially depend on the kind of particles produced by the driver. In the case of a laser driver, η_{prod} is generally higher for electrons than for protons or ions but, on the other hand, the heavier particles are easier to transport and their energy deposition can be higher and better localized.

In recent years, a significant progress has been made in defining and solving key problems related to both the electron FI and proton/ion FI. In the first option, the efforts have been focused on controlling the energy spectrum and the angular divergence of laser-produced electron beams, as well as on the ultrahigh-current (~GA) electron beam transport in dense plasma and the beam energy deposition to the compressed fuel [4, 5, 22]. Fairly impressive progress has also been made in the development of laser-driven ultraintense proton/ion sources for FI. In particular, the methods of highly efficient ($\eta_{prod} >$ 10–20%) generation of proton/ion beams of parameters required for FI have been proposed and investigated experimentally or with the use of advanced computer codes [4, 6, 23].

To summarize, FI is an innovative approach to laser fusion which promises high-energy gain at energy and cost of a driver much lower than in the case of conventional CHSI scheme. The first integrated FI-related experiments strongly support the idea, but great worldwide efforts are necessary to validate the FI concept at full scale and to mitigate a risk. So-far numerical modelling suggests that ignition and energy gain is feasible with total driver energy $\leq$ 300 kJ and the ignition laser energy $\leq$ 100 kJ. The laser facilities with multi-kJ PW lasers just being lunched or constructed make proof-of-principle and benchmark experiments at sub-ignition scale possible. Full-scale FI experiments seem to be technologically feasible in the next decade. They would push FI research in a key stage in which the feasibility of fast ignition as a route to inertial fusion energy would be determined.

4.2. Shock Ignition. Shock ignition (SI) is the newest concept of laser fusion-proposed by Betti et al. several years ago [7] and actually is an intermediate variant between central hot spot ignition and fast ignition (Fig. 6). The fuel is first irradiated symmetrically, but driven at lower velocity than for CHSI. The temperature of the hot spot generated at the end of the implosion is below the ignition threshold. At an appropriate time, towards the end of the implosion, the fuel pellet is irradiated by intense sub-ns laser spike, which drives a strong converging shock wave, with initial pressure of about 300 Mbar. This pressure is amplified by convergence, and further amplified as the converging shock collides with the outgoing shock bouncing from the centre. The hot spot then undergoes additional heating and ignites.

The SI concept was proved by advanced computer simulations [24] and was also confirmed by a "proof-of-principle" experiment in a small scale (at multi-kJ laser energy) [25]. The main advantages of this option are as follows: a) relatively low laser power (200–300 TW) and energy (200–300 kJ) needed for ignition [24], b) high energy gain (like that for FI), c) established physics with relatively simple hydrodynamics, d) employing conventional laser technology and rather simple target. However, there are several serious problems unsolved so far, in particular: efficient generation of a highly symmetric strong shock with a small number of laser beams, a precise timing of the shock, the interaction of the shock with the compressed shell and the bouncing divergent shock, and possible degradation of laser-plasma coupling at the required high intensity of the spike due to parametric plasma instabilities.

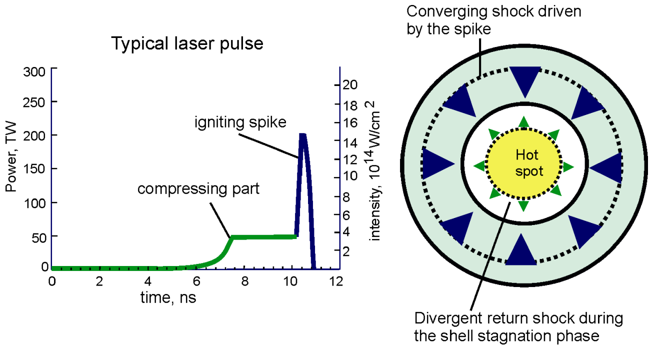


Fig. 6. Shock ignition fusion scheme: a strong, converging shock wave driven by the high- intensity sub-nanosecond laser spike ignites the fuel in the final stage of the fuel compression

SI is consider to be tested at full scale both at NIF and LMJ. However, to accomplish such experiments significant changes in geometry of target irradiation are necessary in both facilities, as SI can be realized basically only in the direct-drive scheme.

4.3. Impact ignition. Impact ignition (II) fusion is an old idea suggested already in the 60 s, however only II schemes proposed in the last two decades seem to be feasible to be accomplished with the current or emerging technologies. In the II scheme proposed by Caruso and Pais in 1996 [8] (Fig. 7a), a ~ 1 μg micro-projectile made of high-Z material (eg. Au) and accelerated to $\sim 5 \times 10^8$ cm/s collides with the compressed ($\rho_f \geq 200$ g/cm^3) DT fuel. Due to the collision, the projectile is rapidly collapsing to high densities (> 1000 g/cm^3) and a large fraction of its energy is transferred to the fuel in very short time (~10^{-11} s). As a result, a hot spot is created which ignites the fuel. In the considered case, the minimum kinetic energy of the projectile is only ~10–20 kJ [8], much lower than the laser energy needed to compress the fuel (a few 100 kJ).

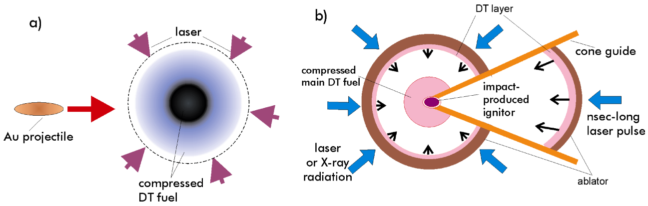


Fig. 7. Impact ignition fusion scheme: a) using a high-Z projectile (Caruso and Pais, 1996), b) using a DT plasma projectile accelerated by laser plasma ablation inside a guiding cone (Murakami and Nagatomo, 2005)

Other, more advanced II scheme was proposed by Murakami and Nagatomo in 2005 [9] (Fig. 7b). In this scheme, the compressed DT main fuel is ignited by impact collision of another fraction of separately imploded DT fuel, which is accelerated in the hollow conical target to hyper-velocities $\sim 10^8$ cm/s. Its kinetic energy is directly converted into thermal energy corresponding to temperatures > 5 keV on the collision with the main fuel, and this self-heated portion plays the role of the ignitor. The ignitor shell is irradiated typically by a ns laser pulse at intensities $> 10^{15}$ W/cm^2 and short laser wavelength (e.g. 0.35 μm) to exert ablation pressures accelerating the DT projectile above 100 Mbar. It was estimated that the total laser energy needed for compression and ignition of DT fuel in this scheme is $\sim$200–300 kJ – much lower than in the CHSI scheme.

The potential of impact ignition for fusion energy production was demonstrated in the experiment performed in Osaka with the multi-kJ Gekko XII laser [26]. In the Murakami et al., scheme with CD shell target, a two-order-of-magnitude increase in the fusion neutron yield was achieved as compared to the conventional CHSI scheme.

Important advantages of impact ignition in comparison with CHSI are much lower laser driver energy and higher energy gain (G$\sim$100 seems to be feasible). As compared with fast ignition, its significant merit is simpler physics and no need for a short-pulse multi – PW laser, which means a lower cost and less demanding laser technology. The main challenge for this scheme is, however, accelerating of multi-μg high-density ($\rho \geq 50$ g/cm^3) projectile to extremely high velocity $> 10^8$ cm/s.

5. Towards inertial fusion power plant

The possibility of using ICF to build a power plant has been studied since the late 70s, and such kind of plants are known as an IFE (inertial fusion energy) plant or an IFE reactor. In this device, the driver (laser or particle accelerator) converts electrical power into short pulses of energy (of light, particles or micro-projectile) and delivers them to the DT fuel pellet to cause implosion, ignition and thermonuclear burn. In the pellet factory, fuel pellets are manufactured, filled with DT fuel and sent to the reaction chamber. In the chamber, the driver beams are directed to the pellet to implode it and to produce thermonuclear energy with a repetition rate of a few times per second. Products of the thermonuclear explosion (in particular – neutrons) are captured in a surrounding structure called a blanket, and their energy is converted into thermal energy (heat). In the rest of the reactor, two major processes for material and energy are performed. Tritium and some other target materials are extracted from the re-circulating blanket fluid material and from the reaction chamber exhaust gases. Then these extracted materials are recycled to the target factory. The thermal energy in the blanket fluid is converted into electricity, a portion of which is re-circulated to power the driver.

In terms of energetic efficiencies of basic subsystems of the IFE reactor, the cycle described above is illustrated by the scheme in Fig. 8. From this scheme we can derive requirements for the energetic efficiency of the driver η_d and the fusion target energy gain G. For the energy balance, the condition:

$$f\eta_d\eta_{th}G = 1 \tag{11}$$

has to be fulfilled (f is a fraction of the electric power recirculated to supply the driver). Assuming $\eta_{th} = 40\%$ (typical value) and $f = 25\%$, we arrive at:

$$G\eta_d = 1. \tag{12}$$

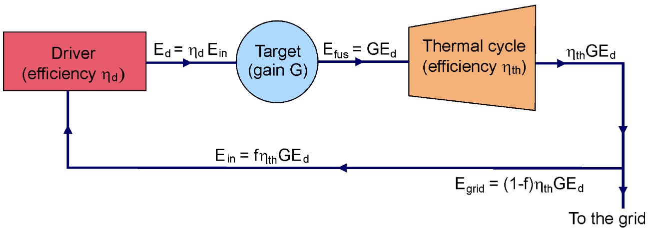


Fig. 8. Scheme of energy flow in the fusion reactor

It means that for $G = 100$, the driver efficiency has to be $\eta_d = 10\%$. In turn, it means that both the target gain predicted for the NIF/LMJ facilities (G$\sim$10) and the efficiency of lasers used in these devices ($\eta_d \sim 1\%$) have to be increased by an order of magnitude to meet the conditions required for the IFE reactor. Moreover, the reactor driver has to work with the repetition rate $\sim$5–10 Hz. Potentially, these requirements are within reach of diode-pumped solid-state lasers and KrF excimer lasers as well as particle (heavy ion) accelerators. As for the target gain, advanced fusion concepts (FI, SI, II or others?) seem to be necessary to be employed to reach the reactor requirements.

General IFE reactor concepts have been developed for more than three decades and several advanced designs like KOYO [27] in Japan and HYLIFE [28] in US have been proposed. At present, three big long-term reactor-oriented projects, which detail all IFE-related issues (driver, target physics and production, reactor chamber, diagnostics etc.) are under development. This is the LIFE project in US, FIREX project in Japan and the HiPER project in Europe.

The main goal of the LIFE (Laser Inertial Fusion Energy) project [29] is to build a prototype IFE plant and to develop the technology of the IFE reactors enabling commercial production of energy from fusion. The plant would use the NIF-like architecture and the indirect-drive fusion scheme with the target energy gain $\geq$60. The laser driver of 2.4 MJ energy in UV would work with the repetition rate of 16 Hz. It would be based on currently available materials and market-based technology using, in particular, semiconductor diodes for laser pumping. The project is now in the design phase and a turning point for its will be a demonstration of ignition and energy gain on NIF. It is believed that the NIF success will push the project into a next phase – the phase of construction of a prototype fusion plant.

The FIREX (Fast Ignition Realization Experiment) project is aimed at demonstrating fusion ignition and burn using fast ignition approach [30]. The project is divided in two phases. The goal of the first phase (FIREX-I) is to demonstrate fast heating of fusion fuel up to the ignition temperature of 5–10 keV by a high-energy short-pulse (10 kJ/10 ps) laser combined with the long-pulse (10 kJ/1 ns) GEKKO XII implosion laser. In the second phase (FIREX – II), the implosion laser is planned to be a 50kJ/3ns blue laser, whereas the heating laser to be a 50kJ/10ps infrared laser. The goal of this phase is to demonstrate fusion ignition and burn. At present, the fast ignition experiments within FIREX-I project are underway.

The European HiPER project is described in the next section.

6. The HiPER project and current fusion-related research of the Polish team

HiPER (*High Power Laser Energy Research Facility) is* a project of the European laser infrastructure for nuclear fusion and studies of extreme states of matter [31, 32]. The main long-term goal of this project is to demonstrate the effective production of energy from nuclear fusion driven by lasers of high power and energy working with a high repetition rate (> 1 Hz). The research program of the project is focused on the laser fusion but also includes the basic research in other fields, as well as works associated with the development of technologies and techniques necessary to build the HiPER device, especially laser technology.

The laser fusion physics studies include theoretical works, numerical simulations and experiments which roughly can be divided into two groups: the studies of DT fuel compression and research on various advanced scheme of the fuel ignition (electron and proton/ ion fast ignition, shock ignition and impact ignition). The main “technical” objective of the former is to optimize the structure of the DT target and specify the parameters of the multi-beam laser compressing the target which would provide the maximum energy gain G.

The research in the second group are focused on various physical and technical aspects of the advanced ignition schemes, including totally new issues related for example to relativistic (with $I_{las} \sim 10^{19}$–10^{22} W/cm^2) interaction of laser light with matter, generation and transport of electron beams of very high current densities ($j_e \sim 10^{14}$ A/cm^2), generation of picosecond ion beams of intensities exceeding many times the intensity of beams produced in the biggest accelerators, or to the acceleration of macroscopic amounts of matter to velocities unattainable never before. The studies include also a range of issues related to the technology of production and transportation of targets (including cryogenic DT targets) and reactor technology as well as to the development of methods and diagnostic equipment necessary to conduct this research.

It is anticipated that the HiPER device will be equipped with two, coupled together lasers with very high energy and power, namely the multi-beam nanosecond laser of energy ∼200 kJ and picosecond laser of energy ∼100 kJ and power of several – several dozen PW and, possibly, femtosecond laser of power > 100 PW. Thus, it would be the unique research infrastructure on a global scale, allowing to conduct fundamental research in various fields, including studies of matter at extreme conditions, so far unattainable in terrestrial conditions. Currently the following fields of research are being considered:

- laboratory astrophysics (simulation in the laboratory conditions of various astrophysical phenomena),
- research on the so-called warm dense matter (occurring inside planets, including the Earth’s interior),
- testing of materials under very high pressures,
- atomic physics with very high pressures and temperatures,
- ultraintense interaction of laser with plasma and relativistic plasma,
- generation of very intense electron and ion beams (for the purposes of nuclear physics, particle physics and nuclear medicine),
- basic physics in super-strong fields.

The project was divided into three phases: a preparatory phase (2008–2013), design and technical phase and a construction one. The five-year preparatory phase of the HiPER project began in April 2008 with the participation of more than 30 scientific institutions including 26 from 9 EU countries. Poland in this project is represented by the Institute of Plasma Physics and Laser Microfusion (IPPLM). The aim of the preparatory phase includes, among others: development – based on experimental studies and numerical simulations – the physical basis for advanced fusion schemes and specifying the physical and technical conditions of their implementation, development of the conceptual design of the HiPER device and proposals for a long-term programs for fusion and basic non-fusion research with the use of this device. The works were divided into 15 work packages (WP). IPPLM contributes to five WP and its works relate to both fusion and basic non-fusion research.

Activities of the IPPLM under fusion-related works are focused on three main issues:

- development of proton/ion source of ultrahigh intensity ($I_p \sim 10^{20}$ Wcm^2) for proton/ion fast ignition (e.g. [21, 23, 33–35]);
- laser acceleration of micro-projectiles for the needs of impact ignition (e.g. [36–38]);
- studies of shock wave generation and non-linear interaction of laser with plasma at the conditions relevant to shock ignition (e.g. [39, 40]).

In the package regarding the non-fusion research, the IPPLM performs studies relating to laboratory astrophysics (such as generation and interaction with gases of supersonic plasma jets [41–43]), laser acceleration of ions with relativistic laser intensities and laser-induced nuclear reactions. All these works, including theoretical analysis, advanced numerical simulations and experiments, are conducted within broad international cooperation, mainly with the research centers participating in the HiPER project.

7. Summary

The fifty-year research on laser fusion resulted in:

- understanding and solving of the basic physical issues of the ICF conventional scheme,
- preparation of alternative, potentially more effective, ICF schemes,
- development of technology enabling the building of megajoule fusion devices such as NIF and LMJ,
- development of the ICF international programs (LIFE, HiPER, FIREX) directed towards the design of a fusion reactor.

Currently we are facing a turning point – in the course of the next two-three years NIF will likely prove the physical and technical feasibility of producing energy from fusion, which would open the door for building the first prototype nuclear power plant,

The main challenges for physicists are presently the physical problems occurring in the advanced ICF schemes such as: generation of ultra-intense particle beams, relativistic laser-plasma interaction, transport and interaction of GA-current beams of particles with plasma, acceleration of micro-projectiles to hyper velocities or various kinds of instabilities in laser plasma.

For the commercial energy production out of the laser fusion the further very considerable progress in the technology is necessary, especially in terms of drivers (lasers), production and handling of DT targets and reactor technology; in case of the latter there are many problems common for ICF and MCF (blanket, tritium production, materials, energy conversion systems…) and the cooperation between communities representing both directions in solving these problems is highly desirable.

The research on the laser fusion, regardless of its main objective – creating an efficient, safe and potentially unlimited source of energy – is also a "driving-horse" of the development of many branches of science, in particular:

- high energy density physics,
- laboratory astrophysics,
- ultra-intense interactions of light with matter and relativistic plasma physics,
- material research,
- particle and dense matter acceleration,
- laser technology,
- and probably many others.

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