The progress of ultra-intensity laser and inertial confinement fusion

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Abstract. Contemporarily, the world is facing the problem of energy crisis, thus novel approach of energy production is needed to address the problem. Among various new energy scenarios, controlled nuclear fusion is an expected solution. This article will discuss the inertial confinement fusion (ICF) with the recent progress of the state-of-art ultra-intensity laser beams. ICF is a way of controlled nuclear fusion based on the ultra-intensity laser, which is originated in the mid 20 century after the born of nuclear weapons. In order to reach the ignition condition, ultra-intensity laser is compulsory. With this in mind, this paper discusses the principles and developments of ultra-intensity laser. Subsequently, the milestones and the state-of-art ICF facilities as well as ignition approaches are demonstrated accordingly. Afterwards, the current limitations and drawbacks as well as future outlooks are proposed. Overall, these results shed light on guiding further development of confinement fusion.

Keywords: inertial confinement fusion, ultra-intensity laser, controlled nuclear fusion.

1. Introduction

Energy has always been an important factor for humankind in the daily life. The body needs energy to move. In the modern society, the energy has become something more important [1]. From daily lives to factories, almost nothing can remain its normal operation without energy. Human being's cell phones and cars need energy. Meanwhile, the machines in the factory also need energy. However, the energy may not always be enough for humankind.

According to the data, the gas reserve in the EU may be exhausted before 2030. The fossil fuels beside coal may run out in 2042 [1]. Moreover, before the fossil fuels run out, other factors can cause the energy crisis. For example, overpopulation, poor distribution of fuels and wars may all lead to the energy crisis [2]. As a result, it may be very important to find a new kind of energy which is efficient and renewable.

Nuclear energy may be the key to the energy crisis. Nuclear energy is producing energy by turning mass into the energy. According to the energy equation of Einstein $E = mc^2$, the energy produced by a small amount of mass can create much energy. Humans have already learned how to use and control the power of nuclear fission. However, the nuclear fission isn't efficient enough. Moreover, it may cause some accidents, e.g., the accident in Chernobyl and Fukushima. As a result, the controlled nuclear fusion, as the other way of achieving nuclear energy, is expected.

Inertial confinement fusion is a way of realizing the controlled nuclear fusion. Such concept began in the 1970s, and people at that time first realized that the laser can be used to make the whole thing come true [3]. In recent days, there are also some experiments reaching the burning plasma regime [4].

The inertia confinement fusion is a method of realizing the controlled nuclear fusion. Once the experiment succeeds, the relevant technology can be quickly used for power plants for actual use. On this occasion, it may solve the energy crisis radically and bring humankind to a new era. The achievement could be so great that it represents one of the great scientific research projects [5].

The rest part of the paper is organized as follows. The Sec. 2 will introduce the basic principles of laser beams. Then, the Sec. 3 would discuss about the progress of ultra-intensity lasers. The Sec. 3 would discuss the progress of ICF. Afterwards, the Sec. 5 will demonstrate the flaws and prospects of current results. Finally, the Sec. 6 will give a brief conclusion.

2. Basic descriptions of lasers

The classical definition of a laser works as a photon trigger a transition of an atom from high energy state to low energy state. The excess energy is transferred into two photons with identical direction and wavelength. As shown in Fig. 1, the total energy of the photon is equivalent to the change in atom energy from excited level to ground level. The two photons then encounter two atom and repeat the process, starting a chain reaction. The atoms in ground level could return to excited level by absorb photons, which stop the chain reaction. Optical pumping is use to pump the atom back to excited level.

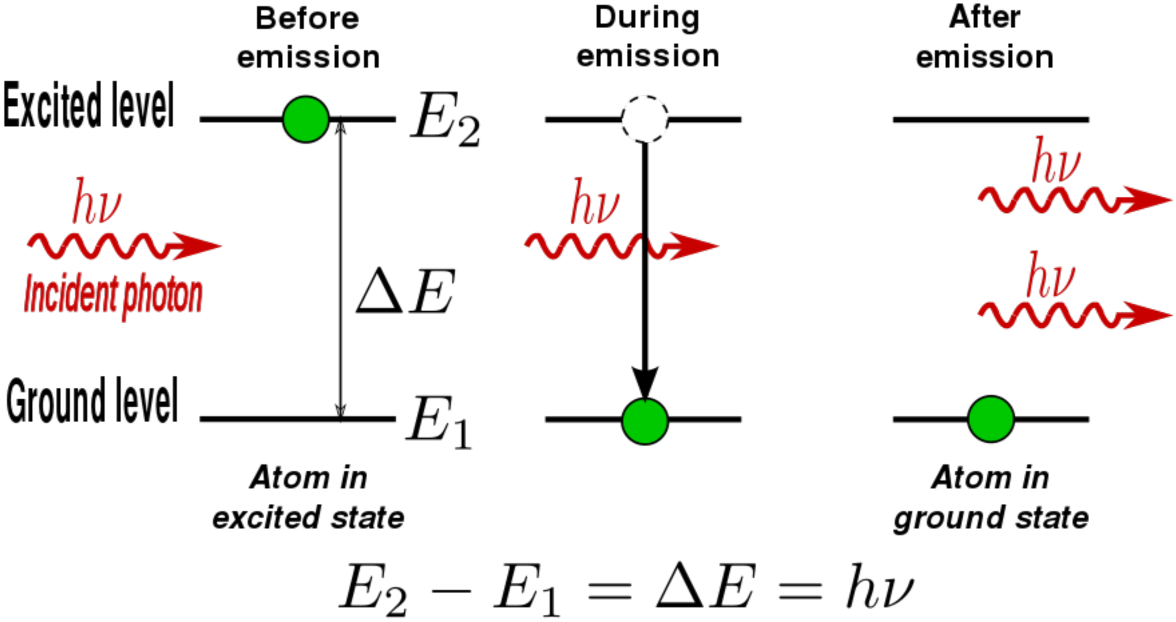

Figure 1. A sketch of the principle for Laser [6].

Different laser types have different kinds of applications. The field of inertial confinement fusion requires extreme optical pulses in a very short period of time, which is feasibly by ultra intense laser. Ultra-intense laser is made possible from the technique of q switching, mode locking, and chirped pulse amplification.

Q Switching allows energy of the laser to be sorted in a gain medium. The sorted energy can reach up to several times of the original laser. However, the power of the laser is limited by the natural spontaneous emission of the medium [7]. After the switch is open, Q factor rapidly increases, resulting in short, high intensity laser pulses [8].

The ultra-intense laser also has the ability to shoot multiple lasers in a short interval. For creating brief optical pulses, laser mode locking has proven to be an effective method. Until now, mode-locking approaches have relied on active or passive amplitude or phase modulation that is synchronized with the pulse's round-trip time in the laser cavity [9]. Nevertheless, many fields such as biomedical imaging, spectroscopy, and nuclear fusion, especially inertial confinement fusion, utilize narrowband optical pulses.

Chirped pulse amplification (CPA) was introduced by Donna Strickland and Gérard Mourou in 1985 [10]. CPA is used in most high-power lasers in the world and proven to be an effective method to amplify optical pulses to petawatt range [11].

2.1 Progress of ultra-intensity laser

The US's National Ignition Facility (NIF) laser started from the John Nuckolls' concept in 1972. In 1980, Lawrence Livermore National Laboratory (LLNL)'s Shiva laser project made breakthrough progress in shortwave energy transfer, which guided future research and development in the glass laser field.

On February 10, 2009, NIF's first test fire emitted 1.1 megajoules (MJ) of ultraviolet. This is also the first time in history that a laser has reached the megajoule level. Test fire on August 8, 2021 generated 10 quadrillion watts of fusion power for 100 trillionths of a second [12]. As shown in Fig. 2, 192 low-energy inferred laser beams (total of 1 billion joules) were initially created and amplified 4 times in the main amplifier. Then, the beams exit the amplifier and pass through by the power amplifier with even more energy. With transport mirrors arranging the pathway, extremely powered inferred beams join at the final optics assembly and turns into ultraviolet. The pulses then hit inside a hohlraum, generating x-ray blasting the target which create fusion reaction.

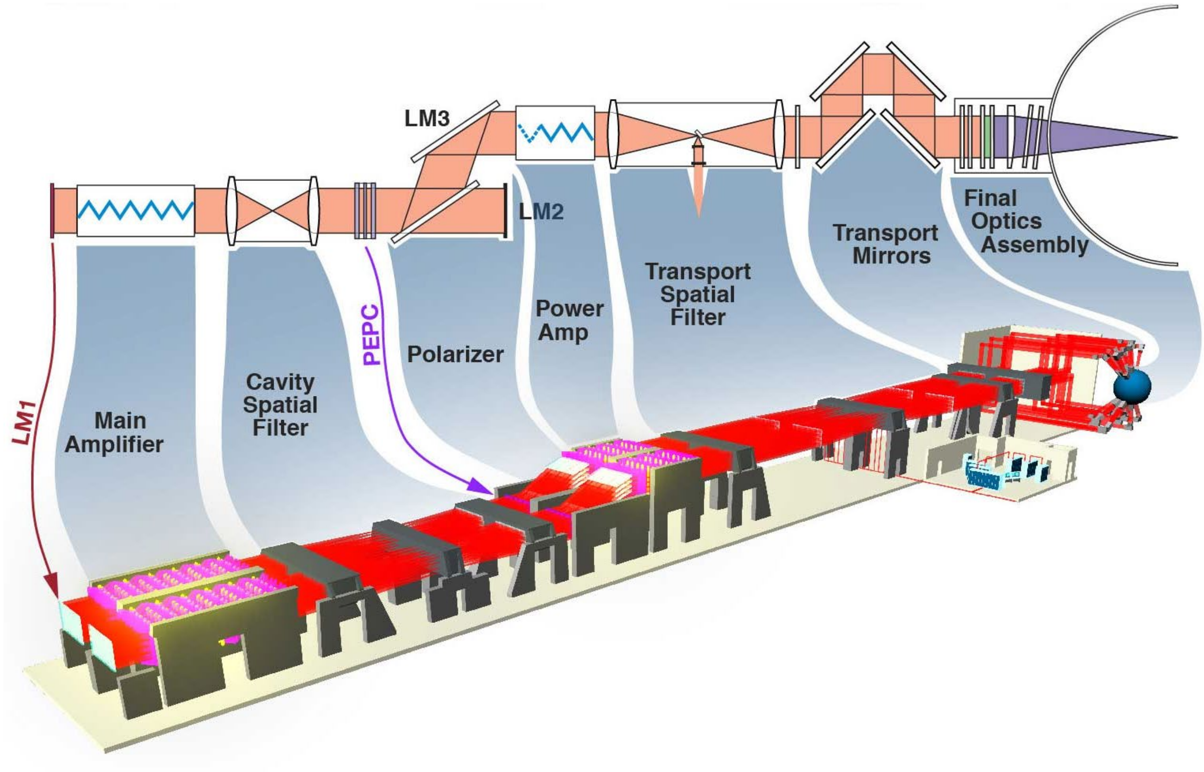

Figure 2. The sketch of the NIF [11].

3. The progress of ICF

3.1 Inertial confinement fusion

One of the difficulties of controlled fusion is that it can be hard to contain all the regimes because the temperature is far larger than the melting point of all known materials. In projects similar to Tokamaks (magnetic confinement fusion, MCF), the plasma is regulated by the magnetic field. The field needed could be really strong. However, in the inertial confinement fusion, the plasma is regulated by itself. When the mass of fuel added is very small, the inertia of the fuel may stop them from escaping. Using devices of strong particle beams (e.g., laser), the nuclear fusion may happen. The energy can be released in the small explosions.

The standard of the ignition is the Lawson criterion, which is the rate of energy being generated by fusion reactions within the fusion fuel to the rate of energy losses to the environment. If the energy generated is higher than the loss and the energy can be captured by the system, it is ignited. In the inertial confinement fusion, the burn-up fraction is proportional to

$$Fraction \propto \frac{(nT)<\sigma v>}{T^{\frac{3}{2}}} \tag{1}$$

where n is the particle density, T is time, σ is the fusion cross section and v is the relative velocity.

3.2 The development of ICF

In the 1960, a man called Maiman demonstrated a practical working laser. Subsequently, in the 1974, Nuckolls realized that this can be used in the inertial confinement fusion. This is because lasers are able to provide the high surface-heating power needed to compress the thermonuclear fuel with small volume. Then, in the 1970s, the concept of laser-fusion was established.

The fuel of inertial confinement fusion is contained by a thing called pellet. The pellet may contain the solid deuterium and tritium. In the process of nuclear fusion, humankind may only need to add the pellets to the facility continuously and the fuels in the pellets may be ignited by the laser. The Fig. 3 illustrates the typical hohlraum of NIF projects.

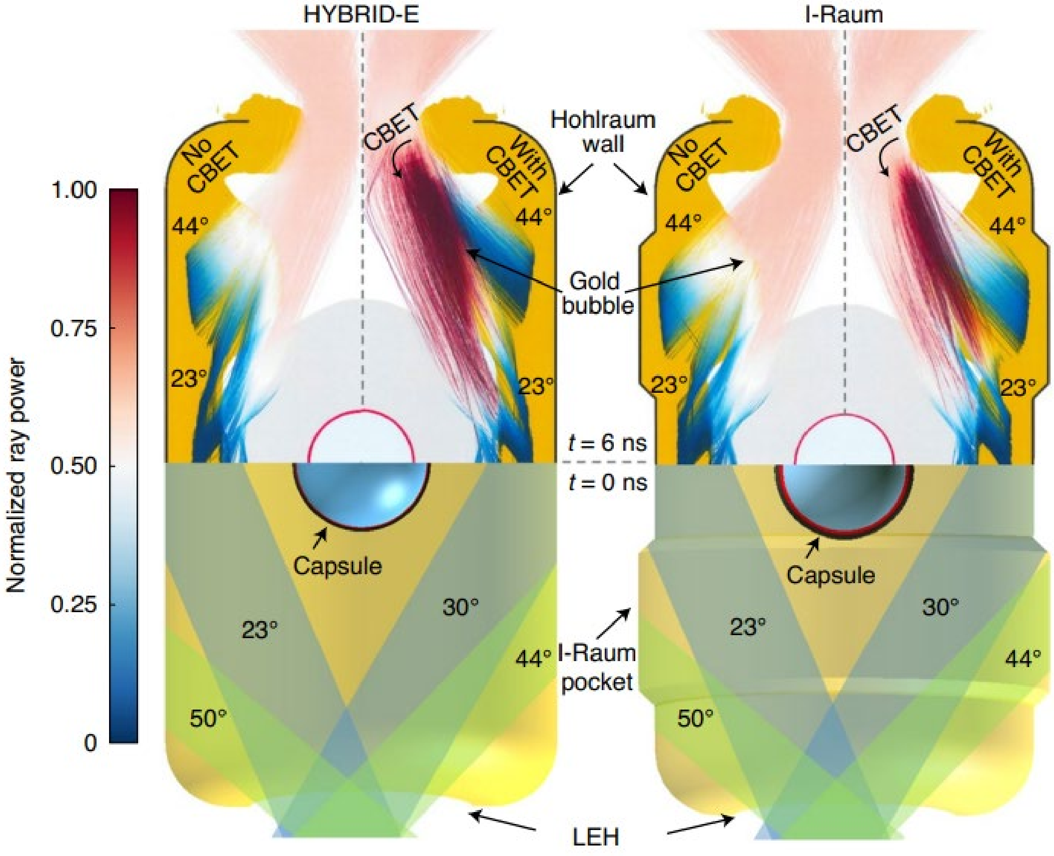

Figure 3. The sketch of hohlraum of NIF [12].

3.3 A recent result reaching the burning plasma regime.

In 26th January 2022, results from the researches in the US National Ignition Facility was posted on Nature, which is pretty close to the ignition as depicted in Fig. 4. To be specific, in these shots after optimization of the various of parameters (high-foot, hybrid target, etc.), the researchers adopt the X-ray laser (transferring from the bremsstrahlung) to ignite the capsules used to contain the fuels. They use the fuel in the outer shell of capsule to provide velocity to the capsule. In this way, they create a rocket by the capsule. The fuel remained may move in the speed of 400km/s towards the centre of the D-T fuel. During the stagnation in the fuel, the kinetic energy of the rocket transforms to internal energy and the nuclear fusion may happen.

The researchers find a way of creating X-ray laser and enlarge the size of the capsule because the small size may limit the laser power. After some developments, the final result is preferable. The fusion power is changed by 1.5 petawatts, which is now higher than the laser power.

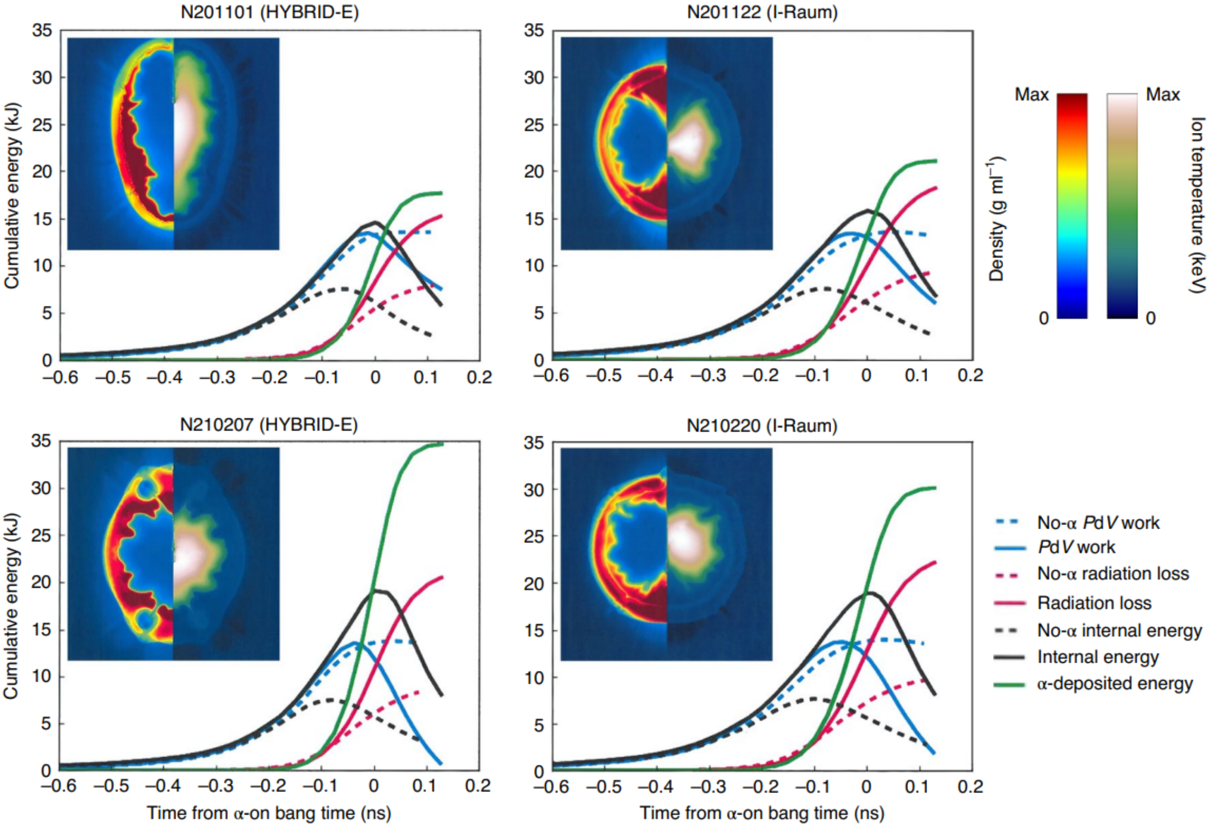

Figure 4. The results for the close-to ignition shots of NIF recently [12].

4. Flaw & future prospect

Contemporarily, the inertial confinement fusion still faces many problems and issues. To begin with, plenty of results are now calculated by the simulation instead of real experiments, especially for some unavailable diagnosed features due to the difficulty for coupling detection. The loss of energy of the laser and conduction is all theoretical value. Some practical experiments are still needed to be carried out. Secondly, though two among four experiments meet all the criteria, there are still some criteria not fit by all the experiments.

However, these flaws may be fixed by the future experiments. Once the ICF succeed, there may be many advantages. First of all, it can be immediately capitalized. There won’t be much barrier in the experiment and actual use. As a result, the power plants can be built quickly after the scientific breakeven. Moreover, the facility built can last for a long time. The lifetime of these kind of facilities is long and the efficiency is expected to be very high.

5. Conclusions

In summary, this paper discusses a potential energy source from the perspective of laboratory data. Specifically, ultra-intense laser provides controllable ignition source to harvest nuclear fusion. According to the analysis, the power of laser pulse reaches the requirement, allow the inertial confinement fusion to fire. If the test fire is a success, it can be put in practical use very quickly. In the future, inertial confinement fusion could provide massive alternative energy source that can replace limited conventional energy. Right now, the fusion is still an experimental idea. Overall, these results offer a guideline for manmade inertial confinement fusion.

References

[1] B. R. Singh, O.Singh, Global trends of fossil fuel reserves and climate change in the 21st century (Vol. 8, pp. 167-192). Chapter, 2012.

[2] R. Poudyal, P. Loskot, R. Nepal, R. Parajuli, S. K. Khadka, Mitigating the current energy crisis in Nepal with renewable energy sources. Renewable and Sustainable Energy Reviews, 116, (2019), 109388.

[3] D. Keefe, Inertial confinement fusion. Annual Review of Nuclear and Particle Science, 32(1), (1982), 391-441.

[4] A. L. Kritcher, C. V. Young, H. F. Robey, C. R. Weber, A. B. Zylstra, O. A. Hurricane, et al., Design of inertial fusion implosions reaching the burning plasma regime. Nature Physics, 1-8 (2022).

[5] S. Glasstone, Controlled nuclear fusion. US Atomic Energy Commission, Division of Technical Information, 1964.

[6] Information on https://en.wikipedia.org/wiki/Laser

[7] Information on https://www.rp-photonics.com/q_switching.html/

[8] Information on https://solarisoptics.eu/optical-modulators-for-laser-q-switching/

[9] D. Strickland, G. Mourou, Compression of amplified chirped optical pulses. Optics communications, 55(6), (1985), 447-449.

[10] Information on https://www.rp-photonics.com/chirped_pulse_amplification.html/

[11] Information on https://lasers.llnl.gov/about/how-nif-works/

[12] B. Bishop, National Ignition Facility experiment puts researchers at threshold of fusion ignition. Lawrence Livermore National Laboratory, 2021.