# Unlocking the future of energy: A comprehensive guide to the challenges and prospects of controllable nuclear fusion

**Jinsong Zhang**

Jinan New Channel-JUTES High School, Jinan,250002, China

911757955@qq.com

**Abstract.** There are different problems with the current ways of providing energy. Now, we are facing an energy crisis. Nuclear fusion has the advantages of cleanliness and efficiency, and has the potential to become our ultimate energy source. Nuclear fusion is a process in which two nuclei combine to form one nucleus, resulting in mass loss and energy generation. It requires high temperature, high pressure, and high density as reaction conditions. At present, people have achieved uncontrollable nuclear fusion - hydrogen bombs, and only controllable nuclear fusion can provide us with stable energy. The main technological routes of controllable nuclear fusion are inertial confinement fusion and magnetic confinement fusion, each with its own characteristics and facing its own problems. The development of controllable nuclear fusion is also constrained by issues such as how to achieving net energy gain and tritium self-sufficiency. Different scientific technologies, such as superconductor, new fuels, and aerospace, will greatly contribute to the future development of controllable nuclear fusion.

**Keywords:** controllable Nuclear fusion, Energy, nuclear physics.

## 1. Introduction

As is well known, human production and life cannot do without energy. Many approaches have been proposed and applied to produce and obtain indispensable energy, such as using chemical energy inside coal, oil, natural gas, as well as physical energy in hydropower, wind energy, solar energy, and nuclear fission. However, despite the current rich energy composition of mankind, there are still many problems that greatly limit long-term development. According to the BP Statistical Yearbook of World Energy in 2022, the three major fossil energies accounted for 85.9% (32.9% for oil, 23.8% for natural gas, 29.2% for coal), and the non-fossil energies accounted for 14.1% (among non-fossil energies, water energy accounted for 6.8%, renewable energy 2.9%, and nuclear energy 4.4%) in the global energy consumption structure. It can be seen that fossil energy is still the absolute leader in global energy consumption now [1]. Although the proportion of fossil fuels such as coal, oil, and natural gas will be gradually reduced by renewable energy, they will still be the source of more than half of the world's primary energy supply even in 2050 [2]. But the consumption of fossil fuels emits large amounts of carbon dioxide and therefore gives rise to global warming and extreme weather. The emission of carbon dioxide will reach more than 36.8 billion tons in 2022, which has increased by 90% over the last century [3]. Besides, fossil fuels will be in danger of being exhausted in the next century or two [4].

The so-called renewable energy or regenerative energy also faces many challenges, although it seems that they will not be exhausted in a short time. Firstly, there are several problems about environment.

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For example, the uneven distribution of solar energy and wind power greatly affects the efficiency of people using them [5]. The hydropower station may also damage the surrounding environment and make the land marshy and salinized [6]. Besides, technical problems, such as the immature energy storage technology, resource problems, such as the tight supply of lithium, cobalt, and other metal elements, and some incorrect development models have a serious negative impact on the development of new energy [7,8]. The high cost is also an obstacle to the development of new energy compared to that of traditional fossil energy. For instance, the cost of solar power generation is five to ten times that of coal-fired power generation, and the price of wind power generation in some regions is also higher than that of coal-fired power generation [9]. Hydrogen energy cannot be commercialized temporarily due to the high cost of hydrogen production and the risk of hydrogen reactions. The development of biofuels may also cause the price of food, meat, and edible oil to rise [10]. These results unambiguously indicate that new energy will not replace fossil energy immediately.

Since last year, global energy has fallen into the dilemma of an imbalance between supply and demand. Officials of the International Energy Agency pointed out that the current energy crisis will be larger than the energy crisis in the 1970s and 1980s with the advancement of modern industry and life [11]. The stability of the energy supply is significantly reduced. The relaxation of epidemic prevention and control, economic rebound, and extreme weather conditions have led to a sharp increase in energy demand, while the energy supply is short due to the decline in early investment and insufficient output of renewable energy [11].

The current energy crisis can be attributed to problems mentioned above. From a different perspective, these problems can be attributed to the intractable problems and shortcomings of existing energy supply methods. If we can find an efficient and green alternative that can continuously output energy in the future, namely the so-called "ultimate energy", people will do not need have to worry about energy crisis.

The nuclear energy source represented by nuclear fission and fusion has captured continuous attention owing to the unique merits of high conversion efficiency, huge energy density, and zero-carbon emission. For example, the energy released by the complete fission of one kilogram of uranium is equivalent to the energy released by the complete combustion of 2500 tons of high-quality coal [12]. Unfortunately, nuclear fission will face the dangers of nuclear radiation and nuclear leakage [12]. The Three Mile Island nuclear accident in the United States, the Chernobyl nuclear accident in the former Soviet Union, and the Fukushima nuclear accident in Japan all prove this point. Apart from nuclear fission, nuclear fusion is another nuclear reaction that can provide endless green energy. The difference lies in that the process of nuclear fusion does not produce nuclear waste, radiation, or greenhouse gases, and therefore is cleaner and more efficient [12]. Therefore, nuclear fusion demonstrates a promising prospect and is expected to become the ultimate energy of mankind in the future. At present, humans are able to utilize uncontrollable nuclear fusion, known as hydrogen bombs, and are trying achieve controllable nuclear fusion and obtain continuous and stable energy. The technical routes of controllable nuclear fusion mainly include inertial confinement fusion and magnetic confinement fusion. Nowadays, controllable nuclear fusion faces challenges in terms of energy gain, operating time, and fuel preparation. However, the development of disciplines such as materials science and aerospace technology will become a driving force for the success of controllable nuclear fusion. Controlled nuclear fusion, with its advantages, is expected to become the ultimate energy source for our humanity in the future.

This article systematically describes the principles and reaction conditions of nuclear fusion, the advantages, technical routes, challenges faced, and future development of controllable nuclear fusion. It has enlightening significance for people to learn, research, and develop controllable nuclear fusion.

## 2. Principle and advantages of nuclear fusion

### *2.1. Physical principle*

It is well known that the universe has four fundamental force, that is gravity, electromagnetic force, strong nuclear force, and weak nuclear force. Among them, the strong nuclear force arises from the

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short-range interaction between hadrons including protons and neutrons inside the nucleus, which implies that huge energy is hidden in these interactions. Nuclear fusion result from strong nuclear force, and produces four times as much energy as nuclear fission reaction [13]. To be specific, there are different physical principles between them. Nuclear fission is the process of splitting an atomic nucleus into several atomic nuclei, then produce mass loss and release energy [14]. Nuclear fusion is also called a thermonuclear reaction [14]. The specific process of nuclear fusion is that two nuclei with smaller mass collide and combine with each other under high temperature and pressure, and produce a new nucleus with a larger mass and mass loss. This is because the outside world needs to do work on the nucleus that is equivalent to sum of binding energies of two nuclei. Binding energy of a nucleus is equal to number of nucleon multiply specific binding energy. When new atomic nucleus is generated, the energy which also corresponding to its binding energy is released to the outside world.,and in fusion reactions, the newly generated atomic nucleus often has a higher specific binding energy and number of nucleon is not change so it release more energy than work done by outside world. The energy released by fission is also due to specific binding energies of the atomic nuclei formed after fission is higher than previous nucleus' specific binding energy. Under the same number of nucleons, the change in specific binding energy caused by nuclear fusion of light nuclei is usually greater than change in specific binding energy caused by nuclear fission of massive nucleus, so fusion has higher energy. Because the fusion between atomic nuclei must reach the femtosecond level, atoms need a lot of kinetic energy to overcome the Coulomb barrier, so nuclear fusion requires extremely high temperature. According to the Einstein mass-energy equation of $E = mc^2$, it can be noted that a small part of the annihilated mass will release very large nuclear energy.

Taking the isotopes of hydrogen, deuterium, and tritium, as an example, deuterium consists of one proton and one neutron, while tritium consists of one proton and two neutrons. A deuterium nucleus and a tritium nucleus combine to produce a helium nucleus composed of two neutrons and two protons, as well as a neutron. More importantly, the mass loss induced by creating just one helium atom will generate 17.6 million electron volts of energy during deuterium-tritium fusion [15].

### 2.2. *Conditions of nuclear fusion*

To achieve nuclear fusion reactions, three conditions need to be satisfied simultaneously, namely sufficient temperature, a certain density, and a certain energy constraint time [16]. First, with regard to temperature, achieving nuclear fusion reactions requires compressing deuterium and tritium atomic nuclei into a very small nuclear force range. Because atomic nuclei are positively charged, they need to obtain sufficient energy to overcome coulomb barriers, which can only be reached at extremely high temperatures. At this point, the atomic nuclei are closed enough, and due to the quantum tunneling effect, the probability of fusion reactions between atomic nuclei is significantly enhanced. But the temperature should not be too high. If the temperature is too high, the contact time between atomic nuclei to approach decreases, and the probability of producing fusion reactions decreases. On Earth, we usually need an environment of 100 million degrees Celsius to achieve efficient nuclear fusion reactions. The second is about density. Maintaining a sufficient density of nuclear fuel means that it has sufficient deuterium and tritium nuclei per unit volume, which can effectively improve the collision efficiency between atomic nuclei and thereby obtain sufficient fusion reaction rates. Finally, regarding energy constraint time. The energy of a high-temperature plasma escapes in the form of thermal radiation and heat conduction, and the "energy constraint time" refers to the time when the energy of the plasma is lost through heat conduction. The longer the time, the better the thermal insulation performance with the fusion reaction device, and the slower the energy loss. It can also further improve the nuclear fusion reaction rate. In short, controllable nuclear fusion requires an extremely high temperature as well as a high-pressure environment like what happened in the sun [17].

### 2.3. *Prominent advantages of nuclear fusion*

First of all, nuclear fusion can undoubtedly provide great energy to people. Every kilogram of fuel fusion produces four times as much energy as fission, and nearly four million times as much energy as the chemical energy arising from oil or coal combustion. For instance, The energy released by these deuteriums can be comparable to burn300 liters of gasoline. Therefore, the energy generated by several grams of deuterium and tritium fusion is enough for the citizens of a developed country to use for 60 years [12]. In addition, Fusion fuel is abundant on Earth. A liter of seawater contains about 0.03g of deuterium. In this regard, compared with nuclear fission and burning fossil fuels, nuclear fusion has a wider source of raw materials and is not easy to be exhausted [12]. Different from nuclear fission and burning fossil fuels, nuclear fusion also does not produce nuclear waste and harmful gas as well as has less radiation [12].

## 3. Main routes of nuclear fusion

There are two main technical routes for controllable nuclear fusion, one is the inertial constraint, and the other is the magnetic constraint, which will be discussed later. The inertial restraint method relies on the inertia of fusion raw materials. For example, National Ignition Facility (NIF) in the United States uses ultra-high power lasers to emit laser beams, which collapse the hydrogen fuel target containing deuterium and tritium, and produces a high temperature of about 100 million degrees Celsius, making hydrogen atoms produce fusion and release energy. A magnetic field that restricts the nuclear fusion of the fusion material in a certain volume to release energy should be used in the magnetically constrained fusion reactor. The types of magnetic confinement fusion reactors include Tokamak, stellarator, reverse field pinch and magnetic mirror, etc. By the end of 2022, there are 130 controllable nuclear fusion experimental devices in the world, of which 90 are in operation, 12 are under construction, and 28 are still planned [13]. It includes 76 Tokamaks, 13 stellarators, 9 laser ignition facilities, and 32 so-called new concept devices.

### 3.1. *Magnetic confinement fusion*

Magnetic-constrained fusion (MCF) is a technology that uses a magnetic field and high-temperature plasma to initiate the controllable nuclear fusion reaction. As long as the highly pure raw materials of deuterium and tritium are mixed and then heated to more than 100’000’000 Kelvin, the mixtures can be completely ionized into a plasma state [18]. The means of heating plasma mainly rely on beam injection, radio frequency waves, etc [19]. It is well known that no material can withstand such high temperatures on the earth, so nuclear fuel cannot be directly contained in a real container. Intriguingly, the plasma state, including free electrons and charged ions in the fusion reaction can be controlled with the assistance of magnetic and electric fields. In this regard, magnetic-constrained nuclear fusion technology has been proposed and applied to constrain plasma. If it is controlled inside the fusion reaction facility without contacting the container wall, the plasma can be constrained and compressed in the facility, and controllable nuclear fusion can be thereby accomplished [18].

MCF can be divided into Tokamak, stellarator, reverse field pinch, and magnetic mirror facilities depending on their different configurations [12]. Magnetically constrained nuclear fusion reactors, represented by tokamaks and stellarator, are the most widely used nuclear fusion reactors at the present. Among Tokamak and stellarator, the former is the most widely used in all MCF and even all controllable nuclear fusion technologies in the world. The term “Tokamak” comes from the Russian prefix of “ring, vacuum chamber, magnetic field, and coil”. At the center of this kind of device is a circular vacuum chamber, like a doughnut, with some coils wound outside. When the coils are electrified, a huge magnetic field will be generated inside the Tokamak to heat the plasma inside to a very high temperature, and then produce nuclear fusion [20].

Specifically, around that annular vacuum chamber, there are several different types of magnets, such as circumferential field (longitudinal field) coils, central solenoid (ohmic heating) coils, and polar field coils. These magnets are fed an electric current to generate a magnetic field to excite, control, and compress the plasma. The typical process of tokamak devices relying on plasma discharge can be summarized as follows: Before zero time (the time when the plasma is established), the fusion gas is injected into the annular vacuum chamber, and the current of the central solenoid is applied to the peak value. At zero moment, the current of the central solenoid decreases, which thereby creates an induced

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current in the annular vacuum chamber to accelerate free electrons, cause collision ionization, and generate plasma substances. After that, the annular vacuum chamber is again filled with fusion gas to increase the density of the reactants and the pressure of the ambient environment in the annular vacuum chamber. At the same time, auxiliary heating methods such as radio frequency wave heating and neutral beam injection heating are used to further enhance the temperature of the plasma in the annular vacuum chamber.

In the contrast, stellarator are like twisted Fried Dough Twists. It limits the hot plasma to the twisted magnetic field, and the twisted structure helps it better control the plasma. The operation risk of the simulator is small, and unlike Tokamak, it is easy to have a sudden interruption of internal current that causes the fusion reaction to stop immediately [21].

From here, we can see that MCF represented by the Tokamak facility can largely be seen as a complicated electromagnetic field system composed of complex coil structures and large current input, which require sufficient space, elaborate design, and strong control of current and magnet.

### 3.2. *Inertial confinement fusion*

Magnetic confinement fusion technology uses a magnetic field to restrain the reaction material, while inertial confinement fusion (ICF) technology uses the inertia of the reaction material itself during the reaction process. There are heavy-ion inertial fusion, laser inertial confinement fusion (LICF), and other technical branches. The LICF is the focus of current research so this paper mainly discusses the LICF [22].

The process of LICF can be divided into four stages. The first is strong light radiation. At this stage, a laser beam or X-ray will heat the target surface to form a plasma ablation layer rapidly. Then it is implosion compression. use the hot material on the target surface to eject outward to compress the fuel in the reverse direction. After that, it is Fusion ignition. nuclear fuel can reach high temperatures and high-density conditions through the centripetal detonation process. Finally, it is fusion combustion. thermonuclear combustion spreads inside the compressed fuel. The energy released by fusion is greater than the energy driving it, achieving net energy gain [22]. “Target” refers to hollow microspheres of fusion fuel [23]. In a laser inertial confinement fusion reactor, we need multiple lasers to radiate the target to achieve uniform heating in all directions. A typical example of LICF is the US National Ignition Campaign (NIC), which achieved net energy gain at the end of last year [12]. LICF has two different ways of driving implosion: direct drive and indirect drive. Direct driving uses laser light to directly irradiate the target, compressing the fusion fuel to achieve conditions for ignition and self-sustaining combustion. This driving method has high laser energy utilization and simple target configuration but requires high uniformity of laser irradiation. Indirect driving uses lasers to irradiate the black cavity to generate X-rays, which drive the target implosion to achieve fusion reactions. Indirect driving has good radiation uniformity, but the process is complex and energy is lost [24,25,26]. In fact, scientists from various countries are also trying other driving methods, such as the concept of “hybrid driving” proposed by Chinese scientists [22].

### 3.3. *Comparison*

At present, LICF and MCF both have their own advantages and disadvantages, which decide their future development and application in the future. Compared to magnetic confinement fusion devices, laser inertial confinement fusion devices have a simple structure and low cost. Due to the unidirectional nature of the laser, the plasma can be controlled in all directions to ensure its stability and obtain a large amount of heat in a short time. This means that a strong restriction ability on plasma, high plasma density, and short time is required for plasma ignition and combustion during the LICF process. However, currently, laser inertial confinement fusion devices can only constrain one target, which cannot achieve the continuity of controllable nuclear fusion reactions. MCF facilities can bind more plasma, which is easy to achieve the continuity of controllable nuclear fusion reactions. At the same time, in the process of magnetic confinement fusion, the efficiency of converting electrical energy into magnetic energy is high,

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while the superposition of lasers with different frequencies and phases leads to the cancellation of laser energy and a low energy conversion rate.

## 4. Key challenges to realizing controllable nuclear fusion

### *4.1. Common problems*

At the present stage, one of the most difficult problems in achieving controllable nuclear fusion is how to reach net energy gain, that is, the energy gain should be greater than input energy. Although the NIF of the United States achieved the net energy gain of nuclear fusion on December 5, 2022, the obtained energy can only boil ten pots of water [17]. In addition, maintaining the long-term stability of the high-temperature and high-pressure environment is also very challenging under the current technical conditions, which makes the existing fusion reaction only last on the order of seconds to thousands of seconds. For example, China's EAST is the longest-running Tokamak device in the world, and it can only run for 1056 seconds, equivalent to less than 20 minutes [17].

The controllable nuclear fusion technology routes mentioned above are both generally based on the fusion reaction between tritium and deuterium. Therefore, it faces serious challenges, that as how to obtain a stable source of nuclear fusion fuel and achieve tritium self-sustainment [27]. For deuterium, one liter of seawater contains about 0.03 grams of deuterium on the earth. In this regard, the oceans covering about seven-tenths of the earth's surface could provide abundant raw materials [12]. In contrast, as for another major raw material for controllable nuclear fusion reactions, tritium, its abundance in nature is extremely low, and there is not much tritium that can be produced artificially, and its half-life is short [28]. Moreover, nuclear fission is often used in the artificial production of tritium, which seems to mean that controllable nuclear fusion still cannot get rid of nuclear fission facilities.

Notably, these limitations are all encountered in the research process of realizing controllable nuclear fusion, but the advantages of nuclear fusion itself have not changed.

### *4.2. Different challenges*

For the MCF, there are three main challenges that should be overcome in the future. Firstly, during magnetic confinement fusion, the breakdown of plasma fuel is unstable owing to the fluctuation of the electromagnetic field, control current, and gas injection; Secondly, especially for magnetic confinement fusion devices such as tokamaks and stellarator, their structures are relatively large, complex, and expensive to manufacture. And because of the closed nature of the Tokamak device, the realization of continuous reactor operation is hindered. Finally, the plasma density used in magnetic confinement fusion is relatively low, and the output energy is small compared to the total investment in achieving nuclear fusion. How to constrain higher concentration plasma is the key to the commercialization of magnetic confinement fusion [18].

For the LICF, first of all, when heating fuel, the utilization rate of laser light in laser inertial confinement fusion devices needs to be further improved. Because laser inertial confinement fusion uses multiple lasers to constrain the target during operation, different lasers have different frequencies and phases, and their superposition can cause energy loss and reduce energy conversion rates. Secondly, the continuous operation, heat transfer, and dust removal of laser inertial confinement fusion reactions are still quite difficult. Laser inertial confinement nuclear fusion requires high laser energy and a long duration. High-energy lasers are generally in the form of pulse waves with short duration. Finally, the loading time of the target is very slow, requiring several hours. How to achieve continuous loading of the target is the key to the commercialization of laser confinement fusion.

## 5. Future development of controllable nuclear fusion

### *5.1. Development of magnetic confinement nuclear fusion in the future*

Firstly, the development of superconducting physics and materials will greatly promote the development of magnetic confinement fusion. We can use superconducting technology to build a fusion facility with

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higher field strength, Superconductors have zero resistance effect, and higher carrying current density is conducive to the construction of more compact fusion devices with higher field strength [16]. With the development of superconductor technology, especially high-temperature superconductor technology, nuclear fusion reaction devices in the future world can achieve true steady-state operation and considerable energy gain. As mentioned above, magnetic confinement fusion requires a strong magnetic field, and magnets require a tremendous amount of current to be applied. Due to the severe loss of conventional metal conductors which is caused by their own resistance, people can try to use superconducting materials with zero resistance to make magnet coils [29,30]. For magnetic confinement fusion, we can also enhance the longitudinal compression of the plasma by increasing the magnetic field strength of the polar longitudinal field or use solid deuterium-tritium targets to shorten the feeding time, thereby increasing the plasma density and increasing the output energy [18].

### 5.2. *Development of laser inertial confinement nuclear fusion in the future*

Different from magnetic confinement nuclear fusion, the optimization of target materials for laser inertial confined fusion gives an enhanced mass transfer process. The use of lithium is significant for laser inertial confinement-controllable nuclear fusion. Adding a certain amount of lithium to the target required for laser inertial confinement fusion can reduce the distance and time of laser energy deposition and transmission in the target, achieving a “fast ignite” for controllable nuclear fusion reactions. For example, a study showed that when doped with 10% lithium, the distance of laser energy deposition and transmission in the target can be reduced by nearly 10%, and the time spent can also be reduced by 6% [31]. For laser confinement fusion, we also need to find ways to improve the utilization rate of the laser used and reduce energy loss and add a pipeline for the manufacturing target in the device to improve the fuel loading speed to achieve the continuity of controllable nuclear fusion [18].

### 5.3. *Common Future Development*

As previously discussed, ongoing nuclear fusion attempts on Earth are facing a severe shortage of nuclear fuel, and it is difficult to find alternative solutions in a short time. However, with the rapid development of aerospace technology, we can turn our attention to places other than the Earth to seek other possibilities for controllable nuclear fusion. With the development of human aerospace technology, in the future, we can not only engage in controllable nuclear fusion on the Earth but also try to engage in controllable nuclear fusion on the moon. The entire surface of the moon is covered with lunar soil. In the lunar sea area, the average thickness of the lunar soil is five meters and even reaches ten meters in the lunar land area. The lunar soil is rich in helium 3, with a total amount of 1 million to 15 million tons. Helium 3 is a clean, safe, and efficient fuel for nuclear fusion power generation. With just 100 tons of helium 3, the global electricity demand for one year can be met. In order to better carry out space exploration and prepare for the establishment of a lunar base, the National Aeronautics and Space Administration (NASA) is attempting to establish a nuclear power station on the moon, using helium 3 to generate electricity. In addition to abundant fusion fuel, nuclear fusion on the moon has another advantage—high vacuum. Taking magnetic confinement nuclear fusion as an example, a high-vacuum environment is required to confine the plasma, avoiding collisions with molecules in the air, scattering, and other factors that destroy nuclear fusion. However, since there is no gas on the surface of the moon, it is always in a high vacuum environment, which provides a natural convenience for generating and controlling plasma. Carrying out magnetic confinement fusion on the moon will effectively reduce the complexity of the fusion system. In addition, with the development of electronic technology, the energy generated by controllable nuclear fusion on the moon can be transmitted back to the Earth through wireless transmission, and can also supplement energy for human exploration in outer space. Conducting controllable nuclear fusion on the moon, the moon will become another energy treasure like Persian gulf for humanity [32].

## 6. Conclusion

Although controllable nuclear fusion still faces the aforementioned problems, firstly, we have achieved net energy gain, and secondly, many different technological routes have been proposed to overcome problems and improve development level of controllable nuclear fusion. With the development of science and technology, these problems have been overcome, and controllable nuclear fusion has the potential to become the ultimate energy source for us humans to solve energy crisis due to its enormous energy and low pollution.

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