Nuclear Fusion and Tokamak

JamesHengrui Zhong[1, *], YiTing Wang[2]

Abstract:
The sun's power source that allowed it to warm up the whole solar system for billions of years has been mysterious. The sun gains power from the continuous nuclear fusion inside it. Understanding the principles and applications of nuclear fusion is essential to human society. Nuclear fusion can be a power source for culture as it powers the sun.
Moreover, it has many more advantages compared to other fuels. It is practical; 1 gram of fuel in nuclear fusion can produce energy equivalent to 12000 kilograms of hard coal. Also, it is clean. Not like petrol produces greenhouse, nuclear fusion produces no pollutants at all. These two factors make nuclear fusion the world's most important potential energy source. However, there are obstacles to the studies and applications of nuclear fusion. To apply nuclear fusion, one must learn the principles, requirements, and choice of materials for nuclear fusion, as well as the structure of tokamak, how tokamak work, and the applications of this device. In this essay, the mechanisms will be presented based on Albert Einstein's Mass Energy Equations and mass defect effect; the calculations of the energy released by nuclear fusion with different materials used will be shown; the prerequisites and limitations of nuclear fusion will be discussed, and the mechanisms and structures of tokamak will be presented.

Keywords: Nuclear Fusion, Tokamak, Energy, Environment, Application, Principles

1 Introduction

The world's energy sources are fossil materials, energy, and renewable resources. Using fossil fuels brings serious environmental pollution and exhausts its limited reserves in the next few decades. The current nuclear power plants fission branch power generation while producing energy and many radioactive wastes. At the same time, the chain reaction of splitting heavy nuclei is often challenging to control. Some people reject and criticize this form of energy because of its potential safety and pollution problems. We are familiar with the 1986 Chornobyl nuclear accident in the Soviet Union and the 2011 Fukushima nuclear accident in Japan.

In contrast, nuclear fusion produces 3-4 times the energy of nuclear fission, and its byproduct is inert, non-toxic nitrogen, which does not affect ring safety; nuclear fusion reactions need to be carried out in a high-temperature plasma and an external maximum field limit environment, and it can be controlled or stopped in a few seconds, which is essentially safe. From the development trend, controlled nuclear fusion is expected to become a clean, safe, and inexhaustible energy production technology with broad application prospects.

Nuclear fusion may be a relatively low-cost way of obtaining sufficient electricity in a future where other fossil energy reserves are significantly reduced and beyond. In addition, nuclear fusion has two significant advantages over nuclear fission. One is that the Earth contains far more fusion energy than fission energy. It is estimated that each liter of seawater contains 0.03 grams of deuterium, so there are 45 trillion tones on Earth in seawater alone. One liter of deuterium in seawater can provide the equivalent of 300 liters of petrol released by nuclear fusion. The amount of fusion energy on Earth is about 10 million times the amount of fission energy that can be released from all the fissionable elements, making it an inexhaustible energy source. According to the Academy of Ocean of China data, although not found in nature, tritium can be produced by interacting neutrons with lithium, which is also abundant in seawater.

Tokamak nuclear fusion, also known as a superconducting tokamak, controlled thermonuclear fusion [1], and superconducting non-circular cross-section fusion experiments, is one of the essential theories in nuclear physics, one of the most important ways to achieve nuclear fusion. Tokamak fusion is a process in which the protium and deuterium contained in seawater are used in a specific environment and at ultra-high temperatures to achieve fusion reactions that release enormous amounts of energy. At the Third International Conference on Plasma Physics and Controlled Fusion Research held in Novosibirsk, USSR, in August 1968, Azimovich announced the achievement of an electron temperature of 1 keV, a proton temperature of 0.5 keV, and $n\tau$=10 to the 18th power m-3.s on the Soviet T-3 tokamak, which was a breakthrough in controlled fusion research. This breakthrough in controlled fusion research has set off a wave of tokamak fusion internationally. Many large tokamak devices have been built or modified in various countries. Some of the more famous ones are STTokamak at Princeton University in the US, Ormark at Oak Ridge National Laboratory in the US, TFRTokamak at the Institut Von Knei-O-Rhodes in France, Cleo at Karam Lab in the UK, and PulsatorTokamak at the Max Planck Institute in West Germany. PulsatorTokamak.

2 Nuclear Fusion

A net-exothermic reaction must be guaranteed to make nuclear fusion a credible and feasible energy source. That means we need to gain more output energy than the amount of reaction-triggering energy inputted. To achieve this goal, a minimization of the input energy and a maximization of the output energy is necessary. Therefore, one must thoroughly study nuclear fusion's mechanisms and prerequisites to use it as an energy source.

Nuclear fusion is the fusion of 2 elements, usually hydrogens and their isotopes, to form a new element. Hydrogen (H), the fuel needed for nuclear fusion reactions, is the universe's most common and abundant element and the periodic table's lightest element. Its atomic number is 1, and its atomic mass is 1.008 amu. Hydrogen has three isotopes: hydrogen (1H, P), deuterium (2H, D), and tritium (3H, T) (As shown in figure 1).

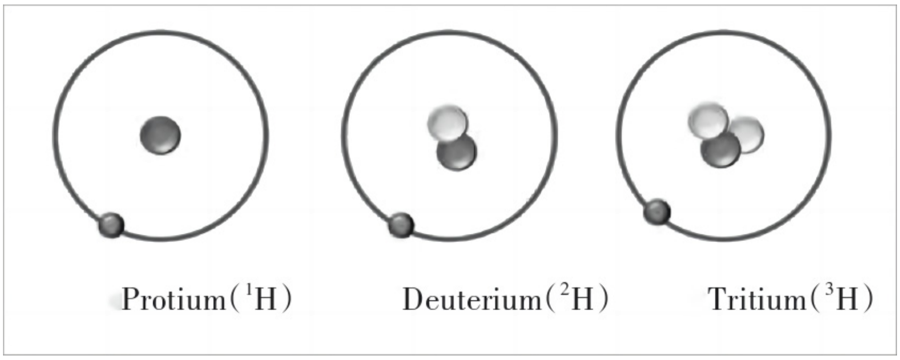

Fig. 1. Hydrogen isotope

Nuclear fusion performs physically, unlike chemical reactions, which emit energy from the formation and decomposition of compounds. It involves the breakdown and formation of the vital force inside nuclei. As a fundamental force, vital force helps protons and neutrons in the nucleus overcome electrical repulsion and stick together. For example, two deuterons, $^2H_1$, can react to form helium, $^3He_2$, and release a neutron. During the process of breaking and forming strong forces, tiny masses are lost, which emits enormous energy.

Mass defect is the energy loss before and after the nuclear reactions. It finds out that the mass of the nucleus is always less than the sum of the mass of protons and neutrons. The following formula can define this:

$M_{nulceus} = M_P + M_N + ?M$

Where M_P is the total mass of the protons, M_N is the total mass of neutrons, and $?M$ is the mass defect. Therefore, there will always be less mass after nuclear fusion. This mass loss during nuclear fusion will emit huge amounts of energy [2]. Einstein's mass-energy equation can calculate this:

$E = ?M \times C^2$

In which C is the speed of light, 299792458m/s. As a result, a slight decrease in mass during nuclear fusion can produce an enormous amount of energy. For example, when two deuterons are used as nuclear fusion fuel, the energy is released as follows:

$^2H_1 + {}^2H_1 \rightarrow {}^3He_2 + N + 4MeV$ (MeV is millions of electron volts)

In this reaction, the energy released is about 270,000 kW-hr per gram ($1kW - hr = 3.6\times10^6 W \bullet S$) of the deuteron, nearly four times the energy produced in a gram of nuclear fission, and it exceeds 10 million times the energy released in the combustion of fossil fuel [3].

Even though nuclear fusion can release a tremendous amount of energy, there are prerequisites for nuclear fusion to take place. Because the positively charged nuclei repel each other significantly when they get close, nuclear fusion aims to form a new element, which requires solid force between two nuclei to stick the repelling nuclei together. This is extremely difficult because according to Coulomb's law, which describes the electrical force between two charged particles as $F = k\frac{Q_1 \times Q_2}{d^2}$ (Q_1 and Q_2 are the charges of two particles, and d is the distance between two particles), the repulsion between two nuclei can be infinitely large when closing together since the repulsion force is inversely proportional the square of the distance. This gives two requirements for nuclear fusion: the high temperature and high pressure needed for the reaction to be initiated. Since enough kinetic energy must be given to the particles to overcome repulsion force, enough temperature and pressure must be created for the reaction. The temperature and pressure are so high that nuclear fission is needed to detonate a hydrogen bomb.

The other requirement is that nuclear fusion fuel must be relatively light since the repulsion force is directly proportional to the charges of two nuclei. Therefore, isotopes of hydrogens are commonly used since they all have only one proton and can minimize the repulsion force and the input energy. Moreover, the reaction releases so much energy and is so hard to control that it requires a highly developed device for the reaction to occur. Tokamak, for example, is the best candidate for nuclear fusion for its ability to create the high temperature and pressure needed to initiate nuclear fusion and its capability to control the process.

3 Tokamak And Its Principles

The tokamak is a toroidal device driven by confined electromagnetic waves to create the environment and ultra-high temperatures for the fusion of deuterium and tritium and to enable human control of the fusion reaction. Its name, Tokamak, is derived from toroidal, Kamera, magnet, and kotushka.

In a tokamak device, the current variation of the ohmic coil provides the volt-second required to generate, build, and maintain the plasma current (transformer principle);

$V \times ?t = L \times ?I = N \times ?B \times Ae$

The polar field generated by the polar field coil controls the plasma cross-sectional shape and positional equilibrium; the toroidal field generated by the toroidal field coil ensures the overall macroscopic stability of the plasma; the toroidal field together with the polar field generated by the plasma current form the magnetic lines of force Rotationally transformed, and magnetically nested magnetic surface structures constrain the plasma. Charged particles do not escape from the confinement zone along the magnetic lines of force. However, due to the inhomogeneity of the ring, particles can drift across the magnetic field, with electrons and ions drifting in opposite directions, thus causing charge separation, a process in which the electric field destroys the overall confinement. The solution is to induce a magnetic field in the direction of the diameter of the ring ("polar" magnetic field), also known as a rotational transformation of the magnetic lines of force so that the magnetic lines of force become toroidal spirals. In this way, the orbits of most of the particles will be closed. If the overall magnetic field is optimally designed, the overall macroscopic stability of the plasma can be ensured [4].

At the same time, the plasma current also produces ohmic heat. The cross-sectional shape of the plasma can be circular or can be designed as a D-shape in combination with a bias filter (a unique component located in the edge zone inside the vacuum chamber, which separates the confinement zone from the edge zone by creating a magnetic separation interface and has functions such as heat removal, impurity control, and helium ash removal). In tokamak devices, it has been possible to bring the plasma up to and beyond the temperature required for effective combustion of deuterium-tritium (>10 K) by high-power neutral beam injection heating and microwave heating, up to 4.4×10 K. By increasing the device's size, the confinement time increases roughly by the square of the size. In addition, the confinement time can be increased by increasing the circumferential magnetic field and optimizing the confinement configuration and mode of operation. The energy confinement time can also be increased by increasing the toroidal magnetic field and optimizing the confinement configuration and operation mode. The experimental results show that the tokamak device meets the requirements for establishing a nuclear fusion reactor [5,6].

The deuterium-tritium self-sustaining fusion reaction can only be achieved if the three conditions of density (>10 cm), temperature (>10 K), and energy confinement time (>1 s) are met simultaneously (or fusion triple product >10 cm-K-s). These three conditions have been met or exceeded in separate devices, but not simultaneously in one device, and the energy gain/loss condition ($Q \approx 1$) has been met mainly in the JET (see figure) and JT-60U devices, with the JET deuterium-tritium experiment, also yielding 17 MW of fusion power output.

4 Conclusion

Nuclear fusion is a physical reaction involving the combination of two nuclei into one. During such a process, according to Einstein's mass-energy equation.

$E = ?M \times C^2$, a tremendous amount of energy will be released due to mass weight loss. However, because of the enormous energy released in nuclear fusion and its environmentally friendly properties, nuclear fusion can be a hopeful and feasible stable energy source. However, nuclear fusion requires breakdowns and formations of strong forces between the nuclei and the need to vying the electrical repulsion force between the positively charged nuclei, significantly large in such a tiny scale due to Coulomb's law, the prerequisites of nuclear fusion can be severe. A high-temperature and high-pressure environment must give nuclei enough kinetic energy to overcome the repulsion force. A relatively light element is used as fuel to minimize the repulsion force between nuclei and the energy needed to initiate the reaction. Apart from the requirements above, a powerful device must be used to control the reaction. Under these considerations, the tokamak is essential for nuclear fusion.

The US Department of Energy and Princeton Plasma Physics Laboratory have discovered a new way to make smaller and more powerful magnets than the original, which could help design and manufacture nuclear fusion facilities. Such powerful magnets would be easier to fit into the tight spaces inside a spherical tokamak, which is shaped more like an apple with an apple core inside rather than the doughnut-shape of a conventional tokamak, and scientists have also been exploring any possible designs as future fusion power plants.

Because the magnet can be placed separately from the rest of the machinery in the spherical tokamak's central cavity to enclose the hot plasma that fuels the fusion reaction, scientists can repair it without removing any other components. "To do this, you need a magnet with a stronger magnetic field and a smaller size than the current magnet." The US Department of Energy scientists explained, "The only way to achieve this is to use superconducting wires, and that is what we did."

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