Chapter 28
Nuclear Fusion: Energy of Future

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1 Introduction

Fusion of light nuclei is by far the foremost process of energy release of energy in the universe. The sun, like all of the stars, is nerved by the fusion of hydrogen nuclei into one helium nucleus. The process of fusion releases the huge energy of 26.72 MeV or 6.7 MeV per nucleon, which means around 180 MWh energy per gram. Hence, the energy released in fusion reaction per unit mass of fuel is nearly seven times the burning of coal. This efficaciously exemplifies the ultimate economic tackling of matter which is chosen by nature for its prime energy release process. Further, these and other fusion mechanisms are also liable for the generation of elements in the stars. Nuclear fusion is a crucial and highly tempting option for a future terrestrial supply of energy, since this source of energy would be environmentally agreeable and the fuel comprising in it is practically limitless. Out of the nearly 80 plausible fusion reactions, this reaction (Figs. 1, 2 and 3)

$D + T \rightarrow {}^4He\ (3.517\ MeV) + n\ (14.069\ MeV)$

between the isotopes of hydrogen, i.e., deuterium, D, and tritium, T, is of utmost use. Around 20% of energy is carried away by alpha particle ${}^4He$, whereas the remaining 80% of energy is released as the kinetic energy of neutron n. The concentration of Deuterium on Earth is practically limitless and is available in the form of heavy water in the oceans which is 0.015% in natural hydrogen. Tritium does not exist due to its radioactivity characteristics with a half-life of 12.35 years, so for a reaction of D–T we have to generate Tritium through the breeding reaction of Lithium

${}^6Li + n \rightarrow T + {}^4He + 4.8\ MeV$

${}^7Li + n \rightarrow T + {}^4He + n'\text{-}2.47\ MeV$

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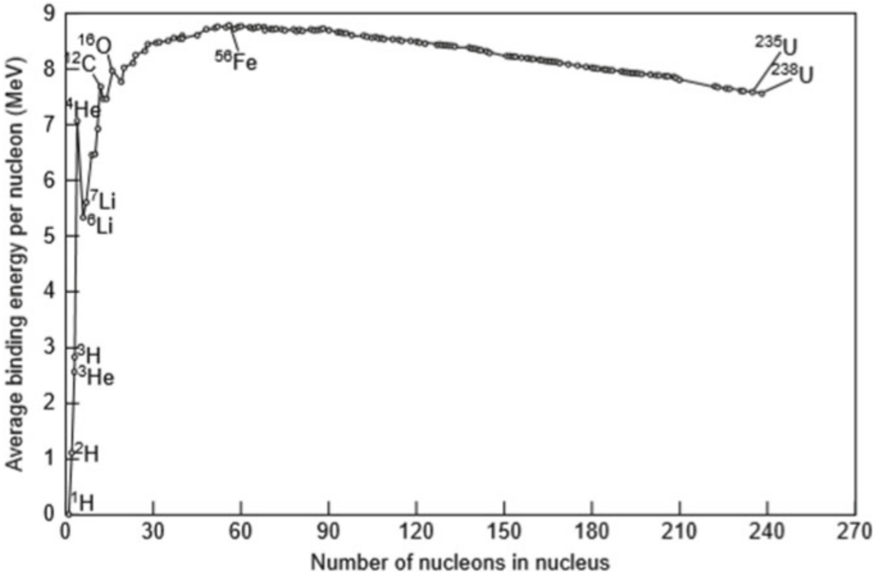

Fig. 1 Average nuclear energy binding curve (Courtesy of Wikimedia Commons)

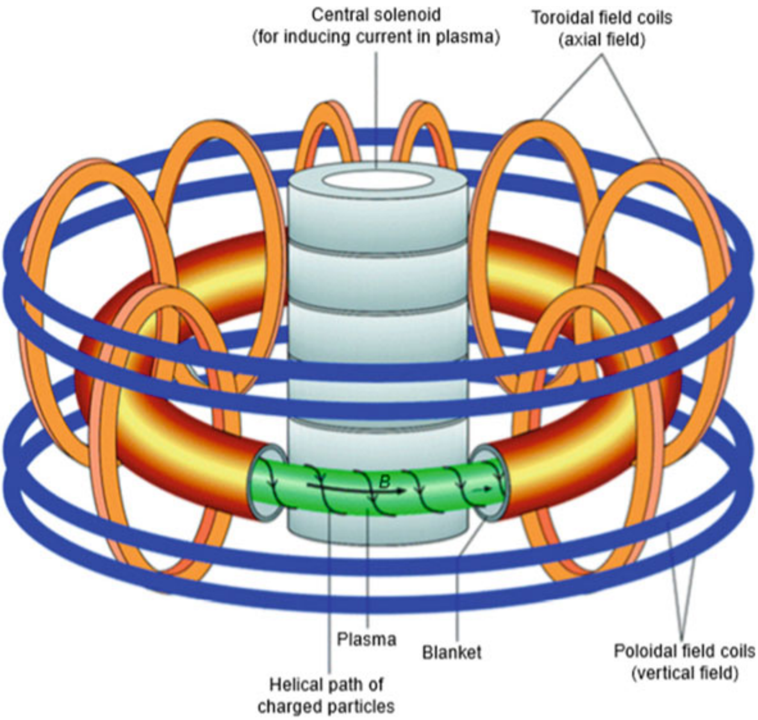

Fig. 2 Schematic diagram of Tokamak (Springer series in Material Science, vol. 214, pg. 314)

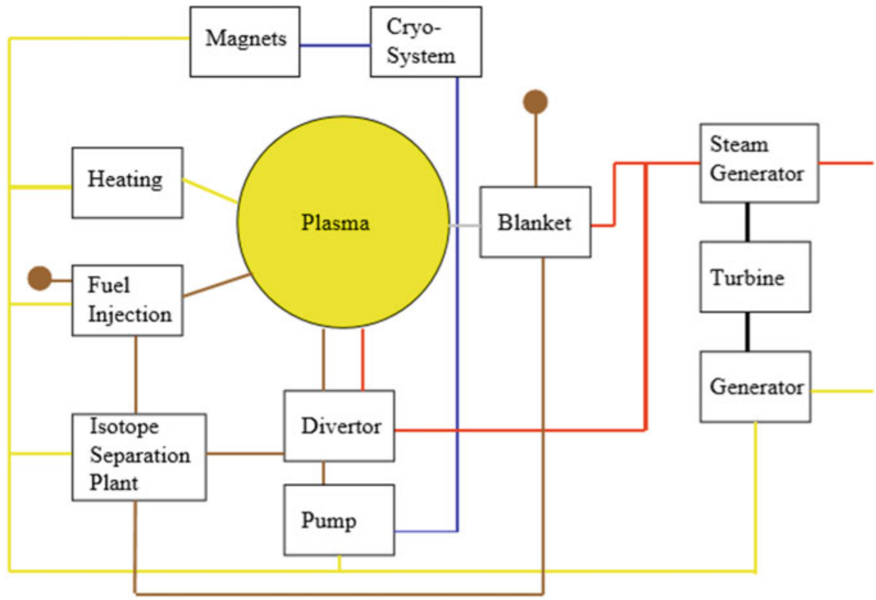

Fig. 3 Flow chart of fusion reactor (reference [3])

where n′ is a slow neutron, which has a contribution for the generation of tritium. Natural lithium comprises 7.42% of ^{6}Li and 92.58% of ^{7}Li. So we use deuterium and lithium as fuel for fusion as they are cheap. According to the present scenario, the resources of deuterium and lithium would be available for more than 30 million years. The radioactive tritium is processed internally only in [1]. For the fusion of two atoms, there is a requirement of binding energy. This binding energy is the converse energy of mass defect according to Einstein's theory of $E = (\Delta m)\, c^2$. This is the energy required for disassembling the nucleus from an atom into separated nucleons and the energy spent on separating each nucleon is average binding energy [2]. For all such elements, the binding energy is shown in Fig. 1. From which it can be interpreted that average binding energy for hydrogen isotopes and helium atom are relatively low and hence fusion can be quite easily possible to meet the conditions [2].

Under normal conditions of temperature and pressure, the fusion cannot take place. For fusion to take place atoms are to be heated so that the motion of electrons and nuclei will increase and electrons will get separated. The state of matter where electrons and nuclei are not together is called a plasma state. The plasmas are very hot and move with a very high velocity which makes the reaction very tough to control as we have to overcome the high repulsive forces. So it is worth to gravitate that fusion depends on plasma temperature and plasma density [3]. For the fusion ignition, there is a requirement of the crossing energy value of the triple product of temperature, density and energy confinement time. The triple product of D–T reaction is two orders lesser than that of D–D & D–^{4}He reaction [3]. Hence it is convenient to go for a fusion of D–T.

2 Confinement

For the fusion reaction, there is a requirement to control the plasma state, i.e., proviso to confine the plasma, which can be done by mainly three processes. The first one is gravitational confinement, which occurs between stars only. The second one is magnetic confinement, which makes use of Lorentz force of magnetic field for the confinement of charged particles. The third one is inertial confinement, in which the fuel is made pellets to pressurize highly and then further the reaction is being proceeded [3].

2.1 Magnetic Confinement

It is evident that no solid material can sustain heavy temperatures of 100 million Kelvin so this dilemma is solved by stating the theory that all charged particles can be confined under magnetic fields. It inspired to go for toroidal closed arrangement.

Only toroidal confinement also has limits to let escape some massive plasma so a better technique is to provide superposition of strong toroidal field with poloidal field [1]. The high temperature plasma experience Lorentz force, which is responsible for confinement. Tokamak is a device or, more precisely, it is reactor which is of donut shape surrounded by magnetic coils [4, 8, 9] as shown in Fig. 2.

2.2 Inertial Confinement

It is entirely different school of thought for fusion process. It compresses the fuel into small solid pellets and due to extreme denseness when these pellets are heated then the possibility exists for microexplosion. Altogether here the confinement is not actually reached by external fields but the inertia binds the atoms together [3, 10]. Basically fuel pellet is enclosed by the layer of another material and extreme intense beams of laser are subjected on the charged particle of high energy. The layer that is the outer one gets heated up and evaporates. The products formed in evaporation get mobile outward, and the pellet is compressed inward, due to momentum conservation (inertial binding) [3]. The initiation of such fusion is done with the help of laser beam and this can even also be done directly by laser driving the pellet itself and indirectly by making use outer another layer usually gold layer and then laser driving.

3 Alternative Fusion: Muonic Fusion

This is an idea which is being investigated in few laboratories, to produce muons, which are so called as the heavy sisters of the electron. The muon is used to inject into a mixture of deuterium–tritium gas and there exist little probability that muon will get captured by the tritium or the deuterium atom and there will be formation of the deuterium–tritium molecule. Due to the heavy mass of muon, the dimensions will be smaller as compared with normal molecule with bounded electrons [3]. Hence the fusion reaction may undergo as the nuclei are closer to each other. But there is problem to this as well, as the cost involved in production of muons is too much and can catalyze fusion reactions about 200 times only [5].

4 Fusion Energy Conversion and Its Transfer

With the help of light isotopes, it is possible to have a fusion reaction possible, i.e., D–T fusion and this identification was responsible reason which has inspired to work on various other factors to utilize this energy as a source of electrification. And hence the need of design of such power plant is there. The features like steam generator, turbine and current generator will be same as that in conventional fossil-fuelled or nuclear power plants. A simple flowchart telling about the material and energy flow can be depicted from Fig. 3. The fuel is injected and the conditions required for fusion with system confinement are done which further leave the plasma and they are stopped in the blankets which are the plasma surrounding modules [3].

5 Blanket System

This is the key system that converts fusion energy into electrical energy. Its main functions are energy extraction, tritium breeding and radiation shielding, which means the transferring of energy from fusion to thermal is being done, it ensures self-sufficiency and it protects external subsystem from neutron and gamma radiation which may cause an explosion. The heat which is produced in the blanket is transported via water or helium to the steam generator and then it is fed to grid. A small part of the same is utilized to power other components of plant. Cryo-system requires the electrical power which produces low-temperature helium for the super-conducting magnets, the current drive, the current in the magnets and the heating systems of plasma [2].

6 India's Role in Fusion Energy

R. Srinivasan and the Indian DEMO Team reviewed that the contribution to energy from the fusion reactor is expected to rise beyond 2060. It will be beneficial if the research program gets accelerated so that fusion reactors can be realized well before 2050 [6]. The multibillion project of ITER which was launched in 2007 to build a Tokamak reactor and to check its feasibility, around 35 countries of the world took their participation for the research and India is also part of that. Around 58% of the ITER project has been completed and is been expected to generate power by 2035 [11].

7 Future Directions

Fusion energy is itself very unique in energy sector and challenging for R&D. ITER is the biggest fusion reactor experiment that expects around 500 MW of power generation in 400 s of pulse operation. The technology involving breeding capacity of blanket is important and is still ongoing R&D but other factors of self-sufficiency of tritium, economic, environmental friendliness, safety are also important [3, 7].

8 Conclusion

Fusion energy is safe and clean energy but needs efforts in implementing for the applications. There is availability of various materials to fuse them like D, T, ^{3}He, but need extreme conditions to initiate the reaction. The reactor for such fusion is still under research and the issues are expected to be solved by ITER and DEMO by 2025. Taming the fusion energy is a promising challenge but its rewards are incalculable for the future energy needs of mankind.

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