

TECHNOLOGY INSIGHTS

A Report from EPRI's Innovation Scouts

A Review of Fusion Confinement Types

INTRODUCTION

Increasing global energy demand and aggressive decarbonization goals are driving innovation throughout the energy sector. Fusion, long sought after as a source of sustainable, non-emitting, scalable, firm energy, is experiencing a surge in private investment and media coverage due, in part, to a number of recent advancements in both public and private efforts [1].

What is fusion? Does the taunting phrase “fusion is always 20 years away” still apply, or is it truly nearing commercialization? After a three-decade hiatus, EPRI is returning with a new strategic focus on fusion energy that includes technology scouting and assessment. Addressing questions on the viability of fusion as a future commercial energy option is one of the primary goals of this new EPRI fusion energy strategic program. In this briefing, three broad categories of fusion energy technologies are reviewed. Specifically, magnetic, inertial, and magneto-inertial confinement are common confinement methods used to manage and control the fusion fuel and reactions to produce a sustained net energy output.

FUSION EXPLAINED

Fusion is the process by which lighter elements such as hydrogen combine to form heavier elements, releasing energy (Figure 1). Because the process of fusion involves the nucleus of the atom, not just the electrons as in chemical processes, fusion is a nuclear process. As lighter elements combine, there is a tiny mass difference (Δm) between reactants and products. This mass difference is converted into

released energy according to the famous equation $E=\Delta mc^2$, where c is the speed of light in a vacuum (a very large number). Fusion occurs across the universe every day, powering the sun and other stars for billions of years.

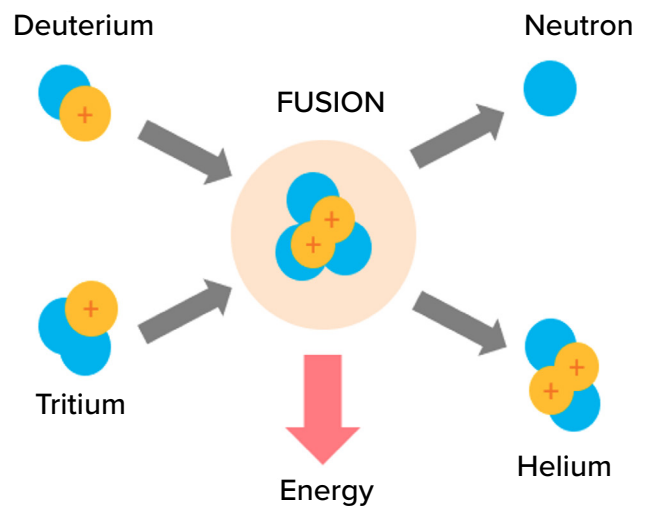


Figure 1. Fusion of deuterium and tritium, two isotopes of the element hydrogen, forming a helium nucleus and releasing a high energy neutron.

While fusion reactions are readily achievable in the laboratory and even in industrial neutron sources [2,3], self-sustaining fusion reactions in which more energy is released than is consumed by the overall facility (engineering gain) have yet to be achieved on earth. Fusion is challenging because it requires positively charged nuclei that normally repel one another to come in close enough contact for the strong nuclear force (that binds the nucleus together) to take over. Therefore, special conditions must be satisfied.

WHO'S WHO OF HYDROGEN

Atoms with the same number of protons that differ in the number of neutrons are called isotopes. Generally, isotopes of the same element exhibit similar chemical behavior but can have very different nuclear properties. For example, some isotopes of lead (Pb) can be stable and others radioactive. For fusion, the lightest element hydrogen plays an important role as a fuel, but that role varies by isotope. Hydrogen has three isotopes:

- ^1H (Protium): "light" or "ordinary" hydrogen. Protium consists of just one proton and no neutrons.
- ^2H (Deuterium): "heavy" hydrogen. Deuterium consists of one proton and one neutron.
- ^3H (Tritium): a radioactive form of hydrogen. Tritium consists of one proton and two neutrons.

The first condition is that the outer clouds of electrons that shield the inner nucleus must be stripped away through a process called ionization, typically achieved by adding heat to the system. Once nuclei are separated from their electrons, plasma is formed. Plasma, a fourth state of matter (beyond solids, liquids, and gases), is this state at which electrons are freed from their nuclei [4].

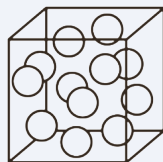
Second, suitable environmental conditions must be provided to allow the now bare nuclei to approach one another for long enough to combine. For simplicity, these conditions can be reduced to a product of three factors: density, temperature, and confinement time [5].

Stars like the sun create the confinement conditions suitable for fusion with the enormous force of gravity present in their interior. Creating these conditions on earth requires application of alternative methods that must yield temperatures in excess of 100 million degrees Celsius [7], over six times hotter than the center of the sun [8]. Three general classes of confinement methods to achieve anthropogenic fusion are described below.

Fusion requires keeping a fuel bearing plasma:



Hot enough
(plasma temperature)



Dense enough
(plasma density)



For long enough
(plasma confinement time)

The Fusion Triple Product

Achieving sustainable fusion reactions that would support commercial energy generation requires producing and maintaining conditions that keep the plasma hot enough, dense enough, for long enough. These conditions allow positively charged nuclei to approach close enough to one another to overcome electrostatic repulsion and allow the strong nuclear force to take over. The strong nuclear force then pulls the nuclei together to form a new, heavier element. There are many different technological fusion approaches being pursued to achieve conditions to support sustained fusion reactions that can yield more energy out than goes in.

CONFINEMENT METHODS

Confinement methods are the mechanisms employed to create the conditions under which controlled fusion can occur. Three general methods are commonly used to categorize fusion approaches and are described below.

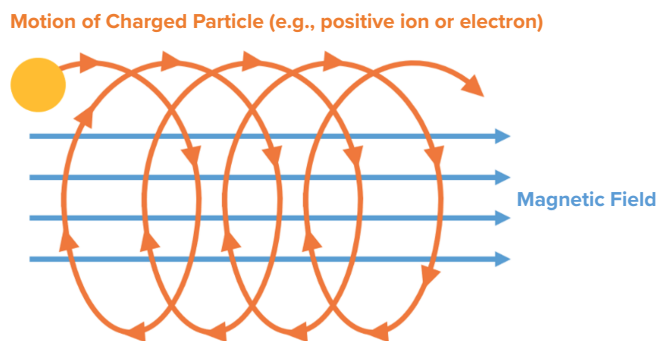


Figure 2. Spiraling motion of a charged particle in a magnetic field.

Magnetic Confinement

Charged particles, like those present in plasma, travel in spiral paths around magnetic field lines (Figure 2). Therefore, magnetic fields can be used to steer and confine plasmas. Magnetic Confinement Fusion (MCF) takes advantage of this behavior to squeeze and shape plasmas, heating them in the process, over relatively long confinement times in order to generate and maintain temperatures and plasma densities needed for fusion [9,10]. Magnetic fields can be generated externally using magnetic coils or self/internally induced as the result of electrical currents.

Externally generated MCF concepts, i.e., those reliant on one or more sets of powerful magnetic coils for plasma confinement, are the most common fusion approaches. Among these, the tokamak (Figure 3) and the stellarator are two prominent examples. Self-generated (or self-ordered) MCF concepts, i.e., those predominately reliant on magnetic fields induced by internal electric currents, include the field-reversed configuration (FRC) and the z-pinch.

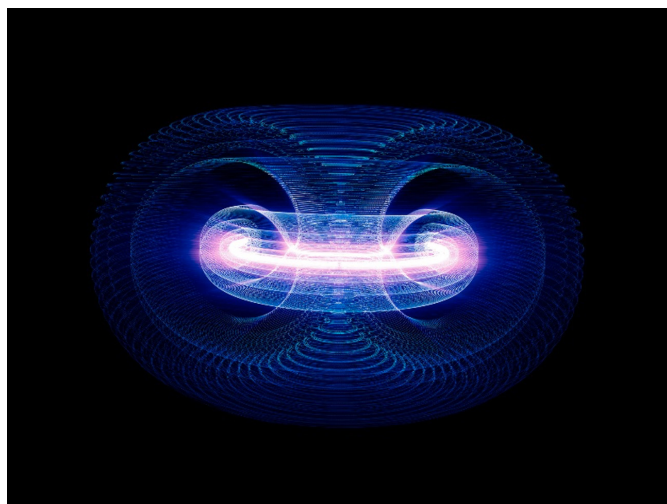


Figure 3. Illustration of plasma confined in the “doughnut-shaped” tokamak.

Magnetic fields are useful for limiting thermal losses caused by escaping ions; however, many concepts still require some form of external heating, such as through injection of radiofrequency energy or neutral ion beams, to maintain fusion conditions [11].

Inertial Confinement

In contrast to MCF, Inertial Confinement Fusion (ICF) approaches achieve confinement conditions for fusion through physical compression. As with magnetic confinement, there are multiple approaches to achieving inertial confinement [12]. The most common approach, laser ICF, employs lasers to drive the compression of a spherical fuel pellet directly or indirectly through the heating of the outer layer of the fuel pellet. This heating results in rapid outward expansion of the fuel pellet, and an equal and opposite implosive force to generate the densities and temperatures needed to initiate fusion. ICF approaches trade the longer confinement times offered by MCF approaches for much higher fuel densities.

In direct drive systems, the laser energy is focused directly on the fuel pellet surface. For indirect drive systems (Figure 4), the laser energy is focused onto the inner surface of a hohlraum, or a hollow cylindrical container, where it is converted to X-rays which then irradiate and heat the surface of the fuel pellet [13].

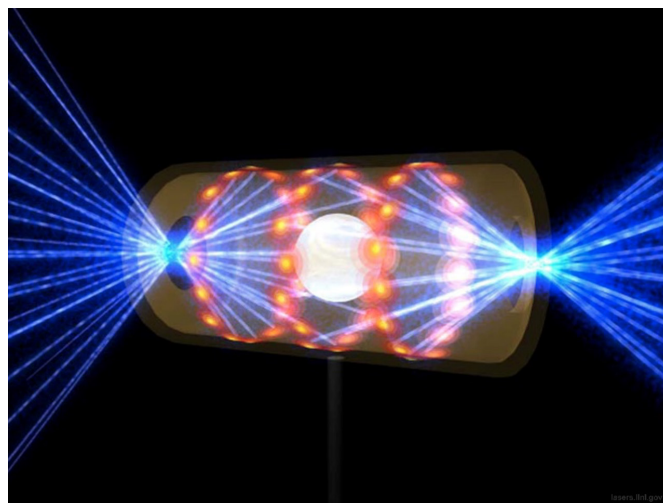


Figure 4. Illustration of indirect drive inertial confinement fusion. Here, the spherical fuel pellet lies at the center of a cylindrical hohlraum and is heated by X-rays produced following absorption of the intense laser light by the inner walls. Source: Lawrence Livermore National Laboratory. Used with permission.

Magneto-Inertial Confinement

Magneto-Inertial Confinement (MIC) combines aspects from both MCF and ICF to provide confinement conditions suitable for fusion. This confinement type takes advantage of magnetic heating and confinement concepts from MCF and compressive driver forces from ICF [14]. In some cases, magnetized target fuel is compressed via a liner material [15]. Solid liners, plasma liners, magnetized liners, laser liners, and liquid metal liners driven by pistons have been under investigation as methods to compress the target fuel [14,16]

In addition to magnetic, inertial, and magneto-inertial confinement fusion, other fusion confinement methods, such as electrostatic confinement and muon-catalyzed fusion exist and are currently under development [1]. These other approaches may offer alternative pathways to controlled fusion should they prove viable upon future exploration.

PATH FORWARD

Today, there is a large diversity of potential fusion concepts under investigation across magnetic confinement, inertial confinement, magneto inertial confinement, and other confinement approaches. Beyond being able to confine plasma and create a fusion reaction, fusion systems must be as efficient as possible to accommodate losses during energy conversion and delivery. Thus, as fusion stakeholders are still identifying viable fusion technologies, it is beneficial to explore many concepts that may provide different benefits and circumvent challenges.

EPRI continues to engage the fusion community and is working to support and accelerate commercialization of fusion technology via collaborative research and development to better align technology attributes with end-user and market needs. Current focus areas include requirements and guidance, advanced materials and manufacturing, testing and qualification, economic analysis, practical operations, and technology development and transfer. More information on EPRI's fusion efforts can be found here: <https://www.epri.com/fusion>.

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Founded in 1972, EPRI is the world's preeminent independent, non-profit energy research and development organization, with offices around the world. EPRI's trusted experts collaborate with more than 450 companies in 45 countries, driving innovation to ensure the public has clean, safe, reliable, affordable, and equitable access to electricity across the globe. Together, we are shaping the future of energy.

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3002026585

December 2023

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