ENERGY for the
COMMON GOOD
Soon enough to make a difference

WHERE IS FUSION TODAY

April 2022

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Table of Contents

Where is fusion today?

An overview of the technologies under development

At Energy for the Common Good (ECG), we believe there are many paths to commercial fusion energy. This paper will explore the main "types" of fusion, explain how they work, their pros and cons, and mention a few companies researching each method.

Introduction

Currently, more than a hundred projects are advancing commercially focused fusion technology in over 35 nations spanning both the public and private sectors. Despite broad international participation in government-sponsored fusion research, most fusion development in the private sector has taken place in the United States.

Private sector development of new technologies can encourage faster advancement and yield more cost-effective products and services while maintaining engagement with grant-based government sponsored research. SpaceX, is one recent example of this. Having fast tracked space travel, they now handle two-thirds of NASA's launches at a fraction of the cost.

Patents and intellectual property laws create financial incentives for private fusion development to explore novel ways to create fusion energy. In the US we know of three[1] private companies that have directly adapted[2] publicly researched fusion technologies. Perhaps unsurprisingly, at least fifteen private companies are focused on developing other novel, proprietary technologies.

To better convey the scope of the physics and applications of fusion, this paper provides a description of the functionality, potential benefits, and potential challenges of the most widely researched fusion methods as well as a sample of the few promising novel approaches to fusion.

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[1] There may be more, but this is the research we have as of February 2022.

[2] All private companies benefit and "use" plasma research from government sponsored research even if it is not directly related to the device they are making.

How is fusion possible?

FIGURE 1: D-T FUSION ANIMATION

Source: Wikimedia Commons

Fusion is the process of combining two light elements into one heavier element. In the process, some mass from the lighter elements is converted into energy.

The difficulty of fusion lies in the fact that nuclei are small and positively charged, making fusion similar to the task of pushing together two small, strong magnets that repel each other. Thus, fusion only happens when matter is in the fourth state: plasma.

Unlike solids and liquids, plasma is most similar in behavior to an extremely hot gas. In this state, the high temperatures greatly increase the likelihood that two atoms will collide and fuse. How we most effectively force this "fusing;" whether through containment or directed action determines the scientific approach being used.

Plasma is difficult to contain because if it interacts with cooler substances (like a solid, liquid, or gas), it will cool significantly, (causing the non-plasma substances to quickly become damaged) making fusion difficult or impossible.

To control plasma, scientists rely on the fact that the extreme temperatures cause electrons to be stripped from matter. In practical terms, this means plasma is electrically charged and, thus it is controllable by magnets or manipulated by laser or some combination of hybrid approach.

Triple Product

A common metric used to judge the success of a fusion device is called the Lawson Criterion, or the triple product.

The Lawson Criterion states that when the product of the plasma density, the reaction rate, and the energy released from a reaction reach a certain value, fusion will release more energy than it took to make the reaction occur. In short, fusion will produce net energy whenever certain atoms are pushed close enough together at a high enough temperature for long enough.

This means there are multiple paths to achieving net energy from fusion. Some devices focus on sustained containment while others focus on achieving high plasma density over a short amount of time.

What are the different ways to create fusion?

Currently, about twenty unique fusion energy device concepts are being researched. Devices can be grouped based on the qualities of the plasma they create.

- **Magnetic confinement devices** hold relatively low-density plasma over longer timeframes using powerful magnets.
- **Inertial confinement devices** create a highly dense plasma over a short timeframe using lasers or accelerators.
- **Hybrid devices** sit in a balance between the two by forming plasma and actively compressing it.

Major Considerations for Devices

Size

Influenced by multibillion dollar fusion projects such as the International Thermonuclear Experimental Reactor (ITER) and the National Ignition Facility (NIF), one misconception of fusion is that the technology will always remain bulky and impractical for widespread power generation. But, remember that one of the first IBM computers was a 20 x 16 x 5.5 inch, 28lbs monstrosity. The first cell phone, Motorola's DynaTAC phone was a brick weighing 2.5lbs, and measured 9 long by 5 inches wide.

Technological innovation tends to start large, and then get smaller, smarter and more powerful with time.

Fusion R&D has already come a long way, and while some developers continue to work with larger sized prototypes, small and very small prototypes are also under development.

ITER's tokomak and MIT's ARC prototype are large scale projects, but smaller devices exist the Princeton Satellite Systems spacecraft propulsion systems or Helion's modular fusion device. Fusion is not a one-size-fits-all technology.

Fuel

All lightweight elements produce energy if fused, meaning companies must decide what *elements* or *fuel* their device will fuse.

The temperature and energy required for each fusion reaction varies based on the fuel, and the energy they produce takes different forms. For example, a deuterium-tritium (D-T) reaction, which is the most efficient fusion reaction and thus the initial planned fuel of many devices, produces most of its energy in the form of highly energetic neutrons. The energy from these neutrons can be converted into heat to power an electricity-producing turbine, or used for other purposes such as district heating.

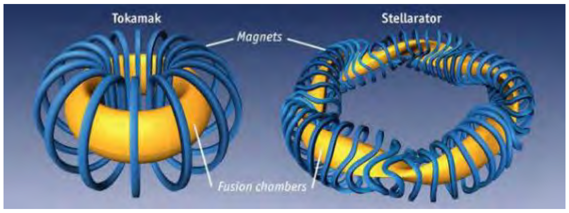
Tritium is considered a short-lived radioactive material with a half-life of 12 years. The neutrons can create "activated material," yet fusion devices are designed with materials to minimize its creation.

Other reactions, such as proton-boron 11 and deuterium-helium 3, produce energy primarily in the form of charged helium ions which are not radioactive. Additionally, since the energy is primarily in the form of charged particles, it can be converted to electricity more efficiently using a magnetic field. Currently, most device prototypes are using pure deuterium, and hope to prove net positive with deuterium-tritium reactions.

Three Types of Fusion Concepts

Magnetic Confinement

FIGURE 2: RENDERING OF PLASMA FLOW IN A TOKAMAK AND STELLARATOR



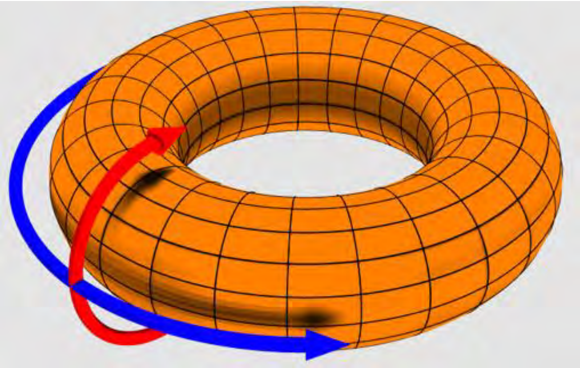
Source: IAEA, Fusion Energy for Peace and Sustainable Development

Magnetic confinement focuses on containing plasma at relatively low densities over longer periods of time. These devices are most similar to the sun, but instead of relying on gravity to contain the plasma, these devices use powerful magnets to create and contain plasma. The two most well-known types of magnetic confinement devices are tokamaks and stellarators. However, there are many other types under development today.

Example Devices

Tokamaks are donut-shaped devices with plasma contained within its ringed vacuum chamber. Many circular magnets are arranged in the poloidal (Figure 3 red) direction to compress the plasma and cause it to spin around the inside of the ring. Additional magnets are added in the toroidal (blue) direction which causes the plasma to corkscrew around the ring. This additional rotation causes the plasma to move more predictably, decreasing turbulence in the plasma, thus allows tokamaks to operate semi-continuously using repeated long pulses.

FIGURE 3: TOROIDAL COORDINATES



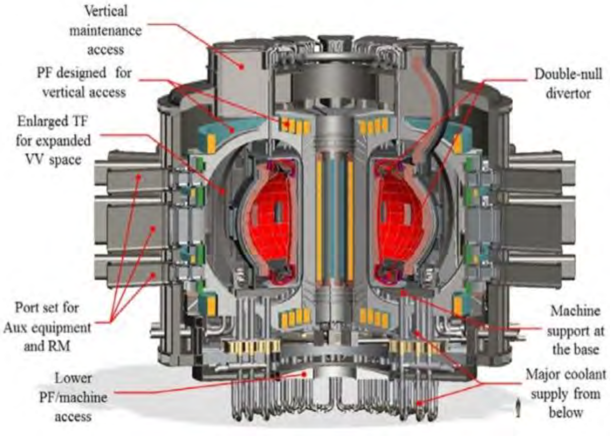
Source: DaveBurke, CC BY-SA 3.0, via Wikimedia Commons

Currently, tokomak prototypes are planning to utilize neutronic D-T reactions to produce energy since engineering constraints limit their maximum plasma density and temperature.

The efficiency of tokamaks scale directly with size, making tokamaks relatively large devices. Currently, tokomaks have the largest body of research supporting their development due to the fact they were the first designs, having captured government funding early.

Companies like Commonwealth Fusion Systems (CFS) and Tokomak Energy are adapting tokamaks using new high temperature superconducting (HTS) magnet technology. These new magnets can create strong magnetic fields more efficiently than previous technology, allowing for smaller or more powerful fusion devices.

FIGURE 4: K-DEMO, POSSIBLE FUTURE KOREAN TOKAMAK



Source: K. Kim et al., via Wikimedia Commons

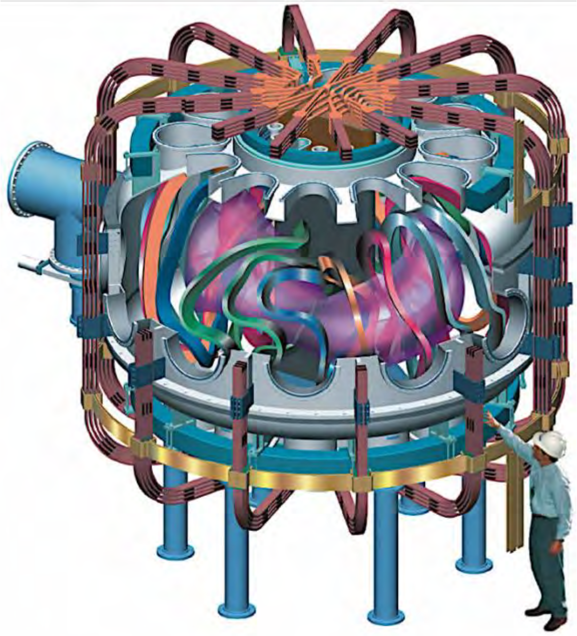
Stellarators are functionally similar to tokamaks, but they use irregularly shaped magnets to force plasma inside the ring to follow a single rotating path. This alternative approach allows the plasma to be controlled more easily, requires less energy to maintain the plasma, and allows the device to operate without pulses.

Determining the optimal shape of these complex magnets requires supercomputing technology, and manufacturing the magnets poses engineering challenges. Historically, these two factors limited stellarator advancement. Like tokamaks, stellarators are primarily focused on fusion with D-T reactions due to temperature constraints, and they are similarly constrained by size, albeit to a lesser extent.

Currently, two private companies are championing stellarator technology, Renaissance Fusion and Type One Energy, both of which are attempting to apply HTS magnets to stellarators similar to CFS.

There are numerous **other approaches** to magnetic confinement which this paper does not describe ranging from well-funded projects with spheromaks to the more experimental dynomak and levitating dipole experiments.

FIGURE 5: QUASI-POLOIDAL STELLARATOR 3D RENDERING

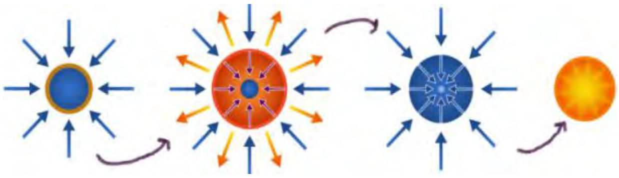


Source: [Public Domain](), via Wikimedia Commons

Inertial Confinement

Inertial confinement attempts to fuse elements by delivering large amounts of energy to a target in a short amount of time. Before the target has a chance to expand and decrease the density, the material will fuse and release energy.

FIGURE 6: INERTIAL CONFINEMENT FUSION



Laser beams rapidly heat the surface of the fusion target, forming a surrounding plasma envelope. Fuel is compressed by the rocket-like blowoff of the hot surface material. During the final part of the capsule implosion, the fuel core ignites at 1M Celsius. Thermonuclear burn spreads rapidly through the compressed fuel, yielding many times the input energy.

Source: Benjamin D. Esham, Wikimedia Commons

The different inertial confinement methods vary based upon how they deliver energy to a target and how they confine the fuel. However, unlike the magnetic confinement fusion technologies, inertial confinement fusion is relatively similar across most devices.

Solid pellets of deuterium and tritium have historically been the most common method for containing the fusion fuel. When the laser hits the pellet, that localized area expands outwards rapidly. Similar to a rocket, the outward expansion of the coating rapidly compresses the inside of the pellet, causing the material to fuse.

Some methods add additional energy to the system by focusing a second laser on the center of the pellet during its expansion, causing more material to fuse.

The largest inertial confinement device ever built is NIF, and it utilizes this exact method. Multiple companies including HB11 and First Light Fusion use the results from NIF, [new technological advancements](), and [newly understood physical principles]() to continue advancing inertial confinement towards commercialization.

While most inertial confinement fusion devices use D-D or D-T fusion to demonstrate the viability of their devices, many plan to transition to aneutronic fusion to generate energy.

Aneutronic fusion utilizes fuels that produces charged particles instead of neutrons, allowing more efficient electricity production, and also reduces neutron exposure (e.g. neutron bombarded material, or the creation of "activated materials").

Hybrid Devices

- Magnetized Target Fusion
- Field Reversed Configuration
- Pinch, and Other Methods

The devices listed above are intended to create fusion energy by forming a plasma and rapidly compressing it.

Unlike magnetic confinement, magnetized target fusion runs a repeated compression cycle, and unlike inertial confinement, a "target" is not being heated and compressed using lasers.

Many novel fusion methods have been proposed and the devices under this classification are significantly more varied than the previous two sections. Additionally, most of these next devices are significantly smaller than the previous two methods, and plan to use aneutronic fusion reactions.

Many of these intermediate devices are being pursued most actively by private companies.

Magnetic Target Fusion (General Fusion)

Magnetized target fusion uses pistons to compress a chamber filled with plasma.

When the central chamber is compressed, the temperature and density of the plasma increases, thus creating the conditions needed for fusion.

Surrounding the chamber are walls of swirling liquid metal which help extract heat from the fusion reaction and shield surrounding equipment from neutrons produced by D-T reactions, the current planned fuel type.

General Fusion is the largest private company working on this method, and they recently gained approval to build a pilot plant at the UK Atomic Energy Authority's Culham Centre for Fusion Energy.

Reversed Field Configuration (TAE and Helion)

The reverse field configuration uses magnets to rapidly accelerate clouds of plasma towards each other[3].

When the clouds collide, they are held together and further compressed utilizing a combination of magnets, lasers, and self-generating magnetic fields.

This method for achieving fusion also benefits from becoming more condensed, thus more efficient as power increases (unlike tokamaks and stellarators).

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[3] TAE's website provides a 3D video, and Helion has a step by step 3D rendering.

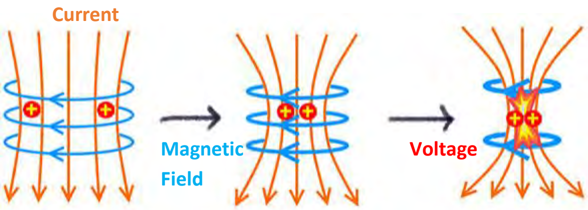
Currently, TAE Technologies and Helion Energy are the two major companies exploring this approach to fusion.

Helion plans to create smaller, modular reactors with a high efficiency electricity generating approach, and TAE plans to use ion beams to better control the inner plasma of one, larger device.

Neither company is planning to use typical deuterium-tritium reactions to create power, and instead they will attempt aneutronic fusion[4] using proton-boron or deuterium-helium-3 reactions.

Stabilized Z-Pinch (ZAP)

FIGURE 7: PLASMA PINCH MECHANISM



Pinches apply a voltage across a tube. This tube is filled with fusion fuel (eg deuterium gas). If the voltage times the charge is higher than the ionization energy of the gas, the gas ionizes. The current jumps across this gap. The current makes a magnetic field, perpendicular to the current. This magnetic field pulls the material together. Atoms get close enough to fuse.

Source: Wikimedia Commons, ECG

One of the first theorized methods of fusion, aptly named the "pinch" method, attempts to fuse flowing plasma by rapidly compressing it with an intense magnetic field.

Early efforts were quickly overshadowed by tokomak research because large instabilities developed using pinch methods. However, some companies such as ZAP Energy and Horne Technologies are revisiting this method utilizing a matured understanding of plasma and better technological capabilities to create a more stable plasma.

A Few of the Many

This summary includes only the largest pieces to this complex puzzle.

There are many more novel approaches to fusion in various stages of development including inertial electrostatic fusion, polywell fusion, beam target fusion, magnetized liner inertial fusion, and inertial electrostatic fusion.

Our purpose is not to create a comprehensive list of every fusion company or device type, but instead elucidate a few devices that are rapidly approaching commercial fusion energy.

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[4] Fusion reaction where most of the energy created is in the form of charged particles rather than neutrons.

How Will Fusion Energy be Applied?

There are many ways to utilize the byproducts of fusion depending on the device used.

The potential uses of fusion devices extend far beyond just the electricity market. As the fusion energy industry grows, direct heat transfer for industrial use may also be possible, with applications to desalination, direct air capture, district heating or creating portable fuel such as ammonia or ionized hydrogen.

There exist two primary ways to extract electricity from plasma.

The first method uses heat from the reaction to boil water and drive a turbine.

The second relies on the fact that positively charged ions can be used to drive a current, thereby producing electricity directly.

The first method can only achieve a maximum efficiency of 33%, yet the heat can be stored more easily for variable uses. The second has a much higher theoretical efficiency cap and efficiencies as high as 95% have been reported.

Since net positive energy has not been demonstrated by any device, their first commercial applications are difficult to predict.

Yet, the various uses for fusion energy offer unique technological flexibility. For example, in markets susceptible to power fluctuations, heat may be the preferable byproduct despite the inefficiency because it can be more easily stored and used on demand.

In either remote or urban settings, small modular devices may one day be deployed to limit land footprint.

Due to the overwhelming need for this dense, carbon neutral source of energy, ECG does not promote any particular device, fuel or potential use – all are celebrated and supported.

Fusion Supporting the Green Energy Portfolio

To meet global CO2 emission caps and maintain grid security, additional technologies must be developed to supplement existing wind, solar, hydro, geothermal and battery storage technologies. ECG believes fusion currently offers the most promising solutions to the green energy challenges. As such, we are helping the fusion economy gain public acceptance, government support, and regulatory partnership so that commercialization can take place soon enough to make a difference.