Confinement Methods in Nuclear Fusion: A Comparative Review of Inertial and Magnetic Approaches

By N/A

Abstract

This literature review focuses on confinement within fusion power plants and the methods involved in confining plasma during fusion energy production and testing. Fusion is often regarded as the future of energy production as it produces large quantities of energy with little fuel and relatively safe waste products. Furthermore, the fuel itself is easy to acquire, needing lithium for tritium and sea water for deuterium. This review attempts to inform the readers on the history and current primary methods of confining plasma in fusion reactors, focusing on inertial and magnetic confinement. Additionally, this review contains a brief explanation of electrostatic and gravitational confinement and comparison of the magnetic and inertial confinement methods.

Introduction

History

The first forays into the idea of nuclear fusion were in the 1920s to 1930s where Robert d'Escourt and Fritz Houtermans provided the first calculations of the rate of nuclear fusion in stars. At this time, Ernest Rutherford was exploring the structure of the atom. The discoveries of these scientists were tied together by Rutherford's student Mark Oliphant when they discovered they could react heavy hydrogen nuclei to form Helium-3 and tritium.(Prager, 2019)

In the 1950s, researchers started looking into reproducing fusion seen in stars on earth. The first designs were done by Soviet scientists Andrei Sakharov and Igor Tamm for the tokamak, followed by Lyman Spitzer designing the stellarator. Initially, the stellarator was more dominant in scientific, however, the design lost sway after the tokamak proved itself as a more efficient concept through experimental research.('History of Fusion', n.d.)

Through the 1970s and 1980s, countries came together to overcome the challenge that was attaining fusion energy. One of the most notable collaborations was the Joint European Torus (JET). The planning and designing of JET began in 1973 and construction of the final project finished a decade later in 1983. The completion of JET saw the first plasmas being achieved.(Prager, 2019)

After JET finished construction, the first experiments using tritium were carried out, making JET the first reactor to run on a fuel with a 50-50 mixture of tritium and deuterium. Using this fuel, JET set a record in both output and net energy gain.

Another notable event in the 1980s was the beginning of ITER at the Geneva superpower summit.

Currently, the ITER project is being built in Cadarache, France. This reactor passed 77.7 percent completion in December 2022. While ITER was being built, the Wendelstein 7-X stellarator was completed. Finally, in 2021, a new fusion record was achieved in JET, where 59MJ was produced in a five-second-long pulse. A significant improvement from the one second pulse of the previous record.('History of Fusion', n.d.)

Safety and Requirements of Nuclear Fusion

Nuclear fusion is often seen as the future of energy production. It produces massive amounts of energy with relatively little fuel. Fusion reactions also produce very little toxic or radioactive waste, producing helium as a main waste product. While tritium, a radioactive isotope, is produced, it is reused as fuel in a closed circuit within the reactor. Moreover, the half-life of tritium is short and, as mentioned above, is not used much as very little fuel is needed. The neutrons resulting from the reaction can cause other reactor materials to become radioactive through reactions. However, the waste is generally much shorter-lived and less hazardous than fission reaction waste.

With regard to safety, fusion power plants would be much safer than fission power plants. This is because fusion energy production is not based on a chain reaction, while fission power plants rely on chain reactions. If containment in a fusion reactor does fail, the plasma will cool, and operation will stop in a matter of seconds.

Nuclear Fusion

Nuclear fusion is a reaction in which two or more atomic nuclei combine to form one or more atomic nuclei and neutrons. This process can either release or absorb energy, depending on whether the difference in mass between the products and reactants is positive or negative. This difference in mass between individual nucleons and a nucleus is a result of the difference in nuclear binding energy and is called the mass defect.(*Fusion - Frequently Asked Questions*, 2016)

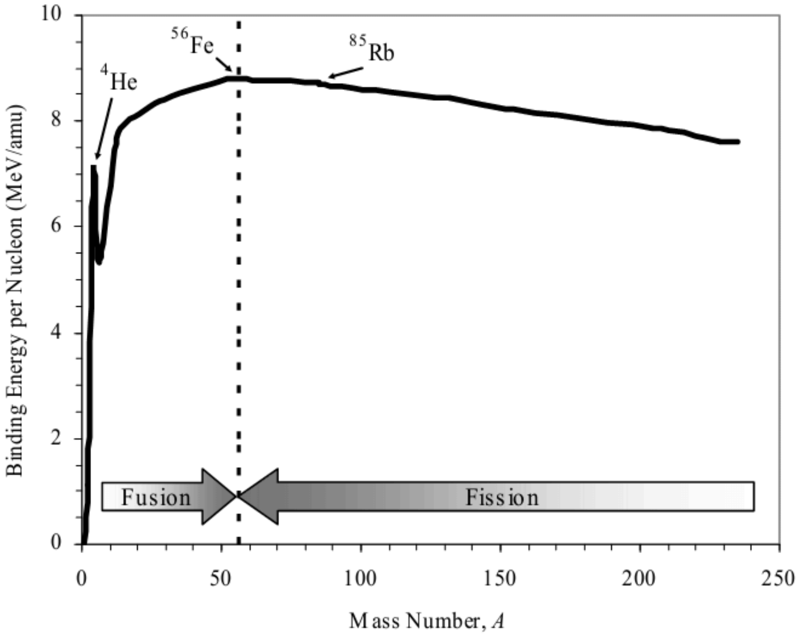
$$ {}^{2}_{1}\mathrm{H} + {}^{3}_{1}\mathrm{H} \longrightarrow {}^{4}_{2}\mathrm{He} + {}^{1}_{0}n + 17.59MeV \tag{1} $$

17.59 MeV represents the energy. Using the equation of mass-energy equivalence, we can calculate the mass defect to be $3.14 * 10^{-29}$kg. (*Nuclear Fusion*, n.d.)

Nuclear fusion that produces nuclei lighter than iron-56 will generally release energy. Atoms with a higher mass number than iron-56 typically have higher binding energy per nucleon, however, the energy required to fuse the nuclei will be even higher, resulting in energy lost if fusion occurs.

Figure 1

Binding Energy per Nucleon against Mass Number

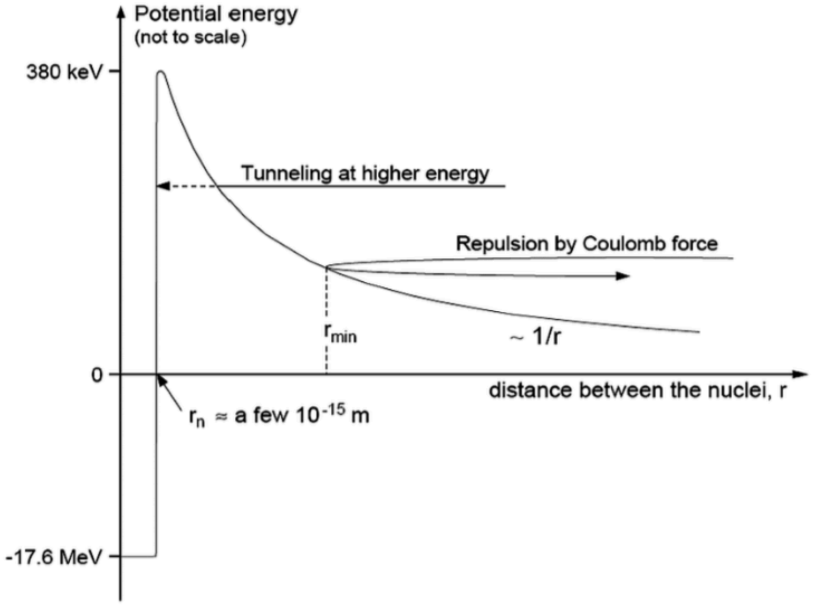


Note. This figure shows how at mass numbers before iron-56, fusion processes will typically produce energy, and at mass numbers after iron-56, fission will more produce energy. From Chapter Two (Binding Energy & Nuclear Models). In *ResearchGate.*

Light nuclei have a lower atomic number. During nuclear fusion, this results in the Coulomb force being weaker as they have a low charge. However, the strong nuclear force has a range much shorter than the Coulomb force. As such, the nuclei have to be very close to each other for the attraction due to the strong nuclear force to overcome the repulsion due to the Coulomb force. In order to provide these conditions, the nuclei must be accelerated to speeds high enough to bring the nuclei close enough to each other. This requires considerable energy, even for the lightest of elements. Once close enough, the strong force will grow and the nuclei will 'fall' into each other, resulting in fusion. One way this can be overcome is through quantum tunneling. Although this process cannot be forced to occur, it would allow the nucleus to bypass the Coulomb barrier, reducing the energy input required.(Ridha, n.d.)

Figure 2

Potential energy against Distance Between Nuclei



Note. This figure shows the repulsion due to the coulomb force as distance between the two nuclei changes. The peak represents the coulomb barrier which a nucleus must overcome in order to undergo nuclear fusion. R_{min} represents the minimum distance the nuclei must reach for fusion to occur, or the maximum distance nuclei can be apart while still being able to undergo nuclear fusion. This is because at this point, the strong nuclear force takes over. From Ongena, J. (2015). Fusion: A true challenge for an enormous reward. *EPJ Web of Conferences*, *98*

Overall, the energy released from most nuclear reactions is much greater than in chemical reactions. This is because nuclear binding energy is greater than the energy that holds electrons to a nucleus. Fusion reactions also have a higher energy density than nuclear fission because they produce far greater reactions and energy per unit mass, though individual fission reactions are typically more energetic than fusion reactions.(Petrescu et al., 2017)

Criteria for Success

The first aspect of nuclear fusion we must establish is our success criteria. One method is to use the Lawson criterion. The Lawson criterion compares the rate of energy generated by the fusion reactions to the rate of energy losses to the environment. Another method is to use the fusion energy gain factor or Q.

The Lawson Criterion and its Derivation

The first value we must find is the rate of fusion processes. This can be defined as the number densities of the fuel multiplied by the reactivity of the fuel.

$$W = \frac{n}{2} \cdot \frac{n}{2} < \sigma v > \qquad (2)$$

Where W is the rate of fusion processes, $\frac{n}{2}$ is the number densities of both deuterium and tritium, σ is the fusion cross-section and v is the relative velocity of the two nuclei. The angle brackets mean the average over the Maxwellian velocity distribution. We also assume that the densities of the deuterium and tritium ions are equal, and their total density is equal to the electron density. It can therefore be inferred that $n_D = n_T$ and that $n_D + n_T = n_e$. This gives us $n_D = n_T = \frac{1}{2}n_e$.

We can also use kinetic theory, giving us.

$$E_k = \frac{3k_bT}{2} \tag{3}$$

Where E_k is the kinetic energy of the particles, k_b is Boltzmann's constant and T is the temperature in Kelvin. Using these, we can find the energy produced as the product of the rate of fusion processes, the kinetic energy of the fusion products, and time.

$$E = \frac{n^2<\sigma v>}{4} \cdot E_F \cdot \tau \tag{4}$$

Where E is energy produced, E_F is kinetic energy of the fusion products and τ is the amount of time the fusion processes take place for. In order to obtain energy from fusion, the energy produced must be higher than the energy required to heat the plasma to the right temperatures$\left(E > E_k\right)$, therefore we get

$$\frac{n^2}{4} < \sigma v > \tau E_F > 12k_bT \tag{5}$$

which can be rearranged to get

$$n\tau > \frac{12k_bT}{<\sigma v>E_F} \tag{6}$$

This is the equation for the Lawson criterion, which shows us that either our number density or our confinement time must be high for our test to be successful.(Schouten, n.d.)

Fusion Energy Gain Factor

Another metric we can use to measure the success of a test is the Q value. This Q value is the ratio between the fusion power produced and the power input needed to maintain the plasma in a steady state. This means that a Q value of one is 'break even'. Usually, a Q value of five is needed for the reaction to self-heat. This is due to energy losses causing not all the energy produced to be reinvested into maintaining the plasma in a steady state.(Yushmanov, 1980)

Inertial Confinement

As seen above in the equation for the Lawson criterion, the two main ways to make the energy gain greater than the energy lost to surroundings are to have high confinement time and having a high number density. Inertial confinement focuses on the latter of these, reaching very high number densities. There are four phases to inertial confinement, the interaction phase, the compression phase, the deceleration phase and the ignition phase.

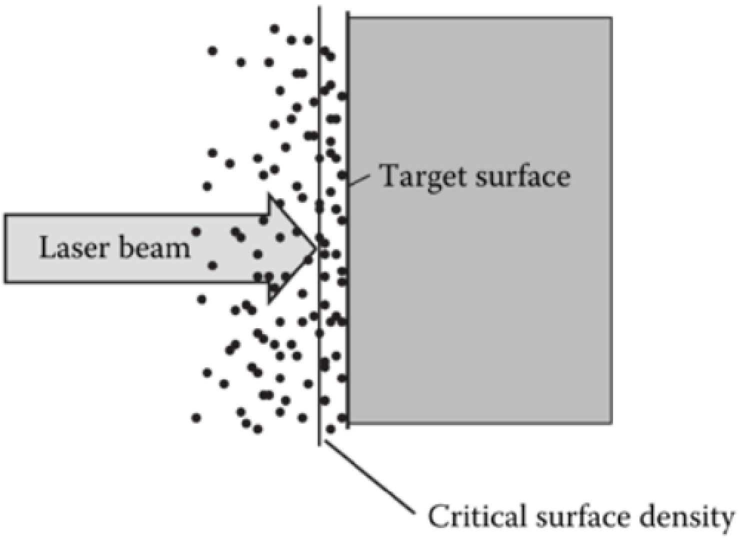
Interaction Phase

The interaction phase is the first phase. It is the phase in which the energy is delivered onto the capsule containing the fuel(usually Deuterium-Tritium mix). The energy is delivered through a driver, which can be either laser light or particle beams. What driver is used is irrelevant when only looking at the energy input, however, the initial interaction process differs significantly between the two options. This difference is due to the properties of the drivers; where laser light will only interact with the surface of the matter, beams will penetrate a certain distance. In both cases, the goal is to transfer as much energy as possible into the material.

Assuming the driver is a laser, plasma will be created as soon as the laser beam encounters the outer surface of the capsule. The plasma then expands outwards from this surface, with a higher density closer to the capsule surface. At some point, the plasma will reach a certain critical density and hinder the laser beam from penetrating any further. The surface of the critical density region will not be at the capsule surface, instead, being located some distance away. This prevents the energy of the laser from being deposited directly onto the surface of the capsule. The location of this critical density surface depends heavily on the wavelength, intensity and pulse length of the laser beam. These parameters also change the amount of ablation and the efficiency of the subsequent compression phase. Therefore, when discussing the efficiency of the overall process, the values of these parameters are essential.(Pfalzner, 2006)

Figure 3

Diagram of a laser driver interacting with a target surface



Note. Shows how a laser interacts with the target surface and how the critical surface density can affect and interfere with the energy transmitted by the laser. From Pfalzner, S. (2006). *An Introduction to Inertial Confinement Fusion*. CRC Press.

Compression Phase

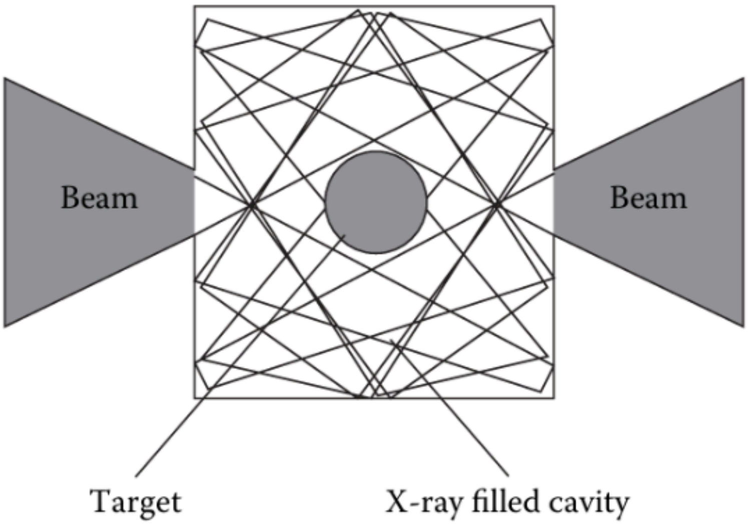
The compression phase is the second phase in inertial confinement fusion. The success of the compression is, to a large extent, dependent on the interaction phase. However, there can still be instabilities in this phase. These illumination nonuniformities occur on two scales: microscopic and macroscopic. Microscopic nonuniformities can be caused by spatial fluctuations within a single beam, causing hotspots or regions of greater intensity to form. Macroscopic nonuniformities can be formed by a power imbalance between the individual beams.

There are two ways to overcome these macroscopic nonuniformities; we can take a sufficient number of beams. This is done in direct-drive ICF. However, this can be very expensive and challenging to accomplish. Instead, many smaller scale direct-drive experiments are performed and we try to infer how a system with more beamlines would perform from these experiments.[1]

Alternatively, an indirect-drive approach can be utilised. In this approach, the energy of the laser is first absorbed by an enclosure around the capsule made of a high-Z material(hohlraum). The energy from the laser is then emitted from the hohlraum as x-rays. These x-rays are what drive the implosion of the capsule.[2]

Figure 4

Diagram of a hohlraum



Note. Shows how the energy from the driver is mostly reflected by the walls of the hohlraum until it hits the pellet. From Pfalzner, S. (2006). *An Introduction to Inertial Confinement Fusion*. CRC Press.

Instabilities cannot be avoided, no matter the method used. An example of one of these instabilities is the Rayleigh-Taylor class of instabilities. These occur at the boundary between two fluids of different densities, when the denser fluid pushes into the less dense one. An example of this would be when water pushes into oil. If perturbed, a mixing between the two fluids can

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[1]

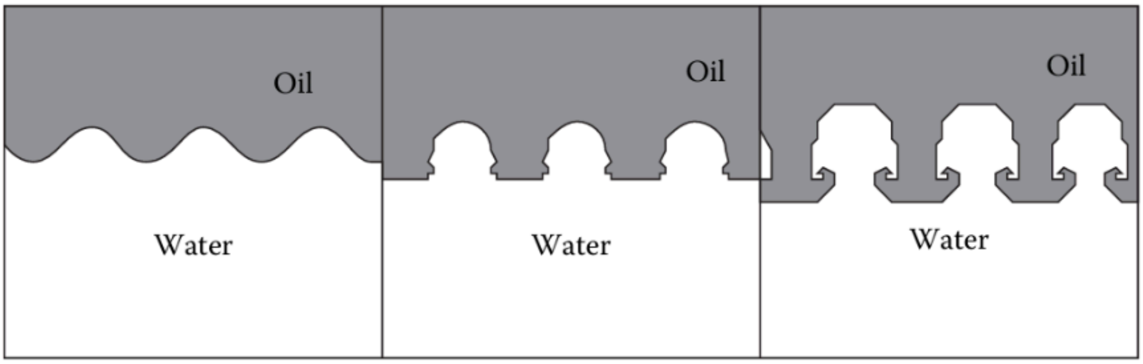
[2]

occur. In the context of ICF, these two fluids are hot and cold plasma. When the mixing of these two plasmas occurs, the hotter plasma is cooled. This is bad for the compression, therefore targets are designed such that these Rayleigh-Taylor instabilities are minimised as much as possible. This is done through the shape of the capsule. The ratio of the shell radius to the shell thickness is a major factor in reducing Rayleigh-Taylor instabilities. This property of the capsule is called the in-flight aspect ratio and has to be in the order of 25-40 at all moments during the implosion.

The acceleration can also be varied to optimise efficiency. This is done by changing the acceleration such that the creation of 'hot electrons' or energetic electrons can be avoided as much as possible. This is because these hot electrons can preheat the fuel and create their own shock fronts, thereby making it harder to compress. Avoiding preheat is especially necessary if the driver is a laser. However, one cannot completely prevent shock waves from forming if they want to build up pressure in a reasonable time. Therefore a low-power prepulse followed by a succession of increasingly intense pulses can accelerate the fuel nearly isentropically(entropy of system remains 0).(Pfalzner, 2006, pp. 21–22)

Figure 5

Rayleigh-Taylor instabilities



Note. This diagram shows the formation of Rayleigh-Taylor instabilities over time, using oil and water as the fluids of different densities. From Pfalzner, S. (2006). *An Introduction to Inertial Confinement Fusion*. CRC Press.

Deceleration

When the inner part of the fuel reaches the center of the capsule, it starts to decelerate. This happens through the kinetic energy of the inner part of the fuel being converted into internal energy. This results in both temperature and density increasing in the center while the rest of the fuel remains relatively undisturbed.

In the hot-spot concept, high fuel densities and temperatures are needed. To reach these densities and temperatures at the hot-spot areas, a succession of increasingly intense pulses is needed. This allows the nearly isentropic compression to take place. The last of the succession of shocks has to act at the same time as the first of the shocks for a successful deceleration phase. Therefore, the timing of the shocks is integral for the success of the phase.(Pfalzner, 2006, p. 22)

Ignition and Burn Phase

Finally, when temperature and density conditions in the hot-spot area are right, ignition occurs. The α particles produced deposit energy primarily in the center area, heating it up. Other products such as the radiation and fusion neutrons then transport the energy from the hotspot region to the outer areas of the fuel. This allows the fusion reactions to take place there and thus the burn propagates outward.

Throughout this process, a very high pressure builds up until it eventually blows apart the remaining fuel and α particles, signalling the end of the ICF cycle.(Pfalzner, 2006, pp. 22–23)

Overall Gain

In the fusion process, energy is only gained if the energy given off by the fusion processes exceeds the input energy. However, this input energy is not just used to heat the fuel. There are several inefficiencies that must be taken into account. These include but are not limited to: the losses in the driver itself, losses in the hohlraum(if used) and energy lost in the compression dynamics due to the Rayleigh-Taylor instabilities. If these inefficiencies can be overcome, providing a net energy gain from these fusion reactions will prove much easier to achieve.(Pfalzner, 2006, p. 23)

Magnetic Confinement

As mentioned before, the two main ways to make energy gain greater than energy lost to surroundings are to have a high number density or high confinement time. Magnetic confinement typically focuses on high confinement time with much lower number densities compared to inertial confinement.

The idea of magnetic confinement is to confine the plasma using magnetic fields. This can be done due to the plasma being partially ionised. Confining the plasma using magnetic fields allows the plasma to reach high temperatures without touching and thus damaging the walls of the confinement chamber.

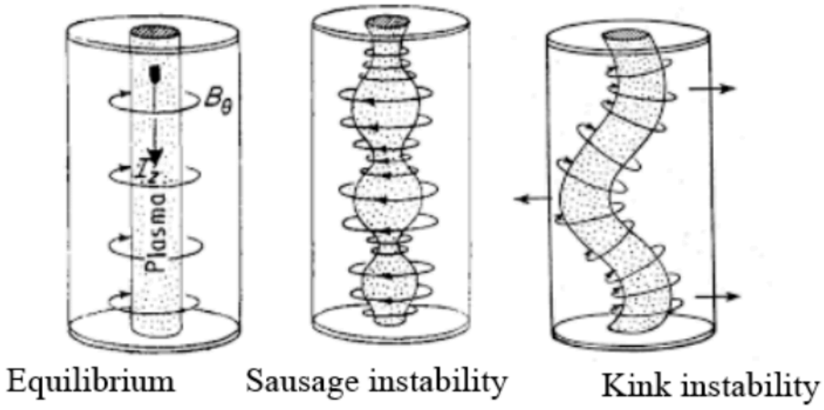
Z-Pinch

One the simplest ways to magnetically confine a plasma is using the Z-Pinch method. This is done by passing a very large current through the plasma. This high current creates ring-like magnetic fields, which exert an inwards force, compressing the plasma. In fusion applications, the current heats the plasma up to the temperatures needed and the inwards force compresses the plasma, raising its density. The downside of this is that it will only last for very short periods of time.

There are also instabilities in this method. The main issues are from non-uniformities in the initial plasma cylinder. If the cylinder is narrower at any points, these points will compress faster and thus pinch off faster, leading to isolated sections. This will eventually cut off the current, breaking the plasma cylinder. This instability is called a sausage type instability. Another instability results from slight bends in the initial shape of the plasma. Force acts from the inside to the outside of the bend, making the bend larger. This instability keeps growing until it ruins the plasma cylinder.(Shumlak, 2020)

Figure 6

Sausage and Kink instabilities



Note. Shows how the uniformly confined plasma can form instabilities due to small instabilities magnifying.

Magnetic Mirror

Another method is the magnetic mirror. A cylindrical magnetic field is created by a pair of magnetic coils. This magnetic field bulges slightly in the middle. The particles moving perfectly parallel to the field lines will feel no force and thus be able to escape. Particles moving perpendicular to the field lines will orbit the field lines and not escape. Orientations in between will either be able to escape or be trapped by the field depending on how closely its motion is aligned with the magnetic field. When a trapped ion tries to escape the confinement, their direction of motion will reverse when it gets too close to the magnetic coils, causing it to reflect back to the center.

An issue with this method is that collisions between trapped ions and electrons will knock an increasing number of them into the right orientation to escape the magnetic mirror. The end effects can be mitigated by making the mirror longer so that a lower proportion of the plasma escapes. However, the main flaw with this method is that it is not magnetohydrodynamically stable. This means that in the middle parts of the field, where the field is weaker, the plasma can ‘balloon’ out, dragging the magnetic field lines with it. This causes the confinement time to be low.(Post, 1987)

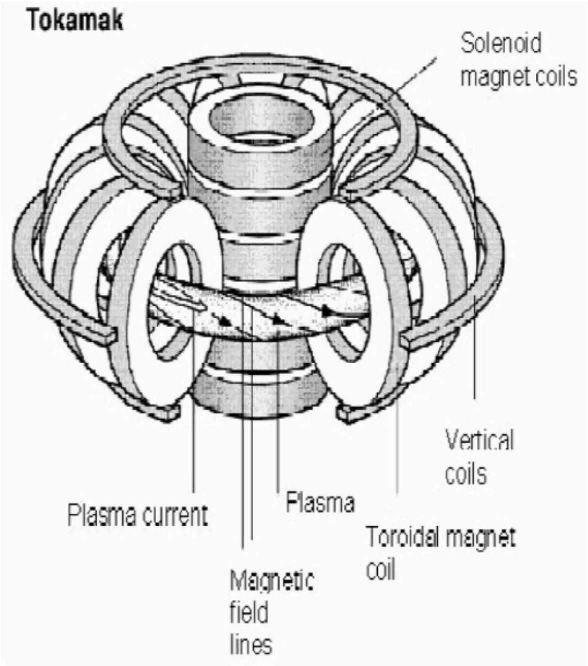
Tokamak and Stellarator

Finally, there are the tokamak and stellarator. In a tokamak, the plasma is confined in a torus, however, there is a current passed through the middle. This current acts similar to the current in the Z-pinch method, creating magnetic fields in circles around the torus. There are also coils around the torus, creating a magnetic field that gives the toroidal shape. Overall, the combination of these two magnetic fields twists the magnetic field so that the magnetic field lines go from outside the torus to inside the torus and back, causing the field to be more uniform in strength.(Artsimovich, 1972)

In a stellarator, the coils themselves are twisted in such a way that the magnetic field lines go from the outside of the torus to the inside and back, making the field strength more uniform.

Figure 7

Diagram of a Tokamak



Note. Shows the magnetic field lines from the toroidal and poloidal(vertical) magnet coils and thus how the plasma is confined within the tokamak. From Kwon, M.-E., Bae, Y.-S., Cho, S.-Y., Choe, W.-H., Hong, B.-G., Hwang, Y.-S., Kim, J.-Y., Kim, K.-M., Kim, Y.-S., Kwak, J.-G., Lee, H.-G., Lee, S.-G., Na, Y.-S., Oh, B.-H., Oh, Y.-K., Park, J.-Y., Yang, H.-L., & Yu, I.-K. (2009). CURRENT STATUS OF NUCLEAR FUSION ENERGY RESEARCH IN KOREA. *Nuclear Engineering and Technology*, *41*(4).

Heating Plasma in the Tokamak

Heating the plasma is done mainly by adding energy via electromagnetic waves and particle beams.

Particles orbit around magnetic field lines at certain frequencies, depending on their mass and the magnetic field strength. This oscillation allows them to absorb electromagnetic radiation with a matching frequency. The issue with this method is that the electromagnetic waves can be reflected or refracted by the plasma.

Instead, beams of particles can be used to deposit energy into the plasma. These particles can also be deuterium particles, giving the plasma some more fuel to fuse. In order to not be affected by the magnetic fields around the plasma, the particles must be neutral, hence the name ‘neutral beam injection’. The overall process requires an electron to be given or stripped off a deuterium atom(this gives it a charge and allows us to accelerate it). Then the deuterium ion is accelerated. After acceleration, the deuterium ion then must be neutralised.(Kunkel, 1981, pp. 10–11)

Often high performance plasmas need additional heating. Neutral beam injection is a standard heating scheme at many major Tokamaks. However, the fusion of the deuterium and tritium into helium should eventually become the primary heating mechanism.(Artsimovich, 1972)

Issues with the Tokamak

There are a few economic issues with magnetic confinement. A major issue is damage to the containment vessel. During operation, when the input power is high enough the plasma transitions from low-confinement mode(L-mode) to high-confinement mode(H-mode). This H-mode is characterised by a much higher rise in plasma density near the edges and a higher peak density overall. This increase to density and thus performance is seen as essential for any future reactor. The main drawback, however, is that there are frequent expulsions of plasma while the plasma is in H-mode, called an edge localised mode(ELM). These ELMs can cause damage to plasma-facing components.(Connor et al., 2008)

Gravitational and Electrostatic Confinement

Gravitational Confinement

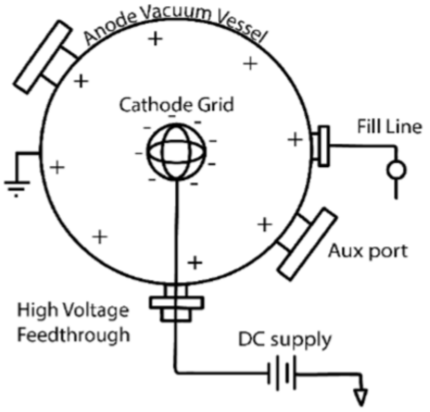
Gravitational confinement is the type of plasma confinement that occurs in stars. Stars use their massive size and mass to their advantage, using the strength of their gravitational field to force nuclei together, causing fusion reactions. Initially, stars ignite using the extreme gravitational force to compress the matter and start fusing. Similar to the gas laws, as the volume decreases, the pressure increases massively, thus starting the fusion processes. The nuclei in the stars fusing provides energy for more fusion reaction to happen, sustaining the stars. These fusion reactions also produce a pressure within the star. This pressure is what stops the star from simply collapsing in on itself. As long as there are fusion reactions happening within the star, the pressure will counteract the force from the gravitational field of the star, creating an equilibrium of sorts. This can be seen in main sequence stars.

Electrostatic Confinement

Electrostatic or inertial electrostatic confinement is another method of confinement. It relies on an anode and a cathode to separate the nuclei from the electrons in an atom. The nuclei are attracted to the cathode, however, the electrons are repulsed, stripping the nuclei of their electrons. Therefore, only the protons and neutrons are within the cathode. Within the cathode, the nuclei accelerate and collide. This can cause fusion reactions to occur, releasing energy. An example of a device that uses this principle to operate is a fusor. Fusors use a high voltage to ionise their fuel(usually deuterium gas) and then fuse. The energy given off by the fusion in a fusor can often be seen as a blue or purple glow due to the charged particles as they are accelerated.(Ligon, n.d.)

Figure 8

Diagram of a Fusor



Note. Shows the cathode grid and the anode vessel that are used to create and confine the plasma within the fusor. From Wolf, A. J. (n.d.). *Measurement of ion velocities in the TU/e Fusor plasma using LIF spectroscopy*.

Discussion

The main difference between magnetic and inertial confinement are the principles behind them. Inertial confinement uses high powered lasers or particle beams to compress a fuel capsule, providing the conditions for nuclear fusion to happen. This leads to very low confinement times but very high number densities, allowing energy to be produced. In magnetic confinement systems, plasma is created within the reactor using induction, neutral beam injection or other methods, then confined using magnetic fields. This leads to longer confinement times but much lower number densities. Both of these methods satisfy the Lawson criterion, however, as of writing this, magnetic confinement is generally viewed as the more advanced promising method of the two.(Lundy, 2024)

The author agrees with this general sentiment due to several reasons. The first of these reasons is due to the collaboration seen with countries researching magnetic confinement, and lack thereof in inertial confinement. There are multiple international projects working on magnetic confinement, ranging from JET(now decommissioned) to ITER. The National Ignition Facility is the most prominent inertial confinement laboratory, with France, China and the UK also actively involved in research. However, joint projects are limited, with PALS(formerly Asterix IV) being one of the few joint inertial confinement laboratories that are currently operational. This lesser degree of international communication and joint projects can be seen as a sign of less interest from the scientific community and therefore less funding towards not just future, but current and past inertial confinement projects and laboratories, leading to less development. The opposite can be seen in magnetic confinement projects. The abundance of joint projects, especially in Europe, shows not just funding but vested interests in making this form of confinement work. This investment can be clearly seen in the continued funding of ITER despite the multiple setbacks(*ITER Fusion Project Confirms More Delays and €5B Cost Overrun* |

Science|Business, n.d.). The construction of the Wendelstein 7-X stellarator furthers this point as, upon its completion in 2015, immediately began achieving record results(Wolf et al., 2019). However, as confinement in nuclear fusion projects is still relatively young, there is still an untapped well of potential advancements for both magnetic and inertial confinement. While magnetic confinement may be more likely to find these key technologies and advancements due to its greater funding, there still remains the possibility that inertial confinement fusion can take the spotlight and become the dominant idea within both scientific communities and the general public.

Another reason the author supports the opinion that magnetic confinement fusion methods are more advanced than inertial confinement fusion methods is the difference in efficiency. JET, a now decommissioned laboratory, was able to achieve a Q value of 0.67, producing 16 megawatts from 24 megawatts of input power over five seconds. Further, ITER is predicted to reach a Q value of 10('History of Fusion', n.d.),meaning the plasma will produce 10 times more energy than the heating power added. This value does not include the total system input such as energy losses in the magnets. In comparison, the National Ignition Facility in the USA used 3.15 megajoules of input energy to produce 2.05 megajoules of output energy, giving a Q value of around 1.54(*Lawrence Livermore National Laboratory Achieves Fusion Ignition | Lawrence Livermore National Laboratory*, n.d.). However, this value is only at the pellet level and does not take into account the energy loss due to the efficiency of the lasers. At the system level, around 400 megajoules of energy was supplied to the lasers, giving an overall(or wall-plug) efficiency of just 0.5%(Author, 2023). This experiment shows that while inertial confinement fusion is a promising idea that has shown its value, the technological advances needed to take advantage of inertial confinement fusion have not been made. Overall, this means that, in the short term, magnetic confinement fusion will most likely prove to be the dominant method of confinement, however, as both methods progress, inertial confinement may prove to be more efficient, bypassing some roadblocks that magnetic confinement experiences.

Finally, the last reason that the author supports this opinion is the different operation types of magnetic confinement fusion and inertial confinement fusion. Where magnetic confinement fusion uses a continuous operation method, inertial confinement fusion uses a pulsed operation method. Many of our current methods of producing energy are continuous methods, and this is for good reason. A pulsed power supply needs additional energy storage systems to provide smoother power delivery. These additional systems add even more complexity to our power grids and will cost more money. Furthermore, the difference in efficiency will only be exacerbated by the repeated startup of inertial confinement plants. Where an inertial confinement plant will have to start up and cooldown every cycle, incurring efficiency losses in both of these phases, a magnetic confinement based fusion plant will only have to start up and cool down during maintenance.(*Electricity Security Matters More than Ever – Power Systems in Transition – Analysis*, n.d.) Overall, the commercial viability of magnetic confinement fusion is much greater than inertial confinement fusion as the current electrical infrastructure is more suited towards continuous methods of power generation, allowing magnetic confinement fusion plants to directly replace coal, gas or nuclear based power plants with minimal changes to the current power grid. This commercial viability of magnetic fusion has seen it get more funding and interest, leading to more developed laboratories and research centers.

Conclusion

This paper reviews the literature on magnetic, inertial, electrostatic and gravitational confinement of plasma, mainly focusing on inertial and magnetic confinement.

In conclusion, the author believes that, in the short term, magnetic confinement will prove to be the dominant method of confinement for potential fusion power plants. This is due to both magnetic confinement fusion's compatibility with our current electrical infrastructure and the more advanced technologies and methodologies used. This allows magnetic confinement fusion plants to directly replace current fossil fuel and nuclear power plants with minimal changes to the power grid. However, it is difficult to predict whether magnetic confinement fusion, inertial confinement fusion or another method will prove to be the most efficient and effective source of energy as the field of nuclear fusion itself is new relative to many other fields, with many problems needing to be solved for both methods. A large breakthrough in either magnetic or inertial confinement could propel its respective method much further, allowing it to become the dominant method.

Regarding more recent progress, there have been several breakthroughs in recent years where several laboratories and tokamak testing sites have managed to produce more energy than was inputted. Furthermore, there are already plans to build the first fusion reactor connected to the US energy grid. This plant is expected to come online in the 2030s and produce four hundred megawatts of electricity.(*'Breakthrough' as Fusion Experiment Generates Excess Energy for the First Time | Imperial News | Imperial College London*, 2022)

Acknowledgement of my mentor: Giannos Charitou

I received guidance from my mentor, who assisted me in selecting articles and research papers relevant to my research topic. Additionally, he provided detailed instruction by walking me through the derivation of the Lawson criterion and providing me with an explanation of Rayleigh-Taylor instabilities.

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Review of: "Confinement Methods in Nuclear Fusion: A Comparative Review of Inertial and Magnetic Approaches"
Author 100027, Submission 100021
Date: July 25, 2025

To the Author,

Recommendation: Accept with minor revisions

I am confident that by incorporating the suggestions below, this paper will be an excellent candidate for publication. You have done a wonderful job on a challenging topic, and I strongly encourage you to incorporate the revisions below. I look forward to reading the next version of your manuscript.

Thank you for submitting your work to Convergence Journal. This is a well-researched and thoughtfully structured review paper, particularly for an early-career scholar. Your ability to synthesize a vast and complex field (from the foundational physics of fusion to the engineering challenges of modern reactors) is commendable. You have tackled a difficult and highly relevant topic with clarity and academic rigor. The feedback below is offered in the spirit of mentorship, with the goal of helping you refine this already impressive manuscript into an even stronger publication.

General Assessment
The paper's greatest strength is its comprehensive and logical structure. It successfully guides the reader from the historical context of fusion research through the fundamental principles, the primary confinement methodologies, and culminates in a well-argued comparative discussion. The clear explanations of concepts like the Lawson criterion, Rayleigh-Taylor instabilities, and the various confinement device types (Tokamak, Stellarator, Z-Pinch) make sophisticated physics accessible. The manuscript demonstrates a remarkable level of engagement with scientific literature.

Detailed Feedback Based on Evaluation Criteria
1. Originality & Significance:
As a review paper, the originality lies not in generating new data but in the synthesis of existing knowledge and the formulation of a unique perspective. You achieve this in the "Discussion" section, where you present a clear, evidence-based argument for why magnetic confinement currently appears to be the more promising path toward commercial fusion energy. This analytical comparison, drawing on factors like international collaboration, demonstrated efficiency, and operational modality, represents a significant and original contribution.

2. Clarity & Structure:
The paper is exceptionally well-organized. The progression from general principles to specific technologies is logical and easy to follow. The use of headings and subheadings effectively breaks down the complex subject matter into digestible parts. The inclusion and explanation of figures and equations (e.g., the D-T reaction, the Lawson criterion) significantly enhance the clarity of the text.

3. Use of Evidence & Research Methods:
Your use of sources is at a good level. The manuscript is thoroughly referenced with a strong bibliography that includes foundational books (Pfalzner, 2006), seminal papers (Artsimovich, 1972), and recent news articles that provide more recent context. Crucially, you demonstrate a sophisticated understanding of your sources. For example, your analysis of the National Ignition Facility's (NIF) recent success correctly distinguishes between the scientific energy gain at the pellet level (Q>1) and the much lower overall "wall-plug" efficiency. This nuanced interpretation is a hallmark of strong academic work.

4. Engagement with Literature:
The manuscript shows deep and broad engagement with the literature. You effectively place current projects like ITER and Wendelstein 7-X within the historical context of earlier experiments like JET. Your discussion acknowledges the key challenges and instabilities pertinent to each method, demonstrating that you have not just summarized but have critically engaged with the research.

5. Grammar & Language:
The writing is clear, professional, and largely free of errors. The tone is appropriate for a scientific publication.

Specific & Actionable Suggestions for Revision
To elevate this paper from a very good manuscript to an outstanding one, I recommend focusing on strengthening the narrative framing and argumentative depth.

Strengthen the Introduction's Hook: The introduction provides a solid history, but it could more immediately establish the paper's contemporary relevance. Consider adding a short paragraph at the beginning that highlights why this review is so timely. Mentioning the recent breakthrough at NIF achieving ignition and the massive global investment in projects like ITER right from the start would create a powerful hook for the reader.

Refine the Flow of the Discussion: Your three main points in the discussion (collaboration, efficiency, and continuous vs. pulsed operation) are excellent. To improve the narrative flow, consider adding clearer transition sentences to link these points. For example, after discussing the efficiency gap, you could write something like: "Beyond the immediate question of energy gain, the fundamental operational differences between the two methods present another critical consideration for their future commercial viability." This would help weave your points into a single, cohesive argument.

Acknowledge and Rebut Counterarguments: The strongest arguments are those that anticipate and address counterpoints. While you correctly identify the current technological and efficiency shortcomings of Inertial Confinement Fusion (ICF), your discussion could be further strengthened by briefly acknowledging the long-term vision of its proponents. For instance, what technological advancements (e.g., in laser efficiency or target manufacturing) do they believe could close the gap? Why might a pulsed system eventually become advantageous? Briefly raising and then refuting these potential counterarguments will make your own conclusion in favor of magnetic confinement's current lead even more persuasive.

Clarify Q-Factor Comparison: On page 14, when comparing the Q values of JET (0.67) and NIF (~1.54), ensure you are comparing equivalent metrics. For maximum clarity, you could explicitly state in the text that both figures refer to the scientific gain factor (fusion power out vs. external heating power in), as distinct from the engineering or "wall-plug" gain. This small addition would further enhance the precision of your comparison.

Current state of the field

Maybe the most important recommendation is the following one. A literature review is incomplete without a proper presentation of the current state of the field. Adding such a section would significantly elevate the manuscript, transitioning it from a strong academic review into a timely and highly relevant analysis of one of today's most dynamic fields of research and investment.

Here is some critical feedback on how you could construct this new section.

The landscape has changed dramatically in just the last few years, driven by private investment and key technological breakthroughs. Adding a new section, perhaps titled "The Current Landscape: A Field in Transition," right before your "Discussion," would provide crucial modern context and powerfully set up your final analysis.

Here are specific areas you should focus on in this new section:

1. The Rise of the Private Sector and a New Pace of Innovation

The most significant recent trend is the surge in privately funded fusion companies, which are pursuing aggressive timelines and diverse technologies. Your paper should capture this shift.

- Highlight Key Private Players: Instead of just mentioning projects like ITER, introduce companies that are now major players. There are a few startups that have received major funding recently.
- Commonwealth Fusion Systems (CFS): Discuss their compact tokamak approach, which is enabled by high-temperature superconducting (HTS) magnets. Mention their successful SPARC demonstrator and plans for the first commercial power plant, ARC. A crucial point to include is their landmark power purchase agreement with Google, a massive vote of confidence from the tech industry.
- Helion Energy: Contrast CFS with Helion, which uses a different method (a field-reversed configuration) and is pursuing a different fuel cycle (Deuterium-Helium-3). Note their Polaris prototype and their own major power purchase agreement with Microsoft, which aims for operation by 2028.
- Tokamak Energy: Mention this UK-based company's focus on spherical tokamaks, a more compact and potentially more efficient design. They have already achieved a plasma temperature of 100 million degrees in their ST40 device, a critical milestone for any fusion concept.

2. Re-evaluating Inertial Confinement Post-Ignition

Your paper correctly notes the NIF's ignition success. The "current state" section should now ask, "What's next?"

- The Path to Inertial Fusion Energy (IFE): Explain that scientific ignition is just the first step. The primary challenge for IFE is now repetition rate. A power plant would need to ignite targets multiple times per second. Discuss the need for new, highly efficient diode-pumped laser systems to replace the NIF's less efficient flash-lamp-pumped lasers, which can only fire a few times per day.
- Beyond the Hohlraum: Briefly mention that researchers are exploring alternative IFE approaches like shock ignition and fast ignition, which could potentially lead to higher energy gains and relax the stringent requirements of the central hot-spot ignition model used at NIF.

3. The Lingering Engineering Hurdles for All Approaches

To provide a balanced and critical perspective, this section must also address the monumental engineering challenges that remain for all fusion concepts, both public and private.

- Materials Science: The "first wall" of any reactor must withstand an environment more extreme than almost any other engineered product: intense neutron bombardment and high heat fluxes. Discuss the challenge of developing materials that won't become overly brittle or radioactive over their operational lifetime.
- The Tritium Fuel Cycle: For D-T reactors (the most common type), tritium is a scarce and radioactive fuel. A viable power plant must breed its own tritium by having the fusion neutrons interact with a surrounding "blanket" of lithium. This is an incredibly complex engineering challenge that no one has yet solved at a commercial scale.
- Heat Extraction: It's one thing to generate heat; it's another to efficiently capture that heat and use it to turn a turbine to generate electricity. This "balance of plant" is a major, often overlooked, engineering problem.

By adding this section, you will show a deeper engagement with the current, fast-moving state of fusion research. It will make your "Discussion" section, where you compare the methods, much more powerful because it will be grounded in the very latest technological and commercial realities.

Conceptual Revisions

Your explanations of key concepts are clear, but in some cases, they could be enriched by including the underlying physical mechanisms.

- Z-Pinch Instabilities: In your discussion of the "sausage type instability," you correctly state that if the plasma cylinder is narrower at any point, "these points will compress faster". To add physical depth, consider briefly explaining why this occurs. The toroidal magnetic field (B) responsible for the pinch is inversely proportional to the radius ($B \propto 1/r$). Therefore, a narrower section of the plasma (smaller r) experiences a stronger magnetic field and thus a greater inward pinching force ($F \propto J \times B$), leading to runaway compression at that point. Adding this brief physical reasoning would strengthen your explanation.

- Benefits of H-Mode: You correctly describe the transition from L-mode to H-mode and note the resulting rise in plasma density. The significance of H-mode could be made more profound by connecting it back to the Lawson criterion. H-mode is primarily characterized by the formation of a "transport barrier" at the plasma edge, which dramatically improves the energy confinement time. This is a critical parameter in the fusion triple product, a more comprehensive figure of merit than the simple Lawson criterion presented. Mentioning that H-mode improves confinement time directly addresses one of the two key parameters from your own "Criteria for Success" section.

Lawson Criterion Derivation: There appears to be a numerical discrepancy or an unstated assumption in your derivation of the Lawson criterion. The left side of your inequality is the fusion energy produced. The right side is stated to be the energy required to heat the plasma. Standard derivations calculate the plasma's thermal energy as E=3/2(ne+ni)kT. Assuming a 50-50 DT plasma where nD+nT=ni and charge neutrality ni=ne, the total particle count is 2ne. This gives a thermal energy of E thermal = 3/2(2ne)kT=3nkT. Your equation uses a factor of 12, not 3. This could be due to an implicit assumption about heating efficiency (e.g., that only 25% of the fusion energy is available to heat the plasma), but this is not explained. I would strongly recommend you re-verify this derivation, check your source, and add a sentence explaining the origin of the factor of 12 for the reader's benefit.

Additional specific recommendations

- I recommend adding a few words in the abstract briefly explaining why you particularly mention tritium and deuterium. Just naming these two isotopes may be unclear for a reader new to the subject.
- To maintain a scholar approach throughout your manuscript, I recommend adding a few more citations in the ‘History’ section. For example, you could add references to the original papers introducing the first tokamak and the first stellarator designs.
- Please clarify or double-check the section “the stellarator was more dominant in scientific” in the Introduction. Did you mean “in science”? As a general rule, aim to be as specific as possible and replace general terms such as “science” with more specific fields (e.g. “in the field of nuclear physics”, “in the scientific community”).
- What is the current state of ITER, JET or Wendelstein 7-X? Your summary points to 2021-2022, but some progress has been made since then. I recommend adding one sentence summarising the current state of these large projects. You can even include the most recent numbers to give the reader a quantitative idea of what can be done at the moment. How much energy can be produced? What is the maximum power output achieved so far? What is the maximum duration for which a fusion reaction has been maintained so far? These numbers could be very interesting for a keen reader.

- For Figure 1, you need to add a reference to the work from where you extracted the diagram (or to the author). ‘ResearchGate’ is a platform where scientists publish their work and is not enough to identify the exact piece of work from which you adapted the diagram.
- Some refinement is possible within the citations. For example, “Ridha, A. A. (n.d.).” actually has a publishing year (2016) which can be found at the link found in the full citation. Please check that this error does not repeat in other references as well.
- ‘R min’ appears as ‘r min’ in Figure 2, so please use a similar notation in the caption of Figure 2
- On page 7, there are a couple of footnotes missing. Did you mean to maybe include citations here?
- I noticed that you do not make any reference to some of the figures in the text. The figures should not be ‘floating around’ in between the paragraphs, but rather augment the text with additional explanations and visual clues. You should reference the figures in the text to guide the reader when to look at each figure. For example, you can use short references (e.g. “as schematically shown in Figure x”) or longer explanations (e.g. “Figure x shows how the energy of the laser pulse is converted into X-rays which, in turn, drive the implosion of the fuel capsule”).
- The author should revisit the statement “due to the collaboration seen with countries researching magnetic confinement, and lack thereof in inertial confinement.”
    - The manuscript's author likely reached their conclusion by comparing everything to the unique case of ITER, which is a massive, centralized project involving 35 nations. While ICF does not have a single project of that scale, the statement that there is a "lack thereof" of collaboration is incorrect. The field is characterized by considerable international research, multiple major national facilities, and significant public-private partnerships driving toward a commercial solution.
    - While the scale of collaboration may differ from magnetic confinement's flagship ITER project, there are indeed important international efforts and significant successes in the field of inertial confinement fusion (ICF).
    - Here is a more detailed breakdown:
        - Major International Facilities: The field of ICF is led by two major facilities: the National Ignition Facility (NIF) in the United States and the Laser Mégajoule in France. The existence of these two multi-billion dollar-class lasers in different countries points to a significant international commitment to this line of research.
        - Active International Collaboration: Contrary to the manuscript's claim, there is "considerable international research and collaboration" within the ICF community. The research is not happening in isolation.
        - Significant Success: The field has achieved more than just "moderate success." The National Ignition Facility has successfully demonstrated fusion ignition, a monumental scientific breakthrough where a fusion reaction produces more energy than the laser energy delivered to the target. This achievement is a cornerstone of the argument for developing Inertial Fusion Energy (IFE).
        - Collaborative Partnerships: In the United States, a significant public-private partnership called "IFE-STAR" has been formed. This partnership includes key players like Lawrence Livermore National

Laboratory, General Atomics, and the University of California, San Diego, demonstrating a collaborative effort to build a roadmap for a commercial fusion pilot plant.

- Adopting a More Objective Voice: In the "Discussion" section, you use personal phrasing such as "The author agrees with this general sentiment" and "Another reason the author supports the opinion". In scientific writing, it is often conventional to maintain a more objective voice. I suggest rephrasing these to focus on the evidence itself. For example: "This general sentiment is supported by several lines of evidence," and "A second factor supporting the view that magnetic confinement is more advanced is the difference in efficiency." This is a stylistic choice, but one that aligns the paper more closely with the tone of many physics journals.

Review of “Confinement Methods in Nuclear Fusion: A Comparative Review of Inertial and Magnetic Approaches”
Recommendation: **Revise and Resubmit (Major Revisions Needed)**

Report: This is an impressively researched and ambitious paper, especially for a student at this level. The author clearly has a strong grasp of nuclear fusion principles and has done extensive reading.

Let us start the review report with some minor suggestions (which are easy to take care of).

1.The references are ok but they are listed in incoherent fashion.

Here's what’s going wrong with the references:

- **Inconsistent formatting styles** (some use full journal names, others don’t; some use access dates, others omit them).
- **Citation order issues** – they don’t follow a standard like APA, MLA, or Chicago.
- Some entries are **missing essential elements** (e.g., author names, publication year, publisher, or page numbers).
- There's **inconsistent use of italics**, hyperlinks, and capitalization.
- "**Author, N.**" is likely a placeholder or an error, not a real citation.

2. The figure name and caption should appear at the end of the figures.

Let us now go deep into key aspects of the referee report

Strong Point:
One of the stronger parts of the paper is the conclusion, where the author makes a well-reasoned case for why magnetic confinement currently seems more promising.

Weak Point:
One area where the paper falls short is in its use of computation. Given that it includes detailed derivations (like the Lawson criterion) and discusses key metrics such as energy gain (Q value), it would have been valuable to see some basic numerical analysis or sample calculations — even rough estimates. For example, a comparison of predicted Q values across different confinement methods, or an application of the Lawson equation using real reactor parameters (e.g., ITER or NIF), would help translate theory into something more tangible. Even a simple table summarizing performance metrics could elevate the paper’s analytical depth. Right now, the math feels a bit detached from application.

Suggestions to fix:
You don't have to do whole new computations but please pay attention to the overall structure.

Transitions between major sections sometimes feel abrupt, and a more clearly stated argument or research question up front would help anchor the review. It would be helpful to step back occasionally and explain why each point matters in the context of comparing the confinement methods

Overall Evaluation:

This paper shows real promise and reflects a high level of interest and effort from the author. With revisions — especially around structure, citation formatting, and the inclusion of some light computation — it could become a compelling and insightful review suitable for publication. I encourage the author to **revise and resubmit.**

To the Reviewer, I appreciate the feedback on my paper, "Confinement Methods in Nuclear Fusion: A Comparative Review of Inertial and Magnetic Approaches." Attached is the revised paper incorporating your feedback. Unfortunately I cannot figure out how to find the line numbers without manually counting them, so instead I have attached the page number where the response has been added.

1. Strengthening the Introduction's Hook [Page 1]
   Response: Added section at the start of the introduction about energy and the increasing importance of finding a clean energy source.
2. Refine the Flow of the Discussion [Page 15-17]
   Response: Added a sentence to the start of each paragraph of the discussion linking to the previous paragraph/s.
3. Acknowledge and Rebut Counterarguments [Page 17]
   Response: Added a paragraph at the end of the discussion addressing possible counterarguments.
4. Clarify Q-Factor Comparison [Page 16]
   Response: Added a sentence within the paragraph clarifying that both of the earlier values I gave referred to the scientific gain factor.
5. Current State of the Field [Page 14-15]
   Response: Added a section describing the current landscape of fusion research. I have included points about Commonwealth Fusion Systems, Helion Energy and Tokamak Energy.
6. Inertial Confinement Post-Ignition [Page 9-10] and [Page 15]
   Response: Added paragraphs in the Current Landscape and Inertial Confinement sections addressing the need to use new diode-pumped lasers and potential alternative approaches to IFE like shock and fast ignition.
7. Lingering Engineering Hurdles for All Approaches [Page 14-15]
   Response: Added paragraphs in the Current Landscape section, addressing the issues and challenges with both confinement methods.
8. Z-Pinch Instabilities [Page 10]
   Response: Added parts to the Z-Pinch section further explaining how the instabilities evolve over time.
9. Benefits of H-Mode [Page 13]
   Response: Clarified that it increases confinement time.
10. Lawson Criterion Derivation [Page 5]
    Response: Fixed the issue with the derivation.
11. Figure 1 [Page 3]
    Response: Replaced the figure and redone the citation.
12. Citations and references [Page 1-22]
    Response: Added the dates and names to those I could find.
13. R min [Page 4]

Response: Done as suggested(changed r to be lower case).

14. Collaborative partnerships for inertial confinement fusion [Page 16]
    Response: Added more about the partnerships for inertial confinement and larger projects, but preserved the original point.
15. Adoption of a More Objective Voice in the Discussion Section [Page 15-17]
    Response: Used evidence instead of my opinion when discussing points.

Kind Regards, Author

To the Reviewer, I appreciate the feedback on my paper, "Confinement Methods in Nuclear Fusion: A Comparative Review of Inertial and Magnetic Approaches." Attached is the revised paper incorporating your feedback. Unfortunately I cannot figure out how to find the line numbers without manually counting them, so instead I have attached the page number where the response has been added.

1. Tables and Calculations [Page 2-3] [Page 6] [Page 16-17]
   Response: Added several tables and shown calculations for the energy released by a DT reaction.
2. Linking the Sections to an Overall Question [Page 15]
   Response: Added a paragraph at the start of the discussion which gives context to the discussion.
3. References [Page 1-22]
   Added page numbers, dates and names where possible, but am unsure about the bibliography section. It is intended to follow APA 7th edition referencing and formatting, which is also why I have put the figure name before the figure.

Kind Regards, Author

Confinement Methods in Nuclear Fusion: A Comparative Review of Inertial and Magnetic Approaches

Sina Naseri

Indigo Research

Abstract

This literature review focuses on confinement within fusion power plants and the methods involved in confining plasma during fusion energy production and testing. Fusion is often regarded as the future of energy production as it produces large quantities of energy with little fuel and relatively safe waste products. Furthermore, the fuel itself is easy to acquire, needing lithium for tritium and sea water for deuterium. This review attempts to inform the readers on the history and current primary methods of confining plasma in fusion reactors, focusing on inertial and magnetic confinement. Additionally, this review contains a brief explanation of electrostatic and gravitational confinement and comparison of the magnetic and inertial confinement methods.

Introduction

With the rise of steam power and the industrial revolution, energy and power from sources beyond the muscles we possess has become increasingly linked to our daily lives. However, much of our energy comes from sources that emit greenhouse gases and other pollution, both atmospheric and otherwise. As such, finding a source of energy that is both clean and can produce enough to sustain our increasing energy demands is one of the biggest challenges to overcome this century. Nuclear fusion is one of the major contenders to fill this role due to its lack of greenhouse gas emissions and the extremely high energy density of its fuel.

Furthermore, there have been recent breakthroughs at the National Ignition Facility(NIF), with ignition having been achieved. This, along with the massive international investment in the ITER project reinforces the idea that nuclear fusion is the future of our energy production.

History

The first forays into the idea of nuclear fusion were in the 1920s to 1930s where Robert d'Escourt and Fritz Houtermans provided the first calculations of the rate of nuclear fusion in stars. At this time, Ernest Rutherford was exploring the structure of the atom. The discoveries of these scientists were tied together by Rutherford's student Mark Oliphant when they discovered they could react heavy hydrogen nuclei to form Helium-3 and tritium(Prager, 2019, p. 1).

In the 1950s, researchers started looking into reproducing fusion seen in stars on earth. The first designs were done by Soviet scientists Andrei Sakharov and Igor Tamm for the tokamak, followed by Lyman Spitzer Jr. designing the stellarator(Spitzer, 1958). Initially, the stellarator was more dominant in the field of nuclear physics , however, the design lost sway after the tokamak proved itself as a more efficient concept through experimental research.('History of Fusion', n.d.)

Through the 1970s and 1980s, countries came together to overcome the challenge that was attaining fusion energy. One of the most notable collaborations was the Joint European Torus

(JET). The planning and designing of JET began in 1973 and construction of the final project finished a decade later in 1983. The completion of JET saw the first plasmas being achieved(Prager, 2019, p. 5).

After JET finished construction, the first experiments using tritium were carried out, making JET the first reactor to run on a fuel with a 50-50 mixture of tritium and deuterium. Using this fuel, JET set a record in both output and net energy gain.

Another notable event in the 1980s was the beginning of ITER at the Geneva superpower summit.

Currently, the ITER project is being built in Cadarache, France. This reactor passed 77.7 percent completion in December 2022. While ITER was being built, the Wendelstein 7-X stellarator was completed. Finally, in 2021, a new fusion record was achieved in JET, where 59MJ was produced in a 5-second-long pulse. A significant improvement from the 1 second pulse of the previous record.(‘History of Fusion’, n.d.)

Safety and Requirements of Nuclear Fusion

Nuclear fusion is often seen as the future of energy production. It produces massive amounts of energy with relatively little fuel. Fusion reactions also produce very little toxic or radioactive waste, producing helium as a main waste product. While tritium, a radioactive isotope, is produced, it is reused as fuel in a closed circuit within the reactor. Moreover, the half-life of tritium is short and, as mentioned above, is not used much as very little fuel is needed. The neutrons resulting from the reaction can cause other reactor materials to become radioactive through reactions. However, the waste is generally much shorter-lived and less hazardous than fission reaction waste.

With regard to safety, fusion power plants would be much safer than fission power plants. This is because fusion energy production is not based on a chain reaction, while fission power plants rely on chain reactions. If containment in a fusion reactor does fail, the plasma will cool, and operation will stop in a matter of seconds.

Nuclear Fusion

Nuclear fusion is a reaction in which two or more atomic nuclei combine to form one or more atomic nuclei and neutrons. This process can either release or absorb energy, depending on whether the difference in mass between the products and reactants is positive or negative. This difference in mass between individual nucleons and a nucleus is a result of the difference in nuclear binding energy and is called the mass defect.(*Fusion - Frequently Asked Questions*, 2016)

To find the mass defect and thus the energy released by the reaction, we must first find the masses of the reactants. In a deuterium-tritium reaction, they are as follows:

- Tritium: 3.016049 u
- Deuterium: 2.014102 u
- Helium-4: 4.002603 u
- Neutron: 1.008665 u

Then we must calculate the total mass before and after the fusion reaction has taken place.

- Initial mass (deuterium + tritium):

$$2.014102\,u + 3.016049\,u = 5.030151\,u \qquad (1)$$

- Final mass (Helium-4 + Neutron):

$$4.002603\,u + 1.008665\,u = 5.011268\,u \qquad (1)$$

To determine the mass defect(Δm), we use Δm = Initial Mass – Final Mass:

$$5.030151\,u - 5.011268\,u = 0.018883\,u \qquad (3)$$

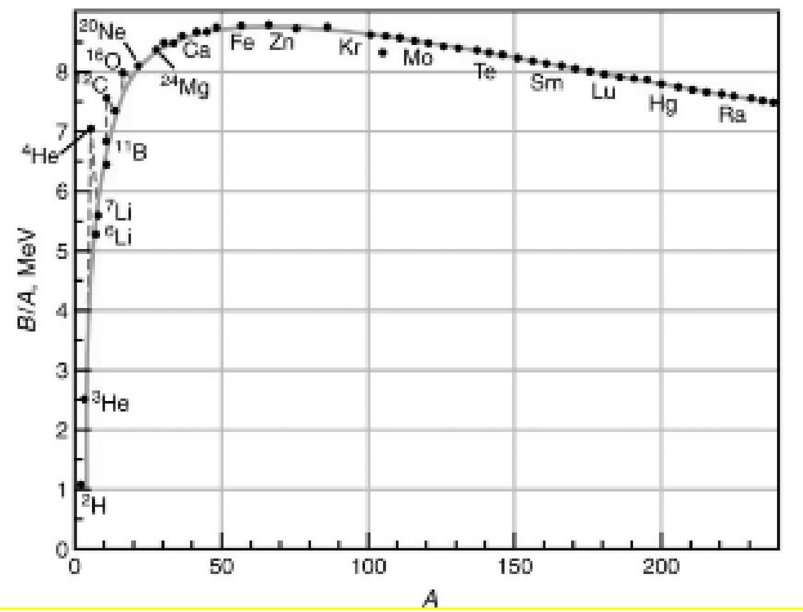
To convert this mass to the energy released, we must multiply by 931.494 MeV/c^2. This gives us 17.589MeV released per fusion reaction.

Doing the same with a deuterium-helium-3 reaction, we get 18.865MeV released per fusion reaction. This is greater than deuterium-tritium reactions, however, deuterium-tritium reactions are still more widely used due to the lower temperatures needed for fusion to occur('Explaining Helion's Fusion Fuel', n.d.).

Nuclear fusion that produces nuclei lighter than iron-56 will generally release energy. Atoms with a higher mass number than iron-56 typically have higher binding energy per nucleon, however, the energy required to fuse the nuclei will be even higher, resulting in energy lost if fusion occurs.

Figure 1

Binding Energy per Nucleon against Mass Number

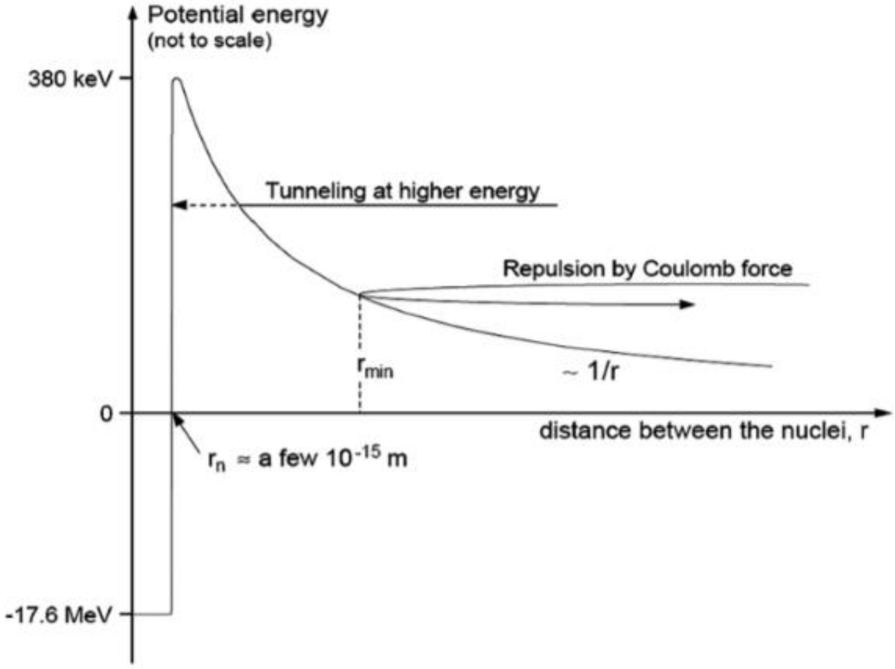


Note. This figure shows how at mass numbers before iron-56, fusion processes will typically produce energy, and at mass numbers after iron-56, fission will more produce energy. From Khairi, A.(2014) Fundamentals in Nuclear Physics.

Light nuclei have a lower atomic number. During nuclear fusion, this results in the Coulomb force being weaker as they have a low charge. However, the strong nuclear force has a range much shorter than the Coulomb force, as seen in figure 2 below. As such, the nuclei have to be very close to each other for the attraction due to the strong nuclear force to overcome the repulsion due to the Coulomb force. In order to provide these conditions, the nuclei must be accelerated to speeds high enough to bring the nuclei close enough to each other. This requires considerable energy, even for the lightest of elements. Once close enough, the strong force will grow and the nuclei will 'fall' into each other, resulting in fusion. One way this can be overcome is through quantum tunneling. Although this process cannot be forced to occur, it would allow the nucleus to bypass the Coulomb barrier, reducing the energy input required.

Figure 2

Potential energy against Distance Between Nuclei



Note. This figure shows the repulsion due to the coulomb force as distance between the two nuclei changes. The peak represents the coulomb barrier which a nucleus must overcome in order to undergo nuclear fusion. r_{min} represents the minimum distance the nuclei must reach for fusion to occur, or the maximum distance nuclei can be apart while still being able to undergo nuclear fusion. This is because at this point, the strong nuclear force takes over. From Ongena, J. (2015). Fusion: A true challenge for an enormous reward. *EPJ Web of Conferences*, *98*.

Overall, the energy released from most nuclear reactions is much greater than in chemical reactions. This is because nuclear binding energy is greater than the energy that holds electrons to a nucleus. Fusion reactions also have a higher energy density than nuclear fission because they produce far greater reactions and energy per unit mass, though individual fission reactions are typically more energetic than fusion reactions(Petrescu et al., 2017, p. 2).

Criteria for Success

The first aspect of nuclear fusion we must establish is our success criteria. One method is to use the fusion energy gain factor, Q. This compares output energy with the energy added to the fuel.

Another method is to use the Lawson criterion, which compares the rate of energy generated by the fusion reactions to the rate of energy losses to the environment.

The Lawson Criterion and its Derivation

In order to find the Lawson criterion, the first value we must find is the rate of fusion processes. This can be defined as the number densities of the fuel multiplied by the reactivity of the fuel.

$$W = \frac{n}{2} \cdot \frac{n}{2} \langle \sigma v \rangle \tag{4}$$

Where W is the rate of fusion processes, $\frac{n}{2}$ is the number densities of both deuterium and tritium, σ is the fusion cross-section and v is the relative velocity of the two nuclei. The angle brackets mean the average over the Maxwellian velocity distribution. We also assume that the densities of the deuterium and tritium ions are equal, and their total density is equal to the electron density. It can therefore be inferred that $n_D = n_T$ and that $n_D + n_T = n_e$. This gives us $n_D = n_T = \frac{1}{2} n_e = \frac{n}{2}$.

We can also use kinetic theory, giving us.

$$E_k = \frac{3k_bT}{2} \tag{5}$$

Where E_k is the kinetic energy of the particles, k_b is Boltzmann's constant and T is the temperature in Kelvin. Using these, we can find the energy produced as the product of the rate of fusion processes, the kinetic energy of the fusion products, and time.

$$E = \frac{n^2 \langle \sigma v \rangle}{4} \cdot E_F \cdot \tau \tag{6}$$

Where E is energy produced, E_F is kinetic energy of the fusion products and τ is the amount of time the fusion processes take place for. In order to obtain energy from fusion, the energy produced must be higher than the energy required to heat the plasma to the right temperatures$(E > E_k)$, therefore we get

$$\frac{n}{4} \langle \sigma v \rangle \tau E_F > 3k_bT \tag{7}$$

which can be rearranged to get

$$n\tau > \frac{12k_bT}{\langle \sigma v \rangle E_F} \tag{8}$$

This is the equation for the Lawson criterion, which shows us that in order to achieve energy gain, either our number density or our confinement time must be high.(Schouten, 2024).

Table 1

Comparison of Lawson Criterion Values for Magnetic and Inertial Confinement Fusion

Key Parameters	Magnetic Confinement Fusion	Inertial Confinement Fusion
Particle density n/cm^{-3}	10^{14}	10^{26}
Confinement time τ/s	10	10^{-11}
Lawson criterion nτ/scm^{-3}	10^{15}	10^{15}

Note. This table shows the particle density and confinement time of both magnetic and inertial confinement fusion. Magnetic confinement fusion has a much lower particle density than inertial confinement fusion, however, it makes up for this with its much longer confinement time. Ultimately, both have similar values for the Lawson Criterion. From Pfalzner, S. (2006). *An Introduction to Inertial Confinement Fusion*. CRC Press.

Fusion Energy Gain Factor

Another metric we can use to measure the success of a test is the Q value. This Q value is the ratio between the fusion power produced and the power input needed to maintain the plasma in a steady state. This means that a Q value of one is 'break even'. Usually, a Q value of five is needed for the reaction to self-heat. This is due to energy losses causing not all the energy produced to be reinvested into maintaining the plasma in a steady state(Yushmanov, 1980).

Inertial Confinement

As seen above in the equation for the Lawson criterion, the two main ways to make the energy gain greater than the energy lost to surroundings are to have high confinement time and having a high number density. Inertial confinement focuses on the latter of these, reaching very high number densities. There are four phases to inertial confinement, the interaction phase, the compression phase, the deceleration phase and the ignition phase.

Interaction Phase

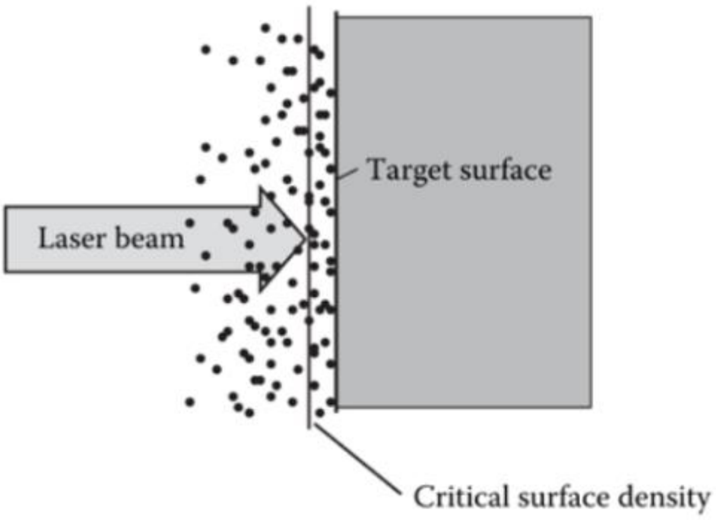
The interaction phase is the first phase of inertial confinement. It is the phase in which the energy is delivered onto the capsule containing the fuel(usually Deuterium-Tritium mix). The energy is delivered through a driver, which can be either laser light or particle beams. What driver is used is irrelevant when only looking at the energy input, however, the initial interaction process differs significantly between the two options. This difference is due to the properties of the drivers; where laser light will only interact with the surface of the matter, beams will penetrate a certain distance. In both cases, the goal is to transfer as much energy as possible into the material.

Assuming the driver is a laser, plasma will be created as soon as the laser beam encounters the outer surface of the capsule. The plasma then expands outwards from this surface, with a higher density closer to the capsule surface. At some point, the plasma will reach a certain critical density and hinder the laser beam from penetrating any further. The surface of the critical density region will not be at the capsule surface, instead, being located some distance away. This prevents the energy of the laser from being deposited directly onto the surface of the capsule.

The location of this critical density surface depends heavily on the wavelength, intensity and pulse length of the laser beam. These parameters also change the amount of ablation and the efficiency of the subsequent compression phase. Therefore, when discussing the efficiency of the overall process, the values of these parameters are essential(Pfalzner, 2006, pp. 17–19).

Figure 4

Diagram of a laser driver interacting with a target surface



Note. Shows how a laser interacts with the target surface and how the critical surface density can affect and interfere with the energy transmitted by the laser. From Pfalzner, S. (2006). *An Introduction to Inertial Confinement Fusion*. CRC Press.

Compression Phase

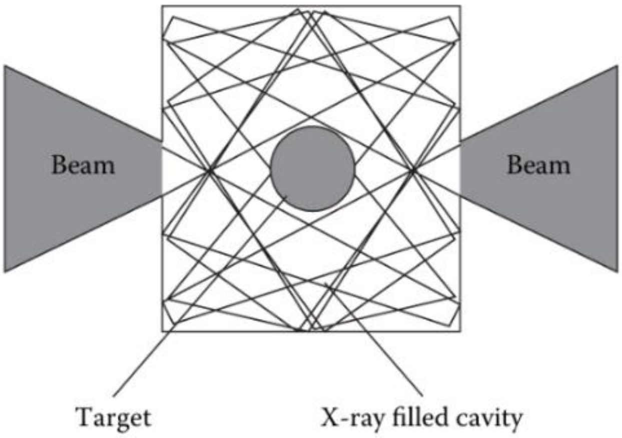
The compression phase is the second phase in inertial confinement fusion. The success of the compression is, to a large extent, dependent on the interaction phase. However, there can still be instabilities in this phase. These illumination nonuniformities occur on two scales: microscopic and macroscopic. Microscopic nonuniformities can be caused by spatial fluctuations within a single beam, causing hotspots or regions of greater intensity to form. Macroscopic nonuniformities can be formed by a power imbalance between the individual beams.

There are two ways to overcome these macroscopic nonuniformities; we can take a sufficient number of beams. This is done in direct-drive ICF. However, this can be very expensive and challenging to accomplish. Instead, many smaller scale direct-drive experiments are performed and we try to infer how a system with more beamlines would perform from these experiments.

Alternatively, an indirect-drive approach can be utilised. In this approach, the energy of the laser is first absorbed by an enclosure around the capsule made of a high-Z material(hohlraum). The energy from the laser is then emitted from the hohlraum as x-rays. These x-rays are what drive the implosion of the capsule. This can be seen in the figure below, where the box surrounding the target is the hohlraum. The x-rays are being absorbed and reemitted by the walls of the hohlraum until they hit the target, heating it(Pfalzner, 2006, pp. 19–22).

Figure 5

Diagram of a hohlraum



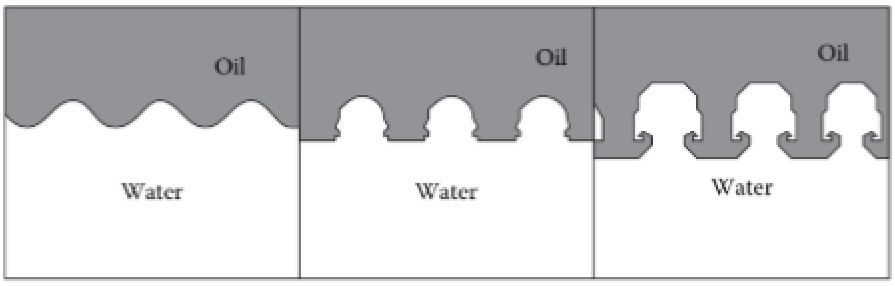
Note. Shows how the energy from the driver is mostly reflected by the walls of the hohlraum until it hits the pellet. From Pfalzner, S. (2006). *An Introduction to Inertial Confinement Fusion*. CRC Press.

Instabilities cannot be avoided, no matter the method used. An example of one of these instabilities is the Rayleigh-Taylor class of instabilities. These occur at the boundary between two fluids of different densities, when the denser fluid pushes into the less dense one. An example of this would be when water pushes into oil. If perturbed, a mixing between the two fluids can occur. In the context of ICF, these two fluids are hot and cold plasma. When the mixing of these two plasmas occurs, the hotter plasma is cooled. This is bad for the compression, therefore targets are designed such that these Rayleigh-Taylor instabilities are minimised as much as possible. This is done through the shape of the capsule. The ratio of the shell radius to the shell thickness is a major factor in reducing Rayleigh-Taylor instabilities. This property of the capsule is called the in-flight aspect ratio and has to be in the order of 25-40 at all moments during the implosion.

The acceleration can also be varied to optimise efficiency. This is done by changing the acceleration such that the creation of ‘hot electrons’ or energetic electrons can be avoided as much as possible. This is because these hot electrons can preheat the fuel and create their own shock fronts, thereby making it harder to compress. Avoiding preheat is especially necessary if the driver is a laser. However, one cannot completely prevent shock waves from forming if they want to build up pressure in a reasonable time. Therefore a low-power prepulse followed by a succession of increasingly intense pulses can accelerate the fuel nearly isentropically (entropy of system remains 0)(Pfalzner, 2006, pp. 21–22).

Figure 6

Rayleigh-Taylor instabilities



Note. This diagram shows the formation of Rayleigh-Taylor instabilities over time, using oil and water as the fluids of different densities. From Pfalzner, S. (2006). *An Introduction to Inertial Confinement Fusion*. CRC Press.

Deceleration

When the inner part of the fuel reaches the center of the capsule, it starts to decelerate. This happens through the kinetic energy of the inner part of the fuel being converted into internal energy. This results in both temperature and density increasing in the center while the rest of the fuel remains relatively undisturbed.

In the hot-spot concept, high fuel densities and temperatures are needed. To reach these densities and temperatures at the hot-spot areas, a succession of increasingly intense pulses is needed. This allows the nearly isentropic compression to take place. The last of the succession of shocks has to act at the same time as the first of the shocks for a successful deceleration phase. Therefore, the timing of the shocks is integral for the success of the phase.(Pfalzner, 2006, p. 22)

Ignition and Burn Phase

Finally, when temperature and density conditions in the hot-spot area are right, ignition occurs. The α particles produced deposit energy primarily in the center area, heating it up. Other products such as the radiation and fusion neutrons then transport the energy from the hotspot region to the outer areas of the fuel. This allows more fusion reactions to take place and thus the burn propagates outward.

Throughout this process, a very high pressure builds up until it eventually blows apart the remaining fuel and α particles, signalling the end of the ICF cycle(Pfalzner, 2006, pp. 22–23).

There are alternate methods for compression and ignition, including shock ignition and fast ignition. In fast ignition, traditional inertial confinement fusion techniques are used to compress the fuel. Then a high current ion beam is directed to a hot-spot within the fuel to heat the hotspot to ignition temperatures. This burn propogates outwards in the fuel, leading to potentially high gain and high burnup(how much of the fuel burns) percentages(Albright et al., 2022).

Shock ignition also uses traditional inertial confinement techniques initially to compress the fuel, only at lower implosion velocities. Close to the point of maximum compression, an intense laser spike is fired, generating a strong converging shock wave. This converging shock wave collides with the rebound shock wave from the initial compression. This collision increases the shock pressure, thus leading to further compression and heating. If this point reaches sufficient temperature and density, it will ignite. The lower implosion velocities can help reduce hydrodynamic instabilities such as Rayleigh-Taylor instabilities(Temporal et al., 2024).

Overall Gain

In the fusion process, energy is only gained if the energy given off by the fusion processes exceeds the input energy. However, this input energy is not just used to heat the fuel. There are several inefficiencies that must be taken into account. These include but are not limited to: the losses in the driver itself, losses in the hohlraum(if used) and energy lost in the compression dynamics due to the Rayleigh-Taylor instabilities. If these inefficiencies can be overcome, providing a net energy gain from these fusion reactions will prove much easier to achieve.(Pfalzner, 2006, p. 23)

Magnetic Confinement

As mentioned before, the two main ways to make energy gain greater than energy lost to surroundings are to have a high number density or high confinement time. Magnetic confinement typically focuses on high confinement time with much lower number densities compared to inertial confinement.

The idea of magnetic confinement is to confine the plasma using magnetic fields. This can be done due to the plasma being partially ionised. Confining the plasma using magnetic fields allows the plasma to reach high temperatures without touching and thus damaging the walls of the confinement chamber.

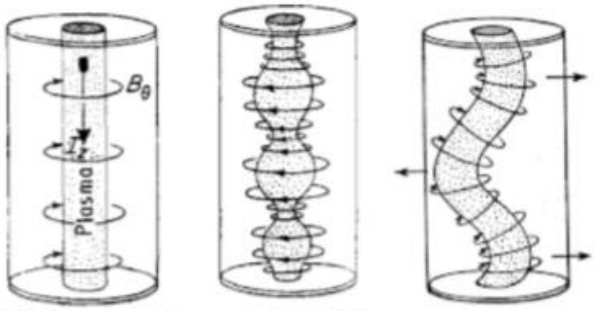
Z-Pinch

One the simplest ways to magnetically confine a plasma is using the Z-Pinch method. This is done by passing a very large current through the plasma. This high current creates ring-like magnetic fields, which exert an inwards force, compressing the plasma. In fusion applications, the current heats the plasma up to the temperatures needed and the inwards force compresses the plasma, raising its density. The downside of this is that it will only last for very short periods of time.

There are also instabilities in this method. The main issues are from non-uniformities in the initial plasma cylinder. If the cylinder is narrower at any points, these points will compress. As the toroidal magnetic field responsible for the pinch is inversely proportional to radius, any narrower section will experience greater inward pinching force. This leads to runaway compression, eventually cutting off the current and breaking the plasma cylinder. This instability is called a sausage type instability. Another instability results from slight bends in the initial shape of the plasma. As seen in figure 6, force acts from the inside to the outside of the bend, making the bend larger. This instability keeps growing until it ruins the plasma cylinder(Shumlak, 2020, pp. 2–3)

Figure 7

Sausage and Kink instabilities



Equilibrium Sausage instability Kink instability

Note. Shows how the uniformly confined plasma can form instabilities due to small instabilities magnifying. From Sadouni, S. (2020) *Fluid modeling of transport and instabilities in magnetized low-temperature plasma sources.*

Magnetic Mirror

Another method is the magnetic mirror. A cylindrical magnetic field is created by a pair of magnetic coils. This magnetic field bulges slightly in the middle. The particles moving perfectly parallel to the field lines will feel no force and thus be able to escape. Particles moving perpendicular to the field lines will orbit the field lines and not escape. Orientations in between will either be able to escape or be trapped by the field depending on how closely its motion is aligned with the magnetic field. When a trapped ion tries to escape the confinement, their direction of motion will reverse when it gets too close to the magnetic coils, causing it to reflect back to the center.

An issue with this method is that collisions between trapped ions and electrons will knock an increasing number of them into the right orientation to escape the magnetic mirror. The end effects can be mitigated by making the mirror longer so that a lower proportion of the plasma escapes. However, the main flaw with this method is that it is not magnetohydrodynamically stable. This means that in the middle parts of the field, where the field is weaker, the plasma can 'balloon' out, dragging the magnetic field lines with it. This causes the confinement time to be low(Post, 1987).

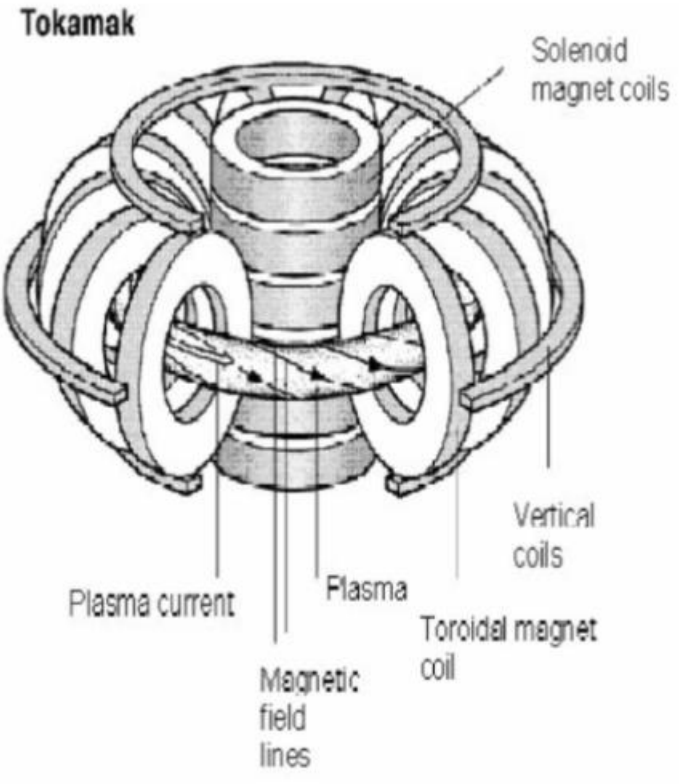
Tokamak and Stellarator

Finally, there are the tokamak and stellarator. In a tokamak, the plasma is confined in a torus, however, there is a current passed through the middle. This current acts similar to the current in the Z-pinch method, creating magnetic fields in circles around the torus. There are also coils around the torus, creating a magnetic field that gives the toroidal shape. Overall, the combination of these two magnetic fields twists the magnetic field so that the magnetic field lines go from outside the torus to inside the torus and back, causing the field to be more uniform in strength(Artsimovich, 1972, p. 1).

In a stellarator, the coils themselves are twisted in such a way that the magnetic field lines go from the outside of the torus to the inside and back, making the field strength more uniform.

Figure 8

Diagram of a Tokamak



Note. Shows the magnetic field lines from the toroidal and poloidal(vertical) magnet coils and thus how the plasma is confined within the tokamak. From Kwon, M.-E., Bae, Y.-S., Cho, S.-Y., Choe, W.-H., Hong, B.-G., Hwang, Y.-S., Kim, J.-Y., Kim, K.-M., Kim, Y.-S., Kwak, J.-G., Lee, H.-G., Lee, S.-G., Na, Y.-S., Oh, B.-H., Oh, Y.-K., Park, J.-Y., Yang, H.-L., & Yu, I.-K. (2009). CURRENT STATUS OF NUCLEAR FUSION ENERGY RESEARCH IN KOREA. *Nuclear Engineering and Technology*, *41*(4).

Heating Plasma in the Tokamak

Even after the creation and confinement of the plasma, it must be heated to sufficient temperatures. Heating the plasma is done mainly by adding energy via electromagnetic waves or particle beams.

Particles orbit around magnetic field lines at certain frequencies, depending on their mass and the magnetic field strength. This oscillation allows them to absorb electromagnetic radiation with a matching frequency. The issue with this method is that the electromagnetic waves can be reflected or refracted by the plasma.

Instead, beams of particles can be used to deposit energy into the plasma. These particles can also be deuterium particles, giving the plasma more fuel to fuse. In order to not be affected by the magnetic fields around the plasma, the particles must be neutral, hence the name 'neutral beam injection'. The overall process requires an electron to be given or stripped off a deuterium atom(this gives it a charge and allows us to accelerate it). Then the deuterium ion is accelerated. Before it enters the plasma, the deuterium ion must be neutralised(Kunkel, 1981, pp. 10–11).

Often high performance plasmas need additional heating. Neutral beam injection is a standard heating scheme at many major Tokamaks. However, the fusion of the deuterium and tritium into helium should eventually become the primary heating mechanism(Artsimovich, 1972, pp. 1–2).

Issues with the Tokamak

There are a few economic issues with magnetic confinement. A major issue is damage to the containment vessel. During operation, when the input power is high enough the plasma transitions from low-confinement mode(L-mode) to high-confinement mode(H-mode). This H-mode is characterised by a much higher rise in plasma density near the edges and a higher peak density overall. This increase to density and confinement time, and thus performance is seen as essential for any future reactor. The main drawback, however, is that there are frequent expulsions of plasma while the plasma is in H-mode, called an edge localised mode(ELM). These ELMs can cause damage to plasma-facing components(Connor et al., 2008, p. 1).

Gravitational and Electrostatic Confinement

Gravitational Confinement

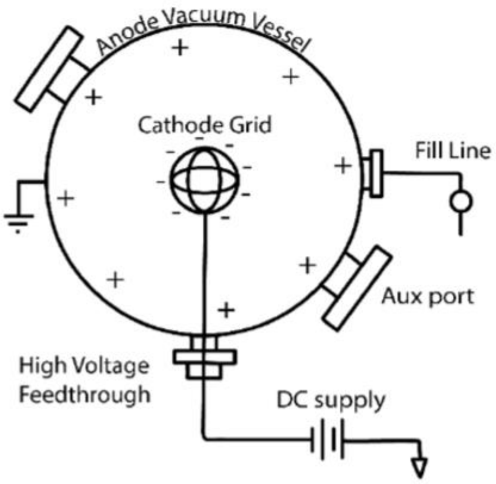
Gravitational confinement is the type of plasma confinement that occurs in stars. Stars use their massive size and mass to their advantage, using the strength of their gravitational field to force nuclei together, causing fusion reactions. Initially, stars ignite using the extreme gravitational force to compress the matter and start fusing. Similar to the gas laws, as the volume decreases, the pressure increases massively, thus starting the fusion processes. The nuclei in the stars fusing provides energy for more fusion reaction to happen, sustaining the stars. These fusion reactions also produce a pressure within the star. This pressure is what stops the star from simply collapsing in on itself. As long as there are fusion reactions happening within the star, the pressure will counteract the force from the gravitational field of the star, creating an equilibrium of sorts. This can be seen in main sequence stars.

Electrostatic Confinement

Electrostatic or inertial electrostatic confinement is another method of confinement. It relies on an anode and a cathode to separate the nuclei from the electrons in an atom. The nuclei are attracted to the cathode, however, the electrons are repulsed, stripping the nuclei of their electrons. Therefore, only the protons and neutrons are within the cathode. Within the cathode, the nuclei accelerate and collide. This can cause fusion reactions to occur, releasing energy. An example of a device that uses this principle to operate is a fusor. Fusors use a high voltage to ionise their fuel(usually deuterium gas) and then fuse. The energy given off by the fusion in a fusor can often be seen as a blue or purple glow due to the charged particles as they are accelerated(Ligon, 2007, pp. 5–6).

Figure 9

Diagram of a Fusor



Note. Shows the cathode grid and the anode vessel that are used to create and confine the plasma within the fusor. From Wolf, A. J. (2015). *Measurement of ion velocities in the TU/e Fusor plasma using LIF spectroscopy.*

The Current Landscape

Historically, much research into nuclear fusion has been conducted in government-funded facilities. However, there has been a recent surge in private companies and startups researching their own methods and approaches to nuclear fusion. These private companies have been receiving substantial investment and funding, including from giants like Google(Terrell, 2025) and Microsoft(Nellis, 2025).

One of the major players in the private sector of nuclear fusion is Commonwealth Fusion Systems. Their approach utilises high-temperature superconducting magnets to enable smaller designs, making them more cost-effective. They are currently building their first commercial reactor, SPARC, in Devens, Massachusetts and plan to produce first plasma in 2026, with net fusion energy production shortly after. Upon this milestone, Google has a deal with Commonwealth Fusion Systems for 200 megwatts of power out of the planned 400 megawatt capacity of the reactor(Gardner, 2025). This deal shows a major vote of confidence from Google, and by extension, the tech industry in the future of commercial nuclear fusion energy.

One of the contenders of Commonwealth Fusion Systems is Helion Energy, which utilises a field-reversed configuration instead of a tokamak. This is a simpler design with a linear instead of toroidal shape. This makes them potentially easier to build and maintain. On the other hand, they are more prone to the instabilities mentioned earlier due to their straight shape. One of the newer machines Helion Energy has built is Polaris, their seventh generation of machines using field-reversed configuration. Another difference is that Helion Energy uses a Deuterium-Helium-3 fuel cycle instead of the more common Deuterium-Tritium fuel cycle. Even though it requires higher temperatures, this alternative fuel cycle outputs more charged particles(mostly protons), allowing the energy to be captured through magnetic fields instead of steam and turbines(‘Explaining Helion’s Fusion Fuel’, n.d.).

Tokamak Energy, a UK based company uses spherical tokamaks which are more compact. Their ST40 design has reached over 100 million Kelvin, a major milestone for any potential fusion machine design(McNamara et al., 2023, pp. 1–2). The main difference between the spherical tokamak and a more conventional design is the shape. Spherical tokamaks are typically more compact with a shape more resembling an apple. This design can result in better plasma stability, thus giving enhanced confinement.

There do remain some key engineering challenges with magnetic confinement. First is how to make the ‘first wall’ of a reactor, which must withstand extreme temperature changes and neutron bombardment without becoming brittle, radioactive or melting. Finding or synthesising a material which meets all these properties is exceedingly difficult. Some materials being considered are tungsten, lithium and graphite, however, each have their issues.For example, Tungsten, while very resistant to heat, could oxidise and release radioactive fumes in the event of a simultaneous air ingress and loss of coolant(Rieth et al., 2013, p. 18).

The fuel also presents a challenge to be overcome. For Deuterium-Tritium reactors, tritium is needed. Unfortunately, tritium is a scarce and radioactive resource. A viable power plant would need to breed its own tritum by having the neutrons from the fusion reactions interact with a surrounding layer of lithium. This presents an engineering challenge that, as of writing this review, remains unsolved at a commercial scale.

Regarding inertial confinement and its future prospects, scientific ignition is only the first step. The next challenge to overcome is repetition. Currently, the National Ignition Facility uses flash-lamp-pumped lasers which can only fire infrequently due to thermal management issues(Garrec & Dumitras, 2010, p. 1). In order to generate energy comparable to power stations, the plant would need to fire and ignite targets multiple times a second. One possible solution to the laser issue could be to use diode-pumped laser systems, reducing energy converted into thermal energy, thus increasing the ‘wall-plug’ efficiency(Garrec & Dumitras, 2010, pp. 3–5).

Discussion

Regardless of method, it is clear that fusion energy is a strong contender in the race for a clean energy source. Its potential for near limitless clean energy has drawn investment from both governments and private players. However, which method will provide better results is less certain, with both inertial and magnetic confinement fusion proving themselves great potential energy sources.

The main difference between magnetic and inertial confinement are the principles behind them. Inertial confinement uses high powered lasers or particle beams to compress a fuel capsule, providing the conditions for nuclear fusion to happen. This leads to very low confinement times but very high number densities, allowing energy to be produced. In magnetic confinement systems, plasma is created within the reactor using induction, neutral beam injection or other methods, then confined using magnetic fields. This leads to longer confinement times but much lower number densities. Both of these methods satisfy the Lawson criterion, however, as of writing this, magnetic confinement is generally viewed as the more advanced promising method of the two(Lundy, 2024).

There are multiple lines of evidence that support this general sentiment. The first of these reasons is due to the level of collaboration seen with countries researching magnetic confinement. There are multiple international projects working on magnetic confinement, ranging from JET(now decommissioned) to ITER. There are also multibillion dollar inertial confinement fusion projects like the National Ignition Facility in the USA and France's Laser Mégajoule, however, even combined, it does not reach the same scale of collaboration and investment of ITER. While the author does acknowledge that ITER can be considered unique in its scale, it nonetheless shows the level of interest the international community has taken in magnetic confinement fusion. Despite this lesser scale, there are still some notable inertial confinement fusion partnerships and successes. Foremost is the fact that the National Ignition Facility has achieved ignition, which is a key part of the argument for further developing Inertial Fusion Energy. There also exists a public-private partnership called IFE-STAR in the United States, which brings together key players like Lawrence Livermore National Laboratory, General Atomics, and the University of California, San Diego. This reflects a collaborative effort to develop a commercial fusion pilot plant roadmap.Overall, the abundance of joint projects, especially in Europe, shows not just funding but vested interests in making this form of confinement work. This investment can be clearly seen in the continued funding of ITER despite the multiple setbacks(Matthews, 2024). However, as confinement in nuclear fusion projects is still relatively young, there is still an untapped well of potential advancements for both magnetic and inertial confinement. While magnetic confinement may be more likely to find these key technologies and advancements due to its greater funding, there still remains the possibility that inertial confinement fusion can take the spotlight and become the dominant idea within both scientific communities and the general public.

Possibly as a result of this difference in collaboration and funding, there is a difference in efficiency between current magnetic and inertial confinement methods. JET, a now decommissioned laboratory, was able to achieve a Q value of 0.67 (see Table 2), producing 16 megawatts from 24 megawatts of input power over 5 seconds. Further, ITER is predicted to reach a Q value of 10('History of Fusion', n.d.),meaning the plasma will produce 10 times more energy than the heating power added. In comparison, the National Ignition Facility in the USA used 2.05 megajoules of input energy to produce 3.15 megajoules of output energy, giving a Q value of around 1.54(Bishop, 2022). Both of these values refer to the scientific gain factor which does not include losses in either magnets or driver. At the system level during the tests at the National Ignition Facility, around 400 megajoules of energy was supplied to the lasers, giving an overall(or wall-plug) efficiency of just 0.5%(Cartlidge, 2023). This experiment shows that while inertial confinement fusion is a promising idea that has shown its value, the technological advances needed to take advantage of inertial confinement fusion have not been made. Overall, this means that, in the short term, magnetic confinement fusion will most likely prove to be the dominant method of confinement, however, as both methods progress, inertial confinement may prove to be more efficient, bypassing some roadblocks that magnetic confinement experiences.

Table 2

Energy Gain from Major Fusion Tests

Fusion Projects	Input Energy	Output Energy	Q Value(scientific)
JET	120MJ	80MJ	0.67
NIF	2.05MJ	3.15MJ	1.54

Beyond the efficiency and energy gain, the differences in operation methods also present a consideration for their future commercial viability. Where magnetic confinement fusion uses a continuous operation method, inertial confinement fusion uses a pulsed operation method. Many of our current methods of producing energy are continuous methods, and this is for good reason. A pulsed power supply needs additional energy storage systems to provide smoother power delivery. These additional systems add even more complexity to our power grids and will cost more money. Furthermore, the difference in efficiency will only be exacerbated by the repeated startup of inertial confinement plants. Where an inertial confinement plant will have to start up and cooldown every cycle, incurring efficiency losses in both of these phases, a magnetic confinement based fusion plant will only have to start up and cool down during maintenance.(*Electricity Security Matters More than Ever – Power Systems in Transition – Analysis*, n.d.) Overall, the commercial viability of magnetic confinement fusion is much greater than inertial confinement fusion as the current electrical infrastructure is more suited towards continuous methods of power generation, allowing magnetic confinement fusion plants to directly replace coal, gas or nuclear based power plants with minimal changes to the current power grid. This commercial viability of magnetic fusion has seen it get more funding and interest, leading to more developed laboratories and research centers.

Despite these points, the author would like to note that technological advancements in inertial confinement fusion is still possible. Key among these advancements are diode-pumped laser systems which can run multiple times per second and with greater efficiency. However, the drivers are only one half of the puzzle. The target itself also presents challenges. In order for a commercial inertial confinement fusion power plant to work, it would need a massive amount of fuel, all shaped into precise pellets that cannot afford even miniscule imperfections. While not impossible to overcome, this would require more time and investment to work. Even though magnetic confinement fusion does have its own issues, money and time have already been invested into overcoming them. As such, headway has been made into solving magnetic confinement's issues.

Conclusion

This paper reviews the literature on magnetic, inertial, electrostatic and gravitational confinement of plasma, mainly focusing on inertial and magnetic confinement.

In conclusion, in the short term, magnetic confinement will prove to be the dominant method of confinement for potential fusion power plants. This is due to both magnetic confinement fusion's compatibility with our current electrical infrastructure and the more advanced technologies and methodologies used. This allows magnetic confinement fusion plants to directly replace current fossil fuel and nuclear power plants with minimal changes to the power grid. However, it is difficult to predict whether magnetic confinement fusion, inertial confinement fusion or another method will prove to be the most efficient and effective source of energy as the field of nuclear fusion itself is new relative to many other fields, with many problems needing to be solved for both methods. A large breakthrough in either magnetic or inertial confinement could propel its respective method much further, allowing it to become the dominant method.

Regarding more recent progress, there have been several breakthroughs in recent years where several laboratories and tokamak testing sites have managed to produce more energy than was inputted. Furthermore, there are already plans to build the first fusion reactor connected to the US energy grid. This plant is expected to come online in the 2030s and produce four hundred megawatts of electricity(Dunning & Gallagher, 2022). ITER is still under construction in France while JET has been shut down and is now in the process of decommissioning. JET's final experiment was conducted outside of standard operational parameters and managed to set a record, producing 69 megajoules of energy over five seconds using 0.2 milligrams of fuel(Honney, 2024). Wendelstein 7-X, having generated a record plasma lasting eight minutes with an energy output of 1.3 gigajoules, has started the new experiment phase OP2.2 after being significantly optimised(Fleschner, 2024).

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This manuscript provides a well-structured and timely review of confinement methods in nuclear fusion, with particular emphasis on inertial and magnetic approaches. It gives a clear account of the historical context, the underlying physics, and the latest developments in both large-scale research projects and private-sector initiatives. The writing is accessible and well-organized, which makes the paper a useful reference for readers new to the field.

The paper's strengths lie in its breadth and clarity, and the revisions made in response to earlier feedback have improved both flow and precision. While the review remains somewhat more descriptive than analytical, and certain sections could be developed further in the future, the work demonstrates good understanding of the subject and effective synthesis of diverse sources.

Overall, this is a strong piece of work that will be valuable for readers. I am pleased with the improvements made, and I encourage the author to continue developing their critical voice in future research.

I recommend this paper for acceptance.

(expanded)

This manuscript provides a well-structured and timely review of confinement methods in nuclear fusion, with particular emphasis on inertial and magnetic approaches. It gives a clear account of the historical context, the underlying physics, and the latest developments in both large-scale research projects and private-sector initiatives. The writing is accessible and well-organized, which makes the paper a useful reference for readers who are new to the field.

What I found particularly strong is the way the author ties together history, basic physics, and ongoing projects. The revisions since the earlier draft have clearly helped with flow and precision — for instance, the discussion of the Lawson criterion now reads much more smoothly. The review also feels more balanced between inertial and magnetic confinement. Including both ITER and JET on the one hand, and newer private initiatives such as Commonwealth Fusion and Helion on the other, makes the work timely and relevant.

The manuscript shows good command of the literature. It does not just summarize the two main approaches but also briefly introduces electrostatic and gravitational confinement, which makes the review more rounded. I also appreciated the effort to point out practical engineering challenges (like materials for the first wall and tritium breeding) — these are often overlooked in student papers, but they help situate the physics in a real-world context.

The review is still more descriptive than analytical in places, but that is not a weakness so much as a stage. It provides a very solid foundation for deeper comparative work in the future. In particular, I think the author could, in time, extend this foundation by drawing out sharper contrasts between the advantages and limitations of different confinement methods, especially as new experimental results become available.

Overall, this is a clear, well-organized, and useful paper. It reflects careful reading, effective synthesis, and thoughtful revision. It will serve as a helpful starting point for readers beginning to explore nuclear fusion, and it points toward fruitful directions for future work.

Confinement Methods in Nuclear Fusion: A Comparative Review of Inertial and Magnetic Approaches

Sina Naseri

Indigo Research

Abstract

This literature review focuses on confinement within fusion power plants and the methods involved in confining plasma during fusion energy production and testing. Fusion is often regarded as the future of energy production as it produces large quantities of energy with little fuel and relatively safe waste products. Furthermore, the fuel itself is easy to acquire, needing lithium for tritium and sea water for deuterium. This review attempts to inform the readers on the history and current primary methods of confining plasma in fusion reactors, focusing on inertial and magnetic confinement. Additionally, this review contains a brief explanation of electrostatic and gravitational confinement and comparison of the magnetic and inertial confinement methods.

Introduction

With the rise of steam power and the industrial revolution, energy and power from sources beyond the muscles we possess has become increasingly linked to our daily lives. However, much of our energy comes from sources that emit greenhouse gases and other pollution, both atmospheric and otherwise. As such, finding a source of energy that is both clean and can produce enough to sustain our increasing energy demands is one of the biggest challenges to overcome this century. Nuclear fusion is one of the major contenders to fill this role due to its lack of greenhouse gas emissions and the extremely high energy density of its fuel.

Furthermore, there have been recent breakthroughs at the National Ignition Facility(NIF), with ignition having been achieved. This, along with the massive international investment in the ITER project reinforces the idea that nuclear fusion is the future of our energy production.

History

The first forays into the idea of nuclear fusion were in the 1920s to 1930s where Robert d'Escourt and Fritz Houtermans provided the first calculations of the rate of nuclear fusion in stars. At this time, Ernest Rutherford was exploring the structure of the atom. The discoveries of these scientists were tied together by Rutherford's student Mark Oliphant when they discovered they could react heavy hydrogen nuclei to form Helium-3 and tritium(Prager, 2019, p. 1).

In the 1950s, researchers started looking into reproducing fusion seen in stars on earth. The first designs were done by Soviet scientists Andrei Sakharov and Igor Tamm for the tokamak, followed by Lyman Spitzer Jr. designing the stellarator(Spitzer, 1958). Initially, the stellarator was more dominant in the field of nuclear physics , however, the design lost sway after the tokamak proved itself as a more efficient concept through experimental research.('History of Fusion', n.d.)

Through the 1970s and 1980s, countries came together to overcome the challenge that was attaining fusion energy. One of the most notable collaborations was the Joint European Torus

(JET). The planning and designing of JET began in 1973 and construction of the final project finished a decade later in 1983. The completion of JET saw the first plasmas being achieved(Prager, 2019, p. 5).

After JET finished construction, the first experiments using tritium were carried out, making JET the first reactor to run on a fuel with a 50-50 mixture of tritium and deuterium. Using this fuel, JET set a record in both output and net energy gain.

Another notable event in the 1980s was the beginning of ITER at the Geneva superpower summit.

Currently, the ITER project is being built in Cadarache, France. This reactor passed 77.7 percent completion in December 2022. While ITER was being built, the Wendelstein 7-X stellarator was completed. Finally, in 2021, a new fusion record was achieved in JET, where 59MJ was produced in a 5-second-long pulse. A significant improvement from the 1 second pulse of the previous record.('History of Fusion', n.d.)

Safety and Requirements of Nuclear Fusion

Nuclear fusion is often seen as the future of energy production. It produces massive amounts of energy with relatively little fuel. Fusion reactions also produce very little toxic or radioactive waste, producing helium as a main waste product. While tritium, a radioactive isotope, is produced, it is reused as fuel in a closed circuit within the reactor. Moreover, the half-life of tritium is short and, as mentioned above, is not used much as very little fuel is needed. The neutrons resulting from the reaction can cause other reactor materials to become radioactive through reactions. However, the waste is generally much shorter-lived and less hazardous than fission reaction waste.

With regard to safety, fusion power plants would be much safer than fission power plants. This is because fusion energy production is not based on a chain reaction, while fission power plants rely on chain reactions. If containment in a fusion reactor does fail, the plasma will cool, and operation will stop in a matter of seconds.

Nuclear Fusion

Nuclear fusion is a reaction in which two or more atomic nuclei combine to form one or more atomic nuclei and neutrons. This process can either release or absorb energy, depending on whether the difference in mass between the products and reactants is positive or negative. This difference in mass between individual nucleons and a nucleus is a result of the difference in nuclear binding energy and is called the mass defect.(*Fusion - Frequently Asked Questions*, 2016)

To find the mass defect and thus the energy released by the reaction, we must first find the masses of the reactants. In a deuterium-tritium reaction, they are as follows:

- Tritium: 3.016049 u
- Deuterium: 2.014102 u
- Helium-4: 4.002603 u
- Neutron: 1.008665 u

Then we must calculate the total mass before and after the fusion reaction has taken place.

- Initial mass (deuterium + tritium):

$$2.014102\,u + 3.016049\,u = 5.030151\,u \tag{1}$$

- Final mass (Helium-4 + Neutron):

$$4.002603\,u + 1.008665\,u = 5.011268\,u \tag{1}$$

To determine the mass defect(Δm), we use Δm = Initial Mass – Final Mass:

$$5.030151\,u - 5.011268\,u = 0.018883\,u \tag{3}$$

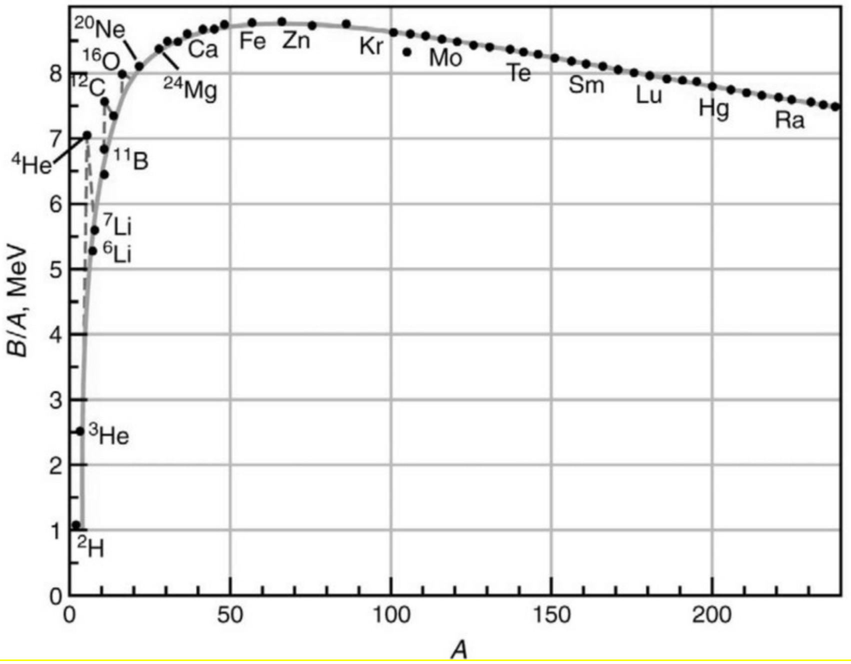
To convert this mass to the energy released, we must multiply by 931.494 MeV/c^2. This gives us 17.589MeV released per fusion reaction.

Doing the same with a deuterium-helium-3 reaction, we get 18.865MeV released per fusion reaction. This is greater than deuterium-tritium reactions, however, deuterium-tritium reactions are still more widely used due to the lower temperatures needed for fusion to occur(‘Explaining Helion’s Fusion Fuel’, n.d.).

Nuclear fusion that produces nuclei lighter than iron-56 will generally release energy. Atoms with a higher mass number than iron-56 typically have higher binding energy per nucleon, however, the energy required to fuse the nuclei will be even higher, resulting in energy lost if fusion occurs.

Figure 1

Binding Energy per Nucleon against Mass Number

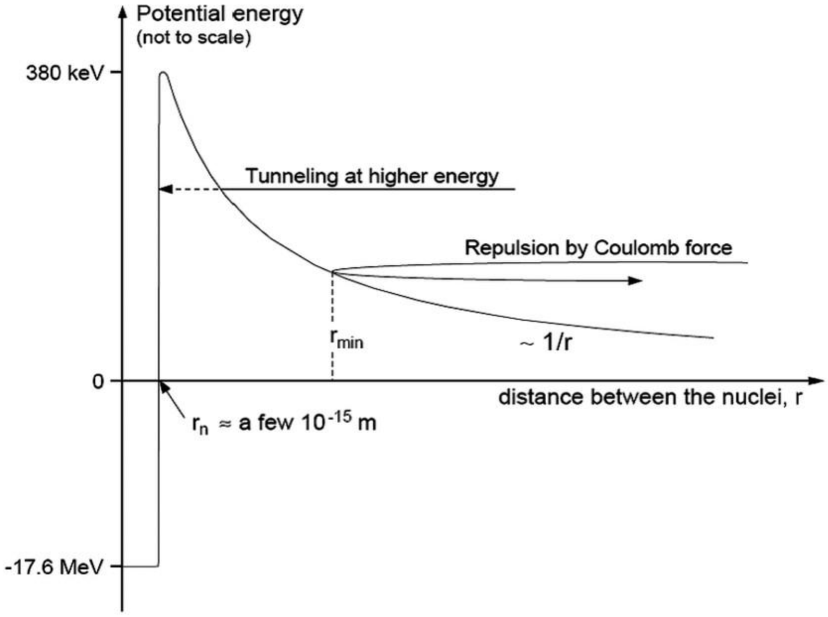


Note. This figure shows how at mass numbers before iron-56, fusion processes will typically produce energy, and at mass numbers after iron-56, fission will more produce energy. From Khairi, A.(2014) Fundamentals in Nuclear Physics.

Light nuclei have a lower atomic number. During nuclear fusion, this results in the Coulomb force being weaker as they have a low charge. However, the strong nuclear force has a range much shorter than the Coulomb force, as seen in figure 2 below. As such, the nuclei have to be very close to each other for the attraction due to the strong nuclear force to overcome the repulsion due to the Coulomb force. In order to provide these conditions, the nuclei must be accelerated to speeds high enough to bring the nuclei close enough to each other. This requires considerable energy, even for the lightest of elements. Once close enough, the strong force will grow and the nuclei will 'fall' into each other, resulting in fusion. One way this can be overcome is through quantum tunneling. Although this process cannot be forced to occur, it would allow the nucleus to bypass the Coulomb barrier, reducing the energy input required.

Figure 2

Potential energy against Distance Between Nuclei



Note. This figure shows the repulsion due to the coulomb force as distance between the two nuclei changes. The peak represents the coulomb barrier which a nucleus must overcome in order to undergo nuclear fusion. r_{min} represents the minimum distance the nuclei must reach for fusion to occur, or the maximum distance nuclei can be apart while still being able to undergo nuclear fusion. This is because at this point, the strong nuclear force takes over. From Ongena, J. (2015). Fusion: A true challenge for an enormous reward. *EPJ Web of Conferences*, *98*.

Overall, the energy released from most nuclear reactions is much greater than in chemical reactions. This is because nuclear binding energy is greater than the energy that holds electrons to a nucleus. Fusion reactions also have a higher energy density than nuclear fission because they produce far greater reactions and energy per unit mass, though individual fission reactions are typically more energetic than fusion reactions(Petrescu et al., 2017, p. 2).

Criteria for Success

The first aspect of nuclear fusion we must establish is our success criteria. One method is to use the fusion energy gain factor, Q. This compares output energy with the energy added to the fuel.

Another method is to use the Lawson criterion, which compares the rate of energy generated by the fusion reactions to the rate of energy losses to the environment.

The Lawson Criterion and its Derivation

In order to find the Lawson criterion, the first value we must find is the rate of fusion processes. This can be defined as the number densities of the fuel multiplied by the reactivity of the fuel.

$$W = \frac{n}{2} \cdot \frac{n}{2} \langle \sigma v \rangle \tag{4}$$

Where W is the rate of fusion processes, $\frac{n}{2}$ is the number densities of both deuterium and tritium, σ is the fusion cross-section and v is the relative velocity of the two nuclei. The angle brackets mean the average over the Maxwellian velocity distribution. We also assume that the densities of the deuterium and tritium ions are equal, and their total density is equal to the electron density. It can therefore be inferred that $n_D = n_T$ and that $n_D + n_T = n_e$. This gives us $n_D = n_T = \frac{1}{2} n_e = \frac{n}{2}$.

We can also use kinetic theory, giving us.

$$E_k = \frac{3k_b T}{2} \tag{5}$$

Where E_k is the kinetic energy of the particles, k_b is Boltzmann's constant and T is the temperature in Kelvin. Using these, we can find the energy produced as the product of the rate of fusion processes, the kinetic energy of the fusion products, and time.

$$E = \frac{n^2 \langle \sigma v \rangle}{4} \cdot E_F \cdot \tau \tag{6}$$

Where E is energy produced, E_F is kinetic energy of the fusion products and τ is the amount of time the fusion processes take place for. In order to obtain energy from fusion, the energy produced must be higher than the energy required to heat the plasma to the right temperatures$(E > E_k)$, therefore we get

$$\frac{n}{4} \langle \sigma v \rangle \tau E_F > 3k_b T \tag{7}$$

which can be rearranged to get

$$n\tau > \frac{12 k_b T}{\langle \sigma v \rangle E_F} \tag{8}$$

This is the equation for the Lawson criterion, which shows us that in order to achieve energy gain, either our number density or our confinement time must be high.(Schouten, 2024).

Table 1

Comparison of Lawson Criterion Values for Magnetic and Inertial Confinement Fusion

Key Parameters	Magnetic Confinement Fusion	Inertial Confinement Fusion
Particle density n/cm^{-3}	10^{14}	10^{26}
Confinement time τ/s	10	10^{-11}
Lawson criterion $n\tau/scm^{-3}$	10^{15}	10^{15}

Note. This table shows the particle density and confinement time of both magnetic and inertial confinement fusion. Magnetic confinement fusion has a much lower particle density than inertial confinement fusion, however, it makes up for this with its much longer confinement time. Ultimately, both have similar values for the Lawson Criterion. From Pfalzner, S. (2006). *An Introduction to Inertial Confinement Fusion*. CRC Press.

Fusion Energy Gain Factor

Another metric we can use to measure the success of a test is the Q value. This Q value is the ratio between the fusion power produced and the power input needed to maintain the plasma in a steady state. This means that a Q value of one is 'break even'. Usually, a Q value of five is needed for the reaction to self-heat. This is due to energy losses causing not all the energy produced to be reinvested into maintaining the plasma in a steady state(Yushmanov, 1980).

Inertial Confinement

As seen above in the equation for the Lawson criterion, the two main ways to make the energy gain greater than the energy lost to surroundings are to have high confinement time and having a high number density. Inertial confinement focuses on the latter of these, reaching very high number densities. There are four phases to inertial confinement, the interaction phase, the compression phase, the deceleration phase and the ignition phase.

Interaction Phase

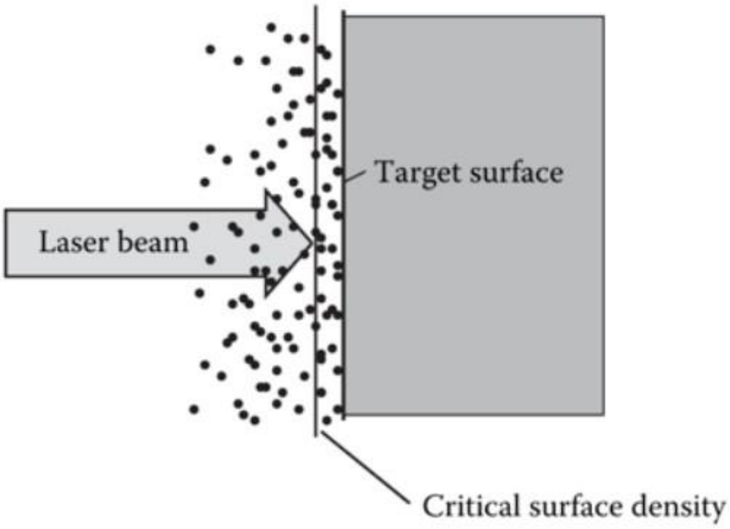
The interaction phase is the first phase of inertial confinement. It is the phase in which the energy is delivered onto the capsule containing the fuel(usually Deuterium-Tritium mix). The energy is delivered through a driver, which can be either laser light or particle beams. What driver is used is irrelevant when only looking at the energy input, however, the initial interaction process differs significantly between the two options. This difference is due to the properties of the drivers; where laser light will only interact with the surface of the matter, beams will penetrate a certain distance. In both cases, the goal is to transfer as much energy as possible into the material.

Assuming the driver is a laser, plasma will be created as soon as the laser beam encounters the outer surface of the capsule. The plasma then expands outwards from this surface, with a higher density closer to the capsule surface. At some point, the plasma will reach a certain critical density and hinder the laser beam from penetrating any further. The surface of the critical density region will not be at the capsule surface, instead, being located some distance away. This prevents the energy of the laser from being deposited directly onto the surface of the capsule.

The location of this critical density surface depends heavily on the wavelength, intensity and pulse length of the laser beam. These parameters also change the amount of ablation and the efficiency of the subsequent compression phase. Therefore, when discussing the efficiency of the overall process, the values of these parameters are essential(Pfalzner, 2006, pp. 17–19).

Figure 4

Diagram of a laser driver interacting with a target surface



Note. Shows how a laser interacts with the target surface and how the critical surface density can affect and interfere with the energy transmitted by the laser. From Pfalzner, S. (2006). *An Introduction to Inertial Confinement Fusion*. CRC Press.

Compression Phase

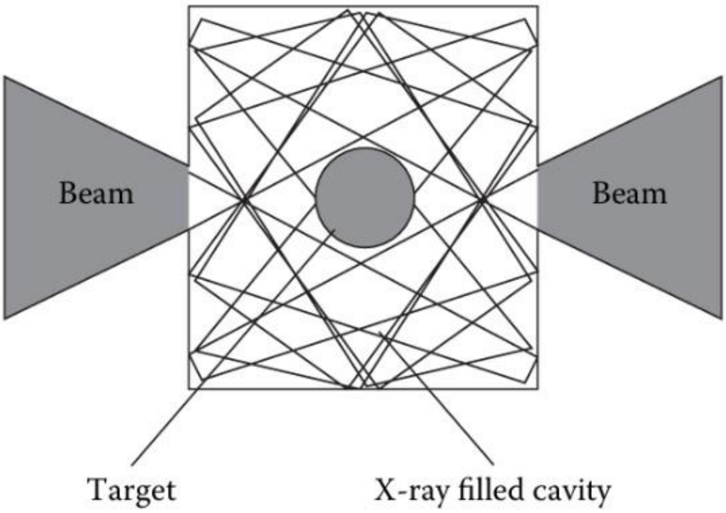
The compression phase is the second phase in inertial confinement fusion. The success of the compression is, to a large extent, dependent on the interaction phase. However, there can still be instabilities in this phase. These illumination nonuniformities occur on two scales: microscopic and macroscopic. Microscopic nonuniformities can be caused by spatial fluctuations within a single beam, causing hotspots or regions of greater intensity to form. Macroscopic nonuniformities can be formed by a power imbalance between the individual beams.

There are two ways to overcome these macroscopic nonuniformities; we can take a sufficient number of beams. This is done in direct-drive ICF. However, this can be very expensive and challenging to accomplish. Instead, many smaller scale direct-drive experiments are performed and we try to infer how a system with more beamlines would perform from these experiments.

Alternatively, an indirect-drive approach can be utilised. In this approach, the energy of the laser is first absorbed by an enclosure around the capsule made of a high-Z material(hohlraum). The energy from the laser is then emitted from the hohlraum as x-rays. These x-rays are what drive the implosion of the capsule. This can be seen in the figure below, where the box surrounding the target is the hohlraum. The x-rays are being absorbed and reemitted by the walls of the hohlraum until they hit the target, heating it(Pfalzner, 2006, pp. 19–22).

Figure 5

Diagram of a hohlraum



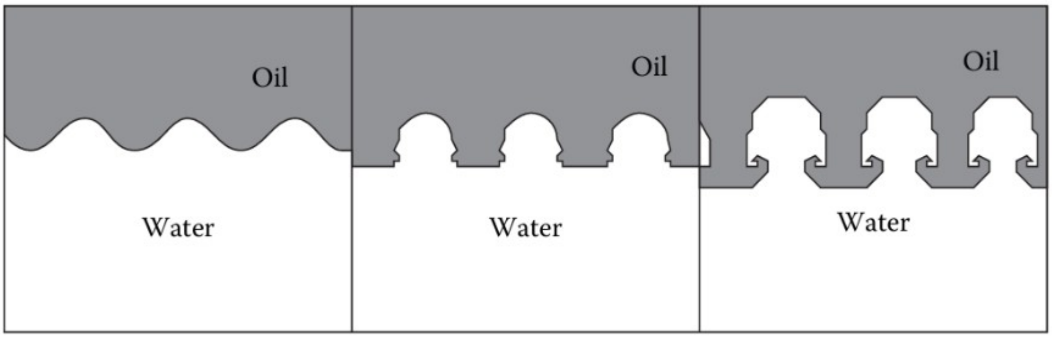
Note. Shows how the energy from the driver is mostly reflected by the walls of the hohlraum until it hits the pellet. From Pfalzner, S. (2006). *An Introduction to Inertial Confinement Fusion*. CRC Press.

Instabilities cannot be avoided, no matter the method used. An example of one of these instabilities is the Rayleigh-Taylor class of instabilities. These occur at the boundary between two fluids of different densities, when the denser fluid pushes into the less dense one. An example of this would be when water pushes into oil. If perturbed, a mixing between the two fluids can occur. In the context of ICF, these two fluids are hot and cold plasma. When the mixing of these two plasmas occurs, the hotter plasma is cooled. This is bad for the compression, therefore targets are designed such that these Rayleigh-Taylor instabilities are minimised as much as possible. This is done through the shape of the capsule. The ratio of the shell radius to the shell thickness is a major factor in reducing Rayleigh-Taylor instabilities. This property of the capsule is called the in-flight aspect ratio and has to be in the order of 25-40 at all moments during the implosion.

The acceleration can also be varied to optimise efficiency. This is done by changing the acceleration such that the creation of 'hot electrons' or energetic electrons can be avoided as much as possible. This is because these hot electrons can preheat the fuel and create their own shock fronts, thereby making it harder to compress. Avoiding preheat is especially necessary if the driver is a laser. However, one cannot completely prevent shock waves from forming if they want to build up pressure in a reasonable time. Therefore a low-power prepulse followed by a succession of increasingly intense pulses can accelerate the fuel nearly isentropically (entropy of system remains 0)(Pfalzner, 2006, pp. 21–22).

Figure 6

Rayleigh-Taylor instabilities



Note. This diagram shows the formation of Rayleigh-Taylor instabilities over time, using oil and water as the fluids of different densities. From Pfalzner, S. (2006). *An Introduction to Inertial Confinement Fusion*. CRC Press.

Deceleration

When the inner part of the fuel reaches the center of the capsule, it starts to decelerate. This happens through the kinetic energy of the inner part of the fuel being converted into internal energy. This results in both temperature and density increasing in the center while the rest of the fuel remains relatively undisturbed.

In the hot-spot concept, high fuel densities and temperatures are needed. To reach these densities and temperatures at the hot-spot areas, a succession of increasingly intense pulses is needed. This allows the nearly isentropic compression to take place. The last of the succession of shocks has to act at the same time as the first of the shocks for a successful deceleration phase. Therefore, the timing of the shocks is integral for the success of the phase.(Pfalzner, 2006, p. 22)

Ignition and Burn Phase

Finally, when temperature and density conditions in the hot-spot area are right, ignition occurs. The α particles produced deposit energy primarily in the center area, heating it up. Other products such as the radiation and fusion neutrons then transport the energy from the hotspot region to the outer areas of the fuel. This allows more fusion reactions to take place and thus the burn propagates outward.

Throughout this process, a very high pressure builds up until it eventually blows apart the remaining fuel and α particles, signalling the end of the ICF cycle(Pfalzner, 2006, pp. 22–23).

There are alternate methods for compression and ignition, including shock ignition and fast ignition. In fast ignition, traditional inertial confinement fusion techniques are used to compress the fuel. Then a high current ion beam is directed to a hot-spot within the fuel to heat the hotspot to ignition temperatures. This burn propogates outwards in the fuel, leading to potentially high gain and high burnup(how much of the fuel burns) percentages(Albright et al., 2022).

Shock ignition also uses traditional inertial confinement techniques initially to compress the fuel, only at lower implosion velocities. Close to the point of maximum compression, an intense laser spike is fired, generating a strong converging shock wave. This converging shock wave collides with the rebound shock wave from the initial compression. This collision increases the shock pressure, thus leading to further compression and heating. If this point reaches sufficient temperature and density, it will ignite. The lower implosion velocities can help reduce hydrodynamic instabilities such as Rayleigh-Taylor instabilities(Temporal et al., 2024).

Overall Gain

In the fusion process, energy is only gained if the energy given off by the fusion processes exceeds the input energy. However, this input energy is not just used to heat the fuel. There are several inefficiencies that must be taken into account. These include but are not limited to: the losses in the driver itself, losses in the hohlraum(if used) and energy lost in the compression dynamics due to the Rayleigh-Taylor instabilities. If these inefficiencies can be overcome, providing a net energy gain from these fusion reactions will prove much easier to achieve.(Pfalzner, 2006, p. 23)

Magnetic Confinement

As mentioned before, the two main ways to make energy gain greater than energy lost to surroundings are to have a high number density or high confinement time. Magnetic confinement typically focuses on high confinement time with much lower number densities compared to inertial confinement.

The idea of magnetic confinement is to confine the plasma using magnetic fields. This can be done due to the plasma being partially ionised. Confining the plasma using magnetic fields allows the plasma to reach high temperatures without touching and thus damaging the walls of the confinement chamber.

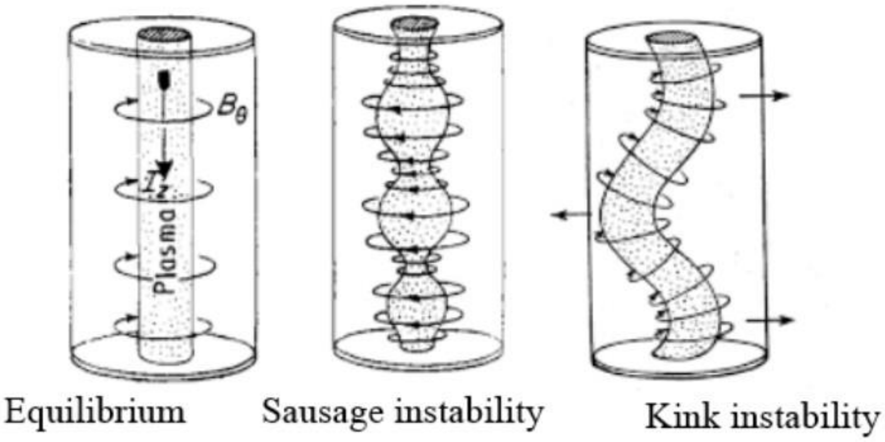
Z-Pinch

One the simplest ways to magnetically confine a plasma is using the Z-Pinch method. This is done by passing a very large current through the plasma. This high current creates ring-like magnetic fields, which exert an inwards force, compressing the plasma. In fusion applications, the current heats the plasma up to the temperatures needed and the inwards force compresses the plasma, raising its density. The downside of this is that it will only last for very short periods of time.

There are also instabilities in this method. The main issues are from non-uniformities in the initial plasma cylinder. If the cylinder is narrower at any points, these points will compress. As the toroidal magnetic field responsible for the pinch is inversely proportional to radius, any narrower section will experience greater inward pinching force. This leads to runaway compression, eventually cutting off the current and breaking the plasma cylinder. This instability is called a sausage type instability. Another instability results from slight bends in the initial shape of the plasma. As seen in figure 6, force acts from the inside to the outside of the bend, making the bend larger. This instability keeps growing until it ruins the plasma cylinder(Shumlak, 2020, pp. 2–3)

Figure 7

Sausage and Kink instabilities



Note. Shows how the uniformly confined plasma can form instabilities due to small instabilities magnifying. From Sadouni, S. (2020) *Fluid modeling of transport and instabilities in magnetized low-temperature plasma sources.*

Magnetic Mirror

Another method is the magnetic mirror. A cylindrical magnetic field is created by a pair of magnetic coils. This magnetic field bulges slightly in the middle. The particles moving perfectly parallel to the field lines will feel no force and thus be able to escape. Particles moving perpendicular to the field lines will orbit the field lines and not escape. Orientations in between will either be able to escape or be trapped by the field depending on how closely its motion is aligned with the magnetic field. When a trapped ion tries to escape the confinement, their direction of motion will reverse when it gets too close to the magnetic coils, causing it to reflect back to the center.

An issue with this method is that collisions between trapped ions and electrons will knock an increasing number of them into the right orientation to escape the magnetic mirror. The end effects can be mitigated by making the mirror longer so that a lower proportion of the plasma escapes. However, the main flaw with this method is that it is not magnetohydrodynamically stable. This means that in the middle parts of the field, where the field is weaker, the plasma can 'balloon' out, dragging the magnetic field lines with it. This causes the confinement time to be low(Post, 1987).

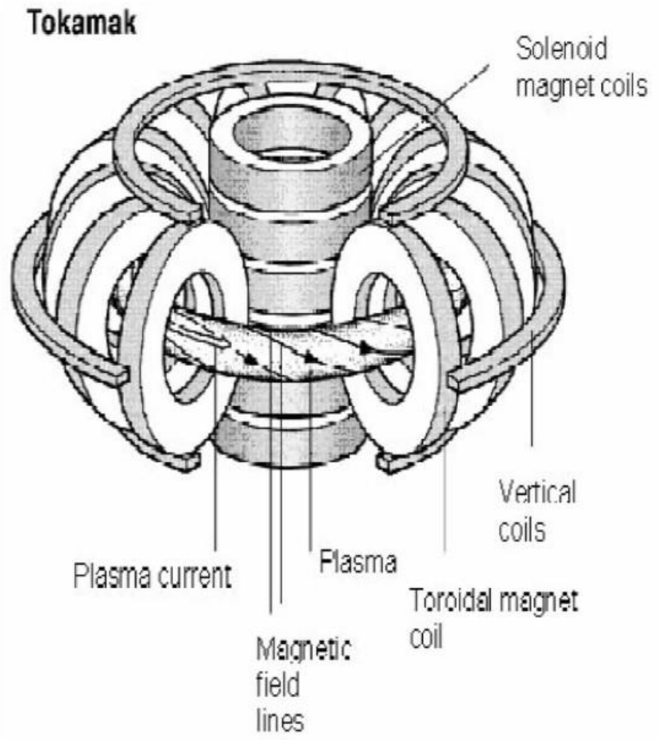
Tokamak and Stellarator

Finally, there are the tokamak and stellarator. In a tokamak, the plasma is confined in a torus, however, there is a current passed through the middle. This current acts similar to the current in the Z-pinch method, creating magnetic fields in circles around the torus. There are also coils around the torus, creating a magnetic field that gives the toroidal shape. Overall, the combination of these two magnetic fields twists the magnetic field so that the magnetic field lines go from outside the torus to inside the torus and back, causing the field to be more uniform in strength(Artsimovich, 1972, p. 1).

In a stellarator, the coils themselves are twisted in such a way that the magnetic field lines go from the outside of the torus to the inside and back, making the field strength more uniform.

Figure 8

Diagram of a Tokamak



Note. Shows the magnetic field lines from the toroidal and poloidal(vertical) magnet coils and thus how the plasma is confined within the tokamak. From Kwon, M.-E., Bae, Y.-S., Cho, S.-Y., Choe, W.-H., Hong, B.-G., Hwang, Y.-S., Kim, J.-Y., Kim, K.-M., Kim, Y.-S., Kwak, J.-G., Lee, H.-G., Lee, S.-G., Na, Y.-S., Oh, B.-H., Oh, Y.-K., Park, J.-Y., Yang, H.-L., & Yu, I.-K. (2009). CURRENT STATUS OF NUCLEAR FUSION ENERGY RESEARCH IN KOREA. *Nuclear Engineering and Technology*, *41*(4).

Heating Plasma in the Tokamak

Even after the creation and confinement of the plasma, it must be heated to sufficient temperatures. Heating the plasma is done mainly by adding energy via electromagnetic waves or particle beams.

Particles orbit around magnetic field lines at certain frequencies, depending on their mass and the magnetic field strength. This oscillation allows them to absorb electromagnetic radiation with a matching frequency. The issue with this method is that the electromagnetic waves can be reflected or refracted by the plasma.

Instead, beams of particles can be used to deposit energy into the plasma. These particles can also be deuterium particles, giving the plasma more fuel to fuse. In order to not be affected by the magnetic fields around the plasma, the particles must be neutral, hence the name 'neutral beam injection'. The overall process requires an electron to be given or stripped off a deuterium atom(this gives it a charge and allows us to accelerate it). Then the deuterium ion is accelerated. Before it enters the plasma, the deuterium ion must be neutralised(Kunkel, 1981, pp. 10–11).

Often high performance plasmas need additional heating. Neutral beam injection is a standard heating scheme at many major Tokamaks. However, the fusion of the deuterium and tritium into helium should eventually become the primary heating mechanism(Artsimovich, 1972, pp. 1–2).

Issues with the Tokamak

There are a few economic issues with magnetic confinement. A major issue is damage to the containment vessel. During operation, when the input power is high enough the plasma transitions from low-confinement mode(L-mode) to high-confinement mode(H-mode). This H-mode is characterised by a much higher rise in plasma density near the edges and a higher peak density overall. This increase to density and confinement time, and thus performance is seen as essential for any future reactor. The main drawback, however, is that there are frequent expulsions of plasma while the plasma is in H-mode, called an edge localised mode(ELM). These ELMs can cause damage to plasma-facing components(Connor et al., 2008, p. 1).

Gravitational and Electrostatic Confinement

Gravitational Confinement

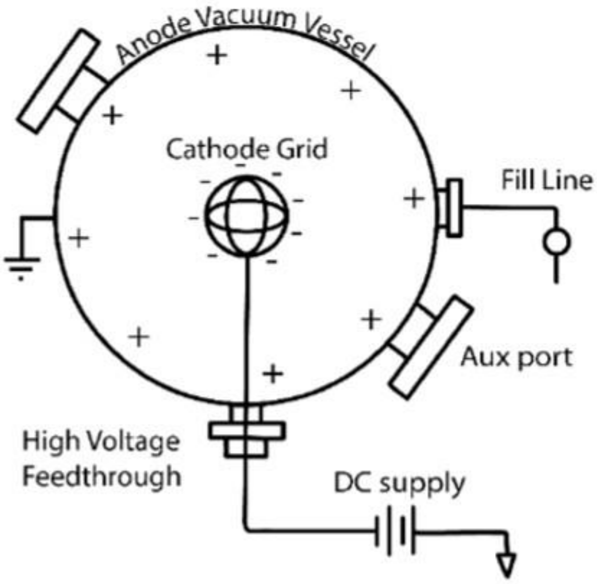
Gravitational confinement is the type of plasma confinement that occurs in stars. Stars use their massive size and mass to their advantage, using the strength of their gravitational field to force nuclei together, causing fusion reactions. Initially, stars ignite using the extreme gravitational force to compress the matter and start fusing. Similar to the gas laws, as the volume decreases, the pressure increases massively, thus starting the fusion processes. The nuclei in the stars fusing provides energy for more fusion reaction to happen, sustaining the stars. These fusion reactions also produce a pressure within the star. This pressure is what stops the star from simply collapsing in on itself. As long as there are fusion reactions happening within the star, the pressure will counteract the force from the gravitational field of the star, creating an equilibrium of sorts. This can be seen in main sequence stars.

Electrostatic Confinement

Electrostatic or inertial electrostatic confinement is another method of confinement. It relies on an anode and a cathode to separate the nuclei from the electrons in an atom. The nuclei are attracted to the cathode, however, the electrons are repulsed, stripping the nuclei of their electrons. Therefore, only the protons and neutrons are within the cathode. Within the cathode, the nuclei accelerate and collide. This can cause fusion reactions to occur, releasing energy. An example of a device that uses this principle to operate is a fusor. Fusors use a high voltage to ionise their fuel(usually deuterium gas) and then fuse. The energy given off by the fusion in a fusor can often be seen as a blue or purple glow due to the charged particles as they are accelerated(Ligon, 2007, pp. 5–6).

Figure 9

Diagram of a Fusor



Note. Shows the cathode grid and the anode vessel that are used to create and confine the plasma within the fusor. From Wolf, A. J. (2015). *Measurement of ion velocities in the TU/e Fusor plasma using LIF spectroscopy.*

The Current Landscape

Historically, much research into nuclear fusion has been conducted in government-funded facilities. However, there has been a recent surge in private companies and startups researching their own methods and approaches to nuclear fusion. These private companies have been receiving substantial investment and funding, including from giants like Google(Terrell, 2025) and Microsoft(Nellis, 2025).

One of the major players in the private sector of nuclear fusion is Commonwealth Fusion Systems. Their approach utilises high-temperature superconducting magnets to enable smaller designs, making them more cost-effective. They are currently building their first commercial reactor, SPARC, in Devens, Massachusetts and plan to produce first plasma in 2026, with net fusion energy production shortly after. Upon this milestone, Google has a deal with Commonwealth Fusion Systems for 200 megwatts of power out of the planned 400 megawatt capacity of the reactor(Gardner, 2025). This deal shows a major vote of confidence from Google, and by extension, the tech industry in the future of commercial nuclear fusion energy.

One of the contenders of Commonwealth Fusion Systems is Helion Energy, which utilises a field-reversed configuration instead of a tokamak. This is a simpler design with a linear instead of toroidal shape. This makes them potentially easier to build and maintain. On the other hand, they are more prone to the instabilities mentioned earlier due to their straight shape. One of the newer machines Helion Energy has built is Polaris, their seventh generation of machines using field-reversed configuration. Another difference is that Helion Energy uses a Deuterium-

Helium-3 fuel cycle instead of the more common Deuterium-Tritium fuel cycle. Even though it requires higher temperatures, this alternative fuel cycle outputs more charged particles(mostly protons), allowing the energy to be captured through magnetic fields instead of steam and turbines(‘Explaining Helion’s Fusion Fuel’, n.d.).

Tokamak Energy, a UK based company uses spherical tokamaks which are more compact. Their ST40 design has reached over 100 million Kelvin, a major milestone for any potential fusion machine design(McNamara et al., 2023, pp. 1–2). The main difference between the spherical tokamak and a more conventional design is the shape. Spherical tokamaks are typically more compact with a shape more resembling an apple. This design can result in better plasma stability, thus giving enhanced confinement.

There do remain some key engineering challenges with magnetic confinement. First is how to make the ‘first wall’ of a reactor, which must withstand extreme temperature changes and neutron bombardment without becoming brittle, radioactive or melting. Finding or synthesising a material which meets all these properties is exceedingly difficult. Some materials being considered are tungsten, lithium and graphite, however, each have their issues.For example, Tungsten, while very resistant to heat, could oxidise and release radioactive fumes in the event of a simultaneous air ingress and loss of coolant(Rieth et al., 2013, p. 18).

The fuel also presents a challenge to be overcome. For Deuterium-Tritium reactors, tritium is needed. Unfortunately, tritium is a scarce and radioactive resource. A viable power plant would need to breed its own tritum by having the neutrons from the fusion reactions interact with a surrounding layer of lithium. This presents an engineering challenge that, as of writing this review, remains unsolved at a commercial scale.

Regarding inertial confinement and its future prospects, scientific ignition is only the first step. The next challenge to overcome is repetition. Currently, the National Ignition Facility uses flash-lamp-pumped lasers which can only fire infrequently due to thermal management issues(Garrec & Dumitras, 2010, p. 1). In order to generate energy comparable to power stations, the plant would need to fire and ignite targets multiple times a second. One possible solution to the laser issue could be to use diode-pumped laser systems, reducing energy converted into thermal energy, thus increasing the ‘wall-plug’ efficiency(Garrec & Dumitras, 2010, pp. 3–5).

Discussion

Regardless of method, it is clear that fusion energy is a strong contender in the race for a clean energy source. Its potential for near limitless clean energy has drawn investment from both governments and private players. However, which method will provide better results is less certain, with both inertial and magnetic confinement fusion proving themselves great potential energy sources.

The main difference between magnetic and inertial confinement are the principles behind them. Inertial confinement uses high powered lasers or particle beams to compress a fuel capsule, providing the conditions for nuclear fusion to happen. This leads to very low confinement times but very high number densities, allowing energy to be produced. In magnetic confinement systems, plasma is created within the reactor using induction, neutral beam injection or other methods, then confined using magnetic fields. This leads to longer confinement times but much lower number densities. Both of these methods satisfy the Lawson criterion, however, as of writing this, magnetic confinement is generally viewed as the more advanced promising method of the two(Lundy, 2024).

There are multiple lines of evidence that support this general sentiment. The first of these reasons is due to the level of collaboration seen with countries researching magnetic confinement. There are multiple international projects working on magnetic confinement, ranging from JET(now decommissioned) to ITER. There are also multibillion dollar inertial confinement fusion projects like the National Ignition Facility in the USA and France's Laser Mégajoule, however, even combined, it does not reach the same scale of collaboration and investment of ITER. While the author does acknowledge that ITER can be considered unique in its scale, it nonetheless shows the level of interest the international community has taken in magnetic confinement fusion. Despite this lesser scale, there are still some notable inertial confinement fusion partnerships and successes. Foremost is the fact that the National Ignition Facility has achieved ignition, which is a key part of the argument for further developing Inertial Fusion Energy. There also exists a public-private partnership called IFE-STAR in the United States, which brings together key players like Lawrence Livermore National Laboratory, General Atomics, and the University of California, San Diego. This reflects a collaborative effort to develop a commercial fusion pilot plant roadmap.Overall, the abundance of joint projects, especially in Europe, shows not just funding but vested interests in making this form of confinement work. This investment can be clearly seen in the continued funding of ITER despite the multiple setbacks(Matthews, 2024). However, as confinement in nuclear fusion projects is still relatively young, there is still an untapped well of potential advancements for both magnetic and inertial confinement. While magnetic confinement may be more likely to find these key technologies and advancements due to its greater funding, there still remains the possibility that inertial confinement fusion can take the spotlight and become the dominant idea within both scientific communities and the general public.

Possibly as a result of this difference in collaboration and funding, there is a difference in efficiency between current magnetic and inertial confinement methods. JET, a now decommissioned laboratory, was able to achieve a Q value of 0.67 (see Table 2), producing 16 megawatts from 24 megawatts of input power over 5 seconds. Further, ITER is predicted to reach a Q value of 10('History of Fusion', n.d.),meaning the plasma will produce 10 times more energy than the heating power added. In comparison, the National Ignition Facility in the USA used 2.05 megajoules of input energy to produce 3.15 megajoules of output energy, giving a Q value of around 1.54(Bishop, 2022). Both of these values refer to the scientific gain factor which does not include losses in either magnets or driver. At the system level during the tests at the National Ignition Facility, around 400 megajoules of energy was supplied to the lasers, giving an overall(or wall-plug) efficiency of just 0.5%(Cartlidge, 2023). This experiment shows that while inertial confinement fusion is a promising idea that has shown its value, the technological advances needed to take advantage of inertial confinement fusion have not been made. Overall, this means that, in the short term, magnetic confinement fusion will most likely prove to be the dominant method of confinement, however, as both methods progress, inertial confinement may prove to be more efficient, bypassing some roadblocks that magnetic confinement experiences.

Table 2

Energy Gain from Major Fusion Tests

Fusion Projects	Input Energy	Output Energy	Q Value(scientific)
JET	120MJ	80MJ	0.67
NIF	2.05MJ	3.15MJ	1.54

Beyond the efficiency and energy gain, the differences in operation methods also present a consideration for their future commercial viability. Where magnetic confinement fusion uses a continuous operation method, inertial confinement fusion uses a pulsed operation method. Many of our current methods of producing energy are continuous methods, and this is for good reason. A pulsed power supply needs additional energy storage systems to provide smoother power delivery. These additional systems add even more complexity to our power grids and will cost more money. Furthermore, the difference in efficiency will only be exacerbated by the repeated startup of inertial confinement plants. Where an inertial confinement plant will have to start up and cooldown every cycle, incurring efficiency losses in both of these phases, a magnetic confinement based fusion plant will only have to start up and cool down during maintenance.(*Electricity Security Matters More than Ever – Power Systems in Transition – Analysis*, n.d.) Overall, the commercial viability of magnetic confinement fusion is much greater than inertial confinement fusion as the current electrical infrastructure is more suited towards continuous methods of power generation, allowing magnetic confinement fusion plants to directly replace coal, gas or nuclear based power plants with minimal changes to the current power grid. This commercial viability of magnetic fusion has seen it get more funding and interest, leading to more developed laboratories and research centers.

Despite these points, the author would like to note that technological advancements in inertial confinement fusion is still possible. Key among these advancements are diode-pumped laser systems which can run multiple times per second and with greater efficiency. However, the drivers are only one half of the puzzle. The target itself also presents challenges. In order for a commercial inertial confinement fusion power plant to work, it would need a massive amount of fuel, all shaped into precise pellets that cannot afford even miniscule imperfections. While not impossible to overcome, this would require more time and investment to work. Even though magnetic confinement fusion does have its own issues, money and time have already been invested into overcoming them. As such, headway has been made into solving magnetic confinement's issues.

Conclusion

This paper reviews the literature on magnetic, inertial, electrostatic and gravitational confinement of plasma, mainly focusing on inertial and magnetic confinement.

In conclusion, in the short term, magnetic confinement will prove to be the dominant method of confinement for potential fusion power plants. This is due to both magnetic confinement fusion's compatibility with our current electrical infrastructure and the more advanced technologies and methodologies used. This allows magnetic confinement fusion plants to directly replace current fossil fuel and nuclear power plants with minimal changes to the power grid.

However, it is difficult to predict whether magnetic confinement fusion, inertial confinement fusion or another method will prove to be the most efficient and effective source of energy as the field of nuclear fusion itself is new relative to many other fields, with many problems needing to be solved for both methods. A large breakthrough in either magnetic or inertial confinement could propel its respective method much further, allowing it to become the dominant method.

Regarding more recent progress, there have been several breakthroughs in recent years where several laboratories and tokamak testing sites have managed to produce more energy than was inputted. Furthermore, there are already plans to build the first fusion reactor connected to the US energy grid. This plant is expected to come online in the 2030s and produce four hundred megawatts of electricity(Dunning & Gallagher, 2022). ITER is still under construction in France while JET has been shut down and is now in the process of decommissioning. JET's final experiment was conducted outside of standard operational parameters and managed to set a record, producing 69 megajoules of energy over five seconds using 0.2 milligrams of fuel(Honney, 2024). Wendelstein 7-X, having generated a record plasma lasting eight minutes with an energy output of 1.3 gigajoules, has started the new experiment phase OP2.2 after being significantly optimised(Fleschner, 2024).

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