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

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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.

Keywords: nuclear fusion, inertial confinement fusion (ICF), magnetic confinement fusion (MCF), plasma confinement, Lawson criterion, fusion energy gain factor, magnetohydrodynamic (MHD) instability

1. 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 of attaining fusion energy. One of the most notable collaborations was the Joint European Torus (JET). 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, and 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 59 MJ 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.

2. 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):

$$4.002603\,u\ +\ 1.008665\,u\ =\ 5.011268\,u \tag{2}$$

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.

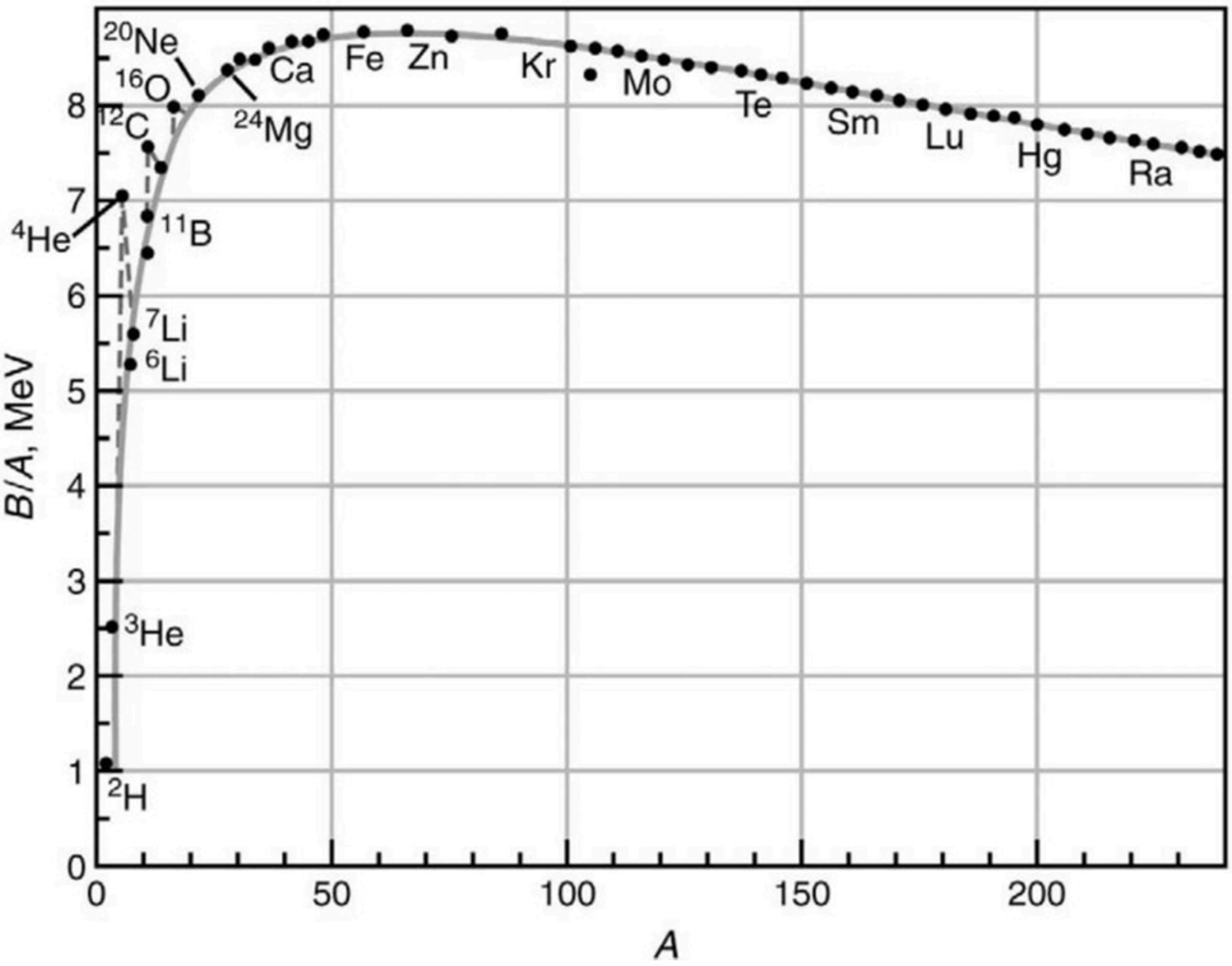


Figure 1: Binding energy per nucleon against mass number.

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. Adapted from *Fundamentals in Nuclear Physics* by A. Khairi, 2014.

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.

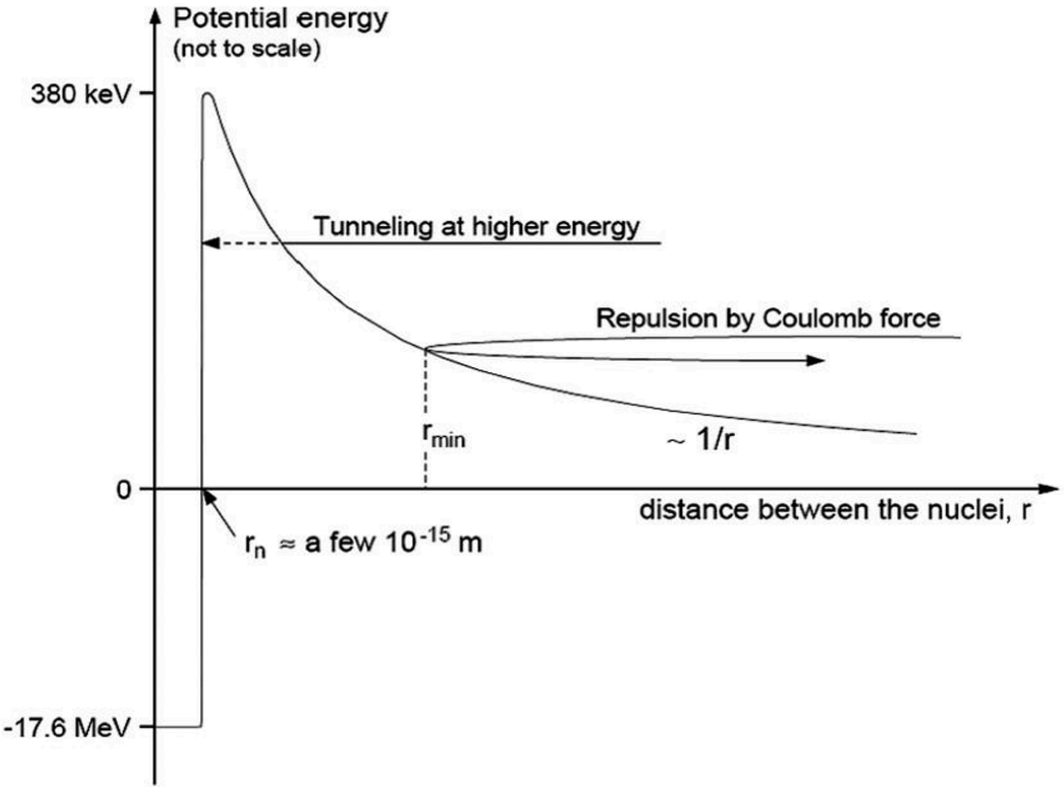


Figure 2: Potential energy against Distance Between Nuclei.

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. rmin 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. Adapted from *Fusion: A true challenge for an enormous reward* by J. Ongena, 2015.

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).

3. 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.

$$W = \frac{n}{2} \cdot \frac{n}{2} < \sigma v > \tag{4}$$

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 to give 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:

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

where E is the energy produced, E_k 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

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

which can be rearranged to give us

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

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^{1}	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 *An Introduction to Inertial Confinement Fusion* by S. Pfalzner, 2006.

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).

4. 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).

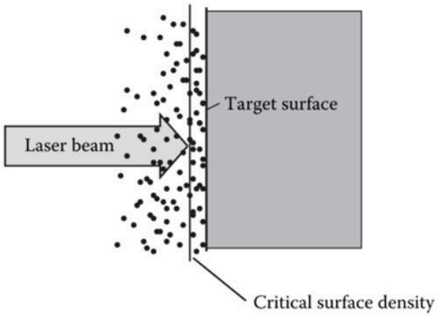


Figure 4: Diagram of a laser driver interacting with a target surface.

Note: This figure 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 *An Introduction to Inertial Confinement Fusion* by S. Pfalzner, 2006.

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).

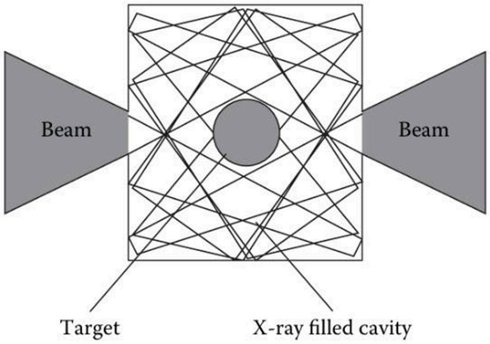


Figure 5: Diagram of a hohlraum.

Note: This figure shows how the energy from the driver is mostly reflected by the walls of the hohlraum until it hits the pellet. From *An Introduction to Inertial Confinement Fusion* by S. Pfalzner, 2006.

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 optimize 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 (i.e., the entropy of the system remains 0) (Pfalzner, 2006, pp. 21–22).

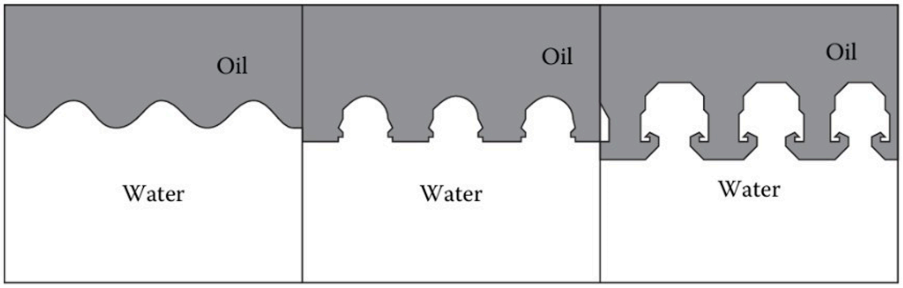


Figure 6: Rayleigh-Taylor instabilities.

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

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 propagates 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).

5. Inertial Confinement

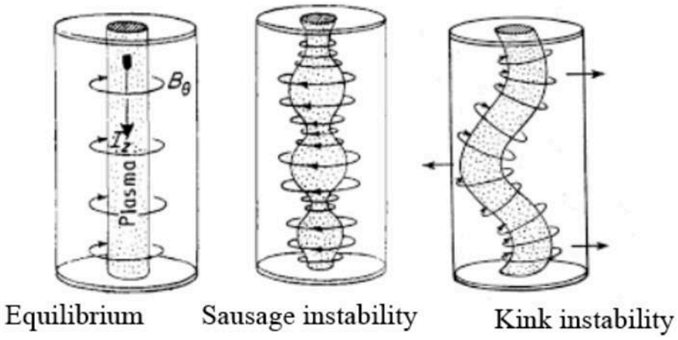
As mentioned before, the two main ways to make energy gain greater than energy lost to surroundings are to have a high number density or high confinement time. Magnetic confinement typically focuses on high confinement time with much lower number densities compared to inertial confinement.

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).



Equilibrium Sausage instability Kink instability

Figure 7: Sausage and kink instabilities.

Note: This diagram shows how the uniformly confined plasma can form instabilities due to small instabilities magnifying. From "Fluid modeling of transport and instabilities in magnetized low-temperature plasma sources" by S. Sadouni, 2020.

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.

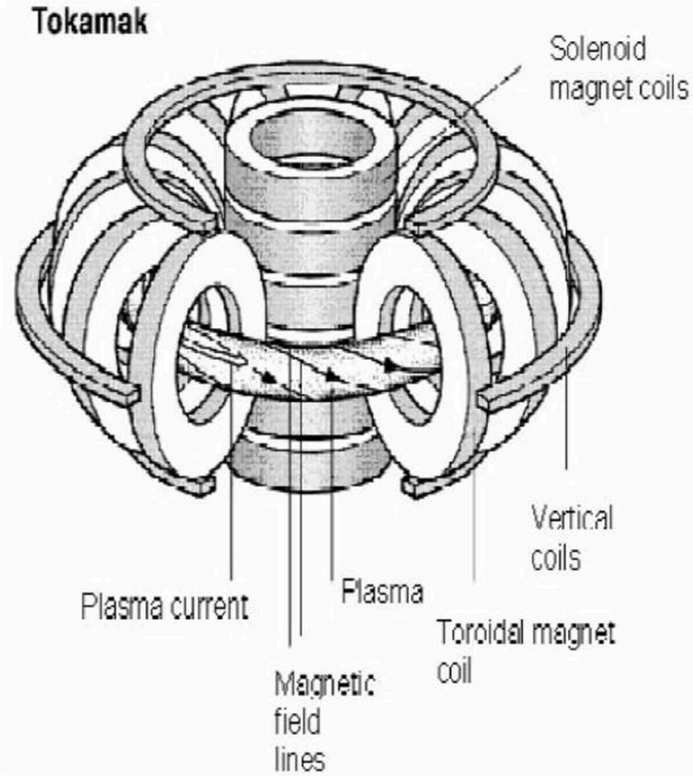


Figure 8: Diagram of a tokamak.

Note: This diagram shows the magnetic field lines from the toroidal and poloidal (vertical) magnet coils, and thereby how the plasma is confined within the tokamak. From "Current status of nuclear fusion energy research in Korea" by Kwon et al., 2009.

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 hence 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).

6. 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 equations of state for gases, as the volume decreases, the pressure increases massively, thus starting the fusion processes. The nuclei in the stars fusing provide energy for more fusion reactions 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).

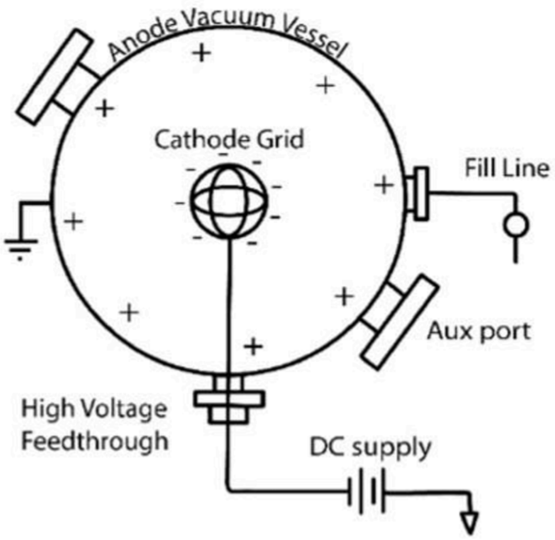


Figure 9: Diagram of a fusor.

Note: This diagram shows the cathode grid and the anode vessel that are used to create and confine the plasma within the fusor. From "Measurement of ion velocities in the TU/e Fusor plasma using LIF spectroscopy" by A. J. Wolf, 2015.

7. 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 megawatts 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 tritium 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 flashlamp-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, thereby reducing energy converted into thermal energy and increasing the “wall-plug” efficiency (Garrec & Dumitras, 2010, pp. 3–5).

8. 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 drivers. 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 Project	Input Energy	Output Energy	Q value (scientific)
JET	120 MJ	80 MJ	0.67
NIF	2.05 MJ	3.15 MJ	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.

9. 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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