Magnetic Confinement Configurations and Heating Methods of Plasma in the Field of Fusion Energy

Kabir Punjwani

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As the world searches for renewable and alternate energy sources, the importance of fusion energy is ever-increasing. Non-renewable energy sources such as fossil fuels are not only depleting but also harming the environment. Fusion energy has, therefore, become one of the most prospective fields to generate and produce clean and abundant energy in the future. Nevertheless, the world has and will face several setbacks in making fusion energy one of the prominent energy sources of the world. With fusion being carried out in a plasma state, difficulties arise in controlling and maintaining such a reaction. The research paper aims to investigate and evaluate the different confinement and heating methods of plasma in the field of fusion energy. By providing case studies, the paper will discuss the strengths and drawbacks of each method providing the readers with an overview of the current and future state of fusion energy.

Introduction

The discovery of a truly clean and abundant energy source would change the world as we know it. Such a source is a globally sought-after goal across countries and industries. Many countries have already begun expanding their usage of currently available renewable sources such as solar, hydroelectric, and wind, which is a necessary first step, but won't take us all the way. These sources suffer from drawbacks in irregularity, dependence on weather and environmental conditions, and accessibility. The World Energy Outlook 2016 put forward some points detailing these disadvantages. It said that the maximum output produced changes according to the real-time availability of wind and sunlight. Such fluctuations can be predicted only up to a few hours or days in advance. Further, renewable sources like solar and wind cannot be transported, thereby increasing connection costs from solar or wind farms to the load[1]. That goal of "clean and abundant energy" is far from being achieved. But that may not be the case for long.

There's another potential clean energy source currently under research in countries across the globe, one that many think will form the future of energy generation: Fusion energy. Fusion energy is the enormous amount of energy released when two light nuclei fuse or combine to form a new heavier one. Fusion produces no greenhouse gases, no long-lived radioactive waste, and has no dependence on environmental conditions. Its main fuel (deuterium) can be found abundantly in seawater or produced within the reactor itself, and for the volume of fuel it consumes, it produces orders of magnitude more power than current sources like oil and coal. These fundamental features of fusion could allow it to provide carbon-free energy at a scale needed to address climate change. Such factors have made it clean due to which the study of fusion energy science and the field of plasma physics which it lies within are of incredible importance to today's world.

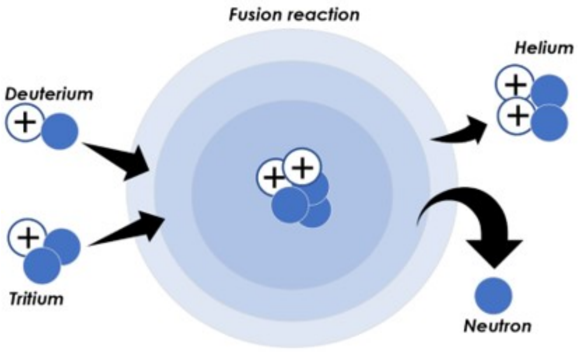

Fig. 1 Nuclear Fusion Reaction involving Deuterium and Tritium – a Major Source of Fuel for Future Nuclear Power Plants[2].

With all these potential benefits, one might ask, why has a fusion energy reactor not become a reality? Given the advanced technology available today, what is stopping fusion energy from achieving the goal of clean and abundant energy? In fact, fusion plants may be feeding power into the grid by around 2050 and then could become steadily more important to the energy economy in the second half of the century, especially post 2060[3]. But why has it taken so long?

These delays have been due to the incredible complexity of the science and engineering required to create and sustain the extreme conditions necessary for fusion reactions to occur, let alone to capture net energy from them. This paper will explore these challenges and the work going to address them: the science behind fusion energy, and the reactors and heating methods used to achieve it.

While there are a range of different schemes under research for fusion reactors today, this paper will focus on the historically most promising one: magnetic confinement reactors.

There are a variety of different configurations of magnetic confinement devices being studied in the field of plasma physics today. Each uses a slightly different magnetic field geometry which comes with its own benefits and disadvantages. This research paper evaluates the factors that differentiate the three most promising magnetic confinement configurations and primary heating methods used in the field of fusion energy.

Background

Nuclear fusion is the process by which two light atomic nuclei combine to form a single heavier one, releasing massive amounts of energy[4]. The actual atomic mass of the fusion product is less than the sum of the initial fuel nuclei. This difference in mass is released as energy and could be harnessed in a reactor to produce electricity. This "mass to energy conversion" can be explained by the famous equation that broke the belief that scientists held for years that mass and energy were completely unrelated: $E = mc^2$, where E is energy, m is mass and c is the speed of light. As fusion is a process with powers the sun and stars, harnessing it in a reactor would truly be akin to creating a star on Earth. One can see why this may be a challenge to achieve.

The most promising fuels for a fusion power plant are deuterium and tritium, two heavy isotopes of hydrogen. Fuel combinations such as deuterium-deuterium, deuterium-helium and proton-boron (B-11) are also used in such fusion reactions. However, a fusion reaction between deuterium and tritium releases the greatest amount of energy at a relatively lower temperature compared to other fuel combinations. Temperature is important because fusion reactions do not occur at temperatures naturally encountered on Earth. In fact, for fusion between deuterium and tritium, the required temperature is around 100 million degrees Celsius[5], which is ten times hotter than the core of the sun! This temperature range will depend on the nuclear power plant and the device it uses, with extremely high temperatures damaging the reactor and lower temperatures not favouring fusion reactions between particles.

During the fusion process, two positively charged nuclei must be forced very close together, requiring that the Coulomb repulsion forces between them must be overcome. This necessitates incredibly high particle velocities. For fusion reactions to occur, the fuel must be at very high temperatures. Hence, to effectively fuse two nuclei, the fuel must be in a plasma state.

Plasma is the fourth state of matter, the state hotter than gas. In the transition between gas and plasma, atoms become ionized: the negative electrons separate from the positive nuclei. This creates a hot fluid made primarily of charged particles. These particles have long-ranged electromatic forces between them which can create behaviours that are very different to the other three states of matter. Plasmas are a very complex media, enough so that an entire field of physics was created to study them: Plasma physics!

Beyond fusion energy, the field of plasma physics encompasses a variety of different topics. Plasmas aren't as unusual as you may think! About 99.9% of all the mass in the universe is made up of plasma. This includes stars and most of the interstellar material. Examples are also evident on Earth in the form of lighting, solar winds, and the aurora borealis.

With an understanding of what plasma is, we can now see one of the foremost challenges to creating a fusion reactor. Due to the extreme temperatures fusion plasmas clearly cannot directly be contained by material vessels.

Additionally, as temperature is proportional to pressure, if a plasma at fusion temperatures was created in empty space, it would dissipate, the nuclei rapidly spreading out, preventing further reactions. If the plasma were contained only by a vessel, it could never reach the necessary temperatures; the heat would be conducted to its walls until they melted and the plasma similarly dissipated. Hence the plasma must be confined properly for a long enough duration to release a greater amount of energy than initial input energy to create the plasma.

Thus, alternate confinement methods are required, of which there are only a small number possible: Gravitational, inertial, and magnetic confinement. Gravitational confinement can be seen in stars, where plasma is sustained by its gravitational pressure. On the other end of the size spectrum, a tiny pellet of fuel can be compressed so quickly by lasers that the mass of the fuel is able to confine plasma simply due to its inertia long enough for fusion to occur.

But the most promising method for fusion energy historically, and the one this paper will address, is using magnetic fields. This is made possible because plasmas are composed of charged particles, which respond to magnetic fields.

Methods

This research paper is a literature review of the different magnetic confinement configurations and heating methods of plasma in the field of fusion energy. By referring to several other research papers, textbooks, and online resources, this paper provides an overview to the readers about the three most common magnetic confinement configurations of plasma: tokamaks, spherical tokamaks, and stellarators. Through several case studies, the strengths and weaknesses of three of the world's most widely used heating methods are compared and discussed:

ohmic heating, neutral beam injections, and radio frequency heating. This paper aims to provide readers with an insight into the current research going into plasma physics and what the future of fusion energy might look like. Best efforts were made to find reputable and trustworthy literature; however, they were taken from a variety of sources and not just peer-reviewed publications. They were largely chosen both for accessibility and their level of difficulty in understanding the content. Best efforts were made to provide an unbiased analysis of the information found, but it can't be guaranteed that there is none. It is important to note that this research paper is largely based on tokamaks and spherical tokamaks in particular – which could be one potential source of bias.

Magnetic Confinement

The positively charged ions and negatively charged electrons that make up a plasma, being charged particles, respond to magnetic fields. The most fundamental motion of charged particles in a magnetic field is called cyclotron motion: in the presence of a magnetic field, particles will take on an orbit in a plane perpendicular to the direction of the magnetic field. This orbit will have a characteristic frequency called the cyclotron frequency, defined as $\omega_{\text{ce}} = \frac{qB}{m}$ where q is the charge of the particle, B is the magnitude of the magnetic field, and m is the particle mass. This behavior is fundamental to understanding many of the more complex and large-scale behaviors that appear in plasmas.

Once such behaviour is called a particle drift. This is the net movement of particles in one direction resulting from a force exerted on them in a direction perpendicular to the background magnetic field. Drifts play a significant role in the basic design of magnetic confinement configuration. In particular, a magnetic field with varying strengths will create a drift which would cause particles in a fusion reactor to collide with container walls. Early magnetic confinement devices (including toroidal pinches) of plasma were found to be extremely unstable due to such particle drifts. Therefore, this was a problem that had to be addressed very early on in reactor design.

Most magnetic confinement reactors, and all the ones discussed in this paper, are toroidally shaped devices: they are shaped like donuts! One of the first magnetic confinement concepts was called a toroidal pinch, and attempted to confine plasma with a purely poloidal field[6]. As can be seen in Figure 2, the poloidal direction is defined as the direction of the "short" way around the torus, whereas the toroidal direction is the "long" direction around the torus.

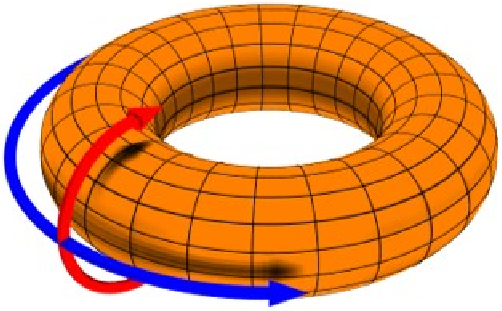

Fig. 2 Toroidal direction (blue) vs Poloidal direction(red) on a Torus[7]

However, a purely poloidal magnetic field proved ineffective due to drifts caused by caused by variations in the magnetic field of the torus. The solution to this problem was to twist the magnetic coils such that the magnetic field was not purely poloidal, but had a toroidal component as well. The field would spiral around the torus with a helical geometry. This twisted field would not get rid of particle drifts, but it would average them out around the torus: particles would drift one way in one location but the other direction in another location as they orbited the torus so overall, the particles would end up where they had started. The idea of a twisted magnetic field was first proposed by Lyman Spitzer at Princeton University. The stellarator concept invented by him allowed researchers and experimenters to control particle drifts and perform additional experiments[8].

Such twisted magnetic field is utilized by three prominent magnetic reactor configurations currently under study in plasma physics: tokamaks, spherical tokamaks, and stellarators.

All three of these reactor types are toroidally shaped devices with helical magnetic fields. A unique sub-type of tokamaks, spherical tokamaks are smaller and more compact in nature. They were introduced as a solution to some of the problems faced in conventional tokamaks, which will be discussed in subsequent sections of this paper. Stellarators are unique in their use of complex helically shaped magnetic coils in alternate directions to precisely the plasma. The next section will discuss the features of the most commonly used magnetic confinement configurations in the form of a comparative study, evaluating the advantages and drawbacks of tokamaks, spherical tokamaks, and stellarators.

Magnetic Confinement Techniques

1] Tokamaks

The tokamak is the most historically successful magnetic confinement configuration for a fusion reactor. The word tokamak stands for "toroidal chamber magnetic coils[9]". Tokamaks are toroidal devices surrounded by the magnetic coils they use to confine plasma, keeping it stable, hot and dense for as long as possible.

Plasmas are made of charged particles, which follow magnetic field lines. This makes a torus an optimal shape for a reactor: particles can simply orbit around the torus endlessly instead.

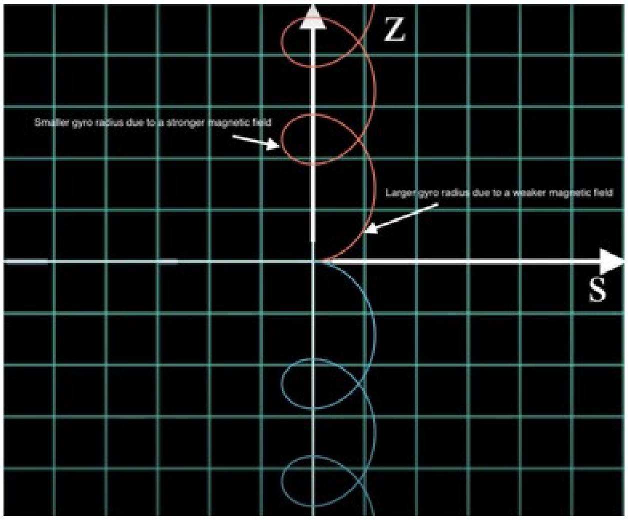

Fig. 3 Drifts of plasma particles[11]

However, in a tokamak, the magnetic field strength decreases in an inverse relation with the device's radius ($B \sim \frac{1}{R}$). Therefore, the magnetic field strength is weaker along the outer curve of the tokamak and stronger along the inner curve.

In a magnetic field, charged particles move in a circular orbit called a gyro-orbit, as mentioned in the previous section. The radius of this motion is called the gyro radius and is given by $r_g = \frac{mv_\perp}{qB}$ where m is the particle mass, q is its charge, $v_\perp$ is its velocity in the direction perpendicular to the magnetic field, and B is the magnitude of the magnetic field.

As this radius depends on B, the gyro-orbit of a particle will not be a perfect circle as it moves into regions with different magnetic field strengths. The gyro radius will be larger around fields with a weaker strength and smaller around fields with a stronger strength. Therefore, variations in the magnetic field strength cause particle drifts, which can cause the particles to move out of confinement radially instead of returning to a location it started at[10].

As discussed previously, a tokamak uses a helically twisted magnetic field to negate the problem of radial drifts caused by varying magnetic fields.

The helical magnetic field of the tokamak can be broken down into three components. As seen in Figure 4, the largest component is the toroidal component, which goes "longways" around the tokamak, and is induced by external electromagnetic coils. The smaller poloidal field component is created by the internal toroidal current of the plasma itself. Lastly, a vertical field is applied by an additional external coil to balance the expansion forces from the toroidal current loop[12]. The combination of these three magnetic field components forms the helical magnetic field structure.

In a tokamak, a toroidal plasma current, and the poloidal magnetic field it creates, are necessary for the confinement of the plasma. This current is generated by the tokamak's central solenoid. A solenoid is essentially a very large coil of wire, with many 'turns' of the wire. In a tokamak, the solenoid is located in the center of the torus and inductively drives the plasma current.

This inductive current drive works in the same a transformer does. A transformer is a device that allows current from one circuit, known as the primary circuit, to be transferred to another circuit, known as the secondary circuit. The central solenoid acts like the primary circuit, inducing a toroidal current in the plasma, which behaves as a secondary circuit.

Like in a transformer, a changing current within the solenoid will create a magnetic field which, in turn, induces a current in the plasma. The magnitude of the plasma current can be altered by changing the size of the central solenoid or the magnitude of current that flows through it[14].

The process of generating the toroidal current in a tokamak must happen upon the startup of the device each time a plasma is created within it. As will be discussed in the Heating Methods section, this process is also able to heat the plasma particles. This "transformer setup" of the central solenoid is an easier and cheaper setup as compared to that of stellarators.

However, as both a heating and current method, it loses its efficiency fairly quickly after the startup period of a tokamak. Additional methods are needed to heat the plasma to fusion temperatures, and to continue driving the necessary toroidal plasma current as the pulse length is increased.

The Bootstrap current is one major source of non-inductively driven current that arises within a tokamak. Due to the varying magnetic field strength along the major and minor radius of the torus, particles move along pathways in tokamak called banana orbits, for their banana-like shape. At one of period of time more particles flow in a given direction of the banana orbit as compared to the other. For example, a greater number of particles travelling along the inner outline of the banana orbit in Figure 5 would imply a greater plasma pressure resulting in a net force in a given direction. The result is a self-driven bootstrap current resulting from the pressure gradient of the particles in a given direction[15] .

The tokamak, however, also has its disadvantages. The superconducting wiring required for tokamaks is vast. ITER, the world's largest tokamak, which is currently still under construction in France, used 100,000 km of niobium-tin titanium material for wiring the tokamak. ITER requires more than 10,000 tons of superconducting magnet[17] for which a mechanism is needed so that no component sags by even the smallest margin. Additionally, the instability of superconducting magnets may give rise to problems. Lastly, efforts to produce an alternating current within the tokamak are also in vain since the toroidal current cannot be reversed as it would cause a short loss of plasma confinement[18].

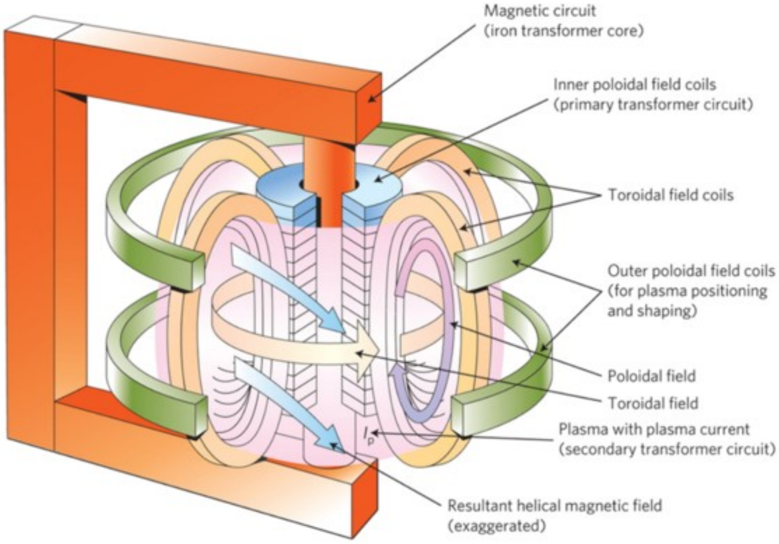

Fig. 4 A representation of the tokamak[13]

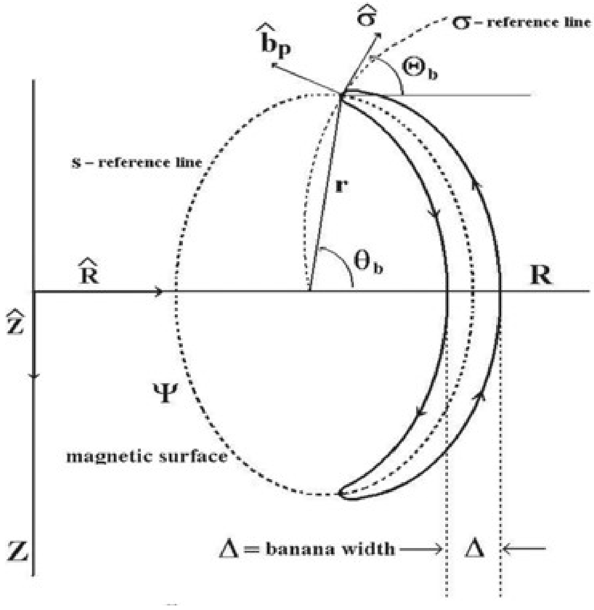

Fig. 5 The Banana Orbit[16]

In conclusion, despite being one of the most studied methods of magnetically confining plasma, tokamaks also have their own disadvantages which need to be addressed for the future of fusion energy.

2] Spherical Tokamak

The confinement of plasma not only depends on external magnetic coils and their features but also other geometrical properties of a tokamak. One important figure for describing this geometry is the device's aspect ratio, defined as the ratio between the radius of the torus (major radius) and the radius of the plasma (minor radius). Conventional tokamaks, discussed above, have an aspect ratio varying between 2 and 3[19]. On the other hand, the spherical tokamak is a "cored apple" shaped tokamak with a low aspect ratio of less than 2.5, and sometimes even being brought closer to 1.

Spherical tokamaks have similar magnetic field configurations to conventional tokamaks including the poloidal, toroidal and axial magnetic field components. However, the physical components of spherical tokamaks are more compact when compared to the conventional ones. The low aspect ratio of the spherical tokamak is the key defining aspect that differentiates it and possibly gives it an edge over the conventional tokamak. This unique feature results in a highly elongated plasma cross-section leading to better confinement. This can be measured using the Troyon beta limit. The "beta" of plasma is defined as the ratio between its thermal and magnetic pressure. The Troyon limit describes how large the thermal pressure can be compared to magnetic pressure before instabilities arise, which can cause

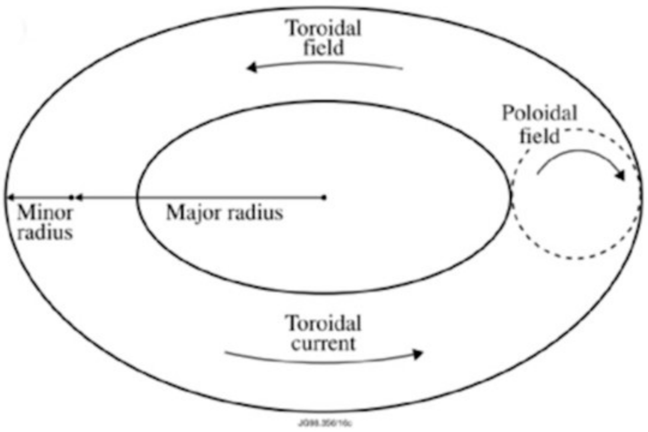

Fig. 6 Major and minor radius of spherical tokamak[20]

a breakdown in confinement.

In conventional tokamaks, the limit is usually around 10% (large magnetic fields are required to balance the plasma pressure). However, spherical tokamaks, with their low aspect ratio, have observed a larger beta limit. For example, experiments like the Small Tight Aspect Ratio Tokamak (START) have achieved a value of 40%[21]. The increase in the beta limit is partly due to an increase in a factor called magnetic shear, which reduces instabilities across the magnetic field lines. The main importance of an increased beta limit is that it allows for lower magnetic fields and thus smaller coils necessary to induce them. Thus, spherical tokamaks could be more economical and cheaper, making them suitable for the sustainable production of fusion energy.

There are other advantages spherical tokamaks have over conventional tokamaks. Spherical tokamaks also have a higher energy confinement time: keeping the plasma hot enough for longer durations of time. Due to higher plasma beta, particles in a spherical tokamak spend a higher proportion of their time in areas of better confinement, towards the inside of the torus, thus requiring a smaller amount of input energy[22].

However, the compactness of spherical tokamaks causes engineering challenges. It leaves little space for components outside the plasma chamber, such as neutron shielding and the tritium breeding blanket, both of which are important components. The blanket allows for the generation of tritium fuel from interactions of neutrons and lithium atoms[23]. Neutron shielding prevents the emitted neutrons from damaging the walls of the reactor. This flaw is evident in the Mega Ampere Spherical Tokamak in the UK which often experiences insufficient neutron shielding[24].

An instability caused by the specific high-density plasma conditions in spherical tokamaks can also cause losses of high-energy particles[25]. Lastly, the smaller central column of the spherical tokamak limits the size and current throughput of the central solenoid as well. This makes inductive startup less efficient for spherical tokamaks.

To solve this particular problem, multiple spherical tokamaks across the world are beginning research on non-solenoidal startup techniques. One example is Local Helicity Injection (LHI) being studied on NSTX-U at the Princeton Plasma Physics Laboratory[26], and on the Pegasus-III device at the University of Wisconsin, Madison[27].

When using LHI as a startup method, the vessel of the spherical tokamak initially contains a vacuum. Injection guns connected to the spherical tokamaks produce an electric arc to ionize deuterium gas, thus creating plasma. By creating a large voltage difference between the injectors and a cathode inside the vacuum vessel, a high-energy beam of electrons is extracted into the vessel. In some cases, the vacuum vessel itself acts as this cathode. Once the electron beams enter the vessel of the spherical tokamak, they follow the magnetic field lines to create a helical structure, spiralling up towards the top of the vessel. As this happens, neighbouring turns of the stream get close enough to each other to combine. Through turbulent processes, the streams relax and fill the vessel with a tokamak-like plasma with a relatively high plasma current.

As a case study on how plasmas created using different startup methods can differ, consider the comparison between an LHI plasma and an ohmic plasma, both of which were created in the Pegasus Experiment[28].

Figure 7 compares a few important plasma parameters between an ohmic plasma and an LHI plasma The top left graph shows plasma current. It can be seen that while ohmic heating has a higher plasma current initially, its efficiency decreases over time and reaches a lower max value than the LHI plasma. The top right graph, however, showcases ohmic plasma to have been heated more efficiently. The ohmic plasma has a higher temperature towards the core of the reactor, and lower towards the edge. This is generally preferred, as heating particles towards the outside of the reactor can lead to wasted energy if the particles leave the plasma and hit the vessel walls.

The ohmic plasma also has a higher electron density towards the core of the reactor than the LHI plasma. In a fusion reactor, higher density could imply a greater number of fusion reactions as well as a greater number of cut-offs towards the core of the plasma. While the implications of the greater magnetic fluctuations in LHI as compared to ohmic heating are not found, the effects of increased magnetic flux due to electron streams created during LHI are an active area of study.

It should be noted, however, that the results obtained above are not a generalization made to all ohmic and LHI plasmas, as there can be wide variations in plasma parameters between different devices using similar startup methods, or even in the same device running with a slightly different startup sequence. This is a case study to demonstrate the kinds of variations that can appear in plasmas created under different conditions, and their possible implications for a fusion reactor. It must also be

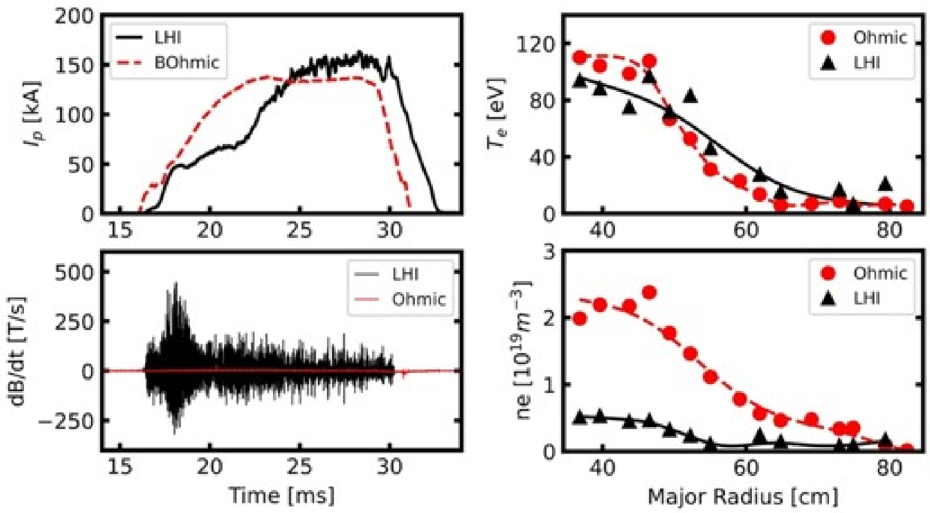

Fig. 7 Comparison between ohmic and LHI[29]

noted that Local Helicity Injection is a very experimental startup technique compared to ohmic startup, and is being researched only in some spherical tokamaks today[30].

To conclude, spherical tokamaks are a compact, smaller and lighter alternative to conventional tokamaks with some key advantages and drawbacks.

3] Stellarators

As seen in the previous sections, a twisted magnetic field is essential to any device aimed at confining plasma. Generally, there are two methods to achieve such a magnetic field: By inducing a self-organized plasma current (tokamak), and by winding the coils surrounding the device (Classical stellarator)

Stellarators, one of the first confinement devices to be developed, make use of extremely strong electromagnets that create a twisted magnetic field. The concept of stellarators was previously abandoned due to its complex structure and construction. However, as advances have been made in technology and design, stellarators have now become competitors to conventional tokamaks.

Over time, several stellarator designs have been developed that have a characteristic complex design and a twisted magnetic field. The classical stellarators were one of the first fusion reactors to be introduced.

As seen in the diagram below, the classical stellarator uses two independent sets of magnetic coils. There exists a set of toroidal field coils that produce the toroidal component of the magnetic field. Helically wound around the plasma, the second set of coils is situated inside the toroidal field coils. These helical coils are arranged in pairs with currents flowing in opposite directions in adjacent coils. The current induced in these coils gives rise to a helical magnetic field component that causes the toroidal field lines to twist at the outer edge. A combination of these two fields creates ideal conditions for the confinement of plasma.

However, the construction of helical coils with extreme precision and accuracy proved to be a complex task. An alternative to the helical coils of the classical stellarators was the invention of modular coils. Modular coils are strong individual magnetic field coils, aimed to produce the twisted magnetic field of the stellarator. The modular coils were introduced to replicate the shape of the magnetic field induced by the complex helical coils. The modular coils can therefore create a range of magnetic configurations, some of which cannot be obtained by the classical stellarators[32].

For example, the structure of Wendelstein 7-X, the world's largest stellarator located at the Max Planck Institute for Plasma Physics (IPP) in Greifswald Germany, is composed of modular coils which shape the magnetic field in great detail. It is testing an optimised magnetic field for confining the plasma. A system of 50 superconducting coils creates a twisted magnetic field[34]. Further, the helical field produced by these coils was able to overcome the disadvantages of previous classical stellarators.

Stellarators avoid the disadvantages of tokamaks, which require large ramping currents to create the confinement fields and therefore can only operate in pulses. Stellarators, in comparison, are designed to operate in a steady state. The asymmetry and the precise, unique arrangement of the magnetic coils keep the plasma stable and contained by a helical magnetic field, avoiding any large-scale disruptions. This has the advantage of avoiding possible field collapses that can occur in tokamaks. It also removes the need for pulsed superconducting coils and therefore eliminates energy storage required to drive these coils.

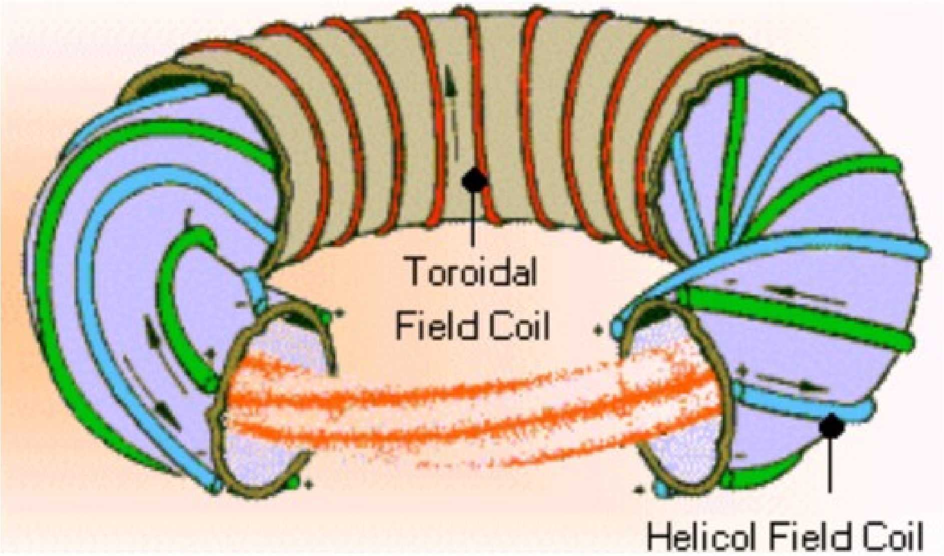

Fig. 8 Magnetic field component of the classical stellarator[31]

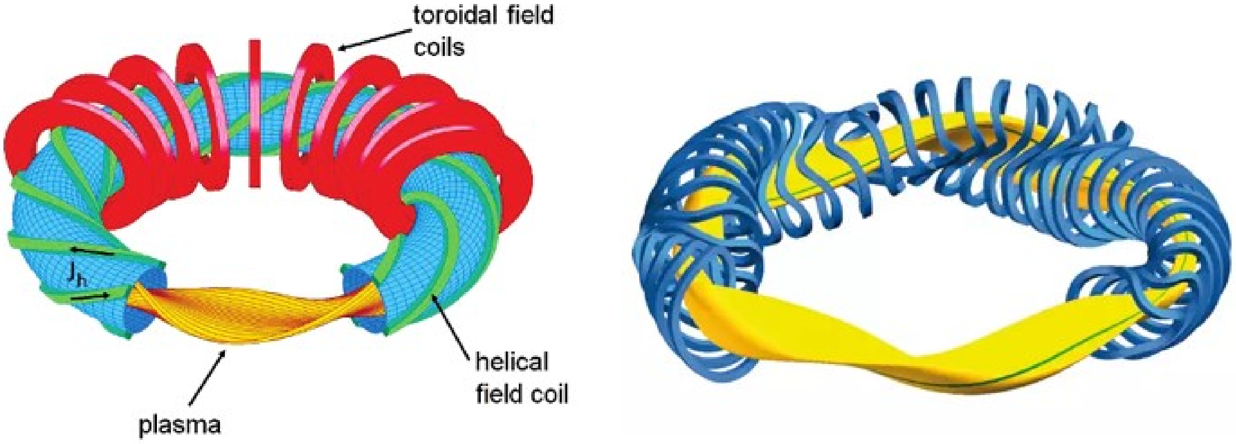

Fig. 9 Difference between a classical (left) and modular (right) stellarator[33]

Although the coils are more intricate and complex to produce, stellarators generate greater power and require a smaller amount of superconducting material as compared to tokamaks[35].

Wendelstein 7-X, for example, demonstrates these advantages; While ITER has a mass of 23,000 tonnes, Wendelstein 7-X has a mass of 425 tonnes[36]. A Second Round of Experiments with it has achieved higher values for the density and the energy content of the plasma[37] and long discharge times of up to 100 seconds – record results for devices of the stellarator type. In the future, work will be conducted on a step-by-step basis with the aim of achieving plasmas that last for 30 minutes.

To summarize, although stellarators have an intricate design and are complex to construct, their potential advantages in the field of fusion energy make them a rising competitor among confinement devices.

Heating Methods

Across the range of reactor configurations discussed above, plasma heating methods are required to bring the fuel to fusion temperatures: hundreds of millions of degrees Celsius. An ideal fusion device is imagined to be a pulsed machine: holding plasma for 23 hours and being switched off for an hour. Heating systems, therefore must be efficient and reliable[39]. Efficiency ensures that maximum output power is derived from the initial input power to be transferred to the electric grid, and reliability is needed to reduce reactor downtime for frequent maintenance and upkeep.

In the following sections, the most widely used and researched plasma heating methods will be discussed. These include ohmic heating, neutral beam injection, and several types of radio frequency heating. Ohmic heating makes use of a discharge current to raise the plasma temperature to 1-2 KeV. Since this temperature is insufficient for the fusion of deuterium and tritium, additional heating methods like neutral beam injections and radio frequency heating are used in tokamaks and stellarators to bring the plasma to fusion temperatures[40].

However one of the most important heating methods to be discussed is alpha heating, which will necessarily play an important role in sustaining fusion reaction in an energy reactor. Alpha heating is also known as self-heating, and is when a product of the fusion reaction itself contributes to the heating of the fusion fuels.

The fusion between deuterium and tritium produces a neutron and an alpha particle (a helium-4 nucleus). The neutron, which contains 80% of the energy, is directed it out of the fusion device to supply power to electric grids. However, the alpha particle still contains 20% of the energy. And, because the alpha particle is charged, it does not leave the device but instead transfers its energy back to the plasma – heating it. This self-heating is proportional to fusion power. Thus, larger reactors will have greater ability to self-heat. As the self-heating increases with the size of the fusion device, the intensity of other heating methods can be reduced. The point at which alpha particles are the only heating method used is colloquially known as ignition. It is now a burning plasma sustaining itself like a flame. Such a heating method could theoretically continue forever[41].

The following sections aim to compare the three major magnetic confinement configurations of plasma and their subsequent heating methods. The following sections will discuss the feasibility and effectiveness of heating methods used in each of these devices.

1] Ohmic heating

To reiterate, plasma is a hot ionised gas consisting of free electrons and positively charged ions. For the magnetic confinement of plasma, an electric current must pass through it to create a poloidal magnetic field in the conventional and spherical tokamaks. The movement of electrons in plasma predominantly drives current in such devices. Usually, a central solenoid is used to induce the plasma current; However, LHI is being used as an experimental start-up technique in some spherical tokamaks.

We can compare the current drive in plasma to a current flowing through an electric wire. An electric wire consists of free electrons and fixed positively charged nuclei. As a voltage is applied across the electric wire, there is a collective movement of electrons towards areas of lower voltage, producing current. However, as the electrons move, they collide with the positively charged nuclei, transferring some of their energy during the process. Every time electrons collide with the nuclei, the wire heats up. This is known as resistance and the heat released as a result of this process is known as ohmic heating. Similarly, electrons in the plasma collide with positively charged ions, therefore producing heat. This makes ohmic heating one of the initial steps to heat plasma up to extreme temperatures[42].

However, ohmic heating is only effective up to a temperature of 80 million degrees Celsius, which is almost half the target temperature of 150 million degrees Celsius. In a plasma, resistivity follows an inverse relation with temperature ($\eta \propto 1/T^{3/2}$), where T is temperature and η is resistivity. As the temperature of the plasma increases, a fall in resistivity is observed, which causes a corresponding decrease in heating efficiency[43]. Therefore, ohmic heating, one of the initial heating methods in conventional and spherical tokamaks, must be complemented with other external heating systems in order to achieve the desired plasma temperature.

2] Neutral Beam Injection

Neutral Beam injections are one of the most common methods to heat plasma in conventional and spherical tokamaks, as well as current-free stellarators. This method introduces high-energy

Table 1 Differences between Tokamaks, Stellarators and Spherical Tokamaks

Key Characteristic	Tokamaks	Spherical Tokamaks	Stellarators
Aspect ratio	Generally, between 2 and 3	Less than 2.5 and sometimes even brought to 1	Usually large. Wendelstein 7-X has an aspect ratio[38] of 10
Presence of central solenoid	Yes	No	No
Plasma current	Yes	Yes	No
Toroidal symmetry	Yes	Yes	No
Steady state operation	Yes	Yes	Yes

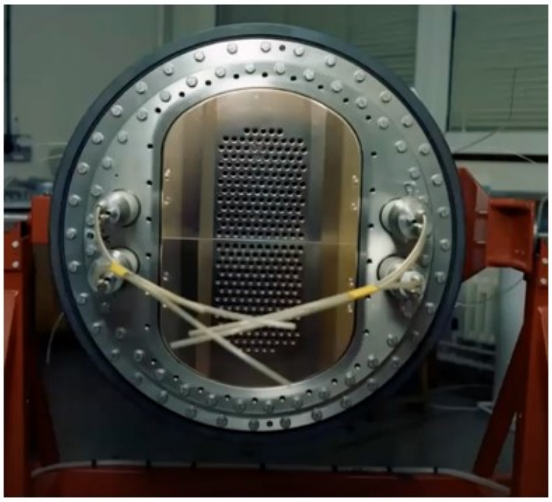

Fig. 10 Charged metal grid used in Neutral Beam Injections for JET[45]

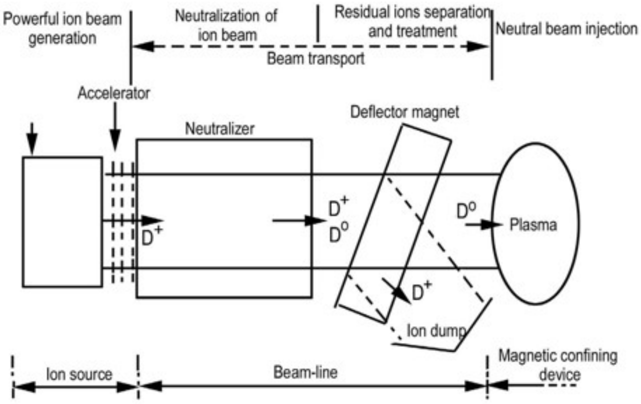

Fig. 11 Neutral beam injection[46]

particles into the plasma. As they collide with ions, these particles transfer their energy to the background plasma in the form of heat.

In neutral beam injection, A particle accelerator introduces high-energy particles into the plasma. The accelerator, neutralizer and bending magnets are the three main components of the neutral beam injector. As seen in Figure 11, the accelerator consists of an ion source, usually deuterium (thereby providing additional fuel to the plasma), and a metal grid with several holes. The source of gaseous ions is placed behind a metal grid which is charged up to a very high voltage. The metal grid is positively charged, which accelerates the positively charged ions towards the neutralizer. A 120,000-volt grid will accelerate a deuterium ion to approximately 1.5% the speed of light[44].

Any device confining plasma will have strong magnetic fields surrounding it. This field will deflect any charged particles introduced in such a device. Therefore, the charged ions of the neutral beam must be neutralized before being injected into the plasma. The neutralizer consists of a cloud of gas molecules through which these fast ions pass through. As ions pass through, there is a probability that some of them get neutralized by the electrons present in the cloud of gas.

Lastly, the charged ions which pass through the neutralizer without becoming neutralized must be removed before the beam of neutral particles is injected into the plasma. To achieve this, bending magnets are connected which are aimed to deflect the charged particles onto ion dumpers resulting in a purely fast neutral beam.

Therefore, as a result of the collision between these neutral and plasma particles, neutral beam injections are successful in heating the plasma up to desired temperatures. This makes neutral beam injections one of the most important heating methods used in both tokamaks and stellarators.

Neutral beam injectors are powerful and consistent in providing energy to the plasma. For example, this method provides 32 MW of power to the confined plasma in the Joint European Torus (JET). However, neutral beam injectors are not energy efficient. Hundreds of megawatts are required to power the injector, while only 32 megawatts make it to the plasma[47]. Therefore, the cost per watt of the neutral beam power is relatively high.

Lastly, the neutral beam must penetrate the centre of the reactor core before it ionizes in order to give the desired heating effect. The penetration depth is usually proportional to the beam energy. A lower energy would cause the heat to be deposited on the outside of the plasma, while extremely high energies would pass through the plasma and deposit its heat on the reactor wall. Both of these situations are undesirable. Hence an important issue in neutral beam injections is to determine the precise energy at which the neutral beam is injected into the plasma[48].

Due to this reason, several other heating methods are being explored all around the world, some of which will be discussed in the following sections.

3] Radio Frequency Heating

Radio frequency (RF) heating is another common method used to heat plasma up to fusion temperatures. By introducing targeted radio waves at a specific frequency, RF heating provides energy to plasma particles, heating them. Although RF heating may have its own implementation challenges, it tends to be more versatile than neutral beam injection: RF heating can be targeted towards specific areas of the plasma.

Broadly, there are two categories of RF heating methods: electron cyclotron heating and ion cyclotron heating. These will be discussed here, as well as a third and more experimental RF heating method which uses electron Bernstein waves.

Electron Cyclotron Heating

Radio waves provide heating only at specific frequencies. Electrons in the presence of a magnetic field oscillate with a natural frequency known as the cyclotron frequency. This frequency ω_{ce} is defined by three factors: $\omega_{ce} = \frac{qB}{m}$, where q, m, and B are the electron's charge, mass, and magnetic field strength, respectively. Owing to these factors, the cyclotron frequency will be different at different locations within a tokamak or stellarator.

When the frequency of a radio wave matches the cyclotron frequency, electrons resonate with the wave and absorb its energy, heating up. This is known as electron cyclotron heating (ECH). Because it requires a specific frequency, the radio waves can be targeted to a specific area in the reactor by tuning the frequency to equal only that cyclotron frequency.

ECH can occur using a variety of different RF waves, but the main two are the extraordinary mode (X mode) and Ordinary mode (O mode) waves. The behaviour of electromagnetic waves in plasmas depends on several factors, including the direction they are moving in with respect to the background magnetic field, and their polarization (the direction of the photon's electric field). Both the O mode and X mode move perpendicular to the magnetic field, but the direction of their polarizations is different. O mode refers to when the polarization of the radio waves is parallel to the ambient magnetic field and X mode refers to when the wave polarization is perpendicular to the ambient magnetic field[49].

For an effective heating system, two factors must be kept in mind. Radio waves are reflected at a certain density limit of the plasma, meaning the wave cannot be absorbed to heat the plasma. Therefore, accessibility is very poor. These density limits depend on the plasma and cyclotron frequency making the step of designing an ECH system with a density limit as high as possible very important. Also, ECH should operate at the lowest cyclotron harmonic as possible (first harmonic is when the frequency of radio waves is equal to cyclotron frequency, second harmonic is when frequency is twice the cyclotron frequency and so on). The absorption of radio waves by electrons is inversely proportional to the harmonic number for the O and X modes.

There are multiple options for setups using radio waves to heat the centre of the plasma. Two prominent examples are an O mode radio wave at the first harmonic frequency or an X mode at the second harmonic. O mode ECH at the first harmonic provides accessibility to the centre of the plasma, however, its absorbance by electrons is smaller than X mode ECH at the first harmonic[50].

In general, X mode waves are preferred as they tend to be absorbed better by the plasma, but it is more challenging to get the wave into the core of the plasma where it needs to be absorbed. If the wave is launched from the outer edge of the plasma vessel at the first harmonic frequency, the wave will encounter a location in the plasma where it is reflected before it has the chance to reach the location where it could be absorbed. The second harmonic of the X-mode must be used instead. Despite the higher harmonic number, it still provides a similar damping rate to the O mode. Its drawback is that the second harmonic is a much higher frequency, which means the technology needed to produce it is more complicated and expensive.

One of the drawbacks of ECH heating is the lack of steady, high-power sources of radio waves which could potentially increase the cost of fusion energy[51]. For instance, ITER's target of reaching 170 GHz of ECH is still under development, with the generators they will use to create the radio waves still being prototyped in Russia, Europe, and Japan[52].

Ion Cyclotron Heating

Similar to electron cyclotron heating, ion cyclotron heating (ICH) involves introducing radio waves at the ion cyclotron frequencies, thereby providing energy to ions present in the plasma. This frequency depends on the same three factors mentioned in the previous section: ion charge, ion mass, and the strength of the magnetic field present in different areas of the tokamak or stellarator.

ICH will play an important role in future experiments and magnetic confinement devices. Ion cyclotron frequencies are lower than electron cyclotron frequencies, making steady-state high power sources more readily available for this method. In addition, ICH directly heats ions and avoids excess electron heating, which could in turn lead to instabilities.

Generally, ICH uses X modes because ion cyclotron frequencies usually correspond to the range of $\sim$ 36 MHz, and O mode RF waves near this frequency are reflected by plasma particles. X-mode waves, on the other hand, do not have a plasma cut-off in the ICH frequency range[53].

For the best absorption of RF waves, the wave also has to have a particular polarization at the cyclotron location. For this reason, the second harmonic X-mode is used for ICH, as it has a better polarization than the first harmonic. It still does not have the ideal polarization, however, so sometimes another trick us used to increase absorption, where a small amount of another type of ion is introduced into the plasma. This other ion type can absorb the energy from the RF wave and then transfer it to the fuel ions by collisions. With this technique, a first harmonic X-mode wave can be used.

One of the major drawbacks of ICH is the need for an internal antenna close enough to the plasma edge to reduce the reflection of radio waves at ion cyclotron frequencies[54] .For this reason, many devices make use of both ECH and ICH as an effective heating method. In ITER, ICH will provide 20 MW to the plasma at frequencies between 40 and 55 MHz and another 20 MW will be provided by ECH at frequencies around 170 GHz[55].

Electron Bernstein Wave Heating

In some plasma devises, particularly spherical tokamaks and stellarators, plasmas may become overdense. This means that plasma densities are large enough that no O or X mode waves can reach their cyclotron absorption locations before they encounter a density cutoff and are reflected from the plasma. This means ECH cannot be used for heating.

In these conditions, Electron Bernstein waves (EBW) may be used for RF heating and is a method under study at several spherical tokamaks worldwide. EBW are a type of wave which moves through plasma via the motion of electrons in a similar way to how the motion of water molecules carries waves in the ocean. Because they propagate by particle motion and are not electromagnetic waves, they don't have density cutoffs and can travel through overdense plasmas.

However, because EBW move via particle motion, they can't travel through a vacuum and so can't be launched into the plasma-like RF waves used in ECH and ICH. There are multiple ways to introduce Electron Bernstein waves into the plasma, with the most common method being the "OXB mode conversion method".

As part of the OXB mode conversion, O mode radio waves are first launched into the plasma at a very precise angle[56]. If the wave has this precise angle when it reaches its density cutoff, it will reflect in such a way that its polarization changes and the wave changes, or 'mode-converts' into an X mode wave.

The X mode wave then travels outwards towards a location where it could be absorbed by the plasma. However, if it is travelling in an over-dense plasma and with the correct angle with respect to the magnetic field, it can instead mode convert again into an EBW. This happens because, as the X-mode wave approaches the location in the plasma where it might become absorbed, its wavelength decreases until it is about the same size as the electron gyro-radius. When it is this size, it can directly affect the motion of electrons and by doing so, creates an EBW. All the energy that was travelling in the X mode instead travels through the plasma as an EBW. During this process, the wave also experiences a reflection and then travels inwards through the plasma until it encounters its cyclotron resonance location and is absorbed in the same way absorption occurs in ECH and ICH. Therefore, the electron Bernstein waves are successful in heating over dense plasma using OXB mode conversion.

While OXB is the most common mode conversion method used, there are others. One involves launching the X mode from the centre stack, and another uses a direct X to EBW conversion scheme. However, they are more challenging to achieve, either technologically, or in the plasma parameters required to make them work. OXB is the conversion scheme that has been researched and used the most often in EBW heating setups.

Experiments are being carried out all over the world to further improve the method of electron Bernstein waves. For example, Wendelstein 7-X demonstrated an increase in the plasma energy[57] using OXB heating.

Conclusion

The field of fusion energy is ever-growing, has endless possibilities, and may undergo several prospective advances with scientists and companies performing experiments all over the world. Efforts are now being made to find the best possible magnetic confinement and heating method to make fusion energy sustainable enough.

This research paper aimed to compare the different magnetic confinement and heating methods used to sustain this reaction. Plasma, being the fourth state of matter, has a completely different behaviour. Therefore, methods have been devised to confine it. Fusion makes use of magnetic confinement for this purpose. With several magnetic confinement configurations available, tokamaks, spherical tokamaks, and stellarators are the most common fusion reactors.

To reiterate, fusion is one of the promising fields intended to produce sustainable, clean and abundant energy in the future. By the fusing of two or more nuclei, this type of reaction can produce a tremendous amount of energy. With many countries in the search for renewable sources of energy, nuclear fusion and plasma physics have become an important field of research. Up till now, three magnetic confinement configurations of plasma have been established: tokamaks, spherical tokamaks and stellarators. While tokamaks are commonly used confinement devices in this field, they still suffer from several setbacks including the requirement of massive amounts of superconducting material and the wastage of electricity for its operation. Even though the spherical tokamak is a smaller version of the tokamak, it may cause the loss of high-energy particles and pose engineering problems in terms of neutron shielding. Modern-day stellarators also face difficulties in designing complex modular coils. Similarly, although several heating methods of plasma have been established, issues such as the inability to reach fusion temperatures for longer periods, accessibility issues and the inability to determine the optimum temperature devoid of any instabilities have not allowed fusion energy to become a commercial source of electricity. Such drawbacks have caused a need for research in fusion energy and plasma physics. Currently, efforts are being made to build and operate ITER, the world's largest fusion experiment. ITER will be capable of producing 500 megawatts of fusion energy[58]. As evident in sections 2 and 3 of "magnetic confinement techniques" research is going on in the Wendelstein 7-X stellarator and the NSTX-U spherical tokamak at the Princeton Plasma Physics Laboratory. Our goal is to develop a prototype of an operational fusion reactor by 2040[59].

This paper has discussed various confinement and heating methods used in fusion energy research. While there may be several effective and efficient methods to confine the plasma, I feel stellarators with modular coils are the future of fusion energy. Although stellarators may have a complex design, their advantages in the form of increased plasma stability, less superconducting material and a higher ratio of output energy make it one of the most prospective confinement methods in the field of fusion energy.

With non-renewable energy sources such as coal and crude oil depleting, fusion energy may be one of the most essential sources of energy in the future, making research in this field extremely important.

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