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NUCLEAR FUSION ENERGY AND COMPARISON OF TOKAMAK AND STELLARATOR REACTORS

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ABSTRACT
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Abstract

This bachelor's thesis presents the basic principles of nuclear fusion energy, its sustainability and compares the two most prominent fusion reactors; tokamaks and stellarators. Work is done through a literature review. Topic is relevant because energy demand is increasing and environmentally friendly ways of producing energy are needed. Fusion energy could have potential to produce vast amounts of pollution free energy without the long-lived radioactive waste or the risk of runaway reactions. However, fusion reactors have not yet been able to prove their feasibility in power generation due to its challenging physics and technology.

Fusion and fission are nuclear reactions. In fusion, light atoms fuse together whereas in fission heavy atoms break apart. The reactions produce energy based on the nuclear binding energy as the created atoms are more stable i.e. have a greater binding energy than the initial ones. Produced energy is related to the created mass defect between the nuclei and the separate nucleons.

Fusion reactions happen inside plasma. Temperature, density and confinement of plasma, i.e. triple product, need to reach high enough values for fusion to work. Both tokamaks and stellarators use magnetic confinement as plasma is electrically charged and can be controlled with magnetic fields. Magnetic configurations set the two reactors apart.

Tokamaks have toroidal and poloidal superconducting magnetic coils. They also have a transformer creating an electric current in the plasma. Their biggest advantage is their symmetrical and simple structure, but a big disadvantage is the transformer-driven current that forces tokamaks to work only in pulses. Stellarators have only magnetic coils and no current inside the plasma. To ensure plasma confinement, their structure is helically twisted and non-axisymmetric making the complicated structure their biggest disadvantage. Lack of current makes them work continuously, which is their biggest advantage.

ITER's tokamak in France and IPP's Wendelstein 7-X stellarator in Germany show the current state of fusion research. These are used as examples in the thesis. Currently tokamaks are more advanced and closer in generating more energy than is needed to heat the plasma. As plasma physics evolves and the stellarator instabilities are fixed, their continuous operation might make them more viable for the future.

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Tiivistelmä

Tämä kandidaatintyö esittelee ydinfuusioenergian perusperiaatteet, sen kestävyysnäkökulmat, ja vertailee kahta lupaavinta reaktoria; tokamakia ja stellaraattoria. Työ on kirjallisuuskatsaus. Aihe on ajankohtainen, sillä energiantarve kasvaa ja ympäristöystävällisempiä energiamuotoja tarvitaan. Fuusioenergialla on potentiaalia tuottaa suuria määriä päästötöntä energiaa ilman pitkäikäistä radioaktiivista jätettä tai suurien ydinonnettomuuksien riskiä. Fuusioreaktorit eivät vielä ole onnistuneet todistamaan fuusiovoimaloiden toteutettavuutta johtuen fuusion haastavasta fysiikasta ja teknologiasta.

Fuusio ja fissio ovat ydinreaktioita. Fuusiossa kevyet atomit sulautuvat yhteen ja fissiossa raskaat atomit hajoavat pienemmiksi. Reaktiot tuottavat energiaa johtuen sidosenergiasta, kun syntyneet atomit ovat vakaampia eli omaavat korkeamman sidosenergian kuin alkuperäiset. Syntynyt energia voidaan laskea massavajeesta atomiytimien ja erillään olevien nukleonien välillä.

Fuusioreaktiot tapahtuvat plasmassa. Plasman lämpötilan, tiheyden ja koossapitoajan eli kolmitulon tulee saavuttaa riittävän korkeat arvot, jotta fuusio voi onnistua. Tokamakit ja stellaraattorit molemmat käyttävät magneettista koossapitoa, sillä plasma on sähköisesti varautunutta ja siten sitä voidaan kontrolloida magneettikenttien avulla. Magneettien kokoonpano on reaktorien suurin eroavaisuus.

Tokamakeissa on toroidaalisia ja poloidaalisia suprajohtavia magneettikeloja. Niissä on myös muuntaja, joka luo sähkövirran plasmaan. Tokamakien suurin etu on niiden symmetrinen ja yksinkertainen rakenne, mutta muuntajan tuottaman epäjatkuvan virran takia voivat ne toimia vain pulsseissa. Stellaraattorit käyttävät vain magneettikeloja, ilman sähkövirtaa plasmassa. Varmistaakseen plasman koossapidon, ovat stellaraattorit epäsymmetrisiä ja kierteisiä. Muuntajan poissaolon takia niiden suurin etu on mahdollisuus jatkuvatoimisuuteen. Suurin haitta stellaraattoreilla on kuitenkin niiden monimutkainen rakenne.

ITERin tokamak Ranskassa ja IPP:n stellaraattori Wendelstein 7-X Saksassa kuvaavat hyvin fuusioreaktoreiden tutkimuksen nykytilaa. Nämä reaktorit ovat esimerkkeinä tässä työssä. Tällä hetkellä tokamakit ovat kehittyneempiä ja lähempänä tuottamaan enemmän energiaa kuin mitä plasman lämmittämiseen tarvitaan. Kun plasmafysiikka kehittyy ja stellaraattorien epävakauksia korjataan, voi jatkuvatoimisuus tehdä niistä paremman vaihtoehdon tulevaisuuteen.

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1 INTRODUCTION

The demand for energy is continuously increasing. Total population in 2050 is projected to reach almost 10 billion while the standard of living will also continue to rise (UN 2015). International Energy Agency (2016) predicts a 30 % increase in energy demand by 2040 when at the same time a substantial portion of people still lack access to everyday electricity.

Energy field is experiencing major challenges in the next decades. Fossil fuels have a negative impact on climate change and they also have restricted supply. The share of renewable energy is increasing and being developed to help the demand. (Klimstra J. & Hotakainen M. 2011, p. 18-21) Countries also aspire to be independent in their energy production which means a diverse power supply should exist. Ministry of employment and the economy of Finland has stated in 2016 that Finland's self-sufficiency must be guaranteed especially minimizing the amount of imported oil (Leskelä J. 2016). Renewable abundant fuel sources are needed to replace old methods.

Increased energy consumption, concerns over climate change and the aspiration of energy independency has also worked as an incentive for nuclear power which in some countries has been experiencing a renaissance. Fission reactors have been in operation since the 1950's. They produce substantial amounts of energy but are controversial due to the quality of radioactive waste and the severity of possible risks.

Fusion energy has been introduced as a part of the solution for growing energy demand and also as a climate friendly way of producing energy. Its main fuel sources could be vastly available, and it doesn't produce waste or radioactivity similar to fission. It also does not work as a chain reaction, so it would not contain similar risks of accidents as fission.

Fusion could provide nearly limitless amounts of energy, but reactors have not yet succeeded in producing a positive net output of energy. Constructing a functional fusion reactor is demanding but many substantial research projects are being conducted. Research on technical configurations and plasma physics are still under way which makes it hard to predict an exact timeframe for fusion energy. (World Nuclear Association 2017)

Fusion requires very demanding conditions to work and many technical components are needed to achieve these levels. Some of them are introduced in this thesis.

Tokamaks and stellarators are the most prominent reactor models for fusion. ITER tokamak and IPP's Wendelstein 7-X stellarator are the most advanced ones, even though they are not planned to produce energy to the grid. (Xu Y. 2016) Both reactors have some advantages and disadvantages and the differences will be reviewed in this paper.

2 NUCLEAR FUSION

Albert Einstein's theory of special relativity shows the relation between mass (m) and energy (E). Atoms consists of nuclei of protons and neutrons, and electrons that surround it. The mass of protons and neutrons separately is greater compared to the system where they are combined into a stable nucleus. This is due to nuclear binding energy which is the required energy amount needed to break apart a stable nucleus into protons and neutrons. When mass is changed in a system it contributes to the change in energy as shown below in Einstein's equation from his theory of special relativity (c being the velocity of light in a vacuum): (Sitton L. 2015)

$$\Delta E = \Delta mc^2$$

In fission, the heavy uranium nucleus used as fuel is split hitting it with a neutron. Most commonly the reaction results in two medium heavy nuclei and two to three free neutrons. Uranium atom has a certain mass that is different compared to the mass of the end products. The binding energy from the change in mass is freed and converted into kinetic energy. Kinetic energy quickly turns into heat energy when neutrons collide into more atomic nuclei breaking them apart in a chain reaction. (Energiateollisuus ry 2009)

In addition to fission, there is another type of nuclear reaction; fusion. In fusion reaction, two light nuclei combine and release energy. Like in fission, produced energy from fusion is based on the binding energy of the nuclei. Binding energy is released and seen as a lower mass with the products than the fuel components. (World Nuclear Association 2017) Fusion reaction is the fundamental energy producing reaction that is occurring in the Sun and the stars using hydrogen nucleus and producing helium but also other heavier elements. Life on Earth is possible due to the fusion in the Sun. Fusion is responsible for the element synthesis generating heavier elements than hydrogen all the way up to iron. (Energiateollisuus ry 2011)

Fusion and fission work in opposite ways because of the size of the nuclei. Light atoms like hydrogen and helium release a lot of energy when they fuse together. Moving toward heavier nuclei the amount of energy released in fusion diminishes until iron in the middle of the periodic table produces none. After that producing fusion for heavier nuclei would contribute to a negative net energy production. For heavier nuclei such as uranium the process is different as they release energy when they break apart. (EUROfusion 2017b) This can be seen in the binding energy curve in figure 1, where the binding energy per nucleon for each element is displayed. The curve shows why energy is released with opposite reactions. As the binding energy increases, the harder it is to break down a nucleus into protons and neutrons i.e. the nucleus is more tightly bound. When big nuclei like uranium splits or small nuclei like hydrogen fuse, they go into a more stable form. Iron (Fe) is at the peak of the curve, showing the stable region from where on the left fusion is more likely and on the right fission more likely to occur. (Hepburn C. 2018)

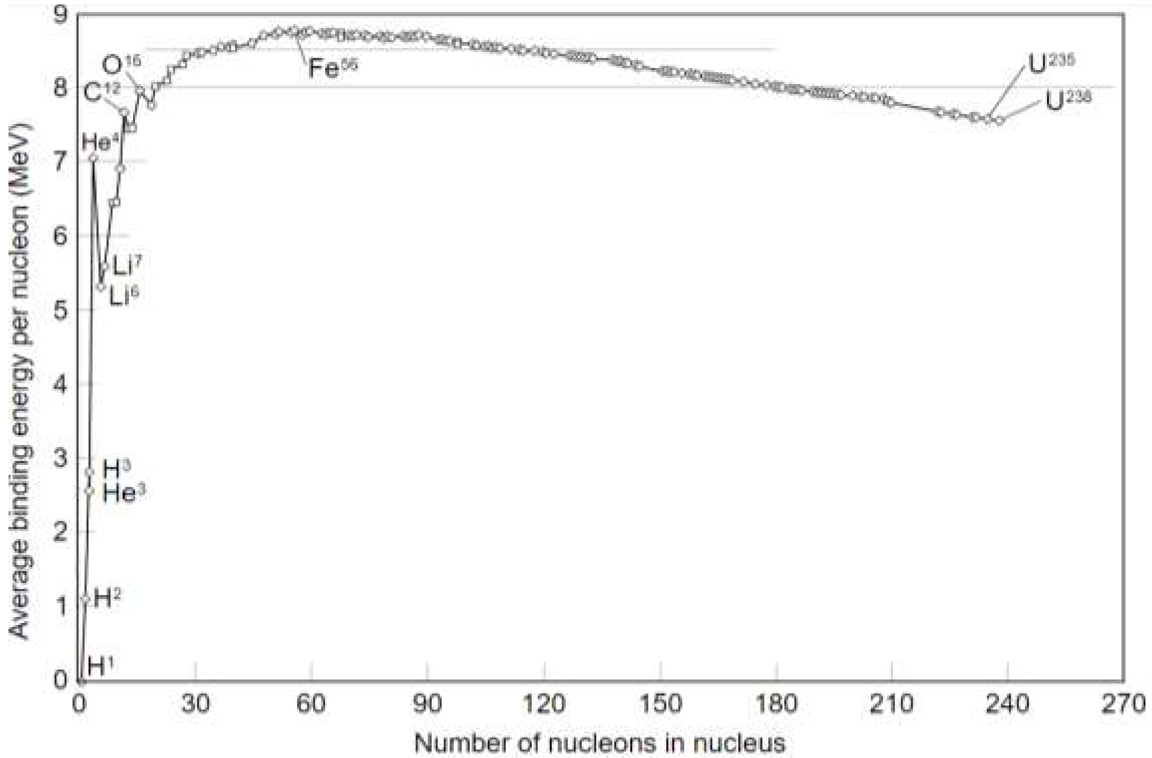

Figure 1. Binding energy curve (Wikipedia Commons, 2018).

Research on fusion fuel is ongoing and so far, two different isotopes of hydrogen have been proven to be the most efficient components to fuse together. Hydrogen-2 or deuterium (D) has one proton and one neutron and hydrogen-3 or tritium (T) has one proton and two neutrons. (ITER 2017c) Nuclei of hydrogen atoms have weak positive charges which means it is easier for them to overcome the resistance due to electric charge and fuse. (Encyclopaedia Britannica 2017b) The end products for D-T fusion is helium and a neutron. The equation is shown below:

$$ {}_{1}^{2}H + {}_{1}^{3}H \rightarrow {}_{2}^{4}He + {}_{0}^{1}n $$

Around 20 % of the gained net energy from the fusion reaction will be in the helium nuclei. Helium will contribute to the heating of the system by colliding into deuterium and tritium and turning kinetic energy into heat. After slowing down, helium will be removed from the vessel. 80 % of the gained net energy from the reactions will be in the neutrons. (EUROfusion 2018a) Uncharged neutrons that can't be confined magnetically will collide the walls of the vessel. The idea of electricity production is the same as in many conventional methods; kinetic energy is turned into heat that is captured in the water cooling pipes and circulated out. The heat would be turned into steam which will in turn rotate turbines and produce electricity through generators. (Energiateollisuus ry 2011)

Other isotopes of light elements can also fuse but D-T fusion has been proven to yield the highest energy with the lowest temperature. Each fusion reaction produced by D-T fuel releases 17.6 MeV (around 100 000 kWh/g) compared to 200 MeV for a fission reaction with Uranium-235 or 3-4 MeV for D-D fusion. When compared with mass, D-T fusion produces over four times more energy than fission with uranium. (World Nuclear Association 2017) One gram of D-T fuel in fusion can release energy almost 100 MW. (Energiateollisuus ry 2011) D-D fusion fuel has been used for example in an experimental reactor JET, but it requires much higher temperatures compared to D-T reaction. D-D reaction equation below: (HyperPhysics 2018)

$${}_{1}^{2}H + {}_{1}^{2}H \rightarrow {}_{2}^{3}He + {}_{0}^{1}n$$

Deuterium can be found in seawater where it occurs naturally around 30 grams per cubic meter. This makes deuterium very abundant and harmless compared to other conventional fuels. Tritium occurs only in trace quantities from cosmic rays, so it has to be produced by other means. Currently the most prominent way for tritium breeding is in a fusion system from lithium. The high energy neutrons without a charge generated in the fusion reaction will escape the plasma and collide the blanket of the vessel walls. The lithium added to the blanket will then absorb the neutron and recombine itself into tritium and helium-4. This way tritium could be produced self-sustainingly and collected back to fuel from the blanket. Lithium is easily available on land and can also be extracted from seawater. (ITER 2017c) Tritium breeding equation from lithium below (Hyperphysics 2018):

$${}_{3}^{6}Li + {}_{0}^{1}n \rightarrow {}_{2}^{4}He + {}_{1}^{3}H$$

3 PLASMA

Plasma state provides the conditions for light elements to fuse. The three main states of matter are solid, liquid and gas, and plasma is sometimes listed as the fourth state after gas. Plasma is ionised gas where the nuclei composed of protons of neutrons have lost the electrons surrounding them. It consists of electrically charged negative electrons and positive ions and is quasi-neutral gas which means the plasma element has equal amount of positive and negative charges. Yet on a smaller scale plasma can have charged regions and electric fields. It has significant amount of free charges which means electromagnetic effects are important. It can be affected through electricity and magnetism and it can also itself produce electromagnetic fields.

State change from gas to plasma is not unambiguous. Ionisation happens slowly and already at 0.1 % level of ionisation matter has some plasma properties. 1 % level of ionisation can then be considered as complete conduction. (Koskinen H. 2001, p. 8)

3.1 Prerequisites for fusion

There are three main variables, often called the triple product, that must reach their limit values for fusion to work on Earth. These variables are temperature, density and confinement time. (EUROfusion 2018e) Spontaneous fusion is possible in the Sun because of its high temperature, pressure and gravity. Pressure and gravity are lower on Earth which means the temperature must reach a level that is up to ten times higher than on the Sun, reaching over 100 million Celsius. (Energiateollisuus ry 2011)

The four fundamental forces on Earth are gravity, electromagnetism, weak force and strong force. Electromagnetic force is seen in our everyday life and affects all components that have an electric charge. Based on Coulomb's law, two positive or two negative charges repulse one another but opposite charges attract one another. (Energiateollisuus ry 2011) In fusion, positive nuclei must fuse together which means the electromagnetic repulsion must overcome. Strong force affects quarks that are the building blocks for protons and neutrons, creating bigger particles from the fundamental smaller particles. Strong force holds the atomic nucleus together overcoming the electromagnetic force but is very short-ranged having power only at distances close to 10^{-15} meters. (Encyclopaedia Britannica 2018)

Extreme temperature is first applied to separate the electrons from nuclei and creating plasma. After ionisation, plasma has positive nuclei that must fuse together by overcoming the electromagnetic force. More heat is added to provoke high speed of the particles and make high-energy collisions possible. (ITER 2017g) This combined with sufficient density makes it possible for some nuclei to reach a distance less than $1.7 * 10^{-15}$ meters where the strong force can have affect. Speed through high temperature therefore makes the particles able to close in on each other so that the strong force can overcome the electromagnetic force. (EUROfusion 2017d)

3.2 Heating

Tokamak is a type of fusion reactor, that induces an electric current inside the plasma. This current makes electrons and ions inside the plasma collide, create resistance and therefore heat. When the plasma heats up, the resistance decreases, and heating is not increased anymore. Therefore the tokamak system needs an outside heat source due to the limitations of heat transfer through high-intensity electric current also called ohmic heating. (ITER 2017i) Electric current is not used to heat and create plasma in stellarators, instead they use only external heating. (IPP 2018e)

Neutral beam injection and high-frequency electromagnetic fields are the two most used external heating sources for both tokamaks and stellarators and they can be used side by side. Neutral beam injection consists of an ion source, accelerator and a neutraliser. Charged hydrogen particles, usually deuterium, are accelerated in a high-voltage electric field and then neutralised through ion beam neutralizer. When the high-speed particles are added to the plasma inside the vessel, they give out their energy through collision. (EUROfusion 2018b)

The second method consist of high-frequency waves that are introduced into the plasma increasing the velocity of the particles and in turn produce heat. As the particles go in circular motion around the magnetic field line, they all have different frequencies. Three different types of waves are involved matching the frequencies of the electrons and ions in the plasma creating suitable resonances and therefore heat. (IPP 2018c)

In fusion the goal is to heat the plasma sufficiently so that the so called burning plasma is achieved. Burning plasma is created with D-T fuel when large amounts of fusion reactions generate enough helium-4 nuclei to sustain the temperature of the plasma by colliding into deuterium and tritium and turning kinetic energy into heat. (ITER 2017i) When the ratio of energy (Q) generated through helium-4 and heating power added is one, the situation is called break even. With factors bigger than one, fusion reactions will start producing a positive net output. (CEA 2001a)

3.3 Confinement

Plasma has a predisposition to expand which means its confinement must be controlled to achieve the triple product. The extreme temperature also means that the reactor vessel walls can't bear the heat load and the interaction would diminish the heating effect. (ITER 2017g) Magnetic and inertial confinement are two the most prominent and most investigated methods, magnetic confinement currently being the most researched and it is used both in tokamaks and stellarators. These methods include the control of density as well.

3.3.1 Magnetic confinement

In magnetic confinement fusion, magnetic fields are used to control the charged particles of plasma. The density can be low with this method as the confinement time is increased to achieve triple product (Energiateollisuus ry 2011). Magnetic field is always perpendicular to the velocity of a charged particle. This means when a particle is subjected to magnetic field in a toroidal shape it will be forced into spherical and helical orbits around the field lines. Plasma then stays confined when no radial magnetic field, which would push the particles outside, is added. (IPP 2017b)

In general, a solenoid creates a uniform magnetic field inside it and charged plasma particles would follow these magnet field lines winding around them. To totally confine the plasma, the solenoid is turned into a toroidal shape avoiding plasma from escaping at the ends. (Lumen Learning 2017) The downside is that the plasma is denser on the inner circle than on the outer circle as the radius is smaller. This leads to positive charges going upwards and negative downwards losing the plasma confinement. Twisting the magnetic field can help avoid this.

Initially magnetic confinement was thought of being a simple way to confine plasma but avoiding turbulence and excess leaking has been proven to be a challenge. Tackling these issues are done in different assemblies of magnets in tokamaks and stellarators, which leads to the differences in the reactors. (IPP 2017b)

3.3.2 Inertial confinement

Inertial confinement is based on the use of lasers in heating and compressing the hydrogen nuclei in order to fuse the two hydrogen isotopes. It focuses on increasing the density in order to achieve the triple product (Energiateollisuus ry 2011). In inertial confinement fusion, the force holding down plasma is its own inertia instead of magnetic fields. A tiny spherical pellet filled with deuterium and tritium is pointed at with a laser or an ion beam. The applying of sudden and intense pressure and temperature causes some material on the outer layer of the pellet to ablate. (NNSA 2017) Newton’s third law, stating that for every action there is an equal and opposite reaction, causes the explosion on the outer layer to result in an implosion. The implosion causes compression and a shock wave to the fuel inside the pellet heating it further up. The heat results in a self-sustaining burn of the fuel that spreads outward. The outward move is faster than the expansion of the capsule which causes inertia of its own mass that confines the plasma. (Lawrence Livermore National Laboratory 2017)

Inertial confinement can be direct or indirect. In direct method the laser or ion beams are focused closely to the small fuel pellet. In the indirect method the lasers are aimed at the gold cavity or hohlraum containing the fuel pellet. When the hohlraum then warms up, it generates x-rays that will in turn cause the same implosion effect as in the direct way. (World Nuclear Association 2017)

3.4 Plasma discharge and refuelling

The fusion process starts by creating an ultra-high vacuum inside the vessel and removing all impurities. The confining magnets in tokamaks and stellarators are turned on and then the fuel gas is injected via a gas injection system. Once the low-density gas is inside the chamber, the electric current is turned on in tokamaks. (ITER 2017b) This breaks down the gas making it ionised and creating the plasma. Stellarators don't use electric current, instead only external heat sources create the plasma (IPP 2018e). Only around one gram of fuel is inside the vessel at once. (ITER 2017b)

The heating determines the length of the discharge. In tokamaks, as the transformer is used to create and control plasma, the current is the limiting factor leading to the pulsed functioning of tokamaks. The slowly reducing current will achieve its minimum where no more flux change can be achieved and the discharge comes to an end. ITER tokamak is proposed to have plasma discharge up to 400-600 seconds. (ITER 2018e) Stellarators don't utilise current in the plasma, which means it can possibly work continuously.

The amount of plasma particles diminish as the divertor works and removes impurities. This means more plasma must be inserted to replace the flow. There are several refueling methods: neutral particle injection, pellet injection and gas puffing from the edge of the vessel. Tokamaks and stellarators usually use pellet injection. In this method hydrogen gas is cooled down and compressed into ice pellets. These pellets are then accelerated and injected into the plasma. The pellets can be aimed at a certain part of the plasma which makes them able to minimize edge localized modes. These are energetic bursts that cause energy loss by leaving the magnetic field. The pellets can be released at any given place to be evaporated and ionised helping to change the plasma's density profile. (IPP 2017h) The divertor collects also unused fuel which then is separated from the waste helium and recycled back into the vessel with the pellets. (ITER 2017b)

4 FUSION REACTORS

In this chapter the two most researched fusion devices are compared. Principles of these reactors are introduced in general but ITER’s tokamak and IPP’s Wendelstein 7-X (W7-X) stellarator are used as case examples. The first plasma for W7-X was achieved in December 2015 and its main goal is to demonstrate the continuous operation of stellarators. W7-X is proposed to sustain plasma discharge for up to 30 minutes. (IPP 2017i). ITER's tokamak is planned to have its first plasma in December 2025, and its larger scale will try to prove the feasibility of fusion power plant and its different components (ITER 2017d).

Fusion power research started developing more after the Second World War. A conference in 1958 called “Atoms for Peace” initiated the international cooperation as nations showcased their research publicly. It became clear that achieving a functional fusion reactor is not an easy task which lead to joint operations between many parties. Different configurations for fusion devices were designed and two of the most prominent ones nowadays are tokamaks and stellarators. Tokamaks are widely researched whereas stellarators are yet not. Initial work on stellarators revealed many main components that are now in use in tokamaks but stellarators were forgotten for a few decades due to their technical complexity until recently. (Encyclopaedia Britannica 2017a)

Both reactors have some advantages and disadvantages. The biggest difference is the way the plasma is confined by twisting the magnetic field and therefore emphasis on this thesis is on the magnet configurations. Xu (2016) introduces the three different ways the twist can be done: making a toroidal electric current create a poloidal field, changing the poloidal cross-section of flux surfaces around the torus, or creating the magnetic axis non-planar. Tokamaks usually use the first approach and stellarators the latter two.

Figure 2 shows that the tokamak is axisymmetric meaning it’s symmetrical around the axis and has toroidal and poloidal field coils. The toroidal field coils shown in blue in figure 2 are constructed around the torus creating the toroidal magnetic field inside it. Both stellarators (figure 3) and tokamaks have toroidal field coils, but they are not symmetrical in stellarators. To improve confinement, tokamaks also have poloidal field coils. In figure 2, the primary transformer circuit, i.e. the central solenoid, is shown in green inside the torus and it is made of the inner poloidal field coils. It induces a current into the plasma working as the secondary transformer current. The toroidal current is created by a transformer, which makes it hard to operate in a steady-state. The additional outer poloidal field coils in grey make the resulting magnetic field helicoidal, seen in black in figure 2, and therefore tokamaks have a good plasma confinement.

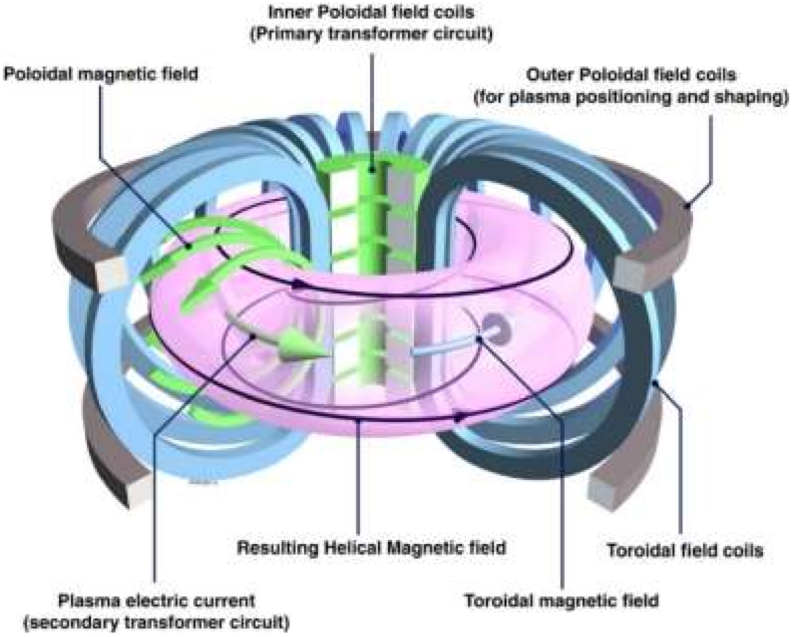

Figure 2. Tokamak with toroidal field coils and inner and outer poloidal field coils (EUROfusion 2018d).

Stellarators avoid the pulsed functioning issue by not creating a current in the plasma and instead ensure only with magnetic coils that every plasma particle feels the same force. The trajectory of a single plasma particle is depicted in figure 3 in the yellow plasma in a green line. Confinement is generated by the complex asymmetric toroidal magnets that can be seen in figure 3 below in blue. Stellarators have only toroidal field coils and no poloidal. The downside to this is the complexity of modelling and building such a device. It is also prognosed that stellarators might have inferior confinement by having more collisional transport called neoclassical transport that is more deeply studied in plasma physics and not discussed in this thesis. (Xu Y. 2016)

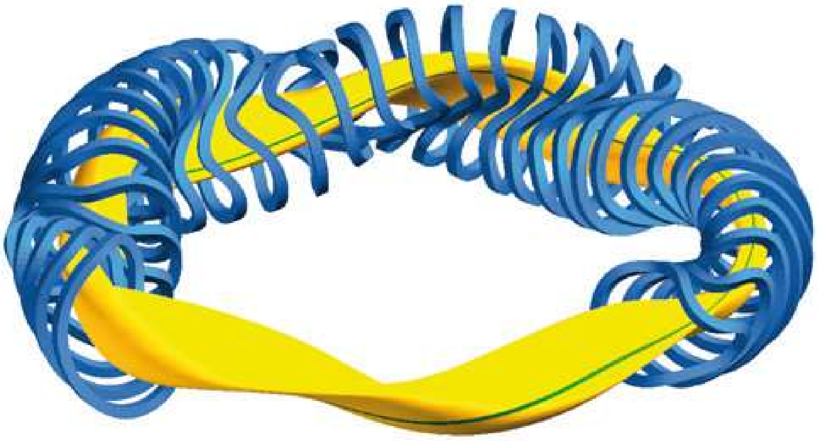

Figure 3. Stellarator magnet coils in blue and plasma in yellow. Plasma particle trajectory in green (IPP 2018f).

4.1 Research organisations

4.1.1 ITER

Progress in the research of fusion and tokamaks led to the birth of the ITER project. The word ITER comes from Latin meaning "the way" and it is the most ambitious project in nuclear fusion energy currently. There are 35 countries involved including European Union, China, United States, India, Russia, Japan and Korea with the aim to build the largest magnetic tokamak. The goal for ITER is to prove the feasibility of fusion-based electricity, its safety, technological and physical properties and material components. (ITER 2017d) The project initially started in the 1980's when leaders proposed the idea of developing fusion for peaceful purposes and the ITER Agreement was signed in 2006. The members decided to locate the premises in southern France and the construction work began in 2010. (ITER 2017e)

ITER tokamak will not produce electricity, its main goal is only to prove the functionality of fusion power. This reactor is designed to produce up to 500 MW of power for up to 1000 seconds from an energy input of 50 MW. (O'Keefe P. et al. 2010, p. 151). Modern fission reactors in Finland are currently producing net energy of 880-1600 MW (Teollisuuden Voima Oyj 2017a & 2017b). Producing tritium and using it as a fuel in a closed fuel cycle is crucial to the future of fusion energy due to the limitations of tritium in the nature. One of ITER's later objective is to test the production of tritium breeding from lithium inside the vessel during fusion reaction. (ITER 2017d)

EUROfusion is a European consortium for the development of fusion energy and it has a joint mission with ITER to plan DEMO or Demonstration Fusion Power Reactor. DEMO's objectives are after 2050 and after ITER Tokamak, to produce several 100 MW net electricity to the grid and to produce tritium in a closed fuel cycle. (EUROfusion 2018f)

Another organisation closely connected to ITER is the Joint European Torus or JET. JET is located in Oxfordshire, UK and has been operational since 1983. (O'Keefe P. et al., 2010, p. 151) It is the most efficient and currently the only functioning tokamak capable of producing energy using deuterium and tritium. It holds the record for produced fusion power of 16 MW from 24 MW input for one second in 1998. Level of breakeven (Q=1), i.e. the ratio of one with input energy to heat the plasma and the output energy, has yet not been achieved with fusion reactors. JET's record makes the biggest ratio at Q=0.67. (ITER 2018d)

JET is a collaboration between European Commission and the Culham Centre for Fusion Energy and initially it was designed to study plasma and make way for future fusion reactors. Research done at JET is now reported for ITER and the tokamak in JET has also been modified to be more equivalent to ITER tokamak. (EUROfusion 2017c) One of the most important transformation has been changing the walls to match those of ITER tokamak. The inner walls of the vessel are now beryllium and tungsten and JET is being tested for erosion and other reactions the walls may have. These results are then benefitted at ITER. (EUROfusion 2017e)

4.1.2 IPP – Max Planck Institute of Plasma Physics

Max Planck Institute of Plasma Physics (IPP) was founded in 1960. It is a part of the Max Planck Society and the Helmholtz Association of German Research Centres. IPP is also associated with the European Fusion Programme and the JET. IPP is unique in a way that it studies both tokamaks and stellarators as fusion devices. This helps immensely to compare the two designs. (IPP 2017a)

The newest stellarator Wendelstein 7-X by IPP branch of Greifswald started operation in 2015. It is currently the biggest stellarator and its objective is to study the continuous operation of a fusion device as it is designed to have a plasma discharge up to thirty minutes. W7-X has many research goals, but it is not intended to yield energy as this is already a target for ITER tokamak. ITER's results on ignited plasma can be adapted to stellarators and therefore IPP's stellarator doesn't have to use tritium as fuel, making its operation cheaper. (IPP 2018a)

Princeton Plasma Physics Laboratory PPPL was one of the pioneers in plasma physics and stellarator design. Project Matterhorn started the fusion research in 1951 and professor Lyman Spitzer designed the early figure-8 fusion device he named stellarator. Its concept was later turned into a tokamak and nowadays PPPL is a part of both stellarator and tokamak research. (PPPL, 2018)

4.2 Tokamak

4.2.1 Vessel

ITER tokamak is a torus-shaped vacuum chamber shown in figure 4 below, which represents the cross-section of the entire device. The magnetic tokamak ITER is building will have interior volume of the chamber of 1400 cubic meters with the potential of 840 cubic meters in plasma volume. The vessel will measure 19.4 meters width and 11.4 meters in height. This will be ten times bigger in plasma chamber volume than any tokamak currently operating. (ITER 2017k) The large size of the vessel results in more reactions as the amount of plasma increases. This will produce more fusion power proving its feasibility. (ITER 2017d)

ITER tokamak's vacuum vessel has a D-shaped cross-section depicted in figure 4 in the centre surrounding the vertical central solenoid. The blanket i.e. the inside surface of the vessel consists of first wall panels and shield blocks. The first wall is designed to capture the heat load as it faces the plasma directly and beryllium is chosen for the surface material. Beryllium is very durable, and it has a high heat conductivity (Blaszczak-Boxe A. 2017). In the future the inner layer will also play a role in testing the tritium breeding during the fusion reaction. Shield blocks provide support and they are designed to block the high-energy neutrons from harming other components such as the magnets. (ITER 2018a)

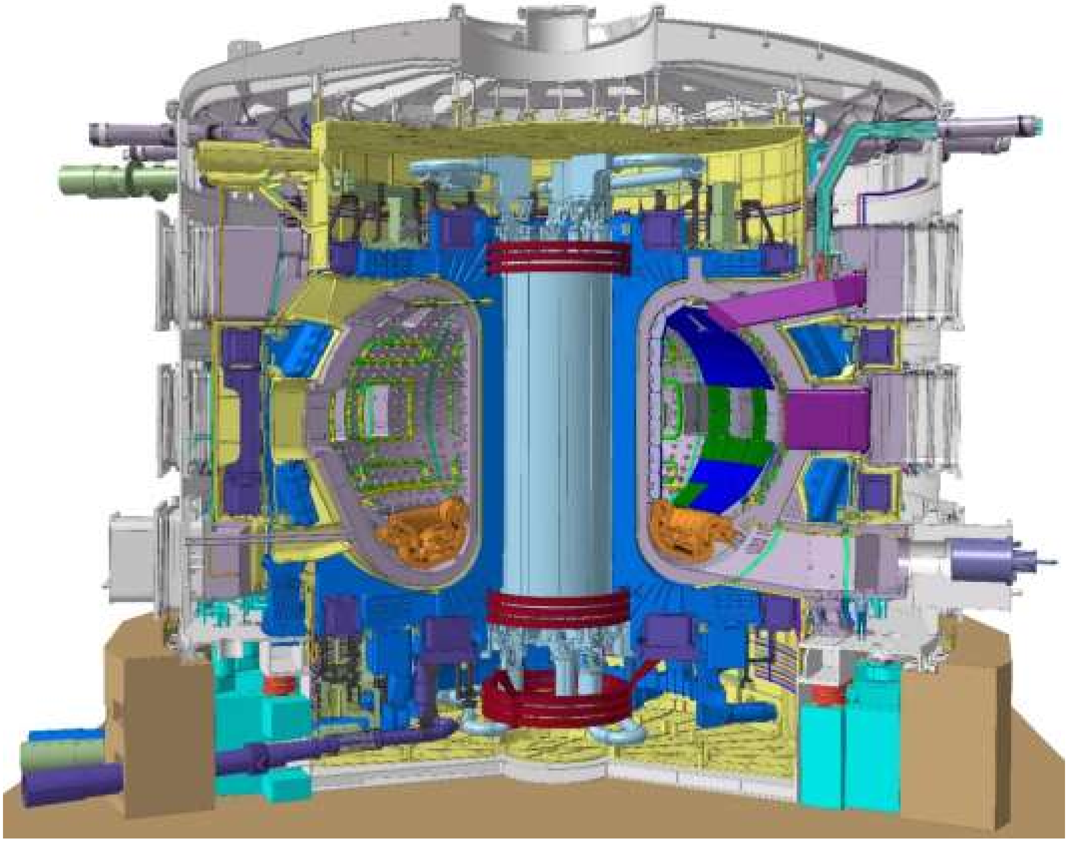

Figure 4. Cross-cut of ITER tokamak with D-shaped vacuum vessel, central solenoid, divertor at the bottom of the vessel and other additional supporting systems enclosed in cryostat (ITER, 2018b).

Tokamak has a divertor which has a purpose of removing ash and heat from the bottom of the vacuum vessel. The divertor can be seen in the earlier figure 4 in orange at the bottom of the D-shaped vessel. The magnetic fields cover the entire vacuum vessel and therefore the plasma spreads until it would touch the walls. The divertor is an auxiliary magnetic field that directs the plasma edge to the targets instead of straining the vessel walls. (IPP 2017e) It keeps the plasma pure and protects the walls from thermal and neutronic loads. Tungsten with the highest melting points of all metals has been selected as the construction material as it will have to endure the highest temperatures. (ITER 2017a)

The vessel has a cooling system inside its double layered walls containing cooling water. As the high energy particles hit the walls, will their kinetic energy turn into heat which is removed. This heat would produce steam and power in the future's power plants.

The ITER vacuum vessel will then be enclosed inside an ITER cryostat. In the figure 4 the cryostat is the outermost grey part concealing the entire device. It is an ultra-vacuum and intensively cooled environment for the vessel and the superconducting magnets. It is the biggest component of ITER tokamak measuring nearly thirty meters in width. It will have several openings for access to operation systems and diagnostics. (ITER 2018f)

4.2.2 Magnets

Tokamaks have toroidal and poloidal field coils but also a central solenoid. The additional solenoid inducing the electric current in the plasma is technically simple, but the downside is that the electric current is induced via a transformer. When the fuel gas is inside the chamber, the transformer is discharged. The current is slowly reducing and once the minimum is reached it can no longer produce a flux change which leads to decreasing current and the shutdown of the reactions. As more effective super-conducting magnets are developed, the pulse length will theoretically be up to an hour. (IPP 2017f)

Figure 2 earlier shows the magnetic configuration used in JET. The same concept is used in ITER tokamak, but here the scale is bigger. D-shaped toroidal magnet coils create the confinement inside the torus-shaped vessel. Inner poloidal coils create the transformer inducing the current inside the plasma. To improve the plasma trajectories and minimize leakage, outer poloidal magnetic coils are added to strengthen the poloidal field created by the plasma current. Figure 2 shows how the poloidal fields are perpendicular to the toroidal and make the magnetic field lines helicoidal improving confinement. (EUROfusion 2018c)

The ITER tokamak consists of eighteen toroidal (Figure 5) and six poloidal field magnets. The toroidal field coils shown in figure 5 are one of the biggest components in ITER tokamak measuring at 17 meters in height and will be built individually. The goal for the toroidal coils is to produce 41 gigajoules of magnetic energy and up to 11,8 tesla magnetic field. The poloidal coils can produce 4 gigajoules of energy and 6 tesla magnetic field. The system also has correction coils in between the poloidal and toroidal superconducting coils. These 18 coils are much smaller but help to correct the deviations caused by geometrical flaws in the assembly.

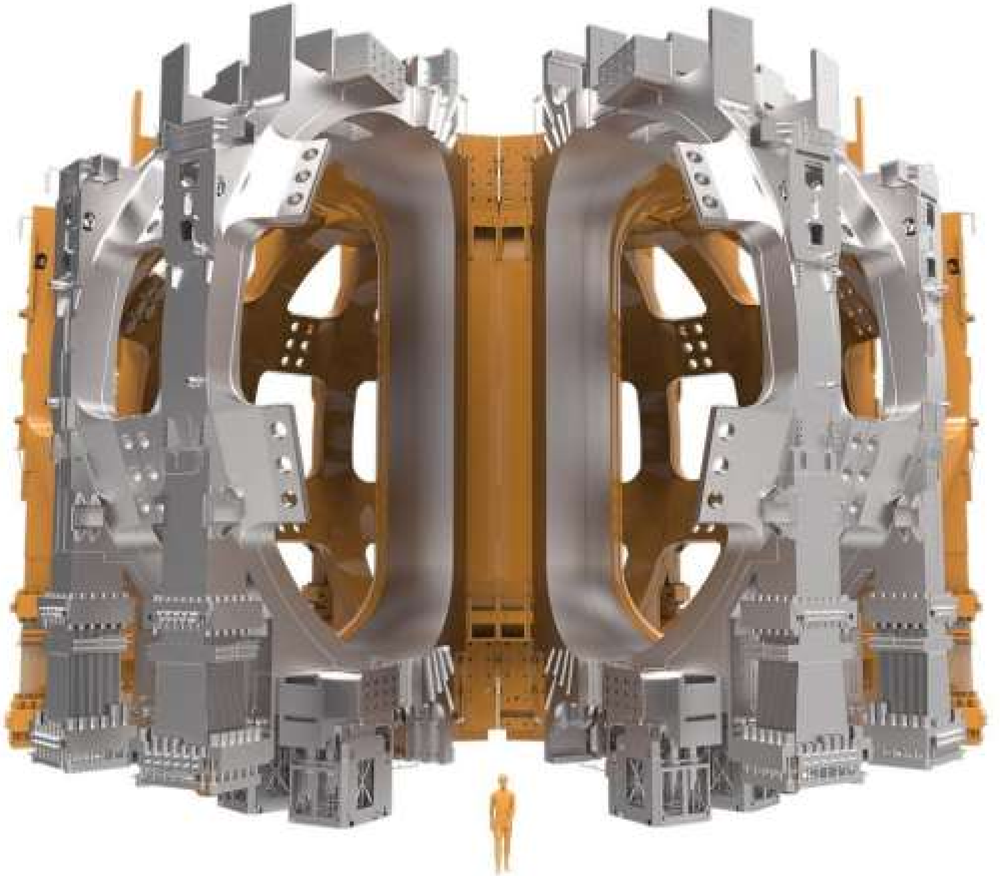

Figure 5. The 18 D-shaped toroidal field coils in ITER tokamak (ITER, 2018c).

Central solenoid is in the middle of the torus producing the electric current inside the plasma. It is thirteen meters tall and four meters wide, consisted of six independent coil packs. This solenoid will initiate the plasma current of 15 megaamperes with its stored magnetic energy of 6,4 gigajoules. The current can only last 300-500 seconds leading to the pulsed functioning of tokamaks. The central solenoid is the most powerful magnet system in ITER tokamak with a field of 13 tesla. Support structure for the solenoid must endure the strong magnetic fields and electromagnetic forces that are created with the independent coil packs. (ITER 2017f)

The ITER magnets will be made of niobium-tin (Nb3Sn) or niobium-titanium (Nb-Ti). The superconducting strands are bundled together and enclosed in a steel outer layer, a method called cable-in-conduit conductors. The magnets become superconducting when they are cooled at 4 Kelvins with supercritical helium. (ITER 2017f) Supercritical helium means it is cooled under its critical point where its phase between liquid and gas is not easily explained (Weisend J. 2016).

4.3 Stellarator

4.3.1 Vessel

Tokamaks are perfectly axisymmetric whereas stellarators are helically twisted. Stellarators have in intricate design for the magnet coils and as the plasma vessel follows the shape of the coils, will the vessel also be asymmetric. This can be seen in a representation of different layers of W7-X in figure 6. Orange and silver coils on the left of the figure 6 are the magnet coils. The vessel inside the coils is seen on the right following the shape of the coils. The plasma shown in pink in the figure 6 mimics the shape and has a different cross-section in separate places of the vessel. (IPP 2018b)

W7-X is substantially smaller than the ITER tokamak. It has a major radius of 5.5 meters and plasma volume of 30 cubic meters. The smaller plasma volume can yield heating power of around 15-30 MW. (IPP 2018a)

Unlike tokamaks, stellarators don't have to have an additional magnetic field to divert the impurities and incident particles. In stellarators, the plasma boundary divides into individual branches that then divert into special isolated parts of the vessel. These parts are made of special plates and located around the vessel walls unlike the tokamak divertor which is located on the bottom of the vessel. These ten plates neutralize the plasma particles and any impurities and then pumps them out. (IPP 2017d)

The vessels that confine the plasma have similar properties both in tokamaks and stellarators. No impurities can enter which means the vessel must be at a pressure less than 10^{-8} millibar meaning ultrahigh vacuum. To protect the vessel walls from the extremely high temperatures, the plasma is confined into the center of the vessel. The vessel is mainly constructed of high-grade stainless steel to sustain the ultimate pressure, temperature and possible magnetic forces caused by regional currents. Cryostat is also used in stellarators like in tokamaks and it conceals all the components inside it. Measurements, observations and remote handling can be done through several ports in the reactor. (IPP 20017g)

4.3.2 Magnets

Stellarators have only external toroidal field coils and no internal longitudinal net-current in the plasma like tokamaks, hoping to make fusion reaction work more continuously. This makes working in longer periods stellarators' main advantage. The downside to stellarators is the very detailed design of each magnetic coil seen in figure 7, which makes them intricate to build. (CEA 2001b)

Figure 6. The 50 non-planar superconducting magnet coils (silver) and 20 planar magnet coils (orange) confine the plasma depicted in pink (IPP 2018f).

W7-X is built to test the optimized magnetic field for confining the plasma in a stellarator power plant. It consists of 50 non-planar superconducting magnetic coils that are depicted in figure 6 as the silver coils. (IPP 2017i) The formation is calculated precisely to ensure the magnetic field is as tight and stable as possible and it is designed to produce a field of 6 tesla on the coils. (IPP 2017c) The 50 magnetic coils that reach 3.5 meters in height will be linked up with additional 20 planar magnetic coils that allow the field to be varied. The planar coils are in orange in the figure 7. When the magnets are turned on and cooled, they will need nearly no added energy. (IPP 2018b)

Superconducting coils are similar to ITER tokamak; made out of niobium-titanium and cooled with helium at 4 kelvins. The magnetic coils are of flexible copper strands bundled together and strengthened with fiberglass and synthetic resin. (IPP 2017c)

4.4 Physics

Magnetohydrodynamics (MHD) studies the dynamics of magnetic fields in electrically conducting fluids like in plasma. The research is crucial for fusion, as MHD govern the functions of the fusion and minimisation of these instabilities will lead to a higher chance of success in fusion power production. (Dorch S. 2018)

Freidberg (2008) mentions there is a possibility of creating a sufficient electric current inside a tokamak without using an external current driver. This would make tokamaks able to work in a steady state and therefore their operation more promising. It could be done by a phenomenon called bootstrap current. It is produced when trapped particles and moving particles collide creating an internal toroidal current due to the different gas pressure inside the vessel. Freidberg points out that this could work in principle but creating a suitable pressure profile might exceed other limit values.

Xu (2016) tells tokamaks are axisymmetric which means symmetrical around an axis and have better confinement for the plasma and control of collisionless particles. Stellarators on the other hand have more unconfined particles which can lead to high unwanted neoclassical transport. Minimising the neoclassical transport is important in the development of stellarators and quasi-symmetry has been proposed as a solution. Quasi-symmetry expresses the magnetic field as a function of only one helicity angle and the flux surface.

Xu points out in her article (2016) that the technical simplicity is a big advantage for tokamaks. However, if the neoclassical confinement is improved in stellarators, they could be more feasible in the future due to their continuous operation since the tokamak current still lacks a solution. Understanding the importance of plasma physics in the design of magnetic configurations is crucial, but a deeper review is not included in this thesis.

5 SUSTAINABILITY

5.1 Environmental

As energy production increases, so does its environmental impacts. Energy produced by combustion like in traditional coal and gas fired plants produce emissions and greenhouse gases. These can also cause acid rains and urban smogs. Nuclear energy generates heat from nuclear reactions instead of combustion which means nuclear reactions don't cause air pollutants. This not only helps to fight climate change but also improves quality of air in urban areas. When considering the entire lifecycle from construction to decommissioning, nuclear power does use natural resources like all industrial applications. (O'Keefe P. et al. 2010, p. 140)

Another environmental aspect to consider is fuel. In traditional nuclear fission power plants, uranium is used as fuel. Uranium must be mined and handled significantly which causes environmental impacts. Mining produces a lot of side rock because the most usable isotope uranium-235 is only 0.72 % of all uranium. Degradation of landscape and impact on nature is large also due to transportation. (Fraas A.P. 1973)

The amount of fuel used is also substantially smaller in fusion than in conventional methods - only a few grams of fuel will be needed inside the fusion reactor at once. Fusion therefore is around four million times more energetic than the burning of some fossil fuels. When this is combined with the fact that deuterium can easily and cheaply be extracted from seawater, are the impacts from fuel production substantially smaller. Technology for distilling deuterium already exists and the reserves are vast. Tritium on the other hand has to be produced by lithium, which makes lithium the limiting substance. Methods of extracting lithium from land, either from hard rock or brines in salt lakes, are already established and the reserves could last over a thousand years after which lithium could be harvested from seawater. (ITER 2017c)

Radioactivity is one concern with nuclear reactions. Deuterium and tritium are the most prominent fusion fuels reacting into a helium-4 and a neutron. Deuterium is a stable isotope of hydrogen, so it is not radioactive. Tritium is a radioactive isotope and hard to contain since it can penetrate even some grades of steel but is dangerous to humans only if it gets inside the body by inhaling, ingesting or absorbing through skin contact. It emits beta-radiation and has a half-life of 12.3 years which is short when compared to radioactive waste from fission reactions. Tritium is very mobile and being an isotope of hydrogen, can easily mix with oxygen creating tritiated water. (Radioactivity 2017b) Tritium however is only an intermediate product before it turns into helium after fusing with deuterium, so it doesn't pose a significant threat. (Energiateollisuus ry 2011) In fusion reactions tritium is produced inside the vessel from lithium since it can't be found in sufficient quantities on Earth. Therefore tritium would only exist in the vessel and quickly fuse with deuterium. Li-6 used for tritium breeding is one of the two naturally occurring isotopes of lithium and is stable.

The main end product helium-4 is identical to alpha particle with two protons and two neutrons. Helium-4 itself is an inert gas and not radioactive, but its high speed from the reactions can be enough to ionise other atoms. Alpha particles however are easily stopped with paper and could only pose a threat to humans if inhaled. This is prevented with the vessel, which inhibits the particles from exiting. During the operation, helium-4 is controlled with magnetic fields and after the magnets are shut down the nuclei will recombine with some electrons to become inert helium gas. (EUROfusion 2018c)

Free neutrons are also created in fusion reactions. Neutrons outside of nuclei are unstable and a subject to beta decay with a half-life of around 10 minutes. (Nuclear Power 2018) Neutrons are the only source of radiation that can change other materials radioactive. Usually this is done indirectly by joining a stable atom and making it unstable by ionisation. (Mirion Technologies 2017) Neutrons can travel thousands of meters in air and penetrate even metal plates but are easily stopped with a hydrogen-rich material such as water or concrete. Often boron is added to increase the capture of neutrons. (Radioactivity 2017a)

Free uncharged neutrons escape the plasma and interact with the vessel walls. Neutrons can be dangerous to humans if leaked out of the reactor vessel so attention to the vessel materials must be paid. Blanket of the vessel is designed to capture the high-energy neutrons and remote handling system is in place so that neutrons won't be in contact with humans during operation. (World Nuclear Association 2017) The neutrons will activate the blanket and therefore the radioactive waste in fusion is the reaction vessel. (Freidberg J. 2008, p. 16-18) This radioactivity is very short-lived and will disappear within 50-100 years, depending on the used materials. Radioactivity will be confined only in the reactor itself meaning no high-level waste to be transported and disposed will arise. Radioactive waste from fission reaction products on the other hand will remain radioactive for thousands of years. (EUROfusion 2017a)

5.2 Economical

Making fusion work has major scientific and technological challenges. Triple product including temperature, confinement time and density has proven to be hard to achieve. Scientific research takes time and the complexity of the issues is the reason why fusion is not yet working. A lot of the instabilities occur only in fusion systems, so no equivalent problems can be found elsewhere. This increases the demand and difficultness of fusion research, adding up to the costs.

As the science is so advanced, it creates more challenges for engineering as well. To create these demanding and precise conditions, must new and effective equipment be developed. A system to create the immense temperature of 100-150 million Celsius has to be created but also a vessel that can sustain the heat and neutronic load. Superconducting magnets to confine and control the plasma efficiently are complicated and also the calculating and modelling of the magnetic structure is a challenge. More developed computers help along with the experiment results. (Freidberg J. 20018, p.18)

The scientific research and building the complex reactors create economic challenges. The investment costs of building a fusion reactor are high but they can be balanced with the inexpensive fuel and no additional costs due to environmental protection during operation. Freidberg (2008) also comments that estimations on the final price of fusion electricity is hard to make. Energy field is constantly changing, and the price of some conventional methods might rise due to fuel reserves and environmental protection.

Fusion devices are extremely expensive which is one of the reasons why they are done in collaboration with many countries and institutions. Building ITER tokamak will cost around 5 billion euros (Energiateollisuus ry 2011). This has also led to changing the mindset of nuclear power into more openness where information is shared between parties. (ITER 2017e)

5.3 Social

Nuclear power can be associated with accidents and radioactivity and therefore its social acceptability is often under debate. These threats are almost uniquely connected only to nuclear reactions and not to other power sources. However, within nuclear power, there are two different reactions that have very different characteristics.

One concern in fission is its chain reaction that can cause runaway reactions leading to radioactive exposure. This means that fission reaction will continue if it is not controlled when new free neutrons from the reactions hit more nuclei splitting them. Severe accidents can happen if a malfunction happens inside the fission power plant. However, this is not possible inside a fusion power plant. Fusion demands very precise conditions to work and if any malfunction would occur, the reaction would shut down automatically and instantly, remarkably improving the safety features. (World Nuclear Association 2017) The amount of D-T fuel inside the vessel at once is only around 1 gram whereas a fission reactor can have fuel inside the core corresponding to years of energy production (Freidberg J. 2008, p. 17). Even if the very unlikely incident would happen that would lead to the fusing of all of the fuel instantaneously, this would result only in a small increase in temperature of the blanket which would not risk the confinement. (Fraas, A.P. 1973)

Additional concern can be nuclear weapons that utilize the same principles as nuclear reactions in energy production. The first thermonuclear bombs utilizing fusion reaction were released in the early 1950’s and soon after it was realised that developing fusion energy is not connected to it. Fuel in fusion reactors is measured in grams whereas the required amount for a thermonuclear bomb is tens or hundreds of kilograms. Research on fusion therefore does not conclude military purposes and cooperation between countries to develop fusion energy has been very open since the beginning. (LPPFusion 2017)

A characteristic for fusion energy research is its transparency and cooperation of multiple parties. Scientific and technologic research is demanding and requires good funding and therefore different organisations and countries have joined together to broaden their expertise and maximise the chance of making fusion energy viable. Both ITER and the Max Planck Institute are developing fusion together with several parties and for example

ITER’s journey began from an agreement of international research of peaceful use of fusion energy. (ITER 2017e)

Energy security is also a subject that can have significant social effects. European Union imports more than half of its energy making EU vulnerable to changes in the supply. Shortages can be caused by political or commercial disagreements but also failures in infrastructure. Energy dependency is acknowledged in Finland but also at EU level, where European Commission has released a strategy with a goal to ensure stable energy supply. This is proposed to be done with increasing internal energy production and diversifying the energy field but still reaching the set climate goals. (European Commission 2018) One proposed solution from the commission was investing in nuclear energy. Fusion energy could extensively contribute to solving this issue in the coming decades if its functionality can be proven.

Produced fusion energy starting from 1970’s has increased from one watt to over 10 MW proving that the development is fast. Yet fusion research is sometimes seen as unnecessary because fusion power plants still have not proven to be feasible. Also the next improvements in power output won’t happen until after ITER and DEMO. Fusion power is related to fusion chamber size and energy losses to the surface area, and no current reactor is large enough to balance these. (Energiateollisuus ry 2011)

6 SUMMARY AND CONCLUSIONS

Fusion and fission are nuclear reactions where energy is released either by fusing atoms together or by breaking them apart, depending on the nuclear binding energy. Binding energy tells the amount of energy that is needed to break apart a nucleus and the produced energy is equivalent to the mass defect. When heavy atoms like uranium split, or when light atoms like hydrogen fuse together, they create more stable atoms. This means they have a higher binding energy. Therefore the energy needed to make the reactions is smaller than the energy released and the nuclear binding energy curve for each sized atom shows the tendency to do this either by fusion or fission. Iron has the greatest binding energy per nucleon and it differentiates energy producing reactions either to fusion or fission – nuclei smaller than iron produce energy through fusion and nuclei bigger than iron through fission.

Created energy can be counted from the mass defect that happens in the reactions. The mass of nucleons separately is greater than when they are combined into a nucleus. The relation between released energy and change in mass is seen in Einstein’s equation.

Fusion is the fundamental energy producing reaction that is occurring spontaneously in the Sun. There hydrogen atoms fuse together creating helium and other heavier elements all the way up to iron. The primary fuels in fusion reactors are different isotopes of hydrogen; deuterium and tritium. One D-T reaction gives a helium-4 and a neutron as end products and releases 17.6 MeV.

Making fusion work needs temperature, density and confinement time, also called triple product, to reach high enough values. Pressure and gravity on Earth are lower than on the Sun, which means temperature in the reactor has to reach 100-150 million Celsius. The process starts by injecting the fuel gas into the fusion reactor and heating it. Heating is most often done by electric current, neutral beam injection or high-frequency waves.

Heating ionises the gas turning it into plasma. Plasma is the fourth state of matter after solid, liquid and gas. In plasma, electrons are separated from nuclei making them electrically charged and exposed to magnetic fields which are usually used to confine the plasma. In order to fuse, positive hydrogen isotopes must overcome the electromagnetic repulsion. This happens if the distances are short enough for the strong force to have affect. Sufficient plasma density and high speed through temperature enable this.

Around 80 % of released energy disappears from the plasma with the created neutrons. They don't have a charge that could be affected by the magnetic fields making them escape the plasma and hit the vessel walls. Neutron bombardment giving out their kinetic energy, and heat radiating from plasma raise the temperature of the cooling system inside the walls. The power generation in the future would work like in many conventional power plants. Heat of the cooling water creates steam which in turn can move turbines and create electricity through generators.

Helium-4 created in the fusion reactions stay in the plasma and contribute to heating it through collisions. When the plasma heating from helium is greater than the energy loss from the neutrons, the plasma has reached ignition. External heating is no longer needed, and plasma is self-sustained. Breakeven is the moment when external heating energy input is equal to the output of energy from fusion reactors. This is when the ratio is at Q=1. So far this has never been achieved, the highest ratio is from JET at Q=0.67.

The two most investigated fusion reactor types are tokamaks and stellarators. Both are using many of the same components, but their overall magnetic configurations are not alike. Using magnetic fields created by superconducting coils to control the plasma is the basic principle in both but their assemblies differentiate them.

Tokamaks have toroidal field coils to confine the plasma in the shape of a torus. The plasma density on the inner circle due to smaller radius is bigger than on the outer circle which would lead to losing the plasma confinement. This is fixed with a central solenoid which is composed of inner poloidal field coils. They work as primary transformer circuit inducing an electric current into the plasma. Additional poloidal field coils are on the outer circle of the plasma vessel to improve the plasma shape. The resultant magnetic field is now helicoidal, which improves the plasma particles' trajectories.

Stellarators don't have an electric current in the plasma, instead they confine the plasma only with intricate magnet configurations. They are composed of toroidal superconducting non-planar and planar magnet coils. To compensate the lack of electric current, the magnetic field must be as tight and stable as possible. Each coil is designed in detail and the vessel and the coils will be asymmetrical unlike tokamaks.

Transformer-driven current in tokamaks can’t be sustained for long and the process will need to be restarted often. An advantage for tokamaks is their rather simple structure, but their biggest disadvantage is the pulsed functioning which is not desirable in power generation. Complexity is the biggest disadvantage for stellarators; modelling the complicated structure for each magnet needs extensive knowledge on plasma instabilities to be efficient. However, they are able to function continuously therefore having a great advantage over tokamaks.

ITER is building a large tokamak in France that is planned to have its first plasma in 2025. It has an objective to produce a tenfold return on energy making the energy ratio Q=10, creating 500 MW of power. ITER tokamak in the beginning is planned to sustain the reactions for 400-600 seconds. IPP has constructed W7-X stellarator in Germany which currently is the biggest reactor of this type and had its first plasma in 2015. IPP’s stellarator can work for up to 30 minutes and one of its goals it to prove the feasibility of steady-state in stellarators.

Although stellarators provided many of the initial design principles for tokamaks, they are yet not as researched and far from producing a positive energy output. The complicated structure has affected the progress and the scale of the projects conducted are in many ways at a lower level when compared to tokamaks. IPP’s W7-X is the biggest stellarator but still substantially smaller than ITER tokamak will be and focuses on the design of the reactor. Despite the advantage of continuous operation, the complex design has slowed down investments in stellarators.

No fusion reactor currently is planned to produce energy to the grid. As fusion power is related to the plasma volume, will ITER tokamak produce the most energy proving the primary feasibility of fusion power plants. The next effort after ITER will be DEMO, which is planned to be the first fusion power plant connected to the grid. However, even though tokamak functionality would be proven otherwise, they will still work only in pulses if no solution to electric current is found. Stellarators avoid the current issues but are currently not as advanced and the plasma trajectories not yet optimised. However, if the stellarator configuration could be improved, would they be more attractive option for the future.

Making fusion work would substantially help the energy field. Energy demand is increasing as the population and standard of living rises. Fossil fuels have limited supply and they also contribute to climate change whereas renewable energy has issues concerning reliability and volume. Nuclear reactions produce a lot of energy without emissions. Fission power plants have been in use for decades but are controversial due to radioactive waste and risk of accidents. Uranium used for fuel must be mined, transported and handled which increases environmental impacts. It also produces long-lived radioactive waste that must be stored for thousands of years and has a risk of runaway reactions.

Fusion could provide practically limitless amounts of energy from abundant fuel sources. Only a few grams of fuel is needed at once and the energy created in D-T reactions is almost 100 MWh/g. Fuel reserves of deuterium are seen to last at least thousands of years and it can be extracted cheaply and relatively easily. Tritium is the other fuel compound but can’t be found on Earth sufficiently. However it is proposed to be bred from lithium, which is an abundant element on Earth. Tritium-breeding is meant to be tested in ITER tokamak.

Fusion doesn’t have the risk of runaway reactions like in fission as its operation is very vulnerable to any changes in reactor conditions. If a malfunction would happen, the reactions would shut down immediately and automatically. The only radioactive waste would be the reactor vessel where the free uncharged neutrons would hit. This however would stay radioactive only for around 100 years depending on the vessel materials.

Fusion energy has immense potential, but the indisputable downside is its complicated nature. Fusion has been researched for decades now and yet no positive energy output has been achieved. Magnetohydrodynamics that studies plasma under magnetic fields is not thoroughly understood field which makes it hard to predict how fusion will evolve as computational modelling does not perfectly fit experimental results. More efficient computers and modelling are now helping to make way for the research.

Another issue in making fusion work is its cost. Scientific and technological research needs a lot of resources and there are not many fields from where knowledge can be directly applied into fusion research. The demanding requirements for fusion reactors also add to the cost. Highly engineered products with supreme characteristics must be built and in large size.

The major benefits of fusion have led countries and institutions invest in fusion. Research is costly and time-consuming, but the results could revolutionise the energy field creating nearly limitless amounts of energy without the many downsides of conventional methods. Currently investments go more into tokamaks because their principles are already quite known. Also the next improvements in fusion energy will be expected to happen with tokamaks as ITER proves the functionality and DEMO after that should prove the power plant mode. However, stellarators still have the benefit of working in steady-state which is crucial for power production. More investments in stellarators therefore would be justified.

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