Module 1

Fusion Basics

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The aim of this module is to introduce nuclear fusion with a focus on the why's and how's. Why is nuclear fusion interesting, not just for scientists but for everyone? How does nuclear fusion work, both as a principle and as a means of producing energy?

These questions automatically lead to a final question. What's the hold-up? Why is it so difficult to produce energy from fusion?

After this module, you will know the basics of nuclear fusion and will be able to compare fusion as a potential energy source to other energy sources. You will be able to discuss the potential of fusion, as well as understand why the road to fusion energy is so challenging.

If you want to learn even more about fusion after this module, you can work through the other modules, which will go deeper into specific aspects of fusion.

1.1 Energy and its role in our world

The energy mix

The first question that is important for fusion can be simply expressed as: “Why is nuclear fusion interesting at all?” To answer that question, we first need to examine not fusion itself, but energy in general. Since the discovery of the steam engine, the concept of energy has become more and more important. Energy is used to heat up our homes during cold winters and cool our homes during hot summers. Energy is what allows machines, cars and devices to do work: from transportation to powering electric appliances, the modern world cannot do without energy.

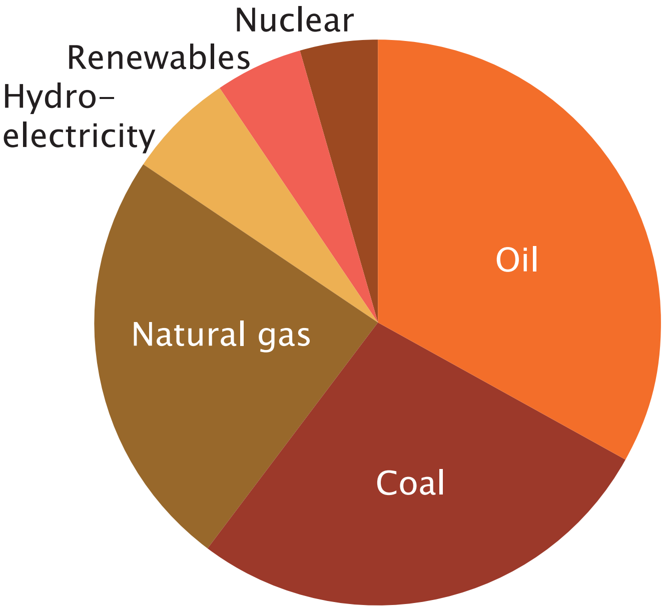

Figure 1. A pie chart of the world energy mix of 2019 divided by resource. By far the largest share is taken up by oil, followed by coal and natural gas. Hydroelectricity, renewables and nuclear follow at some distance. Source: BP Statistical Review of World Energy, 2020.

All this energy that we need has to be produced in some way. Since the industrial revolution, humanity has discovered and developed many clever ways of producing usable energy: so-called energy sources. These energy sources can be categorized, leading to two main categories: **non-renewable energy** and **renewable energy**. To further complicate matters, these can be further categorized as **sustainable energy** or **non-sustainable energy**.

The terms renewable and sustainable are often used interchangeably. However, renewable is not the same as sustainable. Renewable means that it is replenished over time, while sustainable means that it can be "sustained" for prolonged amounts of time (without harmful consequences for the future).

Chopping down trees and planting new ones is renewable, but not always sustainable: the newly planted seeds will grow into new trees and after enough time, the old ones will be replaced by the new ones and the process can begin anew. However, if trees are chopped down faster than new ones are planted, the process is not sustainable: eventually there will be no trees left. On the other hand, processes can also be non-renewable but sustainable: nuclear fission (note: fission is not the same as fusion) is not renewable (uranium deposits are not replenished naturally) but there is enough to sustain a lot of reactors for quite a long time (though not forever) and, with responsible management of nuclear waste, without harmful consequences for the future. Therefore, fission is seen as a non-renewable energy source, but it can be sustainable.

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What about *green* or *clean* energy?

The terms green energy or clean energy are often encountered in daily life. Green and clean are labels that signify the environmental impact of an energy source: they indicate that a source produces no harmful (carbon/greenhouse) emissions (in its production process). It is debatable what defines a truly clean energy source, as the production of a clean source of energy can still lead to emissions during its construction or during transportation. Sustainable energy usually implies that it can be "sustained" for prolonged amounts of time without (known) harmful consequences for the future. Since this is more clearly defined than green or clean energy, the focus here will lie on sustainable energy.

Classroom Exercise 1.1
(a) Estimate what percentage of your country's energy is created by renewable energy sources such as solar, wind, hydro, etc. Explain how you reached your estimate. Did you make any assumptions?
(b) Compare your estimate with the estimate of at least one other student. Do the estimates differ a lot? Compare the reasoning behind the estimates: did you make different assumptions?
(c) Look up the energy mix of your country. Compare your estimates to the data. Were your estimates close?

See also exercises: A.1, A.2, A.3.

The energy problem

Now you have some more insight into the energy mix and the amount of energy needed to keep our modern society running, but we are no closer to understanding why exactly fusion is important here. To understand this, we need to look into the energy problem which can be linked to the following developments.

The world population is increasing. It has increased from 6 billion in 1999 to 7.8 billion in 2020 and is expected to increase towards 8.5 billion in 2030, 9.7 billion in 2050 and 10.9 billion in 2100, see also figure 2.

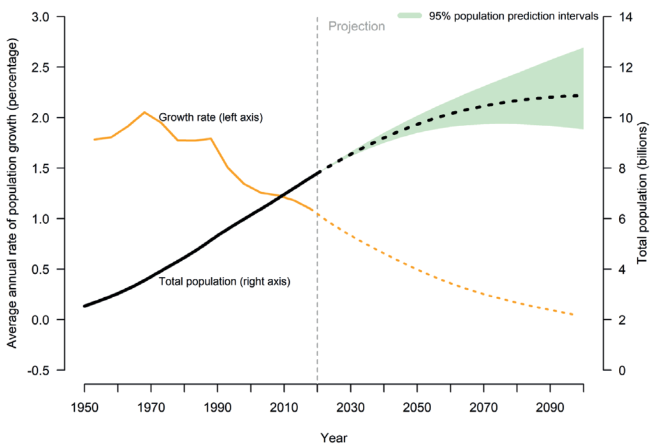

Figure 2. The rate of growth of the world population has been decreasing since the 1970s. This is visible from the orange trend line. As a result, the total population—depicted in black—is steadily moving towards a constant value of about 11 billion world inhabitants. The green area represents the uncertainty in the model used. Source: United Nations, Department of Economic and Social Affairs, Population Division (2019). World Population Prospects 2019: Highlights. ST/ESA/SER.A/423.

The average energy use per person is increasing. Countries are developing further, leading to higher standards of living. A higher standard of living typically means an increase in energy needs, e.g. due to development of basic services, infrastructure or increased access/

availability of electricity and internet. As declared by the United Nations, every human has the right to a standard of living adequate for their health and well-being. Ensuring that everyone gets access to adequate standards of living has a higher priority than reducing the average energy use per person and it would be unethical to deny people these better standards of living.

Most energy still comes from sources that are harmful to the environment, in particular leading to **greenhouse gas emissions**. Fossil fuels dominate our energy supply and while renewable and clean energy sources are growing fast, they are not growing fast enough to replace our dependency on fossil fuels before irreversible **climate change** is expected to occur. Climate change will have many harmful effects on the world: the rising temperatures are expected to lead to more extreme weather (leading to e.g. wildfires and heatwaves), and climate change is also expected to have a negative impact on human health, wildlife and the global economy. So, Fossil fuels are not a sustainable solution for the future: climate change is already happening and action is needed now, urgently.

The combination of these three factors is the energy problem the world now faces.

Solutions to the energy problem

As with any problem, there ought to be some possible solution. For the energy problem, many possible solutions can be thought of, but most of these solutions come paired with severe changes to lifestyle and average standards of living: two things that most people do not wish to sacrifice. Logically, there are two main ways in which the energy problem can be solved:

(1) By drastically decreasing the (average) energy need. This can be done by either making processes a lot more efficient (a technological problem) or by making individual energy consumption go down drastically (a societal problem). Optimising energy efficiency has its limits: there will always be some form of energy loss, be it heat losses in electrical wires or friction within a machine. At the same time, there are also a lot of things that can be made more efficient still, from better insulation in buildings to smarter use of heat, transportation or resources. On the other hand, cutting down the average energy consumption is a very viable, if not necessary, option. Climate change will drastically affect our lives whether we like it or not. As a result, lifestyle changes are unavoidable, especially considering that currently a small rich part of the global population consumes most of the total energy, while the consumption of the poor is much lower: a lot of people still do not even have access to electricity. We cannot expect those without electricity to stay without electricity because others use so much.

(2) By drastically increasing sustainable energy production. If we were to drop all fossil fuels immediately, we could save a lot of emissions! However, this is easier said than done. Political and economic aspects come into play: the fossil fuel industry is large and cannot just vanish overnight: fossil fuels need to be replaced by electric alternatives. In some areas rapid changes can already be observed (think electric cars), but this change towards electric alternatives is only as fast as the production and scale-up of these alternatives. Time is needed for the transition towards electric alternatives, while at the same moment time is running out to prevent harmful effects from occurring due to climate change.

Clearly all of the above leads to a societal problem of massive proportions that will influence all life on our planet.

Looking at ways to increase the amount of energy that is produced sustainably, one invariably ends up at the most famous renewable energy sources: solar and wind energy. The only problem with these is that they cannot run nonstop, while our society does run nonstop. Therefore, these energy sources need to be paired with adequate energy storage solutions. Solar and wind energy vary throughout the day, but the main problem lies in their seasonality and dependence on their location. In winter, the days are shorter and there is less light available when compared to summer days, while the winds are stronger in winter compared to summer. At the same time, depending on geographical location, some places will have strong winds year-round, while some will have calm winds, and some places will get more sunlight than others (think of e.g. dense forests, wide steppes, arid deserts or the arctics). When solar and wind are compared to fossil fuels it is especially easy to see how useful fossil fuels are just because they can generate a lot of energy nonstop: they can provide a constant **baseload** regardless of whether the sunlight or wind is less intense for a certain period of time. Still, continued usage of fossil fuels will come at the cost of a liveable future for many.

As a result, we can identify two main approaches to solve the energy problem: **(1) Make better energy storage.** For example, better and more powerful batteries. **(2) Find an alternative way to provide this baseload.** The best-known option: go nuclear!

Unfortunately, even though batteries are becoming better and cheaper, combinations of sustainable energy like solar or wind and energy storage through batteries are still a lot more expensive than fossil fuels. Sustainable energy sources not only needs to catch up to fossil fuels, they need to overtake and replace them within the next 30 years. And if they do, it is not at all certain whether the combination of renewables and energy storage will be able to provide all the required energy globally in the future. On the other hand, the baseload-providing nuclear fission is also far from ideal as it produces long-lasting radioactive waste.

Fusion as a (back-up) solution

As there are still uncertainties concerning the ideal energy mix of the future, exploring various alternatives could lead to the best energy mix for not just the near future, but for the distant future as well. Here **nuclear fusion** might come into play as a potential future energy source. Nuclear fusion is a process we can observe all the time, it is the process that powers the sun and all life on our planet depends on it. The goal is to create a small, controlled star here on Earth and scientists around the world are getting closer and closer. Still, nuclear fusion will not solve the problems of the immediate future, since it will take time before fusion energy is realised. However, it could be the answer to our energy

problems for centuries to come.
If energy from nuclear fusion could be achieved here on Earth, it would be a sustainable, and inherently safe, solution with (next to) no emissions. It would be able to provide a baseload just like fossil fuels or nuclear fission. It would be a compact energy source with an abundancy of fuel available: enough to generate energy for hundreds if not thousands of years. However, fusion is far from ideal: it is complex and extremely difficult and net energy gain through fusion has not been achieved, yet. Still, fusion would be a great fallback option if the other energy sources were unable to provide enough sustainable energy for the future. Scientists from all over the world are hard at work to solve the great challenge that is fusion energy with the hope of unlocking the high potential of nuclear fusion as the energy source of the future.

In conclusion, there is no "golden" solution to solve the energy problem. Time is running out to prevent irreversible climate change and as shown by the signing of the Paris Agreement in 2015 by 190 countries and the European Union, the world agrees that global greenhouse gas emissions must be reduced to limit the global temperature increase to 2 degrees Celsius. To do so, the energy mix of the world needs to change drastically. Fusion will not solve our issues within the next 50 years, but if it can be made to work, it might solve our energy troubles for many generations to come. Hence, it is seen as a worthy goal by the many people that work on achieving fusion as fast as possible.

In the next chapters of this module the basics of nuclear fusion will be explained. We'll have a look at fusion inside the sun, learn what a plasma is and see what the basic steps to building a fusion device are. It will be shown that achieving fusion isn't that hard, but that creating usable energy from it is the big (and still unsolved) challenge. At the end of this module, you will be able to understand the main physics behind a nuclear fusion device.

1.2

Fusion inside our own Sun

Now that the "why" is out of the way, it's time for the "how". First, let's look at the one fusion reactor that has been working nonstop since before mankind even knew what fusion was: the Sun.

The Sun

The Sun is a massive collection of particles that are held together by **gravity**. To put it simply: due to gravity any object with mass attracts any other object with mass. The magnitude of this attraction (how hard objects "pull" on each other) depends on how large the mass is. On Earth, our planet itself is very heavy and pulls everything towards its centre. This results in the gravity we feel, which keeps our feet firmly on the ground and makes objects fall towards the ground.

The Sun is a lot heavier: about 333,000 times the mass of the Earth. As a result, the gravitational force of the

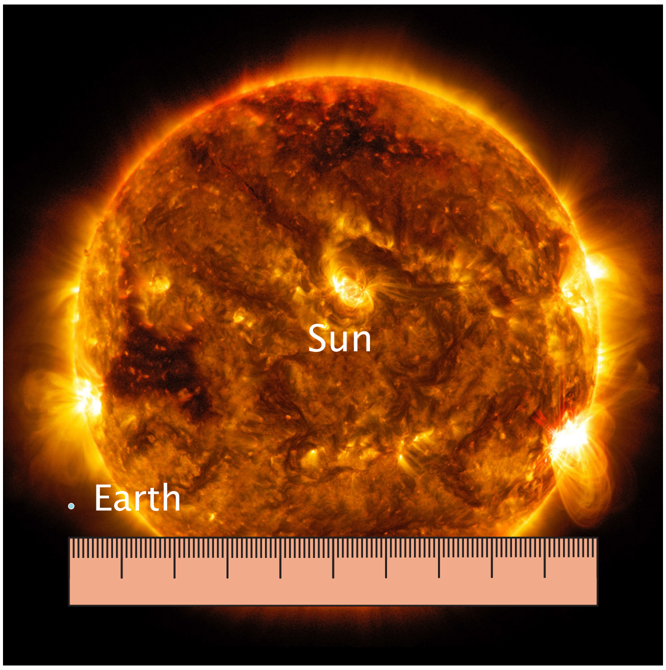

Figure 3. Compared to the Sun, Earth is incredibly small. A pale blue dot, as Carl Sagan put it. Its radius is a hundred times smaller than that of the Sun, while its volume is a million times less. Adapted from: NASA/Solar Dynamics Observatory.

Sun is a lot stronger than the gravity we feel on Earth. Still, there must also be an outward force, otherwise the Sun would just collapse into a point. This outward force is a result of fusion reactions in the core of the Sun.

In the same way that the **pressure** gets higher on Earth as we go deeper towards the centre of the planet, the pressure inside the Sun gets higher and higher, the closer we get to the centre. This is the same principle that leads to high pressures when one goes to very deep places in the oceans: all the mass above presses downwards due to gravity, and if there is a lot of mass above you, this means that the pressure becomes higher. Gravity pulls all the particles towards the centre, in essence trying to compress all the mass. The high pressure in the core of the Sun then leads to an outward force that balances the inward force of gravity. As a result, the Sun does not collapse into a point nor does it expand: it is in **equilibrium**.

In the core of the Sun, the temperature is extremely high. Logically, because the Sun loses heat at its surface (through radiation), the temperature is lowest at the surface and highest in the core. At the same time, due to the compression by gravitational forces the density is the highest at the centre. As a result, the conditions in the core of the Sun are very extreme and because of these extreme conditions there is a chance for separate particles to become one: they can fuse. When two particles fuse, a lot of energy is released and this release of energy leads to the high outward pressure that counteracts the gravitational forces and prevents the Sun from collapsing.

Inside the atom

Let us look deeper into what these “particles” are exactly and what it means if they “fuse”.

All physical objects are built out of something. If we could zoom in increasingly into an object, we would see that (almost) all objects are built out of complex molecular structures, which are made out of individual molecules, which are made out of atoms. Each of these atoms has a similar structure: a **nucleus** (plural: nuclei) and a

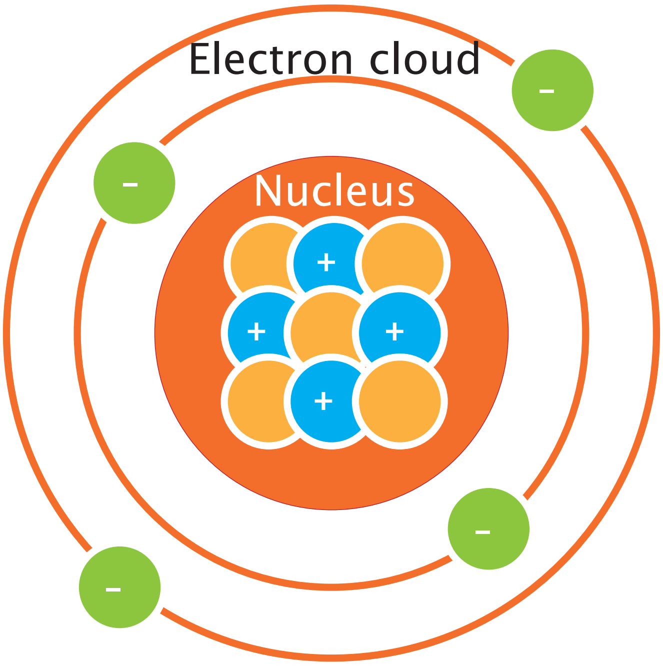

Figure 4. A schematic representation of an atom. At its core lies the nucleus, which is built out of (positively charged) protons and (neutral) neutrons. Surrounding the nucleus lies a cloud of (negatively charged) electrons.

"cloud" of **electrons** that move around this nucleus. The nucleus in turn consists of two types of particles: **protons** and **neutrons**

The number of protons in the nucleus determines what type of atom, or element, it is: if the nucleus has only one proton, we call it **hydrogen**, if it has two protons, we call it helium. A lot of different elements have been found and categorised which can be seen in the periodic table, see the aside. The number of neutrons inside the nucleus can differ, resulting in different versions of a certain element: for example, a nucleus made out of only one proton without any neutrons is just called hydrogen, but if it has both one proton and one neutron, we call it **deuterium**, a different **isotope** of hydrogen. In the case of hydrogen atoms, there exist three possible isotopes: "regular" hydrogen, deuterium and **tritium** (which has one proton and two neutrons).

What then is the difference between a proton and a neutron? A proton is a positively charged particle, while a neutron is a neutral particle. Electric charge occurs in two types: positive and negative. Positive charges repel other positive charges and attract negative charges, while negative charges repel other negative charges and attract positive ones. This is the same process that

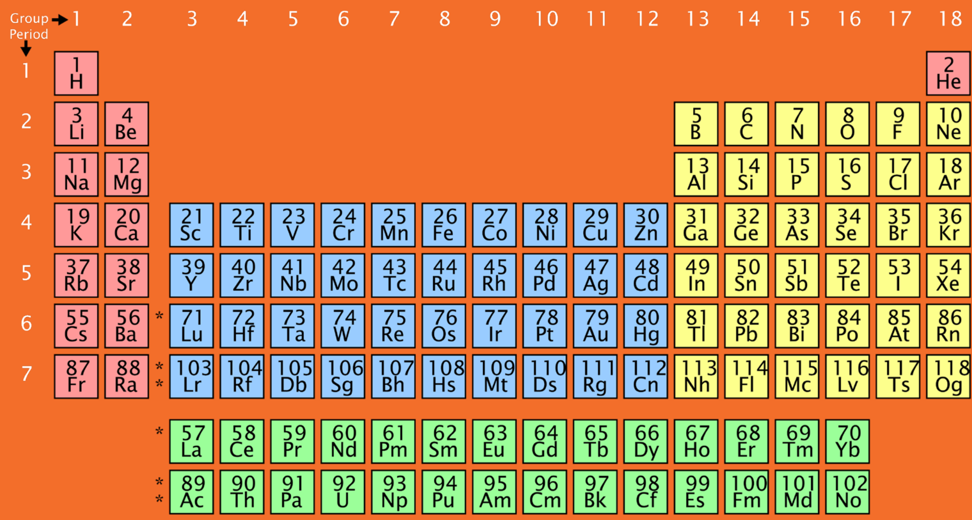

Figure 5. Periodic system of the elements. Source: Wiki-media user Double Sharp (CC BY-SA 4.0)

ASIDE

Atomic notation

Now that we know what atoms and isotopes are, let us briefly look into the notation used for them. Since the number of protons of an atom determines which type of atom, or element, it is, this is the first identifier: the atomic number. For hydrogen (H) this is 1, for carbon (C) it is 6. All hydrogen atoms have atomic number 1, all carbon atoms have atomic number 6, regardless of what isotope it is.

The total amount of protons and neutrons together gives the total atomic mass: the mass number. Since protons and neutrons have approximately equal mass, the unit of atomic mass unit (amu) is commonly used, which is about 1 for a proton (1.007276 amu) and also for a neutron (1.008665 amu). Electrons are much lighter, so for the total mass of an atom these can usually be neglected. So for regular hydrogen the mass number is 1 (just a proton and one electron), for deuterium this is 2 (proton + neutron + electron) and for tritium it is 3 (proton + neutron + neutron + electron).

This leads to a standard notation for atomic isotopes, with the mass number (at the top) and atomic number (at the bottom) displayed next to the letter (on the left side) corresponding to the type of atom. Since the letter contains the same information as the atomic number, we can also choose to leave out the atomic number. The notation with a letter along with both the mass number and atomic number will be used throughout these chapters.

makes your hairs stand up when you become charged yourself: if the hairs on your head all become similarly charged (for instance because you touch something that is charged) then they will repel each other. The result is that all hairs will get as far from the others as possible, resulting in the hairs standing up straight!

Does that then mean that atoms are charged? While the nucleus is always positively charged (since it is made out of only protons and neutrons), it is surrounded by electrons that fly around it. Electrons are negatively charged particles with exactly the same charge as one proton, but negative. Atoms are always neutral, so there must be the same number of negatively and positively charged particles in an atom. Hence there always is an equal number of protons and electrons in any atom.

That does not mean that only particles with the same number of protons and electrons exist: if an atom loses one (or more) electron(s) and becomes positively charged, it becomes a **positive ion** and if it gains one (or more) additional electron(s), it becomes a **negative ion**. The electron that is no longer part of an atom is called a **free electron**. There exist a wide variety of ions, both positively and negatively charged ones.

Nuclear reactions

Back to the process of fusion: now that we know what nuclei are, let's see what happens when two nuclei fuse.

In the Sun, the temperature is high enough that two nuclei can collide, even though they repel each other due to their positive charge, to become a new bigger nucleus. This is called a **nuclear fusion reaction** or fusion reaction in short. Fusion reactions in stars can lead to heavier elements which can themselves also fuse if the temperature is high enough. This way, heavier elements can be created and energy is released in stars via fusion reaction chains.

Let us look at the most interesting fusion reaction, which is the one that is the easiest to cause: the deuterium-tritium fusion reaction, or **D-T fusion**.

Classroom exercise 1.2
The concept of energy density is an important one in physics and although it sounds difficult, it boils down to “how much energy is inside a certain volume of stuff”. If you burn 1 litre of gasoline and measure the amount of energy that is released (in the form of heat) and divide it by the volume that was burned, then you end up with a measure for the energy density. For all fuels, an energy density can be determined.

(a) Out of the fuels listed below, which one would you guess has the highest energy density? Which one would you guess to have the lowest energy density? Order them from highest to lowest.

(b) Compare your ranked list with the list of at least one other student. Discuss why you placed them in this order.

(c) Look up the energy densities. Compare your ranked lists to the data. Were your estimates close?

Gasoline – oil – coal – wood – hydrogen (gas) – ethanol – deuterium – uranium

See also exercises: **A.4, A.5, A.6, A.7, A.8.**

$$^{2}_{1}H^{+} + ^{3}_{1}H^{+} \rightarrow ^{4}_{2}He^{2+} + n + 17.6\ \text{MeV}$$

In this reaction, two isotopes of hydrogen, deuterium (one proton, one neutron) and tritium (one proton, two neutrons) fuse to form a helium nucleus, a free neutron and an enormous amount of energy: 17.6 MeV. Here, MeV stands for mega-electronvolt. The electronvolt (eV) is a unit of energy, like Joule (J), that is frequently used in nuclear and atomic processes.

One electronvolt is very small: 1 eV $= 1.602 \times 10^{-19}$ J, so the 17.6 MeV might not seem like much ($10^{-19} =$ 0.0000000000000000001 so 17.6 MeV$=2.82 \times 10^{-12}$ J or 0.00000000000282 J) but for two nuclei, this is an enormous amount of energy. Since nuclei are very small and since there are very many in a small amount of nuclear “fuel”, the energy density (the energy per unit volume) is enormously high. If we burn a litre of gasoline and compare it to fusing a litre of deuterium and tritium fuel, the fusion reaction will produce much more energy: about 10 million times more!

This holds for all nuclear reactions, both fission and fusion and this makes nuclear reactions so extremely useful for creating energy, but unfortunately also makes them suited for more sinister purposes, as demonstrated by the development of the atomic bomb during World War II (a fission device) and the development of the H-bomb during the 1950s (which used a combination of fission and fusion).

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Electronvolts

Electronvolts sound like an odd type of unit, but it is a very useful one for atomic processes. Since atomic processes happen on a very small scale, we deal with very small amounts of energy. So a smaller unit is much easier to use here (writing down everything in Joules is just cumbersome). In choosing a smaller unit, it is best to choose something that is easily and accurately measurable, while at the same time being related to the processes we want a fitting unit for.

Since the energy of atomic particles is mostly related to their motion, the energy that a particle gains when we accelerate it is a natural choice. Charged particles are the easiest to accelerate (using a potential difference) and electrons play an extremely important role in atomic processes. So 1 electronvolt (eV) is defined as the energy gained by an electron, when it is accelerated by a potential difference of 1 Volt (V) (starting from rest in a vacuum). So one electron with charge e, accelerated over a potential difference of 1 V results in 1 eV.

To put it in some perspective, if we would use an AA battery (which delivers about 1.5 V) to accelerate one electron (in a vacuum, starting from rest) then we would get one electron with an energy of: charge $\times$ Voltage = 1 e $\times$ 1.5 V =1.5 eV.

Back to Earth

Now we can understand why the Sun can exist: gravity pushes inward and the energy that is released in fusion reactions in the core of the sun heats the core and makes it expand, leading to an outward pressure. The balance between the inward and outward pressure ensures that the Sun does not collapse due to gravity or explode due to the energy released in the fusion reactions.

Since humanity figured out how the stars worked, we have tried to replicate that process on Earth to generate energy. But the problem is that even the entire Earth is much too small for fusion to work in the same way on Earth as it does in the Sun. We need to find alternatives to extremely strong gravity. Luckily, we have found several ways to create fusion on Earth. The most common one is by creating a "**plasma**" and using very strong magnets to control it. To figure out the best way to create fusion on Earth, first we need to know what conditions are needed for fusion to occur.

Criteria for fusion

In the Sun, the enormous pressure due to gravity allows for fusion reactions to occur. This pressure is the product of two things: temperature and density. Both are important for fusion reactions to occur. To clarify this, let us look at a hypothetical situation with just two positively charged particles trapped in a box.

The two particles repel each other due to their charge. This repulsion depends on the distance between the particles: if they are close the repulsion is strong, but if there is some distance between them then the repulsion quickly becomes pretty weak. Naturally, the particles get as far from each other as possible, but since they are in a box they will be stopped at opposite walls of the box. If the particles get close enough together, they are able to fuse. Let us assume that once the two particles touch, they automatically fuse into a new bigger particle. To make that happen, somehow we need to bring the particles together: we need to overcome their repulsion by force. Since the repulsion gets stronger the closer the particles get, this is not an easy thing. But it can be done by making the particles fly around fast enough that they might collide and fuse together.

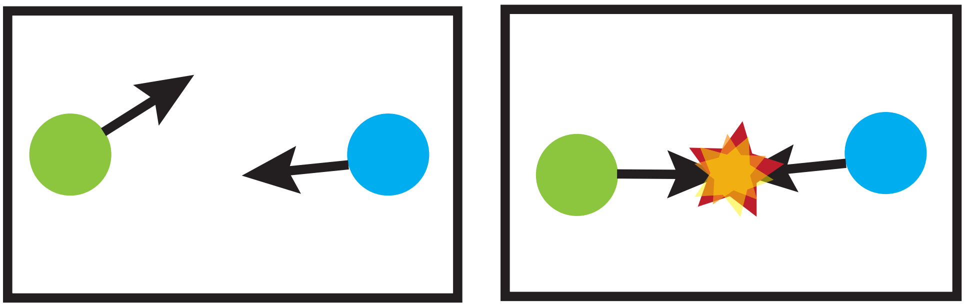


Figure 6. Two positively charged particles with a high velocity inside a box. When the velocity is high enough, the particles can overcome the repulsion and collide so that they touch.

Let us return to the two particles trapped in a box. We give the two particles a high **velocity** and let them fly around in the otherwise empty box: we give the particles **kinetic energy**. The particles will bounce of the walls and randomly fly through the box. If the particles get close to each other, the repulsion between the particles will push them apart. However, when the particles' velocity becomes high enough, the repulsion is no longer strong enough to push the particles apart and they can collide: the particles will touch and fuse. In this scenario, a collision can be seen as a case of very brief high pressure: the particles move very fast and once they collide, they will press against the other particle very hard at the moment the particles touch.

Here the link between kinetic energy and temperature is important. Temperature is a measure for the **average random motion or vibration of a collection of particles**. So in our hypothetical situation with the two particles, we have given the particles very high speeds and as a result, the average speed is high and thus the temperature for the (collection of) particles is high. So by heating our particles, we can increase their average speed and if their speed is high enough there is a chance the particles can fuse.

Still, if there are only two very small particles inside a box the chance of them randomly colliding and fusing is very small. So we need to increase the chance that particles will fuse: we can increase the number of particles inside the box. As long as all the particles have high enough speeds so that there is a chance for each of them to fuse, increasing the number of particles inside the box will lead to a higher chance of fusion to occur. By increasing the number of particles in the box (and keeping the box the same) we increase the density of the particles. Hence, **to achieve fusion a combination of high density and high temperature is best used.** This is observable in the Sun, where the density in the centre is high and the temperature in the centre isn't exactly cold either. Hence, it is this combination of both high density and high temperature that leads to the extreme conditions that are needed for fusion reactions inside the Sun.

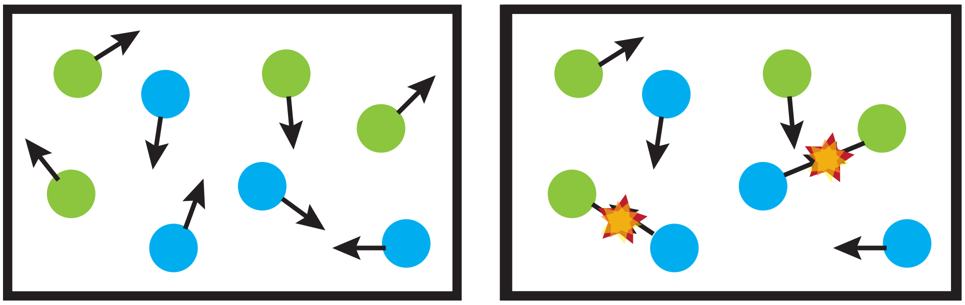


Figure 7. A box is filled with many positively charged particles that each have a high velocity. When the velocity is high enough, the particles can overcome the repulsion and collide. If there are more particles, collissions are more likely to occur.

However, we have glossed over one important factor here: we do need a box for this to work! If the particles are not confined, collisions will not occur. Here it is practical to introduce the **confinement time**. If you can keep up a high enough product of density and temperature for a longer amount of time, you will get more fusion power. However, our collection of particles will not automatically keep its high temperature: it will cool down quickly unless we keep it isolated well. So we need to keep our energy 'confined' to our box, our fusion reactor. Otherwise the heat will quickly leave the reactor.

This is similar to how we keep a room warm: if a window is open while we try to heat the room and if it is very cold outside, we need to heat a lot more to keep the room at the temperature we want and a lot of energy is wasted. We need to confine the energy inside the room and make sure that the temperature can be kept high so that many fusion reactions can occur. If the confinement time is large, this means that the energy stays inside our box for a longer time and as a result the chance for fusion reactions to occur is larger as well.

Fusion on Earth

In the Sun the particles in the core are confined very well, but on Earth gravity does not do the job for us and we need to confine the energy in another way to get as many fusion reactions as possible while using the minimum amount of energy to get these fusion conditions. Luckily, in each of these fusion reactions a lot of energy is released. This energy is not released in the form of light: the energy is released as kinetic energy in the particles that are created in the fusion reaction. This means that at the end of a fusion reaction you get even faster particles that help increase the overall temperature and can help keep the reaction going.

Since we cannot use gravity to create densities and temperatures as high as in the Sun, we need to find another way to get such extreme conditions and we need to confine all this energy in a way. We need to create a combination of both high density and high temperature and confine all the energy to ensure that the likelihood of two particles to fuse becomes high enough in our fusion devices on Earth.

1.3

Plasma

As mentioned earlier, the most common way to create fusion on Earth makes use of a plasma. In this section it will be discussed what a plasma is and how they are used for fusion.

Heating the fuel

As stated before, **temperature is a measure of energy**: it is a measure of the average speed with which particles move or vibrate. The higher the temperature, the faster the motion or vibration. This holds for all matter in all phases: **solids**, **liquids** and **gases**. If a solid object, such as a piece of metal is heated, the atoms start to vibrate with larger oscillations. In a solid, this does not change

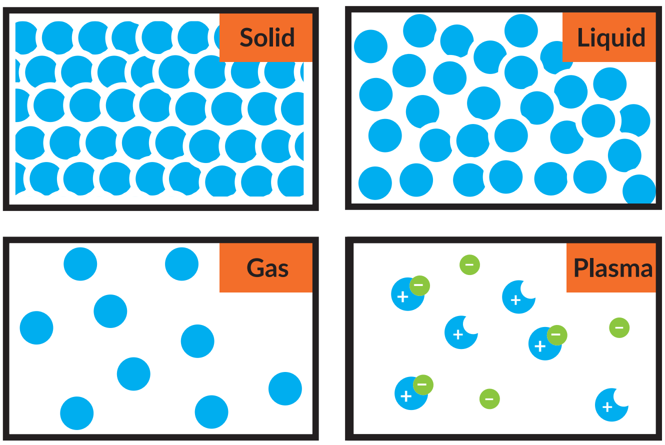


Figure 8. A schematic representation of the three phases of matter and of a plasma. All particles move or vibrate: the average velocity depends on the temperature of the matter. The average motion of the particles increases when matter is heated. In a solid, the particle motion is very restricted. In a liquid the particles can already move more freely and in a gas the particles can move around (almost) completely free. When a gas is heated to high enough temperatures, it starts to break down: a plasma is formed, consisting of separate charged particles.

the form of the object that much; the piece of metal expands a little bit but remains mostly the same. If it becomes hot enough, the macroscopic (= observable by eye) structure of the piece of metal starts to break down. Particles will move around faster and objects will lose their structure: melting will occur. Once it gets even hotter, the macroscopic structure, now a liquid, can break down even further: it can become a gas. During this phase transition from liquid to gas the bonds between the atoms are fully broken down and particles start to fly around freely. The only interactions between the gas particles are collisions.

This process of changing from a solid to a liquid to a gas (or its reverse) is called a **phase change**. The temperature at which a phase change occurs, depends on the type of atoms and the types of bonds between them. Some materials will start to melt at low temperatures (chocolate, candles) while others, such as metals, only melt at very high temperatures. Some forms of matter even boil at such low temperatures that they are only seen in nature in the gas phase: e.g. oxygen in the air we breathe, which already starts to boil at the extremely low temperature of −183 °C.

Remember that our fusion fuel is deuterium and tritium, which are two different isotopes of hydrogen. At room temperature, hydrogen is already a gas. The density of a material is also related to its phase: if we melt a material, in general there will be more space between the particles: the volume will increase and the number of particles remains the same, leading to a lower density. As a consequence, if our fuel is a gas, we generally have low densities. **So to reach fusion conditions, we need to heat the gas to very high temperatures.**

Ionisation

So our fuel is a gas and we need to heat this gas to extreme temperatures. But what happens if we further heat a gas? Can a gas do something similar to “boiling”, such as a liquid does? In a way, yes: if gases become hot enough, there is a sort of **breakdown**. This breakdown is not unlike melting or boiling, where the bonds between atoms and molecules break down, in the sense that now the very bonds inside an atom start to break down: the bonds between the nucleus and the electrons.

This breakdown occurs once a gas is heated such that the energy of the atom reaches beyond a certain threshold, the **ionisation energy**. The atom starts to break apart and nuclei can be stripped of one or more electrons: the atom becomes an ion. This process is called **ionisation**. Since most atoms have multiple electrons, most atoms can be stripped of more than just one electron. If all the electrons are stripped away, the ion becomes fully ionised, resulting in a free positive nucleus without electrons. Once a gas begins to break down into ions and electrons, we speak of a plasma. Hence **a plasma is an ionised gas, consisting of free positive ions and free negative electrons.** Usually, not all atoms are ionised in a plasma. If all atoms are ionised, we speak of a fully ionised plasma. It might not be a surprise that the Sun is not a ball of gas: the Sun is a big ball of plasma!

Figure 9. Examples of plasmas. From top to bottom and from left to right we see the Aurora Borealis (Northern Lights), a neon sign, lightning, an experimental plasma discharge, the Sun and a discharge inside the MAST spherical tokamak. Credits: NASA, Pixabay/Pexels, Pixabay/FelixMittermeier, Plasmalab TU Eindhoven/J.P.K.W. Frankemölle, NASA/Solar Dynamics Observatory & CCFE.

Finding plasmas

“Sounds difficult to create, those plasmas”, you might think. However, plasmas are the most abundant form of matter in the universe. Most objects in space are in the plasma state: stars, nebulas and more. On Earth, plasmas are less common, but they can still be observed a lot. Lightning is a plasma, the Northern Lights are caused by plasmas in the northern sky and, depending on your exact definition of a plasma, (hot) flames could also be counted as plasmas. Because of the abundance of plasmas in nature, it is sometimes referred to as the

fourth state of matter.
Next to their occurrence in nature, plasmas are also often found in industry. From disinfecting tools in hospitals, to making new computer chips, solar panels or the next smartphones, plasma processing is used everywhere. Many different ways to create plasmas exist, for instance using electromagnetic waves (just like the ones generated in a microwave oven!).

Difference between a gas and a plasma

“Now what’s the difference between a gas and a plasma, other than the fancy name then?” The main distinction comes from the fact that a plasma is made out of ions and electrons, i.e. charged particles, while a regular gas is made out of only neutral atoms. So, in a plasma, we have **freely-moving charges**. This means that a plasma can have **currents** and **conduct electricity**, just like a metal wire. Next to its conductivity, another important quality of plasmas is that they are **sensitive to electric fields and magnetic fields.**

Electric and magnetic fields

Electric fields are a way of describing how a charged object influences other charged objects in its surroundings. A charged particle attracts or repels other charged particles, depending on whether they have

Classroom exercise 1.3
So, the difference between a plasma and a gas lies in the bulk of the particles being charged or neutral. However, most plasmas can be observed to glow, while gases are often colourless and definitely don’t glow. So why do plasmas glow?

[Multiple choice]
(A) At sufficiently high temperature everything will start to radiate, so plasmas naturally glow due to the high temperature.
(B) The charged particles move freely and once a free electron and an ion collide, there is a chance that they recombine. In this recombination process the charged particles combine into a neutral particle and light is emitted. If the emitted light lies in the visible spectrum, the plasma will start to glow.
(C) In some nuclear reactions, light is emitted. If the emitted light lies in the visible spectrum, the plasma will start to glow.

ASIDE

Lightning

Because of the conductivity of plasma, lightning can be explained: Lightning is an enormous electric current between a charged cloud and the surface of the Earth. Due to the charge difference between the cloud and the surface, the gas near the cloud starts to break down and a plasma is formed that can conduct the charge. Once the charge is transferred from the cloud to the Earth, the conduction stops and the lightning is gone. This all happens in the blink of an eye: a flash of lightning.

the same (++/ --) or opposite (+-/-+) type of charge. The strength of the interaction depends on the distance between the charged particles. If a charged particle would be fixed in space, then we can imagine that if an imaginary particle—**a 'test' particle**—would be placed close to the particle, then the interaction between the two would be strong (either the fixed particle would attract the other particle or repel it). This means that the electric field from the fixed particle is strong at the location where we placed the imaginary particle. If we would place an imaginary particle far away, then it would still feel an interaction, but only very weakly: the electric field of the fixed particle is weak far away from the particle.

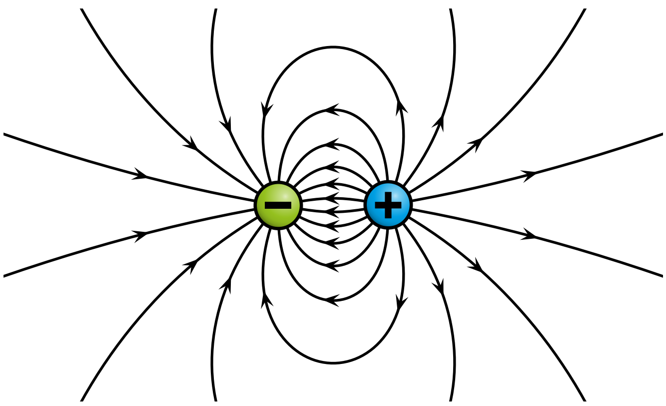


Figure 10. A schematic representation of an electric field between a positively and negatively charged particle. A number of electric field lines is drawn. Note that the field lines have a direction, which goes from positive to negative. Adapted from: Wikimedia Commons/Geek3.

By imagining such 'test' particles everywhere around the fixed particle, we can get an idea of the strength of the interaction at all locations in space: we call this the electric field. We can draw lines starting from the particle that go outward in all directions and never cross each other: electric field lines. This way, we can visualise the field since if the field lines lie close to each other then the electric field is strong and if they lie far from each other then the field is weak. The direction of electric field lines is always from positive to negative charge.

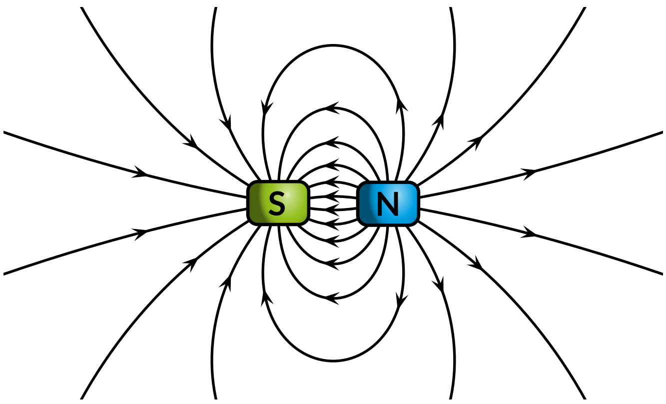


Figure 11. A schematic representation of a magnetic field between two ‘magnetic poles’. A number of magnetic field lines is drawn. Note that the field lines have a direction, which goes from ‘north’ to ‘south’. In reality, the magnetic field lines go through the ‘magnetic poles’ and form closed loops. Adapted from: Wikimedia Commons/Geek3.

A magnetic field is defined in a similar way, but instead of being an interaction between positive and negative charges, the field can be visualized as being an interaction between two ‘magnetic poles’: north and south. Two similar poles repel each other and two opposite poles attract. A more realistic way of visualizing a magnetic field is done by drawing field lines, now called magnetic field lines, which always form closed loops. If the loops go through a (magnetic) material, then the place where the field lines exit the material can be seen as the ‘north pole’ and where the field lines enter the material as the ‘south pole’. When the field lines lie outside of the magnetic material, the field lines then go from ‘north to south’. Since magnetic fields can also exist in a vacuum, it is possible for a magnetic field line to not go through a magnetic material. Then the magnetic field will have no north or south poles, while the magnetic field still exists.

Charged particles in a magnetic field

When a charged particle enters a magnetic field, the charged particle will start to gyrate around the magnetic field lines. This motion due to the magnetic field, the so-called gyromotion, is very useful! If we want particles to collide hard enough to fuse, we need extremely high temperatures. So we need to create a plasma and heat it up to extreme temperatures. The problem then, is that at these extreme temperatures, there are no materials that can keep the plasma contained: the container would start to melt and the hot plasma inside would cool down when touching the container. This is where the usefulness of the magnetic fields starts to show: if we can control the plasma with magnets, we can keep it away from the container walls and suspend the plasma, so that it cannot melt our fusion device (and our fusion device cannot cool down the plasma)! **We can confine a plasma using magnetic fields.**

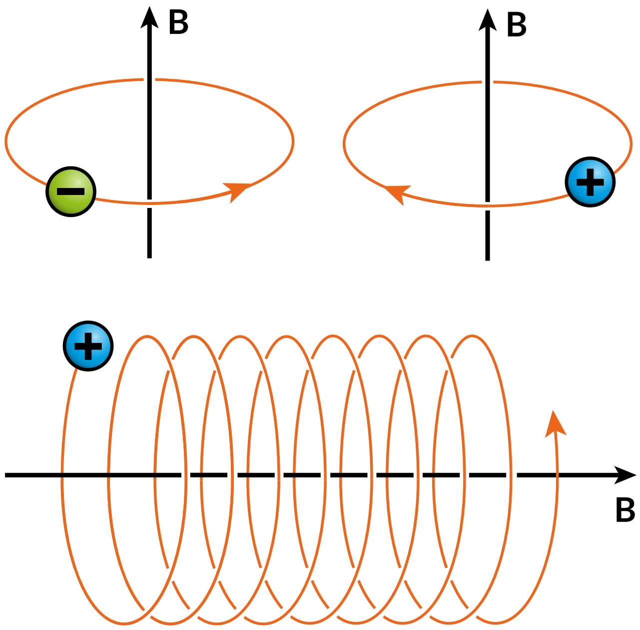


Figure 12. The motion of a (negatively or positively) charged particle in a magnetic field. When the particle is moving perpendicular to the magnetic field, it will start to move in circles around the magnetic field line. If the particle also has a velocity in the direction of the magnetic field, the particle will follow a helical trajectory around the magnetic field line. This circular/helical motion around the magnetic field line is called gyromotion.

Classroom exercise 1.4
The direction of the magnetic field (that is, the direction of the magnetic field lines) depends on the direction of moving charges. Draw the direction of the magnetic field by drawing several magnetic field lines for the following situations:

(a) A straight wire through which a current runs.
(b) A circular loop of wire through which a current runs in the anti-clockwise direction.
(c) An electron moving in a circle (clockwise) and a proton moving in a circle (anti-clockwise). Compare this with the directions of question b: what do you notice?
(d) What can you say about the direction of the magnetic field compared to the direction of motion in general?

See also exercises: A.9, A.10.

1.4 Building a fusion device

Now we have the basic knowledge that is needed to start building a fusion device! We know about nuclear fusion reactions and how the Sun produces fusion. We have identified the criteria for creating fusion reactions: we need to maintain a high enough combination of density and temperature and confine this energy so that many fusion reactions can occur. In the Sun these conditions are met naturally due to gravity, but on Earth we need another way.

The most common approach is to use magnetic fields to confine the plasma and to create high pressures by heating the plasma to high temperatures for a long enough time for fusion reactions to take place. Especially within Europe, most fusion projects that aim for production of fusion energy focus on heating and magnetically confining a plasma. This approach to fusion is called **magnetic confinement fusion** or **MCF**.

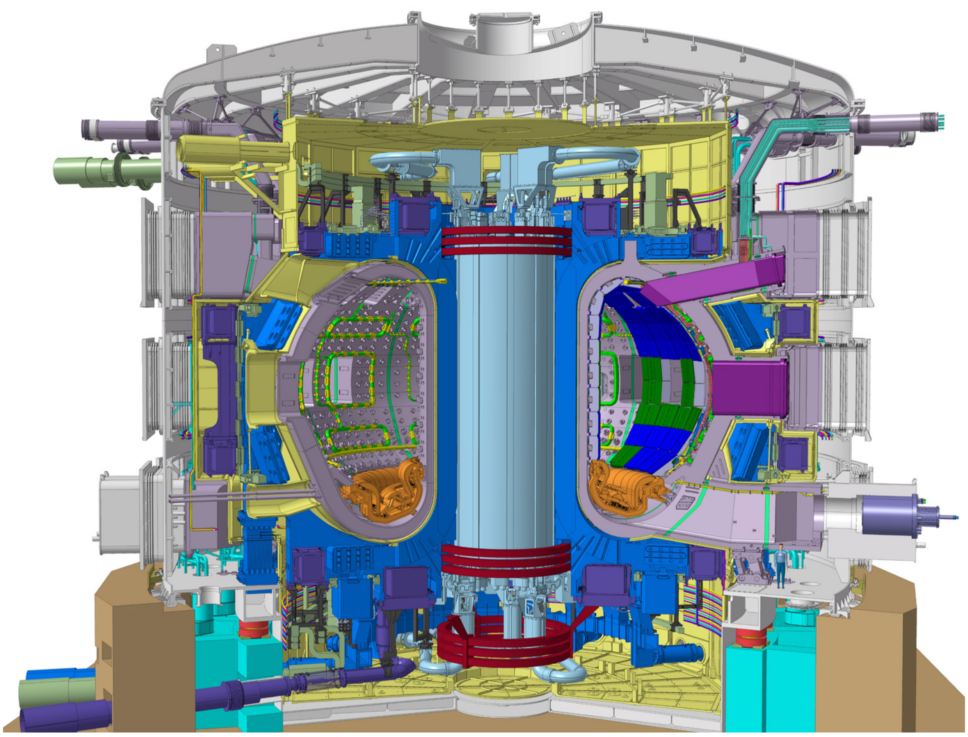


Figure 13. Schematic of the ITER tokamak, which is currently under construction in the South of France. In the schematic, the toroidal field coils (dark blue), poloidal field coils (dark purple) and the central solenoid (light blue, at the centre) can be seen. Credit: ITER Organization, https://www.iter.org.

Now that we understand that magnets can be used to confine a plasma, let us look deeper at what this means for a magnetic fusion device. Let's start by having a look at the most common type of fusion device: the **tokamak**.

The tokamak

The origin of the word tokamak lies in Russian: tokamak is a Russian acronym that stands for either "Toroidal chamber with magnetic coils" or "Toroidal chamber with axial magnetic field". And that is also exactly what it is: a doughnut-shaped chamber surrounded by magnetic coils that can contain a plasma. The inside of the doughnut-shape is a vacuum, in which fusion fuel (hydrogen gas) can be injected, which is then made into a plasma and heated (usually with radio waves). This plasma is then confined using the magnets that lie outside the doughnut-shaped chamber (and sometimes partly inside the chamber, depending on the tokamak).

Geometry of a tokamak

Before we look at the different magnet systems of a standard tokamak, let us first take a look at the geometry of a doughnut-shaped device: a **torus**.

An elegant way is to think of a torus in two constants and two coordinate variables: the **major radius R**, the

Classroom exercise 1.5

Different tokamaks and toroidal fusion devices have different **aspect ratios**: the ratio between the major radius R and the minor radius a. As a result the shapes of these tori can vary quite a bit. Let's take a closer look at these different shapes.

(a) Make a sketch of a torus with a large major radius, but with a small minor radius. What does this look like?
(b) Now make a sketch of a torus with a small major radius and a large minor radius. Why is it more difficult to draw?
(c) What would happen if you make the major radius increasingly small while keeping a large minor radius? What shape do you end up with?
Now look at the aspect ratios of the two sketches from (a) and (b).
(d) What happens if the aspect ratio changes?
(e) What is the lowest possible aspect ratio for a torus?

Classroom exercise 1.6

As we have seen, there are two main directions on a torus: the **toroidal** and **poloidal** directions. These can be quite confusing, so let's take a closer look.

(a) Make a sketch of the two possible cross-sections of a torus.
(b) Which cross-section is the poloidal cross-section? Which one is the toroidal cross-section? What do you notice about the toroidal/poloidal direction and their respective cross-sections?

minor radius a, the **poloidal angle θ** (theta) and the **toroidal angle φ** (phi). An example of a torus can be seen in figure 14 which also includes all these variables.

The major and minor radius can be seen as the radii of the two different circles that can be spotted in a torus: the radius from the centre of the 'hole' of the 'doughnut' towards the centre of the smaller circle of the doughnut is called the major radius R, while the radius of the smaller circle of the donut is called the minor radius a. In reality, the smaller 'circle' of the donut is often more triangular or D-shaped in modern tokamaks. This helps improve the performance of the tokamak. An example of such a coil is found in figure 1.

The other two coordinates are the poloidal and toroidal coordinates or poloidal and toroidal angles, θ and ϕ. The toroidal direction is the 'long way around' the torus, while the poloidal direction is the 'short way around' the torus. Since the torus is symmetric, it is necessary to define where the toroidal angle is equal to zero. For the

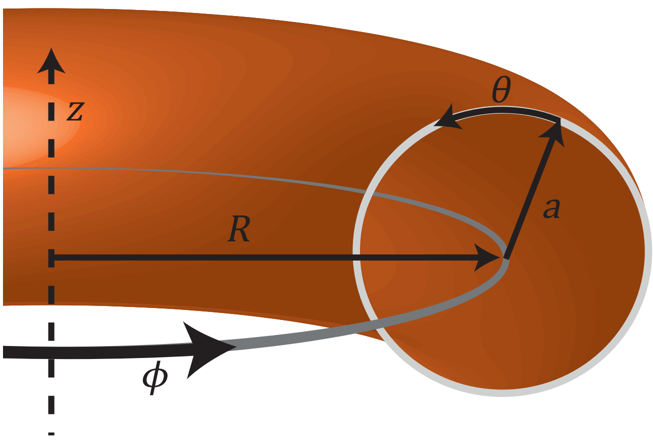


Figure 14. Schematic of the geometry of a torus. Indicated are the major radius (R) and the minor radius (a) of the torus. Also drawn are the toroidal (ϕ) and poloidal (θ) directions. Credit: Jens Peter Frankemölle/TU Eindhoven.

poloidal angle, the outermost point of the torus is usually taken as a poloidal angle equal to zero.

Magnetic coils

Now, that we are more familiar with the geometry of a tokamak, let us take a look at the different magnets of a standard tokamak and how they are called. We will then look at why we need all these different magnets to confine the plasma inside the doughnut-shaped chamber.

By moving charged particles inside a circular loop, we get a magnetic field in the perpendicular direction, see figure 12. When charged particles move in such a closed loop, we speak of a current, with the direction of this current coinciding with the direction of motion of positively charged particles. If a current is made by electrons (or other negative particles), the direction of the particles is opposite to the direction of the current. Under the influence of a potential difference, electrons can move through a metal wire. So, by running a current through (metal) coils and by positioning these coils correctly, a magnetic field can be created in the direction we want.

In figure 13, a schematic of the ITER tokamak can be seen. The first set of magnets that you probably noticed are the ones wrapped around the vacuum vessel, which

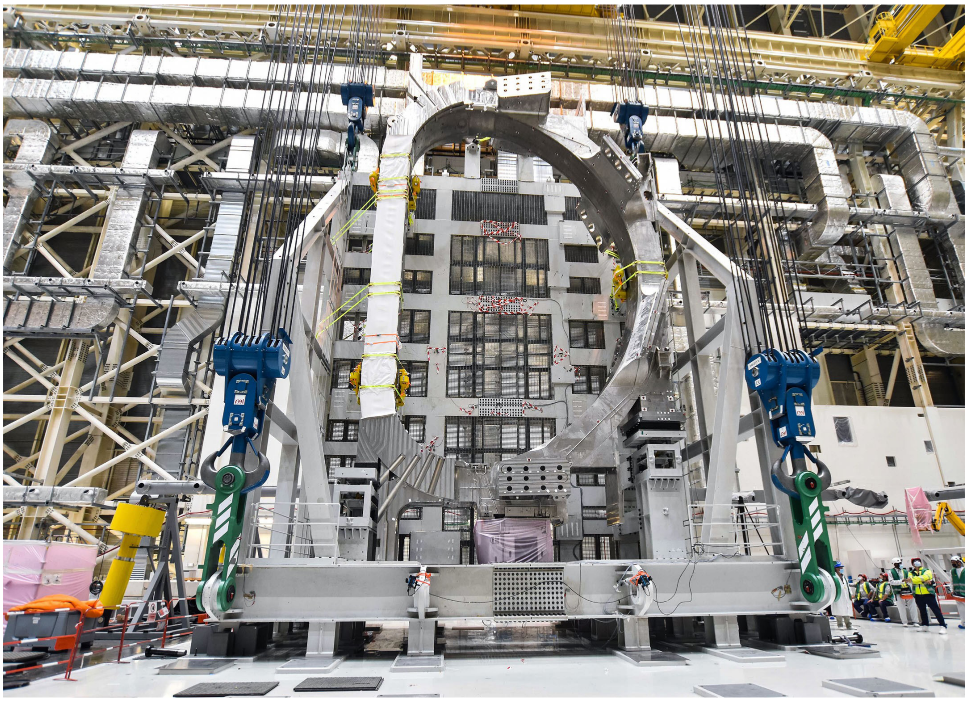


Figure 15. This is TF12, the first of eighteen D-shaped toroidal field magnets placed around the vacuum vessel of ITER. Produced in Japan, this 17-m-high and 9-m-wide giant was sitting inside the ITER Assembly Hall on 9 June 2021. Source: ITER Organization, https://www.iter.org.

ASIDE

Solenoids

To create the required magnetic fields, electromagnetic coils are used. Remember, as discussed at the end of the previous chapter, that if we make a charged particle move in a closed loop, the direction of the magnetic field inside this closed loop is perpendicular to the motion of the particle (and outside the closed loop it is in the other direction) and the direction of the magnetic field depends on whether the moving particle is positively or negatively charged; see figure 12.

Since electrons are able to move freely through a metal, charged particles are able to move through metal wires. When such a wire is wound many times, it is called a coil. When a coil of wire acts as a magnet when carrying a current, we call it a magnetic coil or solenoid.

are shaped a bit like a capital D. These are the **toroidal field coils**. Then we have two other systems of coils that are of importance. First, the stacked coils in the centre of the doughnut hole: the **central solenoid**. Secondly, there are a couple of large magnets lying at the top and bottom of the machine: the **poloidal field coils**. These three groups of magnets are the main magnet system of a tokamak. There usually are some additional smaller magnets to improve tokamak performance, but these are of less importance and will not be discussed here. In the next sections we will look at the toroidal field coils and the central solenoid in more detail.

Toroidal field Coils

The first step towards a stable fusion device is the confinement of the plasma in a toroidal shape. For that, we need to make the plasma go around in loops in the toroidal direction first. Since we now know how to create a magnetic field in a certain direction and because a charged particle follows the magnetic field line (in a helical trajectory), we now have all the knowledge we need to figure out how to make charged particles move in a loop in the toroidal direction: place closed loops of current carrying coils around the path in which we want the particles to go. So, when we want particles to go around in a toroidal direction, we need to wrap magnetic coils around this shape: the toroidal field coils! When we place a lot of these D-shaped coils around the dough-nut-shaped chamber, the magnetic field starts to circle around in loops inside the doughnut. The toroidal field is by far the strongest magnetic field in the tokamak.

So, now the plasma moves around in a toroidal direction. Sounds good, right? But why do we need any coils other than toroidal field coils at all then? Unfortunately, if we only have a magnetic field in the toroidal direction, the plasma becomes unstable. It was discovered that the addition of a poloidal magnetic field to the toroidal magnetic field could solve this problem: the result is a helical magnetic field.

Central solenoid and plasma current

To create this much-needed helical magnetic field, the central solenoid is used (indirectly). The central solenoid is a bit different in that its goal is not to create a magnetic field in itself: it uses **magnetic induction** to create a (toroidal) current in the plasma. To understand the concept of magnetic induction, we first need to go back to magnetic field lines. As discussed in the previous chapter, we can visualise a magnetic field by creating magnetic field lines that form closed loops. The **strength of the magnetic field**, **B**, is directly related to the **density of magnetic field lines**. If the field lines lie close together, the magnetic field is strong in that area. If the field lines are far apart, the magnetic field is weak in that area. Next, the concept of **magnetic flux** is important. Magnet-

Classroom exercise 1.7

Let us take a look at a standard tokamak, focusing on its three main magnet systems.

(a) Which magnets can be seen to lie in the poloidal cross section? How are these magnets called and does this name make sense?
(b) Explain the names of the other two groups of magnets.

ic flux is a quantity that is defined for a certain area. It is equal to the strength of the magnetic field (i.e. the magnetic field line density) multiplied by the (perpendicular) area through which those field lines flow. As a result, the magnetic flux can be seen as a measure of the magnetic energy that ‘flows’ along the field lines through a certain area. The relation between magnetic flux, magnitude of the magnetic field and area can be written as:

$$\Phi = B\,A\cos(\alpha)$$

where Φ (capital phi) is the magnetic flux, B is the magnitude of the magnetic field, A is the area of interest and α is the angle between the surface normal and the magnetic field line direction.

If we have a fixed coil, we can create a magnetic field by running a current through it. If this current through the coil is constant, the magnetic field lines stay at the same location and keep the same field line density: the magnetic field stays constant. This means that for a certain (fixed) area near the coil the magnetic flux is also constant.

On the other hand, when we slowly increase the amount of current through the loop, the magnetic field changes slowly as the current changes: higher currents lead to a stronger magnetic field and therefore to a higher density of field lines. The number of field lines now increases for a certain area near the magnet or coil: the magnetic flux increases.

However, nature does not like changes in magnetic flux! Whenever there is a change in magnetic flux, a so called ‘**electromotive force**’ or **EMF** is automatically **induced**. This EMF then tries to counteract the change in magnetic flux by creating a voltage that leads to a current (which creates an opposing magnetic field).

Taking a coil as an example; when we increase the current through the coil, the magnetic field increases and as a result the magnetic flux inside the wire loop increases. This change of magnetic flux then creates an EMF that tries to resist the change in magnetic flux by creating a current in the opposite direction which creates a magnetic field that opposes the original increasing field. This resistance to a change of magnetic flux occurs in any conducting medium near the coil. It is very important to understand here that the magnitude of the EMF depends on the rate of change of the magnetic flux and not on the strength of the magnetic field.

So, if you have two coils close to each other and a changing current is run through one of them, the magnetic flux changes inside both! This is because the magnetic field of the first coil is felt by the second one. Therefore, a change in magnetic flux also occurs in the second coil and induces a current in it. This process is called **(electro)magnetic induction** and it makes it possible to induce currents and magnetic fields in loops that are not connected!

ASIDE

Magnetic field

The magnitude of the magnetic field *B* is an important concept in the physics of electricity and magnetism. It is also a quantity that can be very confusing, since it has many names: the magnetic field strength, the magnetic field line density, the magnetic flux density or the magnetic induction. The various names are a result of convention, some writers prefer the one, other writers prefer the other. In a more rigorous mathematical treatment of magnetism, field lines are no longer used and replaced by mathematical vector fields. As a result, the definitions for electromagnetic fields are adapted and although we speak of the same *B*, in advanced literature it is most often called the magnetic induction or the magnetic flux density. Since we base our explanation on field lines (and to avoid confusion between magnetic induction and the law of induction) we stick to either 'magnitude of the magnetic field' or 'magnetic field line density'. Also worth mentioning: the unit of the magnetic field strength is the Tesla, named after the inventor Nikola Tesla. The company of the same name takes its name from here as well.

By increasing the number of windings in a coil the induced EMF can be increased: each winding feels the change in magnetic flux and all windings are connected, making the total change in magnetic flux add up for the coil. The total EMF is then obtained by multiplying the change in magnetic flux by the total number of windings of the coil. To use this principle to our advantage, transformers have been invented.

A transformer consists out of two disconnected coils, a primary and a secondary coil, and is used with alternating currents leading to a constantly changing magnetic flux in the coils. In an **ideal transformer**, no power is lost in the process of induction and therefore the power in the primary and secondary coils need to be the same:

$$I_p V_p = I_s V_s,$$

where I_p and I_s are the currents through the primary (p) and secondary (s) coils and V_p and V_s are the voltages through the primary and secondary coils. Since the total EMF felt by the coil depends on the number of windings of the coil we get:

$$V_p / V_s = N_p / N_s ,$$

where N_p is the number of windings of the primary coil and N_s is the number of windings of the secondary coil. As a result, through varying the coil windings, currents and voltages can be converted any way we want.

Now, back to our tokamak. The central solenoid inside the tokamak is one huge primary coil with many windings. Since the plasma is conductive, it can carry a current as well: the plasma essentially acts as a single-wire loop and it makes our tokamak one huge transformer with a primary coil with many windings and a secondary coil made out of one loop of plasma. By creating a changing current in the central solenoid, a varying magnetic field is created that induces a large current in the centre of the plasma. This plasma current then creates the poloidal magnetic field we need! As a result, we have both a toroidal and a poloidal magnetic field, leading to our crucial helical magnetic field for stable confinement!

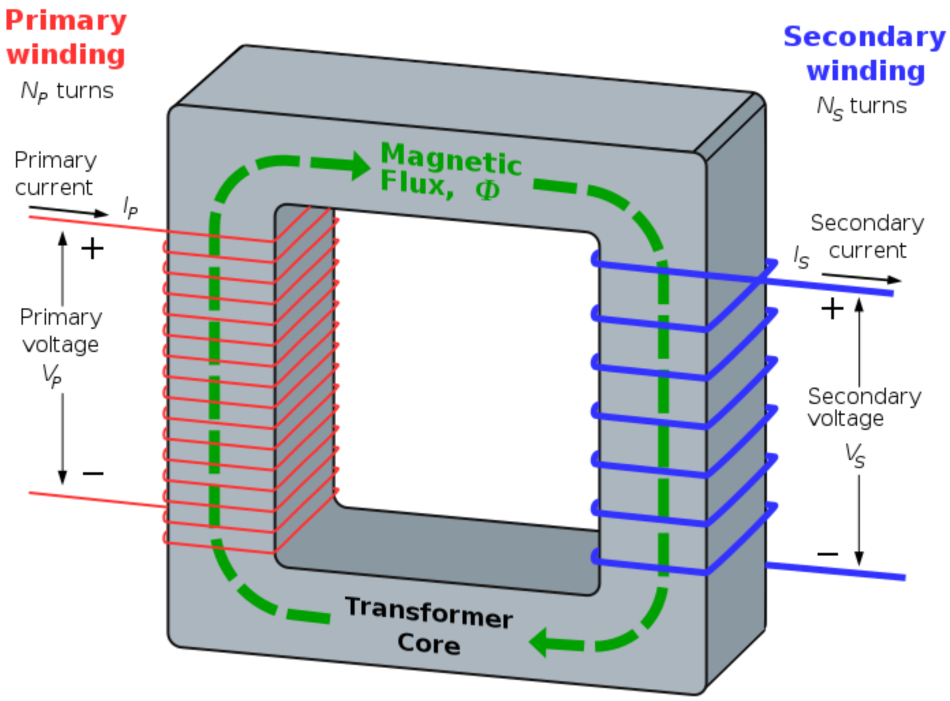


Figure 16. A transformer with an iron core. An alternating current through the primary winding induces a varying magnetic field in the iron core. The iron core carries this field over to the secondary winding, where the change in the magnetic flux induces a current in the secondary windings. In a tokamak we put the primary winding inside the secondary winding.Credit: Wikimedia Commons/BillC

Poloidal field coils and extra coils

So, the plasma current creates the poloidal magnetic field that we need. One might have expected the poloidal field coils to generate a poloidal magnetic field, but in fact the main function of the poloidal field coils is to help control the shape and position of the plasma. The field created by the poloidal field coils is much weaker than the toroidal field or the poloidal field generated by the plasma current.

Next to the toroidal field coils, the central solenoid and the poloidal field coils there are many more coils in a

Classroom exercise 1.8

The use of induction to generate a plasma current which creates our poloidal field has one major drawback: it makes a tokamak a pulsed device.

(a) How does magnetic induction lead to pulsed operation?
(b) Why is this a problem for a fusion reactor?

See also exercise: A.11.

regular tokamak, which are used for more advanced control purposes. However, these additional coils do not add to a basic understanding of nuclear fusion and will therefore not be discussed in the modules.

Magnetic confinement

Now we are finally able to understand how we can create a stable magnetic system in which the plasma is confined: by using toroidal field coils to create a toroidal magnetic field in combination with a plasma current which adds a poloidal field (and is generated by the central solenoid) a helical magnetic field is created.

There is one final part to discuss: the **pressure balance** inside the tokamak. In a tokamak there is an outward pressure and an inward pressure. If these are equal, the plasma remains stable. This is the same as in a bicycle tire: the air in the tire needs to press hard enough outward at the rubber tire to counteract the pressure of the ground. If the air pressure is too low, the ground 'wins' and the tire falls flat.

In a tokamak, we have the outward pressure coming from the plasma, so it will expand unless there is a force that pushes back. So what is the force that pushes the plasma back? There is only one candidate: the Lorentz force! The plasma carries a current, and that current feels a force due to the magnetic field. The result is a force on the plasma that is directed inward. This is the force that keeps the plasma together: **magnetic confinement**.

Hence, through magnetic confinement we can build fusion devices such as tokamaks to create the conditions at which nuclear fusion reactions occurs here on Earth.

Now that you have worked through the first module, you already know a lot about fusion: you know about the energy problem, you know about fusion in the sun, you know when fusion occurs and how we can create these conditions here on earth in the most common fusion device, the tokamak. In the next modules, you will be able to acquire more in-depth knowledge on nuclear fusion, from four different perspectives.

1.5 Further reading

To learn more about nuclear fusion, there are four modules available which look at fusion from a certain perspective. The following modules are available.

Module 2: Road to Fusion

In this module, the history of fusion and its development is discussed by highlighting different reactor designs and attempts. All the important steps to get where we are today are explained up to the current status of fusion today.

Module 3: Plasma Control

In this module, it is explained how a fusion plasma is heated, controlled and measured. There are several ways to heat the plasma and due to the extreme temperature, special measuring techniques are required. Based on different measurements of the plasma, it is possible to keep the fusion reactor under control.

Module 4: Fusion Materials

In this module, the material challenges of fusion are explained. The fusion reactor wall needs to be made out of very special materials that can withstand the harsh fusion conditions. Each component of the fusion device has its own goal and has different material requirements, from stopping neutrons to being cooled to create a strong magnetic field.

Module 5: Deployment

In this module, fusion power is put into perspective by looking at the electricity market and by comparing fusion to other energy sources. Next to numbers, the politics of energy also play a role in whether fusion will make it as an energy source.

Online resources

Besides the different fusion lesson modules, there is a lot of information and educational content to be found online. In each module, interesting books, articles or links can be found.

A fun example of free to use fusion content is the ‘Operation Tokamak’ app, which can be downloaded for free on the iOS AppStore and Android Play Store:

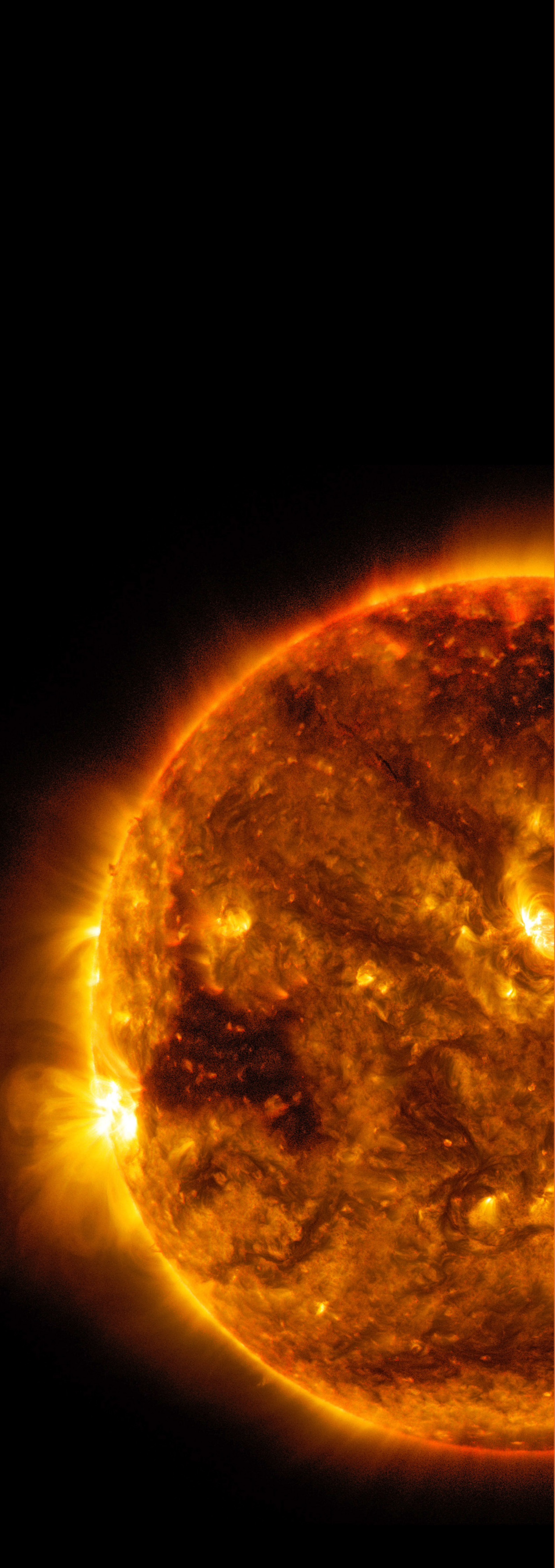
https://apps.apple.com/us/app/operation-tokamak/id808190835

https://play.google.com/store/apps/details?id=dk.markfilm.operationtokamak&hl=nl&gl=US

Operation Tokamak in the iOS AppStore

Operation Tokamak in the Android Play Store

In this app, you can operate a tokamak by controlling the strength of the magnets and the heating system. By keeping the reactor at the right conditions and by suppressing instabilities when they arise, you can keep up the reaction and aim to create as much fusion as possible.



Colophon

Fusion Basics is the first of five modules on nuclear fusion. They teach about basic concepts in nuclear fusion at the secondary school level. All modules can be found free of charge on the website of FuseNet, **https://fusenet.eu**.

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