Module 2

Road to fusion

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The process of science and research isn't solely about discovering the underlying physical principles. Research is not done in a vacuum of science. It is connected to society through stakeholders and funding. As a result, non-scientific factors, such as politics, can greatly influence the progress of research. This module aims to shed some light on the road to fusion energy and why some say that "fusion is always twenty years away".

After this module, you will be able to place fusion research into context as well as explain the main type of fusion reactors and their differences. You will also be able to discuss the influence of politics on scientific research as well as the pros and cons of international collaboration.

If you wish to learn more about the challenges and solutions on the road to fusion, be sure to work through the other modules.

2.1

The discovery of fusion

How does the Sun shine?

People generally think that science starts with an equation and from there on researchers make predictions and do experiments to see whether their calculations are correct. That is the way that we are taught in school, so that's how it is done, right? Not really. Science usually starts with problems and observations. For fusion research, those problems and observations are related to something that we see every day: our **Sun**.

Until the beginning of the 20th century, scientists had a hard time to explain how the Sun and other stars were able to shine so brightly for so long. There were plenty of models that could explain how the sun was able to generate light right now, but the Sun has been around for billions (10^9) of years. At that time, it was a huge mystery why the Sun hadn't burned up yet. If the energy came from chemical reactions, all fuel would have been burned up by now. If the energy was a result of the sun slowly shrinking, the Sun would not have been as large as it is right now. So, where does this energy come from?

Eddington to the rescue

About a hundred years ago, in 1920, it was discovered that the mass of four hydrogen atoms is larger than that of a single helium atom. Combining this observation with the relation

$$E = m c^2$$

from Einstein's paper of 1905, the idea came to be that energy could be generated by transforming four protons into a helium atom. That same year, Arthur Eddington proposed that four individual protons (hydrogen nuclei) could combine into a helium nucleus through a series of fusion reactions. This series of reactions is called the **proton-proton chain (p-p chain)**. During these reactions, a large amount of energy is released. With the large amount of energy emitted during the p-p chain, only a small fraction of the Sun's hydrogen has to fuse to produce its energy output. So, if the Sun uses fusion reactions like the p-p chain to produce its light, the Sun could shine for billions of years and billions yet to come.

However, the p-p chain model was not accepted immediately, because this would require the temperature of a star to be 2 to 3 times the observed temperature. Eight years later, George Gamov introduced a mathematical basis for the concept of **quantum tunnelling**. Quantum tunnelling allows some particles to move closer to each other than their energies would allow. This makes fusion possible at lower temperatures than previously thought. In 1929, Robert Atkinson and Fritz Houtermans redid Eddington's calculations, but with quantum tunnelling. The new results came close to the observed temperature in the core of stars, and the p-p chain provides a good

Figure 2.1. Arthur Eddington. Credit: Library of Congress, Prints & Photographs Division, LC-B2-6358-11.

Classroom Exercise 2.1

(a) The Sun has a mass of about 1.989×10^{30} kg. The mass of a single proton is 1.007 amu. Assuming that the entire Sun is made of protons, how many protons are there in the sun? Remember that 1 amu is equal to 1.661×10^{-27} kg.

(b) The energy released during the p–p chain is 26.73 MeV per helium atom produced. How much energy can be gained if all protons from **(a)** in the Sun were to fuse to helium? Remember that 1 MeV is equal 1.602×10^{-13} J.

(c) For how long can the Sun shine if it radiates this energy away at a constant power of 3.828×10^{26} W?

(d) For how long do you expect the Sun to shine in reality? Discuss with your neighbours.

(e) Astronomers expect that the Sun will only be able to fuse 10% of its protons, before it will go to the next phase in stellar life. Can you think of a reason why the Sun would not be able to fuse all the protons?

explanation for the energy of the Sun. And so, scientists concluded that the Sun obtains its power from a series of fusion reactions.

New avenues of investigation

Now that the energy production of stars could be explained with nuclear fusion, people started to wonder whether fusion could be possible on Earth. And so, experiments were started to test that out. In the beginnings of the 1930's, scientists (notably Mark Oliphant, Paul Harteck and Ernest Rutherford) used particle accelerators to fire super-fast deuterium ions onto stationary deuterium atoms that were trapped in a solid. Some of the ions fused with the atoms, and the first man-made fusion was performed as well as the first artificial production of tritium.

With these questions answered, scientists wondered: "Can we use this technique to produce energy?" They performed multiple experiments and from their results, the probabilities of different fusion reactions were calculated. As expected from theoretical calculations, like how “slow” the Sun fuses its hydrogen into helium, these probabilities were extremely low. It became clear that shooting ions onto atoms would not be an effective method to produce energy. The ions are more likely to bounce of stationary atoms and **scatter** in all directions.

When the ions scatter, they give some of their energy to the atoms on which they scatter. This causes these trapped atoms to vibrate more and consequently raises the temperature of the solid. The ions on the other hand slow down significantly due to this scattering, to the point that they can no longer fuse with the atoms. Because **scattering** is significantly more likely than fusion, it will always cost more energy to accelerate the ions than that is gained from the few fusion reactions that are produced.

To make a fusion power plant, one has to make sure that the particles will stay together long enough with enough energy to fuse. This means recreating conditions comparable to the sun. In other words, high density and high temperatures are needed.

2.2 First devices

Off to a slow start

Around the time of WWII, people started making some first designs of fusion reactors. But governments and funders were hardly familiar with fusion energy and didn't see much potential in it. It wasn't until the start of the 1950's, when a man called Ronald Richter claimed to have produced fusion energy, that the ball really started rolling. Richter's story quickly spread across the globe.

The media coverage of his story had two immediate impacts. Funding fusion became interesting to politicians, as they wished not to be left behind and maybe even find some glory in it themselves. The other impact was introducing fusion research to scientists all over the world. Back then, fusion was mostly researched in the UK, the US and the Soviet Union.

The UK researched fusion mainly through pinch devices, which will be discussed first in this chapter. The US collaborated with the UK on some of these projects, but the main contribution from their researchers was the design of the stellarator, discussed later in the chapter. The contribution of the Soviet Union is the tokamak design, which has been introduced in module 1. The history of the tokamak will be discussed in the last leg of this chapter.

Pinches

The first serious attempts to make fusion reactors were the pinch devices. Within these machines, the plasma is squeezed together using a magnetic field. This is only possible due to the Lorentz force. One example in which you see the Lorentz force is, when two parallel two parallel wires are carrying current in the same direction, the wires will be pulled towards each other. Back to pinch devices, there are two different devices: Z and θ (theta).

Z-pinch

Both these designs use plasmas in the shape of cylinders. The difference between these devices is the direction of the current and magnetic field. The magnetic field of the Z-pinch comes from a current inside the plasma. The current flows parallel to the axis of the cylinder. This direction is referred to as the Z-direction in cylindrical coordinates. The created magnetic field is then pointing along the surface of the cylinder. In this situation, the plasma can be made to contract in on itself. The plasma current behaves like it is made of many parallel wires. Due to the Lorentz force, the plasma is squeezed together, because all the "wires" are pulled together. The squeezing leads to a density increase, thereby allowing the plasma to achieve fusion conditions.

θ-pinch

A θ-pinch is a bit more complicated. In a θ-pinch, the directions of magnetic field and current are swapped. Currents flow parallel to the surface of the cylinder. If you would look along the axis of the cylinder, the currents flow in nice circles. This direction is referred to as the θ-direction. The magnetic field then points along the axis of the cylinder. How the plasma is pinched together in this situation, is more complicated than for a Z-pinch and will not be discussed in this module. What can be said however, is that the plasma in the θ-pinch is more stable than the plasma in a Z-pinch. This means that instabilities, which can damage the machine, are less likely to happen in a θ-pinch than in a Z-pinch.

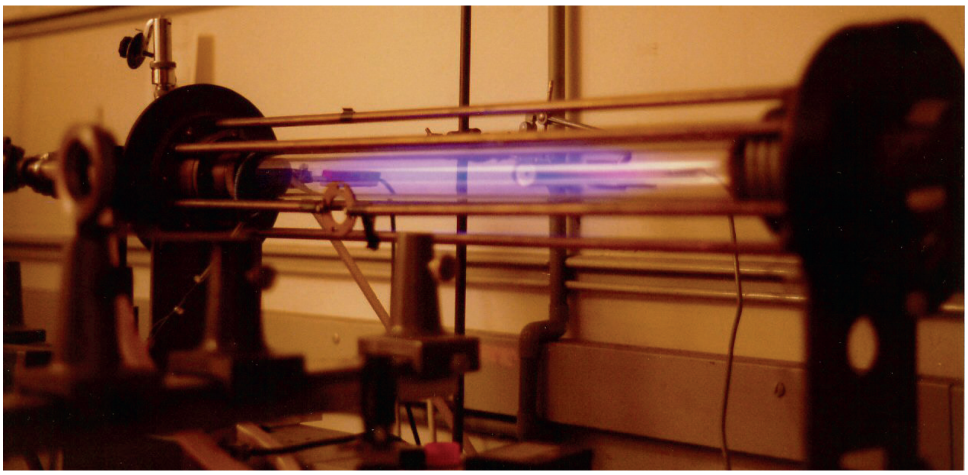


Figure 2.2. A table-top scale Z-pinch with a glowing hydrogen plasma. The metal bars parallel to the glass are there to close the current loop, as the current flows through the plasma in one direction and the through the metal bars in the other direction. Credit: Sandpiper, English Wikipedia.

Classroom Exercise 2.2

(a) What force causes the plasma to squeeze together in a pinch?

(b) For a Z-pinch, can you draw in a figure the direction of the magnetic field from the plasma current and the force on the plasma near the centre of the current, if the direction of the current is into the paper?

(c) For a θ-pinch, an external field is needed. Draw a circle. If the current flows in clockwise direction. What is the direction of the magnetic field in the point most-left, generated by the current in the point most-right? In which direction should the magnetic field point to make the Lorentz force point inwards?

In 1939, a physics student from the UK made the first detailed design to make a Z-pinch machine, but he was told to do something else for his graduation project. It wasn't until 1948 that the first prototype of a Z-pinch was made. The prototype was made from old radar equipment from WWII, due to a lack of serious funding. Things changed when Richter's story became worldwide news. Governments were suddenly prepared to give out funding for fusion research and soon various projects with pinch machines were started in the UK and in the US and Soviet Union.

From Cold War secrecy to collaboration

Because the Cold War was ongoing, fusion research was kept secret. The discovery that technology from pinch machines could be used for bombs as well as an espionage scandal in the UK, made governments even more careful with their results from fusion research. All research was moved from universities to secret locations and information was rarely exchanged between countries. Because the West formed allies during the Cold War, the UK and the US worked together on some projects and exchanged some information with each other.

However, in 1956 a scientist from the Soviet Union gave a talk in the UK about fusion research and the problems they had encountered in their own research. From the talk, it became clear that the UK, the US, and the Soviet

Union were all researching fusion and that all of them came across the same problems. The idea arose that it might be better to make the fusion research openly accessible. It was likely that everyone would figure it out on their own, so they might as well work together to speed up the process.

Soon after, the Soviet Union started publishing research regarding plasma physics. The US and UK followed later, publishing their research just prior to the 2nd Atoms for Peace conference in 1958. That same year, the first high-pressure-high-temperature fusion reactions were achieved in a θ-pinch called **Scylla**. It was a breakthrough in the field, except that the calculations showed that the design was unsuitable for making an effective power plant. Around that same year, the largest "classical" pinch, called **ZETA** was made.

While ZETA was able to produce numerous fusion reactions, it never created more fusion energy than it cost to power the machine. Still, in its 12 years of operation, the experiments performed with it gave access to knowledge that would become very important in the field, including new methods to measure the temperature of a plasma. By the end of the 1960's pinch reactor designs were largely abandoned in favour of more promising designs.

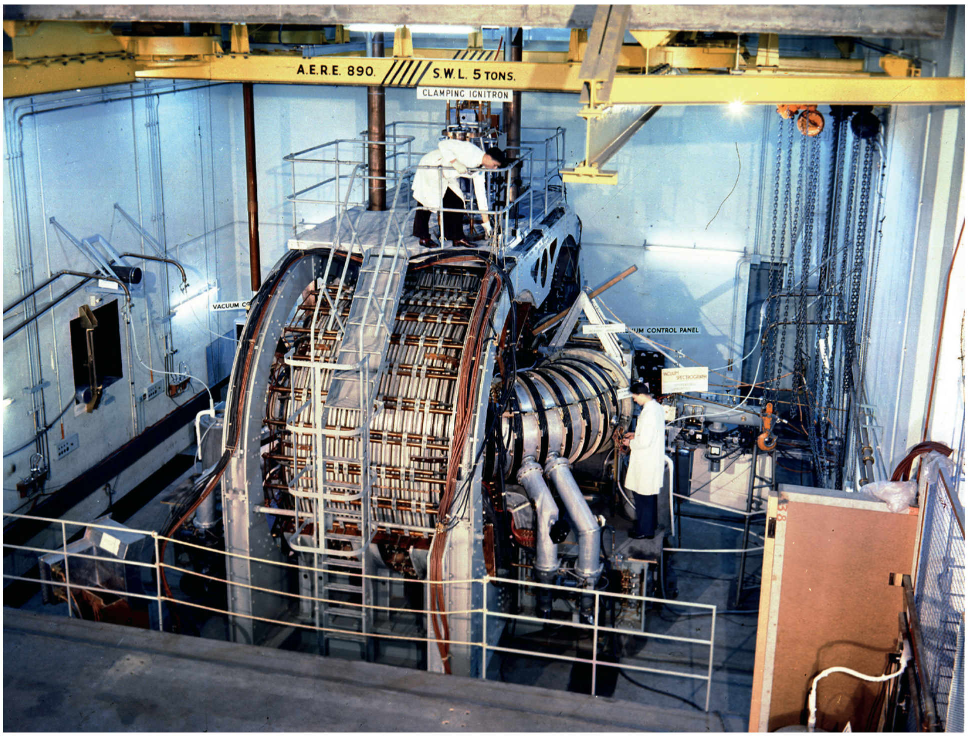


Figure 2.3. Two researchers making adjustments to the largest classical pinch, ZETA. Credit: UKAEA.

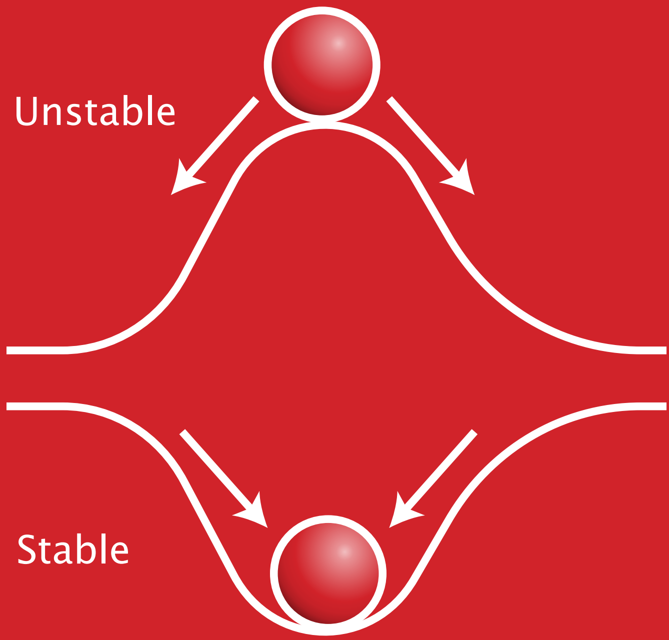


Figure 2.4. Schematic of a stable versus unstable system. In both cases—as long as no one gives them a push—the balls will stay put indefinitely. Give a push against the ball perched on top of the hill, however, and it will come rolling down no matter how small the push. This is why we call the top system *unstable*. Quite the opposite happens with the ball below in the valley. Give a small push to that ball and it will just roll back to where it came from. And thus the bottom system is considered *stable*.

Real-world systems experience tiny pushes or *instabilities* all the time. A gust of wind or a trembling of the ground would be serious issues for the top system but not the bottom one. In fusion plasmas, there are a great many things that can cause the ball to come rolling down the hill and, left unchecked, pose a serious risk to the plasma.

Instabilities

The road to fusion knows many delays, leading to the often-made remark that fusion is, and always will be, twenty years from being realised. Quite some times, the delay was caused by the discovery of a new problem that is caused by an instability. An instability is a disturbance that only needs a small push to start and only becomes worse. Like a ball rolling down a hill, an instability will not stop, unless something makes it stop. There are of course no hills in a plasma, but there are other sorts of instabilities.

For example, currents in a straight plasma are unstable: if the current is only bend slightly, it wants to bend more and more. The conducting plasma will start to bend and continue to do so until it is stopped by the wall. This causes severe damage to a fusion reactor. That is why most instabilities are either avoided or researchers try to control them, so that the instabilities do not disrupt the plasma too much and damage to the reactor can be prevented.

Stellarators

When Ronald Richter claimed to have achieved fusion, the news reached scientists all over the world. Among them was the American scientist Lyman Spitzer, who received a phone call from his father about Richter's so-called achievement just before he went onto his ski vacation. Spitzer quickly concluded that Richter's claim was false, as his device could never have heated the plasma to fusion temperatures. While sitting in the ski lifts, he started thinking about what a working fusion reactor could look like. And so, he came upon the concept of the **stellarator**, about which he wrote a paper that was published in 1958.

The concept of the stellarator is relatively straightforward. It looks very similar to the design of a tokamak, which is briefly explained at the end of module 1. The stellarator uses magnetic fields to confine a plasma. The magnetic field is created with solenoids, wrapped around the doughnut shaped vacuum chamber in which the plasma is held. The magnetic field points mostly in the toroidal direction.

Particle drift

In module 1, it was mentioned that the plasma would become unstable if a purely toroidal field is used. This is because the plasma also tends to move in the vertical direction when it goes around the torus instead of only following the field lines. When a particle is moving away from the field lines, this is referred to as (particle) **drift**. Particles start to drift for multiple reasons.

For example, in a toroidal solenoid the windings near the hole, called the **inboard side**, are closer to each other than the windings on the other side, called the **outboard side**. When windings get closer to each other, the magnetic field gets stronger. Because the magnetic field on the inboard side is stronger than the magnetic field on the outboard side, the particles start to move in the vertical direction. This kind of drift is called **gradient drift** and will be explained more in depth at the hand of an additional exercise.

Drift is a problem, not only because it pushes the plasma against the wall or ceiling, but also because it separates the charges. Ions and electrons drift in opposite direction, so all the positive charges go in one direction, while all negative charges move in the other. This separation of charges makes the plasma extremely unstable and causes even more drift.

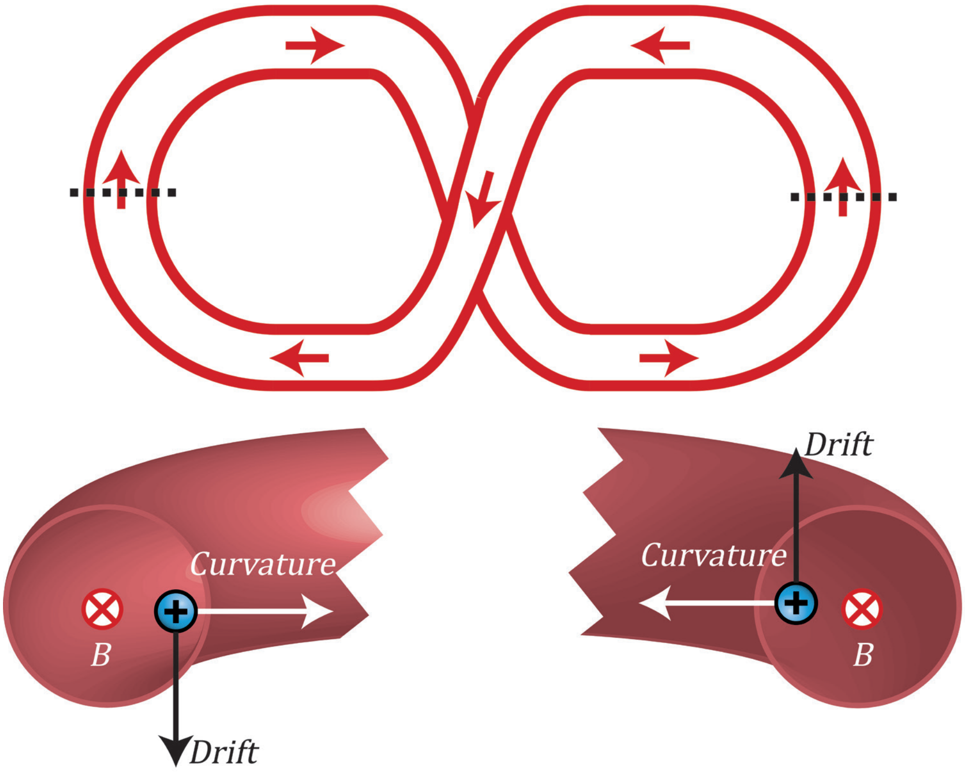
Dealing with the drift

There is no solution to stop the particles from drifting away. The researchers therefore turned to a different solution: let the drift cancel itself out. What is meant by this is that the particle is first allowed to drift in one direction for a short time, before it is made to drift in the opposite direction. For example, the particle is first made to drift upwards, then downwards, and so on such that on average the particle stays at the same height.

The best method to achieve this alternating drift, is by making a helical magnetic field. In such a field, the magnetic field lines spiral through the doughnut, instead of forming horizontal rings as they do in a toroidal solenoid. This causes the particle to drift alternatingly inwards and outwards. Changing the magnetic field from rings to spirals is called “adding **rotational transform** to the magnetic field”. In tokamaks, rotational transform is created with a plasma current. Stellarators, on the other hand, play around with the shape of the coils and the vacuum chamber, to create the rotational transform.

For example, the doughnut shape is sometimes changed for a figure-8 shape. Particles will drift in opposite directions because the curvature that the particle experiences is reversed when crossing the centre of the figure eight. Take e.g. an ion that moves clockwise through the left half of the eight, crosses the centre, and then travels anticlockwise along the right half of the figure eight. Because the curvature switches, the direction of the drift also switches. If the particles do this fast enough, they'll only drift shortly in one direction before drifting back in the other direction, such that there is no net drift. Other methods are to use more coils with complex shapes, to create a more helical magnetic field that provides alternating inwards and outwards drift.

Figure 2.5. An ion travelling along to the magnetic field in a figure-8 stellarator. The red arrows indicate the direction of the magnetic field and the direction of the toroidal velocity of the ion. It travels clockwise in the left part of the figure 8 and anticlockwise in the right part. A poloidal cross-section of the far-left and far-right side are sketched below in the bottom of figure 8. In those poloidal cross-sections, the directions of the drift (black), curvature (white) and magnetic field (red) are shown. Because the curvature is switched when moving from the left part to the right part, the drift in the right half cancels the drift in the left half, so that the particle ends up at the same height when travelling a full round through the figure 8.



First line of stellarators

The first stellarator was a small device that could fit on a table, just to see if the idea worked. In 1953, the first stellator, Model A, was finished and it looked very promising. The next step was to make a bigger version, dubbed Model B. Here, some problems were encountered. Because the magnets carry current, they feel a force due to the magnetic field of other magnets as well as their own magnetic field. These forces cause the magnets to move when not secured carefully. Despite the moving coils, some machines showed good confinement. After further improving the design, another issue was found. The plasma was found to cool faster than expected, because there were a lot of impurities inside the plasma. Impurities are atoms in the plasma that are not part of the 'fuel' itself, but instead come from e.g. the wall. These impurities radiated the energy out of the plasma, cooling it rapidly. To make even hotter plasmas, vacuum chambers were used to keep the plasma clean.

Various versions of Model B were made, all testing out different shapes and layouts to see what worked and

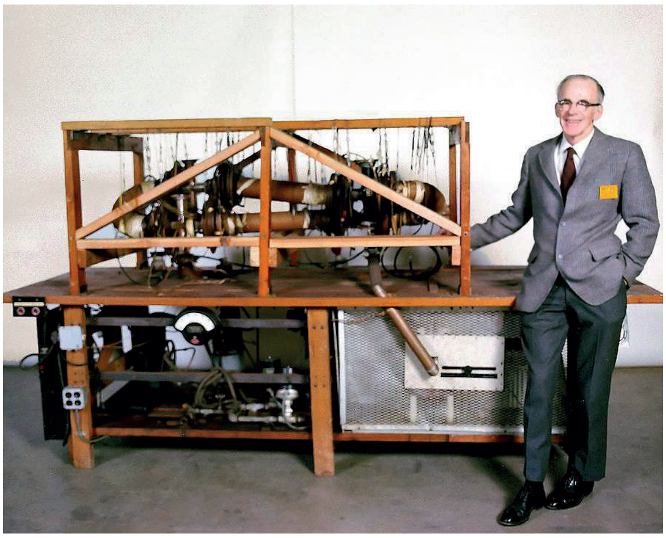


Figure 2.6. Lyman Spitzer next to the Model A stellarator. Credit: PPPL.

where problems needed to be solved. Unfortunately, all Model B machines showed a problem called **pump out**. The "pump out" problem was the observation that the plasma was drifting out of confinement much faster than even the worst theoretical models. After the Model-B series, a new design called Model C was made. Model C had a racetrack-layout with multiple heating sources and a **divertor**. A divertor is the exhaust of a fusion reactor and is explained in more detail in module 4.

Still, the performance of the stellarators remained below theoretical predictions. It became clear that more fundamental research in plasma was needed to understand why the plasma wouldn't stay in the machine nicely. Over the course of many experiments and a few years, physicists were able to understand plasmas better and confinement was improved to the point that they matched the expected values from theory. In 1969, the Model C reached its record electron temperature of 4.6 million degrees Celsius!

No easy solution to confinement

Although it was a relatively high temperature for fusion plasmas at that time, it was still very far from the 150 million degrees Celsius required for a working fusion reactor. Originally, Spitzer believed that stellarators could do better than other designs. He believed that the stellarator would not suffer from enhanced heat loss due to what was known as **Bohm diffusion**. But during

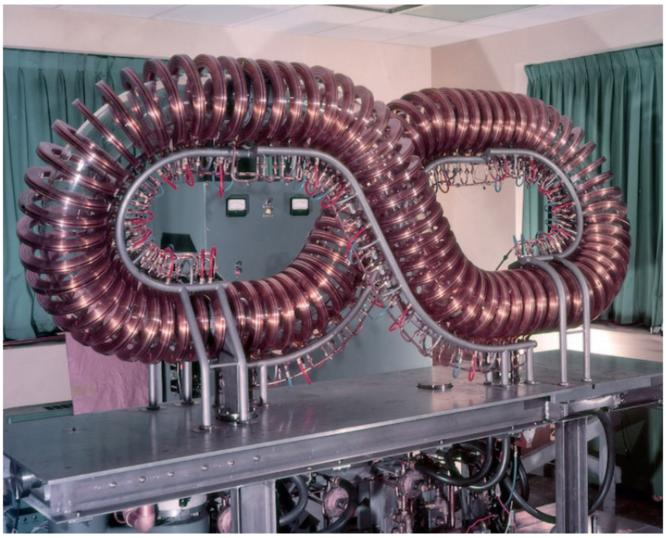


Figure 2.7. The Model B-2 stellarator with a characteristic figure-8 shape. Credit: PPPL.

the experiments and research of the 1960’s, it became clear that Bohm diffusion was a fundamental property of plasmas. Bohm diffusion means that confinement would improve linearly with the magnetic field, instead of quadratically as predicted with “classical” theory. So, classically it was thought that if you doubled the magnetic field, you would get a confinement that is four times better.

However, now it turned out that if you doubled the magnetic field, you only got a confinement that was twice as good. The realisation came that reaching the required confinement become a whole lot harder. In fact, if the scaling was only linear, then fusion would never be possible. The required magnetic field would need to be stronger than what was believed technically possible. This revelation set the fusion community into a period of pessimism. However, one design did not follow that trend: the **tokamak**.

Tokamaks

In 1950, a bored Red Army sergeant stationed on Sakhallin, a Russian island near Japan, wrote a letter to the executive leadership of the Soviet Union, with the idea of igniting fusion fuel into a plasma state with an atomic bomb and then confine the hot plasma for steady-state energy production. The letter was sent to Andrei Sakharov, who found the idea interesting despite major flaws in the sergeant's design. Together with Igor Tamm, Sakharov started a more detailed study on building a fusion reactor. Their first idea was to confine the plasma inside a solenoid bent into the shape of a doughnut. As mentioned before, this did not work out, because the plasma starts to drift out of confinement.

To solve the problem, Sakharov suggested to add rotational transform to the magnetic field, with help of a circular current inside the plasma. This could be done by suspending a current carrying wire in the machine, or by making the charged particles in the plasma move, so that a current is made inside the plasma. Because it is a bad idea to have a wire inside your hotter-than-the-Sun's-core plasma, the former was only used for earlier experiments and proofs of concept.

There are multiple methods to make a current inside a plasma. The simplest is explained in module 1, called magnetic induction, which is the most used method to

Figure 2.8. Igor Tamm on the left and Andrei Sakharov on the right, the minds behind the tokamak design.

Credits: Nobel foundation (left) & RIA Novosti archive, image #25981 / Vladimir Fedorenko / CC-BY-SA 3.0 (right).

create a plasma current in tokamaks. By changing the magnetic field inside the hole of the tokamak, a current is generated inside the plasma. Because the magnetic field cannot change indefinitely, tokamaks operate in pulses. This is an important difference compared to stellarators, which can in principle run indefinitely in a steady state. While experimenting with the tokamak designs, the scientist in the Soviet Union independently discovered the pinch effect and started doing their own experiments with pinch devices, as discussed in the first section of this chapter. Because of this discovery, it took some time before a tokamak as we now know it was built, as there was more focus on experiments with pinch devices.

Classroom Exercise 2.3

(a) Sketch the direction of the magnetic field created by the solenoid in a poloidal cross section and sketch the field direction of the magnetic field created by the plasma current in the same figure.

(b) Now, do the same for a toroidal cross section.

The first tokamaks

The first tokamak, called **T-1**, was built in 1958. However, the scientists also experienced problems with impurities cooling the plasma, so they quickly improved the design with a better vacuum chamber and called it **T-2**. However, the researchers were too late to show the tokamak results at the Atoms for Peace conference of 1958. During that conference, the researchers of the Soviet Union were introduced to Spitzer's stellarator design. The researchers of the Soviet Union were so impressed by the results presented, that they wanted to make their own stellarators.

Most people even suggested to Natan Yavlinsky, the designer of T-1, that the new tokamak **T-3** should be redesigned as a stellarator. Despite the suggestions, Yav-

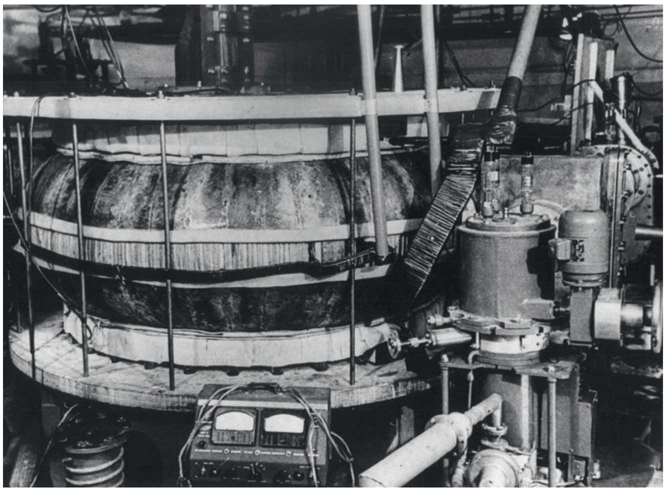


Figure 2.9. T-1, the first tokamak. The major and minor radius of the torus are 0.67 m and 0.17 m respectively. Its magnets could generate a magnetic field of 1.5 T and it used a plasma current of 100 kA. Credit: Nomen nescio/ITER Organization.

linsky stuck to his tokamak design. The plasma current could heat the plasma and good heating for the plasma was still in development for stellarators. Sticking to the tokamak design proved to be an important point in fusion history, as soon the field would experience a time of pessimism.

Sceptical reception

During an international meeting regarding fusion, held in the UK's new research centre in Culham in 1965, it became clear that all major designs were having **problems with confining** the plasma. Bohm diffusion proved to be a **fundamental problem**, that both the stellarator and pinch devices could not solve. Lesser-known devices didn't seem to do any better. But then the Soviet Union presented the results of a toroidal pinch device that resembled a tokamak, which reached temperatures 10 times higher than Bohm diffusion would allow.

These results were received with a high deal of scepticism. Especially the UK believed the researchers to have made some mistake, because the toroidal pinch looked a lot like their ZETA machine. They thought the Soviets made the same mistake they did, when it was believed that ZETA had produced net energy from nuclear fusion. The researcher of the Soviet Union disagreed. They argued that they had made sure to not make the same mistakes, but the method of measuring the temperature was very similar. The debate became heated, with the tension between East and West not helping.

Eventually the claim was dismissed out of hand by Spitzer, who was chairing the meeting, remarking the large uncertainty in measuring the temperature. Even the Soviet Union researchers had to admit that the method of measuring the temperature was not accurate enough to say with confidence that the temperature was above the limit set by Bohm diffusion.

Steadfast

A few years later, in 1968 the Soviet Union published the results of their T-3 reactor. The temperatures were over an order higher than any other device, just like the results in 1965. Again, these results were received with a lot of scepticism, since the results were again obtained through an indirect method. The Soviet Union didn't want this to be a matter of discussion again since it would likely be dismissed like the previous discussion.

So, they allowed the UK to send a team to their research centre in the Soviet Union. Scientist in the UK had developed a new method to measure the plasma directly, called **Thomson scattering**. This was a huge power move for the Soviet Union in more ways than one. It was very rare for the Soviet Union to invite westerners into the Soviet Union, let alone to allow their scientists to do research at a Soviet research centre. The UK sent a highly respectable team, nicknamed the **Culham five**. The Culham five conducted their measurements and a year later they published a paper with the results.

The conclusion of the paper: the results reported by the Soviet Union were correct and were indeed way better than any contemporary fusion device. With the UK confirming the incredible results, fusion scientists became hopeful again and all started to pursue the tokamak design. This led to the Tokamak Stampede (or Tokamak Mania), with many stellarators being converted into tokamaks and new tokamaks being built all across the globe.

The race was on to make the tokamak work.

2.3

Breakthrough and breakdown

Bigger and better

With the focus on tokamaks, countries started to make them bigger and bigger hoping to be the first to make it succeed. Additionally, new discoveries helped make even better reactors. It was thought that it wouldn't take long before someone made a successful fusion reactor. But as the machines got bigger, new instabilities were discovered as well. These new instabilities again required more research to solve and even bigger machines were envisioned to make fusion work. Eventually, these machines started to become so big that it became necessary for countries to start to work together. This resulted in **ITER**. ITER is the biggest project yet and will be discussed in the next chapter. In this chapter, the discoveries, difficulties and achievements of the last 40 years are discussed, apart from ITER.

Better devices

Starting from the 1970's, the US became a front-runner in the race of fusion. The US' Princeton Plasma Physics Laboratory was very adept at solving problems regarding plasma heating. At the end of the 1970's, their tokamak called Princeton Large Torus, or PLT, heated a plasma to 60 million degrees Celsius. That surpassed the record of the Soviet's T-3 by a factor of eight at that time.

This showed that fusion temperatures could be reached, as fusion plasmas can become self-sustaining from a temperature somewhere between 50 million and 100 million degrees Celsius. From these temperatures, the plasma will also start to heat itself and can generally push itself to the required 150 million degrees Celsius. This was a very important milestone. However, PLT could not contain a plasma long enough for self-sustaining fusion to occur. But the real reason why the US became the front runner, was the large budget that it had for fusion research. For example, a tokamak at that time cost about $500.000, but the US had an annual fusion budget of around $25 million at that time.

One reason why the US spend a large amount of money on alternative energy sources was the oil crisis of 1973. In 1973, oil-rich countries in the middle east proclaimed an oil embargo and would not sell oil to countries supporting Israel. The US was hit as one of the hardest, because they heavily relied on oil. To become less dependent on oil in the future, the US increased funding for finding alternative energy sources.

Another thing that was improved were the magnets. Throughout the 20th century, superconductors had been investigated and developed. These superconductors could be used to make extremely strong electromagnets. By the end of the 1970's, superconductors had been developed far enough so that they could be used for fusion reactors. The **T-7** was the first fusion reactor ever to use superconducting magnets.

The last thing that was improved during this period was the design of the tokamak. For example, a design called a doublet used more **D-shaped** magnets. This caused the plasma to become more D-shaped as well. This made it easier to avoid a small group of instabilities, which made it possible to operate with higher densities.

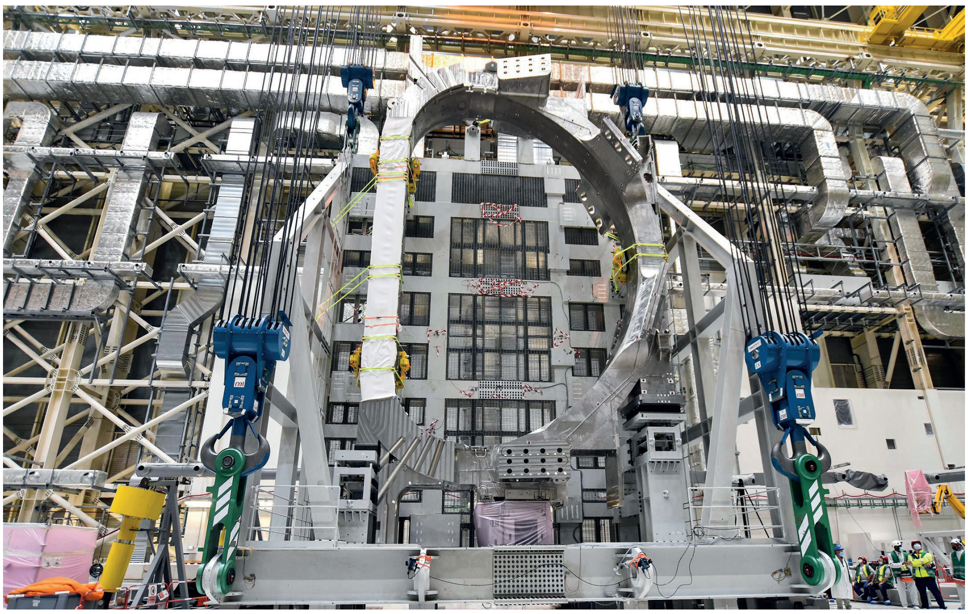


Figure 2.10. The shape of this coil resembles the capital letter D, with rounded corners. The change in shape with respect to circular cross-section makes the plasma in a tokamak more stable. Credit: ITER Organization.

Bigger plasmas

At that point in time, the conditions to make a working fusion reactor had all been reached, but in different machines. The next thing to do, was to make one big device that encompassed the new design with the improved magnets and heating methods. The device would also need to be made bigger for another reason. A bigger reactor can make a bigger fusion plasma. But what is so useful about bigger fusion plasmas? Well, it is easier to make the core of a fusion plasma hotter when it is bigger.

This is most easily seen when you compare the volume of the plasma to the surface of the plasma. In a fusion reactor, there are limits with what the density of the plasma can be, so let's for the moment assume the density of the plasma to be constant. When we increase the size of the reactor, the volume of the plasma increases as well. The number of fusion reactions that takes place is related to the volume of the fusion plasma. The larger the volume is, the more hydrogen there is, and thus the more fusion reactions can take place at the same time. This means that the **fusion power** is directly dependent on the volume of the plasma.

Meanwhile, the amount of produced power that flows out of the plasma depends on the surface of the plasma. Making a plasma bigger, also increases its surface. So, while the amount of fusion power increases, the power flowing out of the plasma also increases. What is important here is that the volume of the plasma increases faster than its surface. Consequently, when the size increases, the fusion power increases faster within the plasma volume than that it can flow out of the plasma through its surface. As a result, the core temperature of the plasma becomes higher.

This higher core temperature then leads to an increased outflow of power: the hotter a thing is compared to its surroundings, the faster it will cool down. So with a bigger plasma volume, a new balance between the fusion power created in the plasma volume and the outflow of that power through the surface is found, where the core temperature is higher than it would have been for a

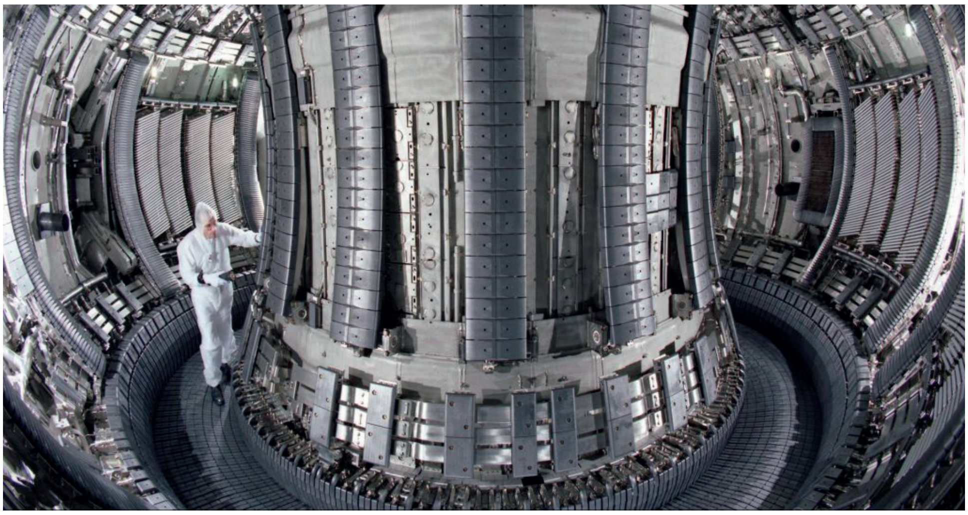


Figure 2.11. A technician working inside the Plasma chamber of JET. Jet is currently the largest tokamak in operation, and it holds the records for most fusion power produced and highest Q-factor. Credit: UKAEA.

smaller plasma volume. In conclusion, a bigger plasma is able to reach a higher core temperature because its volume increases faster than its surfaces. In one of the additional exercises, you will look at how the volume of a sphere compares to the surface of a sphere.

Large national devices

Different countries started to make their own big device in the hopes of being the first to reach or go beyond **scientific breakeven**. Breakeven is the point where the same amount of energy is generated by the fusion reactions as is needed to heat the plasma. Breakeven was often denoted as Q=1. Q in this case, is the **Q-factor**, which is simply the generated energy divided by the provided energy. The Q-factor was a good indicator for how well a fusion reactor worked.

The US finished the construction of their big tokamak in 1982 and named it **Tokamak Fusion Test Reactor (TFTR)**. It looked like a bigger version of the PLT. This device initially did not have D-shaped coils, because the benefits of D-shaped coils were not known at the time of its design-phase. Japan made a similar device called Japanese Torus-60 or JT-60, which was outfitted with D-shaped coils. JT-60 was finished in 1985.

Individual countries in Europe didn't have the budget available to make such a big device. Therefore, they decided to fund a tokamak together. They bonded together and by 1983 the **Joint European Torus (JET)** was made.

Since then, JET has been the largest tokamak in operation. JET was also outfitted with D-shaped coils, even though the benefits of plasma shaping were not known by the designers. The choice for D-shaped coils also provided some constructional benefits, like making it easier to mount the coils on the inside to a central pillar as well as a better distribution of forces on the coils. The Soviet Union also made a large device, finishing their **T-15** in 1988. The hopes for these devices were that they would all be able to reach breakeven. But the first test runs with the machines showed results that were... disappointing, to say the least. For example, TFTR reached only a Q-factor of 0.2, while it was designed to reach around 1. New instabilities had popped up that were not seen in less powerful devices.

Researchers came up with various solutions to various problems, but it quickly became clear that the size of the machines would need to be even bigger. This meant that fusion would be delayed by a few decades, again. This sent another wave of pessimism through the fusion community. Luckily, negotiations had been started to make an extremely big reactor with multiple countries. But as will be discussed in the next chapter, it took some time before the negotiations were completed and we are still waiting for the construction of this machine to be finished. During this time, the fusion community kept improving the knowledge and technology of the fusion field, and multiple records have been set.

Classroom Exercise 2.4

A big difference between stellarators and tokamaks is how long they can operate. Modern stellarators are able to operate a plasma for up to 30 minutes. Tokamaks on the other hand are limited by their pulse duration. The pulse duration can be calculated by $t_{pulse} = (\Psi - L_p I_p)/V_{loop}$. Here Ψ is the available magnetic flux, L_p is the inductance (how strongly it responds to magnetic fields) of the plasma, I_p is the required plasma current and V_{loop} is the loop voltage needed to drive the plasma current. For ITER, the values for these quantities are given below.

How long do ITER's pulses last?

Ψ = 250 Vs **L_p=12.5 µVs/A** **I_p = 16 MA** **V_{loop} = 0.1 V.**

ASIDE

Modern stellarators

While tokamaks have taken the main stage in the fusion community, it does not mean that there has been no progress in the other designs. Stellarators have moved forward as well. The advancement of computers has greatly helped stellarators, as software can be used to optimise very complex designs. This has opened the doors for big stellarator projects. Wendelstein 7X is currently the biggest stellarator in operation. Its design consists of about 50 coils that are bent and twisted in different shapes. In the picture below the coil configuration of W7-X is shown in blue. The theoretical shape of the plasma is shown in yellow. As you can see, this looks a lot more complex than the “simple” doughnut shape of a tokamak.

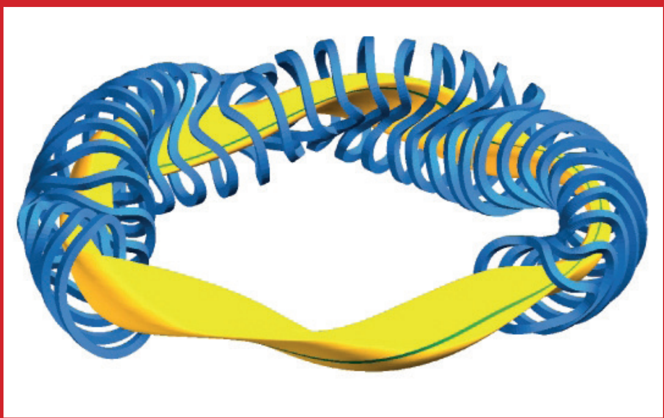


Figure 2.12. A schematic representation of Wendelstein 7-X. The coils are shown in blue, and the shape of the plasma is shown in yellow. The green line running on the yellow surface is a magnetic field line. Credit: Max Planck Institute for Plasma Physics.

Breaking records

Up until the 1990’s, tritium had not been used in any fusion experiments. Achieving fusion with deuterium-tritium (D-T) fuel is much easier than with pure deuterium fuel. However, tritium is a difficult element to work with because of its material properties and therefore expensive. Still, D-T fuel is currently seen as our only option for net energy generation. Tritium is labelled as poisonous because it is a weak emitter of beta radiation. It also likes to stick to everything. For more information on why the properties of tritium make it difficult to work with, see module 5. While JET was the first to do experiments with deuterium-tritium fuel, it was TFTR that set the first record with it. In 1994, TFTR produced a whopping 10.7 MW of fusion power using D-T fuel. By that time, TFTR had been upgraded with D-shaped coils. Later in 1995, it set a world-record temperature of 510 million degrees Celsius. These records didn't hold long, as JT-60 produced a plasma of 522 million degrees Celsius in 1996. In 1997, JET also started to use a D-T fuel mixture. JET managed to produce 16 MW of power for 24 MW of external heating power used. Not only did JET set a world record for highest fusion power produced with this, but they also set a world record for highest Q-factor of 0.67.

Both TFTR and JET were able to reach these extraordinary results due to the **alpha particles** produced by the fusion reaction. The alpha-particles carry 20% of the energy released by the fusion reaction. Because the alpha particles are charged particles, they are also confined by the magnetic field. This allows them to give their energy to the plasma. As a result the plasma is heated by the alpha particles, which reduces the heating required by external sources. This is called alpha particle heating. The alpha particles provided 3.2 MW during JET's record run. It is expected that JET's records will not be broken until ITER is finished. Around the same time, JT-60 was able to create plasma conditions that theoretically would give a Q of 1.25, but JT-60 didn't use a D-T plasma during that experiment. JT-60 is not capable of operating with tritium, so they were never able to show that they could really achieve a Q of 1.25. Still, it is a very impressive performance.

About two decades later, JT-60 set another world record in 2013: that for the highest **triple product**. The triple product, as the name implies, is the multiplication of three things: plasma density, plasma temperature and energy confinement time. It is a good indicator of reactor performance. By this time, the Chinese had also made a large tokamak, called **EAST**. With this tokamak, they set three world records. EAST holds the world record for longest stable operation and highest product of confinement time and temperature. The first of these two records were set in 2017, by operating a stable plasma for 101.2 seconds. The other record was obtained in May of 2021, by operating their plasma for that same duration at a temperature of 120 million degrees.

Also, while not a record yet, a tokamak called **SPARC** is designed. SPARC will use a new type of superconducting coils. These coils will have several different properties that set them apart from the superconductors used in current machines. The most prominent one, is the potential to carry even greater currents and thus generate even greater magnetic fields. Stronger magnetic fields greatly improve the fusion power that a fusion reactor can produce. They can also be used at higher temperatures, although at the cost of their maximum magnetic field. This could also be beneficial as keeping the superconductors cold is one of the costliest parts of operating a fusion reactor. In most designs, this will likely not be used because the added value of stronger magnetic fields will outweigh the cooling costs.

If you want to learn more about superconductors, be sure to work through module 4. Another thing that is special about SPARC is that it is funded by private investors such as big companies and billionaires, instead of public investors such as governments.

ASIDE

Alpha, beta and gamma

When physicists talk about radiation, they often speak about one of three types of radiation: alpha, beta or gamma. Before scientist fully understood what radiation was made of, they could separate all radiation into these categories based on how easy it was to stop the radiation and how the energy of the radiation was absorbed by the material. Later, it was discovered that the three categories corresponded with what the radiation was made of.

Gamma radiation consists of a electromagnetic wave, just like light. However, gamma radiation is more energetic than our eyes can perceive. Beta radiation consists of (one or more) electrons, that move very fast. Alpha radiation is a fast-moving particle made from two protons and two neutrons. Since this is a helium-4 atom without its electrons, a fully ionised helium-4 atom is often referred to as an alpha particle.

2.4 ITER

Nowadays, it is hard to mention fusion without mentioning ITER. ITER is a tokamak, and once its construction is finished, it will be the largest tokamak to date. ITER is made by an international collaboration, with 35 nations involved in its creation. It will be used to perform the world's largest plasma physics experiments. This chapter will start with the history of ITER and then explain what ITER aims to accomplish.

Classroom Exercise 2.5

ITER is a good example of what advantages and disadvantages there are when many parties work on the same project. Discuss the following questions in small groups

(a) What do you expect to be the advantages?
(b) What do you except to be the disadvantages?

In the midst of the Cold War

In 1973, Richard Nixon and Leonid Brazhnev discussed the initial idea of an international fusion reactor. However, it took until 1978 before an official project was started. This project, called **INTOR**, was started by four parties: the US, the Soviet Union, Japan and Euratom, which represented Europe. But the collaboration between opposing sides of the Cold War remained minimal, and no real progress was made. Things changed in 1985. Mikhail Gorbachev had just become the leader of the Soviet Union. He was more willing to collaborate with the West, in hopes of improving the Soviet's stagnating economy. During the Geneva summit that year, he met with US president Ronald Reagan. They disagreed on many things and many believed that the summit would be a failure. However, both parties had been advised by their scientists to really start working on an international fusion reactor, as they foresaw that the costs of a working fusion reactor would be larger than the budget of an individual country. Science as a means to promote peaceful international cooperation, as well as a quest for discovery, was something that happened more often in the twentieth century. Other science projects that stimulated (and still stimulate) peaceful cooperation, are CERN and the International Space Station.

And so, Gorbachev and Reagan managed to find common ground on really starting the INTOR project. A year later, in 1986, a new agreement was signed by the original INTOR parties and a community was formed to oversee the project. The design phase was started, and the name was changed to ITER. The name ITER originally came from an abbreviation. But it also means “the way” or “the path” in Latin, which is very symbolic as this reactor will carve out the path to fusion energy. In 1990, a year after the Cold War ended, the conceptual design phase was finished. Then in 1992 the technological objectives were established and from that year until 1998, an engineering design phase was conducted. Once the reactor design was finished, the reactor could be built, right? Well yes, but actually no. The parties hadn’t been able to decide yet where ITER should be build and who would pay for what.

Figure 2.13. Soviet Leader Mikhail Gorbachev and US president Ronald Reagan. Credit: White House Photographic Office.

Classroom Exercise 2.6

It has been mentioned that ITER is big, but how big are we really talking about? On the website of ITER, many interesting numbers are given on the facts and figures page. Visit https://www.iter.org/factsfigures. Here you will also find that the inside of the torus, which contains the plasma, has a volume of about 830 cubic meters. Do you have a feeling for how big this is?

(a) How many humans (65 litre) can you fit in ITER?
(b) How about elephants (47 m^3)?

Negotiations take time

By the year 1999, the US had got sick of all the discussions and stepped out of the ITER project, attempting to do it on their own, starting the FIRE project. ITER gained a new member in Canada who joined before the discussions about the construction side in 2001. Ironically, two year later Canada had to leave ITER due to lack of funding, and the US returned to ITER after realising how hard it was to pursue fusion on their own.

That same year, two extra members joined: China and South Korea. The last one to become a full member of the project was India, in 2005. By that time, the negotiations for the construction site were still ongoing, but had been narrowed down to two options. A site near Rokkasho in Japan or a site near Cadarache in France. Eventually, a deal was made. Cadarache was chosen as site location, and in return Japan was allowed to fill 20% of the manufacturing orders and research positions, while only holding a 10% share.

All negotiations were finalised in 2006, when the ITER agreement was signed. At that time, the estimated cost was €5.9 billion over a ten-year period. But in 2008, a design review was necessary, and the new estimated price became approximately €19 billion over a ten-year period. One reason why this estimate greatly increased, was that the price for materials had greatly increased. For example, the price of concrete had risen by 50% between the two revisions. By 2016, the last estimate was that the total cost might reach up to €22 billion.

Researchers often like to joke that ITER might be one of the costliest experiments, but it is still relatively cheap for a peace project.

Contributions in kind

Because the economy is different in each country, and because the prices of materials can change greatly over the course of such a large project, it was decided that contributions were to be made in kind. This meant that countries would provide a fixed number of components, materials and workforce rather than providing the money.

The ITER Council distributed the required resources among the partitioners in accordance with the negotiations. This distribution was political. For example, instead of just one or two countries providing parts for the toroidal field coils, China, Euratom, Japan, South Korea, Russia and the US would all provide parts for them. From engineering point of view, this brings another challenge, since all those parts need to fit perfectly together. After all, it is much easier to fit your own component with your own design than with that of someone else. Manufacturing components started in 2008 and all large components are expected to have arrived at ITER by 2023.

Construction well underway

Meanwhile, the construction of ITER is well on its way. During the period of 2007–2009, the ground was cleared and levelled and from 2010–2014, the foundation and ground support structures were placed. ITER has seismic foundations, which help ITER survive an earthquake with 40 times the amplitude and 250 times the energy of the strongest earthquake that has been recorded in the area. The construction of the main building then took place, with a deadline in 2021. Construction on the side buildings started in 2010, with also their deadlines in 2021.

With the construction as good as done, all that is left is to assemble everything and fire up the machine. The main assembly phase has been kicked off in March 2020. As of 31 May 2021, construction and assembly have been finished for 74.5%. Due to the Covid pandemic, the project has been delayed by about a year.

The planning now looks as follows: the torus should be completed somewhere in 2022 and the cryostat (cooling part) will be closed in 2024. Then there is one more year to integrate the last systems. In December 2025, ITER will likely be able to light its first plasma. This will not yet be with a deuterium-tritium fuel. First, it will make some easier plasmas so that they can test out the characteristics of the new machine. These tests will become more extensive over time. By 2035, the real research campaign with a deuterium-tritium fuel will begin. It is expected that this research campaign will last until 2050.

Classroom Exercise 2.7

Another important milestone happened in 2012. That year, ITER was granted a license to work as a Basic Nuclear Installation. The reaction products of the D-T reaction are helium-4 and a neutron. Neither of those are radioactive.

Why would ITER need a Basic Nuclear Installation licence?

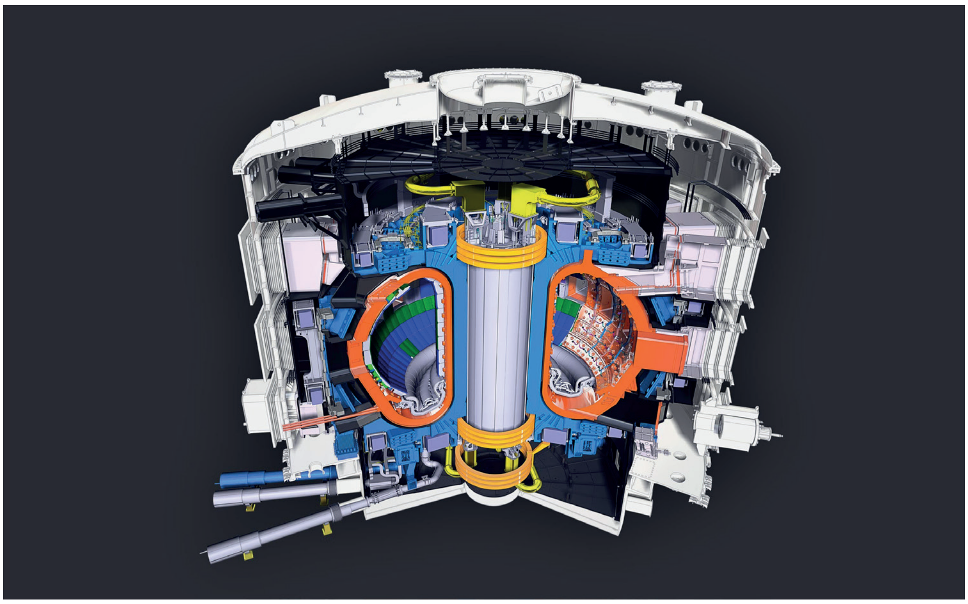


Figure 2.14. A digital rendition of ITER's cross-section. The orange parts indicate the boundaries of the vacuum vessel, which has a volume of 830 cubic meter. To house the entire construction a building with a height of 73 meters is needed. That is higher than the Arc de Triomphe. Credit: ITER Organization.

The goals of ITER

Now that we have discussed the timeline of ITER, let's discuss what researchers hope to achieve with ITER.

ITER's primary goal will be to go **beyond scientific breakeven**. As mentioned before, JET and TFTR were designed with the hope of reaching Q = 1. ITER on the other hand is designed to reach at least **Q = 10**. With 50 MW of heating power, they hope to produce 500 MW of fusion power.

However, ITER is not a power plant. It is not designed to turn the fusion power into electricity. That will be the task of the future DEMO reactors, which are explained in module 5. Still, achieving a Q>1 would be a real breakthrough in the field. Not only would it be the first time that net energy is generated in a fusion reactor, but the behaviour of the plasma will be very different than that of previous plasmas.

In smaller reactors, the plasma is heated by external means. But as mentioned in previous chapter, the alpha particles (helium nuclei) produced in the fusion reaction can help heat the plasma. When ITER reaches Q well above 1, the plasma will be predominantly heated by the alpha-particles. **How alpha-heating influences the plasma behaviour** is something that has yet to be researched. Examining this behaviour is a goal of ITER as well. Especially **how instabilities develop** and how they can be **controlled** under these conditions is an important goal of ITER.

Aside from the plasma conditions, ITER will be one of the first places to test out some material components under the conditions of a fusion power plant. Important designs that have not yet been tested under these conditions are the **divertor**, the **first wall** and **tritium breeding blankets**. These components are extensively discussed in module 4.

However, it should be mentioned that testing the tritium breeding blanket is extremely important. The tritium breeding blanket, which will produce tritium, has never been tested before. This is important as tritium is not found in nature, so we have to make our own.

ITER's last major goal is to prove that **nuclear fusion is inherently safe**. Fusion researchers aim to show that the operation of a fusion reactor, and by extension a fusion power plant, has negligible consequences for the environment. Proving that fusion is inherently safe is an important step for the image of fusion. While improving the know-how is important, improving the image is also important. Because even if fusion works as wonderfully as researchers say, fusion will not have a future if everyone believes it to be dangerous, whether that thought is justified or not. Working on all these goals, ITER will surely bring the field of fusion to the next level.

Summarising

In this module, the history of fusion has been discussed. From the discovery of fusion reactions as the energy source of the Sun, to the first attempts to make fusion work on Earth. From the different designs that people came up with, to the pessimism that none of them would work. From the tabletop-sized reactors, to the biggest experiments in the field. Along the route, the different challenges and achievements were discussed. These challenges had various characters, such as physics-related challenges like how to solve the drift of the plasma, as well as political challenges, such as the tiresome negotiations on where to build a reactor. We talked about were fusion started and where it is right now.

But what about the future? During the work on ITER, major milestones will be set in the field of fusion. There will be multiple points during the operation that could make or break the road to fusion. Should all challenges be overcome, then the road to fusion will have a path set out for itself. But ITER is but a stepping stone on this adventure. After ITER, there are still several challenges to overcome, which are certainly not only related to physics and material sciences. If you are interested in the future of fusion, please look at module 5. If you wish to learn more about how fusion reactors work, please look at modules 3 and 4.

2.5

Further reading

Other modules

FuseNet has developed a total of five modules that look at fusion from different perspective. Visit our website to learn about the four other modules on (1) fusion basics, (3) plasma control, (4) fusion materials and (5) deployment.

They can be found in the FuseNet educational materials browser at https://fusenet.eu/education/material

Online resources

If you like to learn more about the devices and concepts discussed in this module, you can look up the following websites.

https://www.youtube.com/watch?v=0hyEtr_EhVU. The history of fusion told at the hand from fusion scientists who experienced that history.

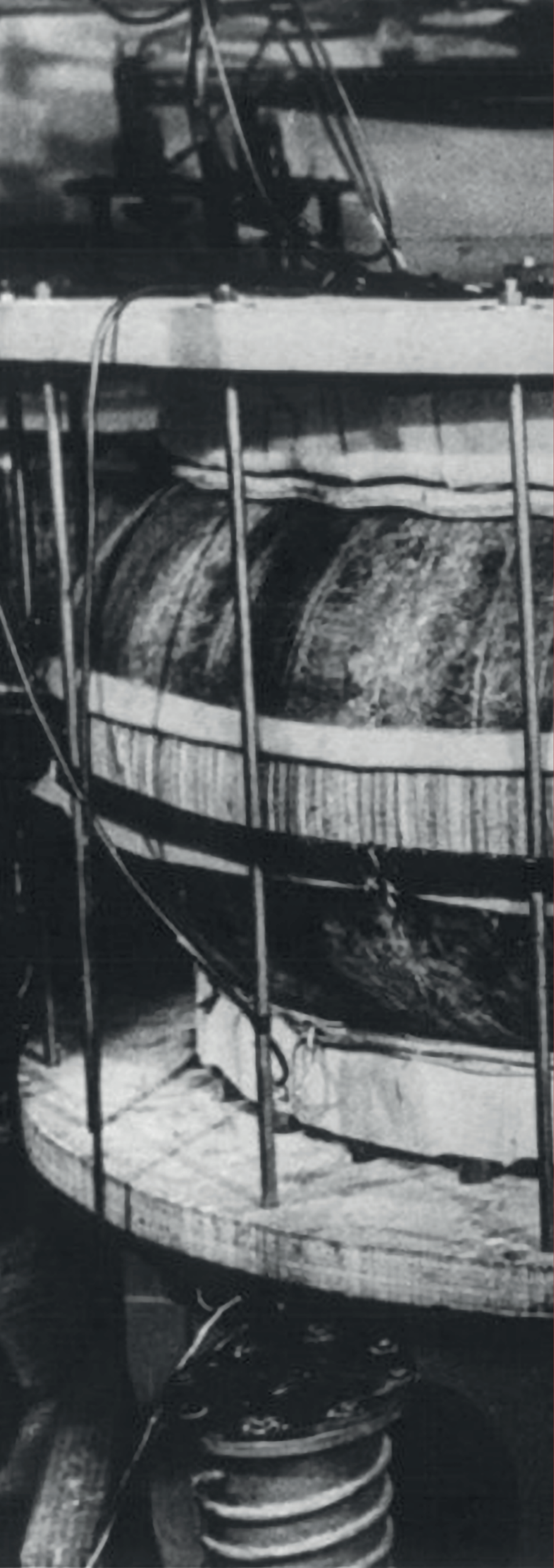
https://www.iter.org. The official website of ITER. On it, the developments of ITER are posted as well as developments in the field of fusion. There is also a virtual tour of the worksite.

https://www2.ipp.mpg.de/ippcms/eng/externe_daten_en/panoramaw7x/. A virtual tour of W7-X.

https://www.ipp.mpg.de/1727365/zeitraffer_w7x. A short video clip of the construction of W7-X.

https://www.iter.org/newsline/-/3033. An article about reusage of fusion devices.

https://www.iter.org/newsline/-/932. An article how technologies developed for ITER are used to make aircraft components.



Colophon

Road to Fusion is the second 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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Cover image
Nomen nescio/ITER Organization

Publisher
FuseNet

Financial support
This project would not have been possible without the financial support of EUROfusion.