

Module 1 – Fusion basics

FuseNet educational materials for secondary school

Teacher's manual

v.1.0

General introduction

Energy plays a fundamental role in our modern society. With the increasing growth of technologies and of the number of users of all these technologies, the world's energy demands are estimated to increase continuously. If we should continue the processes of generating energy than eventually the demand will be higher than we could possibly offer. Therefore, this series of lessons will provide insight into one possible future energy solution: nuclear fusion.

The series consists of five different modules. The first module will start with a broad approach into the energy problem and the corresponding topics in physics needed for nuclear fusion. The next four modules will handle four different aspects of fusion: Road to fusion, Plasma control, Materials for fusion and Fusion deployment. These modules can be chosen independently after completing module 1.

This series of lessons is intended for pre-university education: level ISCED 3-4.

Using the modules

The student readers consist of different lesson materials: the bright coloured boxes, which are called 'aside', will provide extra explanations of the underlying topics. These are optional to use in the classroom.

The light-coloured boxes provide classroom exercises. These can be used during class for further discussion and can serve as a check to test whether the students understand the material.

Next to the module there are also additional exercises. These exercises are scaled from * until ***, in which * corresponds to introductory problems and *** corresponds to more challenging problems.

The full content of a modules consists of:

- A student reader
 - o including classroom exercises
- Additional exercises
- A PowerPoint
 - o Including de classroom exercises
- Teacher manual
 - o Including the following appendices
 - Table of constants and conversion factors
 - Answers to the classroom exercises
 - Answers to the additional exercises

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Chapter 1: Learning objectives

At the end of this module, students are able to:

- Understand the link between climate change and the energy problem
- Explain the basics of fusion
- Compose fusion reaction equations
- Explain the use and content of a plasma
- Understand the basics of magnetic confinement
- Understand the geometry of a tokamak
- Explain the difference between the three different field coils of the tokamak
- Understand the basics of magnetic fields in the tokamak

Chapter 2: Closely related subjects or lessons

The contents of this module can serve as examples or applications of previously learned knowledge. However, the knowledge is *not* required to start this module. This is especially the case if there have been previous lessons on one of the following topics:

- Atomic physics
- Electricity
- Magnetism
- Ideal gas law
- Energy and Energy conservation

If there is already knowledge on one of more of these subjects, it can be used as a recapitulation of these topics.

Chapter 3: Topics of Module 1 per chapter

The first module starts with a broad approach into the energy problem and the corresponding topics in physics:

1. Energy
 - Problems and solutions of the energy demand
 - Climate change
 - Population growth
 - Energy use and production
 - Nuclear fusion
 - Kinetic energy
2. Astrophysics
 - The Sun
 - Atomic physics
 - The atomic model of Rutherford
 - Nuclear reactions regarding hydrogen
 - Isotopes and ions
3. Plasma: the fourth state of matter
 - gas parameters
 - Density
 - Temperature

- Electrostatic interaction
 - Charges
 - Electric fields
- Charged particles in magnetic fields
 - Magnetic field
 - Lorentz force
- 4. Building a Fusion device
 - Electricity
 - Current
 - Transformers
 - Ideal Transformer
 - Electromagnetism
 - Coils
 - Electromotive force
 - Magnetic flux
 - Magnetic field strength
 - Magnetic confinement fusion
 - Geometry of a torus
 - Tokamak

Chapter 4: Brief summary of module 1

The goal of this chapter is to introduce or to give a recap of a selection of topics relevant for the understanding of nuclear fusion and its context. Little to no background on the topics listed above is required for use of this chapter in lessons.

In the first chapter, it is assumed that students have heard of climate change, although in-depth knowledge of the Greenhouse effect or the political debate is not necessary. Climate change is used as a starting point, from which we reason towards a global energy problem, which is then discussed.

In the second chapter, the basics of atomic physics will be explained. If students already possess background knowledge, the chapter can be used mainly as a recapitulation. If no background knowledge is present, this chapter serves as an introductory text. Electric charges and the role of electric charge in atoms and nuclei are explained on a basic level. This chapter can serve as an alternative introduction to atomic physics on a secondary school level, instead of the regular curriculum. The concepts of temperature and density are discussed.

The third chapter introduces the concept of a plasma. It is assumed that the word plasma is known because of the influence of popular culture and the emergence of plasma-based screens, however the concept of a plasma from a scientific point of view is assumed to be unknown. Again, there is a focus on electric charge and the consequent attraction and repulsion of the charged particles.

After the introduction there is a closer look to two main subjects regarding the tokamak: the geometry and the main magnets used to create the magnetic field inside the tokamak. These are the toroidal field coils, central solenoid and the poloidal coils. The combination of these coils results in a helical magnetic field. In this chapter there is a short explanation of a basic solenoid and the possibilities it gives. If the students are unfamiliar with magnetic induction it is recommended to start with the aside.

Chapter 5: Basic lesson schemes

There are four possible basic lesson schemes given. Each scheme will depend on the time available and the knowledge of the students. There is chosen to give a 15-minute lesson scheme and a 1-hour lesson scheme for an introductory lesson on fusion for both average and advanced students.

The starters scheme can be used if multiple or all topics are unfamiliar to the students. The advanced schemes can be used when most important topics for fusion are familiar to the students. Therefore, the advanced scheme will also have a shorter introduction and more time for discussion and exercises.

The advanced schemes serve as an example, feel free to choose the topics and/or chapters suitable for your class.

For all the lesson schemes the student activities involve listening, discussing, asking questions and working on exercises.

15-min introductory lesson for average students

There are two goals for this lesson: first to give a short introduction into climate change and the energy problem, second to create enthusiasm and curiosity towards the subject.

The material needed only covers the first chapter of the module; page 1 until 8 including classroom exercise 1.1. Furthermore, slides 1 until 6 of the PowerPoint can be used, the video about 'do we need nuclear energy to stop climate change?'¹ and additional exercises with *. The aside contains extra reading material for the students.

An option is to have a class-wide discussion after introducing the subject, or to make groups and let students discuss the topic and present their conclusions. After the introduction and/or discussion, the students can read the student reader, work on exercises or work on topics of their choice.

Preparation for this lesson involves:

- Downloading the PowerPoint
- Making the module and exercises available for students
- Preparing classroom exercise 1.1. (This depends on the country you live in, see appendix B)

¹ See chapter 7 for more video's and experiments!

Duration	Teacher activity	Materials	Student activity
3 min	Introduction of the topic	Chapter 1 PowerPoint slide: 1 and 2 And/Or video kurzgesagt Kurzgesagt - in a nutshell: Do we need nuclear energy to stop climate change?	Listen
5 min	Discuss classroom exercise. 1.1	Chapter 1 PowerPoint: slide 3 and 4	Open discussion classroom/small group of 4.
3 min	Presenting chapter 1: Energy problem	Chapter 1 PowerPoint: slide 5 and 6	Listen, ask questions
5 min		Module 1 Additional exercises A.1 until A.3	Read chapter 1 including the aside. Work on the exercises individually/ in pairs at home or in class

15-min introductory lesson for advanced students

There are three goals for this lesson. First is to give a short introduction into climate change and the energy problem. Second is to create enthusiasm and curiosity towards the subject. Third is short recap on one of more topics regarding energy problems.

The material needed covers the first chapter of the module; page 1 until 8 including classroom exercise 1.1. Then the material is depended on the chapter of choice. E.g., chapter three plasma. Furthermore, the slides 1 until 6 and slide 18 until 29 of the PowerPoint and additional exercises from ** and *** can be used. These are exercises A.1 until A.3 and A.9 until A.10. There are some YouTube video's that can be used, see chapter 7.

Preparation for this lesson involves

- Download the PowerPoint
- Make the module and exercises available for students
- Prepare classroom exercise 1.1. (This depends on the country you live in, see appendix B)

The student activities involve listening, discussing and working the exercises. After the introduction, students can read the student reader, work on exercises or work on topics of their choice to increase their knowledge on the personal topic. Student could for a study group for a chosen topic to discuss the material.

Duration	Teacher activity	Materials	Student activity
1 min	Introduction of the topic	Chapter 1 PowerPoint slide: 1 and 2	Listen
3min	Discuss classroom exercise. 1.1	Chapter 1 PowerPoint: slide 3 and 4	Open discussion classroom/small group of 4.
2 min	Presenting chapter 1: Energy problem	Chapter 1 PowerPoint: slide 5 and 6	Listen, ask questions
4 min	Presenting chapter of choice e.g., Chapter 3 plasma	Chapter 3 PowerPoint: slide 18 until 21	Listen, ask questions
2 min	Discuss classroom exercise. 1.3	Chapter 3 PowerPoint: slide 22 and 23	Quick answer!
5 min	Presenting chapter of choice e.g., Chapter 3 plasma	Chapter 3 PowerPoint: slide 24 until 29	Listen, ask questions
		Module 1 Additional exercises: A.1 until A.3 and A.9 until A.10	Read chapter Work individually/ in pairs at home or in class

1-hour lesson for average students

The goal for a one-hour lesson is to create enthusiasm and curiosity towards the subject and to dive into the underlying physical topics of fusion. For starters the goal should be focused on the inner workings of an atom and the understanding of nuclear reactions and only give a short notice on plasmas and magnetic fields.

The material needed covers the whole of module 1, with a focus on chapter one, two and a part of chapter four. From the additional exercises * and possibly ** could be used. The asides material is reading material for the students. The whole PowerPoint can be used.

Preparation for this lesson involves

- Download the PowerPoint
- Make the module and exercises available for students
- Prepare classroom exercise 1.1. (This is depended on the country you live in, see appendix B)

Depending on the students it is an option to give one full lecture of all the topics or to divide the lesson into four different parts. Each part includes an introduction of one of the chapters, time for classroom discussion and room to exercise.

Duration	Teacher activity	Materials	Student activity
3 min	Introduction of the topic	Chapter 1 PowerPoint slide: 1 and 2 And/Or video kurzgesagt Kurzgesagt - in a nutshell: Do we need nuclear energy to stop climate change?	Listen
5 min	Discuss classroom exercise. 1.1	Chapter 1 PowerPoint: slide 3 and 4	Open discussion classroom/small group of 4.
3 min	Presenting chapter 1: Energy problem	Chapter 1 PowerPoint: slide 5 and 6	Listen, ask questions
5 min		Module 1 Additional exercise A.1	Work individually/ work in pairs/ exercise with whole class
10-15 min	Presenting chapter 2: Fusion inside our own sun until classroom exercise 1.2	Chapter 2 PowerPoint slide: 7 until 13	Listen, ask questions,
5 min	Discuss classroom exercise. 1.2	Chapter 2 PowerPoint slide: 14 until 15	Open discussion classroom/small group of 4.
2 min	Presenting chapter 2: Fusion inside our own sun	Chapter 2 PowerPoint slide: 16 and 17	Listen, ask questions

5 min		Module 1 Additional exercise A.4	Work individually/ work in pairs/ exercise with whole class
10-15 min	Presenting chapter 3:	Chapter 3 PowerPoint slide: 18 until 21 And video Ted-ed – Solid, liquid, gas and ... plasma	Listen, ask questions
2 min	Discuss classroom exercise. 1.3	Chapter 3 PowerPoint slide: 22 and 23	Open discussion after students have made a choice
5-7 min		Chapter 3 PowerPoint slide: 24 until 27	Listen, ask questions
2 min	Discuss classroom exercise. 1.4	Chapter 3 PowerPoint slide: 28 and 29	Open discussion after students have made a choice

1-hour lesson for advanced students

The goal for a one-hour lesson is to create enthusiasm and curiosity towards the subject and to dive into the underlying physical topics of fusion. Advanced students are recommended to start with a short recap of the known topics and then a dive into the plasmas and magnetic fields.

The material needed covers the whole of module 1, with a focus on chapter one, three and four. The aside material is self-study material for the students. From the additional exercises ** and *** could be used. The whole PowerPoint can be used.

Preparation for this lesson involves

- Download the PowerPoint
- Make the module and exercises available for students
- Prepare classroom exercise 1.1. (This depends on the country you live in, see appendix B)

If the topics are already known by the students it is an idea to switch the role of teacher and student in the classroom. The teacher only asks questions and the students have to explain the topics. Let the students discuss with each other if they do not agree.

The classroom exercises can be used for students to get a taste of the chapter, let students discuss before the presentation of the chapter.

Duration	Teacher activity	Materials	Student activity
2 min	Introduction of the topic	Chapter 1 PowerPoint slide: 1 and 2	Listen
3 min	Discuss classroom exercise. 1.1	Chapter 1 PowerPoint slide: 3 and 4	Open discussion classroom/small group of 4.
2 min	Presenting chapter 1: Energy problem	Chapter 1 PowerPoint: slide 5 and 6	Listen, ask questions
5 min	Start with discussion of classroom exercise. 1.2	Chapter 2 PowerPoint: slide 14 and 15	Open discussion classroom/small group of 4.
10 min	Change the role: teacher becomes student and student becomes teacher. Show only the slides of the known topics of chapter 2: Fusion inside our own sun, let students explain! Listen/ask questions	Chapter 2 PowerPoint slide: 7 until 11	Let student (shortly) explain the subject and the slides
5 min	Presenting chapter 2: Fusion inside our own sun: criteria for fusion	Chapter 2 PowerPoint slide: 12, 13, 16 and 17	Listen, ask questions

5 min	Presenting chapter 3: Plasma until classroom exercise	Chapter 3 PowerPoint: slide 18 until 21	Listen, ask questions
3 min	Discuss classroom exercise. 1.3	Chapter 3 PowerPoint: slide 22 and 23	Open discussion in class
5 min	Presenting chapter 3: Plasma after classroom exercise	Chapter 3 PowerPoint: slide 24 until 27	Listen, ask questions
5 min	Discuss classroom exercise. 1.4	Chapter 3 PowerPoint: slide 28 and 29	Open discussion in class
15 min	Presenting chapter 4:	Chapter 4 PowerPoint: slide 30, 31, 36, 39 until 45, and 48	Listen, ask questions
<i>Homework</i>	<i>classroom exercise. 1.5, 1.6 and 1.7</i>	<i>Chapter 3 PowerPoint: slide 32 until 35, 37 and 38 and 46 and 47</i>	

Chapter 6: Use of PowerPoint and other materials

There is a PowerPoint (for each module) available at the site. <https://fusenet.eu/education/material>.

The PowerPoint consists of the whole module, including the classroom exercises and answers, and can be used directly in class. There are some extra pictures used to explain the topics. If there is a possible YouTube video of Phet which can be used for a topic, this is recommended in chapter 7. For an overview of extra material see chapter 7. You can adapt the PowerPoint to the topics which are treated in the classroom.

To introduce the different topics of module 1, it is possible to give the students a preparation exercise at home per topic. This could be one or more of the * exercises of the additional exercises. For the preparation also some subjects from 'further references for study and fun' can be used.

Chapter 7: Further references for study and fun for module 1:

For teachers

The following contains general background information (in English) for teachers of this module. This is merely intended to use for your own knowledge and understanding of the subject. It is possible to use this content in the classroom but then it has to be adapted to the level of the students.

Some sites will give information about the topics covered or related to this module. Other sites also give pictures, exercises (with or without answers) and extra lecture notes. Under each URL there is a short introduction of what can be found.

- a. FuseNet website - <https://www.fusenet.eu/education/material>
Here you can find the other four modules. Furthermore, there are also theoretical papers, courses and experiments of topics related to this lesson series.
- b. MIT Open Course Ware - <https://ocw.mit.edu/courses/simulations-applets-and-visualizations/#materials-science-and-engineering>
On this site you can find lecture notes, old exams and exercises about nuclear physics and nuclear magnetic resonance in section 'nuclear science and engineering'.
- c. EUROfusion - <https://www.euro-fusion.org/> There is a special page for students and educators. Educators will find more information on the basics of the topics and there is a Q&A for fusion. There are also slides and PowerPoint presentations available which are free to use. Students can find the same type of content on the website but the information is more to the point and appropriate for students. It can be used for both average and advanced students.
- d. Fusion for energy - <https://fusionforenergy.europa.eu/>
This website has nice animations regarding fusion and the basics of fusion. It uses clear explanation regarding the different topics of module 1 and also ITER. However due to the animation the website can be slow.

For teachers and students

These following sites can be used to explain, to deepen, to discover or to broaden the topics of module one. Some can be used instead of a presentation or as an addition to the presentation of one or more chapters. For all the Phet simulations, which can be used without registration, it is recommended to use a windows computer. Each reference will be placed within the corresponding chapter. After each URL information will be provided about the content and possible use.

Chapter 1: Energy and its role in our world

- Kurzgesagt - in a nutshell: Do we need nuclear energy to stop climate change?
<https://www.youtube.com/watch?v=EhAemz1v7dQ>
Duration: 10 minutes.
The first part of the video can be used as an introduction of the module, until 2:49 or 6:00 can be used as an introduction and part of explanation of chapter 1.

Chapter 2: fusion inside our own sun

- Phet - atoms, ions and charge
https://phet.colorado.edu/sims/html/build-an-atom/latest/build-an-atom_en.html
First Phet can be used to see the relationship of the building blocks and the atomic name. The ions and charge can be determined by adding electrons/protons to the model. It is really basic and can be used by average students.
- Phet – relationship between pressure, volume and temperature
https://phet.colorado.edu/sims/html/gas-properties/latest/gas-properties_en.html
choose the first 'ideal' phet to see the relationship between pressure and temperature. In this Phet these quantities can be changed during the process. For this module it is nice to set the volume as a constant.

Chapter 3: Plasma and electrical fields

- Phet – effect of charges within a field
https://phet.colorado.edu/sims/html/charges-and-fields/latest/charges-and-fields_en.html
Students can place one or more charges in a field and then the electrical field lines will appear. When adding more charges, the field will respond to those changes.
- Phet – electrical field hockey
<https://phet.colorado.edu/sims/cheerpi/electric-hockey/latest/electric-hockey.html?simulation=electric-hockey>
Fun for students: the electrical field hockey consists of three levels. Charges has to be placed to put the puck into the goal.
- Ted-ed – Solid, liquid, gas and ... plasma by Michale Murillo
<https://www.youtube.com/watch?v=tJplytSR-ww>
Duration: 3:15
A short video on YouTube which explains a plasma. Really clear. Can be used for average students, with some explanation of the teacher, and advanced students.

Chapter 4: building a fusion device

- Kurzgesagt - in a nutshell: Fusion power explained
<https://www.youtube.com/watch?v=mZsaaturR6E>

Duration: 6:15

YouTube video which explains the inertial confinement, magnetic confinement and gives a short walk through a fusion device and the possibilities. This can be used as a short recap/introduction of the whole module.

- TSG Physics Lenz's law with copper pipe
<https://www.youtube.com/watch?v=N7tli71-AjA>

Duration: 1:39 minutes

This silent YouTube video shows the result of magnetic induction. A small iron ball and a spherical magnet will be compared when going down a copper pipe. After the experiment, the result will be explained briefly.

- Simon Lloyd- demonstrating Lenz's law with a copper tube and a neodymium magnet
<https://www.youtube.com/watch?v=nrkOZsECrZI>

Duration: 2:40 minutes

A longer YouTube video which also shows the result of magnetic induction. This video explains more about the working of the magnetic induction and therefore can be used for average students.

Appendix A: Table of constants and conversion factors

Quantity	Quantity	Conversion factor to SI units
Energy ²	1 Calorie	4.184 J
Energy ³	1 toe*	$4.2 * 10^{10}$ J
Energy ¹	1 kWh*	$3.6 * 10^6$ J
Mass ¹	1 Ton	$1.0 * 10^3$ kg
Mass ¹	1 amu/u/ame	$1.66 * 10^{-27}$ kg
Temperature ¹	0 °C	273.15 K
Pressure ¹	1 bar	$1.0 * 10^5$ Pa

Table A.1 conversion factors

*students are asked to find these in exercises A.2

Quantity	
Core temperature Sun ²	$1.571 * 10^7$ K
Surface temperature Sun ¹	5780 K
(mean) Density Sun ³	1408 kg/m ³
Core density ²	$1.622 * 10^5$ kg/m ³
Core pressure Sun ²	$2.477 * 10^{11}$ bar
Surface temperature Earth ¹	295 K
(mean) Density Earth ²	5514 kg/m ³
Mass electron ¹	$9.109 * 10^{-31}$ kg
Charge electron ¹	$1.602 * 10^{-19}$ C
Mass proton ¹	$1.673 * 10^{-27}$ kg
Charge proton ¹	$1.602 * 10^{-19}$ C
Mass neutron ¹	$1.675 * 10^{-27}$ kg

Table A.2 constants

¹ Noordhoff uitgevers & NVON (2021). *Binas HAVO/VWO Informatieboek 6de editie (6e havo/vwo)* (01 ed.). Groningen, Nederland: Noordhoff Uitgevers.

² Sun Fact Sheet. (2018). Retrieved 13 July 2021, from <https://nssdc.gsfc.nasa.gov/planetary/factsheet/sunfact.html>

³ IEA Unit converter and glossary, for common energy units. From <https://www.iea.org/reports/unit-converter-and-glossary>

Appendix B: Solutions to classroom exercises

Classroom exercise 1.1

Answer is dependent on the country!

General information can be found at <https://ourworldindata.org/energy-mix>

For specific countries <https://ourworldindata.org/energy#energy-country-profiles>

For The Netherlands <https://ourworldindata.org/energy/country/netherlands#energy-mix>

On these sites the energy mix of many different countries can be found, but there is more. This site also gives information about the different energy sources, the progress in decarbonizing and the energy consumption. There is a lot of data.

Classroom exercise 1.2

The Energy densities from highest to lowest:

Deuterium – Uranium – Coal – Oil – Gasoline – Ethanol – Wood – Hydrogen (gas)

The energy density of Deuterium depends on the reaction conditions. However fusion reactions have the highest energy density of all fuels, even larger than fission reactions. The energy released in 1 fusion reaction is smaller than the energy released in 1 fission reaction, because fissionable atoms are much larger than the small atoms used in fusion. However, the energy per unit mass (per nucleon) is much larger for fusion. So, if you would fill a certain volume entirely by deuterium nuclei and make them all hypothetically fuse at once, then this would result in more energy than that same volume completely filled with uranium nuclei which undergo fission. The three fossil fuels (coal, oil, gasoline) are relatively close in energy densities. In this case the upper limits have been taken from the numbers below:

Uranium: 1 539 842 000 MJ/L, source: https://en.wikipedia.org/wiki/Energy_density

Coal: 34-42 MJ/L (anthracite), or 26-49 MJ/L (bituminous) source: idem

Oil: 37 MJ/L source: idem

Gasoline: 34.2 MJ/L, source: idem

Ethanol: 24 MJ/L, source: idem

Wood: 2.56-21.84 MJ/L, source: https://en.wikipedia.org/wiki/Energy_content_of_biofuel

Hydrogen (gas): 0.01005-0.01188 MJ/L, source: https://en.wikipedia.org/wiki/Energy_density

Classroom exercise 1.3

Answer B

Due to recombination reactions, free electrons and ions can recombine into a neutral atom (gas particle) and in this process light is emitted. Depending on the types of ions, different recombination reactions are possible. Since ions (and atoms) have specific energy levels, certain transitions can occur during this recombination for specific ions. As a result, the colour of the plasma depends on the types of particles.

Due to recombination, a plasma is usually unstable since the plasma particles recombine into neutral (gas) particles. Gas particles need to be ionized continuously to keep the plasma stable. If a newly formed neutral particle collides with an ionized particle, there is a chance that the neutral can become ionized again.

Regarding answer A: not all plasmas have a high temperature; there exist cold plasmas. Heat is one way of ionizing a gas, however there are more which are not treated in this module. Cold plasmas can still glow.

Regarding answer C: Nuclear reactions do not occur naturally in plasmas, except in stars. Most nuclear reactions do not emit light, e.g., D-D or D-T fusion do not emit photons.

Classroom exercise 1.4

- a. The current goes out of the paper
The magnetic field curls anti-clockwise

Using the right-hand rule, we find that if the direction of the current is out of the paper, the magnetic field curls around the wire in an anticlockwise fashion. If the direction of current is into the paper, the magnetic field curls around the wire in a clockwise fashion.

- b. The magnetic field inside the loop is **out of** the paper
The magnetic field inside the loop is **into** the paper

If we draw a circular loop of wire with a current in the anti-clockwise direction, we find that using the right-hand rule, the direction of the magnetic field inside the wire loop is directed out of the paper, while the direction of the magnetic field outside of the wire loop is into the paper.

- c. Because of opposite charge and opposite motion, the magnetic field has the same direction for both particles

If we draw the circular path of the electron on paper, with the electron moving in the clockwise direction, then the magnetic field inside the circle is directed out of the paper, outside of the circle the magnetic field is directed into the paper.

If we draw the circular path of the proton on paper, with the proton moving in the anti-clockwise direction, then the magnetic field is exactly the same as for the electron. The magnetic field inside the circle is directed out of the paper, the magnetic field outside of the circle is directed into the paper. This is because the proton has opposite charge: if an electron and proton were to move in the same way, they would generate opposing magnetic fields. If we reverse the direction and the charge, we end up at the same situation as before.

The directions are exactly the same as for the circular loop of wire with a current in the anti-clockwise direction as well! If the direction of current is the same as the direction of motion of the proton (a positive particle), then the magnetic field is in exactly the same direction. A current in a circular wire is exactly the same as charged particle(s) moving in a circular path, hence the magnetic fields have the same direction.

- d. The direction of the magnetic field is always perpendicular to the direction of the current

The direction of the magnetic field is always perpendicular to the direction of motion of the charges (and therefore also always perpendicular to the direction of the current).

Classroom exercise 1.5

- a. Make a sketch of a torus with a large major radius, but with a small minor radius. What does this look like?

A doughnut

- 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?

The doughnut becomes more spherical, the minor radius cannot be larger than the major radius (otherwise it is no longer a torus!)

- 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?

If we allow the minor radius to be larger than the major radius and take the limiting case we get a sphere

Now look at the aspect ratios of the two sketches from (a) and (b).

- d. What happens if the aspect ratio changes?

The torus changes shape

- e. What is the lowest possible aspect ratio for a torus?

The minor radius cannot be larger than the major radius. If they are equal the aspect ratio is at its minimum, so aspect ratio = 1.

Classroom exercise 1.6



A. Toroidal cross-section:



B. Poloidal cross-section:



C. 3D view:

- a. One is seen from above: a round shaped doughnut
One is seen as an intersection of the doughnut: so two circles.
- b. The poloidal direction is perpendicular to the poloidal cross-section. The toroidal direction is perpendicular to the toroidal cross-section.

Compare it with taking the cross-sections of a cylinder: if we take a cross-section along the z-direction (from top to bottom), we get a rectangular plane that lies perpendicular to the z-direction. If we take a cross-section along the other direction (either the poloidal or radial, in this case both result in the same cross-section), we end up with a circular cross-section that is perpendicular to the poloidal direction.

The toroidal field magnets lie around the torus shape in the poloidal direction. So, the magnets form loops in the poloidal cross section, creating a current loop in the poloidal direction, leading to a magnetic field in the toroidal direction: hence the name, toroidal field magnets.

In the same way, the poloidal field magnets lie in the toroidal directions at the top and bottom of the torus. The current in these magnets follows a toroidal loop, leading to a magnetic field in the poloidal direction.

Classroom exercise 1.7

- a. toroidal field coils lie in the poloidal cross-section of the tokamak

The poloidally oriented magnets create a magnetic field in a direction perpendicular to the poloidal cross section, i.e., in the toroidal direction. Hence these magnets create a magnetic field in the toroidal direction => toroidal field coils (even though they lie in the poloidal plane)

- b. Poloidal field coils lie at the top and bottom of the torus. Central solenoid lies in the hole of the doughnut.

The poloidal field coils lie in a shifted toroidal cross section; however, the magnetic field direction is poloidal. Central solenoid lies at the centre of the tokamak. And is a solenoid

Classroom exercise 1.8

- a. Induction depends on a change of the magnetic flux but the magnetic flux cannot keep changing continuously, at some points there is a limit of the magnets. Therefore, the central solenoid operates in pulses.

Magnetic induction is a result of a change in magnetic flux. It is not possible to keep changing the magnetic flux forever: there is a limit: we start at a certain current and can increase it to a certain current. For as long as we can keep increasing (or decreasing) this current, induction occurs and the tokamak can keep running. If we cannot keep changing the magnetic flux, the induction stops and the poloidal field disappears.

- b. When using pulses there is a time that there is no energy generated, but we want a fusion reactor to run all the time. Therefore, pulses are not ideal.

Coming soon!