# Module 1 – Fusion basics

**FuseNet educational materials for secondary school**

# Teacher’s manual v.1.1

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

## Content of the teacher manual


General introduction.......1

Chapter 1: Learning objectives.......3

Chapter 2: Closely related subjects or lessons.......3

Chapter 3: Topics of Module 1 per chapter.......3

Chapter 4: Brief summary of module 1.......4

Chapter 5: Basic lesson schemes.......5

Chapter 6: Use of PowerPoint and other ideas for introduction of lesson.......12

Chapter 7: Further references for study and fun for module 1:.......12

Appendix A: Table of constants and conversion factors.......15

Appendix B: Solutions to classroom exercises.......16

Appendix C: Solutions to additional exercises.......20

## 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 tokomak
- 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<br>PowerPoint slide: 1 and 2<br><br>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<br>PowerPoint: slide 3 and 4 | Open discussion classroom/small group of 4. |
| 3 min | Presenting chapter 1:<br>Energy problem | Chapter 1<br>PowerPoint: slide 5 and 6 | Listen, ask questions |
| 5 min | | Module 1<br>Additional exercises A.1 until A.3 | Read chapter 1 including the aside.<br>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<br>PowerPoint slide: 1 and 2 | Listen |
| 3min | Discuss classroom exercise. 1.1 | Chapter 1<br>PowerPoint: slide 3 and 4 | Open discussion classroom/small group of 4. |
| 2 min | Presenting chapter 1: Energy problem | Chapter 1<br>PowerPoint: slide 5 and 6 | Listen, ask questions |
| 4 min | Presenting chapter of choice e.g., Chapter 3 plasma | Chapter 3<br>PowerPoint: slide 18 until 21 | Listen, ask questions |
| 2 min | Discuss classroom exercise. 1.3 | Chapter 3<br><br>PowerPoint: slide 22 and 23 | Quick answer! |
| 5 min | Presenting chapter of choice e.g., Chapter 3 plasma | Chapter 3<br>PowerPoint: slide 24 until 29 | Listen, ask questions |
| | | Module 1<br>Additional exercises: A.1 until A.3 and A.9 until A.10 | Read chapter<br>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<br>PowerPoint slide: 1 and 2<br><br>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<br>PowerPoint: slide 3 and 4 | Open discussion classroom/small group of 4. |
| 3 min | Presenting chapter 1: Energy problem | Chapter 1<br>PowerPoint: slide 5 and 6 | Listen, ask questions |
| 5 min | | Module 1<br>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<br>PowerPoint slide: 7 until 13 | Listen, ask questions, |
| 5 min | Discuss classroom exercise. 1.2 | Chapter 2<br>PowerPoint slide: 14 until 15 | Open discussion classroom/small group of 4. |
| 2 min | Presenting chapter 2: Fusion inside our own sun | Chapter 2<br>PowerPoint slide: 16 and 17 | Listen, ask questions |

| | | | |
|---|---|---|---|
| 5 min | | Module 1<br>Additional exercise A.4 | Work individually/ work in pairs/ exercise with whole class |
| 10-15 min | Presenting chapter 3: | Chapter 3<br>PowerPoint slide: 18 until 21<br><br>And video Ted-ed – Solid, liquid, gas and … plasma | Listen, ask questions |
| 2 min | Discuss classroom exercise. 1.3 | Chapter 3<br>PowerPoint slide: 22 and 23 | Open discussion after students have made a choice |
| 5-7 min | | Chapter 3<br>PowerPoint slide: 24 until 27 | Listen, ask questions |
| 2 min | Discuss classroom exercise. 1.4 | Chapter 3<br>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<br>PowerPoint slide: 1 and 2 | Listen |
| 3 min | Discuss classroom exercise. 1.1 | Chapter 1<br>PowerPoint slide: 3 and 4 | Open discussion classroom/small group of 4. |
| 2 min | Presenting chapter 1: Energy problem | Chapter 1<br>PowerPoint: slide 5 and 6 | Listen, ask questions |
| 5 min | Start with discussion of classroom exercise. 1.2 | Chapter 2<br>PowerPoint: slide 14 and 15 | Open discussion classroom/small group of 4. |
| 10 min | Change the role: teacher becomes student and student becomes teacher.<br>Show only the slides of the known topics of chapter 2:<br>Fusion inside our own sun, let students explain!<br>Listen/ask questions | Chapter 2<br>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<br>PowerPoint slide: 12, 13, 16 and 17 | Listen, ask questions |

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

# 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/cheerpj/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=N7tIi71-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*

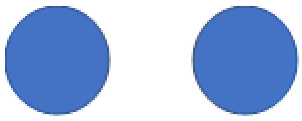
e. What is the lowest possible aspect ratio for a torus?

*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.*

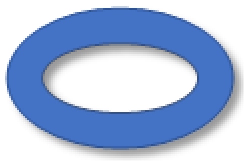
**Classroom exercise 1.6**

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 tokomak

*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 charge 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.

## Appendix C: Solutions to additional exercises v.1.0

**Additional exercise A.1**

a. Look up what a Joule is in SI units. What does this mean? Compare this with the units of velocity (*m/s*) and acceleration (*m/s²*).

*1 J = 1 kgm2/s2, it is the energy required to accelerate a 1 kg mass over a distance of 1 m with an acceleration of 1 m/s2. Note that Work (which is the energy transferred to or from an object via the application of force along a displacement) is Force · distance, which has units: N · m or kgm/s2 · m. So 1 Joule can also be interpreted as the energy as a result of the constant application of a force along a certain distance. Comparing the unit of energy with velocity and acceleration, we see that variation of velocity over time is acceleration and that acceleration times a mass is a force.*

b. [Multiple choice] Which of the following answers represents approximately 1 Joule of energy?

*D, all of the above.*

c. How much do you expect the total energy consumption of the world to be? Look up the total energy consumption of the world in Joules and compare it with your estimate. Was your estimate close?

*The total (primary) energy consumption of the world in 2021 was estimated to be 595.15 exajoules, or 595.15 × $10^{18}$ Joules; source: BP statistical review of world energy 2022 (p.8)*

**Additional exercise A.2**

a. Where did you find the data? How do you know whether the data you found can be trusted? Explain why you trust this information.

-

b. What units are used in the data?

-

c. Compare the units of Joule (J), kilowatt-hours (kWh) and tonnes of oil equivalent (toe). How many Joules is one kWh? How many Joules is one toe? How many Joules is one Mtoe?

*1 kWh = 3 600 000 Joules; 1 toe = 41.868 × $10^9$ Joules (or 41.868 GJ); 1 Mtoe = 41.868 × $10^{15}$ Joules or 41.868 PJ.*

d. What does primary energy mean?

*Energy in the form that it is first accounted for in a statistical energy balance, before any transformation to secondary or tertiary forms of energy. For example, coal can be converted to synthetic gas, which can be converted to electricity; in this example, coal is primary energy, synthetic gas is secondary energy, and electricity is tertiary energy (source: U.S. Energy Information Administration, https://www.eia.gov/tools/glossary/index.php?id=Primary%20energy).*

*So, Primary energy is an energy form found in nature that has not been subjected to any human engineered conversion process. That is, it is the energy as found in nature in things such as raw fuels that have not been changed or altered by humans. Examples are coal, natural gas, natural uranium. These can then be converted into secondary energy by changing it to more useable energy carrier, such as gasoline which is derived from oil. If the gasoline is used to create electricity, then the electricity is tertiary energy. Primary energy is often used to calculate the total primary energy supply (TPES) of a country, which is a common measure to compare countries based on their energy resources.*

e. In most countries, the so-called **fossil fuels** dominate the energy supply. Compare different countries and percentages, what is the contribution by renewable sources such as solar and wind energy?

*Depends on the country. In almost all countries, fossil fuels still dominate the energy mix.*

f. Is a large portion of the energy mix derived from sustainable sources? What about renewable sources?

*This depends on the sources that are used and whether they are seen as sustainable: biofuels could be seen as sustainable, as well as nuclear fission, depending on your point of view and regulations. Hence sustainable often includes renewables and other sources such as fission or biofuels. So the portion of sustainable sources is often seen as larger than the renewable portion. Some countries use a lot of nuclear energy and therefore have lower $CO_2$ emissions than countries that use a bigger portion of solar and wind but still rely heavily on fossil fuels. Society determines what is acceptable and what is seen as truly sustainable.*

**Additional exercise A.3**

***Note**: since this exercise has as its main goal to get some order of magnitude estimates for energy use, the answers given below are not exact. Since there are many different (sometimes even contradicting) sources for energy values on large scales due to the difficulties in measuring energy on such a level, you could find very different results. As long as the logic is correct in coming to an answer, the answer would still be fine if any incorrect number is interchanged with a correct value. So, pay attention to the reasoning instead of the exact numbers.*

a. Make an estimated guess of the used energy in Joules of a household, a city, a country and the world.

*Using data from: ODYSSEE-MURE, Our World in Data and University of Ontario; The average energy consumption per dwelling (i.e. home/household) varies per European country (see also: https://www.odyssee-mure.eu/publications/efficiency-by-sector/households/average-energy-consumption-dwelling.html). On average, 1.3 toe/dwelling was used in Europe in 2019, which is 1.3 toe/dwelling × 41.868 GJ/toe = 54.4 GJ/dwelling. So on average, a household is estimated to use 54.4 GJ/year in Europe.*

*Since cities vary in size and consumption based on the country, it is difficult to find the consumption of a city in Europe. However, taking the average we calculated for a household we can take a city, look up the number of households and get a rough estimate. Taking Berlin as example, a city with (according to Wikipedia: https://en.wikipedia.org/wiki/Demographics_of_Berlin) nearly 2 million households, we get: 54.4 GJ/year × 2 000 000 = 54.4 × 1015 Joules, slightly more than 1 Mtoe. If we compare that with a value given online of 263.2 PJ = 263.2 × 1015 Joules (source: https://www.cleanenergywire.org/factsheets/energy-use-city-berlin), this estimate is within a factor of 5. Given that Germany in 2021 had an energy consumption of roughly 286 Mtoe (according to: https://www.enerdata.net/estore/energy-market/germany) and given that Berlin is one of the biggest cities in Germany and there are roughly 2000 cities in Germany, the estimate seems to be reasonable.*

*Finally, the energy consumption of the entire world is estimated at 580 million terajoules. That's 580 million trillion joules or about 13865 million tons of oil equivalents (Mtoe).*

b. Make an estimated guess of the total used energy in industry and the total energy used by individuals on this planet.

*Using the data from: https://www.eea.europa.eu/data-and-maps/indicators/final-energy-consumption-by-sector-10/assessment (note that the latest version does not contain data per sector anymore, so we use an archived version), where energy is divided over 5 sectors, namely: transport, industry, households, commercial and public services and other, we can see what part of the total energy consumption is due to different sectors. Since household and industry are in there, we can compare them easily. Taking the data from 2017, we get the following numbers for Europe:*

- *Commercial and public services: 154 Mtoe*
- *Households: 288 Mtoe*
- *Industry: 261 Mtoe*
- *Transport: 326.9 Mtoe*
- *Other: 30.1 Mtoe*

*Which makes a total of 1060 Mtoe in 2017 for Europe (note: this is final energy consumption, not primary energy: 1060 Mtoe seems little compared to the 286 Mtoe we found in the previous question for Germany alone, this again shows how much variation there is in numbers and it is not always clear where this variation comes from, it could be due to differences such as final energy versus primary energy, etc.) Still, if we take as the energy used by individuals mainly the household consumption (neglecting transport, as most transport is for commercial/industrial use) we get 288/1060 × 100 = 27%. If we do the same for industry, we get: 261/1060 x 100 = 25%. Note that this depends a lot on your definition of individual energy use and industry energy use and if your definition varies from the definition of your source, the numbers will say very different things.*

Try to find a source for questions a and b above.

c. Which sources did you use?

*All sources used are given within the answers given above.*

d. Does it match with your given answers?

*Within the answers, if possible checks of the validity of the arguments were given, such as with the comparison of the consumption of Berlin with the calculated value based on the average consumption per dwelling and the number found online. Given that we work with rough estimates here, answers that are within a factor of 10 from each other can be taken as very reasonable. If the answers vary with much larger factors, either the data does not correspond due to incorrect definitions or there might be an error or oversight in the calculation.*

e. What do you notice?

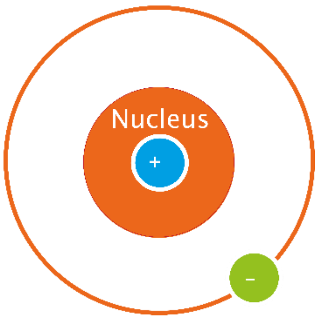
*It is clear from the exercise that it is very difficult to get accurate numbers for energy on the size of the entire world or even a country or city. Problems arise due to the average nature of the calculation, with some homes consuming much more than others and some cities being larger or consuming more than others. Tracking the consumption on all levels (so for all different types of fuels/sources) is very difficult and only becomes more difficult the more we zoom out. It might be that some countries track their energy consumption differently, use different calculations or exceptions. Hence, there will always be a lot of different numbers used in reporting or journalism, some might be very true while others might be less accurate. Using reliable sources is best, but at times difficult if you look for very specific data. Given the large amount of data that can be found online, it can be very hard to know which data to trust. If uncertain, try to find data from trustworthy institutes, such as national governments or European organizations.*

**Additional exercise A.4**

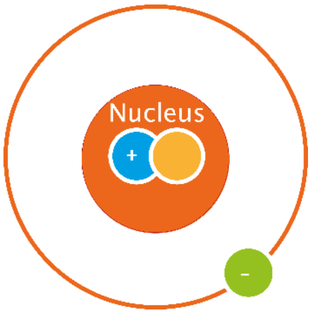
a. What type of atom is displayed in figure 4 of the student reader? Look up what this isotope is used for.

*Beryllium. Beryllium is used in many different areas, such as in X-ray tubes where they are used as radiation windows, but also because of its light weight in a lot of structural components in e.g. aerospace applications. It is also a very important material for nuclear applications! It is used as a neutron reflector in nuclear fission applications and it is an important material for future fusion reactors as a material for parts of the first wall.*

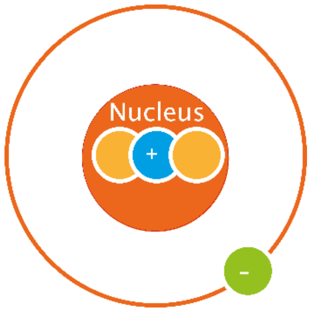
b. Make a schematic drawing similar to figure 4 of a hydrogen atom.



c. Make a schematic drawing similar to figure 4 of a deuterium atom.




d. Make a schematic drawing similar to figure 4 of a tritium atom.




**Additional exercise A.5**

Energy scales: compare the energy of a mars bar with the following energy sources: gasoline, coal, fission and fusion. Hint; first find the factors between Calories, Kcal and Joule.

*Calorie and kcal are often used interchangeably, but they are not the same! 1 kcal = 4184 Joules. One mars bar weighs 51 grams and has an energy content of 450 kcal/100 g according to the package. From this, we can calculate the energy content of one mars bar to be: 450 kcal/100 g x 51 gram/mars = 229.5 kcal/mars. So 230 kcal per mars bar. kCal is: it is a unit of energy. So it can be converted into Joules or Watt hours (1000 Wh = 1 kWh). If we convert a kCal to Wh or Joules, we get: 1 kCal = 1.162222 Wh = 4184 Joules.*

*Calculating the energy content of a mars bar in different units then gives:*
*230 kcal/mars = 962 320 Joules/mars = 267.31106 Wh/mars. If we calculate the energy density of a mars, we want to know the Joules/kg: (962 320 Joules/mars) / (51 x 10-3 kg/mars) = 18.87 MJ/kg. Now we will compare this value with the energy content of gasoline, coal, fission and fusion, taking Uranium as the fission material and D-T for the fusion material. Looking up the energy densities on Wikipedia ([https://en.wikipedia.org/wiki/Energy_density#List_of_material_energy_densities](https://en.wikipedia.org/wiki/Energy_density#List_of_material_energy_densities)) we find:*

- *Gasoline:* *46.4* *MJ/kg*
- *Coal:* *26-33* *MJ/kg*
- *Uranium:* *83 620 000* *MJ/kg*
- *Deuterium-tritium fusion:* *337 387 388* *MJ/kg*
- *Mars bar:* *18.87* *MJ/kg*

*As you can see, there is quite some energy in a mars bar. However, since we cannot simply release this energy from a mars bar, it is of course not a viable energy source. The human body uses many chemical processes to retrieve the energy from it, while gasoline or coal can simply be burned to release the energy. Uranium and D-T have much higher energy densities than the mars or the fossil fuels, as there is a lot more energy in nuclear reactions compared to chemical reactions. Fusion has a higher energy density than fission (though it should be noted that uranium is very heavy, so a kg of uranium is not that much fuel, while in a fusion reactor there is only a couple of grams as fuel).*

**Additional exercise A.6**

a. Find the meaning of 'fusion' and 'fission' in the oxford dictionary and describe the difference between fusion and fission at the level of an atom.

**fusion** *noun also* **nuclear fusion**)
[uncountable] *(physics)* the act or process of combining the nuclei (= central parts) of atoms to form a heavier nucleus, with energy being released

**fission** *noun (also* **nuclear fission**)
[uncountable] *(physics)* the act or process of splitting the nucleus (= central part) of an atom, when a large amount of energy is released

*The difference lies in the combining two nuclei into a heavier one versus the act of splitting a (heavy) nucleus into two smaller parts. Hence the names also make sense: fusion is to put together, fission is to split apart.*

b. Try to describe in terms of binding energy why heavier nuclei are more unstable.

*Nuclei are made up of protons and neutrons, but the mass of a nucleus is always less than the sum of the individual masses of the protons and neutrons. The difference is a measure of the nuclear binding energy which holds the nucleus together. The binding energy can be calculated from the equation $E = mc^2$, which for nuclear binding energy becomes: nuclear binding energy = $\Delta mc^2$, where $\Delta m$ represents the mass difference (or mass-defect) and $c^2$ is the speed of light in vacuum, squared (source: http://hyperphysics.phy-astr.gsu.edu/hbase/NucEne/nucbin.html).*

*In essence there are two forces at work in a nucleus: there is electric repulsion between particles with like charges (electromagnetic force), which causes protons to repel each other, but there is also the strong nuclear force or nuclear force which as the name suggests, is very strong. The electromagnetic force grows weaker as particles are further apart, but even at distances that are big for protons they will feel another particle and repel each other. The strong nuclear force only works at very small distances: when protons or neutrons are really close to each other, there is a very strong attractive force that pulls them together closely. Because the strong nuclear force is much stronger than the electric force (at very small distances!) nuclei can exist. To add to that, two protons will repel each other, but if we add a neutron in between them (so proton-neutron-proton) the repulsion will be a bit less. The strong force between protons and neutrons is the same as for protons and protons or neutrons and neutrons, but the neutrons give a bit more space between the protons, i.e. it can be said that they act as a sort of 'glue'. As a result, as nuclei become heavier, we have more protons and we need more neutrons as the nuclear force quickly grows weaker over larger distances (see also: https://en.wikipedia.org/wiki/Neutron%E2%80%93proton_ratio).*

*(note: protons and neutrons are called nucleons, so a nucleus is made out of nucleons)*
*The net binding energy of a nucleus is the nuclear attraction minus the disruptive energy of the electric force. As nuclei get heavier, their net binding energy per nucleon grows more and more slowly until it has its peak at iron. When nucleons are added, the total nuclear binding energy always increases (as each nucleon will attract the others), but the total disruptive energy of electric forces also increases. When we get to elements heavier than iron, the electric forces start to outweigh the nuclear forces. As a result, the heavier elements become more unstable (source: https://en.wikipedia.org/wiki/Nuclear_binding_energy).*

c. From the graph: what would be the point of change from fusion to fission? Can you explain why?

*The point of change would be the maximum of the graph, which is iron-56. When lighter elements fuse up until iron-56 energy is released, and when heavier elements split into lighter ones energy is released.*

d. Based on this graph, what material do you expect to be present in large quantities in very old stars?

*Iron! In the core of a star fusion happens, starting with protons/hydrogen and eventually the process will continue with heavier elements if the light elements are all fused into heavier ones. After iron, the process cannot continue and iron is a very stable molecule. As a result, iron accumulates in the core of very old stars.*

**Additional exercise A.7**

a. Calculate the energy released through mass defect, with Einstein's formula, for a D-T fusion reaction.

*These calculations can be done by first converting the mass from u to kg, then using $E=mc^2$ to get the energy in Joule of the mass defect and then converting that energy from Joule to MeV. However, it is also possible to make use of the fact that mass is sometimes already denoted in units of energy in nuclear physics, which makes the calculation a bit simpler.*

*Let's first look at the D-T reaction: D + T $\longrightarrow \alpha$ + n + energy (17.6 MeV). The weight of the individual components is denoted in atomic mass units (u) and we can also denote the mass of a particle in energy units if we use: MeV/$c^2$, which is a way of rewriting $E=mc^2$, such that $m = E/c^2$. So we can also express the mass of a particle through its energy using Einstein's formula (often the /$c^2$ part is not even written in the unit). Since this is a unit commonly used in nuclear physics, we have the easy conversion factor: 1 u = 931.49410242 MeV/$c^2$ (source: https://en.wikipedia.org/wiki/Dalton_(unit)).*

*Let's look at the individual components of the reaction:*
*The mass of a deuterium atom is 2.01410177785 u, but we need to subtract the mass of the electron from this, since the reaction is only between the nuclei: (2.01410177785 u - 0.000548579909 u) × 931.49410242 MeV/$c^2$ = 1875.61 MeV. If we do the same for tritium, we get:*
*(3.01604928 u - 0.000548579909 u) × 931.49410242 MeV/$c^2$ = 2808.92 MeV.*

*If we do this calculation for all components of the reaction we get:*

| | |
|---|---|
| ***Before*** | |
| *Deuterium-nucleus* | *1875.61 MeV* |
| *Tritium-nucleus* | *2808.92 MeV* |
| *Total energy before reaction:* | *4684.53 MeV* |
| ***After*** | |
| *Alpha-particle* | *3727.38 MeV* |
| *Neutron* | *939.57 MeV* |
| *Total energy after reaction:* | *4666.95 MeV* |
| ***Energy released in reaction*** | *4684.53 – 4666.95 = 17.6 MeV* |

*And hence we see that the 17.6 MeV is released in the reaction.*

b. Calculate the Energy released through mass defect, with Einstein's formula, for a nuclear fission reaction of Uranium-235.

*Now for uranium-235 it is a bit more difficult, since this can decay into many different reaction products. Depending on the reaction products, the energy that is released can vary, although on average the yield is 215 MeV. Taking the natural decay reaction of U-235:*

*U-235 → Th-231 + α*

*A uranium-235 nucleus thus spontaneously decays into a Thorium-231 nucleus and an alpha particle. Note that we now need to subtract not 1 but 92 electrons to get the nucleus mass instead of the atomic mass! So U-235 atomic mass = 235.0439299 u, and thus:*
*235.0439299 u - (92 × 0.000548579909 u) = 234.993460548 u,*
*234.993460548 u × 931.49410242 MeV/$c^2$ = 218895.022608 MeV.*

*The same calculation for Thorium gives: 231.03630 u - (90 × 0.000548579909 u) = 230.986927808 u, 230.986927808 u × 931.49410242 MeV/$c^2$ = 215162.960989 MeV.*

| | |
|---|---|
| ***Before*** | |
| *Uranium-nucleus* | *218895.02 MeV* |
| *Total energy before reaction:* | *218895.02 MeV* |
| ***After*** | |
| *Alpha-particle* | *3727.38 MeV* |
| *Thorium-231 nucleus* | *215162.96 MeV* |
| *Total energy after reaction:* | *218890.34 MeV* |
| ***Energy released in reaction*** | *218895.02 – 218890.34 = 4.68 MeV* |

**Additional exercise A.8**

If you compare the temperature at the core of the sun, the temperature at the surface of the sun and the density of sun with the temperature and density in fusion reactor on Earth: then why is the needed temperature in a fusion reactor on Earth much higher?

*For fusion to occur, three things are of importance: the right particle density, the right particle temperature, and a good confinement of particles. The combination of density and temperature needs to be right so that the particles on average have the best chance to fuse. The confinement time* *is important because we want to have fusion occurring continuously. In the Sun, the confinement is excellent in the core due to gravity. This confinement is much better than what we can create on Earth with magnets. At the same time, the density of the Sun on average is not that high: about 1.4 g/cm$^3$, while the Earth has an average density of about 5.5 g/cm$^3$. Still, in the core of the Sun the density is a lot higher: it is estimated to be about 160 g/cm$^3$. So the density in the sun is quite high, much higher than in our fusion reactors (which have a couple of grams of fuel and a for example ITER will have a volume of 830 m$^3$). So based on density and confinement, the Sun beats Earth easily.*

*However, temperature-wise, the core of the Sun is about 15 million degrees Celsius, while the surface is only about 6000 degrees Celsius. Based on this, it's easy to see that there is no fusion happening on the surface of the Sun, the temperature is much too low and the density is also low. In the core, the combination of high density, high temperature and good confinement gives an excellent chance for fusion reactions to occur. So if we want to create fusion on Earth, we need to increase the temperature even higher than in the Sun, to compensate for our 'worse' density and confinement (remember: we use hydrogen gas, so the density of such a gas is 0.0899 g/cm$^3$ at room temperature, which is much lower than the density in the Sun; also recall that heating a gas also leads to expansion! We inject very little gas, then heat it up and the plasma will then fill the entire volume of our reactor). Hence, to get a good chance of fusion to occur in our reactors, we have a different optimum which is calculated to lie at around 150 million degrees Celsius, about 10x higher than in the core of the Sun.*

**Additional exercise A.9**

A well-known example of a real life application of plasmas is a plasma tv or plasma display. How do these 'plasma' objects relate to a physical plasma as described in chapter 3? Try to find out, using the internet, how plasma tv's work and what the difference is between a physical plasma and plasma tv's or plasma displays.

*Information on how a plasma tv works can be found online, as an example information can be found here: https://www.explainthatstuff.com/plasmatv.html. A plasma tv is made up out of a grid of red, green and blue pixels, just like LCD screens. But in a plasma tv, each pixel cell is filled with a gas that can be ionized into a plasma by two high voltage electrodes. The gas then starts to emit ultraviolet light (which is not visible!). Since the pixel is coated in a substance that absorbs the ultraviolet light and then emits light of a certain color (red, green or blue), the pixel lights up when a high voltage is set over the electrodes of the pixel cell.*

*In essence, the difference between a fusion plasma and the plasma inside a plasma tv are the conditions of the plasma. No fusion is happening in your tv, there is just a high voltage that leads to ionization and emission of light, which is then turned into the right pixel color. Note that there are many different types of plasma possible, at low temperatures, low densities, high temperatures, high densities, etc. plasma is a very versatile state of matter.*

**Additional exercise A.10**

a. Plasmas can usually be observed to glow. But why do plasma's glow? Explain.

*When something glows, it emits light. Atoms have different energy levels which can be occupied by its electrons. When an electron gets excited to a higher energy level, the atom gets into an excited* *state. The electron can then fall back to a lower level, in which energy is released as a photon: light. The color of the light depends on the energy and hence on the difference between the excited energy level and the level the electron falls back to. Depending on how an atom gets excited, the electron can go to different levels and fall back to different levels, leading to a color spectrum that can be excited by a certain element (see for instance the emission spectrum of hydrogen: https://en.wikipedia.org/wiki/Hydrogen_spectral_series). The energy levels for a certain element are always the same, so hydrogen atoms always have the same energy levels and thus will always emit the same colors of light. At the same time, these energy levels also dictate which jumps the electron can make upwards: if you illuminate hydrogen with a laser (light of one specific wavelength, i.e. photons with the same energy) and the laser is tuned to a jump in energy levels, then you can purposely excite a certain transition in an atom. Still, excitation of electrons to higher levels can also occur if a fast particle collides with an atom and transfers some of its energy to it. If the particle is fast enough, it can even ionize the atom, which means that an electron is not just excited, but knocked out of the atom entirely, creating an ion and a free electron.*

*To get a plasma, we need to ionize particles. So when we have a plasma, there are always particles that can create ions and free electrons, but not all collisions will lead to ionization. Some particles will be a bit slower and will just excite the atoms. After this collisional excitation, the atom can emit light to get rid of the energy and the electron drops back to a lower state. This continuously happens in a plasma and this is where the glow in a typical plasma comes from.*

b. When a plasma is fully ionized, will it still be glowing? Explain your answer.

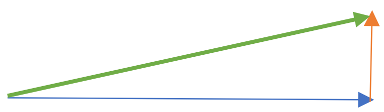
*If we heat a plasma such that all of the particles are completely ionized, this excitation can no longer happen. So in a fusion plasma, where the core plasma is completely ionized, there will be no light! But near the wall, where ionized particles will collide with the metal walls and recombine into atoms, there are some atoms that get excited instead of ionized. These will then emit light, which explains why in a fusion reactor, there is only (visible) light near the bottom of the reactor, where the plasma typically hits the wall.*

**Additional exercise A.11**

Let us have a look at how a toroidal magnetic field, together with a poloidal magnetic field, combines into a helical magnetic field. Follow the following steps:

a. Draw an arrow (or a vector) in a random direction.
b. Draw another arrow (or vector) starting at the end of the first, in a different direction.
c. Draw a third arrow starting at the initial point of the first arrow and ending at the final point of the second arrow.

*arrow (blue) + arrow (orange) = arrow (green). Now the third arrow is the result of (vector) addition of the first two arrows.*



If we now do the same for a poloidal arrow (or vector) and a toroidal arrow (or vector), what is the result?

*When we do this for a poloidal arrow and a toroidal arrow, we get: toroidal arrow (blue) and poloidal arrow (red). Superposition leads to a helical field line (yellow)*