Module 3 – Plasma control

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 to a possible future energy solution: nuclear fusion.

This lesson series start with module 1 *Fusion basics*, which will give the students the basics for all the other modules. **Therefore module 3 *Plasma control* can be used when the content of module 1 has been introduced.**

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

Using the modules

The student readers consists 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 see if the students understand the material.

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

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Content of the teacher manual

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Chapter 1: Learning objectives
At the end of this module, students are able to:
- Name different plasma parameters
- Understand a simple control loop
- Understand the need of feedback and the error signal in a control loop
- Explain the three different methods of (plasma) heating
- Understand how scientists measure and control a hot plasma
- Understand the terminology of plasma diagnostics
- Understand the basics of the ECE plasma diagnostic
- Explain what an electromagnetic wave is

Chapter 2: Closely related subjects or lessons
Next to the concepts discussed in module 1, the following subjects are closely related:

- Heating methods
- Automatic systems

Chapter 3: Topics of Module 3
For each chapter the corresponding physical topics are given. This can be used to adapt the lesson plan corresponding to the knowledge of the students and the needed time in class.

1. Introduction to control
    - Automatic systems
        - The control scheme
            - Reference
            - sensor
            - Actuator
            - Controller
        - Feedback
        - Error signal
2. Heating the plasma
    - Wave heating
        - Electromagnetic waves
            - Frequency
            - Wavelength
            - Particle wave interaction
        - Magnetic field
            - Gyromotion
            - Gyrofrequency
    - Hot particle injection
        - Kinetic energy
            - velocity
    - Ohmic heating
        - Electricity

        - Power
        - Current
        - Temperature
        - Resistance
        - Conductor
3. Measuring the plasma temperature (diagnostics)
    - Measuring methods
        - Active
        - Passive
        - Global
        - Local
    - Measuring materials
        - Calibration
4. Conclusion and further reading
    - Other parameters

Chapter 4: Brief summary of module 3

Chapter one gives an introduction into control and the control loop. The reference, sensor, measurement, actuator and controller of the control loop will be discussed as well as the importance and the working of the feedback and the error signal. This knowledge of the basic control loop will be applied to the control in fusion.

Chapter two introduces three (general) ways of heating: wave heating, hot particle injection and ohmic heating. For the wave heating it is needed to understand the concept of the electromagnetic waves and particle-wave interaction. The knowledge from module 1 about electric fields and magnetic fields will be used to come to the concept of a gyrofrequency which is needed for the two mentioned plasma heating methods: electron cyclotron resonance heating and ion cyclotron resonance heating. The hot particle injection parts focusses on the connection between temperature, kinetic energy and velocity. When looking at a gas not all the particles have the same velocity therefore the average velocity becomes important for plasmas. To obtain these high velocity particles, the neutral-beam injection will be used. For this method the neutralisation of particles is most important. The last heating method is Ohmic heating where the relationship between temperature and resistivity is important. The underlying topic of this part is electricity.

Chapter three starts with the terminology used for diagnostics in fusion. The term diagnostics will be of great importance since it describes the concept of measurements, and a bit of the method and the interpretation. Within the diagnostics there will be a divergence between local and global measurements. Both measurements are important for fusion. The last part of this chapter focusses on an active local temperature diagnostic, the electron-cyclotron-emission (ECE) diagnostic.

Chapter four gives a short summary and conclusion of the module. It describes that temperature is not the only important plasma parameters but that there are many more. The difficulties of the measurements regarding time are mentioned as well.

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Chapter 5: Basic lesson schemes

Like in the first module there are two basic lesson schemes for directly use for a short class (15 minutes) and a longer class (1 hour). For this module there is a difference for teaching average and advanced students.
The goal of this lesson schemes is to give an idea of a lesson and to decrease the preparation for the teacher. It is free to adapt the scheme to your own lesson plan. For both lesson schemes the student activities, preparation and classroom ideas are the same.

The student activities involve listening, discussing, asking questions and working on the exercises.

Preparation for these lessons involves:

- Downloading the PowerPoint
- Making the student reader and additional exercises available for students

15-min lesson for average students

Goal of this 15 minutes lesson is to give an introduction into control and the control scheme. Important diagnostical terms of fusion will be treated and a short explanation about passive and active diagnostics will be given.

The materials needed for this lesson are:

- The student reader
- The PowerPoint

An idea for in the classroom is to find multiple control loops during the lecture as an example to introduce the importance and frequency of these loops.

Duration	Teacher activity	Materials	Student activity
3 min	Introduction of the topic	Chapter 1: PowerPoint slide: 1 until 3	Listen, ask questions
3 min	Discuss classroom exercise 3.1 a and b in class and let students sketch assignment c on their own	Chapter 1: PowerPoint slide: 4 and 5	Work alone on the classroom assignment and then discuss in class
2 min	Presenting chapter 1: The controller and the application into plasma.	Chapter 1: PowerPoint slide 6 and 7	Listen, ask questions
3 min	Presenting chapter 2: heating methods	Chapter 2: PowerPoint slide 8	Listen, ask questions
3 min	Presenting chapter 3: measuring the plasma temperature	Chapter 3: PowerPoint slide 14 and 15	Listen, ask questions

1 min	Discuss classroom ex 3.3	Chapter 3: PowerPoint slide 16 and 17	Work in pairs on the classroom exercise. Listen, ask questions and discuss
			Make additional exercise 3.1

15-min lesson for advanced

The goal of this 15 minutes lesson for advanced students is to give an introduction into control, the control scheme and the diagnostics. The focus will be on the different aspects of the control loop, and the general diagnostic terms: passive, active, local and global. After this lesson, the students can draw their own control loop and can explain the diagnostic terminology written above.

The materials needed for this lesson are:

- The student reader
- The PowerPoint

An idea for in the classroom is to find multiple control loops during the lecture and let the students after the lecture explain the working and application of the found control lop

Duration	Teacher activity	Materials	Student activity
2 min	Introduction of the topic	Chapter 1: PowerPoint slide: 1 until 3	Listen, ask questions
2 min	Presenting chapter 1: The controller and the application into plasma.	Chapter 1: PowerPoint slide: 6 and 7	Listen, ask questions
2 min	Presenting chapter 2: heating methods	Chapter 2: PowerPoint slide 8	Listen, ask questions
2 min	Discuss classroom exercise 3.2	Chapter 2: PowerPoint slide 9 and 10	Discuss
3 min	Presenting chapter 2: heating methods, short introduction not in depth	Chapter 2: PowerPoint slide 11 until 13	Listen, ask questions
3 min	Presenting chapter 3: measuring the plasma temperature	Chapter 3: PowerPoint slide 14, 15 and 18	Listen, ask questions
			Make at home - additional assignment 3.5 - Classroom exercise 3.1

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1-hour lesson for average students

The goal of this 1-hour lesson is to give an introduction into control and the control scheme. Important diagnostical terms of fusion will be treated and a short explanation about passive and active diagnostics will be given. The understanding and application of the control loops and gyromotion will be practiced.

The materials needed for this lesson are:

- The student reader
- The PowerPoint
- Additional exercises

Duration	Teacher activity	Materials	Student activity
3 min	Introduction of the topic	Chapter 1: PowerPoint slide: 1 until 3	Listen, ask questions
3 min	Discuss classroom exercise 3.1 a and b in class and let students sketch assignment c on their own	Chapter 1: PowerPoint slide: 4 and 5	Work alone on the classroom assignment and then discuss in class
2 min	Presenting chapter 1: The controller and the application into plasma.	Chapter 1: PowerPoint slide 6 and 7	Listen, ask questions
5 min	Check the understanding of the students	Additional exercises	Make additional assignment 3.1
3 min	Presenting chapter 2: heating methods	Chapter 2: PowerPoint slide 8	Listen, ask questions
3 min	Discuss classroom exercise 3.2	Chapter 2: PowerPoint slide 9 and 10	Discuss
15 min	Presenting chapter 2: heating methods	Chapter 2: PowerPoint slide 11 until 13	Listen ask questions
5 min	Help to apply the gyromotion formulae	Additional exercises	Make additional exercise 3.3a
5 min	Presenting chapter 3: measuring the plasma temperature	Chapter 3: PowerPoint slide 14 and 15	Listen, ask questions
3 min	Discuss classroom ex 3.3	Chapter 3: PowerPoint slide 16 and 17	Work in pairs on the classroom exercise. Listen, ask questions and discuss
13 min	Presenting chapter 3 and the conclusion	Chapter 3: PowerPoint slide 18 until 21	Listen, ask questions

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1-hour lesson for advanced

The goal of this 1-hour lesson for advanced students is to give an introduction into control, the control scheme and the diagnostics and to apply the gained knowledge on the assignments. After this lesson the students can make their own control loop, explain the diagnostics and make the additional exercises.

The materials needed for this lesson are:

- The student reader
- The PowerPoint
- Additional exercises
- Access to the internet (Laptop, smartphone, tablet)

Duration	Teacher activity	Materials	Student activity
2 min	Introduction of the topic	Chapter 1: PowerPoint slide: 1 until 3	Listen, ask questions
5 min	Discuss classroom exercise 3.1	Chapter 1: PowerPoint slide 4 and 5	Work alone on the classroom exercise, then discus in class.
2 min	Presenting chapter 1: The controller and the application into plasma.	Chapter 1: PowerPoint slide: 6 and 7	Listen, ask questions
10 min	Make additional exercise 3.2. Divide the assignment in class (three groups: A, B and C) help with research. Let students exchange the found information	Additional exercises Access to the internet	Research! Answer your assigned question.
2 min	Presenting chapter 2: heating methods	Chapter 2: PowerPoint slide 8	Listen, ask questions
2 min	Discuss classroom exercise 3.2	Chapter 2: PowerPoint slide 9 and 10	Discuss
10 min	Presenting chapter 2: heating methods	Chapter 2: PowerPoint slide 11 until 13	Listen, ask questions
10-15 min	Make additional exercise 3.4 and discuss in class	Additional exercises	Work in pairs on the assignment
3 min	Presenting chapter 3: measuring the plasma temperature	Chapter 3: PowerPoint slide 14 and 15	Listen, ask questions
3 min	Discuss classroom exercise 3.3 quickly	Chapter 3: PowerPoint slide 16 and 17	Discuss

	to see the understanding		
10 min	Presenting chapter 3: global, local and temperature measurement methods and conclusion	Chapter 3: PowerPoint slide 18 until 21	Listen, ask questions

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. If there is a possible YouTube video of Phet which can be used for a topic, the link can be found in the notes of the corresponding slide. 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 3, 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. See chapter 7.

Chapter 7: Further references for study and fun for module 3

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. 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.

For Teachers and students
At the end of the module you can find further reading material. The material in this chapter can be used as an extra explanation for the students in class. Some URLs give a more in-depth look on the different topics ór give an example of an experiment. After each URL information will be provided about the content and possible use.

Chapter 1:

- Matlab – Understanding PID control, part 1, What is PID control?
  https://www.youtube.com/watch?v=wkfEZmsQqiA duration 11:41 minutes
  An in-depth explanation of a PID controller. Recommended for advanced students.

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- Horizon 4 electronics - PID demo
  https://www.youtube.com/watch?v=qKy98Cbcltw duration
  A small demonstration of the working of a PID controller

Chapter 2:

- Physics made easy – What is an Electromagnetic wave?
  https://www.youtube.com/watch?v=hk63uUhkZH4 duration 3:40 minutes
  Explanation of an electromagnetic wave from an electrotechnical view. The electromagnetic waves will be related to the magnetic fields and electric fields which are mentioned in module 1.
- Cognito – GCSE Physics – Electromagnetic waves #64
  https://www.youtube.com/watch?v=7v2gs8rdQzU duration 4:51 minutes
  The electromagnetic spectrum and electromagnetic waves will be explained. Mostly basic information, regarding frequency, wavelength, spectrum.
- Physics lectures – Dr. Quantum's double slit experiment
  https://www.youtube.com/watch?v=NvzSLByrw4Q duration 5:41 minutes
  Wave particle interaction: how a wave also can behave like a particle. Can be used as extra information when knowing more about the different aspects of waves and particles.

Chapter 3:

- Tokamak Energy – a faster way to fusion - Neutral Beam injection and its importance for tokamaks
  https://www.youtube.com/watch?v=Hc1jcpsp8Zs duration: 4:07 minutes
  NBI explained in the context of a tokamak. It shows the machinery needed for the NBI.

Appendix A: table of constants

Quantity	Quantity	Conversion factor to SI units
Energy[1]	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

Quantity	
Core temperature Sun[2]	$1.571*10^{7}$ K
Surface temperature Sun[1]	5780 K
(mean) Density Sun[2]	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

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Appendix B: Solutions to classroom exercises

Classroom exercise 3.1

a. Identify (1) the controller, (2) the sensor, and (3) the actuator, for the temperature in a refrigerator.

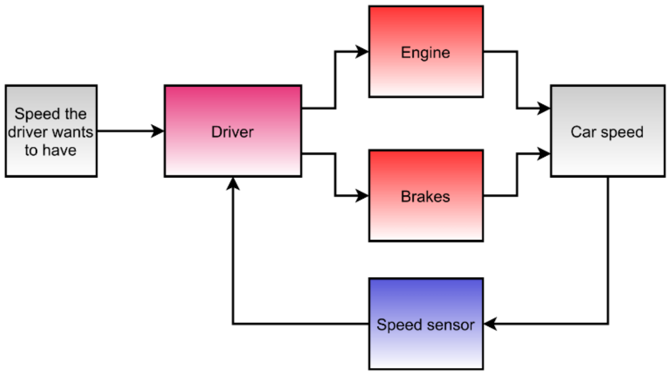
(1) internal computer, (2) temperature sensor, (3) cooling system.

b. Now do the same for the speed of a car.

(1) car driver, (2) velocity sensor, (3) engine and brakes.

c. Finally, sketch the control loop of the speed of a car like it was done for home temperature in figure 3.1.

See the figure below. Note here, that there are two actuators: the engine and the brakes. The engine can both increase and decrease the speed of the car (by applying more or less gas to the engine). The brakes can only decrease the speed of the car.



Classroom exercise 3.2
In two of our heating methods, we mentioned the soup example. There is of course another way to heat soup: by pouring it into a pan, and heating it above a stove. The heat of the stove is conducted to the pan, and then to the soup. Can we also use this technique for our fusion plasma?

Simply put: no. The temperature we want for our plasma is far higher than the temperature we would like soup to have. This gives us two problems: we do not have a stove that is hot enough, and all the pans that we have will melt at this high temperature. The metal with the highest melting temperature is tungsten, which melts around 3400 °C, far below the temperature of our fusion plasma! So, conductive heating is not applicable to fusion plasmas. Module 4 discusses more problems concerning the "pan" around the plasma.

Classroom exercise 3.3
Are the following diagnostics examples of active or passive diagnostics?

a. Temperature measurement of a room by one mercury thermometer.

Passive

The mercury thermometer shows the temperature by naturally expanding. There is no additional device needed to let the mercury expand.

b. Speed measurement of a car by applying an infrared laser as the car drives by, and calculating the speed from the observed Doppler shift.

Active
The laser needs to be artificially applied to the car; it is not there by nature. We need to operate another device for this diagnostic (namely a laser gun).

c. Speed measurement of a car by applying a small magnet to the wheels, and counting the number of times it passes per minute. The speed is calculated from this count, and the known circumference of the wheel.

Passive
It is true that there is another device involved (the magnet), but we do not need to operate this device: the magnetic field of the magnet is there by nature. It would have been different if we used an electromagnet, which is only magnetic when a current is actively applied.

Appendix C: Solutions to additional exercises

Exercise A.1

a. The physical quantity, reference, controller, actuator, and sensor.

b. Feedback is used to provide the controller with real-time information of the physical quantity. This information is provided by the sensor. Based on the feedback and the reference, the controller can create an error signal. This signal is used to instruct the actuator. Feedback is essential in control.

Exercise A.2

In the **proportional (P) controller**, the error signal is multiplied with a fixed constant (often written as k_p). Hereby, the output of the controller is directly proportional to the error signal, and the actuator is used more advanced than in the case of the simple on-off controller. If we have a constant reference value (online often represented by a "step function"), the output of the controller oscillates around the reference, which is undesirable. The main disadvantage of the P controller is the **steady-state error** it introduces. This means that the reference value is never reached, there will always be some error present. For example, an airplane with a steady-state error in its altitude, will never reach the requested altitude, but remain flying somewhat below this.

In the **proportional-integral (PI) controller**, the error signal is not only handled as in the P controller, it is also accumulated over time. A small steady-state error will accumulate into a significantly large error term, with which the actuator is instructed to counteract the steady-state error. Thus, using a PI controller, the steady-state error will disappear. Because of its accumulative nature, the integral part of the controller is said to consider the "past" of the error signal.

In the **proportional-integral-derivative (PID) controller**, the error signal is not only handled as in the PI controller, its derivative is also taken to predict the behaviour of the error signal (is it increasing/decreasing?). By predicting the behaviour of the error signal, the reference value can be reached much quicker than in the PI controller. Because of its predictive nature, the derivative part of the controller is said to consider the "future" of the error signal. PID controllers are often found in industrial applications, and have been a large topic of research within control theory.

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Exercise A.3

The answers are calculated using the equation and numbers provided. Note that the gyrofrequency of the electron is a positive number, because the absolute value of q is taken.

d. $f_{gyro,electron}$ = 140 GHz. ($q = -e$, $m = m_e$)
e. $f_{gyro,deuterium}$ = 38.1 MHz. ($q = e$, $m = 2m_p$)
f. $f_{gyro,tritium}$ = 25.4 MHz. ($q = e$, $m = 3m_p$)

Exercise A.4

The answers are calculated using the equation and the numbers given. Note how large the velocities are of the plasma particles compared with the room-temperature hydrogen atom.

a. $v = 2.50 \times 10^3$ m/s. (T = 298K, $m = m_p$)
b. $v = 1.36 \times 10^6$ m/s. ($T = 175 \times 10^6$ K, $m = 2m_p$)
c. $v = 1.11 \times 10^6$ m/s. ($T = 175 \times 10^6$ K, $m = 3m_p$)
d. $v = 82.2 \times 10^6$ m/s. ($T = 175 \times 10^6$ K, $m = m_e$)

Using the velocity calculated in question A.4d, we have

e. $\gamma = 1.04$.

It might not seem like a large value, but it is large enough to make relativistic effects important in specific cases in fusion plasmas.

Exercise A.5

We start of by equating $E_{ionization} = hc/\lambda$, and rewrite for λ. The ionization energy is given to be 13.6 eV, which is 2.18×10^{-18} J. Hence, we end up with a wavelength of 91.2 nm.

Note that this wavelength provides the *minimum* energy needed for the photo-ionization. It is also possible to use photons with a higher energy, thus with a smaller wavelength. The calculate wavelength is thus the *maximum* wavelength that we can use in our NBI device.

Exercise A.6

For this terminology, it is important to understand the following differences:

a. *Redundant* diagnostics are used in the same range for a plasma parameter. *Complementary* diagnostics are used in different ranges for a plasma parameter.
b. An *active* diagnostic requires the input of “something” (electromagnetic waves or neutral particles) into the plasma. A *passive* diagnostic does not require this, as the measurement is taken from some “naturally” occurring phenomenon in the plasma.
c. A *global* measurement contains information about the plasma in its entirety. An easy example is the average or maximum of some physical quantity (e.g. temperature) in the fusion reactor. A *local* measurement is taken at multiple points in space in the fusion reactor.

Appendix D: Sources

Other plasma parameters

H.-J. Hartfuss, and T. Geist. (2013). "Fusion Plasma Diagnostics with mm-Waves". Wiley-VCH, Verlag GmbH & Co. KGaA: Boschstr. 12, 69469 Weinheim, Germany.