# Additional exercises v.1.0

This document contains additional exercises to accompany Module 3: *Plasma control* of the FuseNet educational materials for secondary schools.

**Legend:**

*: introductory exercise: short exercise, requires little to no calculation.

**: intermediate exercise, could require some calculation or some more advanced thinking.

***: challenging exercise, might require advanced calculation or derivation.

## Chapter 1: Introduction to control

*Exercise A.1: Control loops*

In Chapter 3.1, we have delved into control loops.

a. Name the five characteristic parts of a control loop.
b. Control loops often make use of feedback. What is feedback used for?

***Exercise A.2: PID controllers*

In Section 3.1.2 we discussed how error signals are handled, and how we can form control schemes using the error signal. In this exercise, we are going to look into three additional control schemes, which are more advanced than our simple on-off controller for the home thermostat.

a. On the internet, look up "proportional controller". How is the error signal handled in this controller? What is the main disadvantage of the proportional controller?
b. Now, look up "proportional-integral controller". How does this controller solve the problem of the proportional controller?
c. Finally, look up "proportional-integral-derivative controller". How does this controller improve the performance of the proportional-integral controller?

## Chapter 2: Heating the plasma

**Exercise A.3: Gyrofrequency*

As mentioned in Section 3.2.1, the frequency of the gyromotion of a particle in a magnetic field is called the gyrofrequency, and its value is given by

$$f_{\text{gyro}} = \frac{|q|B}{2\pi m}.$$

Assume we have a tokamak with a magnetic field strength of $B$ = 5T (5 Tesla). Calculate the gyrofrequency of the following:

a. An electron.
b. A deuterium ion.
c. A tritium ion.

It is given that the elementary charge $e = 1.602 \times 10^{-19}$ C, the electron mass $m_e = 9.11 \times 10^{-31}$ kg, and the proton mass $m_p = 1.67 \times 10^{-27}$ kg.

**Exercise A.4: Particle velocity

As mentioned in Section 3.2.2, the average velocity of the plasma particles is given by

$$v_{\text{avg.}} = \sqrt{\frac{8k_B T}{\pi m}}.$$

Calculate the velocity of the following particles:

a. A hydrogen atom at room temperature (T = 298K).
b. A deuterium ion at 175 million Kelvin.
c. A tritium ion at 175 million Kelvin.
d. An electron at 175 million Kelvin.

It is given that the Boltzmann constant $k_B = 1.38 \times 10^{-23}$ J/K, the electron mass $m_e = 9.11 \times 10^{-31}$ kg, the proton mass $m_p = 1.67 \times 10^{-27}$ kg.

Furthermore, from the theory of relativity we have the Lorentz factor given by

$$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}.$$

e. Calculate the Lorentz factor of the electron at 175 million Kelvin. Is this a large value?

**Exercise A.5: Photo-ionisation

For the NBI device we need a way to ionise the slow neutral particles (Step 1 of Figure 3.6). There are several ways to do this. A common method in plasma science, is using high-energy photons (light) to ionise the neutrals. Hence, this method is called **photo-ionisation**.
Consider the case where we use a NBI device based on hydrogen atoms. We know that a hydrogen atom has one proton, and one electron. The energy *minimally* needed to take away its electron is called the **ionisation energy**, which is $E_{ionisation}$ = 13.6 eV for the hydrogen atom.

Calculate the maximum wavelength we can use to photo-ionize the hydrogen atoms in our NBI device.
Hint: the energy of a photon is given by

$$E = \frac{hc}{\lambda},$$

with $E$ the photon energy, $h = 6.626 \times 10^{-34}$ Js the Planck constant, $c = 2.998 \times 10^{8}$ m/s the speed of light in vacuum, and $\lambda$ the photon wavelength.

## Chapter 3: Measuring plasma temperature

*Exercise A.6: Terminology of diagnostics

Explain what the difference is between:

a. redundancy and complementarity.
b. active and passive diagnostics.
c. global and local measurements.