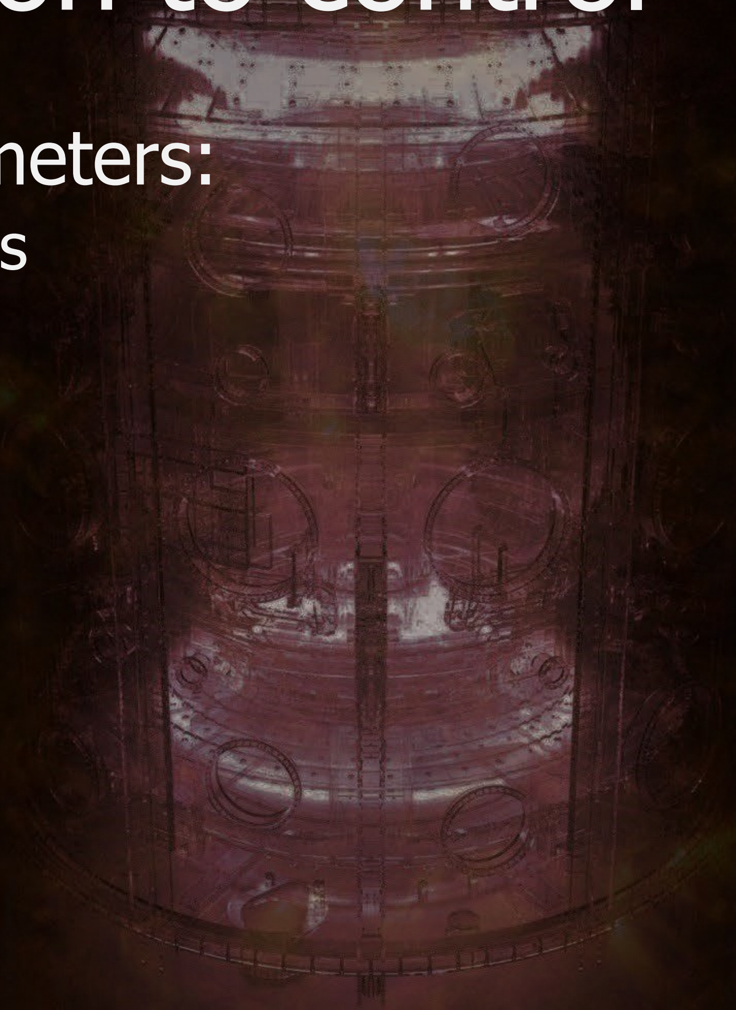
Module 3

Plasma Control

3.1 Introduction to control



Optimal plasma parameters:

- Most fusion reactions
- Smallest instabilities

Parameters are:

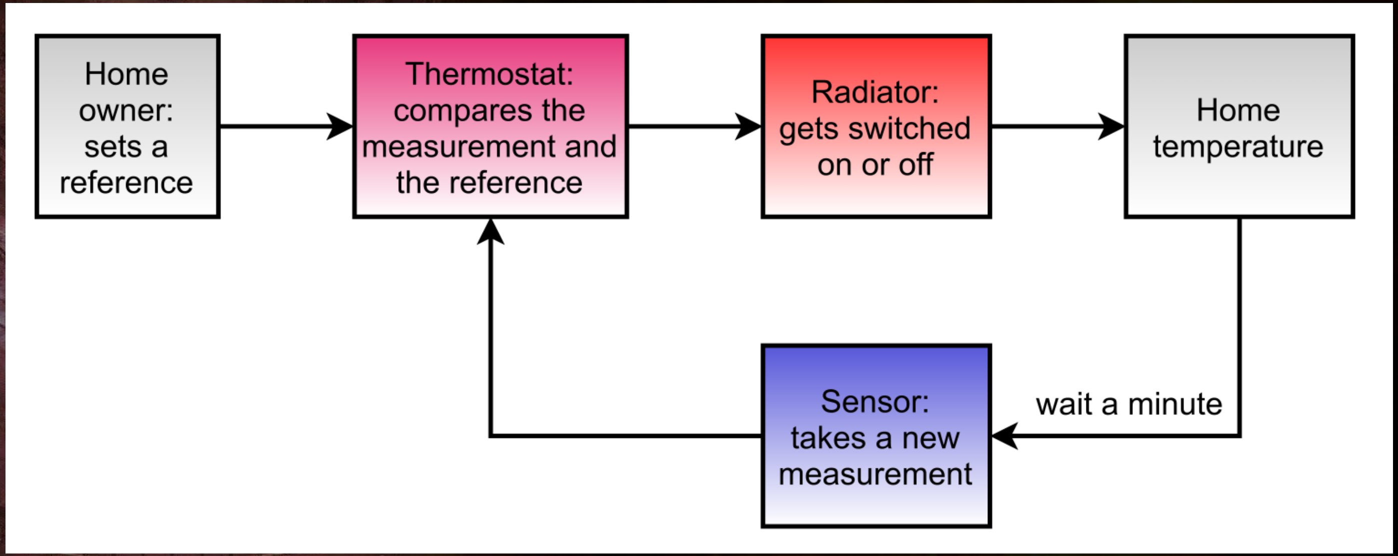
- Particle density
- Temperature
- Magnetic field
- Electric field
- ...

Example: home thermostat

Thermostat controls temperature

Control loop:

- physical quantity
- reference
- sensor
- controller
- actuator



Home owner: sets a reference

Thermostat: compares the measurement and the reference

Radiator: gets switched on or off

Home temperature

wait a minute

Sensor: takes a new measurement

Classroom Exercise 3.1

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

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

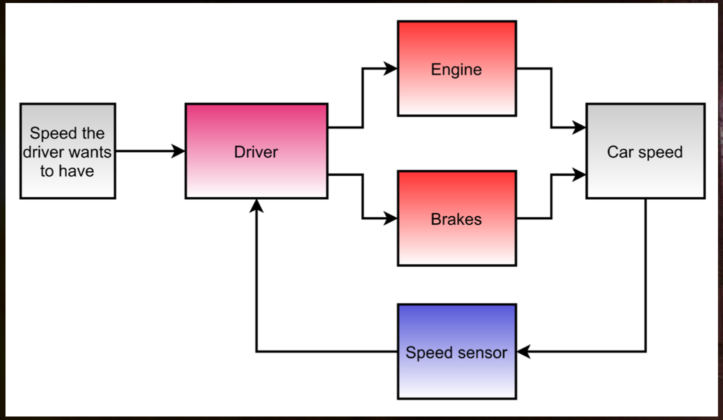
(c) Sketch the control loop of the speed of a car, like the control loop of the home thermostat.

Answer to Classroom Exercise 3.1

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

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

(c)



The controller

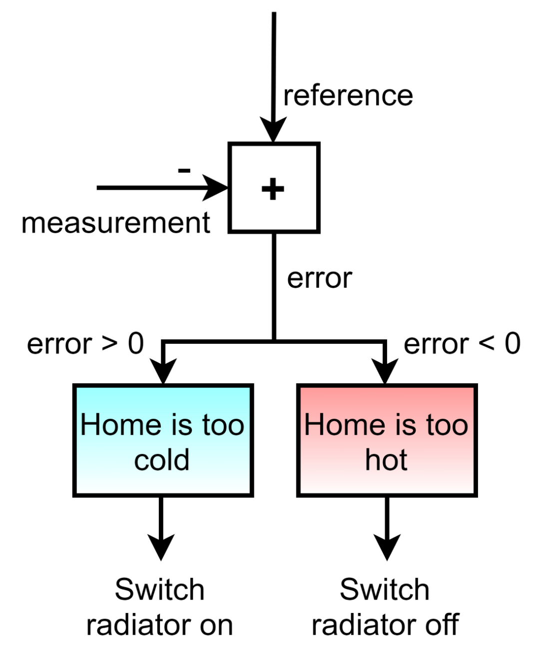
Use "error signal" to instruct the actuator:

error signal = reference – measurement

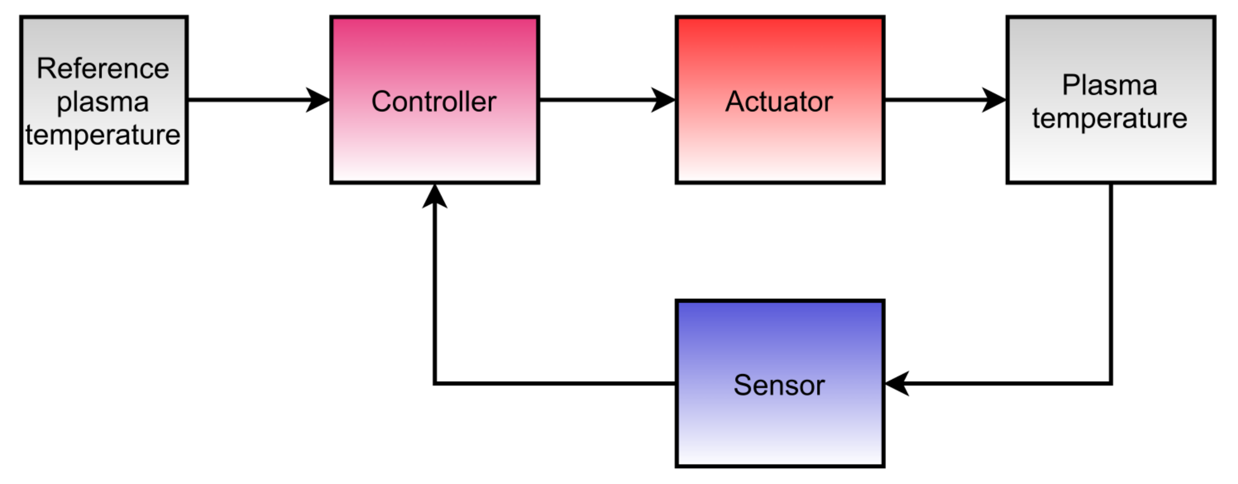
Control scheme: how the error signal is used

Here, positive and negative error lead to

Different actions by the actuator



Control in Fusion: plasma temperature

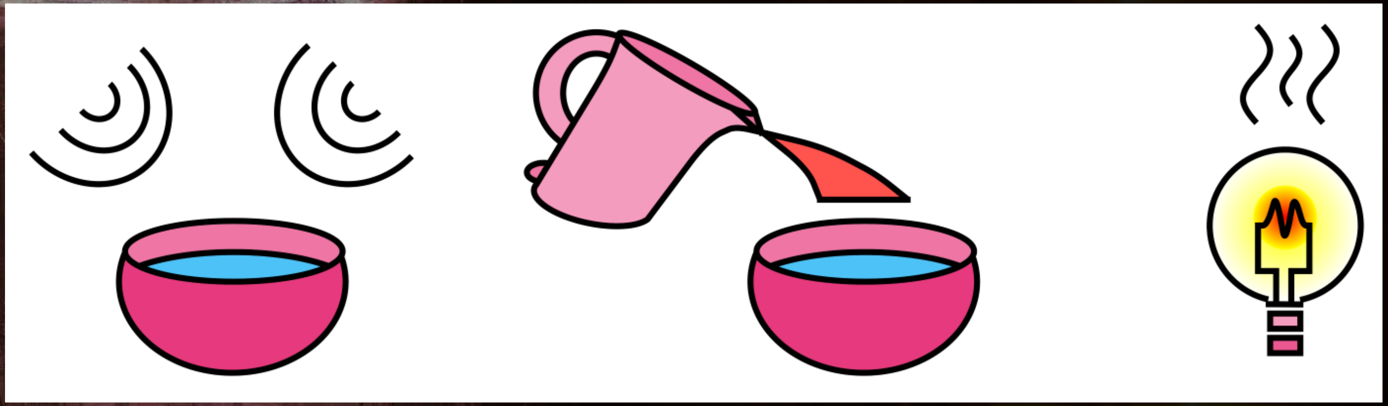


Temperature reference: **120-230 million ^{o}C**

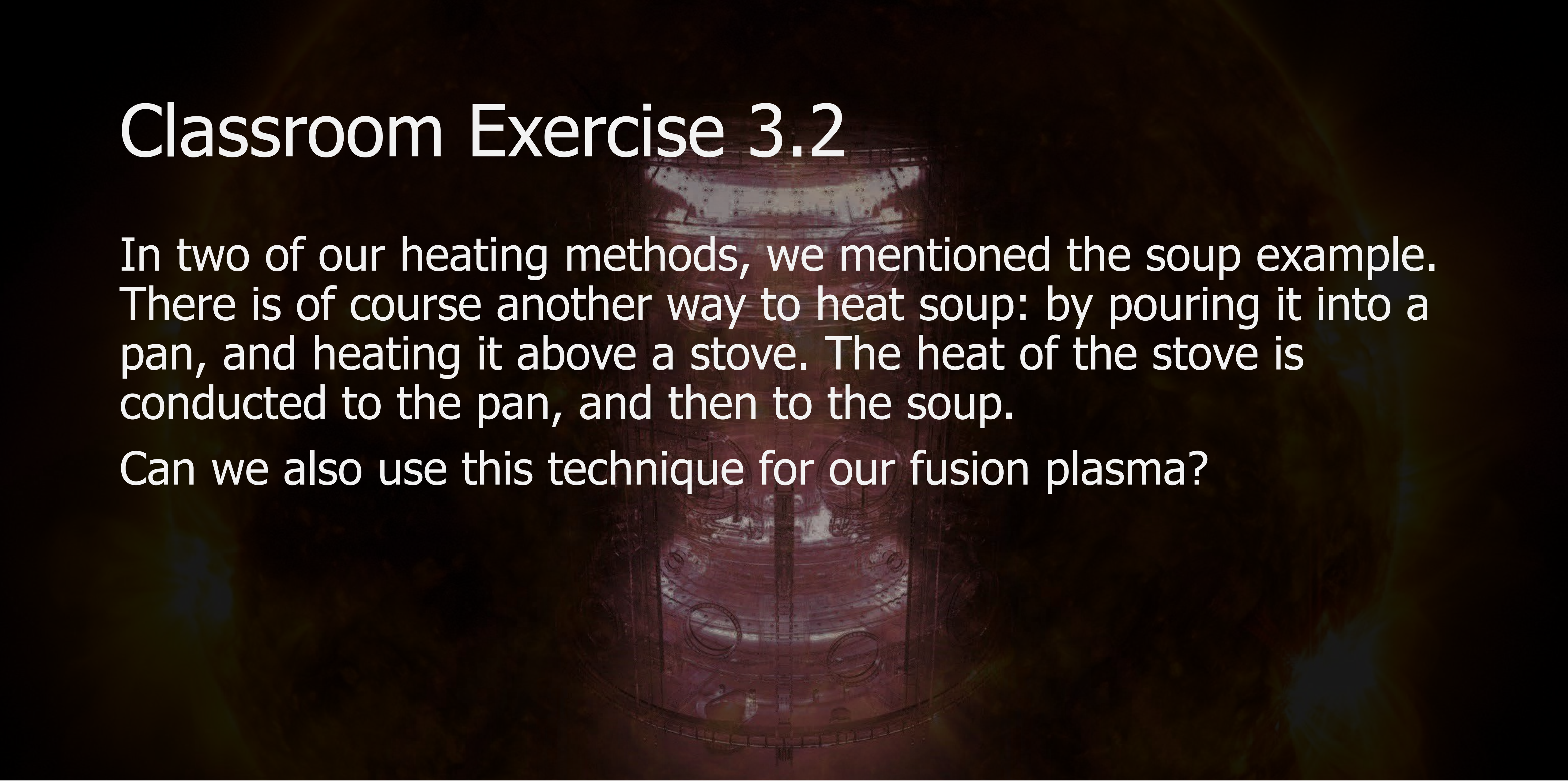
3.2 Heating the plasma

Three methods:

- wave heating
- injecting hot particles
- ohmic heating



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?

Answer to Classroom Exercise 3.2

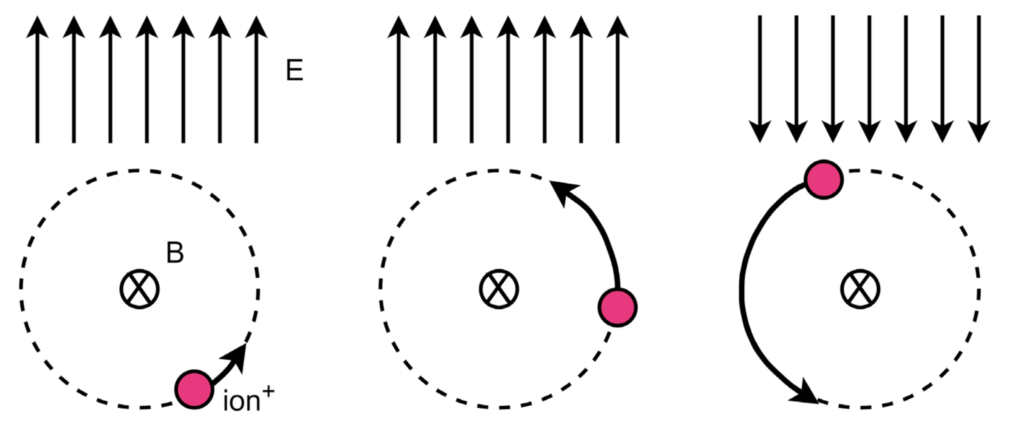
Simply put: no. The temperature we want for our plasma is far higher than the temperature we would like soup to have. This gives us two problems: we do not have a stove that is hot enough, and all the pans that we have will melt at this high temperature.

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.

Method 1: wave heating

Wave-particle interaction

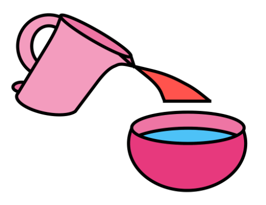
"gyrofrequency" of $f_{\text{gyro}} = \frac{|q|B}{2\pi m}$



Heat either the:

- electrons (ECRH) **+** very locally - limited access to plasma
- ions (ICRH) **+** direct ion heating - difficult injection of waves

Method 2: injecting hot particles

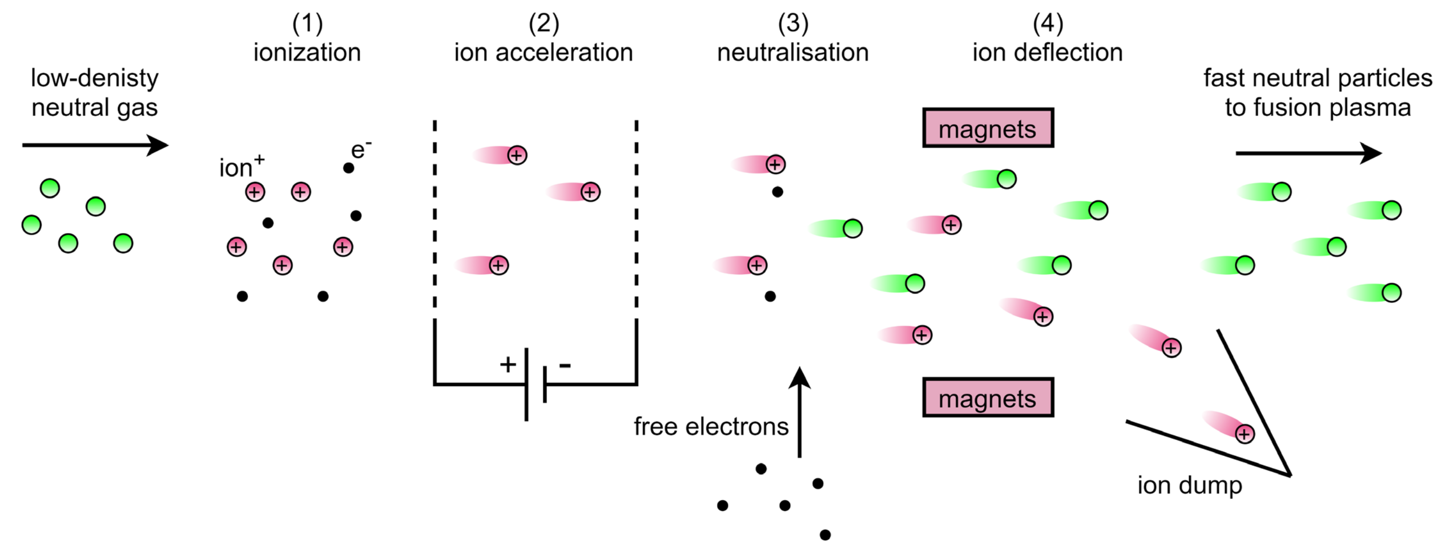


High-temperature particles = high-velocity particles

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

\+ fuelling, plasma spin

\- large machine, low neutralisation-efficiency



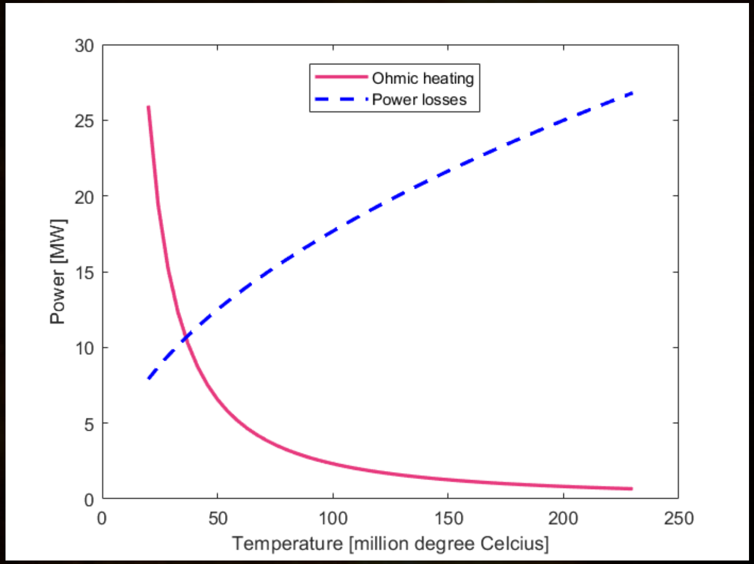
Method 3: ohmic heating

Plasma contains free charges (by definition), we run a current using these charges

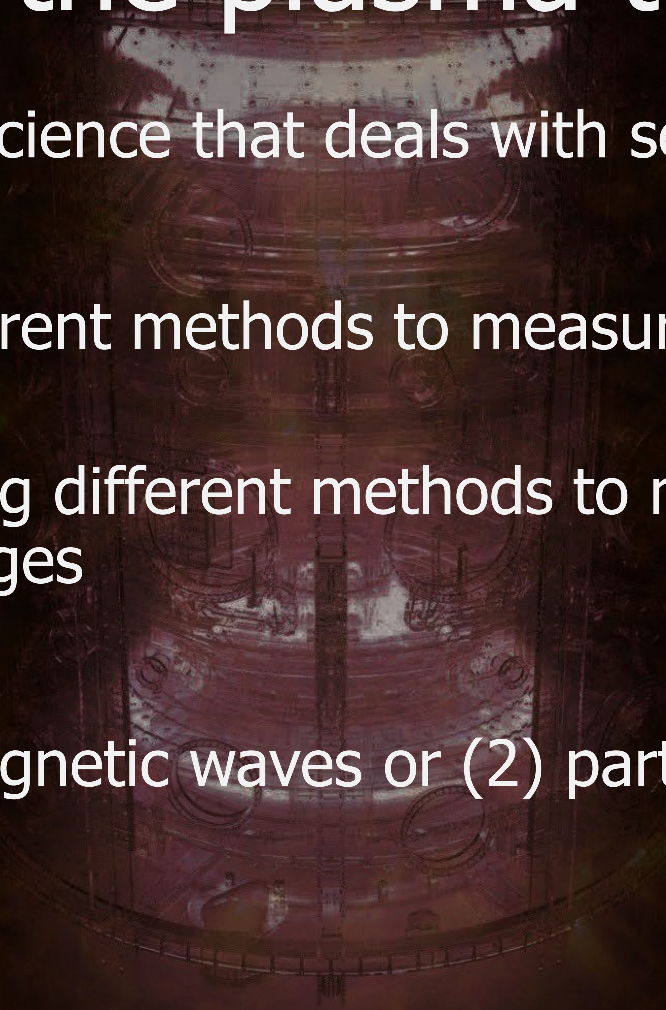
Ohmic heating power: P = I^2R

For plasmas: R drops with increasing temperature

Max. temperature: 10-40 million ^{O}C



3.3 Measuring the plasma temperature



Diagnostics : branch of science that deals with sensors and measurements

Redundancy : using different methods to measure the same quantity on the same range

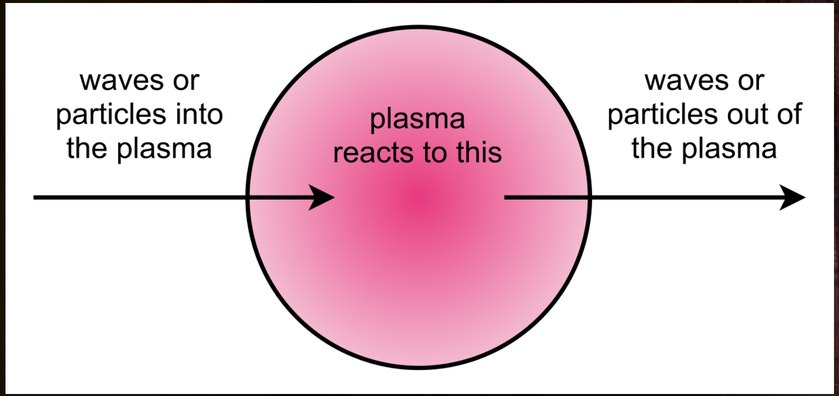
Complementarity : using different methods to measure the same quantity over different ranges

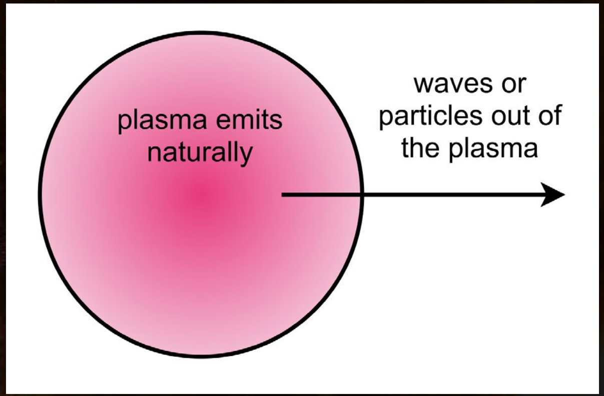
We measure (1) electromagnetic waves or (2) particles that come out of the plasma

Active v.s. passive diagnostics

Active: we insert something into the plasma, and measure the response

Passive: we measure some naturally occuring phenomenon, without putting additional energy into the plasma for this





Classroom Exercise 3.3

Active or passive diagnostics?

(a) Temperature measurement of a room by one mercury thermometer

(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.

(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.

Answer to Classroom Exercise 3.3

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

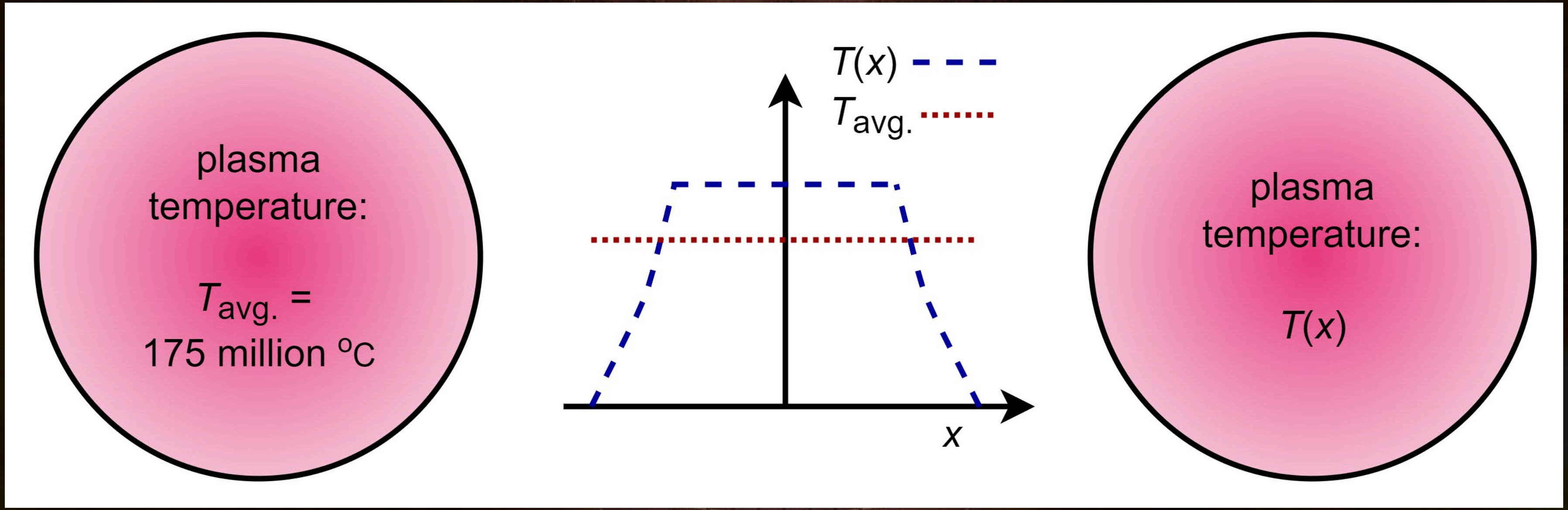
(b) active. The laser needs to be artificially applied to the car; it is not there by nature. We need to operate another device for this diagnostic (namely a laser gun).

(c) 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.

Global v.s. local measurements

Global: measuring a single value for the physical quantity

Local: measuring multiple values for the physical quantity, placed throughout the measurement space



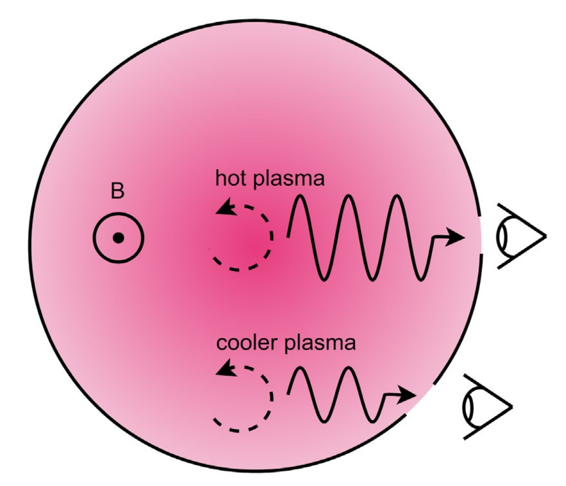
Temperature measurement: ECE

Electron cyclotron emission (ECE): electron temperature diagnostic

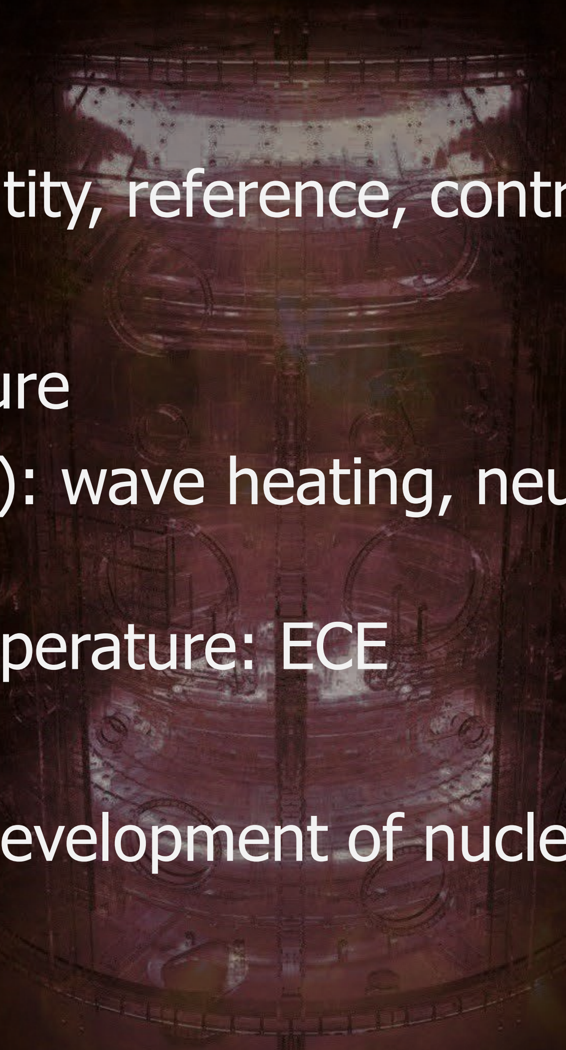
Passive and local

Due to the gyromotion of the electrons

Measure electromagnetic waves, with frequency in the order of 100 GHz



Conclusion



Control loops: physical quantity, reference, controller, actuator, sensor

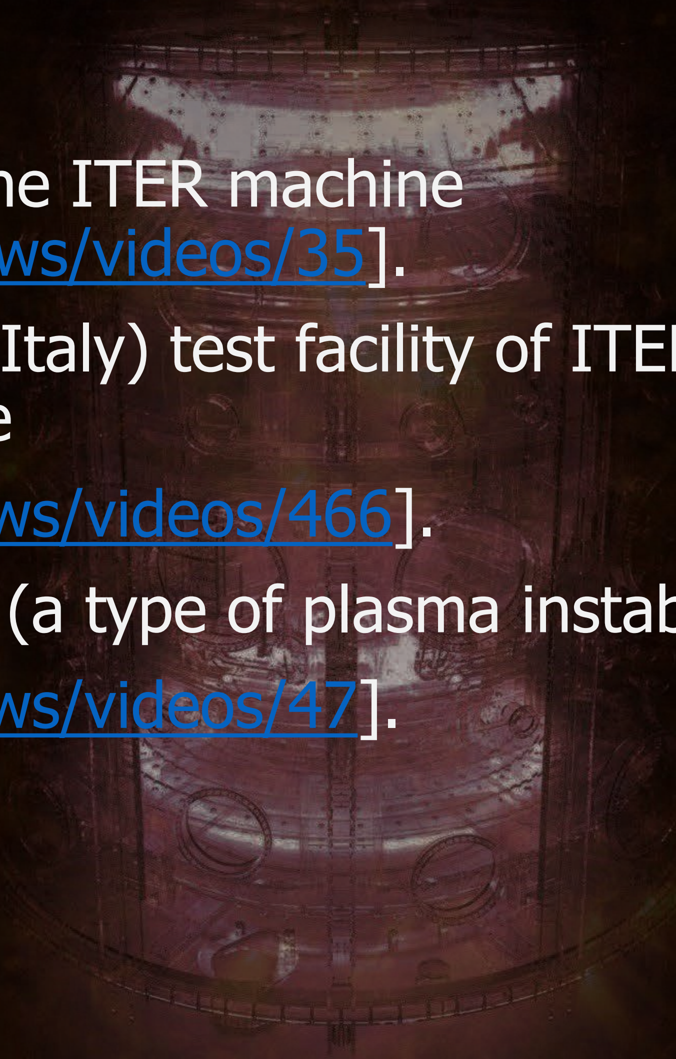
Control of plasma temperature

Heating methods (actuators): wave heating, neutral-beam injection, and ohmic heating

Diagnostics for electron temperature: ECE

Control is essential for the development of nuclear fusion reactors.

Videos



About the diagnostics of the ITER machine [https://www.iter.org/news/videos/35].

About the Consorzio RFX (Italy) test facility of ITER's NBI device, showing how large these machines are

[https://www.iter.org/news/videos/466].

About the control of ELMs (a type of plasma instability) in the ITER machine

[https://www.iter.org/news/videos/47].