

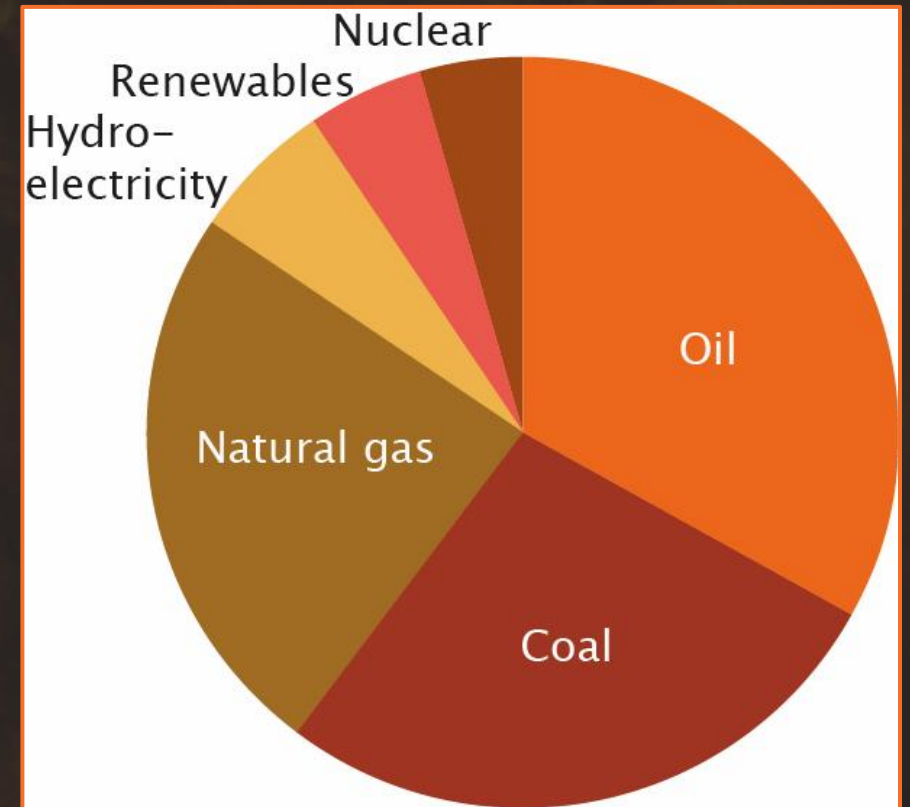
Module 1

Fusion Basics



1.1 Energy and its role in our world

- The energy mix
 - Renewable vs non-renewable



Source: BP Statistical Review of World Energy, 2020.

Classroom exercise 1.1

- (a) Estimate what percentage of your country's energy is created by renewable energy sources such as solar, wind, hydro, etc. Explain how you reached your estimate. Did you make any assumptions?
- (b) Compare your estimate with the estimate of at least one other student. Do the estimates differ a lot? Compare the reasoning behind the estimates: did you make different assumptions?
- (c) Look up the energy mix of your country. Compare your estimates to the data. Were your estimates close?

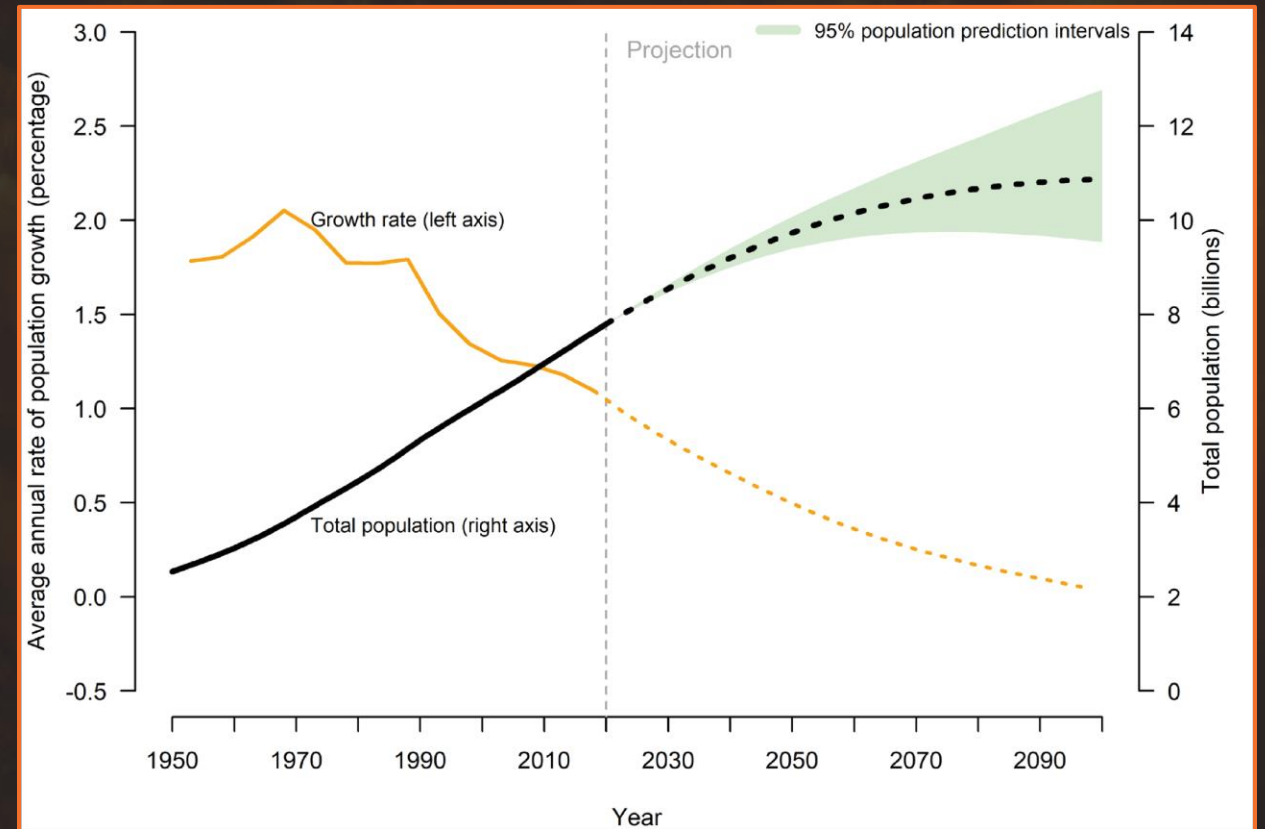
Classroom exercise 1.1 - answers

- Discuss!

The energy problem

- Problem

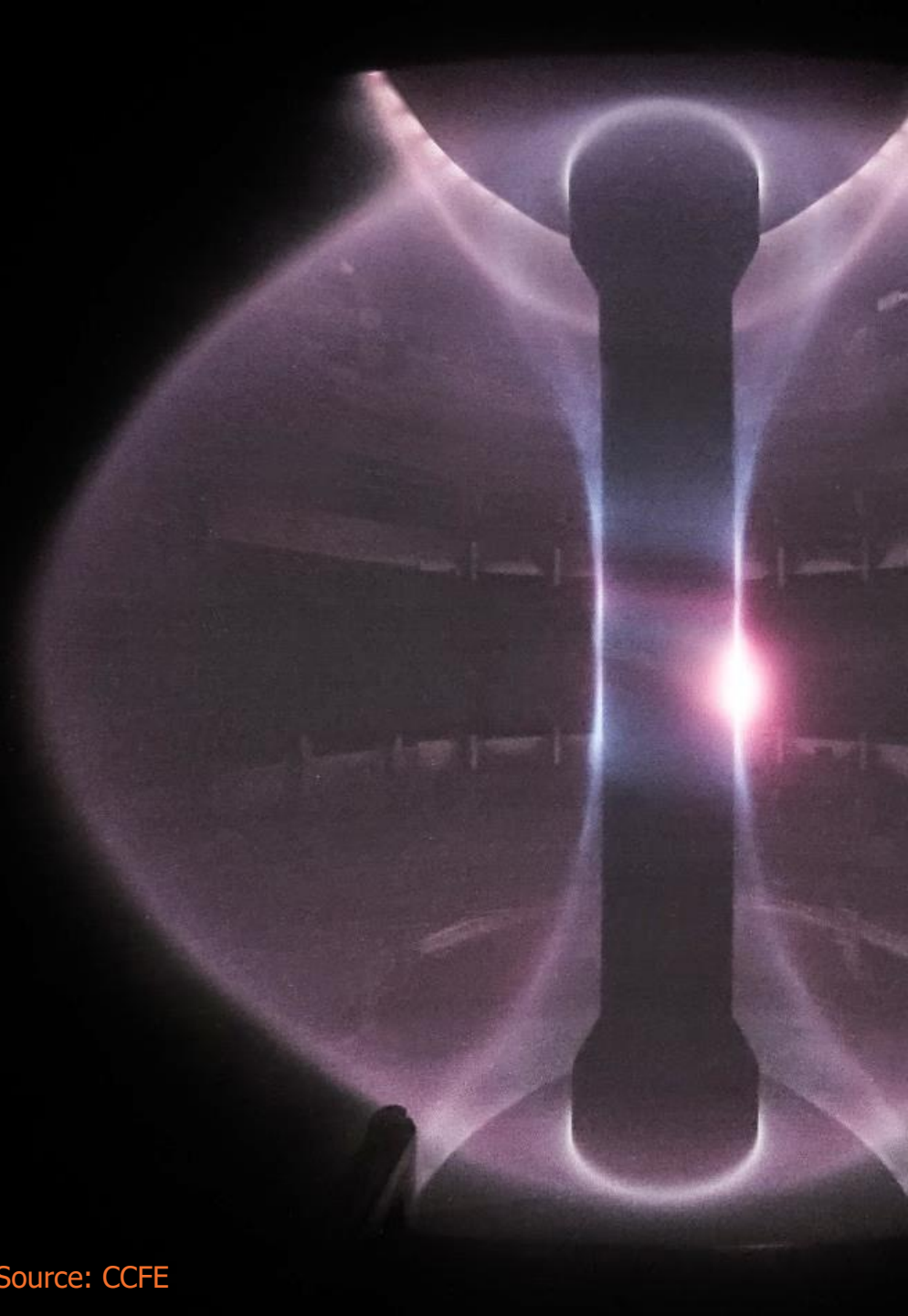
- Increasing **population**
- Increasing **energy use**
- Environmental harmful sources



Source: United Nations, Department of Economic and Social Affairs, Population Division (2019). World Population Prospects 2019: Highlights. ST/ESA/SER.A/423.

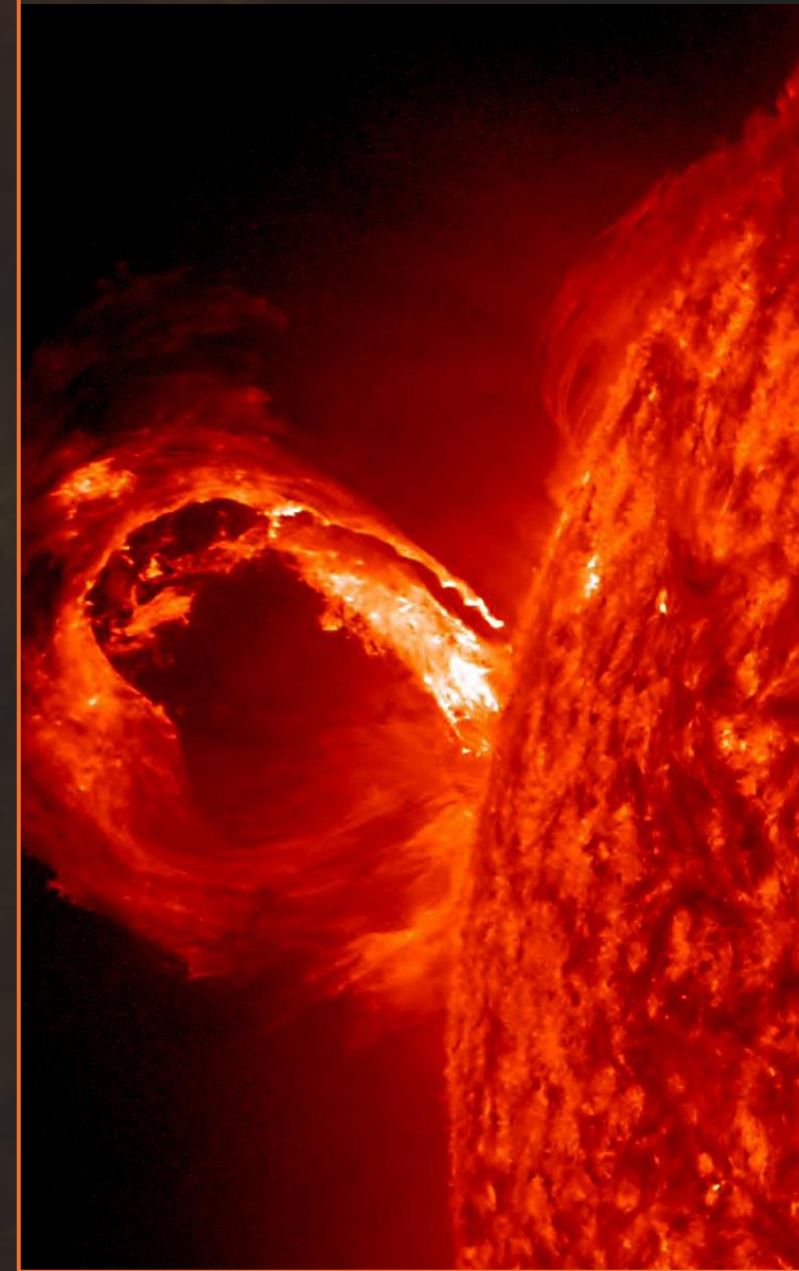
The energy problem

- Solutions
 - Decreasing energy needs
 - Increasing sustainable sources
- How?
 - Better storage
 - Alternative energy sources
 - Backup solution: **Nuclear fusion!**



1.2 Fusion inside our own sun

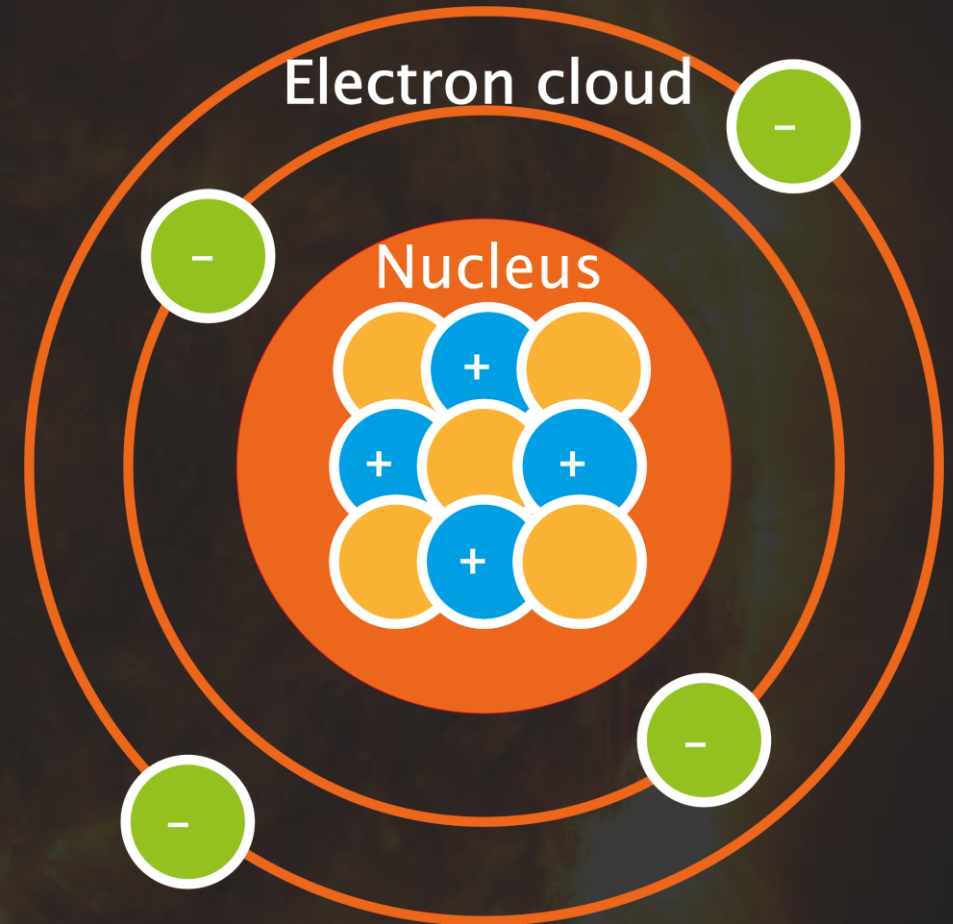
- The Sun
 - Star
 - Held together by **gravity**
 - Immense **pressure**
 - In **equilibrium**
- Gets its energy from **fusion!**
 - Let's take a really close look!



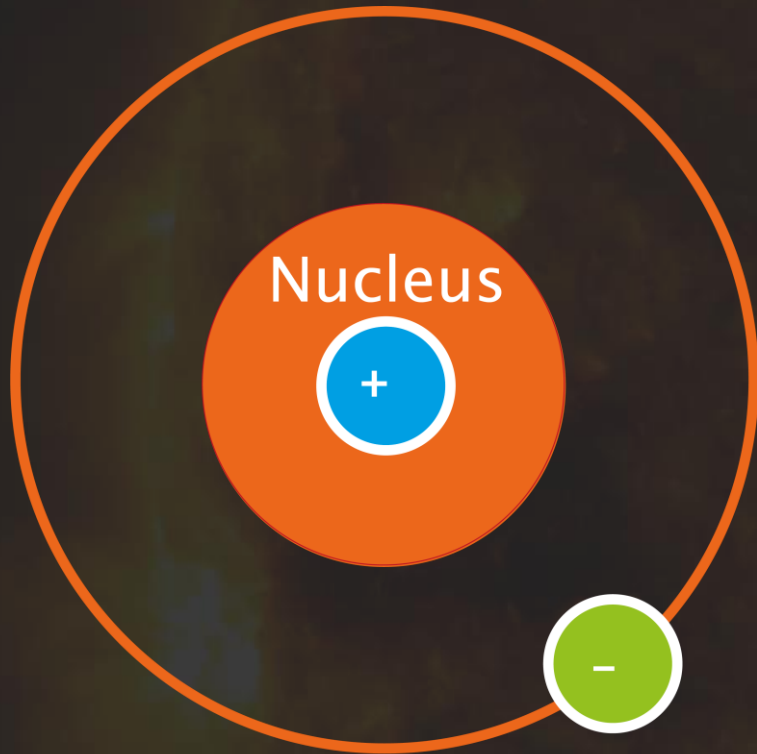
Source: NASA

Inside the atom

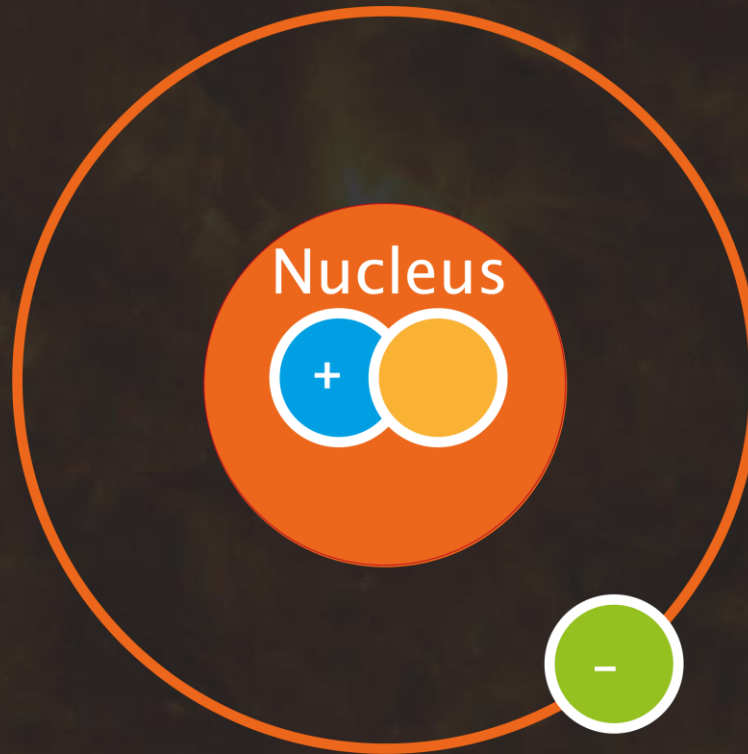
- Nucleus
 - **Proton**: determines which element, positive charge
 - **Neutron**: determines which isotope, no charge
- Electron cloud
 - **Electron**: determines charge/ion, negative charge



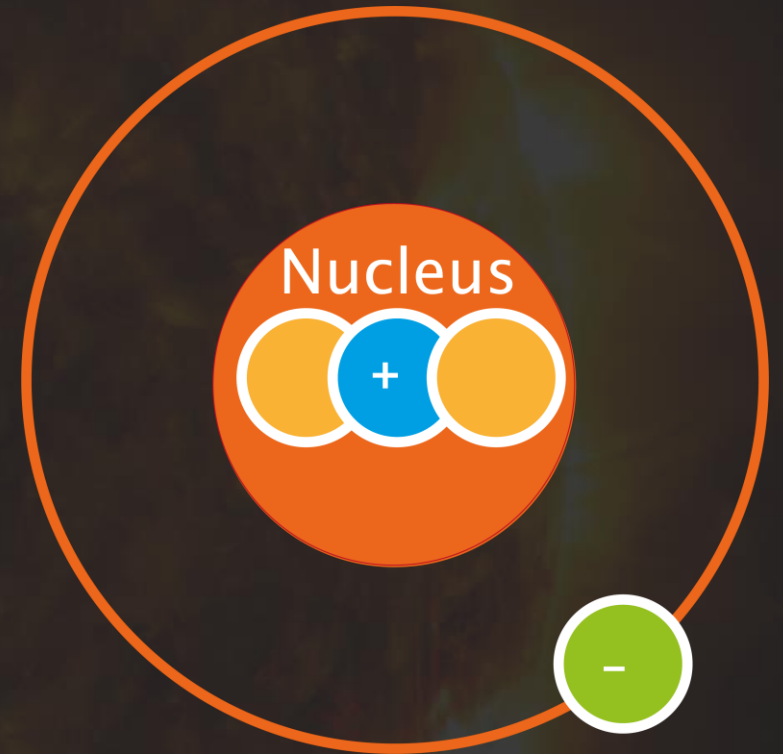
Isotopes



Hydrogen



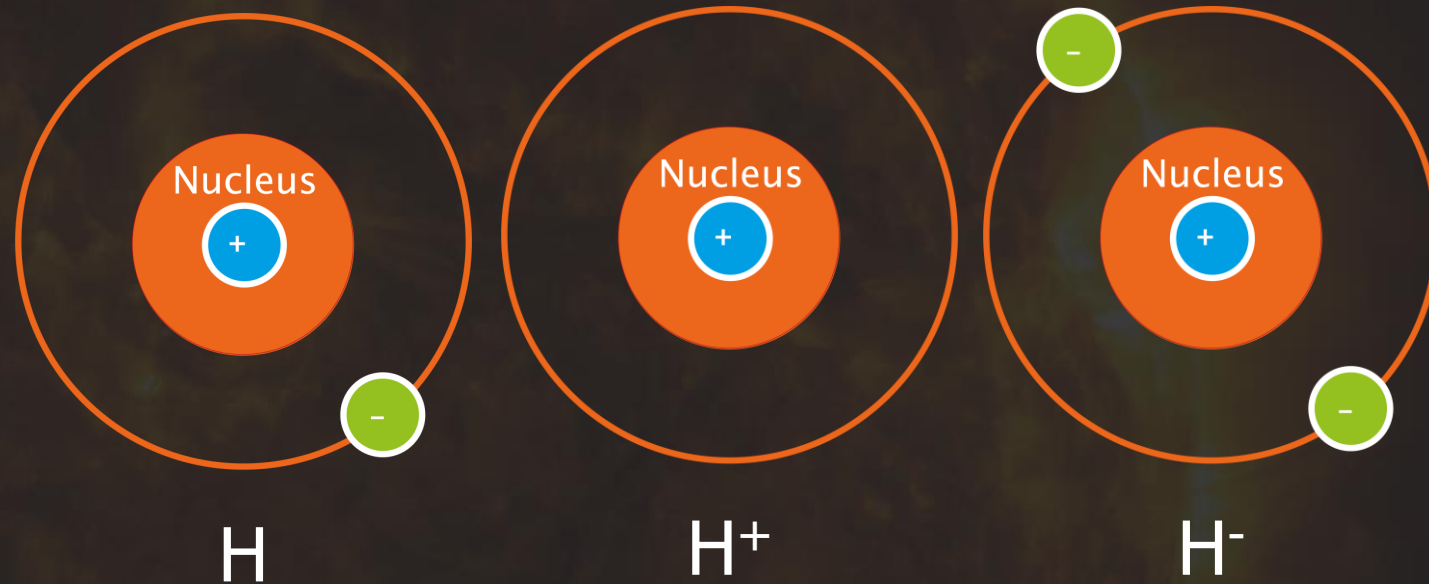
Deuterium



Tritium

Atoms and ions

- Atoms
 - Neutral
- Ions
 - Charged
 - Can be **positive** or **negative**



Charge

- Charged particles interact with each other



Attraction: (+/-)



Repulsion: (+/+) or (-/-)

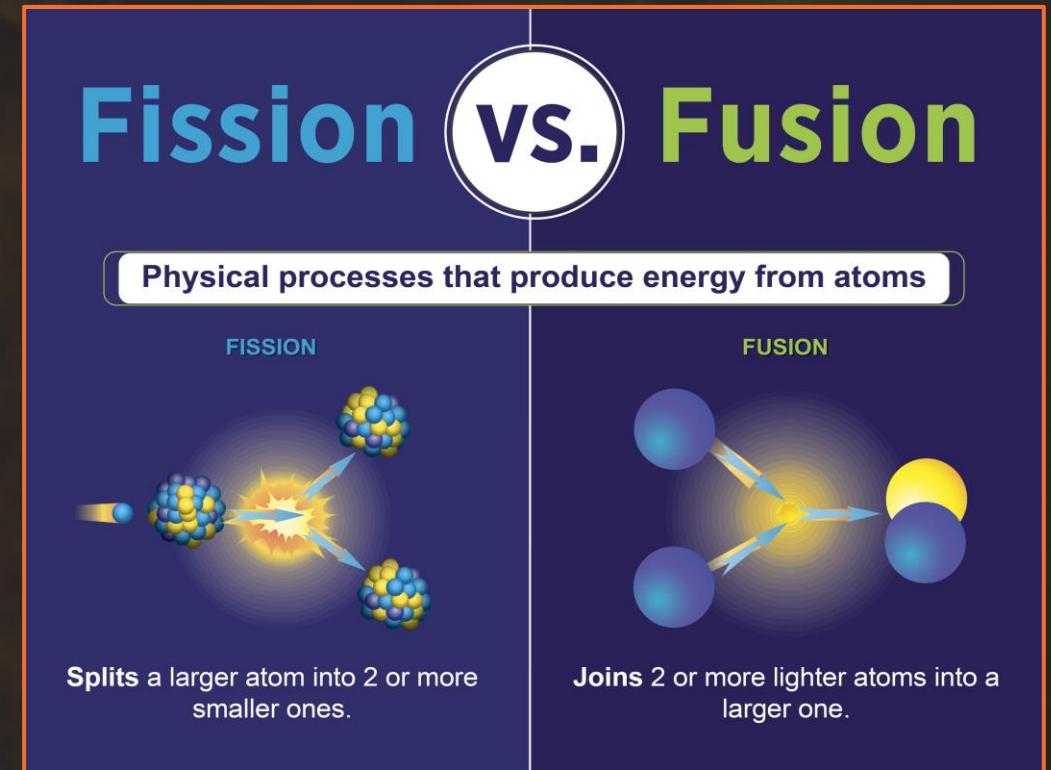
Nuclear reactions

- Fission

- One heavy nucleus splits into two (or more) parts and releases energy

- Fusion

- Two light nuclei fuse together to form one heavier nucleus and release energy



Graphic by Sarah Harman | U.S. Department of Energy

The nuclear fusion reaction

- Easiest: D-T fusion



- Deuterium and tritium
- Two isotopes of hydrogen

[illegible]

Classroom exercise 1.2

The concept of energy density is an important one in physics and although it sounds difficult, it boils down to “how much energy is inside a certain volume of stuff”. If you burn 1 litre of gasoline and measure the amount of energy that is released (in the form of heat) and divide it by the volume that was burned, then you end up with a measure for the energy density. For all fuels, an energy density can be determined.

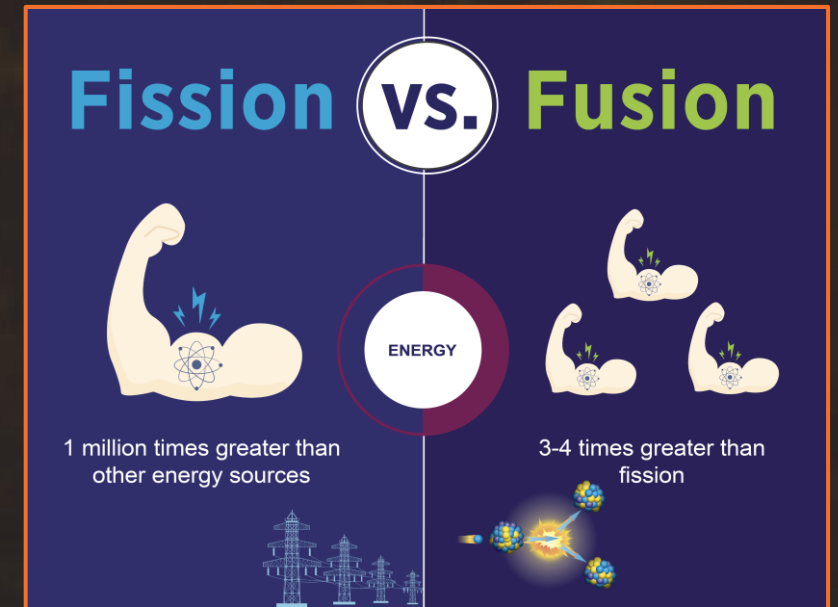
- a) Out of the fuels listed below, which one would you guess has the highest energy density? Which one would you guess to have the lowest energy density? Order them from highest to lowest.
- b) Compare your ranked list with the list of at least one other student. Discuss why you placed them in this order.
- c) Look up the energy densities. Compare your ranked lists to the data. Were your estimates close?

Gasoline – oil – coal – wood – hydrogen (gas) – ethanol – Deuterium – Uranium

Classroom exercise 1.2 – answers

From high to low:

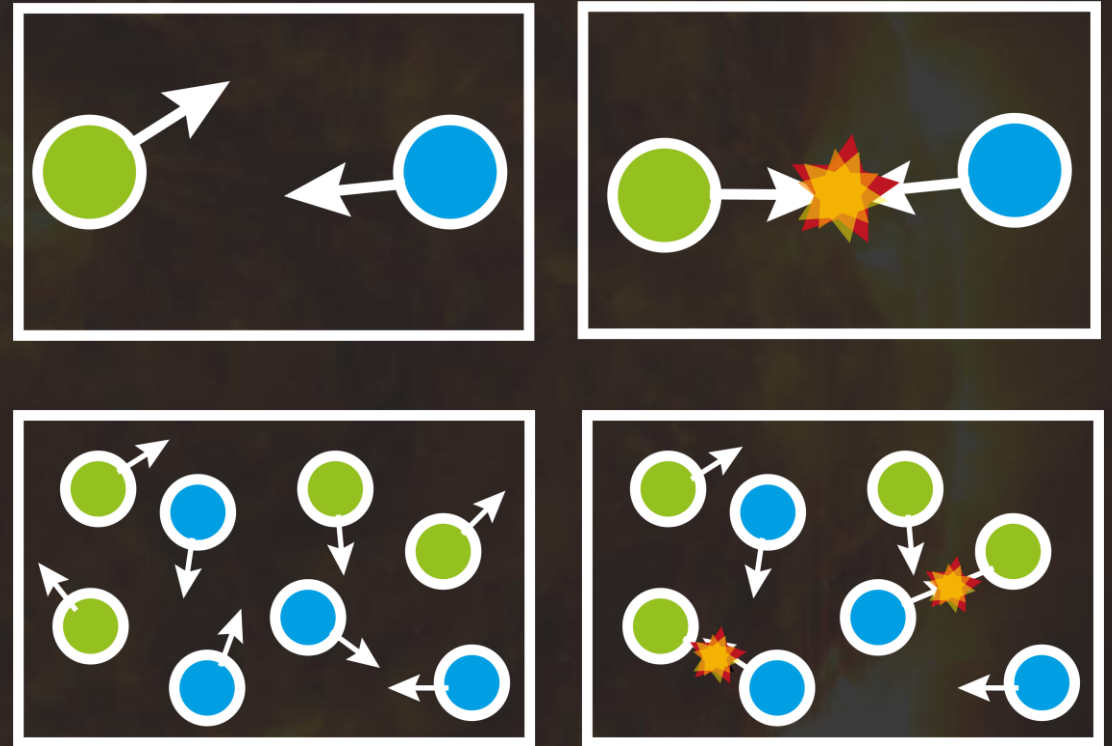
- | | |
|--------------|-------------------|
| 1. Deuterium | 5. Gasoline |
| 2. Uranium | 6. Ethanol |
| 3. Coal | 7. Wood |
| 4. Oil | 8. Hydrogen (gas) |



Graphic by Sarah Harman | U.S. Department of Energy

Criteria for fusion

- We need:
 - High **temperature**
(= high velocity)
 - High **density**
- And:
 - **Energy confinement time**

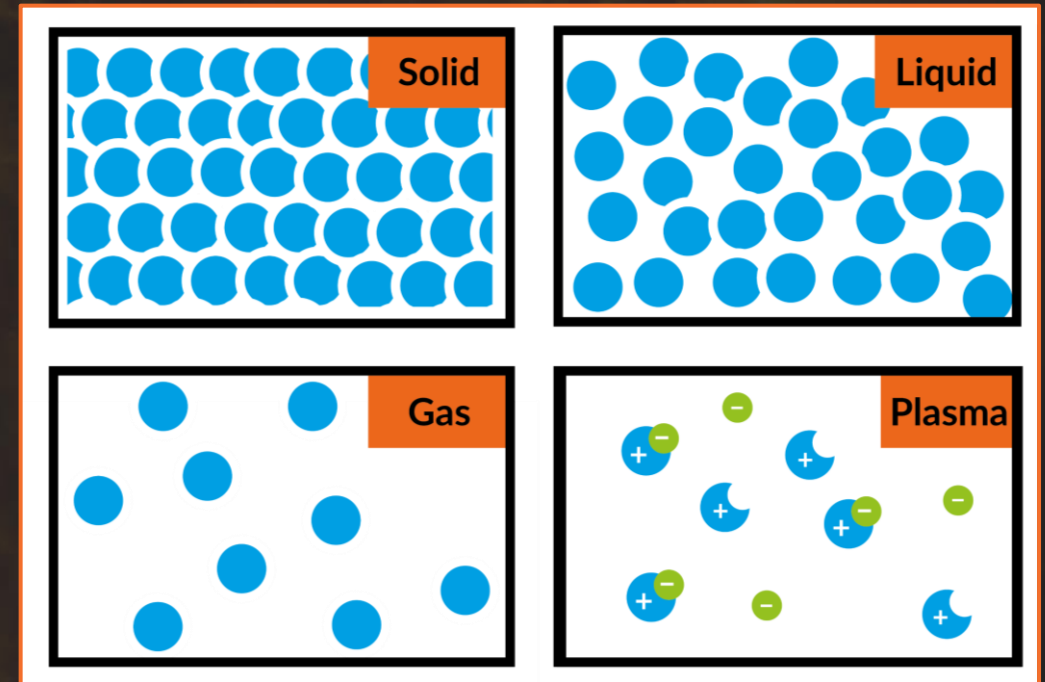


Criteria for fusion

- In the sun: **gravity**
 - Leads to extreme conditions and confines the energy for a long time
- On earth: we need another way
 - **Fusion reactors**
 - **Plasma!**

1.3 Plasma

- The 'fourth' state of matter
- **Ionised gas**
 - Contains free moving charges:
 - Positive ions
 - Negative electrons
 - Fully ionised plasma
 - If it has only ions and electrons



Ionisation vs phase change

- **Ionisation**

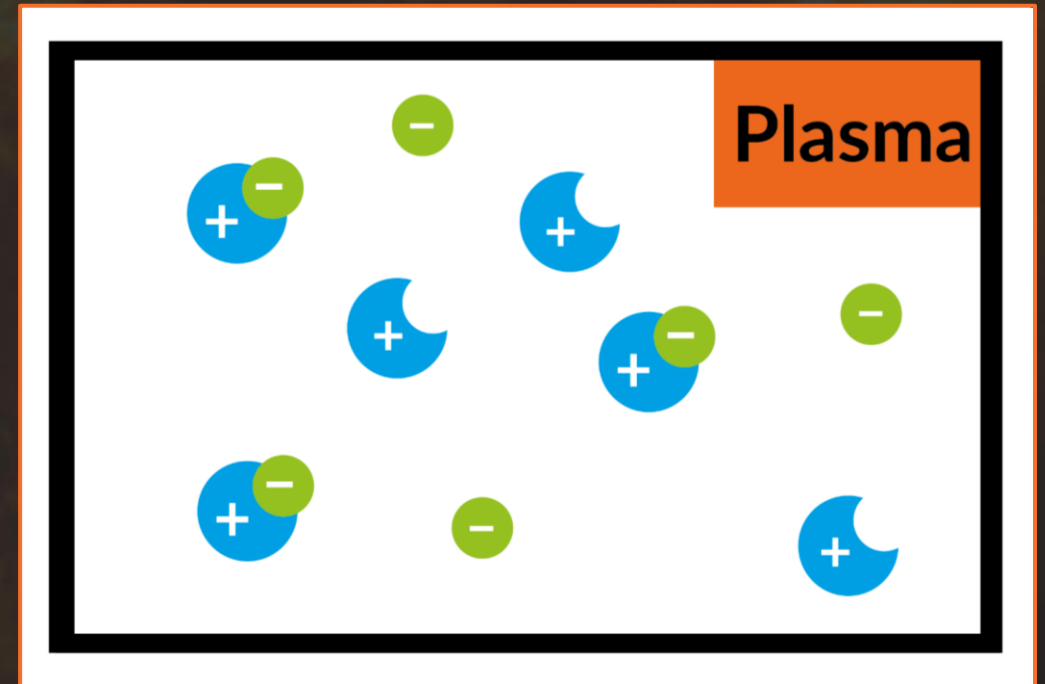
- Gas
- High pressure and temperature
- **Breakdown:**
bonds *within* atom break
- Condition for breakdown
 - Energy higher than **ionisation energy**

- **Phase change**

- Solid/liquid/gas
- At specific pressure and temperature
- **Breakdown:**
bonds *between* atoms break
- Condition for breakdown
 - Energy higher than **threshold energy**

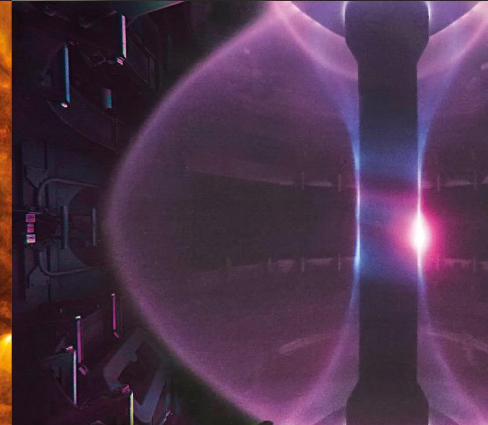
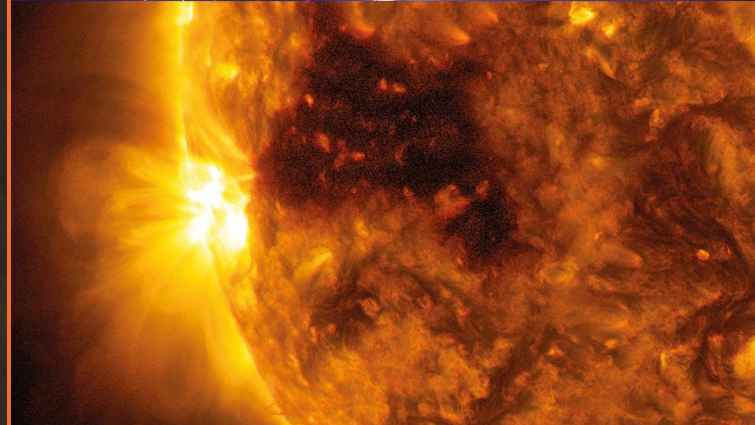
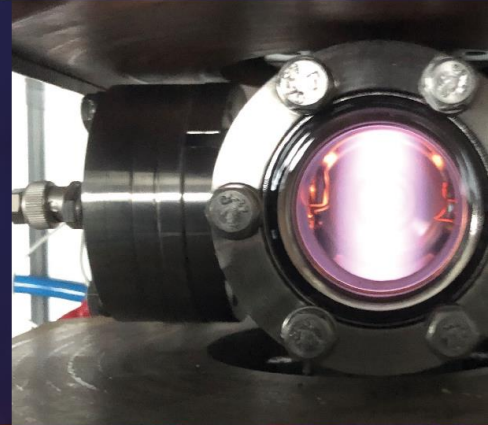
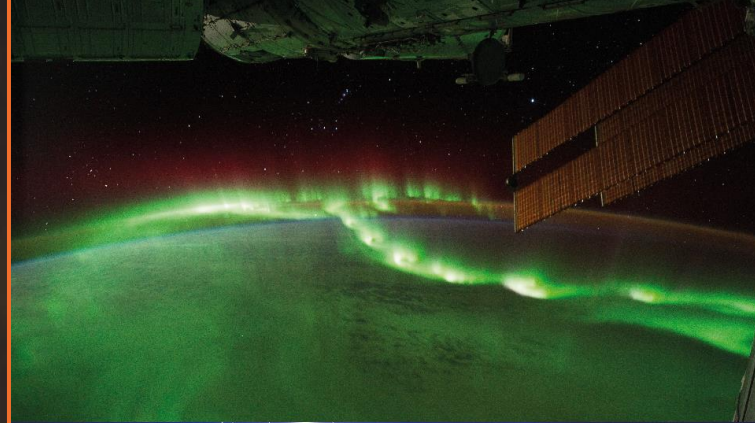
Plasma conductivity

- Plasma consists of freely moving charged particles
- Can conduct **electricity**
 - **Currents** in plasma
- Sensitive to
 - **Electric fields**
 - **Magnetic fields**



Examples of plasmas

- Most common state of matter in the universe!
- Northern lights (Aurora Borealis)
- Neon lights
- Lightning
- Plasma discharge
- Sun
- Inside a tokamak



Classroom exercise 1.3 – multiple choice

So, the difference between a plasma and a gas lies in the bulk of the particles being charged or neutral. However, most plasmas can be observed to glow, while gases are often colourless and definitely don't glow. So why do plasmas glow?

- a) At sufficiently high temperature everything will start to radiate, so plasmas naturally glow due to the high temperature.
- b) The charged particles move freely and once a free electron and an ion collide, there is a chance that they recombine. In this recombination process the charged particles combine into a neutral particle and light is emitted. If the emitted light lies in the visible spectrum, the plasma will start to glow.
- c) In some nuclear reactions, light is emitted. If the emitted light lies in the visible spectrum, the plasma will start to glow.

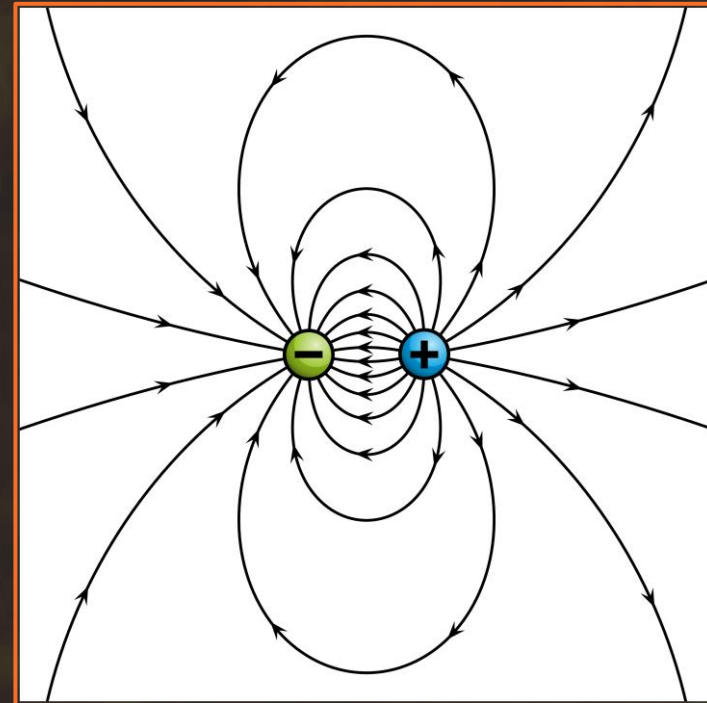
Classroom exercise 1.3 – answer

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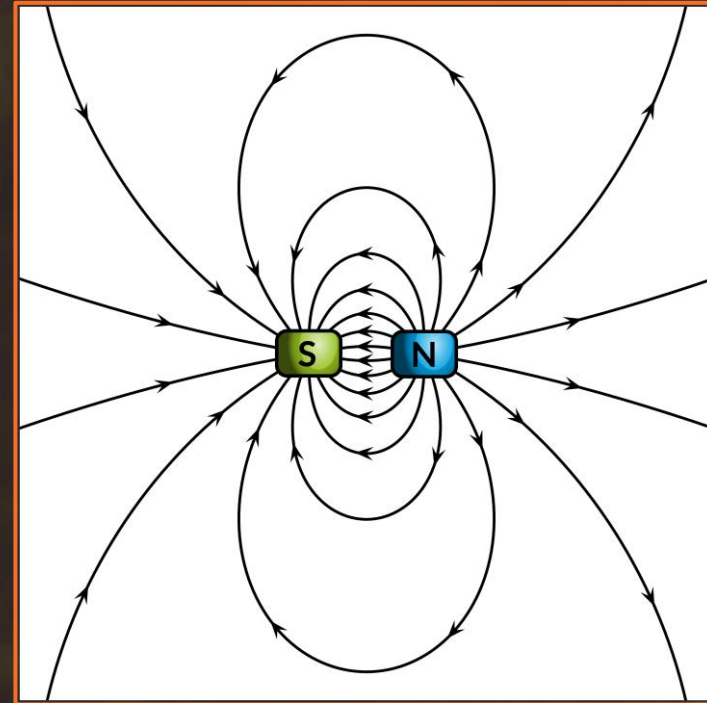
Electric field

- Influence of charge on the surroundings
- Strong field close to **charge**
- **Electric field lines**
 - Imaginary
 - Never cross
 - Close = strong!
 - From + to -



Magnetic field

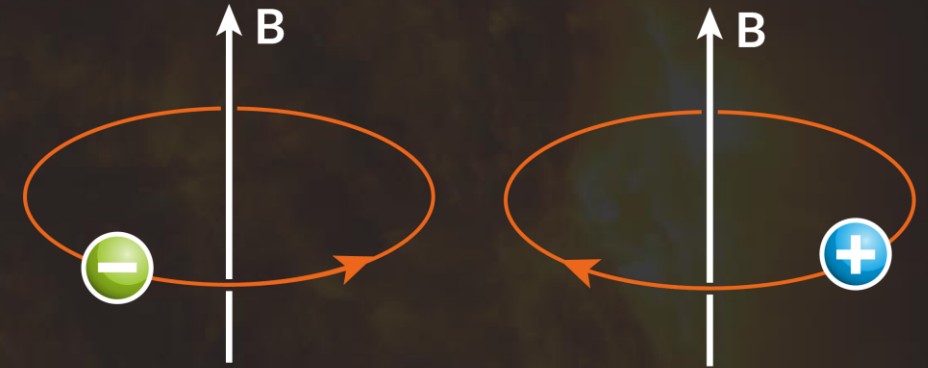
- Influence of charge on the surroundings
- Strong field close to **poles**
- **Magnetic field lines**
 - Imaginary
 - Never cross
 - Close = strong!
 - From N to S
 - Always closed loops



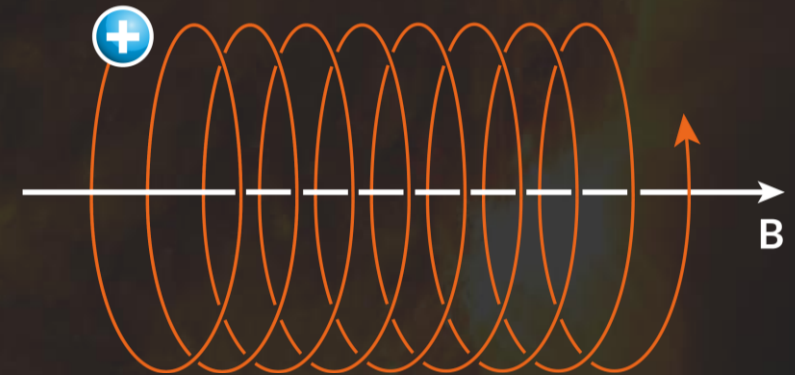
Charges in a magnetic field

- Gyromotion

- Charge interacts with magnetic field
- Circular motion around the field line



- If particle has velocity in direction of field line:
 - **Helical trajectory** around the field line



Plasma confinement

- Why do we need electric and magnetic fields in fusion?
- To **confine** the plasma!
- Plasma → high temperature and high velocity particles
- If the particles reach the reactor wall, it will **melt**
- We can use a **magnetic field** to keep the particles away from the wall!

Classroom exercise 1.4

The direction of the magnetic field (that is, the direction of the magnetic field lines) depends on the direction of moving charges. Draw the direction of the magnetic field by drawing several magnetic field lines for the following situations:

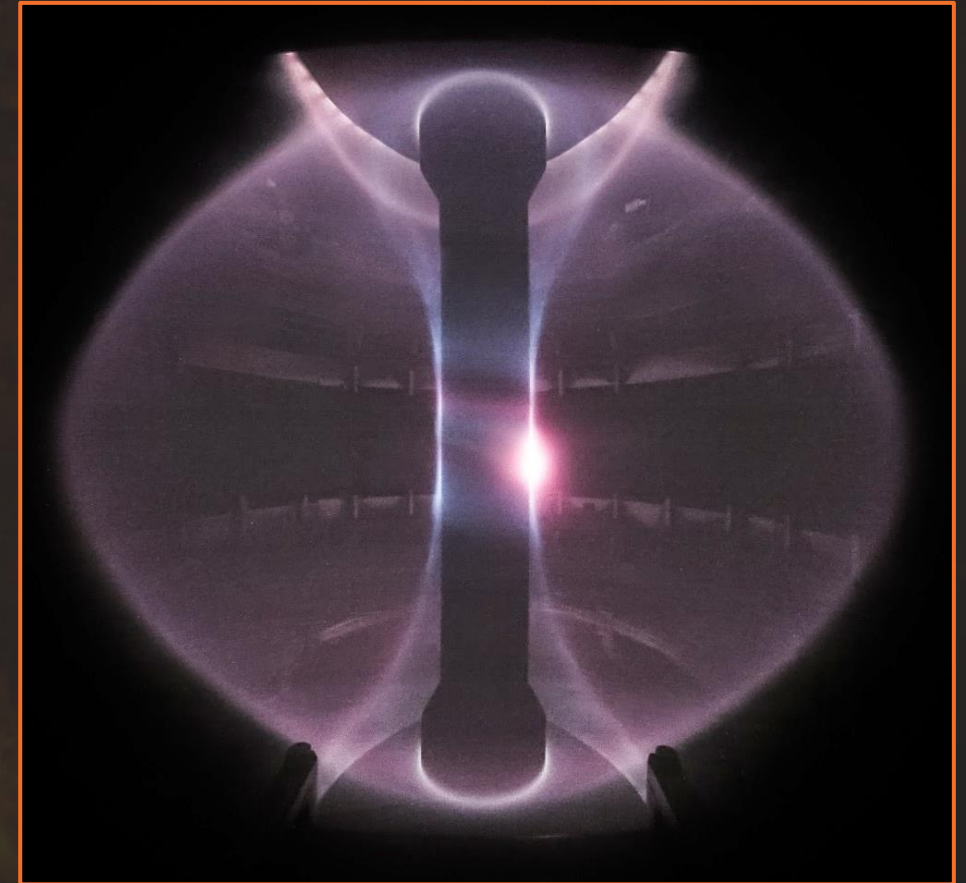
- a) A straight wire through which a current runs.
- b) A circular loop of wire through which a current runs in the anti-clockwise direction.
- c) An electron moving in a circle (clockwise) and a proton moving in a circle (anti-clockwise). Compare this with the directions of question b: what do you notice?
- d) What can you say about the direction of the magnetic field compared to the direction of motion in general?

Classroom exercise 1.4 – answers

- a) The current goes out of the paper.
The magnetic field curls anti-clockwise.
- b) The magnetic field inside the loop is out of the paper
The magnetic field outside the loop is into the paper.
- c) Because of opposite charge and opposite motion the magnetic field has the same direction for both particles
- d) The direction of the magnetic field is always perpendicular to the direction of the current

1.4 Building a fusion device

- Magnetic confinement fusion (MCF)
 1. Confine a plasma with a magnetic field
 2. Heat the plasma to fusion conditions
- Best known type of fusion device:
- Tokamak
- Russian:
“Toroidal chamber with magnetic coils”



MAST (Mega Ampere Spherical Tokamak) | Source: CCFE

The tokamak

- Doughnut shape (torus)
 - Inside donut: **plasma**
 - Outside donut: **magnetic coils**
- Geometry
 - major radius R
 - minor radius a
 - poloidal angle θ
 - toroidal angle φ



Source: Powerpoint stock image

Classroom exercise 1.5

Different tokamaks and toroidal fusion devices have different 'aspect ratios': the ratio between the major radius R and the minor radius a . As a result the shapes of these tori can vary quite a bit. Let's take a closer look at these different shapes.

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

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

- d) What happens if the aspect ratio changes?
- e) What is the lowest possible aspect ratio for a torus?

Classroom exercise 1.5 – answers

- a) A doughnut
- b) The doughnut becomes more spherical, the minor radius cannot be larger than the major radius (otherwise it is no longer a torus!)
- c) If we allow the minor radius to be larger than the major radius and take the limiting case we get a sphere
- d) The torus changes shape
- e) 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

As we have seen, there are two main directions on a torus: the “toroidal” and “poloidal” directions. These can be quite confusing, so let’s take a closer look.

- a) Make a sketch of the two possible cross-sections of a torus.
- b) Which cross-section is the poloidal cross-section? Which one is the toroidal cross-section? What do you notice about the toroidal/poloidal direction and their respective cross-sections?

Classroom exercise 1.6 – answers



Poloidal cross-section

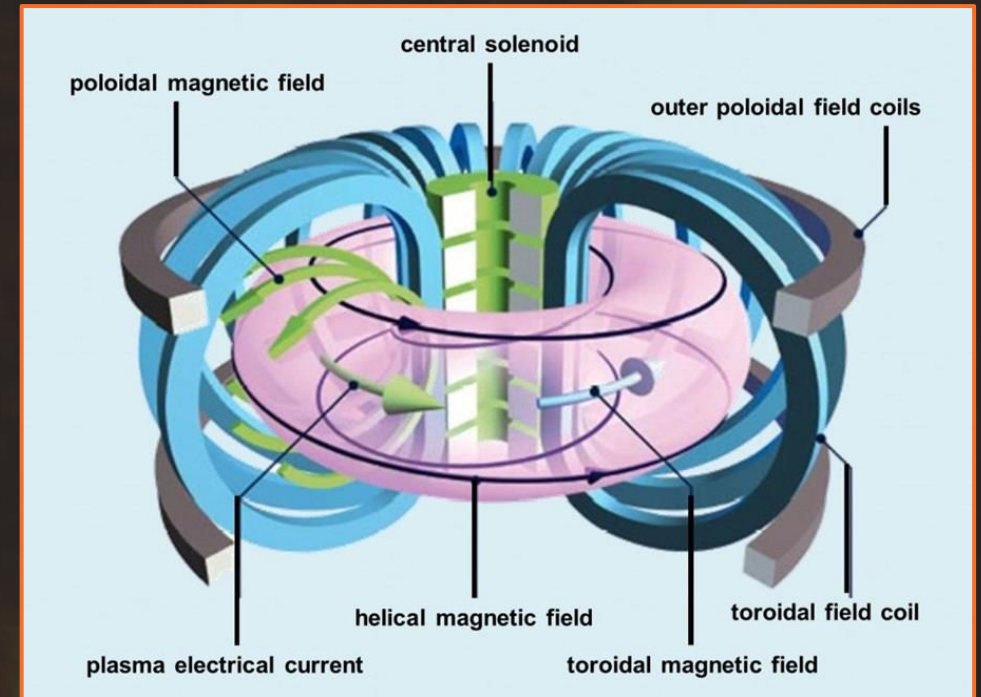


Toroidal cross-section

Magnetic coils of a tokamak

- Three main magnet systems:

- Toroidal field coils
- Central solenoid
- Poloidal field coils

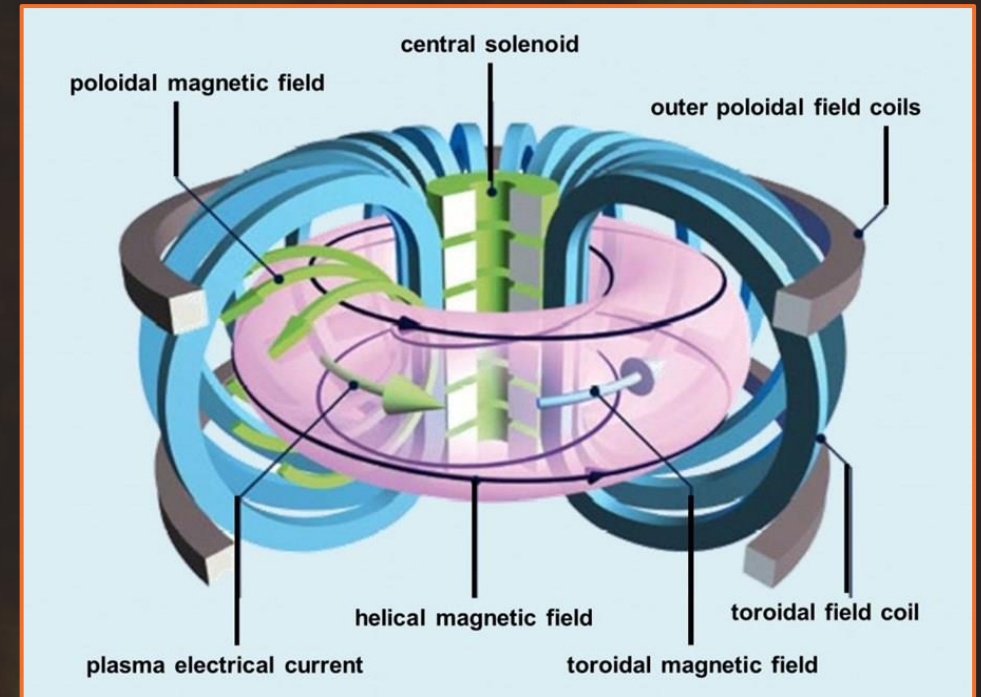


Credit: S. Li et al. <https://tinyurl.com/4ybcpw65> (CC BY 4.0)

Classroom exercise 1.7

Let us take a look at a standard tokamak, focusing on its three main magnet systems.

- a) Which magnets can be seen to lie in the poloidal cross section? How are these magnets called and does this name make sense?
- b) Explain the names of the other two groups of magnets.



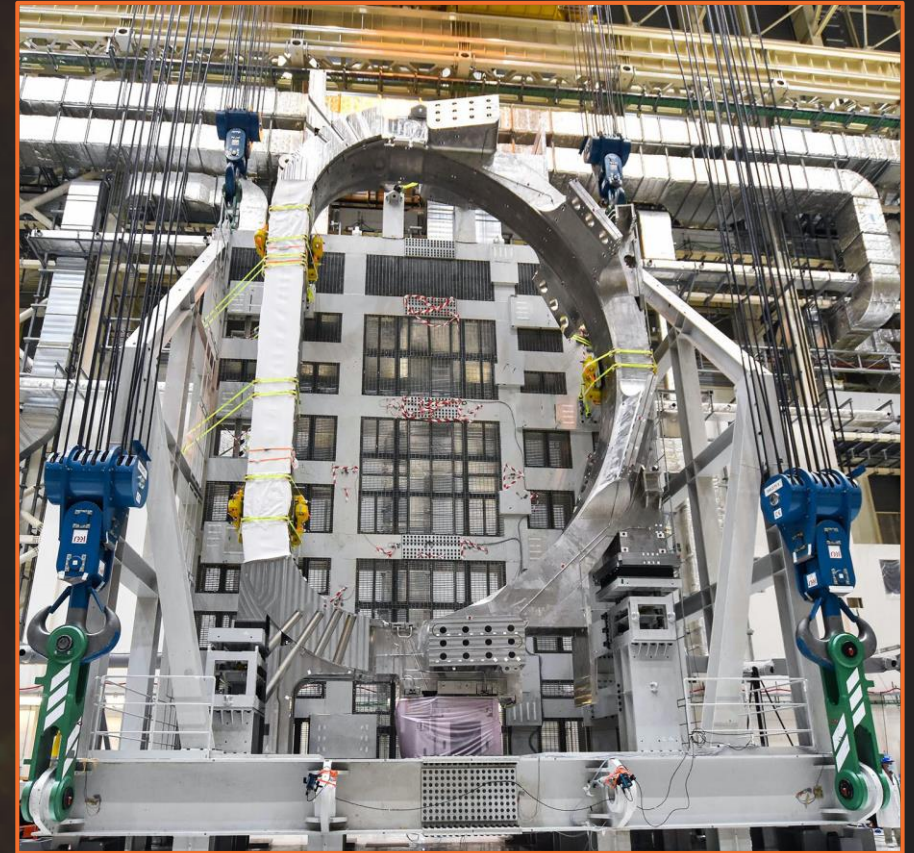
Credit: S. Li et al. <https://tinyurl.com/4ybcpw65> (CC BY 4.0)

Classroom exercise 1.7 – answers

- a. **Toroidal field coils** – lie in the poloidal cross-section of the tokamak
- b. **Central solenoid** – lies in the hole of the doughnut, i.e. in the centre
Poloidal field coils – lie at the top and bottom of the torus

Toroidal field coils

- Strongest field in tokamak
- D-shaped
- Wrap around doughnut
- Additional magnetic fields needed for stable confinement



Credit: ITER

Central solenoid

- Stacked set of coils located in the hole of the doughnut
- Field used indirectly:
magnetic induction to create a **current** in the plasma
- This current creates a **poloidal magnetic field**
- Toroidal + poloidal field → **helical magnetic field**
- Helical field necessary for stable confinement

Magnetic properties

- Magnetic field strength B

- Higher density of magnetic field lines leads to higher value of B

$$\Phi = B \cdot A \cos(\alpha)$$

- Magnetic flux Φ

- 'Phi'
- Density of magnetic field lines through a surface
- Field lines are perpendicular to surface

Electromotive force (EMF)

- Depends on the **rate of change of magnetic flux**
- Calculated by:

Number of windings of the coil \times change in magnetic flux

- EMF: ε (epsilon)

$$\varepsilon = N \cdot -\frac{d\Phi}{dt}$$

- Used by transformers

EMF & Magnetic induction

EMF counteracts the change in magnetic flux

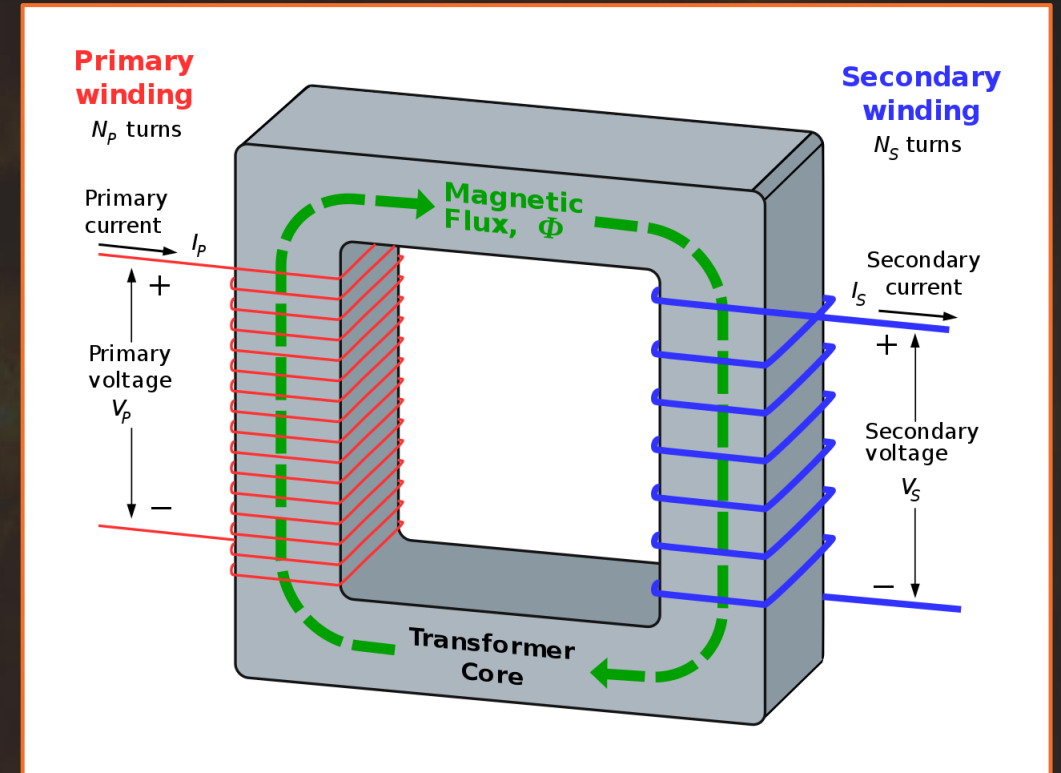
1. Creating a voltage
2. Voltage creating current
3. Current creating opposing magnetic field

So an opposing magnetic field is **induced** by the EMF:
Magnetic induction

This way, varying current through one loop can induce a current in another loop when the loops are not connected!

Transformers

- Consist out of two coils
 - Primary coil
 - Secondary coil
 - Different amount of windings
 - Uses **magnetic induction**
- Ideal transformer
 - No power loss: $P_{\text{coil1}} = P_{\text{coil2}}$

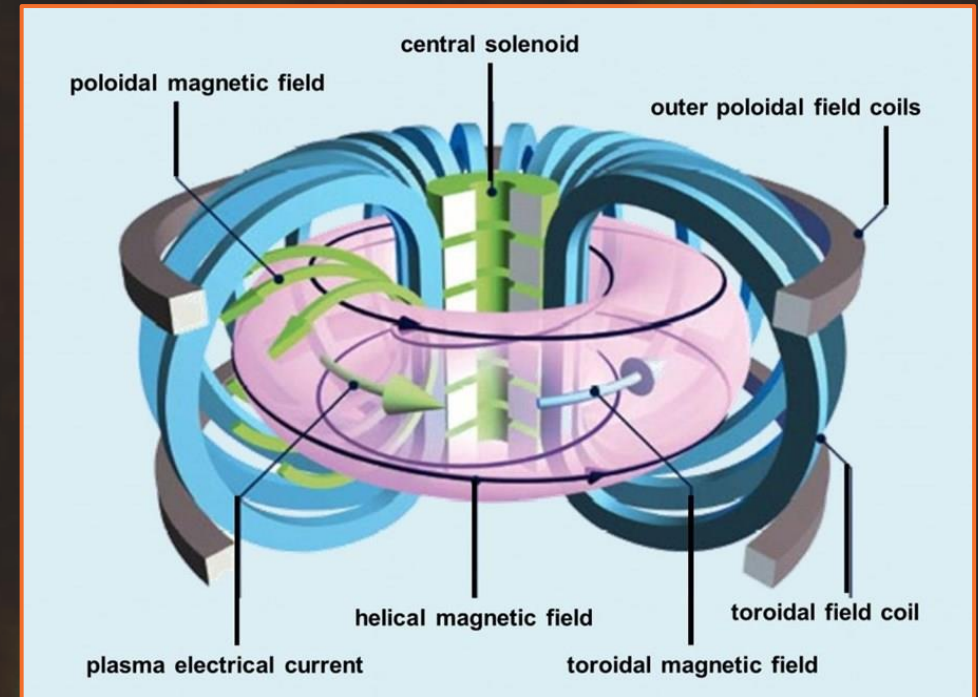


Remember!

$$\text{Power} = \text{Voltage} \times \text{Current}$$
$$P = V \times I$$

Poloidal field coils

- Help control the shape and position of the plasma
 - Necessary to keep plasma stable
- So not used to create a poloidal field!
(Central solenoid creates poloidal field through magnetic induction)



Credit: S. Li et al. <https://tinyurl.com/4ybcpw65> (CC BY 4.0)

Classroom exercise 1.8

The use of induction to generate a plasma current which creates our poloidal field has one major drawback: it makes a tokamak a pulsed device.

- a) How does magnetic induction lead to pulsed operation?
- b) Why is this a problem for a fusion reactor?

Classroom exercise 1.8 – answers

- a) Induction depends on a change of the magnetic flux.
The magnetic flux cannot keep changing continuously, at some point the magnets are at their limit.
Hence, the central solenoid operates in pulses, leading to pulsed operation
- b) Ideally, a fusion reactor runs non-stop. If it is pulsed, there are times in which no energy is generated

Magnetic confinement

- Pressure balance in tokamak
 - Outward pressure: plasma
 - Inward pressure: magnetic field
→ Lorentz force!
- Equilibrium!
- Allows for fusion on Earth!

Want to learn more about fusion?

Have a look at the other 4 modules!

- Module 2: Road to fusion
 - Module 3: Plasma control
 - Module 4: Fusion materials
 - Module 5: Fusion deployment
-
- Or look at 'Further reading' in the student reader

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For more information, see <https://fusenet.eu>

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