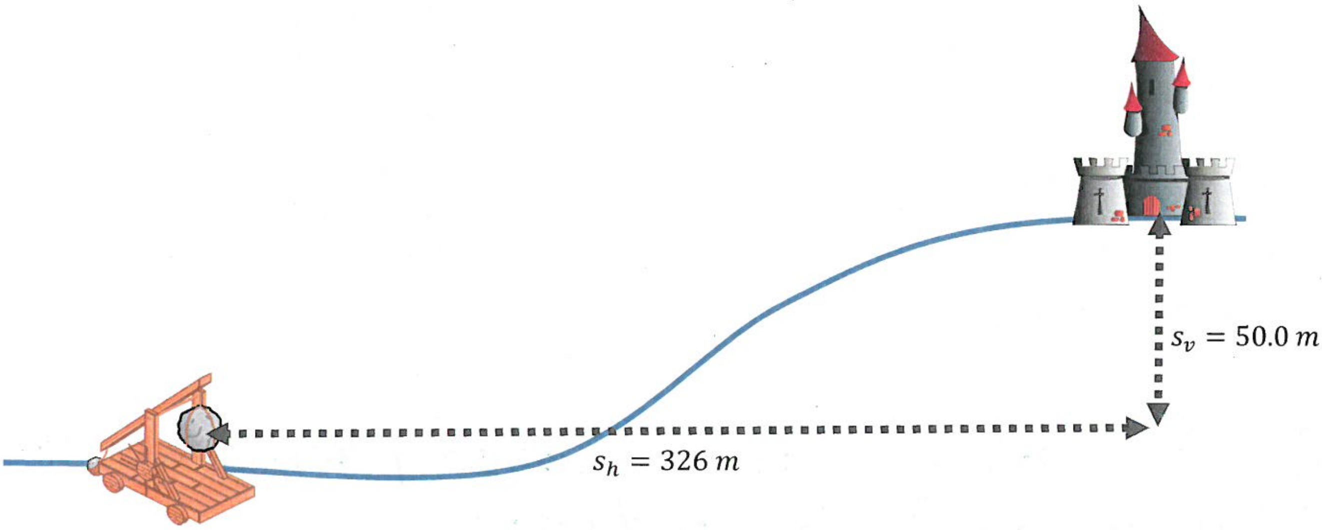
Medieval castles were often built at higher elevations to give an advantage to those under siege.



(b) A launched boulder is in the air for 4.80 s. The distances, s_h and s_v above indicate how far the boulder travelled to hit the castle. Determine both the speed and angle above the horizon the boulder was launched at. You may make use of the trigonometric identity $tan\theta = \frac{sin\theta}{cos\theta}$ and air resistance can be ignored. (6 marks)

Speed: ____________________ m s^{-1} Angle: ____________________ ^{0}

Question 18 **(11 marks)**

Transmission of radio waves by an antenna is intrinsically polarised. An AC voltage is supplied to the antenna which generates the radio waves, with a polarisation matching the orientation of the conducting metal of the antenna. Receiving antennae, like those on the roofs of most homes, must have the same orientation to receive a strong signal – the wrong orientation won't pick up the radio wave.

Each television network sends out a channel's picture and sound data via radio waves. A television has electronic components that can isolate the data from a single frequency of radio wave. Each television network has **one** frequency they are allowed to transmit over.

(a) Describe how an AC voltage applied to a conductor can produce electromagnetic waves. Describe why an equivalent DC voltage could not. (3 marks)

- An AC voltage causes charged particles to oscillate on/in a conductor.
- Oscillating charged particles create EMR, including radio waves.
- DC voltages do not cause charged particles to oscillate ⇒ no EMR

(b) Compare polarised light and unpolarised light. (2 marks)

- Polarised light – the electric/magnetic fields oscillate in only a single plane.
- Unpolarised light – the E/M fields oscillate randomly in all directions/orientations.

(c) Some satellite television networks will transmit two different channels over the same frequency. To achieve this, both the television network transmission antenna and the household receiving antenna must have a conductor with a horizontal orientation and another with a vertical orientation

(i) By referring to physical behaviour of waves, describe why it would generally be an issue if a frequency of radio wave had more than a single channel broadcast on it. (3 marks)

- Waves can interfere, resulting in a distorted signal.
-
- A single freq. per antenna results in the clearest single.

(ii) Explain how two channels of a satellite television network can be on the same frequency without the issue of part (i) being a concern. (3 marks)

- By polarising the emitted EMR on orientations 90° to each other, ~~on~~ minimal interference will occur.
- Horizontal...
- Vertical...

Question 19 **(14 marks)**

The Large Hadron Collider is the largest synchrotron in the world, with a total circumference of 26.7 km. While capable of accelerating protons up to 6.50 TeV, first operations in 2013 were run at the relatively lower 3.50 TeV. The Large Hadron Collider has multiple stages of particle accelerators, starting with a simple linear accelerator and eventually confining the proton beam in the main ring. Very powerful, expensive magnets, powered and cooled to near absolute zero are required to confine the beam.

(a) Describe how a magnetic field can help keep protons confined within the ring of a synchrotron. (3 marks)

- Charged particles moving through magnetic fields experience a force.
- If the motion of the particles is perpendicu to the mag. field direction, the direction of the force will be perpendicular to both the field and particle's velocity.
- The force causes a deflection resulting in circular motion.

(b) Explain why the protons in the Large Hadron Collider must first be accelerated in a straight line, with a linear accelerator, rather than starting in a ring like in the synchrotron. (2 marks)

- In order to travel in the synchrotron the protons need a velocity.
- The electric fields in the LINAC increase the velocity of the protons, (which mag. fields can't do).

(c) What percentage of the energy of the proton beam used in 2013 is due to the rest mass of the proton? (3 marks)

$E_{rest} = mc^2 = 1.67 \times 10^{-27} \times (3.00 \times 10^{8})^2 = 1.503... \times 10^{-10}$ J

$E_{2013} = 3.50$ TeV $= 3.50 \times 10^{12} \times 1.60 \times 10^{-19}$

$= 5.60 \times 10^{-7}$ J

$\% = \frac{1.503 \times 10^{-10}}{5.6 \times 10^{-7}} \times \frac{100}{1} = 0.0268\%$

(d) Explain a benefit of making the confinement ring so large. (3 marks)

The radius of travel is given by: $r = \frac{mv}{Bq}$

For any given proton energy, m, v and q are constants

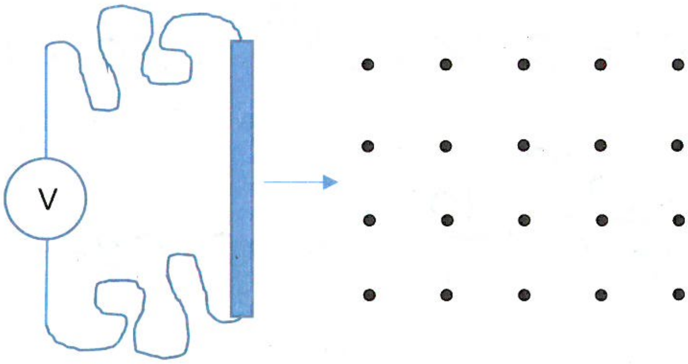
Using large rings (ie lge r) means B, which are provided by expensive, power hungry electro-magnets, can be lower.

(e) Describe how the Large Hadron Collider is used to make new scientific discoveries. (3 marks)

- The LHC collides fast (ie high energy) particles together.
- The combined energy of these collisions is very large.
- This high energy is converted into mass via $E = mc^2$ (ie $m = E/c^2$) allowing new particles to be created.

Question 20 **(18 marks)**

A pair of students entering a STEM competition proposed a method of determining the magnetic flux density of a uniform magnetic field. The students took a 30.0 cm long, straight conductor and attached either end to a voltmeter. The conductor was pushed into a uniform field while the voltmeter remained in place.



(a) Explain why a voltage is measured as the conductor moves through the field. (2 marks)

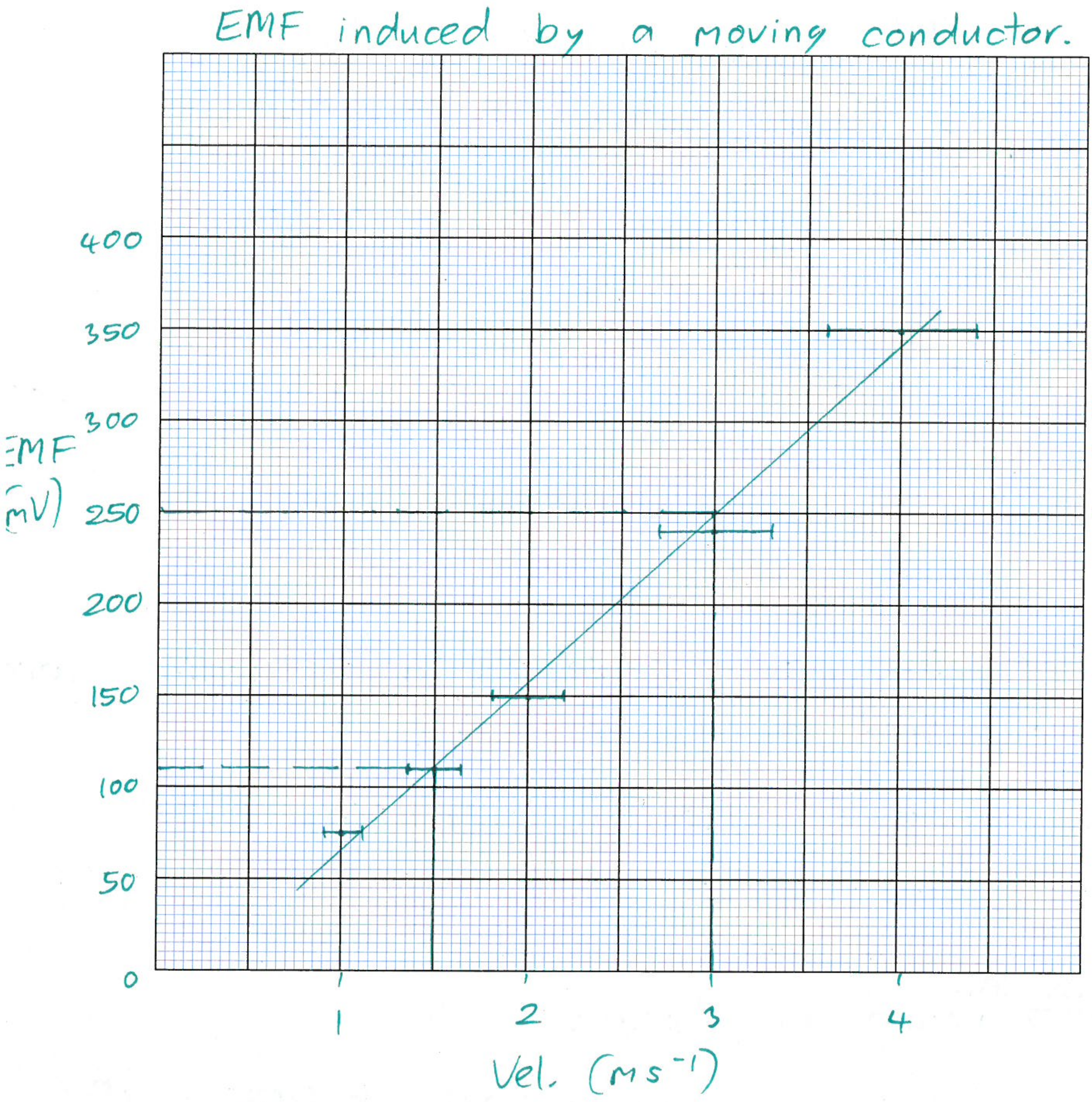
- The conductor cuts through flux lines (or the loop area in the field increases)
- This induces an EMF (Faraday's Law) (or the charges on the conductor experience a force).

The velocity of the conductor was carefully controlled just prior to the conductor entering the field and the accompanying voltmeter reading was recorded over multiple trials. The students estimated their velocity measurements had a ±10% uncertainty while the voltage measurements had negligible uncertainty.

Velocity (m s^{-1})	Velocity Uncertainty (m s^{-1})	Voltage (mV)
1.00	± 0.100	75
1.50	± 0.150	110
2.00	± 0.200	150
3.00	± 0.300	240
4.00	± 0.400	350

(b) Complete the table by adding the absolute uncertainty of the velocity measurements. (2 marks)

(c) Produce a graph, using the grid provided on the next page, to show the relationship between the voltage and the velocity. The velocity needs to be placed on the horizontal axis. Include error bars and a line of best fit. (5 marks)



- 1 for
· Title
· no LOBF
· Error bars
· axes wrong way
· scales

(d) Calculate the gradient of the line of best fit. (2 marks)

$m = \frac{rise}{run} = \frac{(0.250 - 0.110)}{(3-1)} = \frac{0.14}{2} = 0.07$

-1 for
· not shown on graph.
· didn't convert to V.

Depends on LOBF ←

Answer: 0.070 T m

(1 or 2 sf)

(e) Using the gradient and any other necessary data, calculate the magnetic flux density of the uniform field. (2 marks)

$m = \frac{EMF}{v}$ and $EMF = vBl$

$\therefore m = Bl$

so $B = \frac{Grad.}{l} = \frac{0.07}{0.3} = 0.23$

Answer: 0.23 T (1 or 2 SF)

(f) The students found that the voltage reading decreased the longer the bar was moving through the field – so the students recorded the voltage when the conductor was in the middle of the uniform field.

(i) In addition to air resistance and friction, explain the other cause of the change in the voltage reading. (2 marks)

- The moving bar experiences a retarding forc as explained by Lenz's Law.
- This decreases velocity, reducing EMF induced (ie $EMF = vBl$).

(ii) If the students had instead taken the voltage measurement soon after the conductor entered the field, how would their determination of the flux density differ from the result calculated part (e)? Justify your response. (3 marks)

- ~~EMF~~ Flux den. would be larger.
- Larger v ⇒ larger EMF (ie $EMF = vBl$) as B and l are constant.
- This result in a steeper gradient of the plotted points / LOBF ⇒ larger B.

End of Section 2

This page has been left blank intentionally

Section Three: Comprehension 20% (36 Marks)

This section contains **two (2)** questions. You must answer both questions. Write your answers in the spaces provided. Suggested working time for this section is 40 minutes.

Question 21 (18 marks)

The Universe Has A Speed Limit, And It Isn't The Speed Of Light

When it comes to speed limits, the ultimate one set by the laws of physics themselves is the speed of light. Moreover, anything that's made of matter can only approach, but never reach, the speed of light. If you don't have mass, you must move at the speed of light; if you do have mass, you can never reach it. But practically, in our Universe, there's an even more restrictive speed limit for matter, and it's lower than the speed of light. Here's the scientific story of the real cosmic speed limit.

When scientists talk about the speed of light—299,792,458 m/s—we implicitly mean "the speed of light in a vacuum." Only in the absence of particles, fields, or a medium to travel through can we achieve this ultimate cosmic speed. Even at that, it's only the truly massless particles and waves that can achieve this speed. This includes photons, gluons, and gravitational waves, but not anything else we know of. But there's no such thing, practically, as a perfect vacuum. Even in the deepest abyss of intergalactic space, there are three things you absolutely cannot get rid of.

1. The WHIM: the warm-hot intergalactic medium. This tenuous, sparse plasma are the leftovers from the cosmic web. While some matter clumps into stars and galaxies, other matter remains in the great voids of the Universe. Starlight ionizes these atoms, creating a plasma that may make up about 50% of the total normal matter in the Universe.

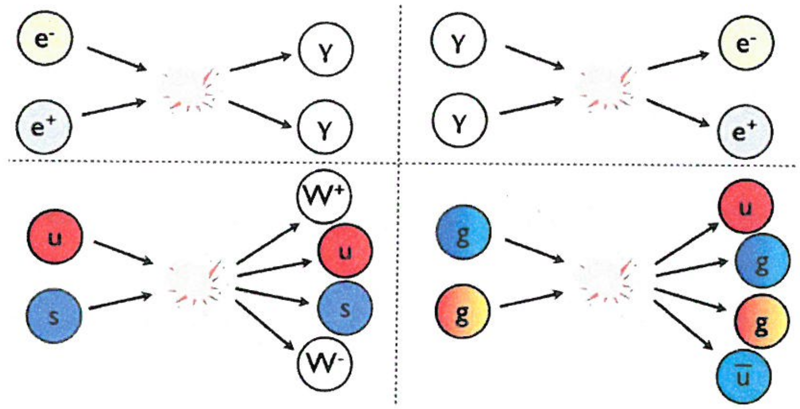
2. The CMB: the cosmic microwave background. This leftover bath of photons originates from the Big Bang, where it was at extremely high energies. Even today, at temperatures just 2.7 degrees above absolute zero, there are over 400 CMB photons per cubic centimetre of space.

3. The CNB: the cosmic neutrino background. The Big Bang, in addition to photons, creates a bath of neutrinos. Outnumbering protons by perhaps a billion to one, many of these now-slow-moving particles fall into galaxies and clusters, but many remain in intergalactic space as well.

Any particle traveling through the Universe will encounter. No matter how high the energy is of a particle, it has to pass through particles from the WHIM, neutrinos from the CNB, and photons from the CMB

The Large Hadron Collider accelerates particles here on Earth up to a maximum velocity of 299,792,455 m/s, or 99.999999% the speed of light. The highest-energy cosmic rays have approximately 36 million times the energy of the fastest protons ever created at the Large Hadron Collider. Assuming that these cosmic rays are also made of protons gives a speed of 299,792,457.99999999999992 m/s, which is extremely close to, but still below, the speed of light in a vacuum. There's a very good reason that, by time we receive them, these cosmic rays aren't more energetic than this.

If there is a particle with energies in excess of 5.00×10^{19} eV, they can only travel a few million light years—max—before a photon from the CMB, interacts with it. When that interaction occurs, there will be enough energy to produce a neutral pion, which steals energy away from the original particle, following from $E = mc^2$.



The more energetic your particle is, the more likely you are to produce pions, which you'll continue to do until you fall below this theoretical cosmic energy limit of 5.00×10^{19} eV, known as the GZK cutoff.

We believe that every charged particle in the cosmos—every cosmic ray, every proton, every atomic nucleus—should be limited by this speed. Not just the speed of light, but a little bit lower, thanks to the leftover glow from the Big Bang and the particles in the intergalactic medium. If we see anything that's at a higher energy, then it either means:

1. particles at high energies might be playing by different rules than the ones we presently think they do,
2. they are being produced much closer than we think they are: within our own Local Group or Milky Way, rather than these distant, extragalactic black holes,
3. or they're not protons at all, but composite nuclei.

The few particles we've seen that break the GZK barrier are indeed in excess of 5×10^{19} eV, in terms of energy, but do not exceed 3×10^{21} eV, which would be the corresponding energy value for an iron nucleus. Since many of the highest-energy cosmic rays have been confirmed to be heavy nuclei, rather than individual protons, this reigns as the most likely explanation for the extreme ultra-high-energy cosmic rays.

There is a speed limit to the particles that travel through the Universe, and it isn't the speed of light. Instead, it's a value that's very slightly lower, dictated by the amount of energy in the leftover glow from the Big Bang. As the Universe continues to expand and cool, that speed limit will slowly rise over cosmic timescales, getting ever-closer to the speed of light. But remember, as you travel through the Universe, if you go too fast, even the radiation left over from the Big Bang can fry you. So long as you're made of matter, there's a cosmic speed limit that you simply cannot overcome.

(a) Name three things in the Universe that can move at the cosmic speed limit and describe the requirements to reach the cosmic speed limit. (3 marks)

- Photons, gluons and gravity waves
- Must be massless
- Move at the cosmic speed limit but only in the absence of fields, particles or a medium.

(b) A neutral pion has a rest mass of 135 MeV/c^2. Calculate the minimum number of neutral pions that need to be produced by a 5.03×10^{19} eV particle to reduce to the cosmic energy limit. (3 marks)

- Rest E of pio = 135 MeV = 1.35×10^8 eV
- Cosmic $E_{limit} = 5.0 \times 10^{19}$ ∴ E to be lost

$= (5.03 \times 10^{19}) - (5.00 \times 10^{19}) = 3.00 \times 10^{17}$ e

- no of pions $= \dfrac{(3.00 \times 10^{17})}{(1.35 \times 10^8)} = 2.22 \times 10^9$ pions

(c) The article compares the Large Hadron Collider and cosmic rays. Protons in the Large Hadron Collider are accelerated up to 6.50 TeV. What is the energy of the most energetic cosmic rays in eV? (2 marks)

- Most En. CR have 36 million times the energy, so
- $E = 6.50 \times 10^{12} \times 36 \times 10^6$

$= 2.34 \times 10^{20}$ eV

Answer: 2.34×10^{20} eV

(d) Calculate the average frequency of a photon from the CMB (3 marks)

?

Answer: ____________________ Hz

(e) Explain why the interaction of a very energetic particle with a photon can cause the particle to slow down. (3 marks)

- Photons interacting with high energy particles can create a new particle.
- These particles require energy ($E = mc^2$)
- This energy comes from the high energy particle, slowing it down. as its KE is lowered.

(f) Describe which of the three reasons given in the article is the most likely cause when we have detected particles more energetic than the GZK barrier. (3 marks)

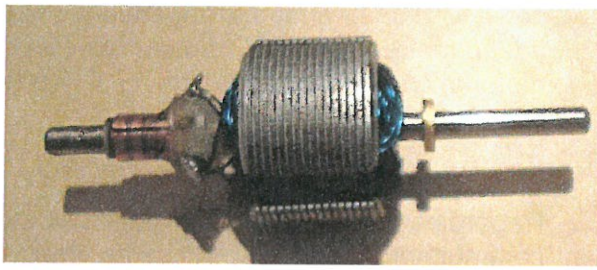
- no 3 – composite nuclei
- Their energies have never exceeded that of an iron nucleus
- High energy cosmic rays have previously been confirmed to be composite nuclei.

Question 22 **(18 marks)**

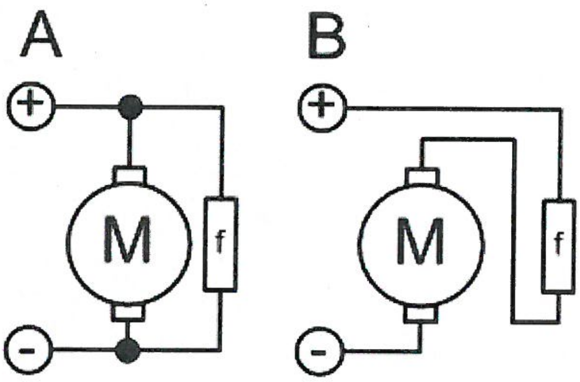
Brushed and Brushless DC Electric Motors

In this course you were introduced to the DC electric motor. An emf source drives a current through an armature coil, in the presence of a magnetic field, which produces a torque. Brushes and a commutator are used to ensure the direction of rotation is maintained. The motor then produces mechanical energy which is transferred to a load (the thing that we want to spin). This motor design was first used over 100 years ago but there are now many variations of motors, each with their own advantages and disadvantages.

The motor you are most familiar with from this course is referred to as a brushed DC motor. It is powered by a DC emf source and, as mentioned before, requires brushes and a commutator to operate. These motors are still used today. The smallest examples are found in toy cars and battery-operated fans. Being so small, a permanent magnet suffices to create the magnetic field required.



Larger brushed DC motors are used in printing presses. The size of these motors makes using a permanent magnet impractical. An electromagnet is used to produce the magnetic field, which can be powered by the same emf source that drives the current through the armature coil. These electromagnets are referred to as field coils – as in the coils in a motor responsible for producing the magnetic field. There are two methods by which the emf source can be connected to both the armature coils and field coils. Diagram A below is for a shunt wound DC motor and Diagram B is a series wound DC motor.

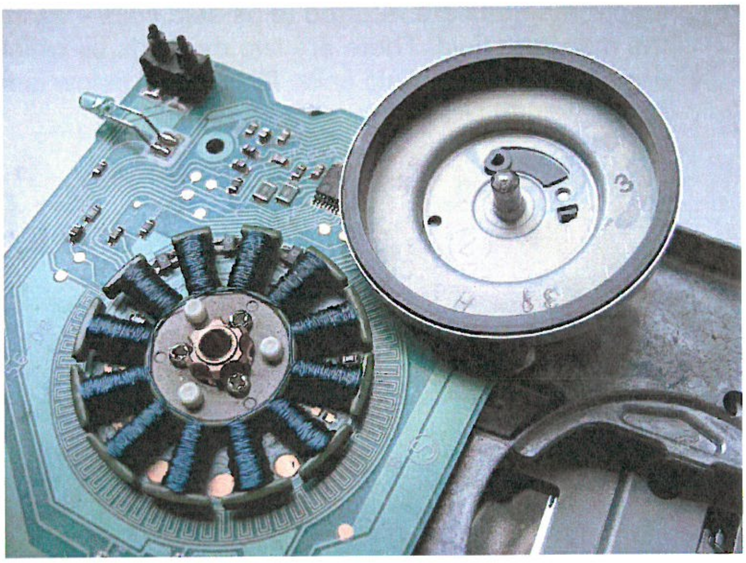


A: Shunt wound
B: Series wound
M is the armature coil, f is the field coil

A shunt wound design has the field coils in parallel with the armature coils. Both coils receive the same voltage from the emf source. When electric voltage is supplied to the shunt DC motor, due to high resistance of the shunt winding, it draws very low current. The higher number of turns of the field coil helps in generating a strong magnetic field. The armature draws a high current, thus needs thicker wires. A shunt DC motor is naturally excellent at controlling its speed. As the armature coil rotates, it generates a back emf which limits the current in the armature which also limits the torque at high speeds. When a load is attached, this reduces the rotational speed of the motor initially, but this also reduces the back emf which results in more torque that speeds the motor back up. To change the operating speed of the motor, a rheostat (variable resistor) is placed in the field coil branch - increasing the resistance here results in a decrease in field strength which speeds the motor up.

A series wound DC motor has the field coils in series with the armature coils. At all times the current in both coils will be the same. As the current is the same in both armature and field coils, and the field in a coil is proportional to the current, the torque produced is proportional to the square of the current. When first started the current through the coils is limited only by the internal resistance of the wires. So the field coils are very thick but are few in number. This can produce very large starting torques but often puts the wires at risk of overheating. An additional resistor is added during motor startup which is gradually removed as the motor picks up speed. When a load is added this slows down the motor. This reduces the back emf from the armature, resulting in a larger current. Since this current also flows through the field coils, there is an increase in magnetic flux which actually increases the back emf – so overall the net effect is that the motor will slow down whenever a load is added to it. Having large initial torque and dropping in speed as a load is added makes series DC motors ideal as starter motors, like those used in cars. A petrol-based motor in a car cannot start itself – it needs to be given a "push" by a starter motor to get things going.

Regardless whether shunt or series, when both motors are designed with brushes and commutators they suffer the same disadvantage – the relatively high wear and tear of these components. There was no avoiding this until the 1970s when semiconductor technology was developed. In a brushless DC motor, there are no brushes to achieve the necessary reversal of current/magnetic field. Electrical transistors (the semiconductor technology) perform the reversal instead.



In a brushed motor the rotor (rotating part) is the armature coil and the stator (stationary part) is the permanent magnet or field coils. A brushless motor reverses these roles. The armature coils remain stationary in the centre while a permanent magnet rotates around the outside. This reduces the inconvenience of designing a method to drive a current through a rotating armature without tangling the wires.

As the rotor rotates it triggers the transistor switches which rapidly change the direction of the current in the armature windings. Maximum speed is still reached when the back emf of the armature equals the supplied emf but speed can easily be controlled by adjusting the supplied voltage. This motor is also quieter than the brushed types because most of the noise of a motor comes from the rotation and grinding of the commutator against the brushes.

(a) State the defining components of a DC brushed motor and one place where these motors are used. (2 marks)

- Commutator and brushes
- Toys cars / fans / Printing Presses

(b) State the name of the conductor windings used as an electromagnet in a large motor. (1 mark)

Field coils

(c) Compare the difference in the construction of a shunt wound motor and a series wound motor. (2 marks)

- Shunt – field coils is connected in parallel to the armature.
- Series – field coils and armature are connected in series.

(d) Explain why the components in a brushed motor have high wear and tear. (2 marks)

- There is high rotation between the brushes and the commutator.
- This results in large frictional forces that wear these components away.

(e) Explain, referring to physical principles, why increasing the resistance in the field coils of a shunt wound motor results in:

(i) A decrease in the magnetic field strength. (2 marks)

- Increasing resistance results in lower current. (Ohm's Law)
- Lower current results in lower field strength ($B \propto I$)

(ii) An increase in the speed of the motor. (3 marks)

- Smaller field means less back EMF generated
- Smaller back EMF ⇒ higher net current in armature
- Larger net current ⇒ increase in motor speed.

(f) By referring to formulae in the Formulae and Data Booklet and physical principles, show why torque of a series wound motor is proportional to the square of the current supplied, as suggested by the article. (Note: you are **not** required to derive a new formula) (3 marks)

- Current and Mag. Field strength is proportional (ie $B \propto I$)
- Current in the armature creating a force propotional to the field and current (ie $F \propto B \times I$)
- ∴ τ is proportional to the square of the current. $\tau \propto F \propto BI \propto I^2$)

(g) Describe how a brushless motor overcomes the biggest disadvantage shared by all brushed motors. (3 marks)

- No high friction ~~betw~~ contact between components.
- Uses transistors to reverse current instead of commutator / brushes.
- ∴ Less wearing of components.

End of Questions

Additional working space

Additional working space

Spare grid for graph

End of examination

Acknowledgements

Question 16
Trebuchet Diagram
CC0 Public Domain
https://openclipart.org/detail/48559/trebuchet

Castle Diagram
CC0 Public Domain
https://openclipart.org/detail/24916/castle

Question 20
The Universe Has A Speed Limit, And It Isn't The Speed Of Light,
https://medium.com/starts-with-a-bang/the-universe-has-a-speed-limit-and-it-isnt-the-speed-of-light-543b7523b54f
Used with permission from Ethan Siegel

Question 21
Small DC motor image
User Jfer91
CC BY SA 3.0
https://en.wikipedia.org/wiki/Brushed_DC_electric_motor#/media/File:Motor_internals.JPG

Question 21
Field and motor windings image
User Haade
CC BY SA 3.0
https://en.wikipedia.org/wiki/Brushed_DC_electric_motor#/media/File:Serie_Shunt_Coumpound.png

Question 21
Brushless motor
User Sebastian Koppehel
CC BY SA 3.0
https://en.wikipedia.org/wiki/Brushless_DC_electric_motor#/media/File:Floppy_drive_spindle_motor_open.jpg