AWARENESS-CUM-TRAINING PROGRAMME

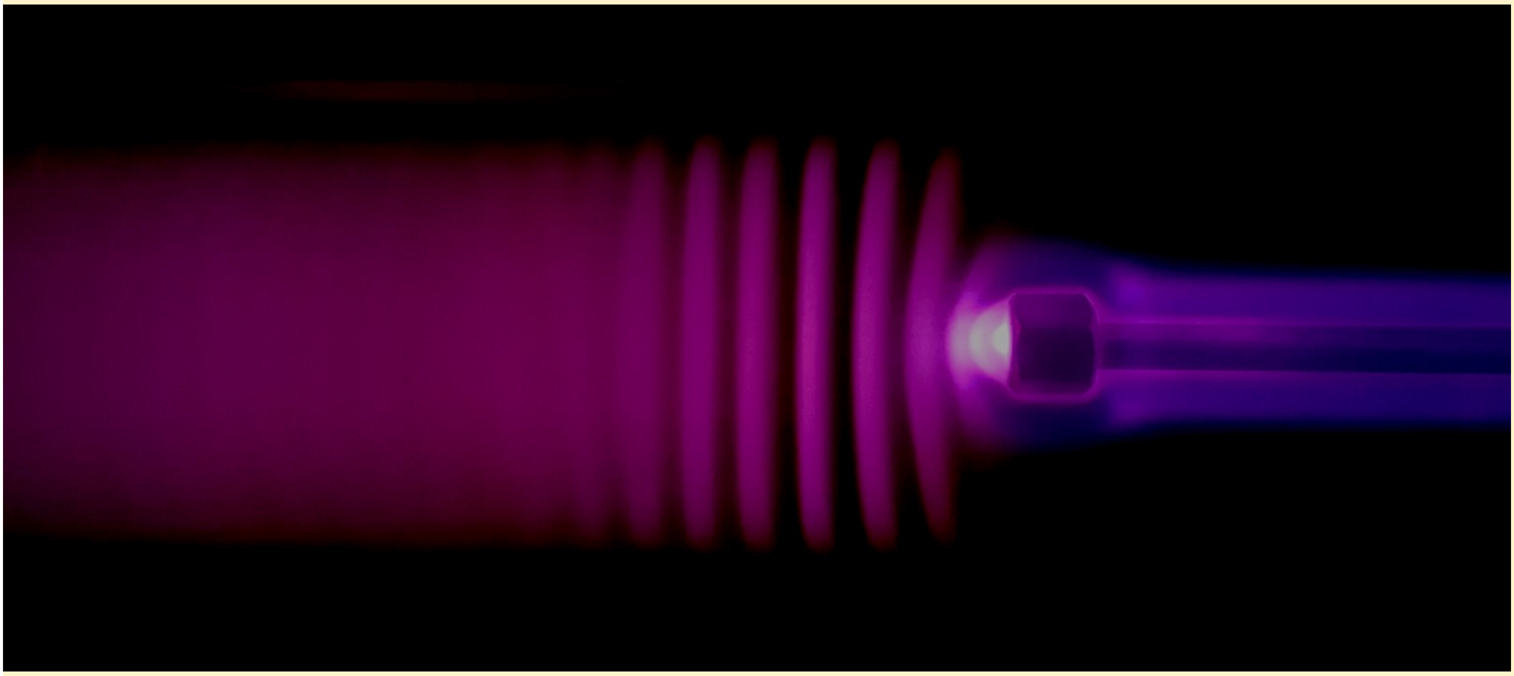
ON

PLASMA SCIENCE & TECHNOLOGY

AND

ENERGY FROM NUCLEAR FUSION

Science Activity Kit



Information Booklet

राविप्रौसंप NCSTC

A Joint Initiative of the Institute for Plasma Research, Gandhinagar
&
The National Council for Science and Technology Communication, DST, New Delhi

Plasma Kit Activities Detailed Document

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1 : Plasmas in Nature

Soon after the universe began in a Big Bang, it was dominated by plasma at high temperature. Plasma continues even today to comprise more than 99 percent of our visible universe! In the beginning there was plasma and that is where we all came from!

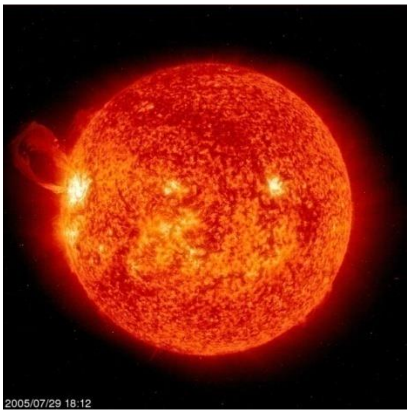
When plasma cooled after the big bang, it formed a gas. On further cooling gas turned to liquid and then to solid. As matter cools, it reaches temperatures at which the atoms and molecules bind together, condensing to form the next state of matter in the cooling sequence. Plasma remains the most prevalent form of matter in the universe! Nearly all the visible matter in the universe exists in the plasma state, occurring predominantly in this form in the Sun and stars and in interplanetary and interstellar space.

Do we find plasmas on the Earth? Lightning and auroras (Northern lights) are plasmas. Plasmas exist in the flame of a candle, in the crystal structure of metallic solids; and in many other phenomena and objects. The Earth itself is immersed in a tenuous plasma called the solar wind, and is surrounded by a dense plasma called the ionosphere.

(Source: wikigag.com)

(Source: images.nationalgeographic.com)

Lightning and Aurora Borealis



The Sun and stars that shine continuously have virtually all the matter existing in the plasma state (Source: www.universesimplified.com)

The Sun and stars that shine continuously have virtually all the matter existing in the plasma state. Since the Sun and stars shine continuously, virtually all the matter becomes ionized in such cases, and the plasma is said to be fully ionized. This need not be the case, however, for a plasma may be only partially ionized. In space the dominant plasma formation process is photo-ionisation, wherein photons from sunlight or starlight are absorbed by an existing gas, causing electrons to be emitted. A completely ionized hydrogen plasma, consisting solely of electrons and protons (hydrogen nuclei), is the most elementary plasma.

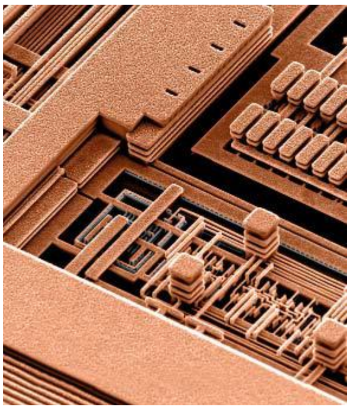
2 : Plasmas in Everyday Life

Both day and night, most of the light we work by is due to fluorescent lamps, say, either tube lights or CFLs. Today, plasma displays have become a part of our lives. We see plasma displays on store signs and in ads promoting large-screen, flat-panel plasma television sets. The flat plasma display is a major flat panel display technology today in High Definition (HD) TV market.

Panasonic’s 145 inch plasma TV
(Source: Panasonic Corporation)

Plasma Signage
(Source: news.slacs.stanford.edu)

Almost all electrical devices rely on electronic chips. Not just our computers, but our cars, our microwave ovens, our alarm clocks - all these gadgets have chips inside. And none of these chips could be manufactured without using plasma. That is because plasma technology is capable of forming transistors and wires that are much smaller than the width of a single hair. Without plasma, the transistors would have to be made much bigger, making the chips more expensive, slower, and much less powerful.

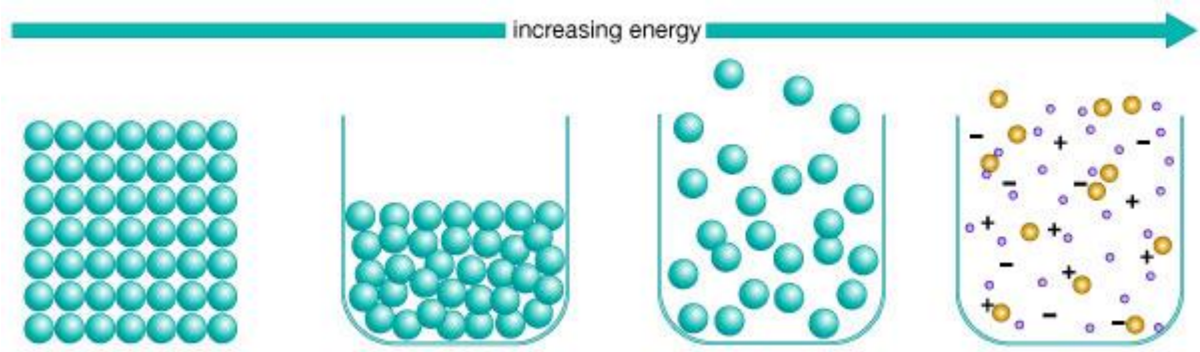


In this microscope photo of the wiring on a chip the smallest wires are more than 100 times thinner than a single hair
(Source: Computer Chips and Plasma, www.plasmacoalition.org)

Cars, bridges, ships, jet engines, pipelines, hot-water systems, the metal framework of buildings, - in fact most manufactured goods depend on thousands of metal-to-metal joints. Many of those joints are welded using plasmas.

3 : The States of Matter

We are familiar with three states of matter as taught in the school: solid, liquid and gas. Adding heat leads to breaking of bonds between molecules and a substance changes from one state to the next, say from solid to liquid and from liquid to gas. For example, adding heat changes ice to water; and adding heat to water changes it to vapour, that is, gas. What happens when we further add heat to a gas? Adding heat energy to gas breaks the internal bonds of the individual atoms, and in the process the atoms lose some electrons and get ionised, and electrons are freed. When this happens to a significant number of atoms, the resulting collection of electrically charged particles forms an ionized gas called plasma.



The States of Matter (Picture Source: *Encyclopaedia Britannica*)

Solid: Molecules in a solid are arranged in regular repeating patterns. They are held in place firmly and can vibrate in a limited area about their mean positions.

Liquid: Molecules in a liquid flow easily around one another. However, they do not fly apart due to attractive forces between them. Liquids assume the shape of their containers.

Gas: Molecules fly in all directions in a gas at great speeds. Being very far apart from each other, attractive forces between them are insignificant.

Plasma: At the very high temperatures of stars, atoms lose their electrons. The mixture of electrons and nuclei is the plasma state of the matter.

Activity :

1. You will need about 50 glass / plastic beads (of the size of a marble) available from a craft shop; and much smaller glass / plastic beads. Using a very small quantity of glue - just a very, very small drop - stick each small bead to the larger bead. Both should loosely stick to each other. The larger bead represents the ion, while the smaller bead represents the electron attached to it. Both together represent a neutral molecule.
2. Fill up a transparent plastic box with the 'molecules'. When kept stationary, it represents the solid state of matter.
3. Now turn the box gently holding it in both the hands. The 'molecules' move easily around each other as if in a liquid, representing the liquid state.
4. If you shake the box gently, the 'molecules' appear to fly in all the directions, but the electrons do not get separate, as if in a gas.
5. Now, if you shake the box vigorously, the 'electrons' separate from the neutral 'molecules' forming a mixture of 'ions' and 'electrons' as if in a plasma state.

Remember, more vigorously you shake the box, faster the molecules move and hence higher the temperature of the system. Thus, change of phase from solid to liquid, liquid to gas, and gas to plasma state needs application of heat energy at each stage.

4 : Plasma Globe (Demonstration)

The illustration shows a plasma globe, with filaments extending from the inner electrode to the outer glass insulator giving the appearance of multiple beams of coloured light. The globe is a clear glass sphere filled with a mixture of noble gases like neon, argon and xenon to a pressure of about one atmosphere, with a high voltage electrode in the centre of the sphere. When the radio-frequency power is turned on, the whole globe will glow a diffuse red if it is filled only with neon. If a little argon is added, the filaments will form. If a very little xenon is added, the “flowers” bloom at the end of the filaments. When we touch the globe while it is on, a colourful strand of light is drawn to the finger. This occurs because a discharge path with less resistance than the surrounding glass or gases is created.

5 : Discharge of Electricity through Gases

Electric discharge in gases occurs when electric current flows through a gaseous medium due to ionization of the gas. Depending on several factors, the discharge may radiate visible light. If the supply of electrical charge is continuous, the discharge is permanent, but otherwise it is temporary. Usually, the medium is a gas, often the atmosphere, and the potential difference could be from a few hundred volts to millions of volts. The transfer of matter between the two points is necessary, since only matter can carry electric charge. This matter is usually electrons. Where both electrons and ions are available, however, the electrons carry the majority of the current. Ions can be positively or negatively charged, but usually positively.

Electrical discharges have been studied since the middle of the 19th century. The laboratory discharges in partially evacuated tubes are very familiar, but there are also electrical discharges in nature, lightning being the primary example. There are also the aurora borealis and Aurora Australis, sparks from walking on a rug in dry weather and rubbing fur, and similar phenomena, many resulting from the high potentials of static electricity. Technology offers a wealth of examples, such as arc welding, fluorescent lights, neon advertising signs, neon and argon glow lamps, mercury and sodium lamps, and several other devices. In this activity, we shall consider two examples of plasma discharges that you can produce.

Activity : A gas lighter produces a plasma discharge

To produce a gas discharge, you will need a gas lighter used in your kitchen to light the cooking gas coming out of the burner of the stove. When you press the button of the lighter, you will observe a spark in a narrow region. This is plasma. If your fingers are close to this region, you could even get a shock! The gas lighter is mostly cylindrical in shape and consists of a piezo-electric crystal over which a spring-loaded hammer is placed. The hammer and spring set up is attached to a button. When this button is pressed, the hammer is moved away from the piezo-electric crystal. When the button is pressed over a particular limit, the spring releases the hammer. The hammer then hits the piezo-electric crystal. Due to piezo-electric effect, a high voltage is generated in the range of 800 volts. The lighter is wired in such a way that this whole voltage is applied in a small region of air gap between two metallic points. Due to high voltage generated, the air is ionized and becomes plasma acting as a path for the discharge, and you see a spark flying between these two points. This electric discharge is the spark which when exposed to the combustible gas from the stove ignites it to produce flame.

Gas Lighter

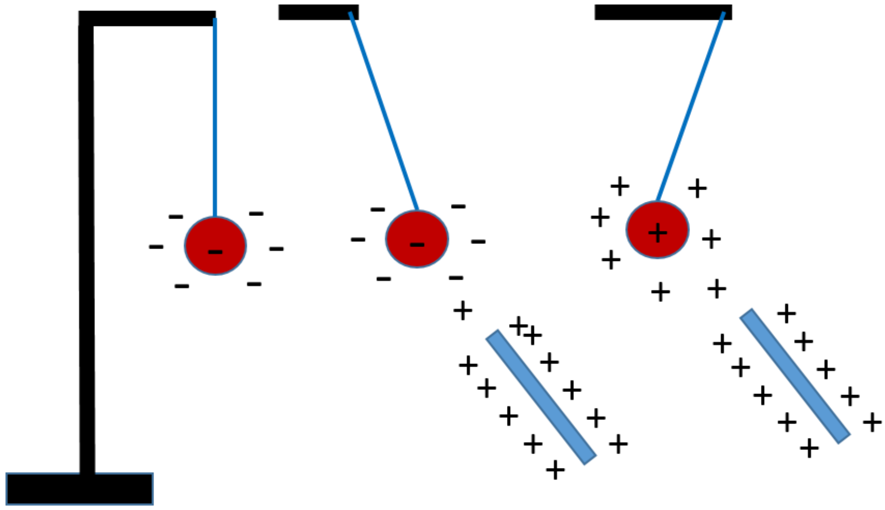
Activity : Comb your hair and produce plasma discharge!

If the air is quite dry, and if your hair also is completely dry, you may stand in a dark room in front of a mirror and move a dry plastic comb through your hair. You would not only observe sparks flying, but also hear crackling sounds along with the sparks! Friction between comb and hair generates a potential difference high enough to ionize the air between them and producing a plasma that provides a path for discharge of electrical charges! This is how you see sparks! Of course, in monsoon this activity will not work! Why?

6 : A Simple Electroscope

That some bodies would experience a force of attraction after they are rubbed together was known for centuries. In 18th century it was discovered that there are two types of charges called positive and negative which separated when appropriate bodies are rubbed against each other, and that like charges repel each other and unlike charges attract each other. You can observe this effect using a simple electroscope that you can assemble using a Styrofoam ball coated with aluminium given in the kit.

Activity : Electrostatic force



Attach the ball to a silk thread about 15 cm in length using a needle and tying a knot. Set up the L-shaped plastic stand given in the kit vertically. Hang the ball from the hook like a pendulum. Rub a glass rod (not given in the kit!) with a piece of silk and bring the rod near the Styrofoam ball. Observe that the ball is first attracted and then repelled. In this case, when the glass rod is rubbed with silk it gets positively charged. When the charged rod is brought near the Styrofoam ball it attracts the ball, but the moment it touches the ball, part of its positive charge is transferred to the ball. Since like charges repel, the positively charged rod now repels the positively charged ball. If you take the glass rod away and again bring it near the ball after rubbing with silk, the ball would be repelled.

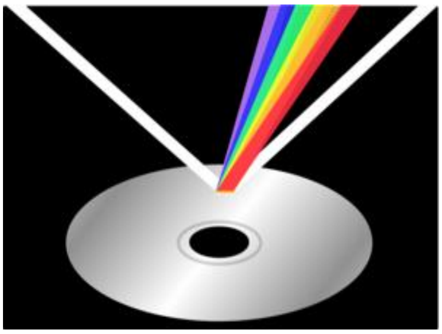
In a similar manner, rub a plastic comb with a piece of wool and bring the comb near the uncharged ball. The ball is first attracted to the comb and then repelled. In this case, the comb gets negatively charged and part of its negative charge is transferred to the ball on touching. If you bring the comb that has been rubbed with wool, close to the charged ball, it gets repelled.

However, if you bring a negatively charged comb near the positively charged ball, the ball is attracted to the comb. Likewise, if you bring a positively charged glass rod near the negatively charged ball, the ball gets attracted.

The nature of electricity remained a mystery until 1897 when J. J. Thomson discovered negative electricity in subatomic particles which were later called electrons. Positive electricity was later found to reside in heavier particles called protons in the atomic nucleus. Electric currents were shown to be flows of electrons. In our experiment, a positively charged body implies a deficiency of electrons (that is, a body consisting of atoms with some electrons stripped), and a negatively charged body implies an excess of electrons (that is, a body consisting of atoms with some extra electrons). In either case, when you bring a positively charged glass rod or the negatively charged comb close to the uncharged Styrofoam ball, it first gets attracted; and only on touching it gets repelled! Can you explain why?

7 : The CD Spectroscope: Observing Spectra with a CD

Composition of the Sun and stars can be studied by observing their spectra. Likewise, optical spectroscopy is one of the fundamental diagnostic tools to study characteristics of laboratory plasma, or plasma in a fusion reactor. This is because spectroscopic measurements allow determination of the plasma composition and also the information about temperature and energy distribution. Each element emits its own set of lines of characteristic wavelengths. The two yellow lines of at 5890 Å and 5896 Å are the famous D lines due to the element sodium (Å stands for the unit Ångstrom, 1 Å = 10^{-10} metres). The other lines originate due to other elements. Molecules too emit their own characteristic spectra.



A Compact Disc dispersing white light into colours (source Wikimedia, nakedscientist.com

You can see the spectral lines emitted by different elements with the given CD that acts as a spectroscope. The CD acts as a crude diffraction grating that scatters the light of different frequencies at different angles. To see the spectrum of mercury, hold the given CD in your front, with a tube light about 10 metres behind you. Now tilt the CD slightly. You will see bright bands. If the tube light is at a greater distance, the bands will become narrower, and appear like (curved) lines. The bright lines you see are the spectral lines of mercury, while the continuous spectrum is due to the phosphors coated on the inside of the tube. These phosphors convert the ultraviolet emissions from mercury atoms into visible light. Repeat the experiment at night in street light, say, mercury, neon or sodium lights about 100 metres behind you. Do you see a different spectrum in each case?

Similar spectra taken with better equipment will show spectrum of Sun showing dark lines called Fraunhofer lines. The lines emitted by various elements on the Sun are absorbed by the Sun's atmosphere (called corona), which is in the plasma state, and thus appear dark.

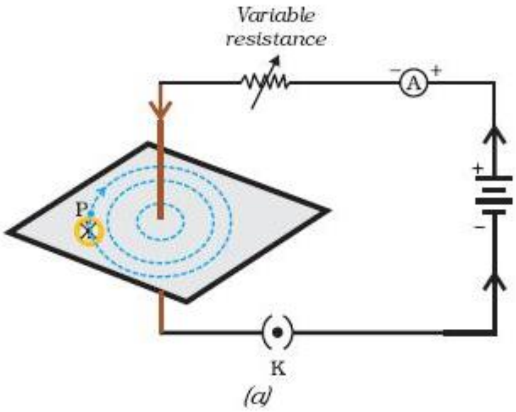
Do not directly look at the reflected image of the Sun from CD. The bright image of the Sun may damage your eyes.

8 (A) : Magnetic Field Associated with Electric Current

Activity: To show that a magnetic field is associated with an electric current

If you hold a compass near a wire through which current is flowing, the needle on the compass will be deflected. This implies that there must be a magnetic field near the wire through which the current is flowing. Take a battery (9-12 V), a variable resistance (a rheostat), an ammeter (0–5 A), a plug key, and a long straight thick copper wire. Insert the thick wire through the centre, normal to the plane of a rectangular cardboard. Take care that the cardboard is fixed and does not slide up or down. Connect the copper wire vertically as shown in Figure below, in series with the battery, a plug and key. Sprinkle some iron filings uniformly on the cardboard. You may use a salt sprinkler for this purpose. Keep the variable of the rheostat at a fixed position and note the current through the ammeter.

Close the key so that a current flows through the wire. Ensure that the copper wire remains vertically straight. Gently tap the cardboard a few times. Observe the pattern of the iron filings. You would find that the iron filings align themselves showing a pattern of concentric circles around the copper wire. What do these concentric circles represent? They represent the magnetic field lines. To find the direction of the magnetic field, place a compass at a point (say P) over a circle. Observe the direction of the needle. The direction of the north pole of the compass needle would give the direction of the field lines produced by the electric current through the straight wire at point P. Show the direction by an arrow. Observe that the direction of magnetic field lines gets reversed if the direction of current through the straight copper wire is reversed.



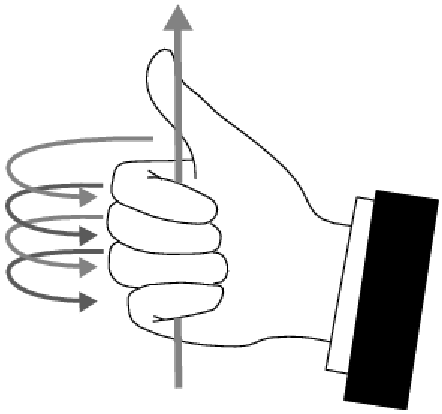
(a) A pattern of concentric circles indicating the field line of magnetic field around a straight conducting wire. The arrow in the circles show the direction of the field lines. (b) A close up of the pattern obtained.

What happens to the deflection of the compass needle placed at a given point if the current in the copper wire is changed? To see this, vary the current in the wire. We find that the deflection in the needle also changes. In fact, if the current is increased, the deflection also increases. It indicates that the magnitude of the magnetic field produced at a given point increases as the current through the wire increases. What happens to the deflection of the needle if the compass is moved from the copper wire but the current through the wire remains the same? To see this, now place the compass at a farther point from the conducting wire. You will find that the deflection in the needle decreases. Thus the magnetic field produced by a given current in the conductor decreases as the distance from it increases. From the Figure, it can be noticed that the concentric circles representing the magnetic field around a current-carrying straight wire become larger and larger as we move away from it.

Note: Even if you do not have a rheostat and an ammeter, still you can see the basic effect of the magnetic field due to a current carrying conductor.

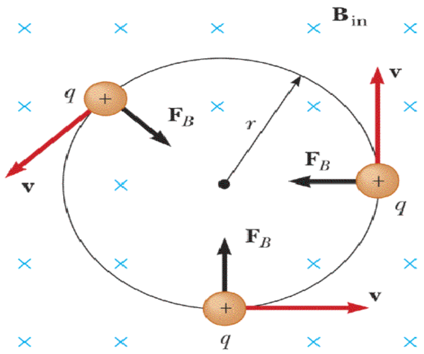
8 (B) : The Right Hand Rule

Activity: How to determine the direction of magnetic field of current flowing in a conductor



Magnetic field is associated with an electric current, and the direction of the magnetic field can be found with the help of a magnetic compass. But, there is a simple method of finding the relationship between the direction of the current flowing in a conductor and the direction of the magnetic field around the same conductor. The method is called *the Right Hand Rule*. The Right Hand Rule says that the magnetic field lines produced by a current-carrying wire will be oriented in the same direction as the curled fingers of a person's right hand, with the thumb pointing in the direction of the current flow. The circles are field lines and they also have a direction indicated by the arrows on the lines. Similar to the situation with electric field lines, the greater the number of lines (or the closer they are together) in an area the stronger the magnetic field.

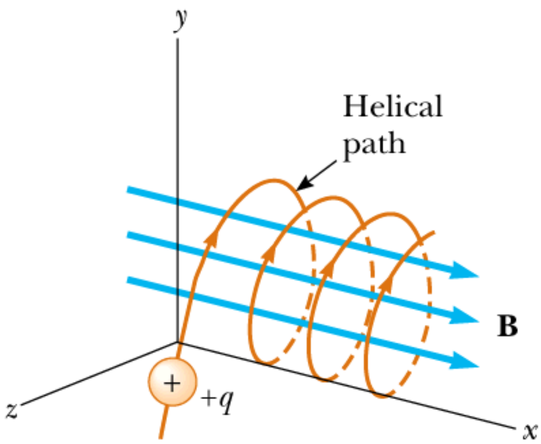
9 : Motion of charge in a uniform magnetic field



Consider a case of a positive charge moving in a uniform magnetic field. In the diagram, the direction of the magnetic field is into the paper ('x' denotes the backend of the arrow moving into the paper!). If a positive charge is fired, perpendicular to it, it will describe a uniform circular motion with the magnetic force described towards the centre of the circle. An electron would describe circular motion in the *opposite* direction.

Take a wire loop or a plastic bangle cut at one point, and pass a bead through it. Hold the loop with the bead horizontally. The magnetic field is upward. Now turn the bead in the anticlockwise direction in a uniform manner when looked from above. This is how a positive charge moves in a uniform magnetic field. If you turn the bead clockwise, the motion of the bead shows how an electron would move in a uniform magnetic field.

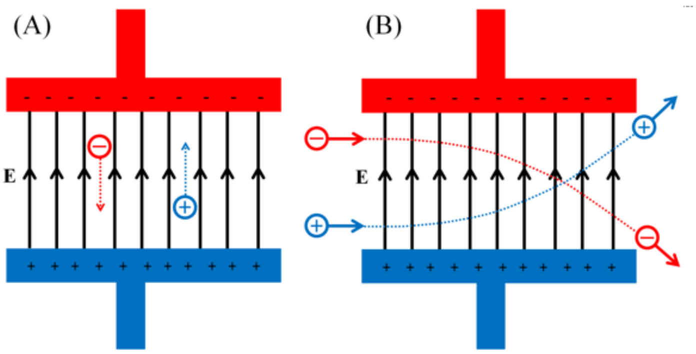
How if the electric charge has some initial velocity in the direction of the magnetic field? In this case, the charge would describe a helical motion along the magnetic field (See figure). An electron would describe helical motion in a direction opposite to the field.



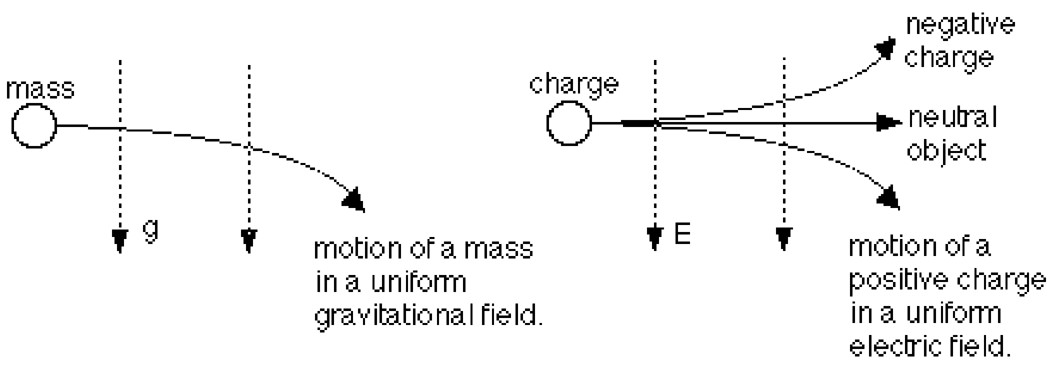
Take wire (or the soft spring) given in the kit and make it into a spiral. Ask your friend to pass a rod through the spiral and hold it firmly denoting the direction of magnetic field **B** as shown in the figure. Now pass a bead through the wire and slide it along the wire as shown in the figure. The bead denotes a positive charge that moves along a helical path in the direction of the magnetic field shown by **B**. Sliding the bead in the opposite direction would describe the motion of an electron.

10 : Motion of charge in a uniform electric field

Plasma is regarded as an electrically conducting medium in which there are roughly equal numbers of positively and negatively charged particles, produced when the atoms / molecules in a gas become ionized. The negative charge is usually carried by electrons, each of which has one unit of negative charge. The positive charge is carried by ions - atoms or molecules that are missing those same electrons. The plasma state is unique due to the importance of electric and magnetic forces that act on a plasma in addition to gravity. To illustrate how the motion of charges is influenced by electric and magnetic fields, we shall consider a few simple cases in this activity.



The direction of the electric field is in the direction of the arrow, which is upwards (shown in black). A positive electric charge (shown in blue) moving in the direction of the field accelerates in the same direction, while an electron, experiencing force in the opposite direction, accelerates in the opposite direction. If the positive charge (or the electron) is fired in the horizontal direction, it would move along a parabolic path as shown in the diagram (shown in blue). Due to its negative charge, electron would move in the opposite direction (shown in red). A neutral particle, however, would continue to move with its motion undisturbed in the field.



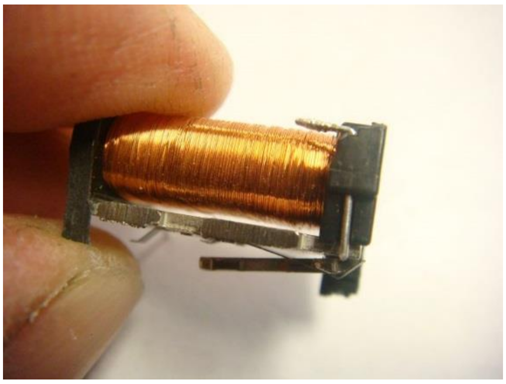
If you release a stone (mass) from some height, it would come vertically down due to the attractive gravitational force. And if you throw it horizontally, it would come down describing a parabola as shown in the figure. The situation is really similar to a positive charge moving in an electric field pointing downward (with no gravitation!). A positive charge released at some height would move downwards, and if fired horizontally, would could describe a parabola, just like the stone in a gravitational field. However, an electron would move in the opposite direction, and a neutral particle would continue to move undisturbed!

All bodies - positive charges, electrons (negative charges), and neutral objects - all experience gravitational force which is only attractive for all and does not distinguish between charged and uncharged bodies, and hence they all would describe motion the same way - just like a stone in a gravitational field!

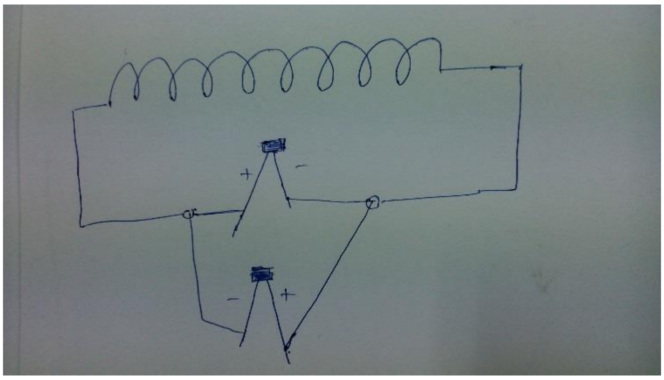
11 : Electromagnetic Induction

This activity shows how electricity and magnetism are intimately related. We shall generate an electric current in a coil of wire using only a magnet. You will need a solenoid with several hundred turns, two LEDs, (one red and the other green) and a bar magnet. LED stands for Light Emitting Diode.

If relative motion is produced between a coil (solenoid) and a magnet, an electric current begins to flow through the coil - a phenomenon called the electromagnetic induction. You can get a readymade solenoid by the name 'relay' in the market. Connect the two LEDs at the two open ends of the solenoid as shown in the diagram below. Be careful about the way positive and negative leads of the LEDs are connected to the solenoid.



A relay coil (solenoid)



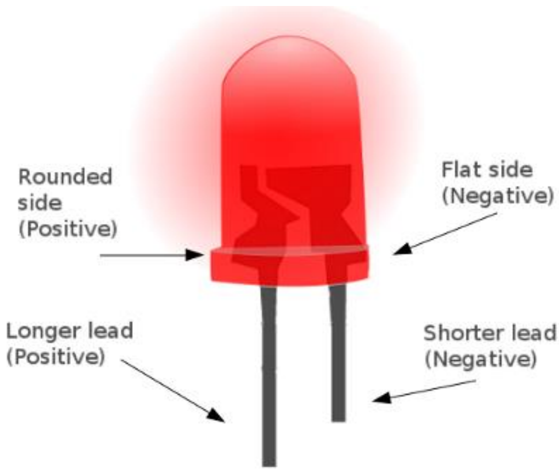
Connecting LEDs to the ends of the relay coil

The two leads of LEDs are not alike. The positive lead is to be connected to a positive terminal while the other lead should be connected to the negative terminal of the current source for the current to flow through the LED and make it glow. If the connections are reversed, the LED will not glow. We make use of this property of LEDs in this activity.

Now, rapidly move the bar magnet rapidly toward the solenoid. You will find that one of the LEDs starts glowing. Now move the bar magnet rapidly away from the solenoid - towards you. Now, the other LED glows. Next, keep the bar magnet stationary either inside or outside the solenoid. Neither LED would glow. Now, keeping the bar magnet steady, at some position, move the solenoid towards one of its poles. One LED glows. If you move the solenoid away from the bar magnet, the other LED glows. It is to be noted that one of the LEDs glows only when there exists a relative motion between the (coil) solenoid and the magnet.

Due to the relative motion between the magnet and the solenoid, an electromotive force (EMF) is produced in the solenoid. One end of the solenoid becomes the positive terminal of the current source, while the other end becomes the negative terminal. Which end of the solenoid is positive and which end is negative depends on which pole of the magnet is toward the solenoid, and it also depends on the direction of the motion. Therefore, when the direction of motion is reversed, the other LED glows. The end that was positive becomes negative and vice versa, and so when the first LED stops glowing the other LED starts glowing.

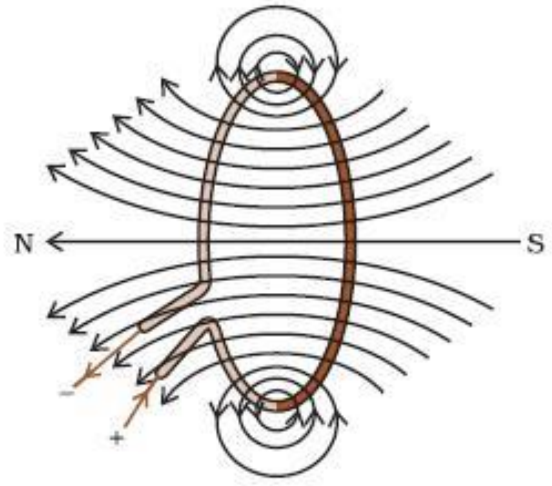
How will you know which lead of LED is positive and which one is negative?



If the LED has two leads - one longer than the other - the longer lead is the positive (also known as the anode) lead. If the LED has two leads with leads that are equal in length, you can look at the metal plate inside the LED. The smaller plate indicates the positive (anode) lead; the larger plate belongs to the negative (cathode) lead. If the LED has a flat area (on the plastic housing), the lead adjacent to the flat area is the negative (cathode) lead.

12 : A Solenoid

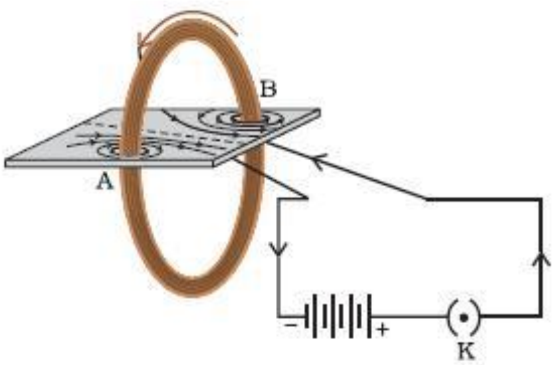
Suppose a straight wire is bent in the form of a circular loop and a current is passed through it. How would the magnetic field lines look like? As the magnetic field produced by a current-carrying straight wire becomes weaker with the distance from it, at every point of a current-carrying circular loop, the concentric circles representing the magnetic field around it would become larger and larger as we move away from the wire as shown below. By the time we reach at the centre of the circular loop, the arcs of these big circles would appear as straight lines. Every point on the wire carrying current would give rise to the magnetic field appearing as straight lines at the centre of the loop. By applying the right hand rule, it is easy to check that every section of the wire contributes to the magnetic field lines in the same direction within the loop.



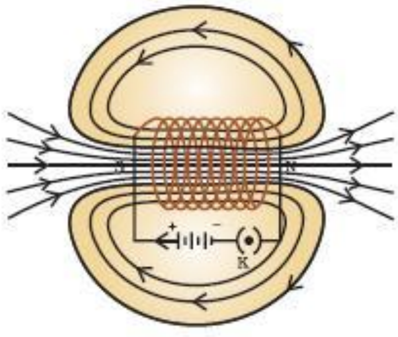
Magnetic field lines of the field produced by a current-carrying circular loop

Activity A: Magnetic field produced by a current-carrying circular loop

The magnetic field produced by a current-carrying wire at a given point depends directly on the current passing through it. Therefore, if there is a circular coil having n turns, the field produced is n times as large as that produced by a single turn. This is because the current in each circular turn has the same direction, and the field due to each turn then just adds up. Take a rectangular cardboard having two holes A and B as shown in Figure (A). Insert a circular coil having large number of turns through them, normal to the plane of the cardboard. Connect the ends of the coil in series with a battery and a key, as shown. Sprinkle iron filings uniformly on the cardboard. Plug the key. Tap the cardboard gently a few times. Note the pattern of the iron filings that emerges on the cardboard. You may find out the direction of the magnetic field at the centre of the solenoid using a magnetic compass as well.



(A)



(B)

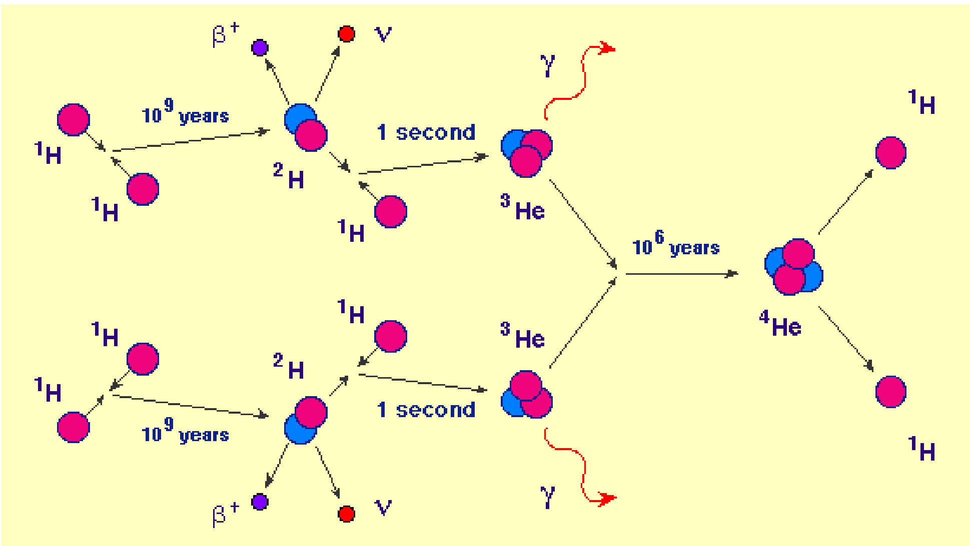
(A) Magnetic field produced by a current carrying circular coil, and (B) Field lines of the magnetic field through and around a current carrying solenoid

Activity B: magnetic field produced by a solenoid

A coil of many circular turns of insulated copper wire wrapped closely in the shape of a cylinder is called a *solenoid* (Figure B). You can make a solenoid using a flexible wire and winding it as shown over a circular pipe or a cylinder as shown in the Figure. Connect the ends of the coil to battery and the key as shown. You may use a magnetic compass to find the direction of the magnetic field produced at different points. The pattern of the magnetic field lines around a current-carrying solenoid is shown. One end of the solenoid behaves as a magnetic north pole (which one?), while the other behaves as the magnetic south pole (which one?). Find out using the magnetic compass. You would find that the field lines inside the solenoid are in the form of parallel straight lines. This indicates that the magnetic field is the same inside the solenoid close to its axis. That is, the magnetic field is uniform inside the solenoid. Compare the pattern of the field of a solenoid with the magnetic field around a bar magnet. Both would look similar.

13 : How Sun Produces Energy: The PP Cycle

Fusion is the source of energy of the Universe, occurring in the core of the Sun and the stars. Hydrogen nuclei collide, fuse into heavier helium atoms and release tremendous amounts of energy in the process. What we see as light and feel as warmth is the result of energy produced in the Sun this way. The gravitational forces at play in the Universe have created the perfect conditions for fusion. Over billions of years, these forces caused the hydrogen clouds of the early Universe to gather into massive stellar bodies. In the extreme density and temperature of their cores, fusion occurs.



The PP Cycle

Atoms never rest: the hotter they are, the faster they move. In the core of our Sun, temperatures reach 15,000,000° Celsius. Hydrogen atoms are in a constant state of agitation, colliding at very great speeds. In the process, the natural electrostatic repulsion that exists between the positive charges of their nuclei is overcome, and the atoms fuse. The fusion of light hydrogen nuclei produces a heavier element, helium, through what is called a proton-

proton (PP) cycle. Two protons (^1H) undergo a simultaneous fusion and beta decay to produce a positron, a neutrino, and a deuteron (^2H), or a heavy hydrogen nucleus. The positron, incidentally, very quickly encounters a free electron in the Sun, and both particles annihilate. Their rest energies appear as two gamma rays. The deuteron reacts with another ^1H to produce a nucleus of helium with two protons and one neutron ($^3He_2$) and a gamma-ray. Then, two $^3He_2$ nuclei produced in two separate events fuse to form a nucleus plus two protons. The net effect is to convert hydrogen to helium, with the energy released going into the particles and gamma-rays produced at each step of the sequence. We may note that we started with two protons; and at the end of the process, we were left with two protons and a helium ($^4He_2$) nucleus. This is called a PP cycle.

We find that the PP cycle effectively amounts to the combination of four protons and two electrons to form an alpha particle ($^4He_2$ atom). The mass of the resulting helium atom is not the exact sum of the four protons (plus two electrons), but somewhat less. The mass lost appears as great amount of energy. This is what Einstein's formula $E=mc^2$ describes: the tiny bit of lost mass (m), multiplied by the square of the speed of light (c^2), results in a very large figure (E), which is the amount of energy created by a fusion reaction.

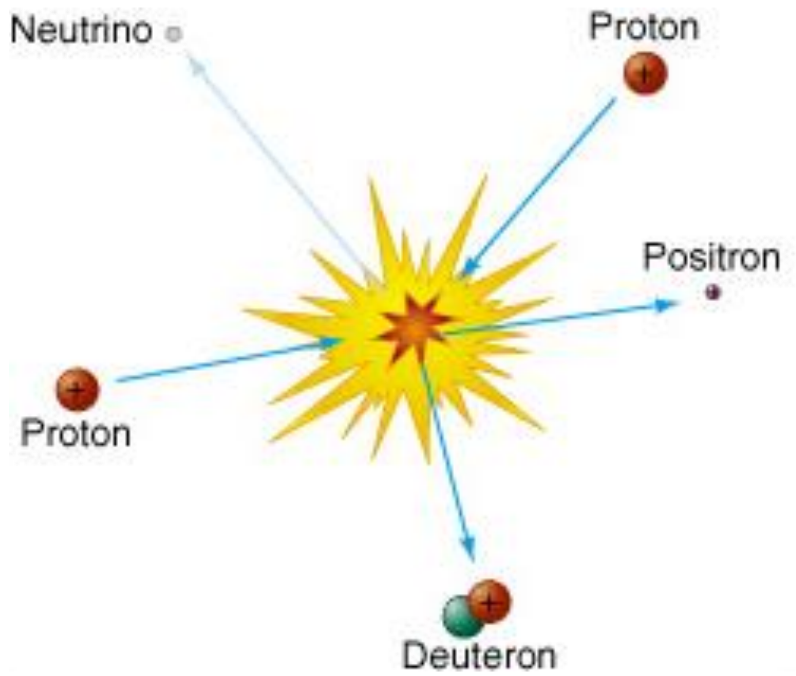
The average time required for a nucleus to undergo each step of this sequence in a typical stellar interior is indicated in the figure. Thus, for example, a hydrogen nucleus waits on the average 1 billion years before it undergoes an interaction with another hydrogen nucleus to initiate the sequence! Since all other steps require much less time than this, it is this initial step that controls the rate of the reaction. This incredibly small rate nevertheless accounts for the luminosities of normal stars because there are so many hydrogen atoms in the core of a star that at any one instant many are undergoing the reactions of the PP chain. Every second, our Sun turns 600 million tons of hydrogen into helium, releasing an enormous amount of energy. We may, however, note that without the benefit of gravitational forces at work in our Universe, achieving fusion on Earth has required a much different approach.

14 : Tunnelling and Fusion

(A) The Coulomb Barrier

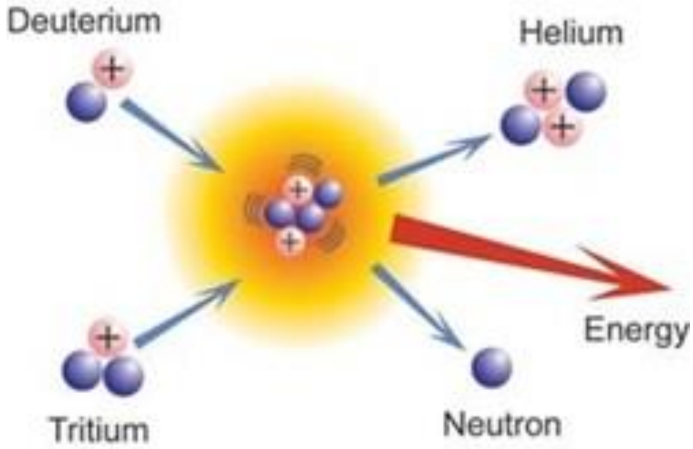
Stars produce their energy from nuclear fusion processes in which two light nuclei fuse into a heavier nucleus producing energy. For stars like the Sun which have internal temperatures around fifteen million degrees Celsius, the dominant fusion process is proton-proton fusion, called the proton-proton (or P-P) cycle. For more massive stars which can achieve higher temperatures, the carbon fusion cycle becomes the dominant mechanism. However, the colliding nuclei are positively charged, and hence repel each other in accordance with the Coulomb's law of electrostatics. Closer they are, higher is the repulsive force! The colliding nuclei must have enough kinetic energy, that is, high temperature, to overcome the electrostatic repulsive force between them – the so called Coulomb barrier. At room temperature, the mean thermal kinetic energy of a particle is quite small, and hence we do not expect the fusion reaction to take place. Even at the centre of the Sun the mean thermal kinetic energy is 100 times less than what is required to overcome the Coulomb barrier! And yet we know that thermonuclear fusion not only occurs in the solar interior, but is its central and dominant feature. How does the nuclear fusion reaction proceed in the Sun's interior, then? There may be particles with much higher energy than the mean thermal energy in the core of the Sun that can overcome the Coulomb barrier, but their number is extremely small. However, there exists a novel mechanism for the particles with kinetic energies *below* the barrier energy to "tunnel" through the barrier to a significant level - a purely quantum mechanical phenomenon! It is through quantum tunnelling process that fusion reaction predominantly takes place in the interior of the Sun, and stars like the Sun.

Atomic nuclei do not stick together easily. Protons have a positive electrical charge which prevents them combining with other protons due to the repulsion caused by the electromagnetic force between the two nuclei. However, at distances of 10^{-15} metres, there is an attractive force which acts on the nuclei to keep them together and it is much stronger than the electromagnetic force. Appropriately, this force is called the Strong force. Over such short distances the strong force wins over the electromagnetic force and so the nuclei stay together. Shown in the diagram is Proton-Proton (PP) reaction that gives rise to a deuteron nucleus and emission of a positron (positive electron) and a neutrino.



15 : The D-T Reaction

In principle, the production of energy from fusion on Earth is simple. Just take two heavy isotopes of hydrogen – deuterium ('d' or $^1H_2$ - hydrogen nucleus consisting of one proton and one neutron) and tritium ('t' or $^1H_3$ - hydrogen nucleus consisting of one proton and two neutrons), squeeze them together, and we get a helium atom and a very energetic neutron. This product is slightly lighter than the ingredients we started with, and the tiny loss of mass results in huge release of energy in accordance with Einstein's mass-energy equivalence equation $E=mc^2$. Once this energy released is harnessed in an efficient way, we have produced controlled nuclear fusion solving the problem of world’s energy needs! This is the d-t reaction.



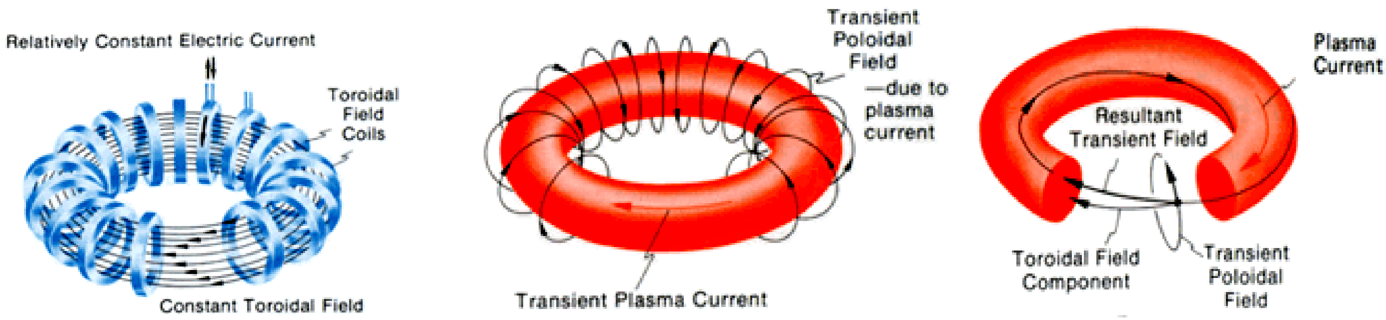
The D-T Reaction

However, there is one glitch! The atomic ingredients of fusion we started with carry positive charge, and like all nuclei, repel each other! In the core of the Sun, the huge gravitational pressure allows fusion reaction to proceed at temperatures of about 15 million °C. In contrast, we need temperatures of the order of 150 million °C to achieve fusion in the machines like ITER. But, no materials on Earth can withstand such high temperatures. Hence, to achieve fusion, ITER will use a device called a tokamak. A tokamak holds the reacting plasma away from the furnace's walls with intense magnetic fields.

16 : A Simple Model of a Tokamak

International Thermonuclear Experimental Reactor (ITER) is based on the concept of tokamak. The word tokamak is a transliteration of the Russian word токамак, an acronym for Russian standing for “toroidal chamber with magnetic coils”.

A tokamak is a device able to produce and confine a large volume of high temperature plasma - a mixture of electrons and ions - in a toroidal shape (doughnut shape) by means of strong magnetic fields. The original design principle was developed at the Kurchatov Institute in Moscow in the 1960s and due to its ability to maintain the temperature in the plasma, the tokamak has become the most advanced magnetically confined fusion plasma concept in the world. Because fusion plasmas are extremely hot – above 100 million degrees C – it is necessary to keep the plasma particles away from the walls of the confinement device as much as possible. This is achieved with a combination of magnetic fields, generated through external coils, and by the current that flows in the plasma. This “magnetic cage” creates helical field lines inside the machine around which the charged particles of the plasma gyrate and are kept confined. The magnetic field in a tokamak is a combination of ‘toroidal’ and ’poloidal’ magnetic fields. The toroidal field has the shape of a torus (doughnut) that surrounds the plasma, and the poloidal field moves in circles around the plasma. The result is a magnetic field that has a similar shape to the toroidal plasma it is trying to confine and surrounds it on all sides, thereby trapping it.



(A) (B) (C)

Tokamak magnetic fields and current

Activity: Making a simple model of a tokamak

You can make a simple model of a tokamak by taking a hollow play-ring made of plastic and winding a wire or a string with turns as shown in the figure. The ring you have used (shown in pink) represents the vessel that contains the hot plasma, while the turns (shown in blue) of wire represent the coils through which the electric current flows producing the toroidal field and the plasma current as shown in Figure (A). The poloidal field produced by the plasma current is shown in red, as in Figure (B). The resulting twisted magnetic field when both are overlaid is shown in Figure (C). The result is a hot confined plasma!

17 : Simulating Nuclear Fusion

In nuclear fusion, two nuclei join together and form a new nucleus. But this reaction depends on a number of different variables. In this activity, we shall try to simulate the processes that occur in a real fusion reactor. For particular nuclei in a certain amount of time, the number of fusions that one gets in a reactor depends on the rate at which fusion occurs, which in turn depends on the rate at which nuclei "collide" or come close enough for fusion to take place. It also depends on there being enough kinetic energy to result in the nuclei coming close enough together in spite of the repulsive electrical forces between positive nuclei. At high temperatures T, about 100-150 million ^{0} C, necessary to achieve the required kinetic energy, a plasma forms. A plasma consists of freely moving charged particles, in this case the nuclei. Further, longer the time for which the nuclei interact, more would be the fusion reactions taking place. This time is denoted by the letter τ (a letter in Greek pronounced 'tau').

The total number of collisions depends in part upon the time during which the plasma is hot enough for collisions to take place. The rate of collisions also depends upon how many nuclei there are in a given volume. This is the particle density (n). The rate of collisions should depend upon how fast the nuclei are moving. However, in a real experiment we cannot measure speeds of individual nuclei. Instead we need a variable that relates to the plasma as a whole that depends on speed and is measurable. This variable is temperature T.

Activity: Simulating Nuclear Fusion

Transparent box

Bottle tops

Velcro

Take a transparent box made of plastic. We shall model particles with bottle tops (with Velcro attached) and will confine them in the box. Since temperature is related to the speed of the particles, you will simulate temperature by how rapidly you shake your system of particles (bottle tops). You may start with 50 bottle tops with Velcro attached on them.

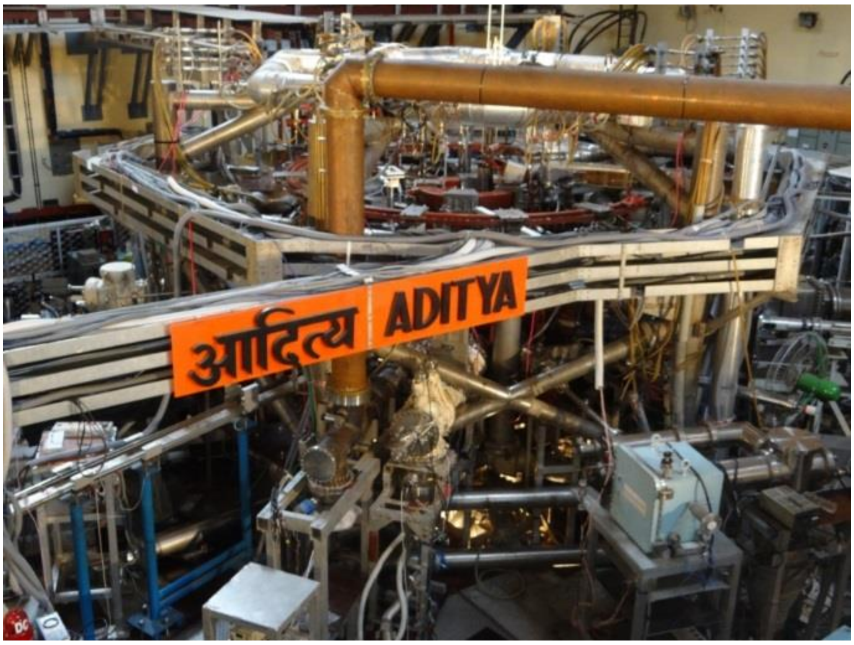
1. Shake the box vigorously but at a constant rate for different time intervals (10 s, 20 s, 30 s). See how many nuclei have 'fused'. As you already know, this parameter for time is called τ. You would find that longer you shake (longer τ), more nuclei fuse together. By shaking the box at a constant rate, you are maintaining a constant temperature and a constant collision rate of nuclei.

2. Shake the box at different speeds. When you shake slowly (low temperature and hence low collisional speeds), hardly any nuclei fuse. As you shake little more vigorously (higher temperature and hence higher collisional speeds), more nuclei fuse. This temperature parameter is T. When you shake even more vigorously (still higher temperature and higher collisional speeds), still more nuclei fuse. This shows the need for a very high temperature for fusion reactions to take place. You would need to practise doing so!

3. The rate of collisions also depends upon how many nuclei are there in a given volume. This is the particle density n. Do the experiment now taking 15, 30 and 50 nuclei (bottle tops) at a time. Shake the box at the same rate and for the same time (10 s, 20 s, 30 s), and observe how many nuclei fuse as the particle density is changed. You would observe that as the particle density is increased more nuclei fuse.

As in this activity, in an actual nuclear fusion reactor too, it is necessary to optimize the time τ during which we can hold the nuclei, temperature T, and the particle density n for efficient working of the reactor and for maximum power output. Further, it is necessary that the energy produced by the fusion reactor be greater than the energy consumed, for it to be commercially viable. The product nτT sets a limit for the operation of a fusion reactor. This limit is today commonly known as the "fusion product", and it has the value of **$n\tau T > 3.10^{28}$ K m^{-3} s.**

18 : Aditya: India’s First Indigenous Tokamak

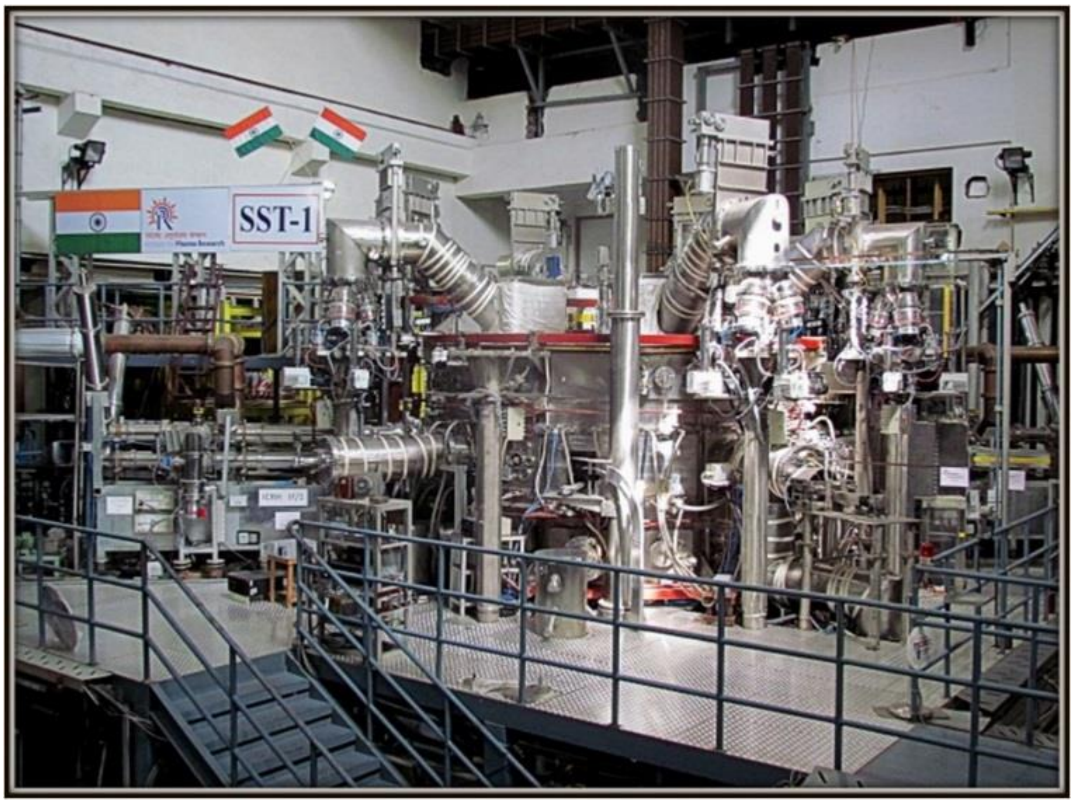


Aditya is the first indigenously designed and built tokamak of India, located at Institute for Plasma Research, Gandhinagar, Gujarat. Tokamaks have a toroidal structure which resembles the tube of a cycle. Aditya is a medium sized tokamak and is in operation since 1989. It has a major radius of 75 cm and minor radius of 25 cm. It has the capability of producing 1.2 Tesla of toroidal magnetic field with the help of 20 magnetic field coils placed symmetrically around the torus. We may note that 1 Tesla = 10^4 gauss. Incidentally, Earth’s magnetic field is only about 0.36 gauss on the surface of the Earth.

Discharges are produced in the tokamak machine with the Ohmic transformer. The tokamak machine works as a secondary of the transformer. This is really a single turn secondary and is a step down transformer. Primary of the transformer is the standard transformer winding. The primary of the transformer works with 2,000 Volts, and 20,000 Amperes. Gas is fed into the torus machine and then discharged under high electric field. Plasma current flows in the tokamak machine (normally called tokamak vessel). This plasma has certain resistance; and temperature of the plasma increases due to Ohmic heating I^2R. Plasma has a property that its resistance decreases with the rise of temperature. This reduces the heating efficiency. Hence above a certain temperature range auxiliary heating is required. This heating is provided in the form of ion cyclotron resonance heating (ICRH) and electron cyclotron resonance heating (ECRH) in which ions and / or electrons resonate with the wave launched into tokamak from outside.

ADITYA is being regularly operated. Plasma discharges of about 100 milli second duration, 80 - 100 kilo Amperes of plasma current at 0.8 Tesla of toroidal field are being regularly experimented. Plasma properties like edge plasma fluctuations, turbulence, auxiliary heating, disruptions and its control are being studied during these experiments. Aditya machine is upgrade from time to time depending upon the need of experiment.

19 : Steady State Superconducting Tokamak (SST-1)

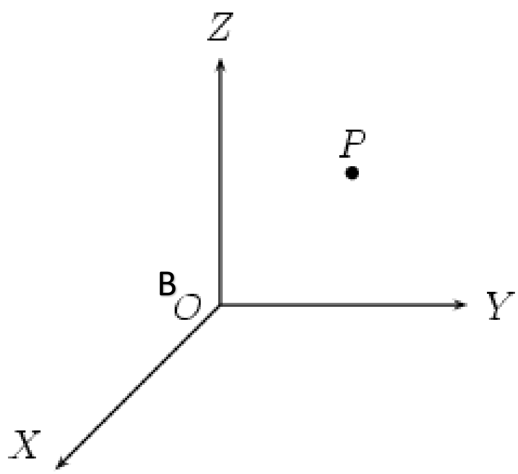


Steady State Superconducting Tokamak (SST-1) is a second generation tokamak machine built at Institute for Plasma Research, Gandhinagar. In the first generation tokamak like Aditya, copper coils are used to generate magnetic fields. Copper coils get heated up due to their relatively high resistance at a very high current. As a result, long pulse discharges cannot be carried out in first generation tokamaks. In the second generation tokamaks, as in SST-1, superconductors are used for making magnetic field coils. Being superconductors, high magnitude of current can flow into these coils generating high magnetic fields for much longer period of time. This is the essential requirement of fusion reactors. SST-1 will study long pulse, or steady state operation of plasma. The SST-1 is essentially a medium sized tokamak with major and minor radii of 1.1 m and 0.2 m respectively. The main subsystems include Super Conducting Magnets, Cryogenic systems required for superconducting coils, Plasma Facing Components, Radio Frequency systems, Neutral Beam Injection system, Diagnostics, Power Supplies, large volume for plasma confinement, and high and ultra-high vacuum systems. The systems designed are for a long duration (about 1000 seconds) plasma operation. The maximum plasma current is 220 kilo amperes; and the toroidal magnetic field is 3 Tesla, or 3 x 10^4 gauss.

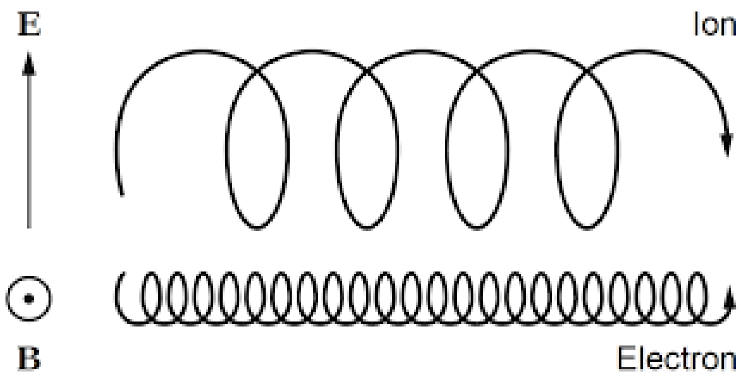
20 : Drifts in Plasmas: EXB Drift

A plasma consists of electric charges, and hence in the presence of a magnetic field (**B**), the charges gyrate about the magnetic field as described in the activity on electric charges in a magnetic field. Now, any force that is capable of accelerating or decelerating particles as they gyrate about the magnetic field, will result in drifts perpendicular to both B and the force. The force could be due to electric field, gravity, non-uniform magnetic fields, or even due to the magnetic field lines being curved (curvature drift). We shall consider only the **E**X**B** drift in this activity.

You may use the given plastic (or metallic) wire given in the kit to understand the **E**X**B** drift. Before we start, let us understand the co-ordinate system and the convention we have used. We shall use the Cartesian coordinate system as shown below, and the magnetic field along the X-axis coming out of the page.



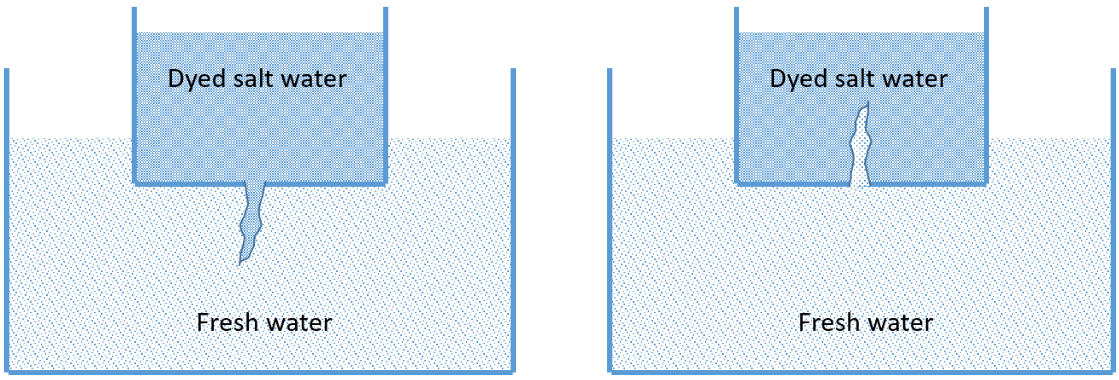
EX**B** Drift (pronounced E *cross* B drift) is the most familiar drift in the presence of uniform electric and magnetic fields, both being perpendicular to each other. We shall take electric field **E** along Z-axis, and magnetic field along X-axis (coming out of the paper). An ion (positive charge) would gyrate about the magnetic field in a clockwise manner, while the electric field would accelerate it upward in the Z direction. But, interestingly, under the combined effect of both **E** and **B**, the ion drifts along the Y-axis as shown with a drift velocity E/B! An electron gyrates about the magnetic field in the oposite direction (anticlockwise), but also experiences the electric force in the opposite (downward) direction. As a result, an electron also drifts in the same direction as that of an ion and with the same speed (E/B) – only it is more tightly bound to the magnetic field, being much lighter than the ion! As a result, **E**X**B** drift is the same for ALL particles irrespective of their charge and mass, and is perpendicular to both, the electric and magnetic fields, and no electric current flows!



Using the given plastic (or metallic) wire, with **E** and **B** representing electric and magnetic fields along the Z and X directions, show the paths of ions and electrons as they drift in the YZ-plane along the Y direction.

We may note that other kinds of drifts like gravitational drift, and due to non-uniform electric and magnetic fields, or due to the curvature of the fields, in general depend on factors like charge, mass, and velocity of the particles.

21 : Rayleigh – Taylor Instability



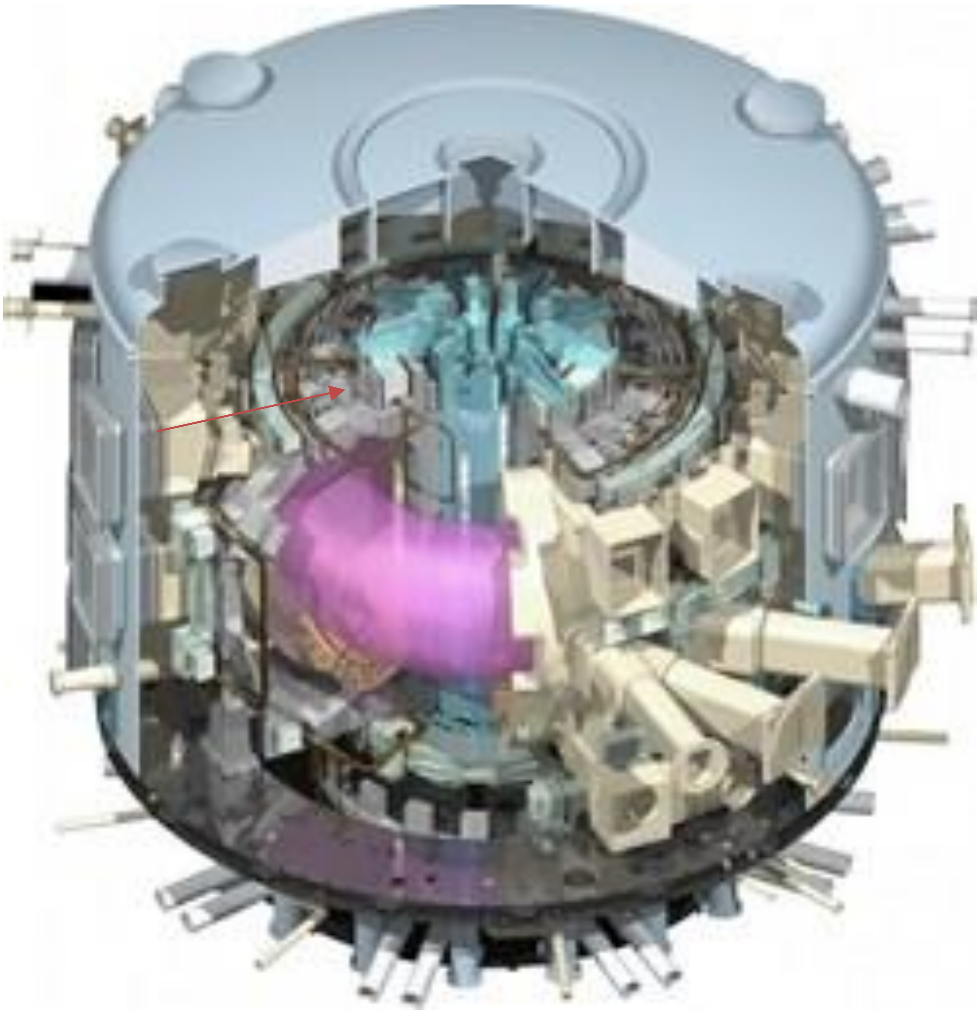
Take an ordinary transparent plastic container and punch a pinhole in the bottom. Even a large transparent syringe (made of glass or plastic) would do! Fill it with saturated salt water, and partially immerse it in a container of fresh water. You expect the two solutions to eventually mix - and they do, but in a surprising way! Colour the salt water solution with a dye, so you can see which is which. There will be an alternating exchange of solutions. Salt water will flow down through the hole, then fresh water will flow up, and so on as shown in the figure. This oscillation may continue for four to five days, with an oscillation period of about four seconds.

What we observed in this activity is really a consequence of what is known as the Rayleigh–Taylor instability, or RT instability (after Lord Rayleigh and G. I. Taylor). It is an instability of an interface between two fluids of different densities which occurs when a denser fluid is on top of a lighter fluid, and the lighter fluid is pushing the heavier fluid. Water suspended atop oil (and both subject to Earth's gravity) is an everyday example of Rayleigh–Taylor instability. The equilibrium here is unstable to any perturbations or disturbances of the interface: if a parcel of heavier fluid is displaced downward with an equal volume of lighter fluid displaced upwards, the potential energy of the configuration is lower than the initial state. Thus the disturbance will grow and lead to a further release of potential energy, as the more dense material moves down under the (effective) gravitational field, and the less dense material is further displaced upwards.

Other examples of Rayleigh – Taylor instability include mushroom clouds like those from volcanic eruptions and atmospheric nuclear explosions, supernova explosions in which expanding core gas is accelerated into denser shell gas, instabilities in plasma fusion reactors where hot plasma is confined by strong magnetic fields, and inertial confinement fusion machines. Rayleigh-Taylor instability structure is also evident in the Crab Nebula, in which the expanding pulsar wind nebula powered by the Crab pulsar is sweeping up ejected material from the supernova explosion some 1000 years ago. This instability is also observed in the Sun's outer atmosphere, or solar corona, when a relatively dense solar prominence overlies a less dense plasma bubble – a clear example of the magnetically modulated Rayleigh - Taylor instability.

22 : How ITER Works

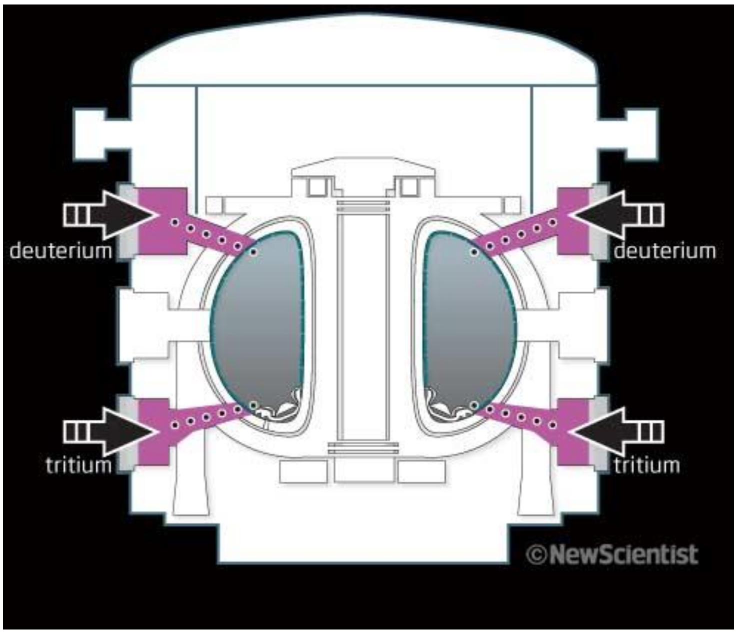
The ITER (International Thermonuclear Experimental Reactor) is an ambitious international nuclear fusion research and engineering megaproject, which would be the world's largest magnetic confinement plasma physics experiment. It is an experimental tokamak nuclear fusion reactor that is being built at Cadarache, south of France. The ITER fusion reactor has been designed to produce 500 megawatts of output power for several seconds while needing 50 megawatts to operate. Thereby the machine aims to demonstrate the principle of producing more energy from the fusion process than is used to initiate it, something that has not yet been achieved in any fusion reactor. The project is funded and run by seven member entities—the European Union, India, Japan, China, Russia, South Korea, and the United States. Construction of the ITER Tokamak complex started in 2013. The facility is expected to finish its construction phase in 2019 and will start commissioning the reactor that same year and initiate plasma experiments in 2020 with full deuterium–tritium fusion experiments starting in 2027. When ITER becomes operational, it will become the largest magnetic confinement plasma physics experiment in use.



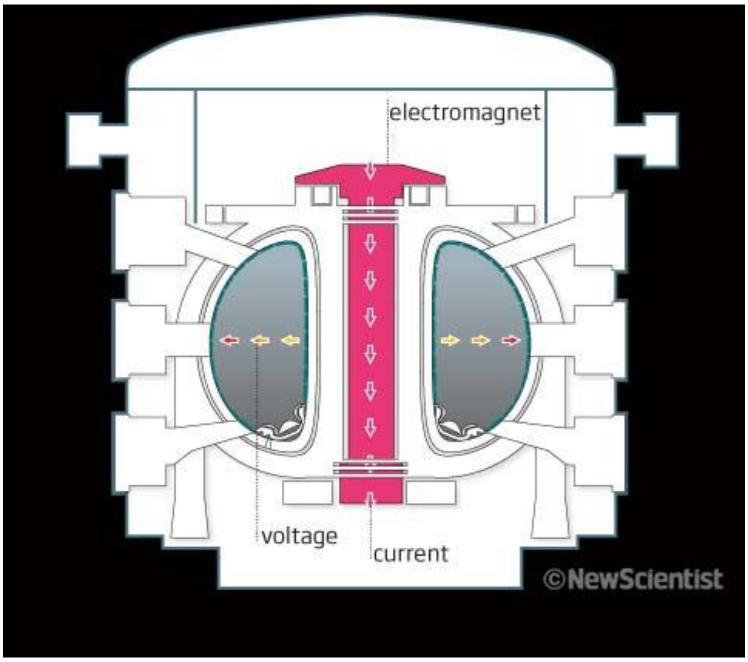
A cut-away view of the ITER Tokamak, revealing the doughnut-shaped plasma inside of the vacuum vessel. Do you see a man standing at the lower left of the tokamak? (Source : ITER, France)

How ITER Works

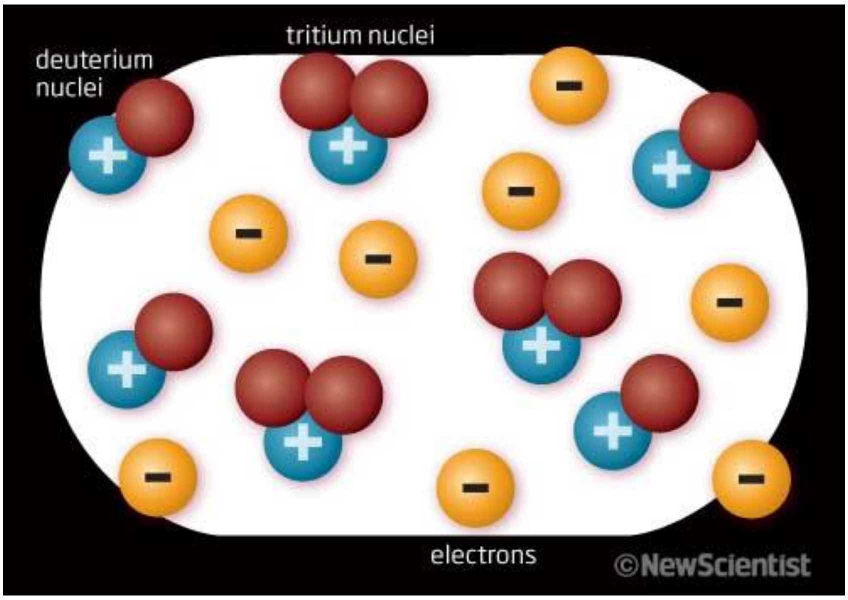
We describe in this section how ITER would work in a step-by-step manner. (Source : New Scientist)



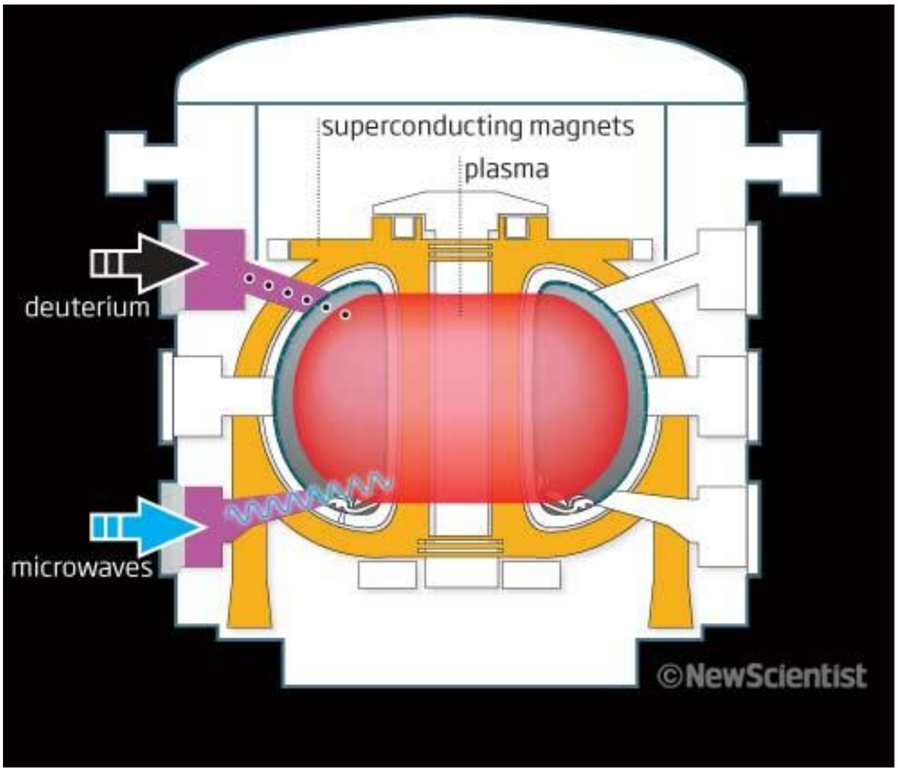
Step 1. Puffs of deuterium and tritium gas are injected into the donut-shaped vacuum vessel, called a Tokamak. The gas weighs less than a postage stamp and fills a volume one-third that of an Olympic swimming pool.



Step 2. Electricity flowing through this electromagnet (central solenoid) produces a voltage across the gas.

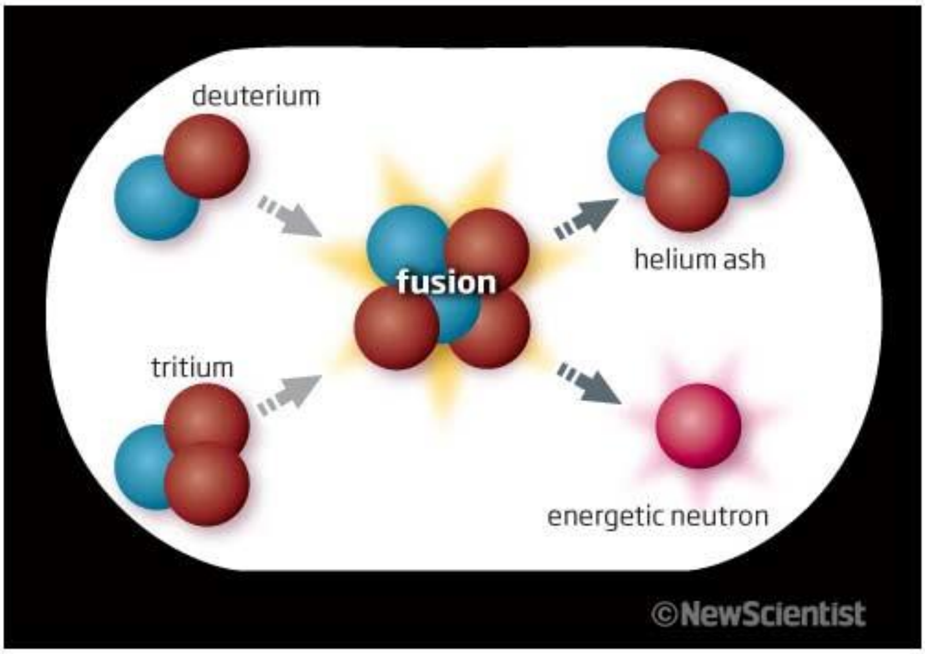


Step 3. Voltage rips electrons from the deuterium and tritium atoms. They turn into charged atoms (ions) within a few microseconds, forming a particle soup called a plasma.

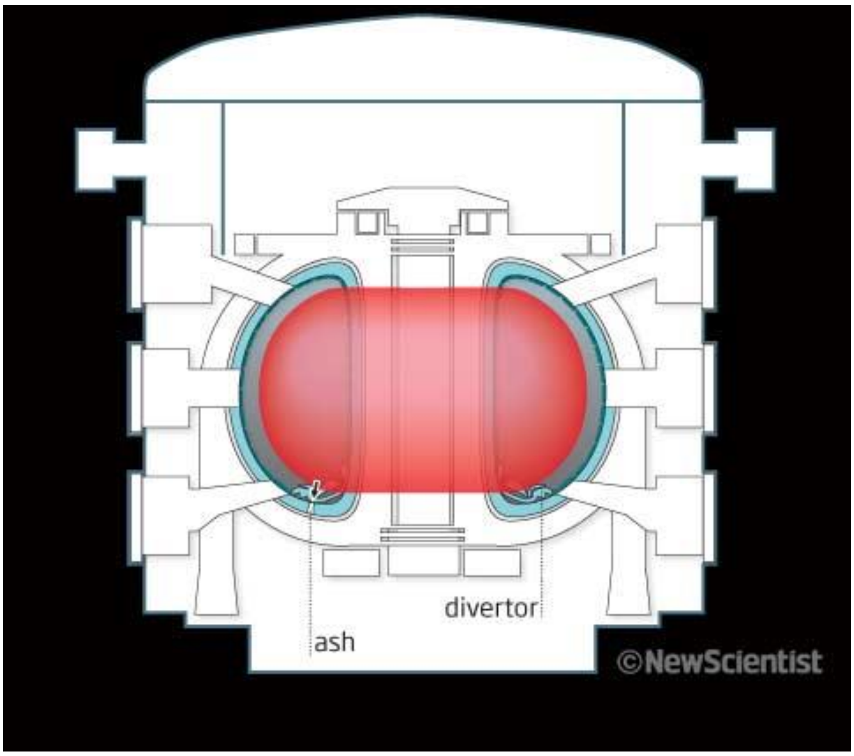


Step 4. Plasma is locked inside the vacuum vessel by magnetic fields that are created by an array of superconducting magnetic coils. The magnetic coils generate a current in the plasma

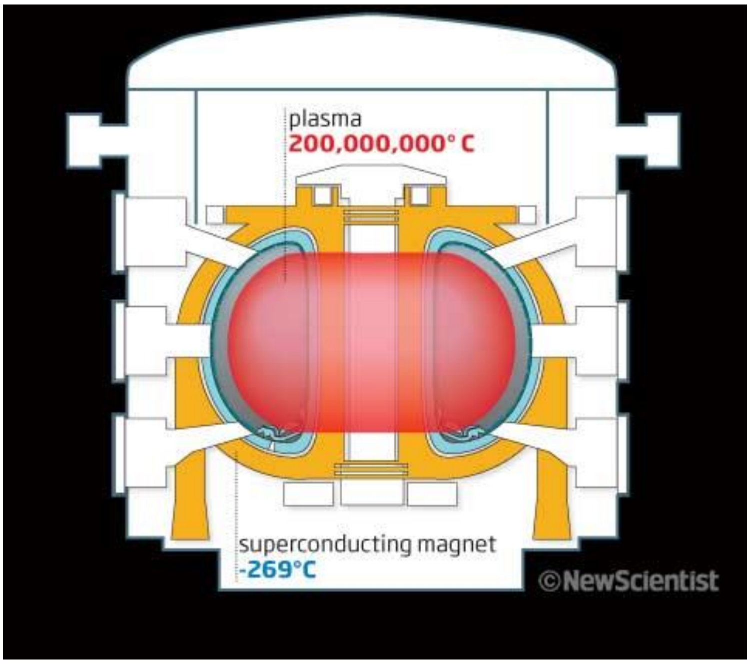
as well as confining it, heating the plasma to 10 million °C. But that's not hot enough for fusion to occur.



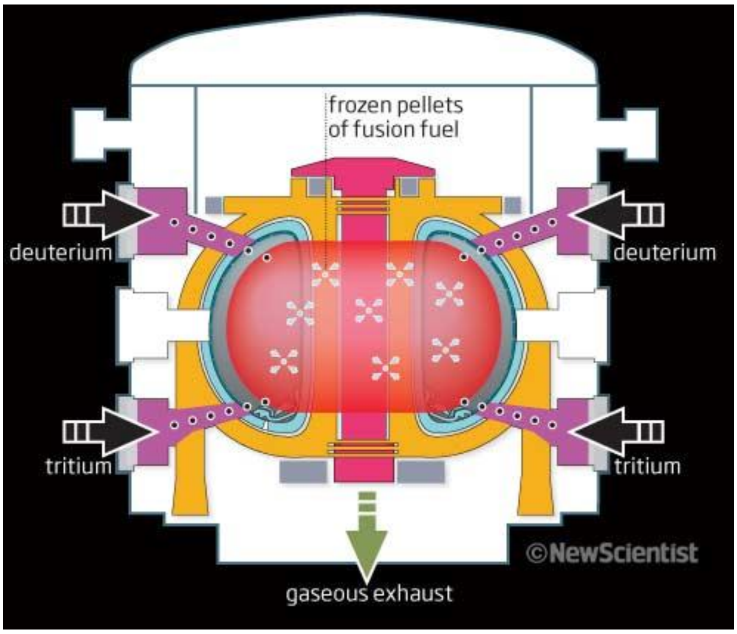
Step 5. To raise the temperature further, scientists fire radio and microwaves into the plasma and high-energy beams of deuterium atoms. The plasma then reaches 100 - 200 million °C, hot enough for the deuterium and tritium nuclei to fuse.



Step 6. Fusion produces high-energy neutrons and helium particles that deposit their energy into the plasma and keep it hot, before becoming “ash”. The “ash” is eventually forced out through the divertor.



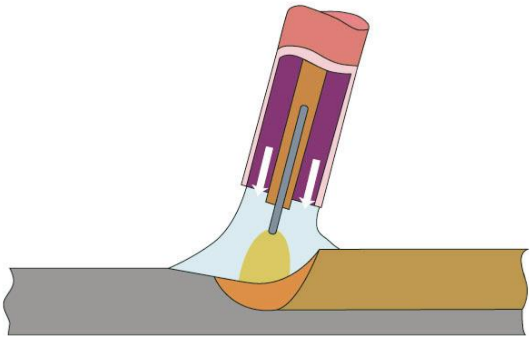
Step 7. Neutrons and other particles bombard the tiles on the plasma-facing components and heat them. In a future power station this heat will be harnessed to make electricity. Superconducting magnets operate near absolute zero. The distance to the magnets from the heart of the plasma sees the greatest temperature gradient in the universe.



Step 8. The plasma must be continuously refuelled with deuterium and tritium for the process to continue. Unburnt fuel is also recovered from the gaseous exhaust and the reaction is fine-tuned by firing frozen pellets of fusion fuel deep into the plasma.

23 : Welding and Cutting with Plasmas

Plasmas hold the world together. Perhaps it may sound like an exaggeration, but not quite! Most of the goods manufactured today depend of thousands metal to metal joints. Cars, ships, trains, aeroplanes, pipelines, hot-water systems, and even the metal framework of buildings, and bridges. Many of those joints are welded using plasmas.



(A)

(B)

(A) An electrical current bridges the gap between the electrode and the metal to be welded.
(B) Plasma can be used to cut through metals at high velocity

In arc welding, an electrode is connected to one end of an electrical power supply, and the metal to be welded is connected to the other end. The welder touches the tip of the electrode to this metal, and draws it away to produce a short gap, about a fraction of a centimetre in length or so, between the electrode and the metal. The voltage in the power supply causes an electrical current to bridge this gap. The current heats the air to create a plasma, which emits a very intense light. This is the welding arc. The welder must protect his eyes from the intense arc light by using the welding helmet that allows only a very small fraction of the light to enter his eyes.

The plasma arc process has proved to be the fastest and most economical method of cutting virtually any metal. With nitrogen plasma, metal plates up to 8 centimetres thick can be cut at speeds up to 35 centimetres per minute. With oxygen plasma, 1 centimetre thick steel can be cut at 4 metres per minute! Plasma arcs, used for both welding metals together and cutting metals apart, have revolutionized the way we construct bridges, buildings, pipelines, energy generation facilities, cars, trucks, ships and airplanes. We can fabricate these and other metal structures more quickly, more safely, more economically, and in greater quantity and size than would otherwise be possible.

24 : Cleaning the Environment with Plasmas

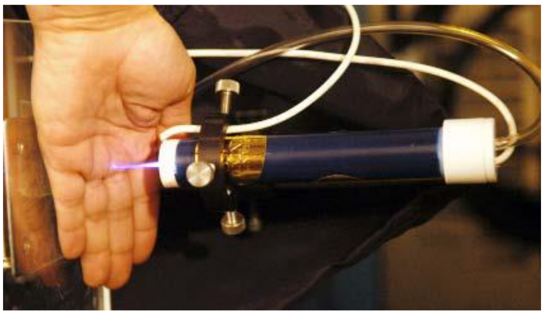
Plasma furnaces using "plasma pyrolysis" technique are being used in many countries in including India to treat a variety of wastes, say, hospital waste, and waste produced by organic, and rubber products; and wastes produced by plastics and residues from other petroleum products. In plasma pyrolysis, generation of heat is independent of chemistry of material used. It is fast heating, 5000 ^{0}C can be achieved in milliseconds. In plants for treating hospital wastes, the high ultraviolet radiation flux destroys pathogens. In some systems, the pyrolysis phase is followed by a second gasification stage. This is with a view that more of the energy carrying gases are liberated from the waste. These gases can be used as a fuel to generate steam or electricity as a basic chemical feedstock in the petrochemical and refining industries. FCIPT wing of the Institute for Plasma Research, Gandhi Nagar, Gujarat, has developed Plasma Pyrolysis for treating wastes of different kinds using plasma technology.

Plasma Pyrolysis Unit developed by FCIPT, IPR, Gandhinagar

Plasmas (both thermal and non-thermal) can be used to monitor environmental pollution with high sensitivity in air and smoke stacks. Some low-pressure plasmas can emit large amounts of ultraviolet (UV) radiation, X- radiation or electron beams. These plasmas can be used for controlling water pollution. For example, intense UV radiation can disable the DNA of a microorganism in water, thereby making it impossible for that microorganism to replicate. This plasma-based UV method takes only few seconds, has no effect on the taste or smell of the water, and is effective against all known water-borne bacteria and viruses. Contamination of soil also can be controlled using plasma processing.

25 : Plasma in Medicine

Plasmas are used in treating several health problems. Medical plasmas are hot enough to produce the reactive species of atoms and molecules needed for effective treatment, but cold enough to leave tissue unharmed! Scientists have discovered ways to apply plasmas directly to living tissues to deactivate pathogens (any disease causing agents like bacteria, viruses or other microorganisms), to stop bleeding without damaging healthy tissue, or to disinfect wounds and accelerate wound healing; and even to selectively kill some types of cancer cells.



(A)

(B)

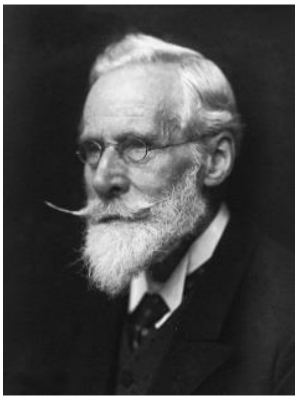
(A) A cold plasma in contact with skin without harming it, making it ideal for disinfecting wounds.
(B) Plasma can be used to control plaque, tooth decay, and periodontal diseases

Bacteria cannot cope with the harsh environment created by plasmas. They die in large numbers in a matter of minutes or even seconds, depending on the strength of the bacterial strain. This property of plasma has been exploited to develop plasma devices that can be used to sterilize medical tools and instruments without the risk of damaging them. Reactive plasma species of atoms and molecules near room temperature can rapidly kill bacteria, viruses and fungi deposited on the surfaces of surgical instruments and medical devices. Reactive plasma species appear to cause little or tolerable damage to living animal and plant tissues, and at the same time are capable of destroying bacterial cells.

In dentistry, cold plasma has found applications in controlling oral bio-films, commonly known as slime. It is essentially a highly organized, three-dimensional bacterial community. Dental plaque is one example of an oral bio-film. In a laboratory environment plasma has been shown to inactivate bacteria that cause tooth decay, and thereby control periodontal diseases. Thus, one day plasma may replace the universally feared dentist's drill - causing little or no pain to the patients!

26 : Makers of Plasma Physics

William Crookes



Sir William Crookes (17 June 1832 – 4 April 1919) was an English chemist and physicist who worked on spectroscopy. Most notable among Crookes's chemical studies led to includes the discovery of the element thallium. The existence of plasma was first discovered by Crookes using an assembly that is today known as a "Crookes Tube", an assembly in which air (or a gas) is ionized by the application of a high voltage through a voltage coil. He suggested that the tube was filled with matter that he called the "fourth state", that is, the mean free path of the molecules is so large that collisions between them can be ignored. Crookes tube was an early experimental electrical discharge tube, with partial vacuum, in which cathode rays, or streams of electrons were discovered. Crookes pointed out the significant properties of electrons in a vacuum, including the fact that a magnetic field causes a deflection of the emission.

Hannes Alfven

Hannes Olof Gösta Alfvén (30 May 1908 – 2 April 1995) was a Swedish electrical engineer, plasma physicist and winner of the 1970 Nobel Prize in Physics for his work on magneto-hydrodynamics (MHD). He was originally trained as an electrical power engineer and later moved to research and teaching in the fields of plasma physics and electrical engineering. Alfvén played a central role in the development of plasma physics, charged particle beams, Interplanetary medium, magneto-hydrodynamics, and solar phenomena investigation such as the solar wind, and the science of aurorae. He also made seminal contributions to the understanding of Van Allen radiation belts, the effect of magnetic storms on the Earth's magnetic field, the terrestrial magnetosphere, and the dynamics of plasmas in the Milky Way galaxy. He described a class of MHD waves (low frequency hydro-magnetic plasma oscillations), now known as Alfvén waves in his honour. Many of his theories about the solar system were verified as late as the 1980s through external measurements of cometary and planetary magnetospheres.

Peter Debye

Petrus (Peter) Josephus Wilhelmus Debye (24 March 1884–02 November 1966), was born in Maastricht, the Netherlands. A Dutch-American physicist, he developed methods using induced dipole moments and x-ray diffraction to investigate molecular structures. He advanced Albert Einstein's theory of specific heat, by factoring low-frequency phonons into Einstein's methodology. In 1915 he showed how temperature alters x-ray diffraction patterns in crystalline solids. Though he was a physicist by training and career, he won the Nobel Prize for Chemistry in 1936, for his contributions to the study of molecular structure through his investigations on dipole moments and on the diffraction of x-rays and electrons in gases. He also studied electric conductivity in salt solutions, the heat capacity of solids, the theory of polar molecules, and the Van der Waals forces between molecules. In plasma physics, he is best known through a term called "the Debye length", which is the scale over which mobile charge carriers (e.g. electrons) screen out electric fields in plasmas and other conductors. In other words, the Debye length is the distance over which significant charge separation can occur. In a gas discharge, or a tokamak, the Debye length could be as small as 10^{-4} m, while in the intergalactic medium it could be as large as 10^{5} m.

Irving Langmuir

Irving Langmuir (31 January 1881 – 16 August 1957) was an American chemist and physicist. His initial contributions to science came from his study of light bulbs. His first major development was the improvement of the diffusion pump, which ultimately led to the invention of the high-vacuum rectifier and amplifier tubes. A year later, he and his colleague Lewi Tonks discovered that the lifetime of a tungsten filament could be greatly lengthened by filling the bulb with an inert gas, such as argon. He was one of the first scientists to work with plasmas and was the first to call these ionized gases by that name, because they reminded him of blood plasma. Langmuir and Tonks discovered electron density waves in plasmas that are now known as Langmuir waves. He introduced the concept of electron temperature, and in 1924 invented the diagnostic method for measuring both temperature and density with an electrostatic probe, now called a Langmuir probe and commonly used in plasma physics. He also discovered atomic hydrogen, which he put to use by inventing the atomic hydrogen welding process; the first plasma weld ever made. Plasma welding has since been developed into gas tungsten arc welding. He was awarded the 1932 Nobel Prize for Chemistry for his discoveries and investigations in surface chemistry.

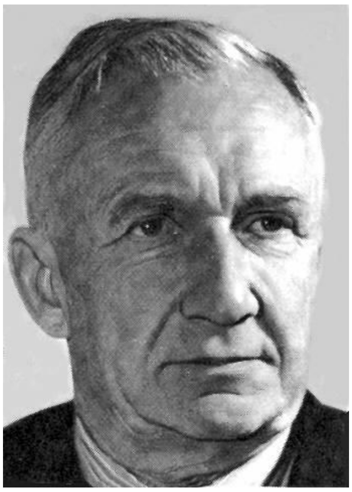
Lev Andreevich Artsimovich

Lev Andreevich Artsimovich (25 February 1909 – 01 March 1973) was a Russian physicist, who worked in the field of nuclear physics and plasma physics; and was a pioneer in the field of controlled nuclear fusion. The research that Artsimovich did with Kurchatov (1935) was the first to show clearly that the cross section of the capture of slow neutrons by protons is comparatively very large. He worked on the Soviet atomic bomb project during 1944-1949. From 1951 to his death in 1973, he was the head of the Soviet fusion power program. Since early 1950s, under Artsimovich's directorship of the scientific section of the I. V. Kurchatov Institute of Atomic Energy, large and complex plants for thermonuclear research were built. He is known as "the father of the Tokamak". In particular, under his guidance the lifetime of high-temperature plasma was sharply increased in tokamak machines; and a thermonuclear fusion reaction was produced in the laboratory for the first time.

Andrei Sakharov

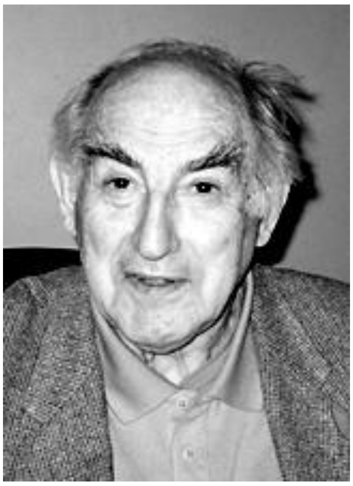
Andrei Sakharov (21 May 1921- 14 December 1989) was an eminent Soviet Russian nuclear physicist, and a Nobel Peace Prize winner. After the Second World War, Sakharov contributed to Soviet weapons research, and participated in the Soviet atomic bomb project till testing of the device in 1949. Later, Sakharov played a key role in the development of the thermonuclear hydrogen bomb, which was first tested in 1953, followed by the first megaton-range Soviet hydrogen bomb, which was tested in 1955. The making of the hydrogen bomb involved three "fundamental ideas" with Sakharov contributing first and third ideas (the layer structure for the bomb and the radiation implosion, respectively). Ginzburg contributed the second idea, which concerned breeding the essential thermonuclear fuel tritium. In 1950, in association with Igor Tamm, he proposed an idea for a controlled nuclear fusion reactor, the tokamak, which is still the basis for the majority of work in the area, based on the premise of confining extremely hot ionized plasma by torus-shaped magnetic fields. He was elected to the new parliament in 1989, and briefly co-led the democratic opposition. Sakharov died soon after.

Igor Tamm



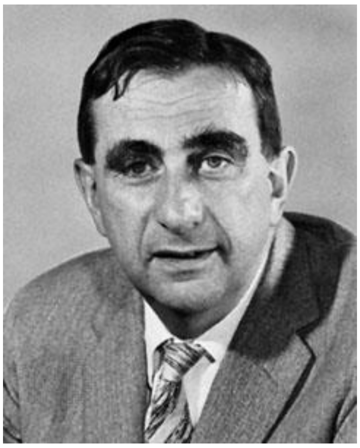
Igor Tamm was a Soviet Russian physicist and mathematician (08 July 1895 – 12 April 1971), who was jointly awarded Nobel Prize in Physics in 1958 with fellow physicists Pavel Alekseyevich Cherenkov and Ilya Frank, for elucidating along with Frank the science behind the Cherenkov radiation. Tamm's initial work on specific types of electron bonding on the surfaces of crystalline solids was significantly applied in the development of solid-state semiconductor devices. He also contributed towards devising the first thermonuclear bomb of the Soviet Union with Vitaly L. Ginzburg and Andrei D. Sakharov, among others. A tokamak system for realising controlled thermonuclear fusion (CTF) using a toroidal magnetic field for confinement of plasma was proposed by him and Andrei Sakharov in 1951, which was successfully developed a few years later.

Vitaly Lazarevich Ginzburg



Vitaly Lazarevich Ginzburg (4 October 1916 - 8 November 2009) was a Russian physicist and a member of the group along with Igor Tamm and Andrei Sakharov that developed the Soviet hydrogen bomb. The making of the hydrogen bomb involved three "fundamental ideas" with Sakharov contributing first and third ideas (the layer structure for the bomb and the radiation implosion, respectively). Ginzburg contributed the second idea, which concerned breeding the essential thermonuclear fuel tritium (using lithium duteride ^6LiD and obtaining tritium, ^3H, through the reaction of ^6Li and a neutron). At the same time that he was involved with the secret weapons programme, he was also working in fundamental pure research, producing his famed paper with Landau on the phenomenon of superconductivity in 1950. Superconductivity has vast implications in technology, as in the construction of powerful electromagnets used in MRI, Large Hadron Collider, and ITER. He was awarded the Nobel Prize in Physics for his work on superconductivity (along with Alexei Alexeevich Abrikosov and Anthony James Leggett) in 2003. He contributed significantly in diverse fields like quantum theory, propagation of electromagnetic waves through the ionosphere, origin of cosmic rays, radio-astronomy, and astrophysics.

Edward Teller



Edward Teller (15 January 1908 - 09 September 2003) was a Hungarian-American theoretical physicist who is colloquially known as the Father of the Hydrogen Bomb. Teller received his Ph.D. in physics under Werner Heisenberg in 1930 at the University of Leipzig. Later, he moved to the George Washington University, USA, working in the fields of quantum, molecular and nuclear physics. Teller was an early member of the Manhattan Project, charged with developing the first atomic bomb. Teller made valuable contributions to bomb research. During this time he made a serious push to develop the first fusion-based weapons as well, but these were deferred until after World War II. Teller began work on the hydrogen bomb in 1950 at Los Alamos. In 1951 Teller and Stanislaw Ulam came up with a practical megaton-range hydrogen bomb design that would eventually work. The first hydrogen bomb was detonated on November 1, 1952 on Enewetak, an atoll in the Pacific Ocean, and was about 1,000 times more powerful than the fission bomb dropped on Hiroshima a few years earlier. In his later years, Teller became especially known for his advocacy of controversial technological solutions to both military and civilian problems.

Marshall Rosenbluth

Marshall Rosenbluth (05 February 1927- 28 September 2003) was a brilliant American plasma physicist who was a dominant contributor to the development of the American hydrogen bomb in early 1950s. In 1950, he was recruited by Edward Teller to the team that created the hydrogen bomb at Los Alamos. The United States detonated the world's first hydrogen bomb, on Eniwetok atoll in the Pacific that was 700 times more powerful than the conventional fission type bomb dropped on Hiroshima a few years earlier. Later, Rosenbluth's attention turned to harnessing nuclear fusion for peaceful purposes. He was a strong supporter of the formation of the International Centre for Theoretical Physics in Trieste, Italy, and of the International Thermonuclear Experimental Reactor (ITER), a programme to demonstrate the feasibility of using fusion to generate power. The Rosenbluth formula is used in the experimental investigation of electron scattering. In 1953, Rosenbluth derived the Metropolis algorithm which is widely used in statistics and statistical physics. In plasma physics, he widely contributed to the theory of plasma instabilities. Rosenbluth was one of the driving forces behind 50 years of research into controlled thermonuclear fusion.

Meghnad Saha

Meghnad Saha FRS (6 October 1893 – 16 February 1956) was born in Shaoratoli village near Dhaka, British India (present Bangladesh). He was an eminent astrophysicist best known for his work on thermal ionisation of elements, and it led him to formulate what is known as the Saha Equation. This equation is one of the basic tools for interpretation of the spectra of stars in astrophysics used to describe chemical and physical conditions in stars. Saha was the first scientist to relate a star's spectrum to its temperature, developing thermal ionization equations that have been foundational in the fields of astrophysics and astro-chemistry. He was a professor at Allahabad University from 1923 to 1938, and thereafter a professor and Dean of the Faculty of Science at the University of Calcutta until his death in 1956. He became Fellow of the Royal Society in 1927. He was president of the 21st session of the Indian Science Congress in 1934.

Predhiman Krishan Kaw

Predhiman Krishan Kaw (15 January 1948 – 18 June 2017) born in Srinagar (J&K) on 15 January 1948. After finishing his Ph.D. in plasma physics in 1966 at a young age of 18 from Indian Institute of Technology, Delhi, Kaw went to Princeton University, USA, where he worked as a post-doc; and later as an assistant professor. He returned to India in 1971, and after a stint at Physical Research Laboratory, Ahmedabad, as Associate Professor, went back to Princeton in 1975 as a professor. In 1982, he returned to India to initiate and direct the DST founded plasma physics programme at PRL. The Program flourished and grew rapidly; and in 1986, culminated into the establishment of Institute for Plasma Research (IPR), of which Kaw became the founder Director. Under his leadership the Institute carried out construction and operation of the first indigenous tokamak ADITYA, construction and commissioning of superconducting tokamak SST-1, development of a multitude of fusion technologies; and a variety of basic plasma experiments and associated theory and computer simulations. The Institute has successfully developed a number of plasma processing technologies beneficial to the society. In 2005, under his leadership India became a partner in 2005 of the prestigious ITER (International Thermonuclear Experimental Reactor) project with Europe, US, Russia, Japan, China and South Korea. Kaw's research has been in nonlinear plasma physics, where he has contributed many novel ideas related to laser fusion, magnetically confined fusion, dusty plasmas, quark gluon plasmas, non-neutral plasmas, space and astrophysical plasmas, etc. Kaw has been a recipient of numerous national and international awards, including Padmashri.