THE PHYSICS OF
RADIOLOGY AND IMAGING

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(Targeted to postgraduate students of medical physics and radiology, appearing for MSc, DMRD, MD, DNB and FRCR examinations)

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New Delhi • London • Philadelphia • Panama

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The Physics of Radiology and Imaging

First Edition: **2014**

ISBN 978-93-5152-171-6

Printed at

FOREWORD

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It is a great privilege to me for writing the foreword to this book 'The Physics of Radiology and Imaging' written by Professor Dr K Thayalan, Former Professor and Head of the Department of Radiology Physics, Barnard Institute of Radiology, Madras Medical College, Chennai, India. Dr K Thayalan has vast experience in teaching Medical Physics of Radiology, Radiation Oncology and Nuclear Medicine. He authored many textbooks earlier relating to radiological physics and radiological safety; they are being considered as reference books in many institutions and universities.

There has been a long-felt need for comprehensive textbook in the field of physics applied to medical imaging, for medical postgraduates in radiology, medical physicists and technologists, and this book meets the requirement.

This book is a quintessence of basic and applied physics thoroughly explaining principles of physics of computed and digital radiography, image intensifier fluoroscopy, mammography, ultrasound, computed tomography and magnetic resonance imaging. All the chapters are well laid out with good explanations and illustrations. Fundamentals have been brought out in a unique way for easy assimilation into memory of teachers and students. Explanations on image resolution, contrast, artifacts on different modalities are very vivid and nice for good understanding of the complex details.

It was a real pleasure for me to go through the entire contents to write this foreword and readers will agree with me that all details looked for relating to physics of imaging is available in this book. I am sure that this book will be referred globally in the field of medical imaging, helping the residents of FRCR (UK) and MD postgraduates of different universities in India.

R Ravichandran

PREFACE

Radiation has been used in medicine since from the discovery of X-rays in 1895 by the German physicist WC Roentgen. Over the period, its application has grown enormously and it is used today in the form of radiography, fluoroscopy, mammography and computed tomography. Non-radiation tools are also competing in medicine in the form of ultrasound and magnetic resonance imaging. These tools not only provide early differential diagnosis of the disease but also improve the accuracy of clinical diagnosis. The uniqueness of the above tools is that they all work on the basis of physics principle.

Understanding the physics of the above instruments is very much essential, for those connected with radiological sciences. It helps not only the education, but also the equipment selection, its optimal use, maintenance, and safety. Hence, an attempt is made to explain the physical principle, instrumentation, function, its application and limitations in the form of a single book. Attempt is also made to incorporate nuclear imaging and radiological safety in the same book. Large numbers of figures and tables are incorporated wherever it is necessary, for better understanding of the concept. This book is intended for postgraduate students of medical physics, diagnostic radiology, Diplomate National Board (DNB), and FRCR. This is the first book of its kind from an Indian author, giving single solution for the entire range of radiology and imaging equipment.

I am very proud and happy to come out with this book, incorporating my three decades of experience in radiological/medical physics teaching. I am very happy and thankful to Dr R Ravichandran for writing the foreword to this book. I am also thankful to M/s Jaypee Brothers Medical Publishers (P) Ltd., New Delhi, for publishing this book as usual in a neat and elegant manner. Constructive comments are invited from the readers for the future betterment of the book.

I am very much thankful to my wife Tamilselvi, son Parthiban and daughter Kayal Vizhi for their support and cooperation during the book writing process.

I thank and acknowledge Dr Kamakshi Memorial Hospital, Chennai, especially the medical physics division for the support and assistance.

K Thayalan

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1

Fundamental Concepts

MATTER AND ENERGY

Physics is a science dealing with nature. It is concerned with the study of two concepts, matter and energy, and how they interact with each other. Matter is one, which occupies space, and it is made up of molecules or atoms, e.g. gold, wood, water and air. Matter exists in solid, liquid, gas, liquid crystal, and plasma state. Matter can be converted from one form to another by physical or chemical means, e.g. melted ice converts from solid to liquid form by physical process and burning of wood into ash is a chemical process.

Energy is the ability to do work, it has several forms, and it can be converted from one form to another, e.g. human body converts chemical energy (food) into kinetic energy (work). Law of conservation of energy states that energy can neither be created nor destroyed, and the total energy in the universe is constant. This law holds good for all forms of energy.

In general, physicist studies the behavior of matter and energy under different physical conditions.

MEASUREMENT AND UNITS

To study, the matter and energy and their various properties, measurements of physical quantities, such as length, mass, and time are required. Physical quantity is measured accurately in terms of its own standard, e.g. distance is measured in meter, mass in kilogram, and time in second. Therefore, unit is a quantity adopted as a standard of measurement in terms of which similar quantities can be measured. The units which are independent of one another and having their own standard (base) are called fundamental units, e.g. kilogram, meter and second. The units, which are not having their own standard (base) and obtained from the fundamental units are called derived units, e.g. area-meter^2, velocity-meter per second, and density-kilogram per meter^3.

One meter is the distance traveled by light (Krypton-86) in 1/299,792,468 second. One kilogram is the mass of 1000 cm^3 of water at 4°C. The second is measured by an atomic clock and is based on the vibration of atoms of cesium.

SI UNITS

In 1960, a new system of units called Systems International d'units (SI Units) was introduced. The SI system is superior to all other systems and more convenient in practice and is used throughout the world. There are 7 fundamental units and 2 supplementary units in the SI system as shown in the Table 1.1.

TABLE 1.1 **SI system of units**

Physical quantity	Unit	Symbol
Length	meter	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Temperature	kelvin	K
Luminous intensity	candela	cd
Amount of substance	mole	mol
Plane angle	radian	rad
Solid angle	steradian	sr

Conventions for SI Units

i. When the unit is named after a scientist, it should not be written in a capital initial letter, e.g. newton, ampere. The symbol of the unit is expressed in capital letters, e.g. N for Newton.
ii. The symbol of all other units should be written with small letters, e.g. 'm' for meter.
iii. Only singular form of the unit is to be used, e.g. 500 meters is written as 500 m. No full stops or punctuation marks should be used at the end of the symbol.
iv. Space is to be left between the numerical and symbol, e.g. 20 s and not as 20s.
v. Mathematical indices notation should be used than slash sign (/), e.g. meters per second should be written as ms^{-1} not m/s.

TABLE 1.2 Prefixes used with SI units

Prefix	Symbol	Factor
tera	T	10^{12}
giga	G	10^{9}
mega	M	10^{6}
kilo	k	10^{3}
deci	d	10^{-1}
centi	c	10^{-2}
milli	m	10^{-3}
micro	µ	10^{-6}
nano	n	10^{-9}
pico	p	10^{-12}

vi. In the temperature unit Kelvin no degree sign is used, e.g. 273 K and not as 273° K.

Prefixes

Though the SI units are a coherent system, they are found to be either too large or low in practice, e.g. the activity of an isotope for bone scan is expressed in billions of becquerel's. Hence, prefixes are used to overcome the above difficulty, as shown in Table 1.2. These prefixes are conveniently used to describe very large or small physical quantities. In radiation physics, giga becquerel (GBq), kilovolt (kV), centi gray (cGy), milli ampere (mA), and nanometer (nm) are commonly used.

DENSITY, MOLE, PRESSURE, AND GAS LAWS

DENSITY

The density of a body (ρ) is defined as the ratio of its mass (m) and volume (v) and its unit is kgm^{-3}. The density of a body is same, if it is made up of identical material. If its composition is changed, its density will be vary.

$$\rho = m/v$$

The relative density or specific gravity of a substance is the ratio between its density with that of water.

MOLE

The amount of matter in a body is expressed by the number of elementary particles (atoms or molecules) it contains and its unit is mole. One mole of matter contains 6.022×10^{23} elementary particles, and it is known as Avogadro's number.

PRESSURE

The total force acting on a liquid surface is called thrust. The pressure (p) is defined as the force (F) per unit area (A) and its unit is Nm^{-2} or pascal (Pa). The atmospheric pressure is about 1.01×10^5 Pa. The pressure is caused by the weight of material pressing on its surface. It may be also due to collisions of atoms or molecules of a gas within a container. The pressure of a liquid at rest is always perpendicular to the surface in contact with it. The pressure at a point within a liquid is directly proportional to the depth of the point from the free surface, density, and acceleration due gravity.

GAS LAWS

Boyle's law states that the volume (V) of a given mass of gas is inversely proportional to its pressure (P), at constant temperature. Charles's law states that volume of a given mass of gas, at constant pressure, is proportional to its temperature (T). The above two laws can be combined and stated as follows:

$$PV/T = \text{constant}$$

This is known as the perfect gas equation.

MECHANICS

VELOCITY AND ACCELERATION

Displacement (d) is defined as the shortest distance between the initial and final positions of a body. The velocity (v) of a moving body is the rate of change of displacement of the body in a particular direction and its unit is ms^{-1}.The magnitude of velocity is called speed, which is a scalar quantity. Velocity is a measure of how fast the matter is moving or rate of change of its position with time. It is given by the relation;

$v = d/t$, where d is the displacement in t seconds.

Acceleration (a) is defined as the rate of change of velocity and its unit is ms^{-2}. It is a measure of how quickly or slowly the velocity is changing. If the velocity is constant, the acceleration is zero. It is given by the relation

$$a = (v_f - v_0)/t$$

where, v_0 is the initial velocity and v_f is the final velocity, that undergone during the time interval t.

SCALAR AND VECTOR QUANTITIES

All physical quantities can be classified into two broad categories, namely, scalar and vector quantities. Quantities that have only magnitude and no direction are called scalar quantities, e.g. length, mass, time, etc. Quantities that have magnitude as well as direction are called vector quantities, e.g. displacement, velocity, force, etc.

A vector quantity is usually represented graphically by an arrow (→), whose length is proportional to the magnitude of the vector. In an equation, vector quantity is represented by bold letters, e.g. $\mathbf{F} = m\mathbf{a}$, where, force and acceleration are vectors and mass is a scalar quantity.

FORCE

Force is the influence that changes the state of rest or uniform motion of the body along a straight line. If a force F acts on a body of mass m, and produces an acceleration a, then $F = m \times a$. Hence, the force acting on the body is equal to the product of mass of the body and the acceleration produced by the force on the body.

The SI unit of force is newton and it is denoted by the letter N. One newton is the force acting on a body of mass one kilogram producing an acceleration of one ms^{-2} in its direction.

WORK

If a force acts on a body and the point of application of the force moves, then work is said to be done by the force. If the force F moves a body through a distance s in its direction, then the work done by the force is given by $W = F \times s$. The displacement does not always take place in the direction of force. If the direction of displacement s is inclined to F at an angle of θ, then the work done,

$$W = F \cos\theta \times s,$$

where, $F \cos\theta$ is the component of force. The SI unit of work is joule (J). One Joule is the amount of work done, when the point of application of force of one newton acting on a body, moves it through a distance of one meter in the direction of force.

POWER

The rate of doing work is called power. It is measured by the amount of work done in unit time. If W is the work done in time t, then power P = W/t.

The SI unit of power is joule per second (Js^{-1}). It is also given by a special unit watt, which is equal to 1 joule per second. A larger unit of power is called kilowatt, which is equal to 1000 watt. The unit of electrical energy consumption is kilowatt-hour (kWh). One kilowatt-hour is the power consumed at the rate of 1000 watts for one hour. 1 kWh = 1000 × 60 × 60 = 36,00,000 watt per second = 36,00,000 joules. The older unit of power is horse power (HP), and 1 HP is equal to 746 watts.

ENERGY

The Energy of a body is its ability to do work. It is measured by the amount of work that it can perform. The SI unit of energy is joule. The electron volt (eV) is also used as unit of energy in radiation physics. There are many forms of energy, such as mechanical energy, heat energy, light energy, electrical energy, chemical energy, atomic energy, etc. There are two forms of mechanical energy, viz. potential energy and kinetic energy.

Potential Energy

The potential energy of a body is the energy it possesses by virtue of its position or state of strain, e.g. water stored up in a reservoir, a wound spring, compressed air, etc. For a body of mass 'm' remaining at rest at a height h above the ground, the potential energy is equal to the work done in raising the body from the ground to that height.

The work done = force × displacement
= mg × h
Potential energy = mgh joule, where 'g' is the acceleration due to gravity.

Worked Example 1.1

A patient of weight 50 kg on a wheel chair has to be lifted onto a examination couch, which is 25 cm higher than wheel chair. Calculate the work done to carry out the above task ($g = 9.81\ ms^{-2}$).

$$\begin{aligned} W &= \text{Force} \times \text{distance} \\ &= mg \times \text{distance} \\ &= 50 \times 9.81 \times 0.25 \\ &= 120 \text{ J} \end{aligned}$$

The work done in lifting the patient on to the couch needs 120 J energy, which will increase the potential energy of the patient.

Kinetic Energy

The kinetic energy of a body is the energy possessed by the body by virtue of its motion. Let a body of mass m moves with a velocity v, then,

$$\text{Kinetic energy} = (1/2)\ mv^2 \text{ joule}$$

Worked Example 1.2

A film cassette of mass 2 kg is kept in a shelf at a height of 1.5 m, possess a potential energy of 25 J. If the cassette falls on to the floor, what will be its speed?

$$\begin{aligned} \text{Kinetic energy} &= \tfrac{1}{2} \times 2 \times v^2 \\ 25 &= \tfrac{1}{2} \times 2 \times v^2 \\ v &= 5 \text{ ms}^{-1} \end{aligned}$$

The cassette may fell on the floor with a speed of 5 ms^{-1}.

MOMENTUM

The momentum (P) of a moving body is the product of mass (m) and velocity (v) and it is given the relation:

$$P = mv$$

The momentum is a vector quantity and its direction is the same as its velocity, the unit is kg-ms^{-1}.

TEMPERATURE AND HEAT

Matter is made up of atoms or molecules. These atoms and molecules are in regular movement in solids and random movement in liquids and gases. They possess potential energy as well as kinetic energy. The total energy of the molecules in the system is called as internal energy of the system. The kinetic energy is responsible for the hotness and coldness of the body.

Temperature is the measure of hotness and coldness of the body. When a body is heated, its molecules are in vigorous movement, and therefore have high energy, and the body is said to be in high temperature. When a body is cooled lower and lower, its kinetic energy decreases, and the body is said to be in lower temperature. Change of temperature may alter the electrical resistance, conductivity, viscosity and rate of chemical reaction of the substance, e.g. change of body temperature alter metabolism. Temperature is measured in degrees with the help of thermometers. There are three scales of temperature, namely, (i) Celsius scale, (ii) Kelvin scale, and (iii) Fahrenheit scale.

Celsius Scale

In this scale, the temperature of the melting of ice is zero (0°C) and temperature of the boiling water is 100°C. The range between melting point and boiling point is divided into 100 intervals called degrees.

Kelvin Scale

In the Kelvin scale or absolute scale of temperature, 0 degree is named as absolute zero and it is denoted as 0 K. The absolute zero is the temperature at which the molecules will have zero speed. In this scale, the temperature of melting ice is 273.15 K and the temperature of boiling water is 373.15 K. The range between the two is divided into 100 intervals. One interval is the same in both centigrade and Kelvin scale of temperature. The 0 K temperatures is equal to –273°C in Celsius scale. At 0 K, the atomic particles are at rest and hence, it is called absolute zero. It means that the body do not have internal energy at absolute zero.

Fahrenheit Scale

In this scale, the melting ice is at 32°F and boiling water is at 212°F. The entire range is divided into 180 degrees. The body temperature is about 98.4°F equal to 37°C or 310 K. The relation between Celsius and Fahrenheit scale is given by

$$C/100 = (F - 32) \div 180 \text{ or } 1.8\ C = F - 32, \text{ or } C = (F - 32) \div 1.8$$

Worked Example 1.3

Convert 86° F into degrees of celsius

Here $F = 86$

$C = (F - 32) \div 1.8 = (86–32) \div 1.8 = 54 \div 1.8 = 30°C.$

HEAT

Heat is a form of internal energy, which can be transferred from one part of the body to another. If a hot body and a cold body are placed in close contact, the hot body will transfer some of its heat energy to the cold body until the temperature of the two become equal. The difference in temperature creates temperature gradient. There are three methods of heat transfer, namely, conduction, convection and radiation.

Conduction

It is the process in which heat energy is transferred by collisions between neighboring atoms, without the visible motion of the particles. Conduction takes place in solids, liquids and gases. Let us consider a rod of length L and area A and temperature θ_1 and θ_2 of at their ends. The rate of flow of heat (dQ/dt) is directly proportional to cross-sectional area (A), temperature gradient $(\theta_1 - \theta_2)/L$ and thermal conductivity (k) of the material. The thermal conductivity of a material is its inherent ability to conduct thermal energy and it is expressed in $Wm^{-1}K^{-1}$. The relation for thermal conductivity is given by

$$dQ/dt = kA\ (\theta_1 - \theta_2)/L$$

The thermal conductivity of various materials are listed in Table 1.3. Metals in general are good conductors of heat, e.g. silver, copper, etc. Nonmetals are bad conductors of heat, e.g. glass, rubber, wood, etc.

Convection

It is the process in which heat energy is transferred by the actual motion of the particles of the body. Heat in liquid causes the fluid to expand and making it less dense and starts rising. The cold, dense fluid molecules move to their place from other area. Convection takes place in liquids

TABLE 1.3 Thermal conductivity of various materials

Material	Specific heat capacity, $Jkg^{-1}K^{-1}$	Thermal conductivity, $Wm^{-1}K^{-1}$ at 20°C
Aluminum	910	237
Tungsten	136	178
Molybdenum	246	140
Graphite	711	130
Copper	386	401
Rhenium	138	48
Water	4200	0.59
Glass	67	0.9–1.3

and gases, e.g. trade winds, land and sea breezes. Convection current in air remove heat from X-ray tube housing to the atmosphere. Oil and then water circulation remove heat from large X-ray systems like CT scan. Convection forms the basis for domestic heating system and air-conditioning. Convection may be caused by natural or forced circulation

Radiation

It is the process by which heat energy is transmitted from one place to another without the aid of any material medium. When a body has internal energy, its atoms and molecules vibrate and emits electromagnetic radiation, which can transport energy across a vacuum, e.g. heat reaches the earth from the sun. A black body and matt surface will radiate and absorb energy efficiently, while white and glossy surface will not. Stefan's law states that the rate of heat energy emission (dQ/dt) is directly proportional to the area of the emitting surface (A) and the fourth power of its temperature (T)

$$dQ/dt \propto \sigma A T^4$$

where, σ is the Stefan–Boltzmann constant = 5.670×10^{-8} W $m^{-2}K^{-4}$

The SI unit of heat is joule. However, the special unit calorie is still in use. One calorie is the amount of heat which will raise the temperature of one gram of water by one degree Celsius. 1 calorie = 4.2 joules.

HEAT CAPACITY

The heat capacity of a material is the heat required to raise its temperature by 1 K. It is independent of material size or shape and expressed in JK^{-1}. The heat required to raise temperature of a 1 kg material by 1K is called specific heat capacity, and it is expressed in $Jkg^{-1}K^{-1}$.

ATOMIC STRUCTURE

All matter is composed of elements and compounds. Elements are the simplest chemical entity, which cannot be broken further, e.g. hydrogen, carbon. Two or three elements form a compound, e.g. water. The smallest particle of an element is the atom, which forms the fundamental unit of matter. The atoms are very small and its diameter is of the order of 10^{-10} m. Every atom posses a central core called a nucleus, which is positively charged. The diameter of the nucleus is of the order of 10^{-14} m (Fig. 1.1).

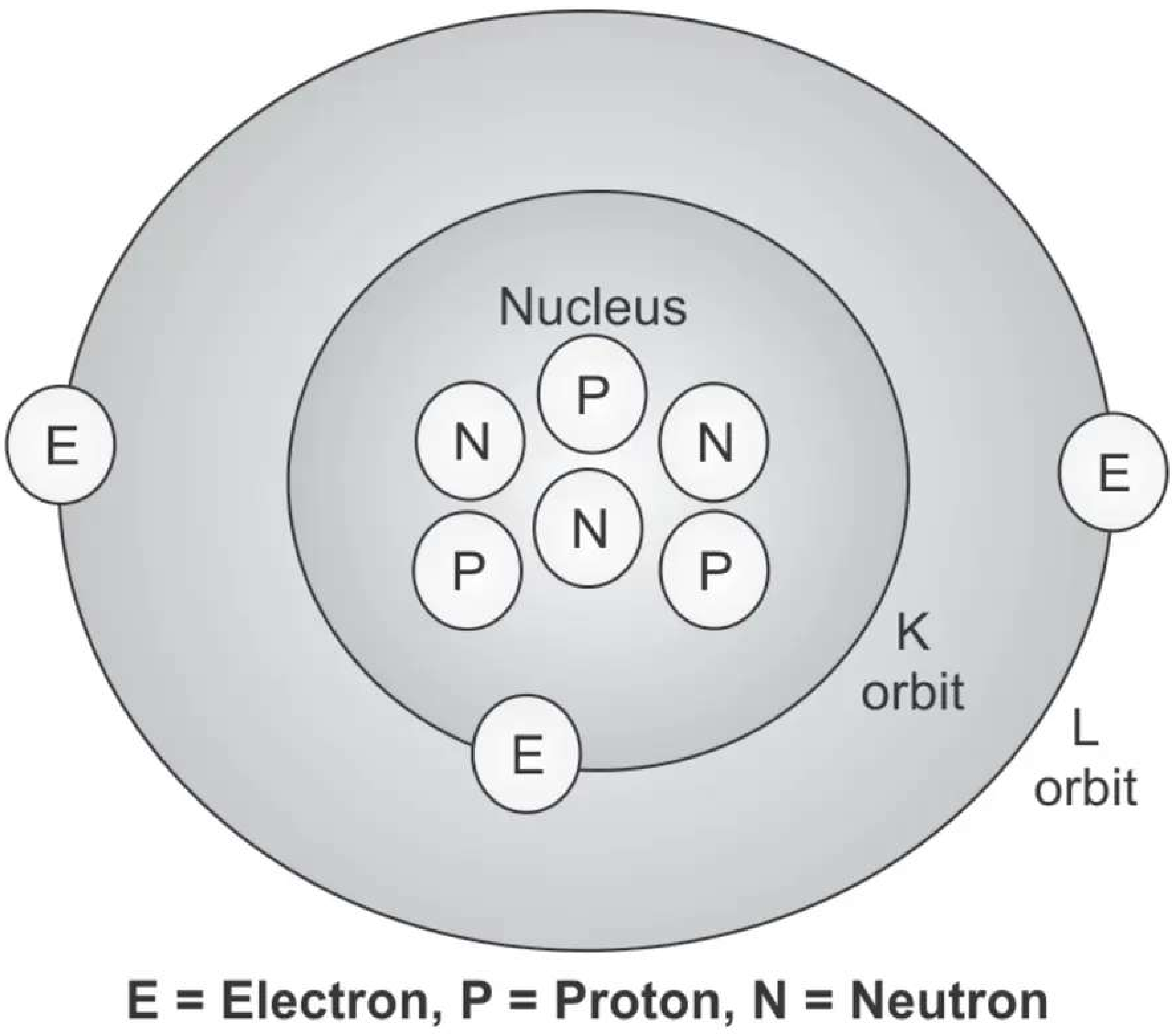


FIG. 1.1: Atomic structure

The nucleus consists of two particles called protons and neutrons and collectively known as nucleons. The protons are positively charged and the neutron has no charge. The space around the nucleus consists of another important particle, called electron. The electrons are negatively charged particle, and they circulate around the nucleus at varying distances, similar to planets rotation around the sun. The number of electrons in an atom is equal to the number of protons and hence, atom is said to be neutral.

There are two types of forces exist in the nucleus. The electrostatic repulsive force, exist between particles of similar charge. The strong forces (attractive) resulting from the exchange of pions among all nucleons, hold the nucleus together. These two forces act in opposite directions. The nucleus has energy level and the lowest energy state is called the ground state. Nuclei with energy excess of the ground state are said to be in an excited state. Excited states that exists $> 10^{-12}$ s are referred to as meta stable or isomeric states.

ATOMIC NUMBER AND MASS NUMBER

In 1913, HGJ Mosley stated that the atomic number of an atom is the number of protons in the nucleus. It is also equal to the number of electrons of the atom, which is represented by Z. The mass number of an atom is the total number of protons and neutrons in the nucleus and it is denoted by A. An element (X) is symbolically described as $_{Z}X^{A}$. The subscript gives the atomic number Z while superscript gives the mass number A. Some of the important elements, their symbol, atomic number and mass number are given in Table 1.4.

TABLE 1.4 Symbol, atomic number, and mass number of few elements

Element	Symbol	Atomic No. (Z)	Mass No. (A)
Hydrogen	H	1	1, 2, 3
Aluminum	Al	13	27
Cobalt	Co	27	59, 60
Copper	Cu	29	63, 65
Tin	Sn	50	116, 118, 120
Iodine	I	53	125, 127,131
Cesium	Cs	55	133, 134, 137
Barium	Ba	56	137, 138
Tungsten	W	74	182, 183, 184, 186
Lead	Pb	82	206, 207, 208
Radium	Ra	88	224, 226, 228

EFFECTIVE ATOMIC NUMBER

The effective atomic number (Z_{eff}) is meant for a compound or mixture, which has more than one element. Z_{eff} is the atomic number of an element with which photons interact the same way as with the given composite material. Mayneord has defined the effective atomic number as follows:

$$Z_{eff} = (a_1 Z_1^{2.94} + a_2 Z_2^{2.94} + \ldots\ldots a_n Z_n^{2.94})^{1/2.94}$$

where, $a_{1,}$ a_2…… a_n are the fractional contribution of each element to the total number of electrons in the mixture. The density and effective atomic number of few compounds are given in Table 1.5.

ISOTOPES

The atoms composed of nuclei with the same number of protons but different number of neutrons is called isotopes. In other words, isotopes have the same atomic numbers and different mass numbers, e.g. hydrogen have 3 isotopes, namely:

${}_1H^1$ have 1 proton (Hydrogen),
${}_1H^2$ have 1 proton and 1 neutron (Deuterium)
${}_1H^3$ have 1 proton and 2 neutrons (Tritium).

Isotopes of an element have the same chemical properties but have different physical properties. Isotopes capable of performing radioactivity are called radio-isotopes and their nucleus is said to be unstable. Nuclides

TABLE 1.5 Density and effective atomic number of few compounds

Material	Effective atomic number (Z_{eff})	Density (ρ), $kgm^{-3} \times 10^{-3}$
Air	7.78	1.205
Muscle	7.64	1.04
Water	7.5	1.0
Bone	12.3–14	1.65
Fat	6.46	0.916
PMMA	6.56	1.18
Polystyrene	5.74	1.044
LiF	8.31	2.675

having the same mass numbers but different number of protons are called isobars. Nuclides having same number of neutrons but different number of protons are called isotones. An isomer is the excited state of a nucleus, and it will have same number of proton and neutron.

ELECTRON SHELLS

In 1921, Burry and Bohr independently gave a scheme for the arrangement of electrons in an atom. According to this scheme, the orbits in the atom are named as shells and denoted as K, L, M, N, etc., from the nucleus. The following are the rules of their scheme: The maximum number of electrons in each shell can be obtained from the formula $2n^2$ where n = 1, 2, 3, 4, etc. In the case of K shell, n = 1, the number of electrons in the K shell = $2 \times 1^2 = 2$. In the case of L shell, n = 2, the number of electrons in the L shell = $2 \times 2^2 = 8$ and so on. Each shell is provided with subshells, which are denoted as s, p, d, f, etc. The K shell (n = 1) has one subshell, namely, 1s. The L-shell (n = 2), has two subshells, namely, 2s and 2p and so on. One electron in the s subshell of K shell is denoted as $1s^1$, while 2 electrons in the same subshell is denoted as $1s^2$.

The outermost orbit is called valence shell, which is responsible for chemical, thermal, optical and electrical properties of the element. No valence shell has more than 8 electrons, e.g. metals have one, two or three valence electrons. The elements are arranged in the periodic table based on the similarities of chemical properties of different elements. As we go across the periodic table the atomic number of the atom increases. The number of electron also increases in the same step.

QUANTUM NUMBER

The energy level of an electron or position in an atom is described by quantum numbers as follows:

i. The principle quantum number (n) defines the main energy level or shell of an orbiting electron. For K shell, $n = 1$; for L shell, $n = 2$ and so on.
ii. The azimuthal quantum number (l) describes the angular momentum of the orbiting electrons. It can have values 0, 1, 2, 3…. n-1, e.g. M shell principal quantum number is 3 and its azimuthal quantum numbers are $3 - 1 = 2$, which are 0, 1 or 2.
iii. The magnetic quantum number (m) describes the spatial orientation of the plane of the orbiting electron and it can have values from $-l$ to $+l$. When $l = 1$, m can have -1, 0, $+1$ values.
iv. The spin quantum number (s) describes direction of spin of the electron and it can value $+1/2$ (spin up) or $-1/2$ (spin down).

IONIZATION

Removal of one or more electrons from a neutral atom is called ionization. After ionization, the remainder of the atom is left with positive charge and is known as positive ion. The positive atom and the removed electrons form one ion pair.

BINDING ENERGY

The binding energy of an electron in an atom is the energy required to remove the electron completely from the atom against the attractive force of the positive nucleus. The magnitude of the binding energy depends on the atomic number and the shell from which the electron is being removed. It is greater for elements of higher atomic number and greatest for the K shell (inner most shell).

Binding energies are negative because they represent amounts of energy that must be supplied to remove electrons from atoms. Electron shells are often described in terms of the binding energy of electrons occupying the shells, e.g. the binding energy of hydrogen K shell is – 13.5 eV and – 3.4 eV for L shell. The K-shell binding energies of various elements are given in Table 1.6.

EXCITATION

In an atom, if energy is supplied, the electrons can be moved from the inner orbit to the outer orbit. Now, the atom will have more energy than its

TABLE 1.6 Atomic number (Z) and binding energies (E_k) of few elements

Element	Z	E_k, keV
Aluminum	13	1.6
Calcium	20	4
Molybdenum	42	20
Iodine	53	33
Barium	56	37
Gadolinium	64	50
Tungsten	74	70
Lead	82	88

normal state. It is said to be in an excited state and the process is known as excitation. For example, to move an electron from K to L shell of the hydrogen atom, the energy required is (–3.4 eV) – (–13.5 eV) = 10.1 eV.

ELECTRON VOLT

The electron volt (eV) is the unit of energy in radiation physics, where it deals with microscopic objects. One electron volt is the kinetic energy imparted to an electron accelerated across a potential difference of one volt. In practice, we use kiloelectron volt (keV) and million electron volt (MeV) and

$$1 \text{ eV} = 1.6 \times 10^{-19} \text{ J} = 1.6 \times 10^{-12} \text{ erg} = 4.4 \times 10^{-26} \text{ kWh}$$

The electron volt describes potential as well as kinetic energy. The binding energy of an electron in an atom is a form of potential energy and it is expressed in keV.

ELECTROMAGNETIC RADIATION

An electric charge is surrounded by an electric field and if the charge moves, a magnetic field is produced. When the charge undergoes an acceleration or deceleration, the magnetic and the electric fields of the charge will vary. The combined variation of the electric and magnetic fields results in loss of energy. The charge radiates this energy in a form known as electromagnetic radiation. The electromagnetic radiation moves in the form of sinusoidal waves (Fig. 1.2). The nature of the electromagnetic radiation (X-rays, ultraviolet, etc.) depens on the way in which the electric charges are disturbed. Electromagnetic radiations are transverse waves that transfer energy away from the electric charge. Electromagnetic radiations may be absorbed or scattered in a medium, resulting in loss of energy.

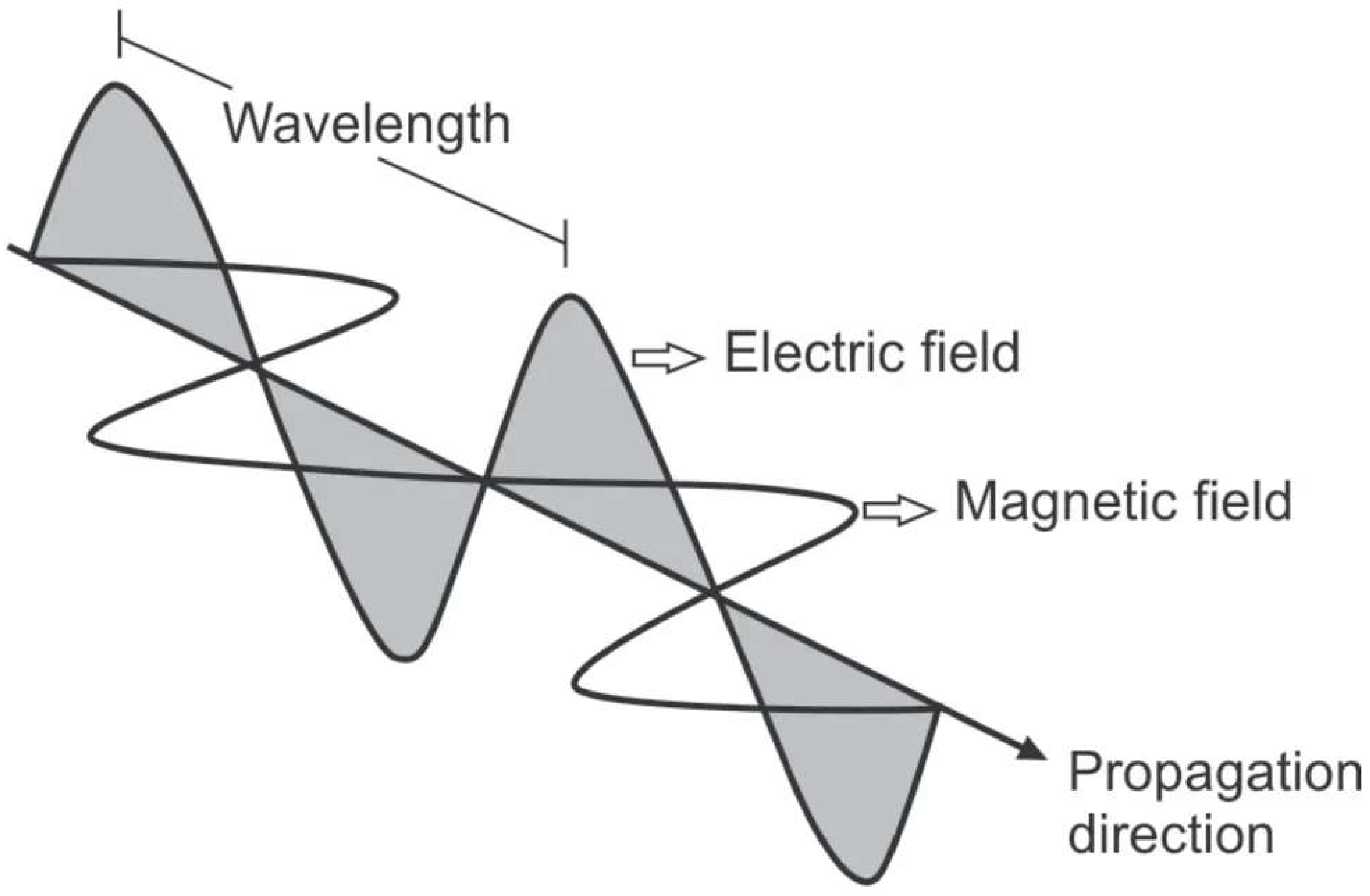


FIG. 1.2: Electromagnetic wave

WAVE CHARACTERISTICS

The electromagnetic wave have wavelength (λ), frequency (ν), and velocity (c). The distance between two consecutive positive peaks is known as wavelength. The number of cycles of the wave which pass a fixed point per second is known as the frequency of the wave. The velocity of the wave is the distance traveled per second by the wave. The relation between wavelength, frequency, and velocity of the electromagnetic wave is

$$c = \nu\lambda$$

All electromagnetic waves, travel at the same velocity in a given medium and its velocity in vacuum is about 2.998×10^{8} ms^{-1}. The wavelength of X-rays and gamma rays are in nanometers (nm).

PARTICLE CHARACTERISTICS

Though electromagnetic radiations have the properties of waves, they also behave like particle during interaction with matter. The actual amount of energy (E) carried by a photon is given the equation $E = h\nu$, where, h is the Planck's constant = 6.63×10^{-34} J. Substituting the value of $\nu = c/\lambda$ in the above equation, the energy

$$E\ (\text{keV}) = hc/\lambda = 1.24/\lambda$$

where, λ is in nanometer (nm). It is seen that the energy of the photon is inversely proportional to its wavelength and as the wavelength decreases, the energy increases.

MASS ENERGY EQUIVALENCE

Einstein's theory of relativity states that mass and energy are equivalent and are interchangeable. In any reaction, the sum of the mass and energy must be conserved. Einstein showed that the speed of some nuclear processes approach the speed of light. At these speeds, mass and energy are equivalent.

$$E = mc^2$$

where, E represents the energy equivalent to mass 'm' at rest and 'c' is the speed of light in a vacuum. For example, the energy equivalent of an electron of mass 9.109×10^{-31} kg is

$$\begin{aligned} E &= 9.109 \times 10^{-31}\ \text{kg} \times (2.998 \times 10^{8}\ \text{m/s})^2 \\ &= 0.511\ \text{MeV} \end{aligned}$$

ELECTROMAGNETIC SPECTRUM

Electromagnetic spectrum includes radiowaves, microwaves, infrared, visible light, ultraviolet, X-rays, gamma rays and cosmic rays (Fig.1.3). All of them travel at a velocity 'c' in a vacuum. The wavelength and photon energy of the whole range of electromagnetic radiation are summarized in Table 1.7.

IONIZING RADIATION AND NON-IONIZING RADIATION

Ionization is a process of removal of electron from neutral atom. The radiation which does ionization in a medium, by removal of electron is called ionizing radiation, e.g. UV, X-rays, and gamma rays have sufficient energy to do ionization. As a result, ionized atoms and molecules or ion-pairs are produced. This forms the basis for biological effects of radiation. Radiation that do not have sufficient energy to produce ionization are called non-ionizing radiation, e.g. visible light, infrared, radiowaves, and TV broadcasts, etc.

FLUORESCENCE

When electromagnetic radiation falls on a phosphor, visible or ultraviolet light is emitted from the phosphor and it is called as luminescence. The electromagnetic radiation raises the valence electrons to the conduction band, which return to the valence band to fill up the holes. As electron falls through the luminescence centers, they emit the surplus energy in the form of flashes of light, called luminescence. If the luminescence is instantaneous, within 10^{-8} s, it is called fluorescence.

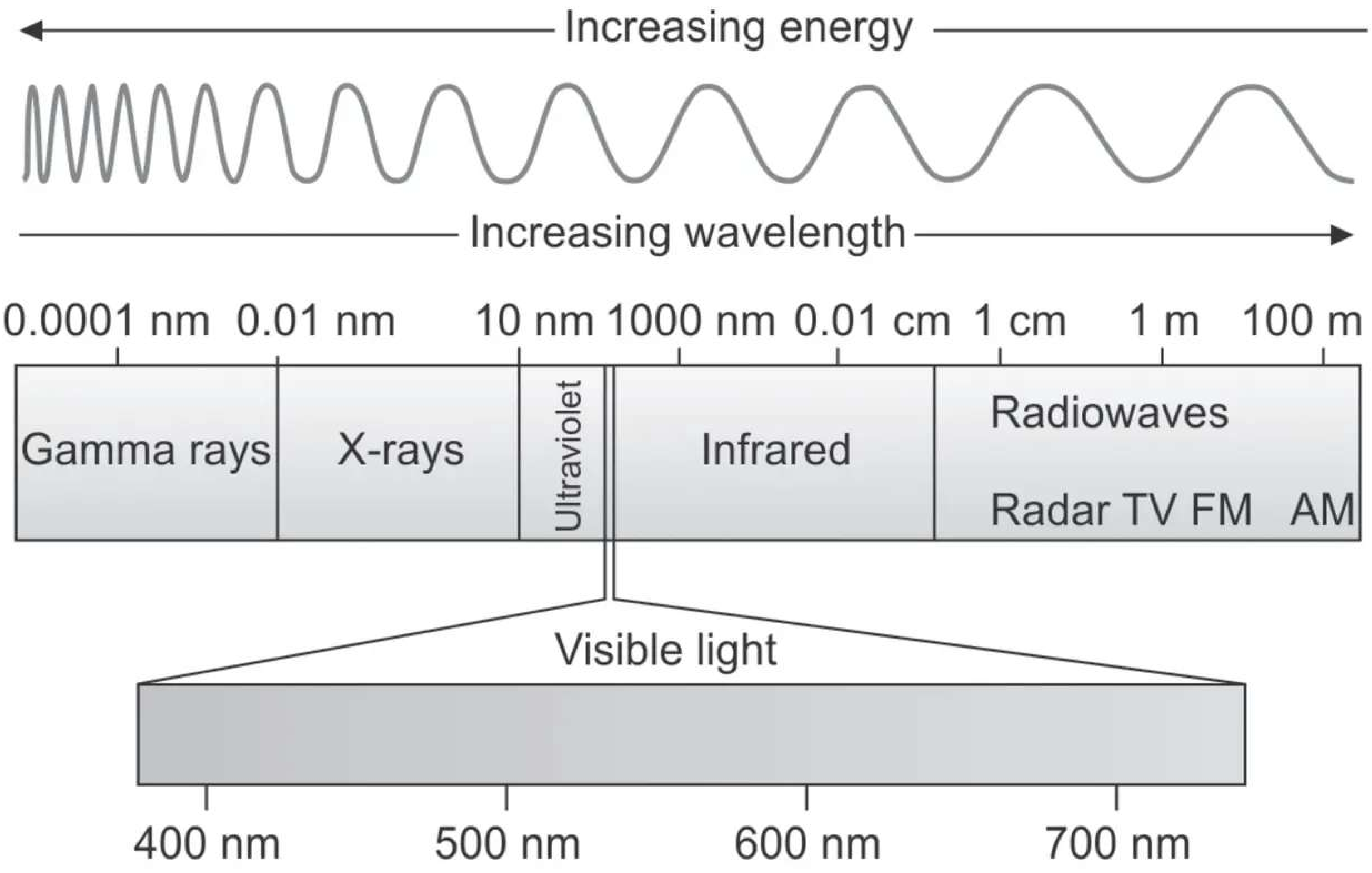


FIG. 1.3: Electromagnetic spectrum

TABLE 1.7 Electromagnetic radiation spectrum

Radiation	Wavelength	Frequency	Energy
Radiowaves	1000 – 0.1 m	0.3 – 3000 MHz	0.001 – 10 μeV
Microwaves	100 – 1 mm	3 – 300 GHz	10 – 1000 μeV
Infrared	100 – 1 μm	3 – 300 THz	10 – 1000 meV
Visible light	700 – 400 nm	430 – 750 THz	1.8 – 3 eV
Ultraviolet	400 – 10 nm	750 – 30000 THz	1.8 – 100 eV
X- and gamma rays	1 nm – 0.1 pm	$3\times10^5 - 3\times10^9$ THz	1 keV – 10 MeV

The energy of light emitted depends on the difference in energy across the luminescence centers. It is always less than the energy which originally stimulated the fluorescence, e.g. a phosphor exposed to ultraviolet may emits visible light. Fluorescent phosphors, such as thallium activated sodium iodide (NaI:Tl, gamma camera), terbium activated gadolinium oxysulfide (intensifying screen) and sodium activated cesium iodide (image intensifier) are used in diagnostic radiology.

If the emission of light is delayed beyond 10^{-8} s, it is called phosphorescence. When the valence electrons are stimulated, they get trapped in the conduction band. They acquire energy from the atom (internal energy) and return to the valence band by emitting luminescence. It is a random process, which takes time to accomplish. The emission of light decays exponentially with a time constant, that depends upon the temperature of the phosphor.

INVERSE SQUARE LAW

The intensity of electromagnetic radiation is inversely proportional to the square of the distance from its source. Let us consider a point source ‘s’, emitting radiation at constant rate. The radiation spread over the inner surface of an imaginary sphere of radius d with surface area $4\pi d^2$. Then the radiation intensity at a point ‘d’ is given by the relation

$$I \propto 1/d^2$$

The inverse square law is based on the following assumptions:

i. The source of radiation is a point source.
ii. The radiation travels in straight lines.
iii. The radiation is emitted equally in all directions.
iv. The energy is radiated at a constant rate.
v. No radiation energy is lost on its way from the source to the point of measurement.

Let 100 mR be the radiation exposure at 1 m for a point source (Fig. 1.4). The radiation exposure at 2 m is found to be 25 mR, by inverse square law. Hence, if distance is doubled, the radiation is reduced by a factor of 4. Keeping higher distance always reduce radiation exposure.

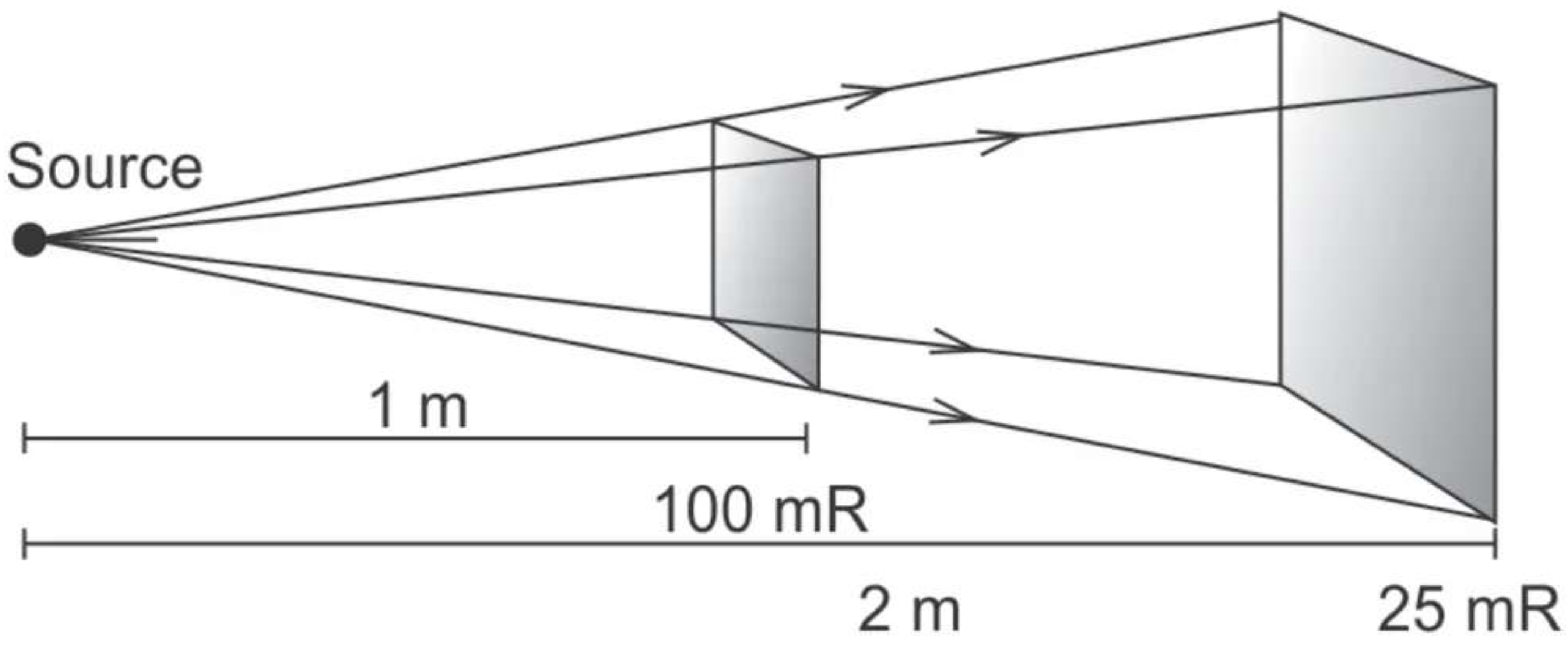


FIG.1.4: Inverse square law

RADIOLOGICAL MATHEMATICS

LOGARITHMS

The logarithm of a decimal number is the exponent to which the base must be raised to produce the number. For example, the logarithm of 1000 to base 10 is 3, because 1000 is 10 to the power 3: $1000 = 10^3 = 10 \times 10 \times 10$. More generally, if $x = b^y$, then y is the logarithm of x to base b, and is written as $\log_b(x)$, so $\log_{10}(1000) = 3$. There are three types of logarithms, namely, common logarithm ($\log_{10}$), natural logarithm ($\log_e$), and binary logarithms ($\log_2$), where ‘e’ = 2.71828, e.g. $\log_{10}2 = 0.301$, the base 10 must raised to power of 0.301, $10^{0.301} = 2$.

Similarly, $\log_e 2 = 0.693$, the base 'e' must be raised to power of 0.693, $e^{0.693} = 2$.

The measurements of optical density and sound intensity are expressed in logarithm to base 10. Radioactive decay, and X-ray attenuation uses logarithm of base 'e', which is denoted by $\ln_e$ (natural logarithm). Logarithmic scales reduce wide-ranging quantities to smaller scopes. Logarithm is useful to describe many radiation events such as X-ray absorption, radioactive decay, etc.

GRAPHS

Graph gives the relationship between physical quantities, plotted as series of points or lines with reference to the set of axis. A Cartesian graph has two axis, namely, 'x' axis called abscissa and 'y' axis called ordinate. The x axis contains independent variable (time, distance) and the 'y' axis contains dependent variable (velocity, exposure).

If a physical quantity 'y' varies with 'x' in a proportional way, then a linear plot can be drawn. It is straight line graph obeying the equation

$$y = mx + c$$

where, m is the slope of the line and c is the intersection with the y axis.

Logarithmic functions such as e^x and e^{-x} can also be plotted as curve, where a rapid increase or rapid decrease may be seen. A semi-log graph is a way of visualizing such data that are changing with an exponential relationship. One axis is plotted on a logarithmic scale and the other in linear scale. On a semi-log graph the spacing of the scale on the y-axis is proportional to the logarithm of the number, not the number itself. It is equivalent to converting the Y values to their log, and plotting the data on linear (lin-lin) scales. The term log-lin is used to describe a semi-log plot with a logarithmic scale on the y-axis, and a linear scale on the x-axis (Fig.1.5).

This kind of plot is useful when one of the variables being plotted covers a large range of values and the other has only a restricted range. The advantage being that it can bring out features in the data that would not easily be seen if both variables had been plotted linearly. Semi-log plot requires only few measurements of the exponential function.

TRIGONOMETRY

Trigonometry is a mathematics which deals with triangles and the relation between angle and sides (Fig.1.6). If one angle of a triangle is

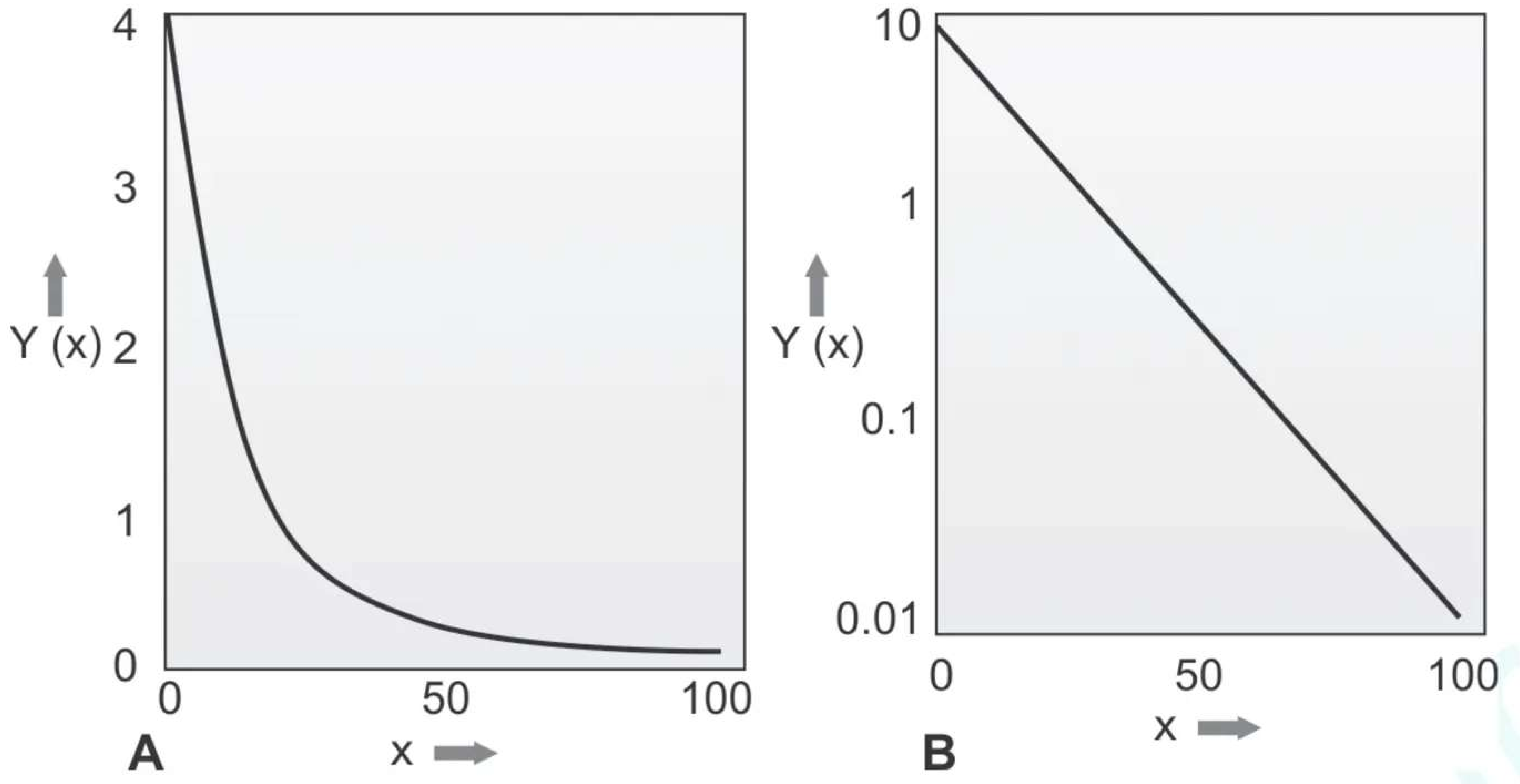


FIG. 1.5: (A) In a lin-lin (linear) graph; (B) Log-lin (semi-log) graph

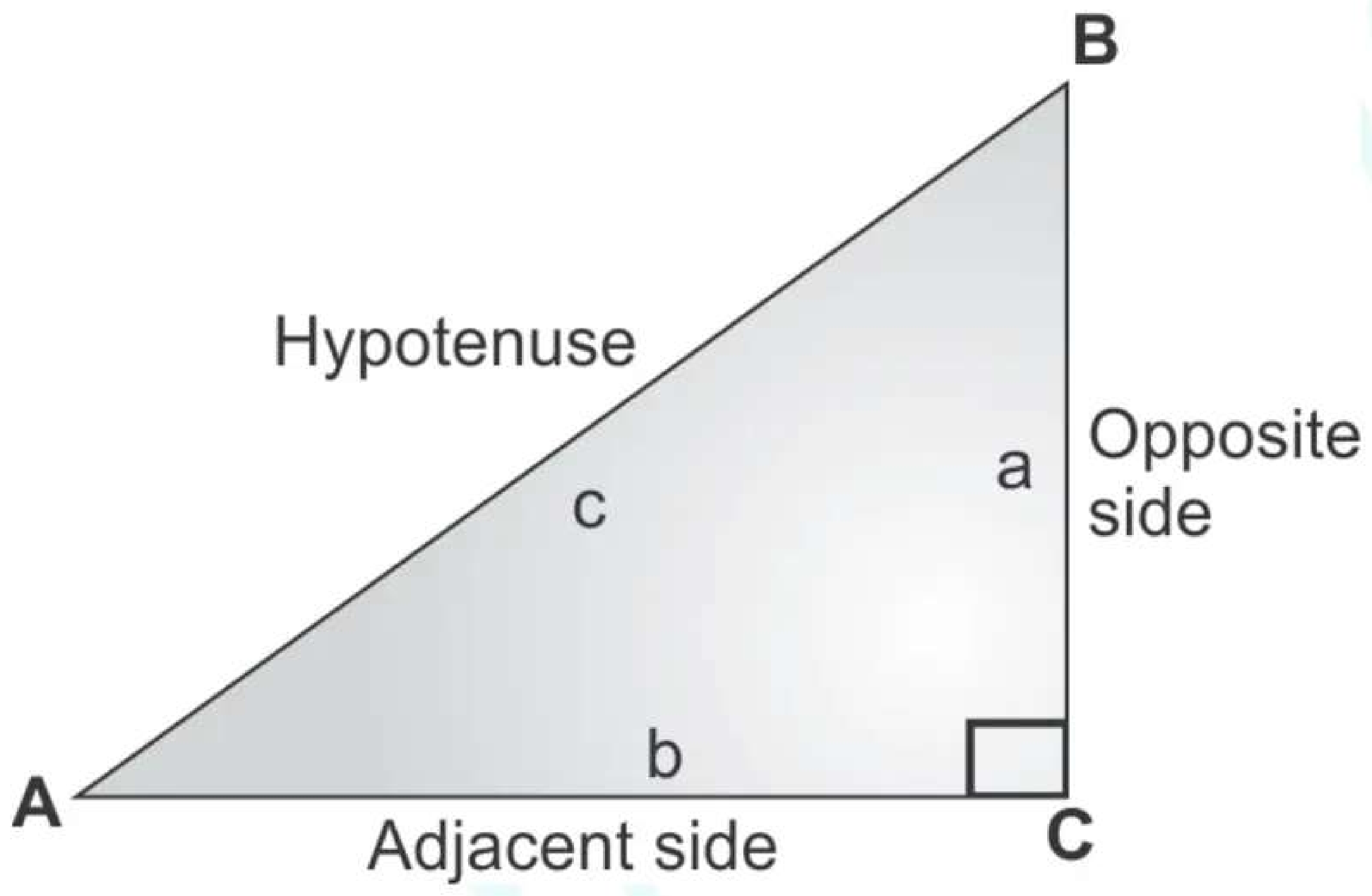


FIG. 1.6: Relation between angles and sides in a trigonometry

90 degrees and the other angle is known, then the third angle can be obtained easily. Since the sum of the angles is 180 degrees, the two acute angles therefore added up to 90 degrees, they are said to be complementary angles. The shape of a triangle is determined by the angles. Once the angles are known, the ratios of the sides can be determined, regardless of the overall size of the triangle. If the length of one of the sides is known, the other two can be determined. These ratios are given by the following trigonometric functions of the known angle A, where a, b and c refer to the lengths of the sides in the accompanying figure:

Sine function (sin), defined as the ratio of the opposite side to the hypotenuse.

$$\text{Sin A} = \frac{\text{Opposite side}}{\text{Hypotenuse}} = a/c$$

Cosine function (cos), defined as the ratio of the adjacent side to the hypotenuse.

$$\text{Cos A} = \frac{\text{Adjacent side}}{\text{Hypotenuse}} = b/c$$

Tangent function (tan), defined as the ratio of the opposite side to the adjacent leg.

$$\text{Tan A} = \frac{\text{Opposite side}}{\text{Adjacent side}} = a/b$$

The hypotenuse is the side opposite to the 90 degrees angle in a right triangle; it is the longest side of the triangle, and one of the two sides adjacent to angle A. The adjacent leg is the other side that is adjacent to angle A. The opposite side is the side that is opposite to angle A. The terms perpendicular and base are sometimes used for the opposite and adjacent sides, respectively.

STATISTICS

Source of errors: There are three types of errors in measurements, namely, systemic error, random error and blunder. Systemic error occurs when measurements differ from the correct values in a systemic fashion. Random error is caused by random fluctuations in the measurement process itself. The processes by which radiation is emitted and by which radiation interacts with matter are random in nature. Therefore, all radiation measurements are subject to random error. The counting statistics helps us to judge the validity of measurements.

Accuracy and precision: If a measurement is close to the correct value, it is said to be accurate. If measurements are reproducible, they are said to be precise. Precision does not imply accuracy. If a set of measurements differ from the correct value in a systematic fashion, the data are said to be biased.

Mean, median and standard deviation

The mean is the arithmetic average of a group of data. The mean (x) of a set of measurements is defined as

$$x = \frac{x_1 + x_2 + x_3 + \ldots\ldots\ x_N}{N}$$

where, N is the number of measurements. The median is measure of the central tendency and is the value that separates the data in half and defines the 50%. It is the middle most measurement, if the number of measurements is odd. It is the average of the two middle most measurements, if the number measurements are even. For example, the median of the five measurements 5, 8, 9, 12 and 14 is 9.

The variance (σ^2) and standard deviation (σ) are measures of the variability of a set of measurements. The standard deviation is used to describe the spread of a data set and is the square root of the average of the square of all the sample deviations. The variance is determined from a set of measurements as follows

$$\sigma^2 = \frac{(x_1 - x)^2 + (x_2 - x)^2 + \ldots..(x_N - x)^2}{N - 1}$$

where, N is the total number of measurements and x is the sample mean. The standard deviation is the square root of the variance,

$$s = \sqrt{\sigma^2}$$

When samples are taken from a large population, there is uncertainty between the sample mean and the actual population mean. This is measured by the standard error, given by the relation

$$\text{Standard error} = \sigma/\sqrt{N}$$

The coefficient of variation (CV) is a measure of spread within the samples, given in percentage. It is given by the relation

$$CV = (\sigma / x)100$$

where, σ / x is the fractional error in the measurements.

2

Electricity, Electronics and Magnetism

ELECTRIC CHARGE

The term electric is derived from the Greek word electron. Electric bodies said to possess electric charge (q) and it is a basic property of any matter. There are two types of charges, namely, (i) positive charge and (ii) negative charge. Two like charges repel each other and two unlike charges attract each other. The unit of charge is coulomb. One coulomb (C) is defined as the quantity of charge which when placed at a distance of 1 meter in air or vacuum from an equal and similar charge experiences a repulsive force of 9×10^{-9} N. The amount of charge in an electron is equal to 1.6021×10^{-19} coulombs.

The charges can neither be created nor be destroyed, and the total amount of charge in the system does not change. While calculating the total charge in a system, the signs of the charges should be taken into account.

ELECTRICAL FORCE AND FIELD

The force between two charged particles is directly proportional to the product of the magnitude of the charges and inversely proportional to the square of the distance (r) between them. If F is the force between two charges q_1 and q_2, separated by a distance r then,

$$F = \frac{q_1 q_2}{4\pi \varepsilon r^2}$$

where, 'ε' is the absolute permittivity of the medium. The permittivity of free space is $8.85 \times 10^{-12}\ C^2 N^{-1} m^{-2}$. The force between the particles may be a attractive force or repulsive force.

The space surrounding an electric charge in which another charge experiences a force is called an electric field. The electrical field strength

(E) at a point is the force experienced by a unit positive charge kept at that point and it is given by

$$E = F/q \text{ newton/coulomb}$$

Electric field is a vector quantity and has a magnitude and direction. An electrical field is represented by electrical lines of forces (Fig. 2.1). They start form positive charge and terminate on negative charge. An electrical dipole possess positive and negative charge distribution, but net charge is zero. When placed in an electric field, the dipole tends to align with the field, because of the torque exerted by the field. When a charged particle is placed in an electrical field, it experiences a force (qE) and acceleration (a) = qE/m, where, m is the mass and 'q' is the charge of the particle.

Electric induction is the phenomenon in which positive and negative charges are accumulated or separated in a substance, when a charged body is brought nearer to it.

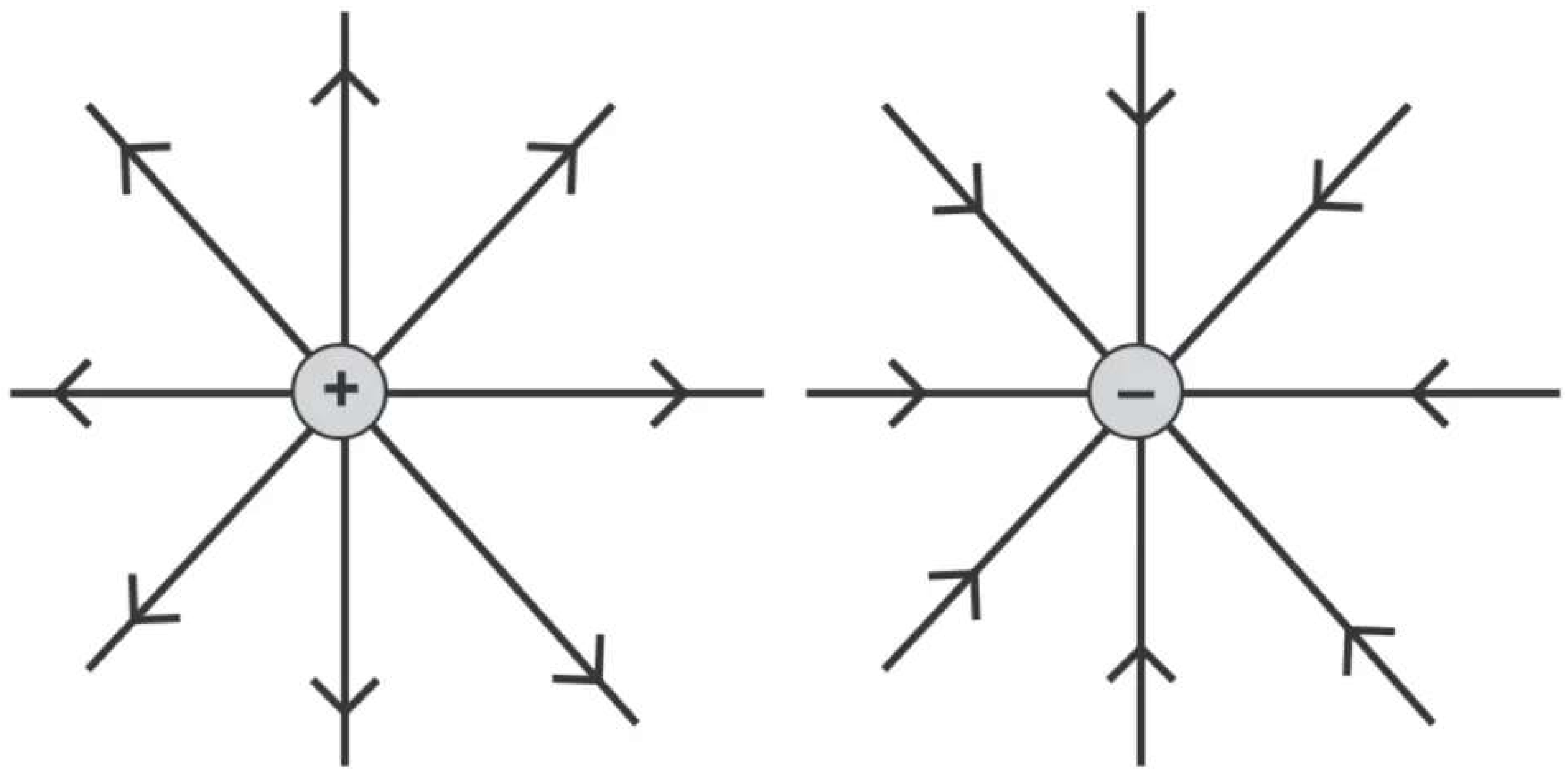


FIG. 2.1: Electric lines of force

ELECTRICAL POTENTIAL

The electric potential (V) at a point in an electric field is the work done (W) in taking a unit positive charge (q) from infinity to that point, i.e.

$$V = W/q$$

Positive charges flow from a point of higher potential to point of lower potential and negative charges flow in the reverse direction. The unit of potential is volt and one volt is equal to 1 joule per coulomb. The potential is a scalar quantity and the potential of earth is taken as zero. In practice, kilovolt (kV) and megavolt (MV) are used as units, 1 kV = 1000 volts and 1 MV = 10^6 volts.

CONDUCTORS, INSULATORS AND SEMICONDUCTORS

Substances in which electric charge moves freely are known as conductors. Substances, which do not allow charge to move freely through them, are known as insulators or dielectrics. The term insulator or conductor is only a relative term and nobody is perfectly insulating or conducting. Substances, which are having their conductivity intermediate between conductor and insulator, are known as semiconductors.

As per the band theory of conduction, matter is made up of three energy levels, namely, filled band, valence band, and conduction band. Valance band is the highest energy band whose electrons are tied up to individual atoms. It corresponds to the valence shell of a single isolated atom. The filled bands are below the valance band, and they do not contribute to electrical conduction. Hence, it is normally not included in the energy band diagrams.

The conduction band is above the valance band and the electrons are not tied to particular atoms. Hence, it offers free electrons for electrical conduction. The gap between the valance and conduction band is called forbidden gap, which is responsible for the conduction properties of materials. Based on the forbidden gap width, materials may be classified as conductor, insulator and semiconductors (Fig. 2.2).

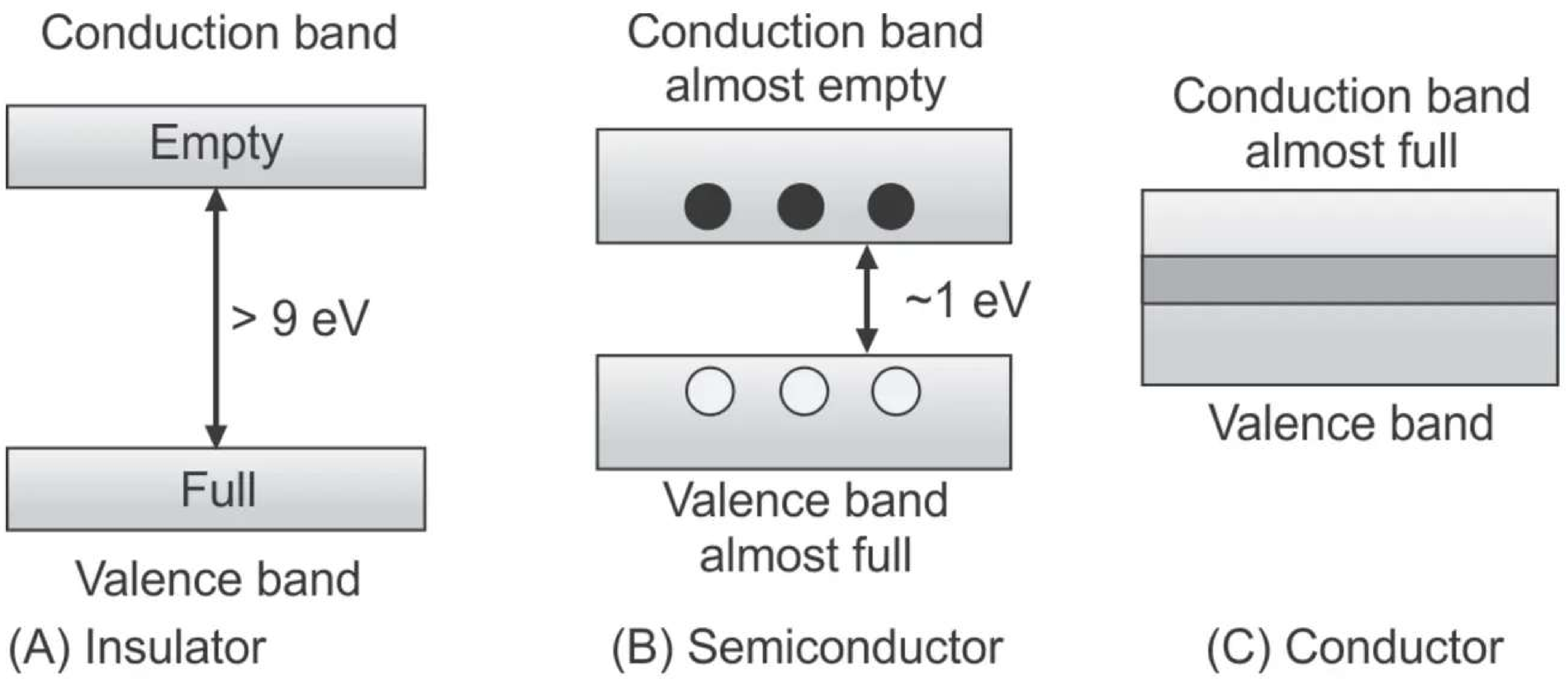


FIG. 2.2: Insulator, semiconductor, and conductor

CONDUCTOR

In conductors, the highest electron energy levels are partially filled and hence its electrons are free to move. There is no forbidden gap between valance and the conduction band, hence electrons move easily from valance band to conduction band. Metals, such as copper, silver and aluminium are good electrical conductors.

INSULATOR

In insulators, the forbidden gap is large, > 9 eV and the electrons unable to flow to the conduction band. Hence, the conduction band is empty and no flow of electric current, e.g. oil, glass, rubber and plastic. At very high temperature, few electrons may move from the valance band, but the material undergo breakdown. This breakdown depends on the applied voltage and the thickness of the material. Hence, X-ray cables are made up of higher thickness of insulation material.

SEMICONDUCTOR

In semiconductors, the width of the forbidden band is 1 eV, e.g. germanium and silicon. At low temperatures, there is no electron flow from valance to conduction band due to lack of sufficient energy and they behave like an insulator. However, at room temperature, they utilize the internal energy of the system and gain > 1 eV energy. This is sufficient to offer electron flow from valance to conduction band, but in a limited way. As the temperature increases, number of electron also increases, resulting higher conductivity. As the electron leaves the valance band, holes are created, which also act like charge carriers. This type of conduction that takes place in a pure semiconductor is called intrinsic conduction.

The conducting property of a semiconductor can be modified by adding impurities to it, which is called doping. By doing so it is possible to create additional energy levels in the forbidden band, resulting higher conductivity. This type of conductivity made out of doping is called extrinsic conductors. There are two types of extrinsic conductors, namely, N-type and P-type (Fig. 2.3). In N-type, there are extra-energy levels, which helps the electrons to move from the valance band to conduction band. In P-type semiconductor, the extra-energy level helps the holes to move, and offer higher electrical conduction.

N-type Semiconductor

When a pentavalent impurity such as phosphorous or arsenic is added to a pure silicon in the ratio $1:10^6$, N-type semiconductor is formed. Four out of five valence electrons of the impurity phosphorous atom form covalent bonds with neighboring silicon atoms. The fifth electron is not associated with any covalent bond and it is free, responsible for conduction. In this type, the majority charge carriers are electrons and the minority charge carriers are holes. Since the impurity donates one electron to the conduction band, it is called donor impurity.

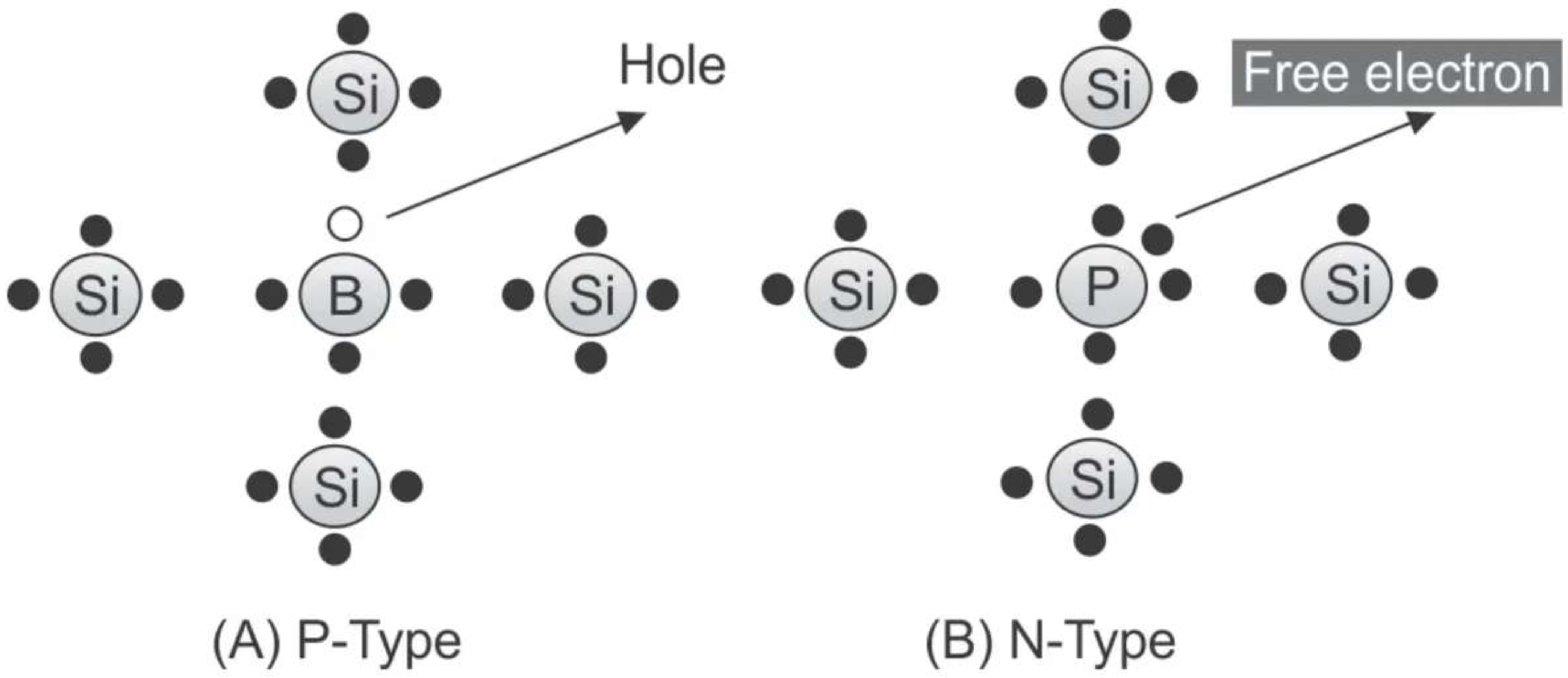


FIG. 2.3: P and N types semiconductor

P-type Semiconductor

When a trivalent impurity such as boron is added to a pure silicon (Si), P-type semiconductor is formed. The three valence electrons of boron atom form covalent bands with the three neighboring silicon atoms. The fourth electron of the Si atom is unable to form a covalent bond with the boron atom. Hence, a vacancy is available in the fourth covalent bond. This vacancy is called hole (positive charge) which can accept electrons from other atoms. The majority charge carriers are holes and the minority charge carriers are electrons. Since, there is a hole in the impurity, it is called acceptor impurity.

SEMICONDUCTOR DIODE

A semiconductor (solid state) diode consists of a P-type and a N-type semiconductors which are joined together (Fig. 2.4). Such a arrangement is called the P-N junction diode. When a P–N junction is formed, the holes diffuse from P region and electrons diffuse from N region due to thermal energy. As a result, the holes and electrons combine with each other and neutralize near the junction. After a short interval of time, a potential barrier is setup near the junction with immobile negative and positive ions which stops further diffusion. The above potential barrier which is created, when a P-N junction is formed is called internal

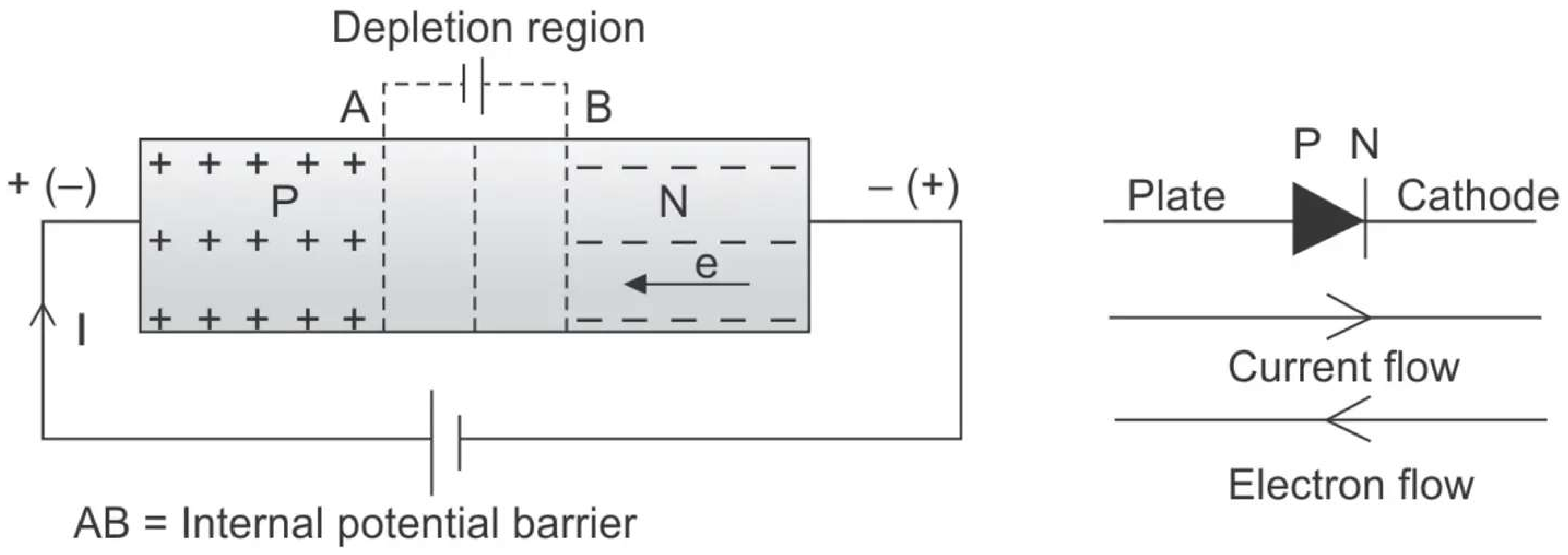


FIG. 2.4: Junction diode and current flow

potential barrier or depletion layer. The width of this barrier region is about 10^{-6} to 10^{-8} m.

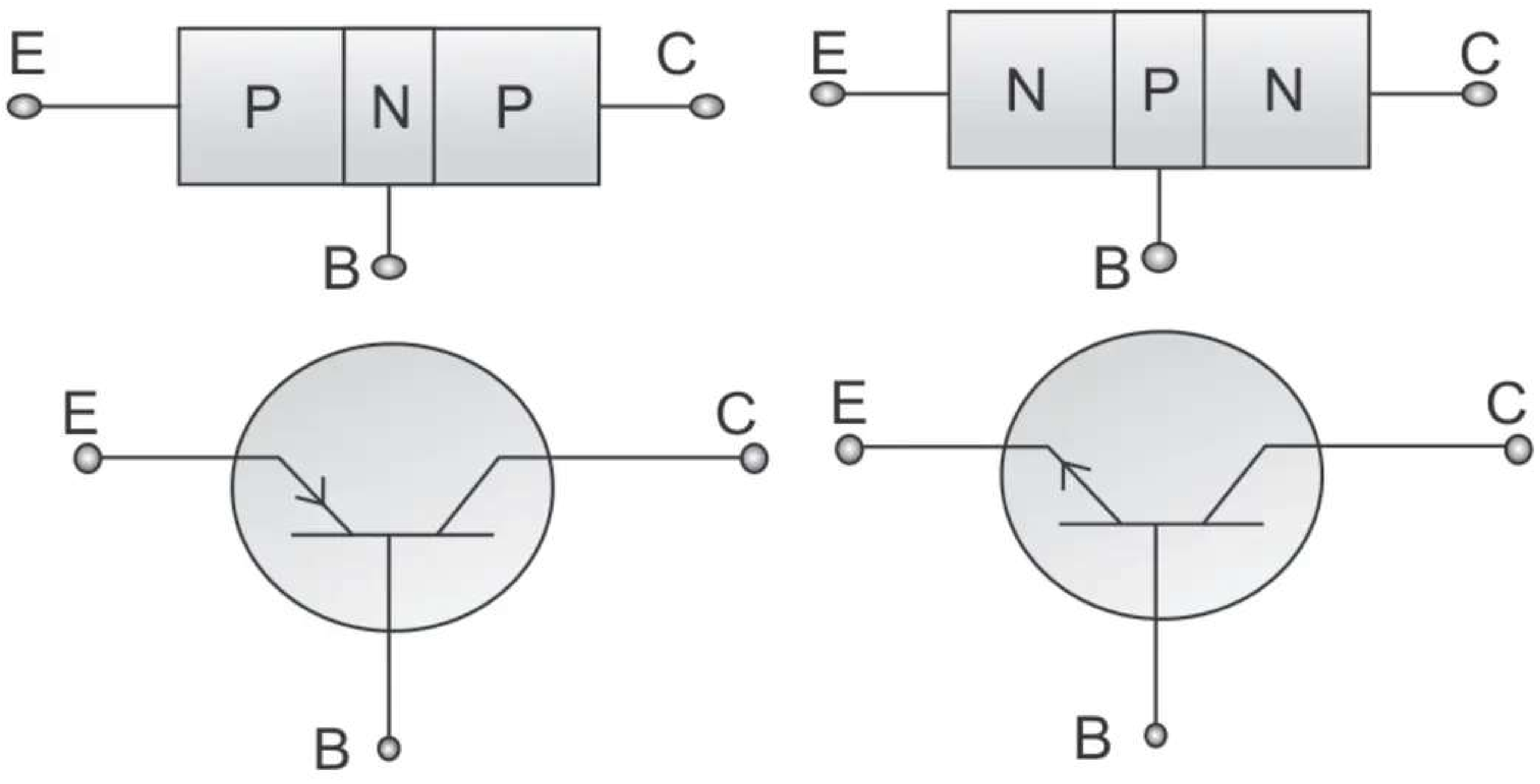
A battery is connected to the terminals of the diode. When P is positive and N is negative, the diode is said to be forward biased. Now, the holes in the P region are repelled from the positive terminal of the battery and moves towards the junction. Similarly, the electron move towards the junction. These ions penetrate the depletion region, there by reducing the internal potential barrier. There is a continuous flow of electrons through the junction from N to P region, which will constitute a current. The current flow is in the order of mill amperes.

When P is negative and N is positive, the diode is said to be reverse biased. Since the battery terminals attract both holes and electrons, the internal potential barrier is increased. Hence, there is no flow of electrons across the junction and there is no current flow. Only the minority carriers cross the junction constituting very low reverse saturation current. This current is of the order of microamperes. Thus, the PN junction diode allows the electron flow only when P is positive. This property is used for the conversion of AC into DC, which is called rectification.

TRANSISTORS

A transistor is formed by three semiconductor materials, which are sandwiched together. Schematic symbols for PNP and NPN transistors are shown in Figure 2.5. There are three regions in a transistor and are called emitter, base and collector. The emitter, base and collector are provided with terminals which are labeled as E, B and C. In the schematic symbols, the arrow head is always at the emitter. The arrow head indicates the conventional current direction flow. The junction between emitter and base is called emitter base (EB) junction. The junction between collector and base is called collector base (CB) junction. Hence, a transistor basically consists of two junctions manufactured back to back in a single piece of a semiconductor.

The emitter forms the left hand side of the transistor and its main function is to supply majority charge carriers to the base. The base forms the middle section of the transistor and it is very thin. The collector forms the right hand side of the transistor and its main function is to collect majority charge carriers through the base. In most transistors, the collector region is made physically larger than emitter region, because it has to dissipate much greater power.



E = Emitter, C = Collector, B = Base

FIG. 2.5: PNP, NPN transistor block diagram and symbol

Principle of Operation

In a PNP transistor the following biasing is required: (i) emitter-base junction is always forward biased and (ii) collector-base junction is reverse biased. The forward bias causes the majority carriers (holes) to diffuse from emitter into base, as a result emitter current (I_E) flows. Once the emitter injected holes reach the base, there is a recombination of holes and electrons. Since the base is thin, only few holes recombine with electrons. The other holes reach the collector, causing a collector current, I_c. If I_B is the base current due to flow of holes out of base, then applying Kirchhoff's law, that total emitter current equals to the sum of the collector and base current, i.e. $I_E = I_B + I_c$. This is true for all type of transistors, irrespective of type and configurations.

Transistor circuit connections are made either by common base, common emitter or common collector types. The common base circuit configuration enables the transistor to function as power amplifier. In this circuit, the collector current is higher than the base current and collector voltage is higher than the emitter voltage. Similarly, a common emitter circuit enables the transistor to function as current amplifier. The gain of transistor is a ratio between the collector current and base current and this is in the order of 100.

Transistor Applications

Transistors enable a small current to control the flow of a larger current and have applications in switching and amplification, etc. Large number of transistors along with resistors and capacitors are incorporated in a single silicon chip, known as large scale integration (LSI) and very large scale integration (VLSI) circuits that have multiple applications in medicine and industry.

CAPACITANCE

The property of a conductor to store electric charge is known as capacitance. It is defined as the ratio between the charge and its potential. If Q is the charge in a conductor of potential V then, the capacitance C is given by,

$$C = Q/V$$

Capacitance also refers the amount of charge that can be transferred per unit change in its potential. The unit of capacitance is farad (F) and one farad is the capacitance of a capacitor, which requires one coulomb electric charge to raise its potential by one volt. In practice, microfarad and picofarad are used as capacitance units.

1 farad = 1 coulomb/volt
1 microfarad (μF) = 10^{-6} farads
1 picofarad = 10^{-12} farads.

CAPACITOR

A capacitor is a device, which increases the capacitance of a conductor. It usually consists of two conductors, one is charged and the other is earthed. The space between the plates is filled with some insulating material called dielectric. To understand the principle, consider a conductor A as shown in Figure 2.6. When it is negatively charged, there is a rise in negative potential, and its capacitance is very small. When a second similar conductor B is brought very nearer to the first, positive charges are induced in B by electric induction. This positive charge decreases the negative potential on A. Hence, for the same charge Q, the potential V has fallen. Since C = Q/V, the capacitance of the first conductor increases.

The capacitance of a capacitor depends on (i) area of overlap between two plates (ii) distance between the plates and (iii) nature of dielectric medium. The capacitors are in different types, the most commonly used one is the parallel plate capacitor.

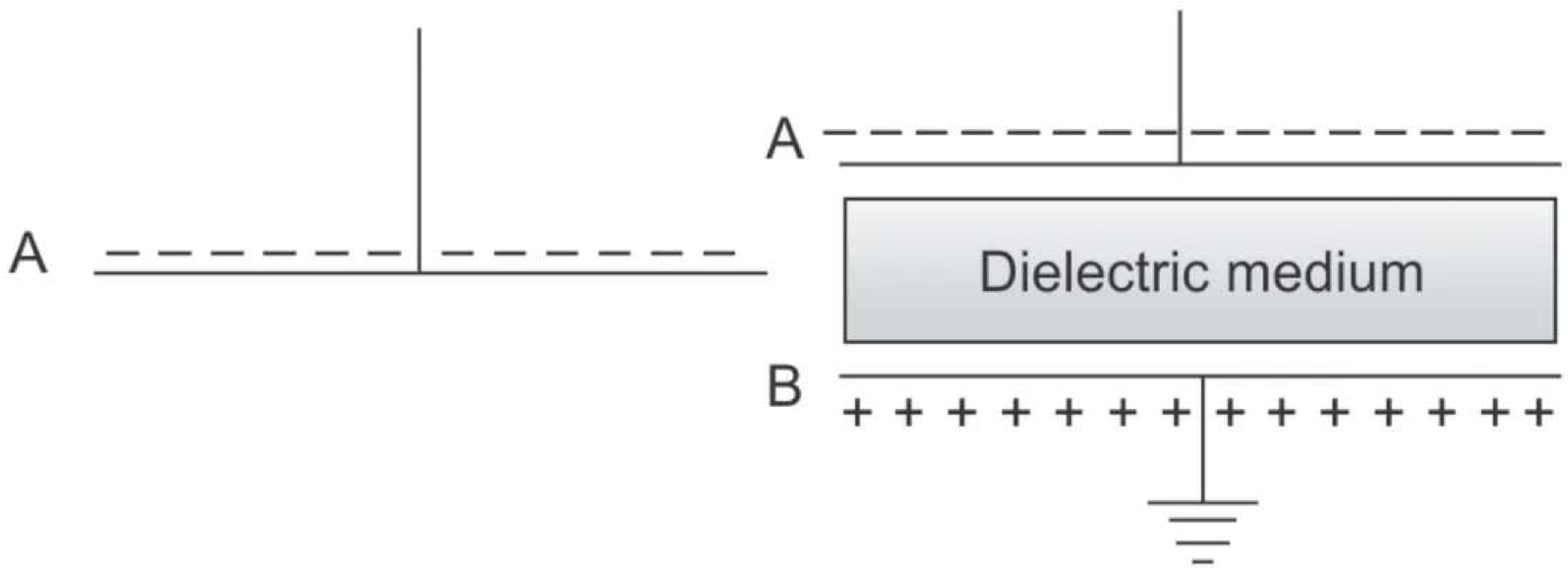


FIG. 2.6: Principle of capacitor

Capacitors are used (i) to store electric charges, (ii) to measure potential difference and small currents, (iii) to reduce voltage fluctuations, generating oscillations, for providing time delay in various electric circuits, and (iv) to obtain required electric field.

When capacitors are connected in parallel, the total capacitance in the circuit is equal to the sum of the individual capacitance. If three capacitances, C_1, C_2 and C_3 are connected in parallel, then the total capacitance C is given by the relation:

$$C = C_1 + C_2 + C_3$$

If the capacitances are connected in series, then the total capacitance is given by the relation:

$$1/C = (1/C_1) + (1/C_2) + (1/C_3)$$

PARALLEL PLATE CAPACITOR

The parallel plate capacitor consists of two parallel conductors (electrodes) of area A and separated by a distance d (Fig. 2.7). A thin layer of dielectric material is sandwiched between the electrodes. One plate is charged positively and the other is negatively charged.

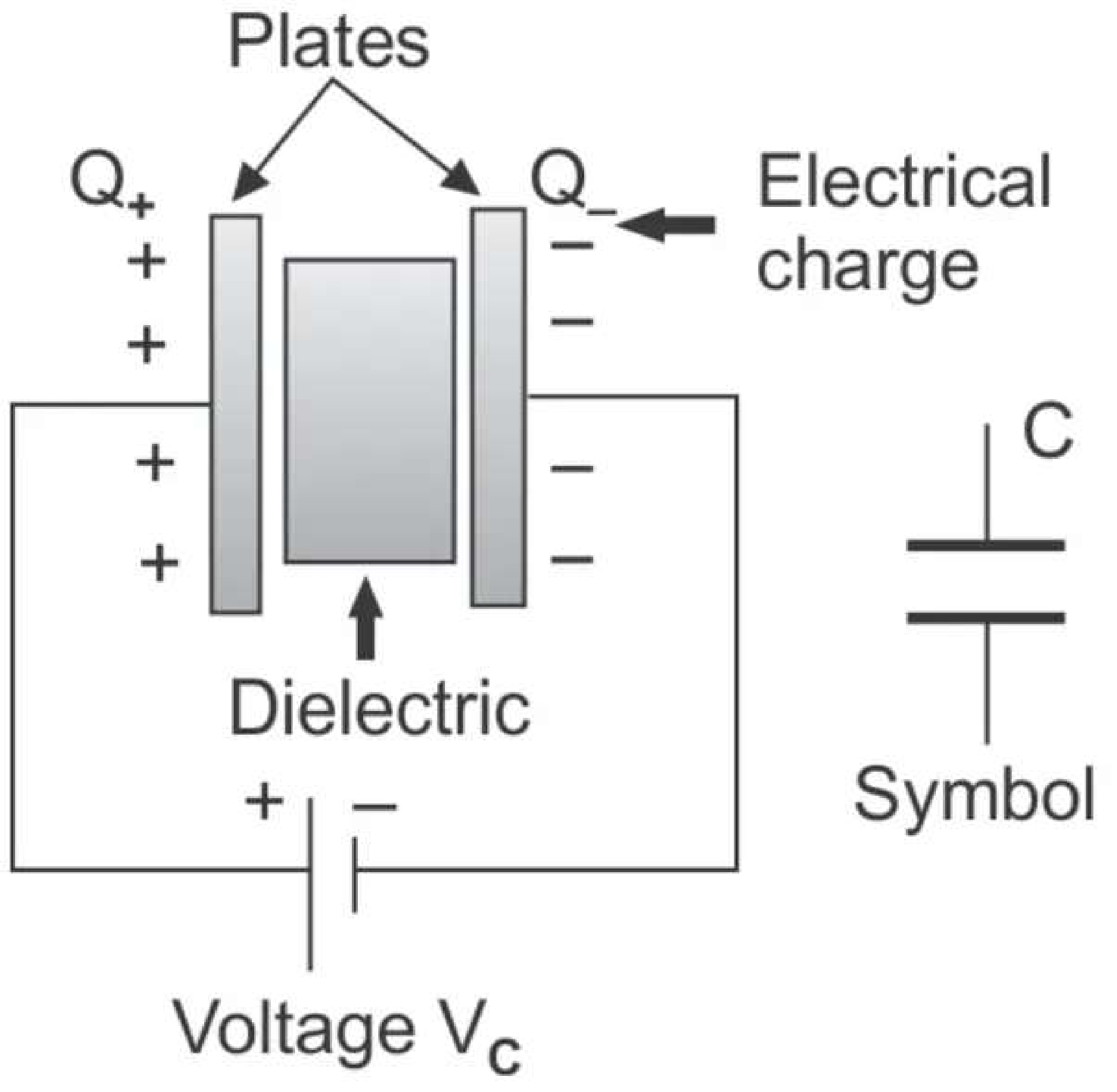


FIG. 2.7: Parallel plate capacitor

The capacitance of a parallel plate capacitor is proportional to the area of the plates and inversely proportional to their separation distance, and is given by the relation:

$$C = k\ (A/d)$$

where, k is a constant called permittivity and it is equal to 8.84×10^{-12} Fm^{-1} in free space. Generally, the conductive plates of a capacitor are separated by air or some kind of insulating material or gel rather than the vacuum of free space.

ELECTRICAL CURRENT

The flow of electric charge in a conductor is called an electric current. It is equal to the quantity of charge passing a given point in one second. Charge may flow through solid, liquid and gas or vacuum. The unit of current is called ampere (A). The electric current through a wire is called one ampere, if one coulomb of charge flows through the wire in one second. It is found that one ampere current consists of 6.281 × 10^{18} electrons/s. In practice, milliampere (mA) and microampere (μA) are used as units, 1 mA = 10^{-3}A, and 1 μA = 10^{-6} A.

DIRECTION OF CURRENT

Initially, physicists thought that the current is due to the flow of something from positive end to the negative end. This is only an imaginary flow, which is now known as conventional current. After the discovery of electron, it is found, that the electrons are responsible for current and it flows from the negative terminal to the positive terminal. However, the direction of current is given by the conventional current, which is always opposite to the electron flow (Fig. 2.8).

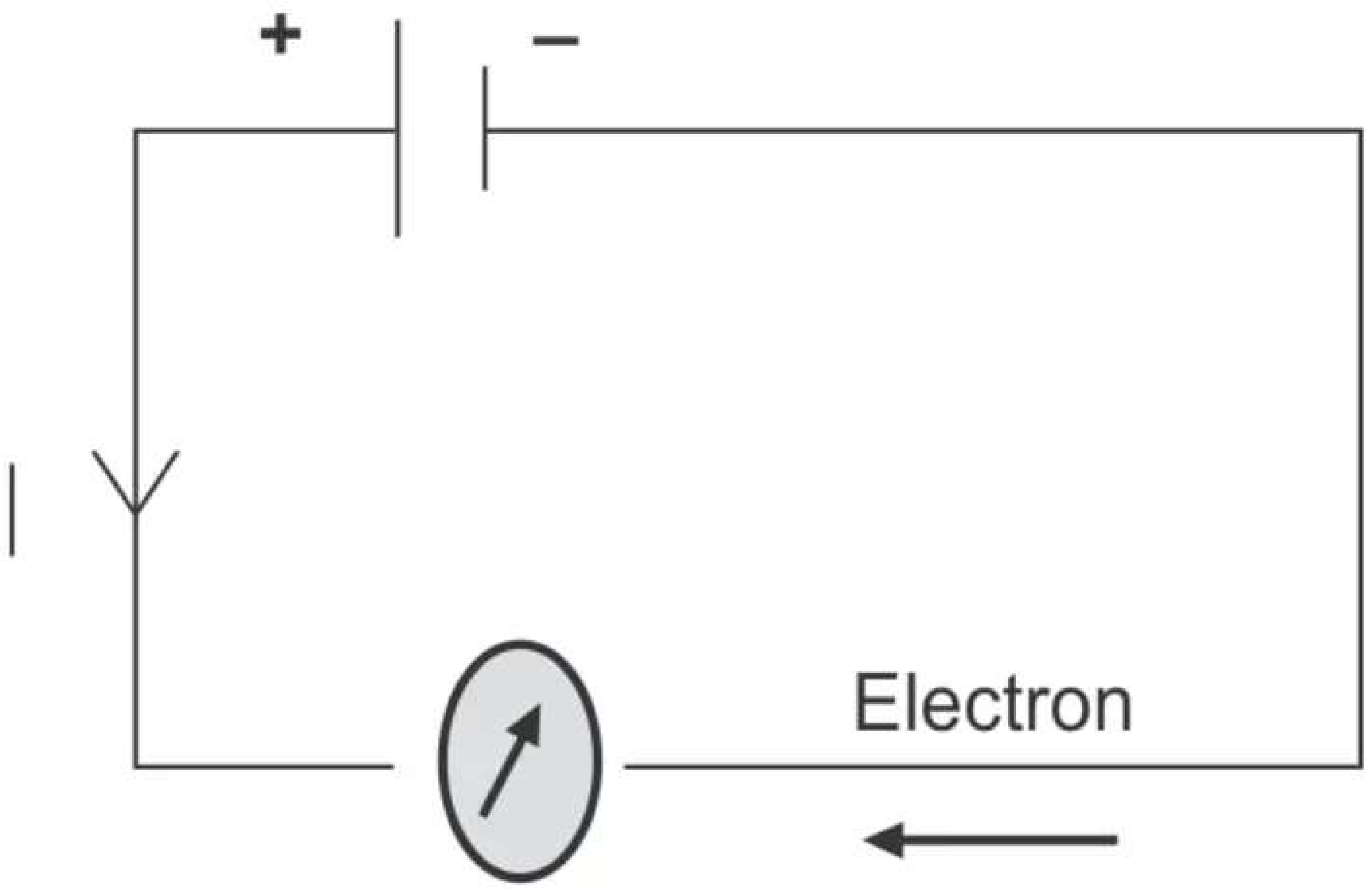


FIG. 2.8: Direction of current

OHM'S LAW

The Ohm's law states that, a steady current flowing through a metallic conductor is proportional to the potential difference between its ends, provided the temperature remains constant. If I is the current in ampere and V is the potential difference in volts then, $I \propto V$, at constant temperature, i.e. $I = V/R$, where, R is a constant known as resistance of the conductor. Ohm's law is applicable only for metallic conductors.

RESISTANCE

Resistance is the property of a conductor by which it opposes the flow of electric current. It is defined as the ratio of the potential difference applied across a conductor to the current flowing through it:

$$\text{i.e.,}\quad R = V/I.$$

The device which offers resistance to the flow of current is called resister. In a conductor, the atoms are vibrating and the electrons move randomly. When a voltage is applied, the electrons move towards the positive terminal. During the process, they collide with vibrating atoms, resulting resistance. The unit of resistance is ohm (Ω). One ohm is the resistance of a conductor through which a steady current of one ampere passes, when a potential difference of one volt exists across it. In practice, kilo ohm (kΩ) and mega ohm (MΩ) are used as units and 1 kΩ = 1000 Ω, and 1 MΩ = 10^6 Ω.

When resistances are connected in series, the total resistance in the circuit is equal to the sum of the individual resistances. If three resistances, R_1, R_2 and R_3 are connected in series, then the total resistance R is given by the relation:

$$R = R_1 + R_2 + R_3$$

If the resistances are connected in parallel, then the total resistance is given by the relation:

$$1/R = (1/R_1) + (1/R_2) + (1/R_3)$$

SPECIFIC RESISTANCE

The resistance of a resistor at a given temperature depends upon the material and its dimension. The resistance (R) is directly proportional to the length (L) and inversely proportional to the area (A) of cross section of resistor.

$$R \propto \frac{L}{A}, \; R = \frac{\rho L}{A}$$

where, ρ is a constant, called the specific resistance or resistivity and the unit is ohm-meter. The specific resistance is given by:

$$\rho = RA/L$$

This relation reveals that the resistance of a thick wire would be lesser than that of a thin wire. The resistance is greater if the length is greater. The reciprocal of the resistivity (1/ρ) is called the conductivity (σ) and its unit is $(\text{ohm-meter})^{-1}$.

SUPERCONDUCTIVITY

At very low temperatures, the resistivity of some materials (metals, compounds or alloys) becomes zero. Materials in such state are called superconductors. In general conductors, become superconducting at certain temperatures called super conducting transition temperature (T_c). Current in a ring shaped super conducting material has been observed to flow for years in the absence of a potential difference, with no measurable decrease.

Superconductors are mainly used for generating very strong magnetic fields, since it has ability to with stand large magnetic fields and carry large currents. A material in the super conducting state requires no power to carry large currents. Since the resistance of the material in the super conducting state is zero, no thermal losses are associated with passage of large currents.

Metal alloys like niobium-titanium become a superconductor below 10 K. It is used in magnetic resonance imaging equipment, but requires liquid helium as a coolant system. Ceramic metal oxide compounds become super conductors at higher temperatures, e.g. yttrium barium copper oxide at 93 K and thallium-calcium-bismuth copper oxide at 125 K. Since they operate at higher temperatures, liquid nitrogen can be used as effective coolant, which is cheaper than helium.

ELECTRICAL POWER

The electrical power (P) is the rate at which energy is expended and it is equal to the product of potential difference (V) and current (I) in a circuit, i.e. $P = VI$. The unit of electrical power is watt, which is equal to one joule per second (Js^{-1}). In practice, kilowatt and kilowatt hour (kWh) are used as units of electrical power and one kilowatt hour is equal to 3.6×10^6 J.

HEATING EFFECT OF AN ELECTRIC CURRENT

When electric current flows through a conductor having a resistance, certain amount of electrical energy is converted into heat energy. This heat energy will raise the temperature of the conductor. The above heat is produced by the free electrons as they move through the conductor. On their way, they collide frequently with atoms and give some of their kinetic energy to the atoms. The atoms which gains kinetic energy, generate heat in the conductor.

Joule's law of heating: The heat (H) developed in a current carrying conductor is directly proportional to (i) the square of the current (I) passing through the conductor, (ii) resistance (R) of the conductor and (iii) time (t) of flow of current

$$\text{i.e., } H = I^2Rt \text{ joule}$$

If the current is doubled, the heat generated is four times higher. This concept is applied in fuse wires, as the current goes to higher value, the heat generated in the circuit is sufficient to melt the fuse wire. The melting point of the fuse material is very critical, for material selection.

MAGNETISM

Magnetism is a fundamental property of a matter and it is produced by motion of electrical charges. As we are aware that electrons are in random motion in materials. The atoms and molecules that have paired electrons cancel their magnetic fields and the net magnetic field is zero. Whereas, the atoms with unpaired spinning of electrons in different shells, present net magnetic field. A magnet possess, two poles namely, north pole and south pole (Fig. 2.9). The term pole refers the end of the magnet in which the entire magnetism appears to be concentrated. The pole that points north under the influence of earth's magnetic field is called north pole and the other is called south pole. As in the case of electric charge, like poles repel and unlike poles attract each other. When a magnet is broken into two, each part became a magnet with north and south pole. The simplest magnet at the atomic level is the magnetic dipole.

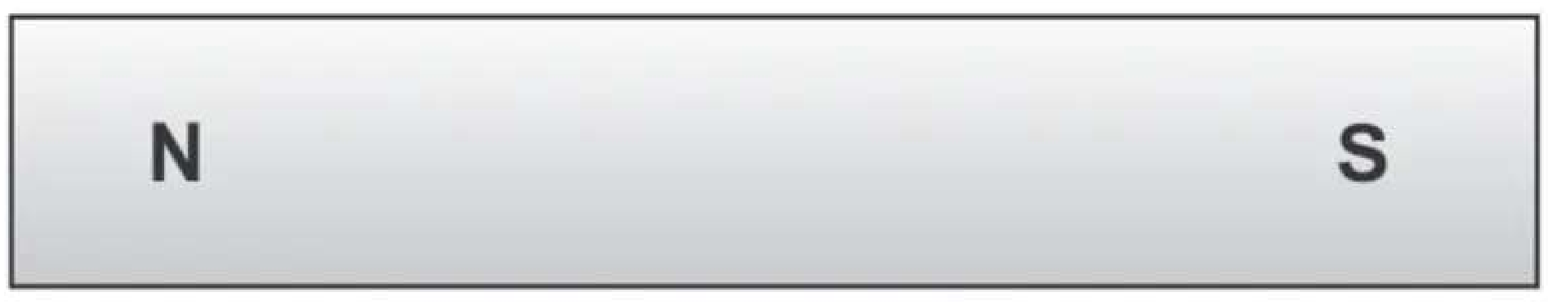


FIG. 2.9: Magnetic dipole

The force of attraction (F) between two magnetic poles is given by the relation:

$$F = \frac{m_1 m_2}{4\pi\mu r^2}$$

where, m_1 and m_2 are the pole strength of two magnetic poles which are separated by distance r, μ is the absolute permeability of the medium, expressed in henry per meter (Hm^{-1}). The permeability of free space is 1.26×10^{-6} Hm^{-1}. The unit of pole strength is weber (Wb).

MAGNETIC FIELD AND FLUX DENSITY

The space around a magnetic pole in which another pole experiences a force is called the magnetic field. Magnetic fields can be visualized by magnetic lines of forces, which are imaginary lines (Fig. 2.10). A line of force can be defined as the path taken by an independent north pole moving from the north pole of magnet to south pole. The total number of lines of force used to express pole strength is called the magnetic flux. The term magnetic flux density is defined as the magnetic flux per unit area and its unit is Wbm^{-2}. The SI unit of magnetic flux is tesla (T) and one tesla = 1 Wbm^{-2}. The older unit of pole strength is gauss (G) and one tesla is equal 10,000 gauss. The earth's magnetic field strength varies from 0.5 to 1.0 G.

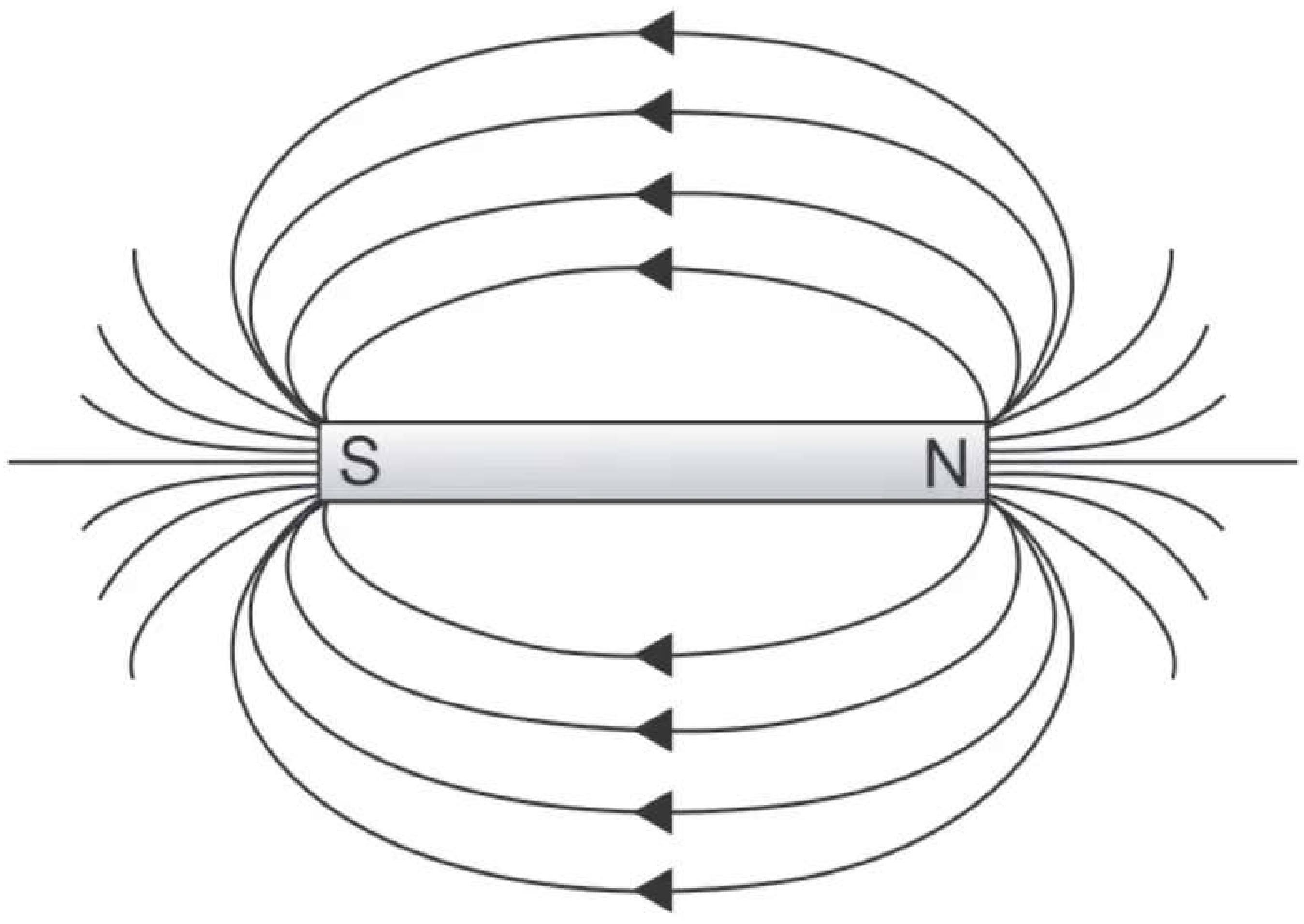


FIG. 2.10: Magnet and magnetic lines of force

MAGNETIC INDUCTION

If a material is placed in a magnetic field, magnetism may be induced in that material by the magnetizing force. The atoms of the material tend to align with the direction of magnetizing force and induce a magnetic flux with in the material. If H is the magnetizing force that induces a magnetic flux B in the material, then,

$$B = \mu H$$

where, μ is the permeability of the medium = $\mu_r \times \mu_0$, where μ_r is the relative permeability and μ_0 is the permeability in vacuum.

MAGNETIC PROPERTIES

The magnetic properties of materials are determined by the atomic and molecular structures in relation with electron behavior. Magnetic susceptibility is one of the property, which describes the extent to which the material becomes magnetized, when placed in a magnetic field. Based on susceptibility, the material can be classified as diamagnetic, paramagnetic and ferromagnetic substances.

Diamagnetic Substances

They have negative susceptibility, e.g. calcium, water, and organic materials. In these materials, the orbiting electrons do not lie in a given plane and the net magnetic field is so small to be measured. When they are placed in a external magnetic field, the electron motions are altered, by the induced electromotive force. As a result, a reverse magnetic field is created, which will oppose the applied magnetic field. Thus, diamagnetic materials tend to reduce the applied magnetic field.

Paramagnetic Substances

They have slightly positive susceptibility, which tend to move from weaker to stronger parts of the magnetizing field. They will enhance the local magnetic field, but do not have measurable self magnetization, e.g. molecular oxygen (O_2), blood degradation products, and gadolinium contrast agents. Paramagnetic materials have unpaired electrons (odd number), which have a magnetic field. When placed in an external magnetic field, the electron magnetic field align themselves with the applied field, enhancing the applied field.

Ferromagnetic Substances

They are those, which are attracted by magnets and also be magnetized, e.g. iron, cobalt and nickel. The susceptibility of these materials is very high. Ferromagnetic materials are basically transition elements; in which electron fill the outer orbital shells, before inner shells are completely filled. When the spins are in random motion, usual cancellation of field do not take place, resulting in higher magnetic moment. When they are placed in an external magnetic field, the magnetic dipoles non-randomly aligned with applied field. Thus, ferromagnetic materials enhance the applied magnetic field.

MAGNETIC EFFECT OF AN ELECTRIC CURRENT

When current is passed through a straight wire, a magnetic field is produced. This magnetic field is in cylindrical form and the lines of force form concentric circle about the conductor. A compass needle placed very close to the conductor gets deflected. If the direction of the current is reversed, the compass needle also gets deflected in the reverse direction (Fig. 2.11A). This shows that the current carrying conductor produces magnetic field, which exert a force on the compass needle. This is an example for conversion of electrical energy into mechanical energy. This effect is called the motor effect.

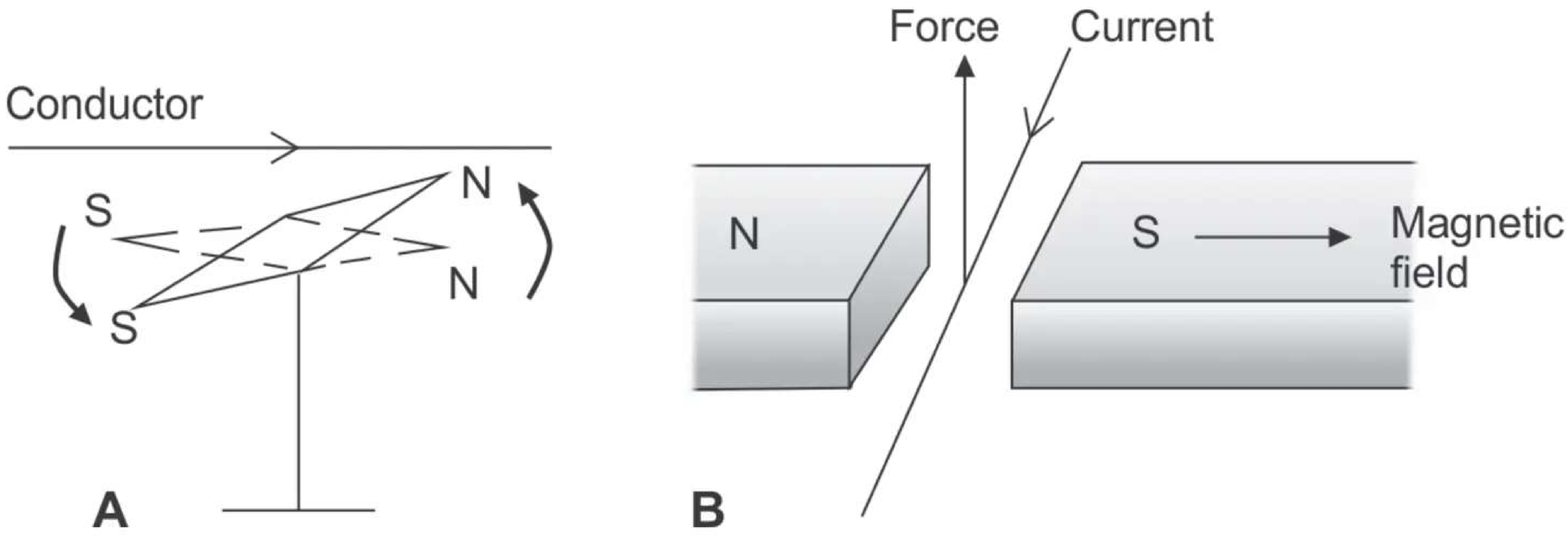


FIG. 2.11: (A) Compass needle and (B) Motor effect

The motor effect can also be obtained by the following method. Consider a conductor, which lies at right angles to the magnetic field. The magnetic field is produced by the fixed pole pieces as shown in Figure 2.11B. If current is passed through the conductor, it produces a magnetic field around the conductor. This magnetic field interacts with the original magnetic field and a force is developed. As a result, the conductor moves in a direction which is perpendicular to both the magnetic field and current. The direction of movement (force) of the conductor is determined by the Fleming's left hand rule.

MAGNETIC FIELD DUE TO A COIL AND SOLENOID

When current is passed through a coil, each electron produces anticlockwise magnetic lines of force about itself. Within the coil, the lines of force is in one direction; whereas outside the coil, it is in the opposite direction. The lines of force is similar to that produced by a bar magnet. Thus, a coil-carrying current, give effects the same way as that of a bar magnet.

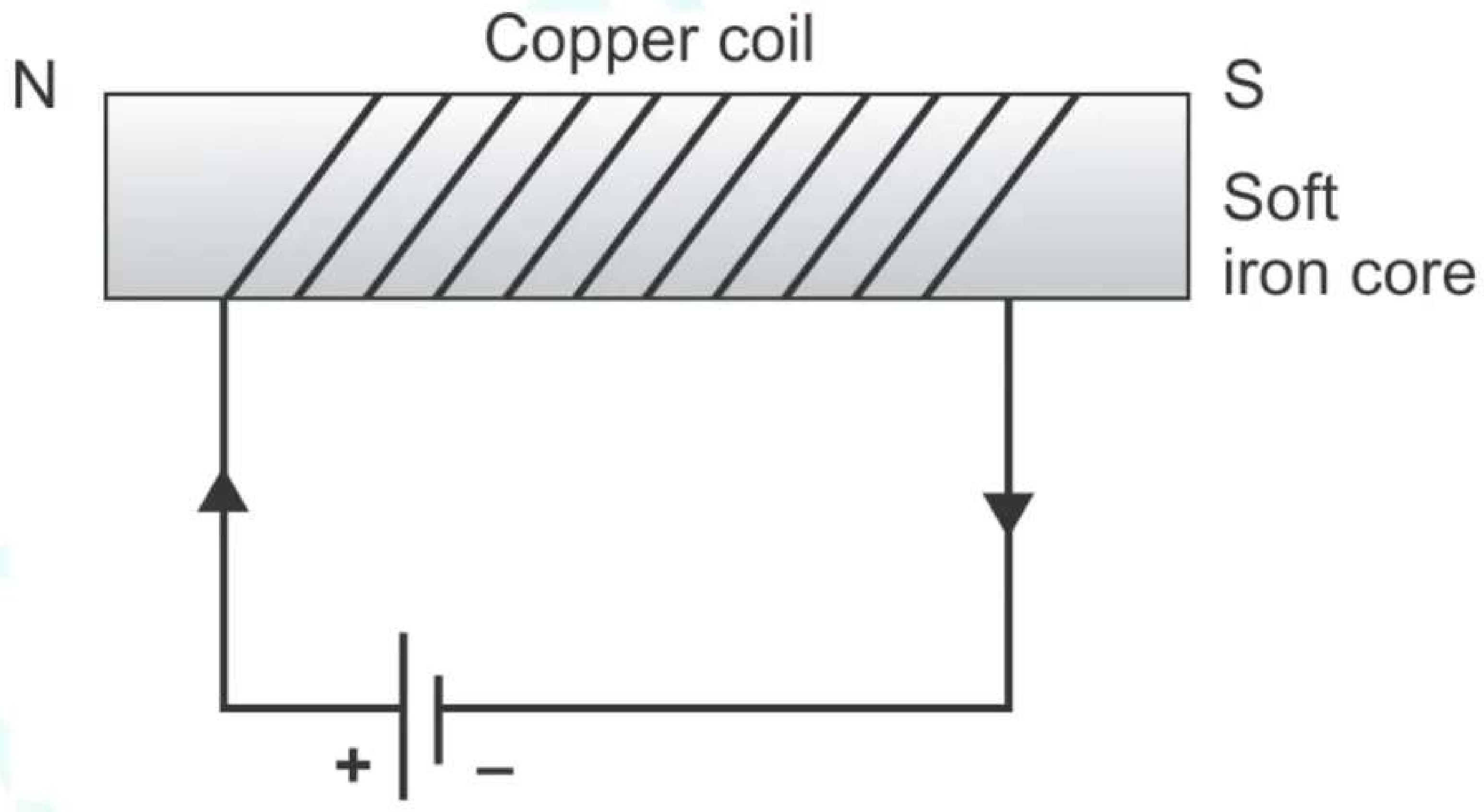


FIG. 2.12: Current-carrying solenoid or electromagnet

A solenoid consists of several coils joined together, usually made by winding insulated copper wire around soft–iron core (Fig. 2.12). The solenoid may be considered as equivalent to a large number of circular loops placed in contact with each other. When current is passed through the solenoid, magnetic field is produced and the solenoid behaves just like a bar magnet.

The magnetic field of the solenoid also magnetizes the soft iron. The magnetic field of the iron core adds with that of the solenoid. As a result, many hundred times stronger magnetic field is obtained. This arrangement is called an electromagnet. One of the advantages of the electromagnet over the permanent magnet is that the former can be switched on and off. This principle is used in relay which is called the contactor in X-ray circuits.

ELECTROMAGNETIC INDUCTION

In 1831, Michael Faraday showed the production of current from a magnetic field. According to Faraday, current can be produced in a closed conductor, whenever, there is a change in the magnetic flux passing through the conductor. The current exists only so long as the change takes place. The current produced in the conductor in this way is called an induced current. The electromotive force (emf), that produces the current is called an induced emf. The whole phenomenon is known as electromagnetic induction.

FARADAY'S EXPERIMENTS

Consider a coil connected to a galvanometer (Fig. 2.13). If a bar magnet is moved into the coil, the galvanometer will show a deflection in one direction. If the magnet is withdrawn from the coil, the galvanometer will show the deflection in the opposite direction. This shows the production of induced emf in the coil, whenever, the magnet is moved. Reversal of the movement results in a reversal of the emf. The reversal of the emf can also be produced by reversing the magnet or by reversing the direction of winding of the coil. If the magnet is moved more quickly relative to the coil, a larger emf will be induced. Similarly, a stronger magnet will induce a larger emf. If the experiment is tried with a coil of more number of turns, the induced emf will be larger.

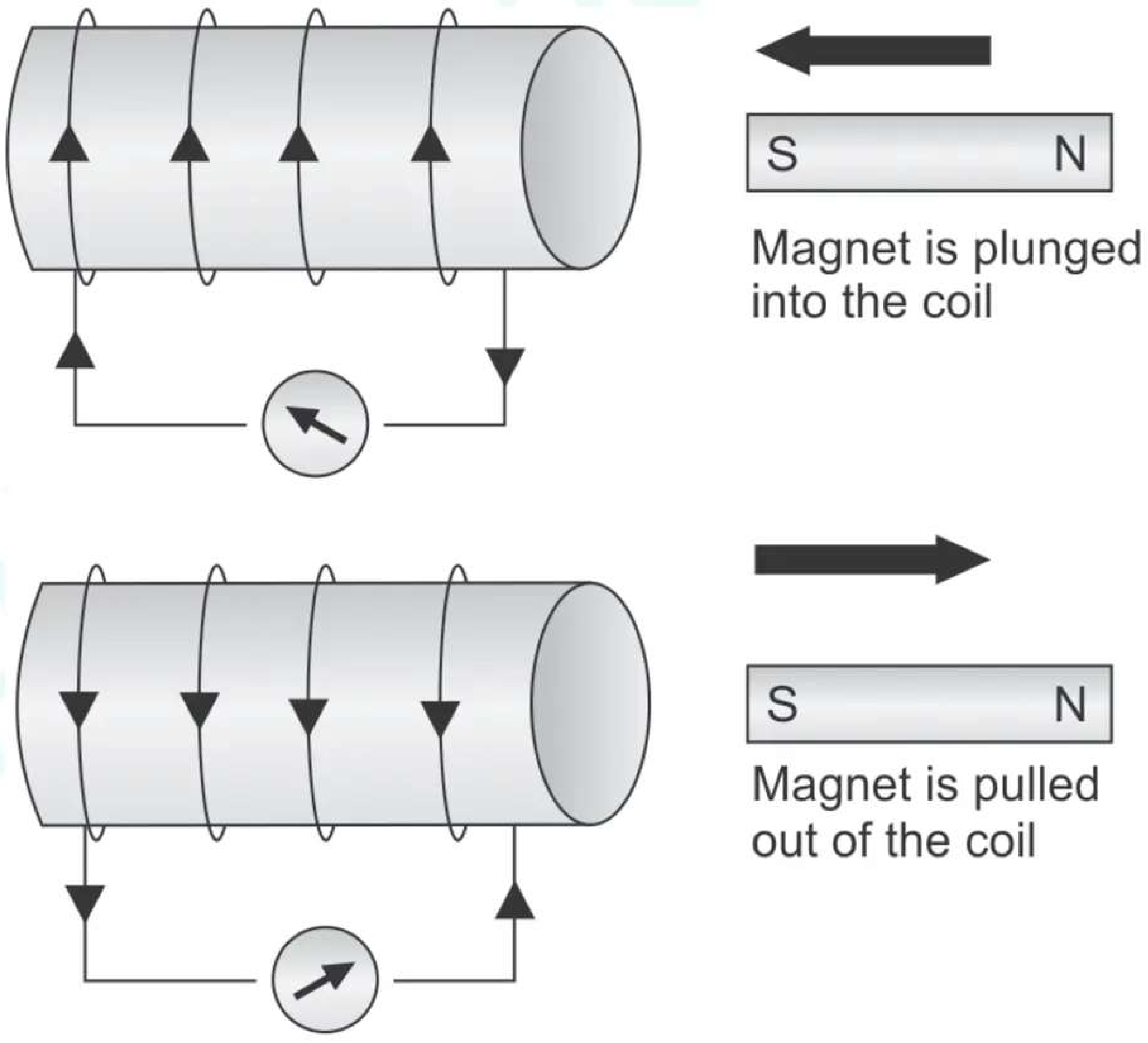


FIG. 2.13: Electromagnetic induction

In the above experiment, when the magnet is moved, the magnetic flux linked with the coil changes. Hence, an emf is induced the coil. If the magnet is stationary, there is no change in magnetic flux, and hence no induced emf. Instead of moving a magnet, one can also use current to perform electromagnetic induction. If the current passing through a closed circuit is switched on or off, the magnetic flux will change. As a result, current will be induced in the neighboring circuit.

LAWS OF ELECTROMAGNETIC INDUCTION

i. A change of magnetic flux linked with a conductor induces an electromagnetic force (emf) in the conductor.
ii. The magnitude of the induced emf is proportional to the rate of change of magnetic flux and to the area of the circuit.
iii. The induced emf is in such a direction that it always opposes the change of magnetic flux, which induced the emf.

The first two laws are called Faraday's law, while the third is called as Lenz's law. Let ϕ is the magnetic flux linked with a coil of N turns, and the induced emf (e) is given by

$$e \propto -N\,(d\phi/dt)$$

where, $d\phi/dt$ is the rate of change of flux linked with the coil. The negative sign represents the Lenz's law. The direction of the induced emf may be predicted by using Fleming's right hand rule. To apply this rule, one's right hand is arranged so that the thumb, the forefinger, and the middle finger are at right angles to each other. If the thumb denotes the motion of the conductor, the forefinger denotes the magnetic field, then the middle finger will denote the direction of the induced emf.

SELF INDUCTION

In a single coil or solenoid, if there is a change in the magnetic flux, an emf will be induced in the same coil. This phenomenon is known as self induction (Fig. 2.14). Consider a coil of N turns, carrying a current of I and ϕ be the magnetic flux linked with the coil. Then $\phi \propto I$, and the induced emf, e is given by:

$$e \propto -N\,(dI/dt) \text{ or}$$
$$e = -L\,N\,(dI/dt)$$

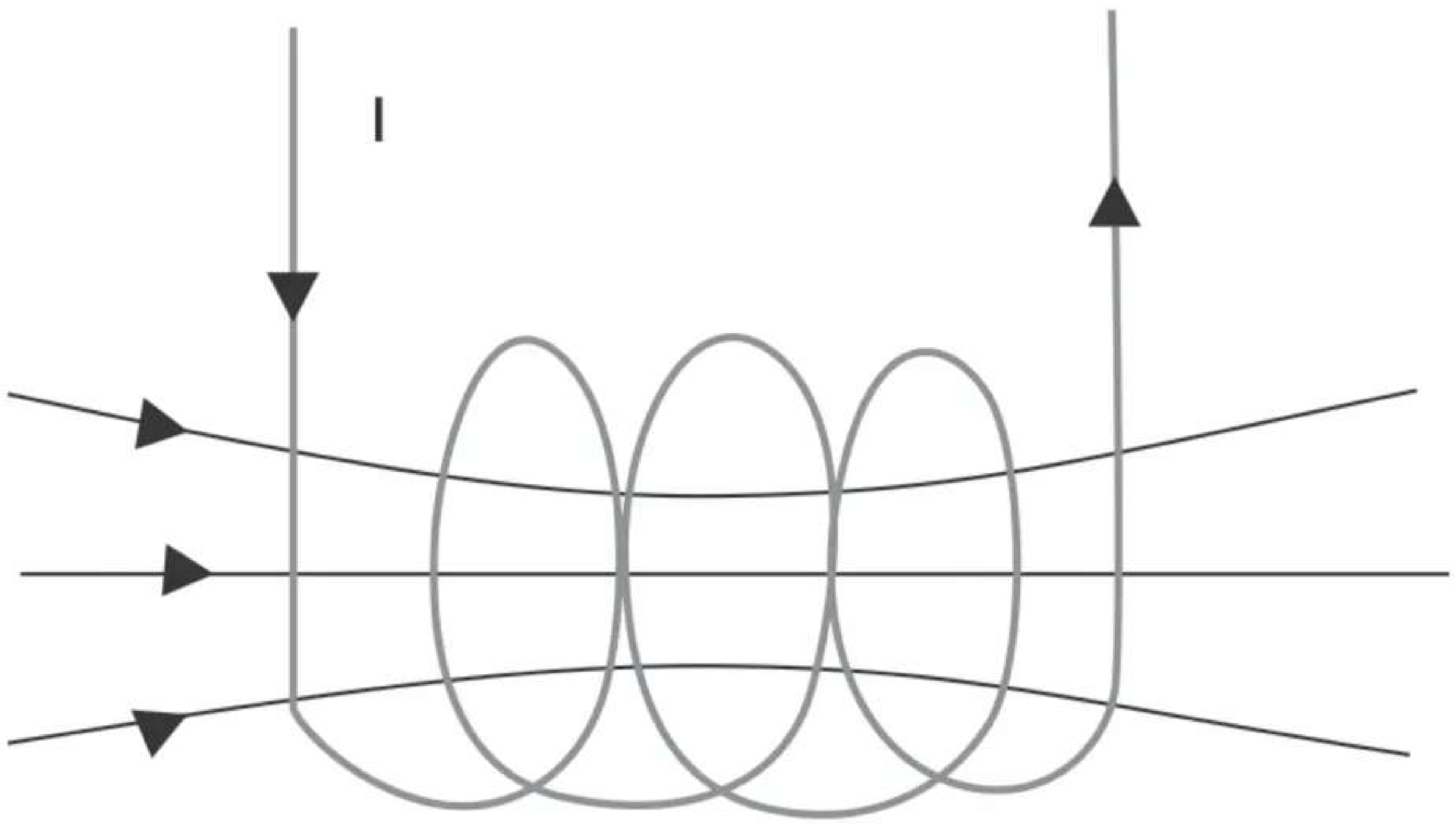


FIG. 2.14: Self induction

where, L is a constant called coefficient of self inductance. The unit of self induction is henry. One henry is the inductance of a circuit in which an emf of 1 volt is induced, when the current in it changes at the rate of 1 ampere per second.

MUTUAL INDUCTION

When two coils are placed very close to each other, the magnetic flux change in one coil induces an emf in other coil. This phenomenon is known as mutual induction (Fig. 2.15).

Consider two coils P and S placed close to each other. If a current is passed through P, a change in magnetic flux takes place. This will induce an emf in the coil P, which, in turn induces an emf in the coil S. Let ϕ_1 be the flux in the coil P due to current I_1 flowing in it and ϕ_2 be the flux induced in the coil S due to the ϕ_1 in the coil P, then,

$$\phi_2 \propto I_1 \text{ and } \phi_2 = MI_1$$

where, M is a constant, called coefficient of mutual inductance for the two coils. If e_1 and e_2 are the emf's in P and S then,

$$e_2 \propto -N\ (d\phi_{2/}dt) \text{ or}$$
$$e_2 = -MN\ (dI_1/dt)$$

Hence, the coefficient of mutual induction of the given pair of coil is equal to the emf induced in one coil, when the current through the other coil changes at the rate of one ampere per second. This principle is applied in the transformer. The unit of mutual induction is also henry.

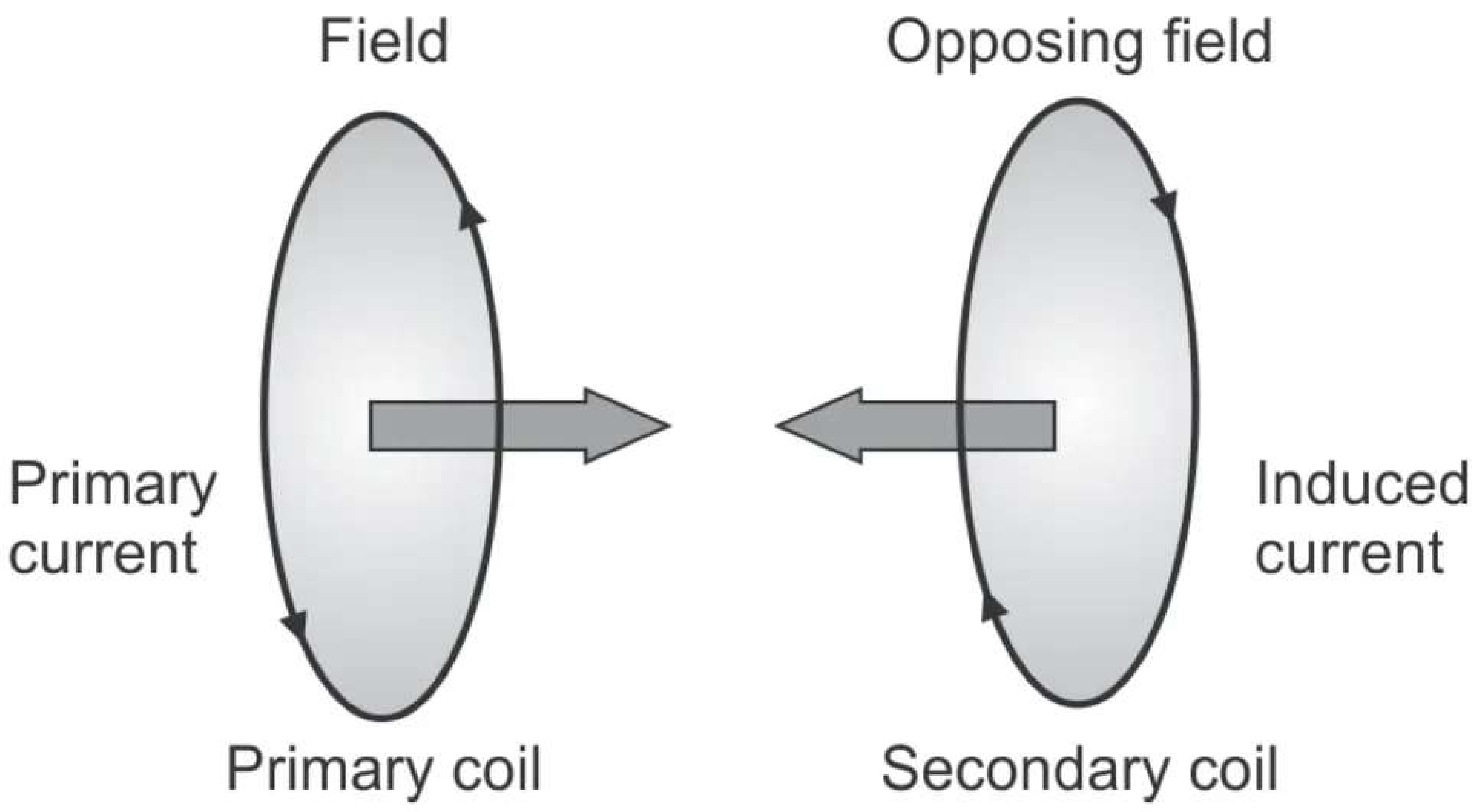


FIG. 2.15: Mutual induction with two coils

ALTERNATING CURRENT

Current can be classified into direct current and alternating current. A constant current which is flowing in only one direction is called the direct current. Cells or batteries are used to produce direct current in a small quantity. In the cells or batteries, chemical energy is converted into electrical energy. However, the production of large quantity of direct current is very costly.

A varying current, which reverses direction periodically, is called alternating current. This is generated in power stations, making use of the phenomenon electromagnetic induction. The machine used in the production of alternating current is called AC generator or alternator. Alternating currents are widely used because it is less costly.

AC GENERATOR

The AC generator makes use of the principle of electromagnetic induction. It consists of four main parts, namely, armature, magnet, slip rings and brushes (Fig. 2.16). It is designed in such a way, so that a conductor cuts the magnetic lines of force continuously. A permanent magnet produces a parallel magnetic field between pole pieces N and S in the case of low power systems. Electromagnet is used in the case of high power generators.

The armature rotates between the poles of a strong magnet and this cut the magnetic lines of force from north pole to south pole. The soft iron core serves two purposes: (i) it serves to support the coils and (ii) increases the magnetic field, by substituting air with iron. The armature is mounted on a soft, which is driven continuously by means of a pulley, which is rotated by a engine through the belt.

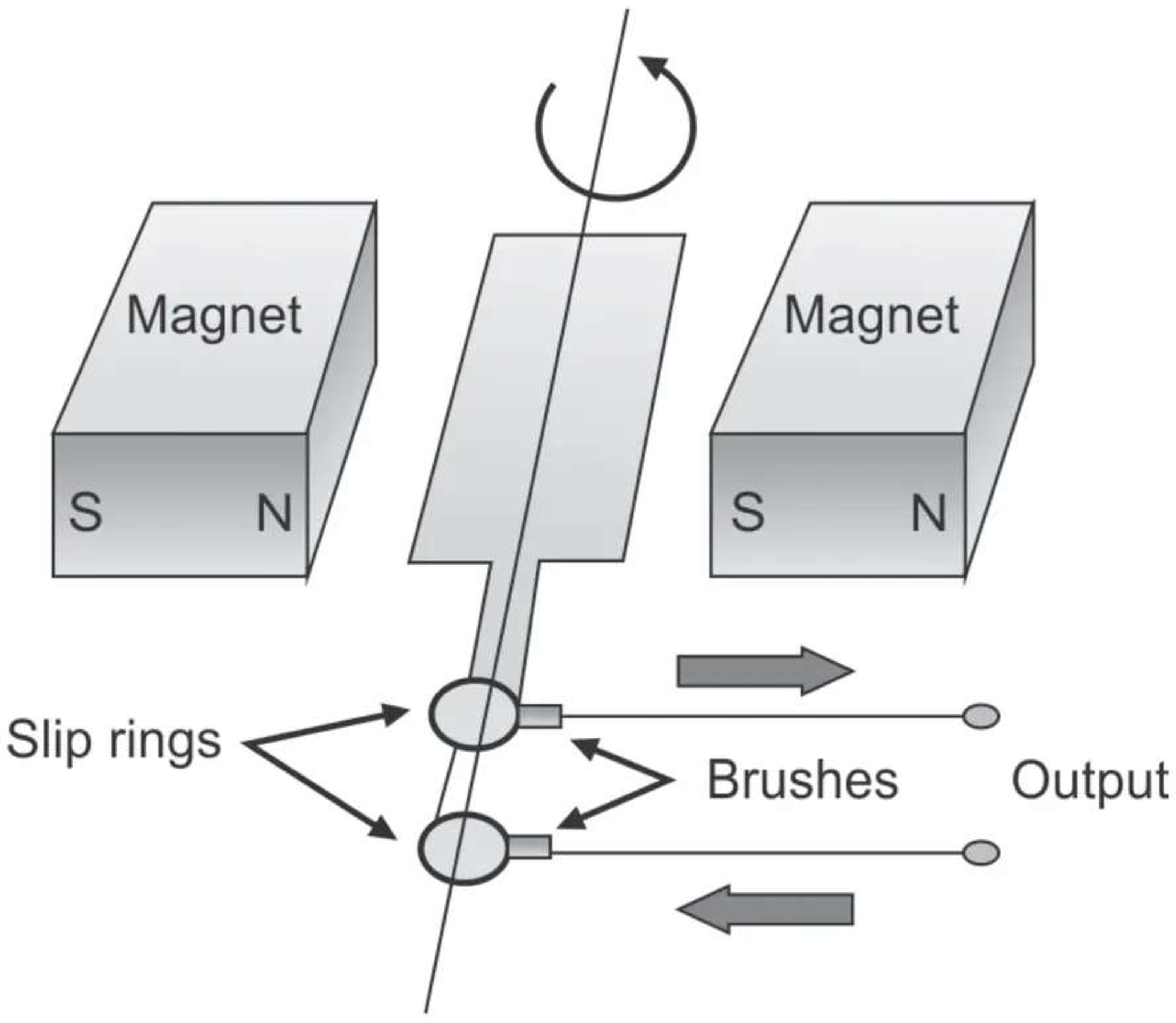


FIG. 2.16: Alternating current generator

The two slip rings are metal rings to which the ends of the armature coil are connected. These rings are fixed to the soft, which rotates the armature coil. The slip rings also rotate along with the armature. There are two flexible metal plates or carbon brushes, which are fixed and constantly touch the revolving slip rings. With the help of these brushes current is passed out to the external circuits from the armature.

As the armature rotates at a constant speed, a varying emf will be induced across the ends of the coil. The induced emf will be at a maximum, when the magnetic lines of force cut the coil windings at right angles (90° and 270° position). The emf will be zero when the magnetic field is parallel to the coil windings (0° and 180°). Thus, the induced current changes its direction after every half rotation.

The emf values can be plotted against the position of the armature in a graph. It can be seen that the emf starts at zero, reaches a positive maximum, or peak, drops to zero, goes to negative peak then return again to zero. The whole series of operations is called one cycle (Fig. 2.17). This emf is called an alternating emf and the current it would produce is called the alternating current. This emf is also called as sinusoidal voltage because; the emf is proportional to the sine of the angle of rotation. The induced emf at any instant time t is given by

$$e = E_0 \sin \omega t$$

The corresponding alternating current is given by $i = I_0 \sin \omega t$, where, E_0 and I_0 denote the peak value of the emf's and the current respectively, $\theta = \omega t = 2\pi\nu$ and ν is the frequency of the alternating current. The term, ωt is the phase angle.

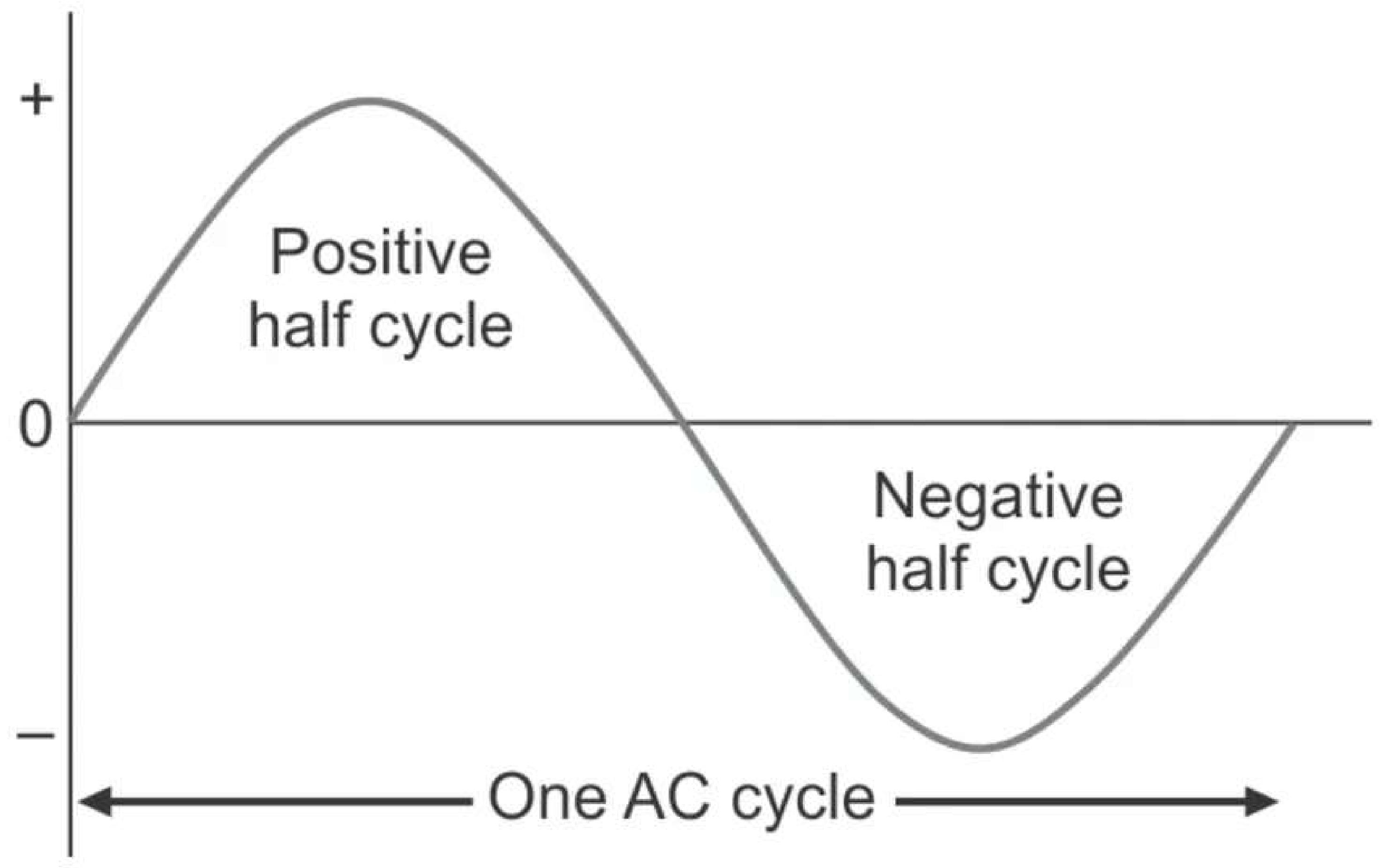


FIG. 2.17: Alternating current waveform

The frequency of the alternating voltage is the number of cycles made in one second. If the armature rotates 50 times per second, the frequency will be 50 cycles per second (hertz, Hz).The phase of an AC voltage or current is the fraction of the cycle that has elapsed, since the starting of the voltage or current waveform. It is expressed in terms of angle of armature rotation.

Peak and RMS Values

Since the alternating voltage is changing continuously, it is usually referred by instantaneous values. The instantaneous values of 'e' and 'I' merely give the value at any specified instant in time. But the instantaneous values are of limited application in normal use. The peak values E_0 and I_0 are the maximum instantaneous values. Since the peak value occur only for two instants in each cycle, its application is also limited.

The most useful measure of alternating quantity is root mean square value (rms). The rms value of an alternating current is that value of direct current which has the same average heating effect as the alternating current. The relation between the peak and rms values are as follows:

$$\text{rms voltage } (E_{eff}) = \text{Peak voltage } (E_0)/\sqrt{2}$$
$$= E_0 \times 0.707$$
$$\text{rms current } (I_{eff}) = \text{Peak current } (I_0)/\sqrt{2}$$
$$= I_0 \times 0.707$$

whenever the voltage and current values are given without any mention, it refers to rms value only.

AC ammeters and voltmeters are calibrated to give effective values of current and voltages respectively. When it is said that the electric main line is 220 V, 5 A, it means that the effective value of voltage and current are 220 V and 5 A respectively. A voltage rating of 220 V means that the incoming sinusoidal voltage has peak value of 220 ÷ 0.707 = 310 V. A fuse having a current rating of 5 ampere indicates that the current through the fuse wire can have a peak value of 5 ÷ 0.707 = 7.07 amperes.

Power in AC Circuit

In AC circuit, the emf and the current vary continuously and also there is a phase difference (θ) between them. To estimate power at any instant, the power for a complete cycle is calculated. The average power of the circuit containing only resistor is given by,

$P_{av} = E_{eff} \times I_{eff}$.

The average power for a circuit containing a resistance (R) and inductance (L), over a full cycle of AC is given by, $P_{av} = E_{eff} \times I_{eff} \cos \theta$, where, $\cos \theta$ is known as the power factor of the AC circuit.

$$\text{The power factor, } \cos \theta = R/\sqrt{R^2 + (L\omega)^2}$$

where, $\omega = 2\pi f$ and f is the frequency of the alternating current.

THREE PHASE ALTERNATING CURRENT

Every country requires wide variety of AC power supply, to meet its demands. This can be achieved by having more than one phase of AC supply. Instead of single coil, three coils are used, to design a three phase AC generator. In this three symmetrical windings, separated by an angle of 120°, are mounted on a soft. Though the coils are mounted on the same soft, but connected to three separate pairs of slip rings. If the soft is rotated, each coil in turn moves through the magnetic field and induce three alternating voltages. Since the coils are inclined at 120° to one another and each having its pair of slip rings, the emf and the currents in the three coils will differ in phase by 120°. Such a generator is called a three phase generator and the current produced by it is three phase AC (Fig. 2.18).

Three phase supply provides more constant voltage to the circuit. When X-ray units are provided with three phase supply, it gives short exposure times. However, it is very expensive, difficult to install due to bulky hardware.

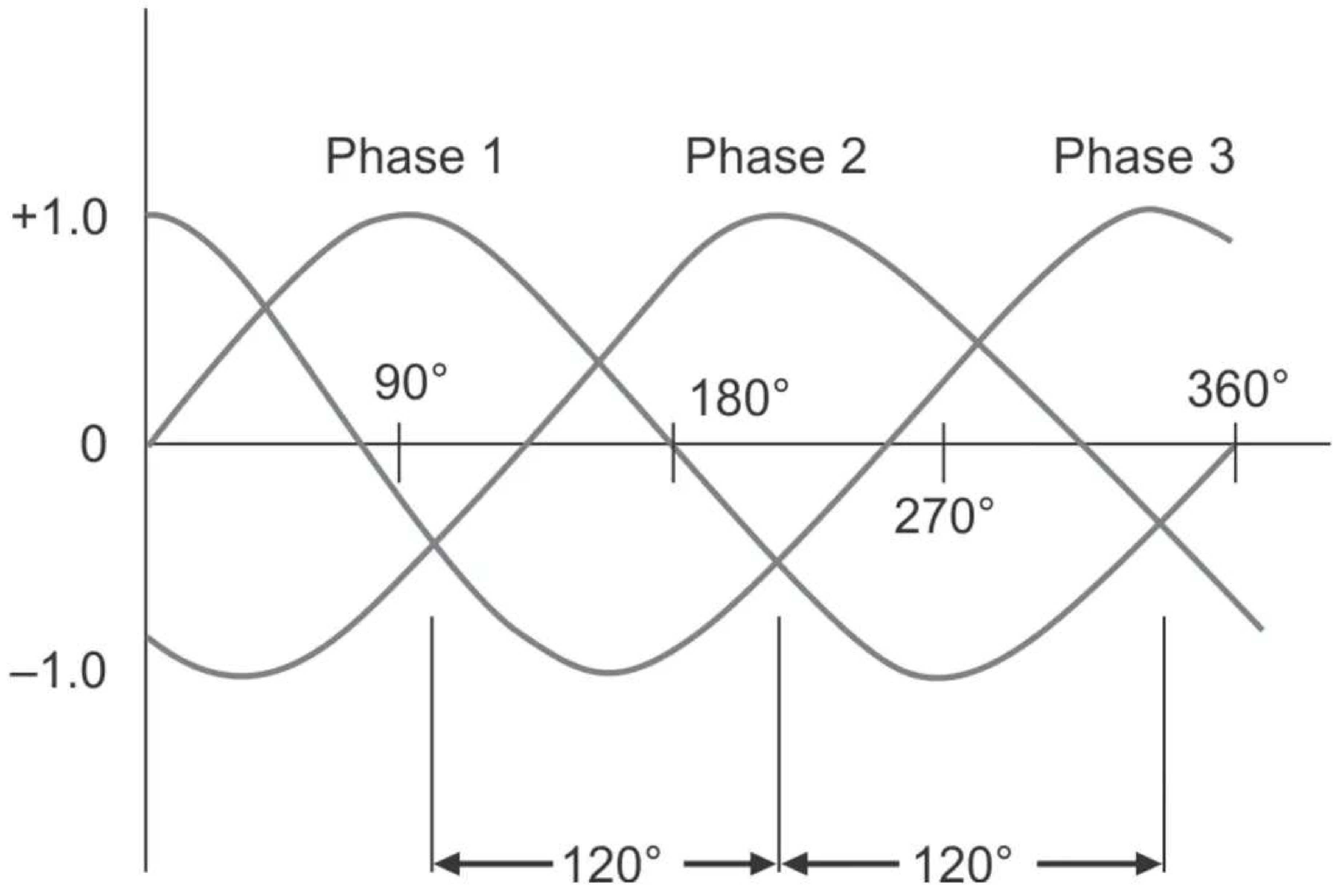


FIG. 2.18: Three phase AC waveforms

Three-phase Supply Connections

The three phase supply is connected in two ways namely, star or wye connection and delta connection (Fig. 2.19). In the star connection, one end of each of the three windings is connected to a common center point, which is earthed (neutral). The other three terminals are used for connections, which are called line conductors. If equal load is given in all the three lines, the current flowing towards the center in one of the windings is equal to the sum of the currents flowing away from the center in the other two. In practice, the electrical loads placed on the three phases may not be equal. Therefore, the fourth line, neutral acts as a common return path for current flowing from any of the other winding.

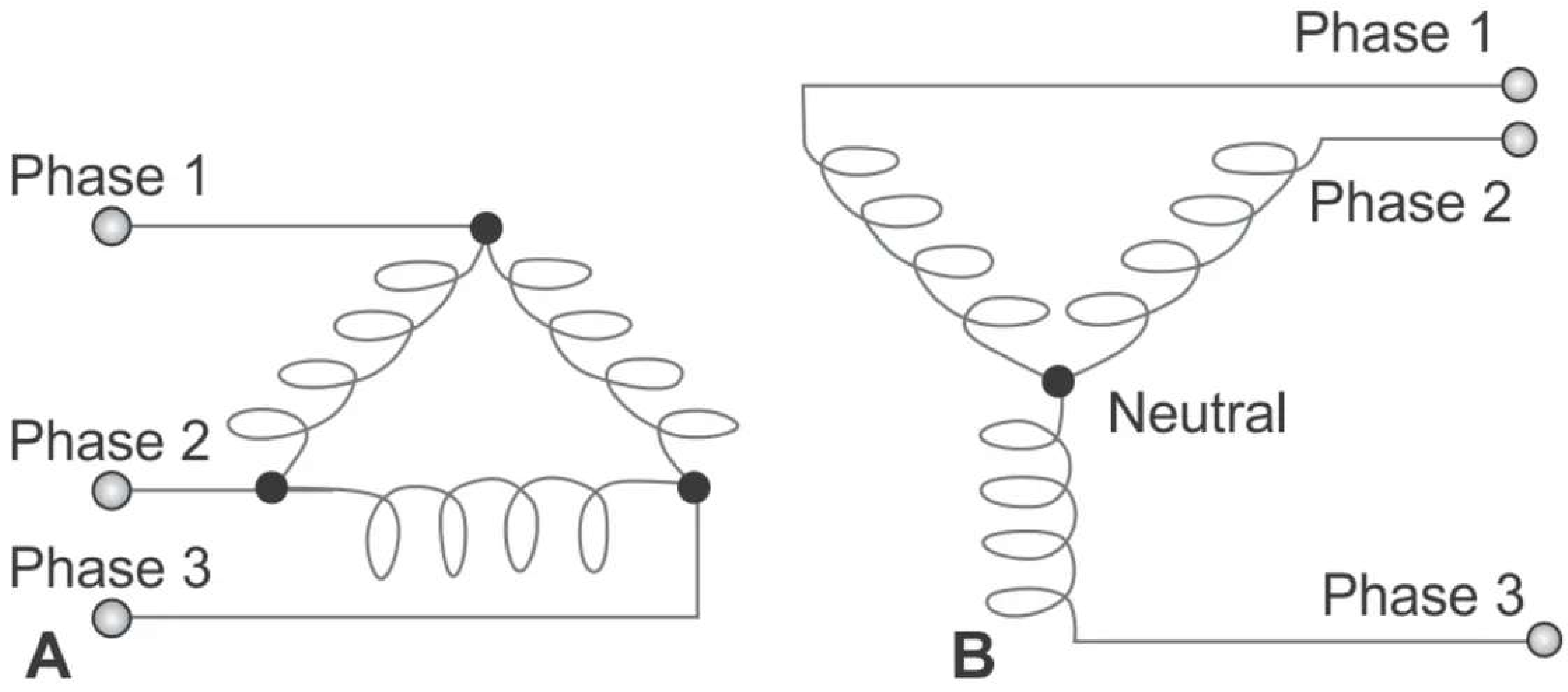


FIG. 2.19: (A) Delta and (B) Wye connection circuit

In delta circuit, the coils are connected like a triangle. Since triangle is similar to the Greek capital letter delta, this is called as Delta connection. The star connection has certain advantages over the delta connection as follows: (i) it is cheaper to produce and less stress and liability to breakdown, (ii) provide two different voltages, and (iii) reduces the number of conductors required for electrical transmission.

CHOKE COIL

A choke coil consists of a large number of turns of insulated conducting wires wound over a soft iron laminated core. Its self inductance (L) is very high and it offers a very high resistance to the flow of AC, thereby reducing the value of the current. It plays the same role in AC circuits as resistance in DC circuits. For many purposes, it is required to reduce the current in a given circuit, without wastage of energy, when the voltage is constant. If the resistance of the choke is R and the inductance is L, then the power factor

$$\cos\theta = R/\sqrt{R^2 + (L\omega)^2}$$

If a pure inductance having no resistance is used (R = 0), then the power factor is zero and the power absorbed by the inductance is zero and the impedance offered is equal to $L\omega$. Even though there is no wastage of energy, the current is reduced due to the inductive reactance $L\omega$. The only wastage of energy is due to hysteresis loss in the iron core but it is very less compared to I^2 R losses.

Choke coils are used both in low frequency (audiofrequency) currents and in high frequency (radiofrequency) currents. A typical radio frequency choke coil consists of one or more coils mounted on an insulating rod. A long single layer solenoid is also sometimes used as choke coil. Choke coils are used in radio sets, mercury lamps and sodium vapor lamps in AC circuits.

EDDY CURRENT

When a conducting metal is placed in a varying magnetic field, current will be induced in the metal. This current will flow in closed paths inside the material. This current is called the eddy current or Foucault current. The production of eddy current leads to loss of energy due to heating.

Eddy currents tend to flow at right angles to the direction of field. Eddy currents cannot be completely eliminated but can be minimized by using metallic conductor in the form of thin sheets, called lamina insulated from one another. The core of dynamos, transformers and electric motors are laminated, to reduce the eddy current formation.

Eddy current has variety of applications: (i) In galvanometer, it is used to stop the motion of the oscillating coil, (ii) eddy current brakes are used in stopping electric trains, (iii) in induction furnace, it is used to produce heat, in order to melt and separate a particular metal from the ore, and (iv) the speedometer of the car involves eddy current principle.

ELECTRIC POWER TRANSMISSION

In the transmission of electricity, transformers play an important role. Power plants are often situated at far off places, electricity must be transmitted over long distances, and there is always some power loss in the transmission lines. This loss can be minimized if the power is transmitted at high voltage.

Suppose an electric power P has to be delivered at a potential difference V by supply lines of total resistance R, then

$$\text{Current } I = P/V \text{ and}$$
$$\text{Power loss} = I^2 R = (P/V)^2 R$$

It is clearly seen here that, higher the potential difference, smaller will be the power loss. It is for this reason, the power is usually transmitted at very high voltage. By using a thick wire, resistance can also be minimized.

A typical power generator gives an output of 1000 kW at 6600 V. In practice, this voltage is stepped up to 132000 V before transmission. The cable used for transmitting power over long distances, are suspended by the large porcelain insulators from large steel structures called pylons. The main transmission lines from power station form part of a common system called the grid. Power from all the power stations in the region is fed into the grid, which covers a large region of the country. This forms a common pool from which power can be drawn. This allows an efficient power distribution and acts as a safeguard for ensuring a minimum power supply to the consumers in the event of failure of power generation at some station.

From the grid, the power is fed to the cities at 33000 V by using a step down transformer. At the substation, the supply is again stepped down to 6600 V. Power is supplied to the big factories at this voltage and they step down it according to their needs. For ordinary domestic consumers, the voltage is reduced to 220 V by using step-down transformers.

3

Physics of X-rays

DISCOVERY OF X-RAYS

X-rays were discovered by WC Roentgen, the German physicist in 1895 when he was investigating the conduction of electricity through gases at low pressure in glass tubes. He noticed that the positive electrodes in the tubes gave off invisible rays which made fluorescent screens (Barium platinocyanide screen kept near the tube) to glow and fogged photographic plates. The rays were highly penetrating, they passed through black paper and even thicker objects. They were not deflected in magnetic field. Therefore, Roentgen concluded that they were not charged particles. As their nature was not known he called them X-rays; later, they were shown to be electromagnetic radiation of very short wavelength. Roentgen received the first Nobel prize in physics in 1901 for his discovery.

PROPERTIES OF X-RAYS

1. X-rays are electromagnetic radiation of shorter wavelength (few nm).
2. They travel in straight line with a velocity equal to light.
3. X-rays are not influenced by electric and magnetic fields.
4. X-rays penetrate through substances that are opaque to visible light.
5. X-rays produce fluorescence in materials like calcium tungstate, and cesium iodide, etc.
6. X-rays affect the photographic film and form latent image.
7. X-rays produce ionization and excitation in the substances through which they pass.
8. X-rays produce chemical changes in substances through which they pass.
9. X-rays produce biological effects in living organisms. The cells can be either damaged or killed due to X-ray exposure.

PRODUCTION OF X-RAYS

X-rays are produced when fast moving electrons are stopped by means of a target material. The moving electrons possess kinetic energy. When the electron is suddenly stopped, its kinetic energy is converted into heat and X-rays. This conversion is taking place in the target material. Therefore, the interaction of electron with the target is the basis for X-ray production.

ELECTRON INTERACTION WITH THE TARGET

When the electron arrives at the target, it interacts in four ways as follows (Fig. 3.1).

The electron interaction involves ionizational collisions (i) and radiative collisions (ii), (iii) and (iv).

i. Ionization of target atoms: The fast moving electron enters the surface layer of the target and undergoes collisions. In this process, the incident electron transfers sufficient energy and removes an electron from the atom. This involves small energy transfer, resulting in ionization of target atoms. The incident electron may undergo number of such collisions and each time its direction gets altered. A 100 keV electron may encounter 1000 of such interactions, before coming to rest and most of its energy appears as heat in the target. The displaced electron, known as a secondary electron, may have sufficient energy and produce further ionization of target atoms. They are few in number and produce their own track, known as delta rays.

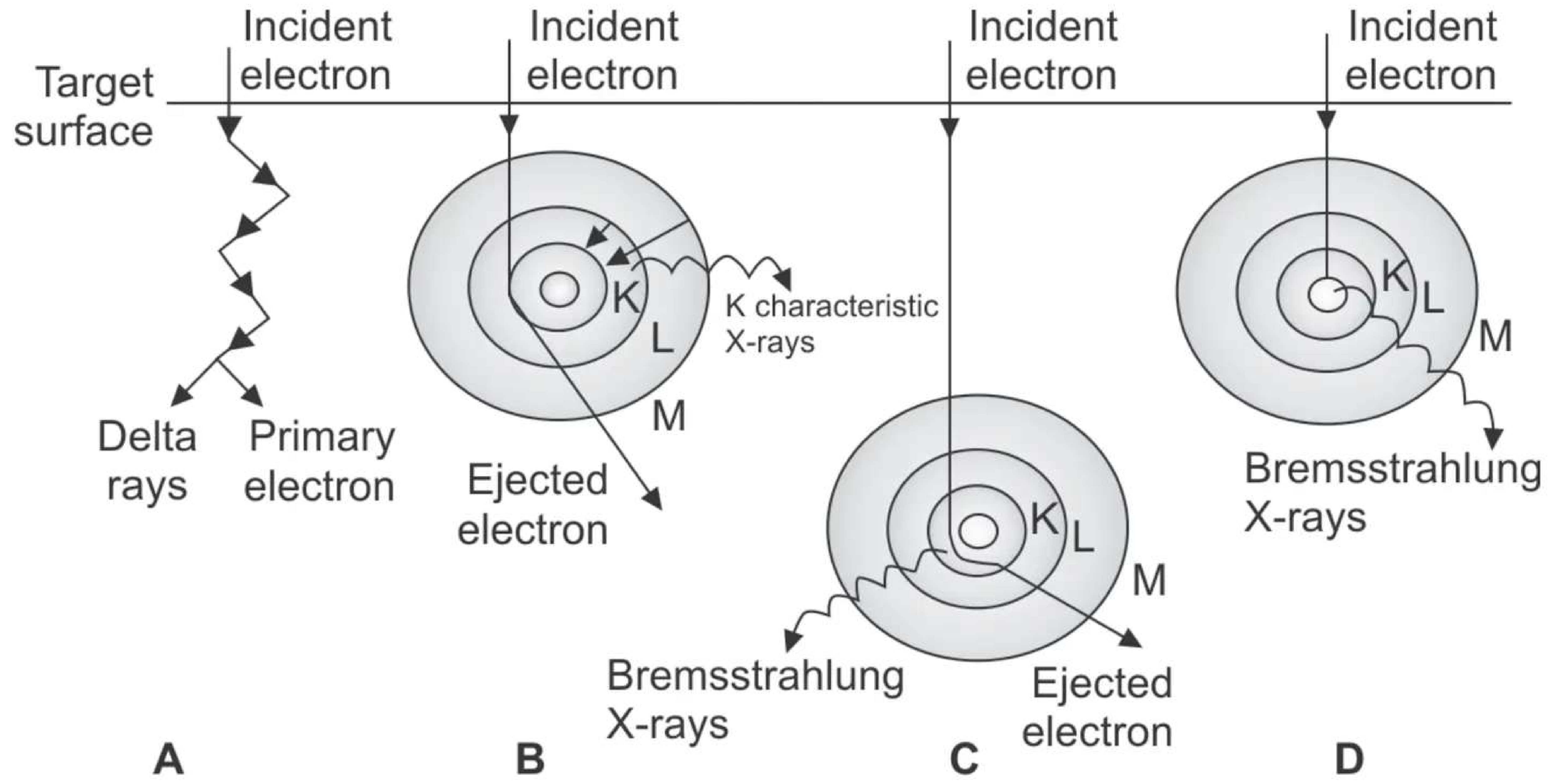


FIG. 3.1: Interaction of electron with target atoms: (A) Ionization of target atoms, (B) Characteristic X-rays, (C) Interaction with nuclear field, (D) Interaction with nucleus

ii. Characteristic X-rays: This is an interaction between the incident electron and the electron in the K shell. In this process, the incident electron directly hit the K shell, transfers sufficient energy and removes the K shell electron. The vacancy in the K shell is filled by an electron moving inwards from the outer shell. During this transition, the difference in binding energies of the two shells is given out as X-ray photon. This photon is known as the characteristic X-ray. The ejected electron may produce further interaction in other target atoms.

iii. Interaction with nuclear field: The incident electron occasionally reaches nearer to nucleus of an atom in the target. Since the electron is a negative particle, it is attracted by the positive nucleus. It is made to orbit partially around the nucleus, decelerates and goes out with reduced energy. The loss of energy appears in the form of X-ray photons, known as Bremsstrahlung. The energy of the X-ray photon depends on the degree to which the electron is decelerated by the nuclear attraction. The photon energy can take any value from zero to a maximum. This process is unlikely at low energies, but dominant at high energies.

iv. The electron may hit the nucleus directly and is stopped completely in a single collision. The entire electron energy appears as bremsstrahlung radiation. This type of interaction is very rare, but capable of giving high energy X-rays.

In general, the interaction of B, C and D are very rare in the diagnostic range of energies, leading to lesser amount of X-ray production. The ionizational collision dominate (> 99%) the interaction process and produce heat. Thus, a X-ray tube is inefficient in the conversion of electron energy into X-rays.

X-RAY SPECTRA

X-ray photons produced by an X-ray tube are heterogeneous in energy. There are two types of X-ray spectrum, namely, (a) bremsstrahlung or continuous spectrum and (b) characteristic spectrum. A bremssrahlung spectrum consists of X-ray photons of all energies up to maximum in a continuous fashion, which is also known as white radiation, because of its similarity to white light. A characteristic spectrum consists of X-ray photons of few energy, which is also called as line spectrum. The position of the characteristic radiation depends upon the atomic number of the target.

The intensity of the X-rays can be plotted against photon energy in a graph (Fig. 3.2). The area under the curve is proportional to the total number of photons emitted. The highest X-ray energy is determined by the peak voltage (kV_p) applied in the X-ray tube. The characteristic spectrum is superimposed on the continuous spectrum. An unfiltered beam spectrum (theoretical) will be a straight line and mathematically given by Kramer's equation

$$I_E = KZ\ (E_m - E)$$

where, I_E is the intensity of photons with energy E, Z is the atomic number of the target, E_m is the maximum photon energy and K is a constant. The unfiltered X-ray spectrum looks like a ramp.

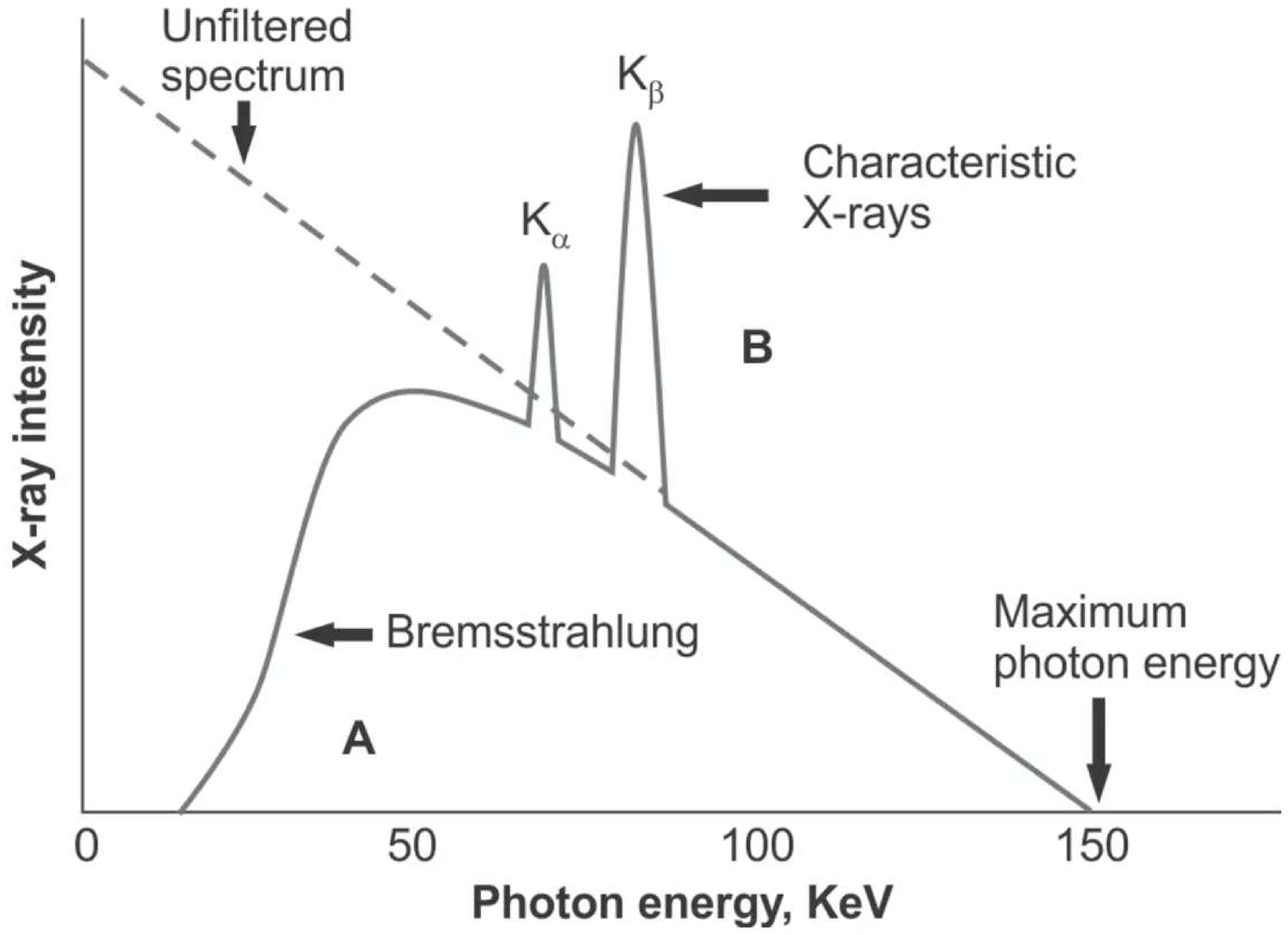


FIG. 3.2: X-ray spectrum, (A) Bremsstrahlung and (B) Characteristic spectrum

In practice, the X-ray beam is a filtered beam, due to inherent and added filtration. The filtration hardens the beam, by absorbing the low energy X-rays up to 10 keV, which is evident by the bremsstrahlung spectrum. The number of photons increases initially, with photon energy and later decrease linearly up to maximal photon energy. The X-ray spectrum is influenced by applied voltage, target material, tube current, exposure time, bremsstrahlung process and filtration. To specify the quality of X-rays, a rule of thumb is used, which states that the effective energy is about 1/3 to 1/2 of maximum X-ray energy.

BREMSSTRAHLUNG

The bremsstrahlung is a German word meaning braking radiation. It is a process of radiative collision between the electron and a nucleus in the target (Fig. 3.3). The electron while passing near the nucleus may suffer a sudden deflection and acceleration by the action of coulomb forces of attraction. As a result, the electrons may lose their kinetic energy, in the form of bremsstrahlung X-rays. The electron may have one or more such interactions and this may result in partial or complete loss of energy.

The amount of bremsstrahlung production is determined by the distance between the bombarding electron and the nucleus. At very large distance, the columbic force is weak, only low energy X-rays are created, but this process has higher probability to occur. When the electron is very close to the nucleus, columbic force is strong, electron lose more kinetic energy, resulting production of high energy X-rays. But this process has lower probability to occur. When the electron is in the middle, the electron interaction is moderate and the X-ray energy is also moderate. If the electron hit the nucleus directly, it lose all its kinetic energy, but the probability of this type of interaction is very low (5%). To conclude low energy X-rays are produced in greater abundance compared to high energy X-rays.

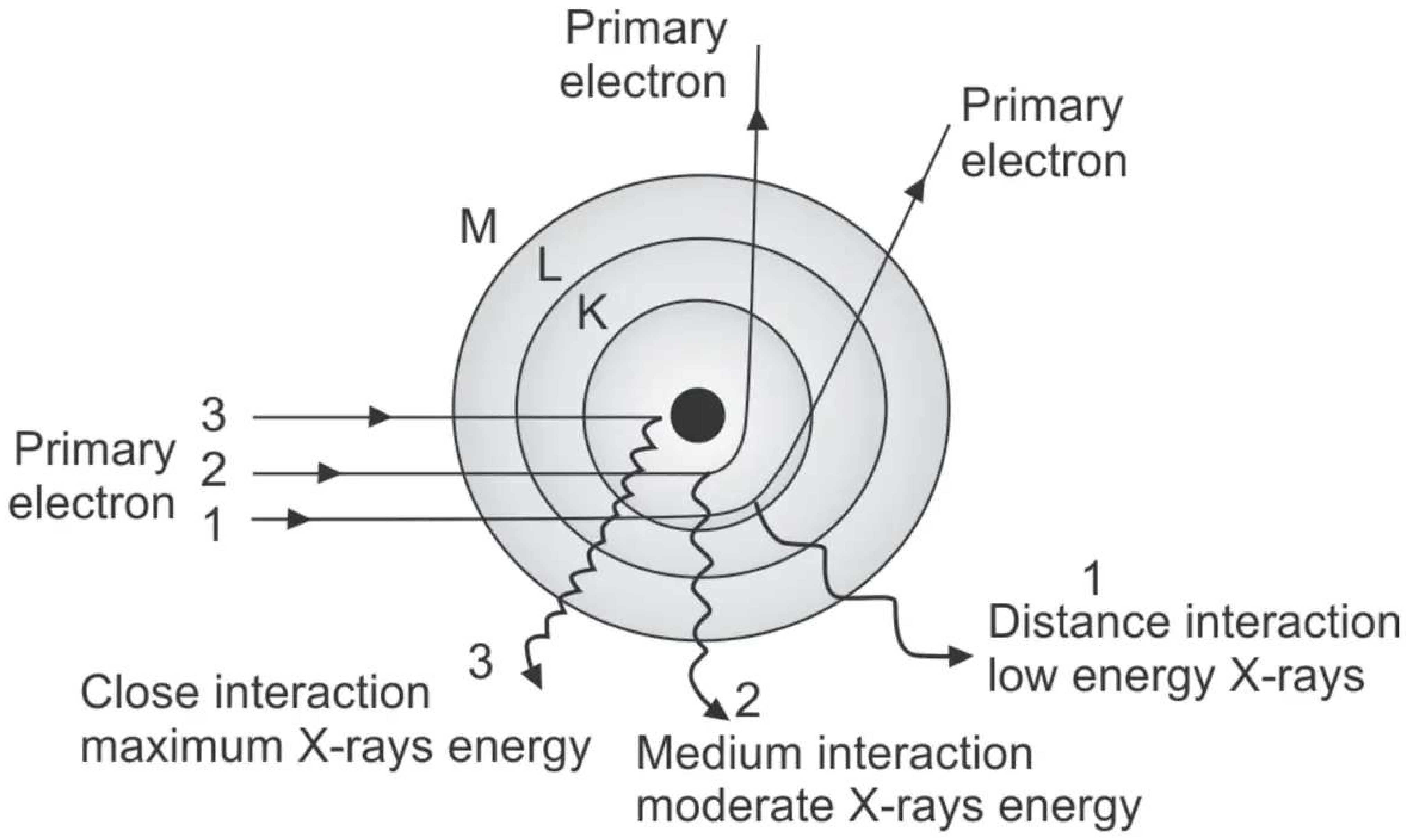


FIG. 3.3: Production of bremsstrahlung radiation

Thus, the bremsstrahlung radiation will have all possible energy from zero to maximum. The maximum energy is determined by the maximum kinetic energy of the incident electron. Also the direction of emission of bremsstrahlung photons depends on the energy of the incident electron. At electron energies below 100 keV, X-rays are emitted equally in all directions. As the kinetic energy of the electron increases, the direction of X-ray emission becomes increasingly forward. In diagnostic radiology, it is technically advantages to obtain the X-ray beam on the same side of the target, i.e., at 90° with respect to the electron beam direction.

In diagnostic X-ray tubes, thicker targets are used, to stop the entire electron beam. Hence, X-rays are produced in all directions around the target. Those X-rays that are produced in the forward direction will be absorbed by the target itself. The term efficiency of X-ray production is defined as the ratio of output energy emitted as X-rays to the input energy deposited by the electron. It can be shown that

$$\text{efficiency} = 9 \times 10^{-10} \times Z \times V$$

where, Z is the atomic number of the target material, V is the tube voltage in volts. Thus, the bremsstrahlung X-ray production increases with accelerating voltage and atomic number of the target material. Alternatively, the X-ray production efficiency may be expressed in terms of radiative and collisional losses as follows:

$$\frac{\text{Radiative energy loss}}{\text{Collisional energy loss}} = \frac{E_k \times Z}{820{,}000}$$

where, E_k is the kinetic energy of the incident electron. Radiation loss is due to bremsstrahlung production, whereas collisional loss is due to excitation and ionization. If an electron with 100 keV energy interacts with a tungsten target ($Z = 74$), then the above ratio = $(100 \times 72)/820{,}000 = 0.9\%$. Thus, the efficiency of tungsten target is found to be less than 1% and the rest of the input energy, > 99% appears as heat. Higher the photon energy, greater the X-ray production efficiency, and lesser the heat production. The X-ray production efficiency is more than 50% for a 6 MV electron, resulting lesser production of heat.

CHARACTERISTIC X-RAYS

Electron incident on a target may produce characteristic X-rays. An electron with kinetic energy E_0 may interact with the atoms of the target, by ejecting an orbital electron from the K shell. Now, there is a vacancy in the K shell and the atom is said to be ionized. The original electron will have energy E_0 -E, where, E is the energy given to the orbital electron. The outer orbital electrons (from M or L) will fell down to fill the vacancy in the K shell (Fig. 3.4). In doing so, the difference in binding energy of the two shells is radiated as X-ray photons, which is called the characteristic radiation. This will have only discrete energies. Since the binding energy difference is unique to an atom, the X-rays emitted are characteristic of that element. If the transition involved an electron from L shell to K shell of a tungsten target, then the emitted photon will have energy:

$$\begin{aligned} h\nu &= E_K - E_L \\ &= 69.5 \text{ keV} - 10.2 \text{ keV} \\ &= 59.3 \text{ keV} \end{aligned}$$

where, E_K and E_L are the binding energies of the K and L-shells of tungsten atom respectively. The K-shell characteristic X-ray energies are slightly lower than the K-shell binding energy. Electron transition may be from adjacent and non-adjacent shells.

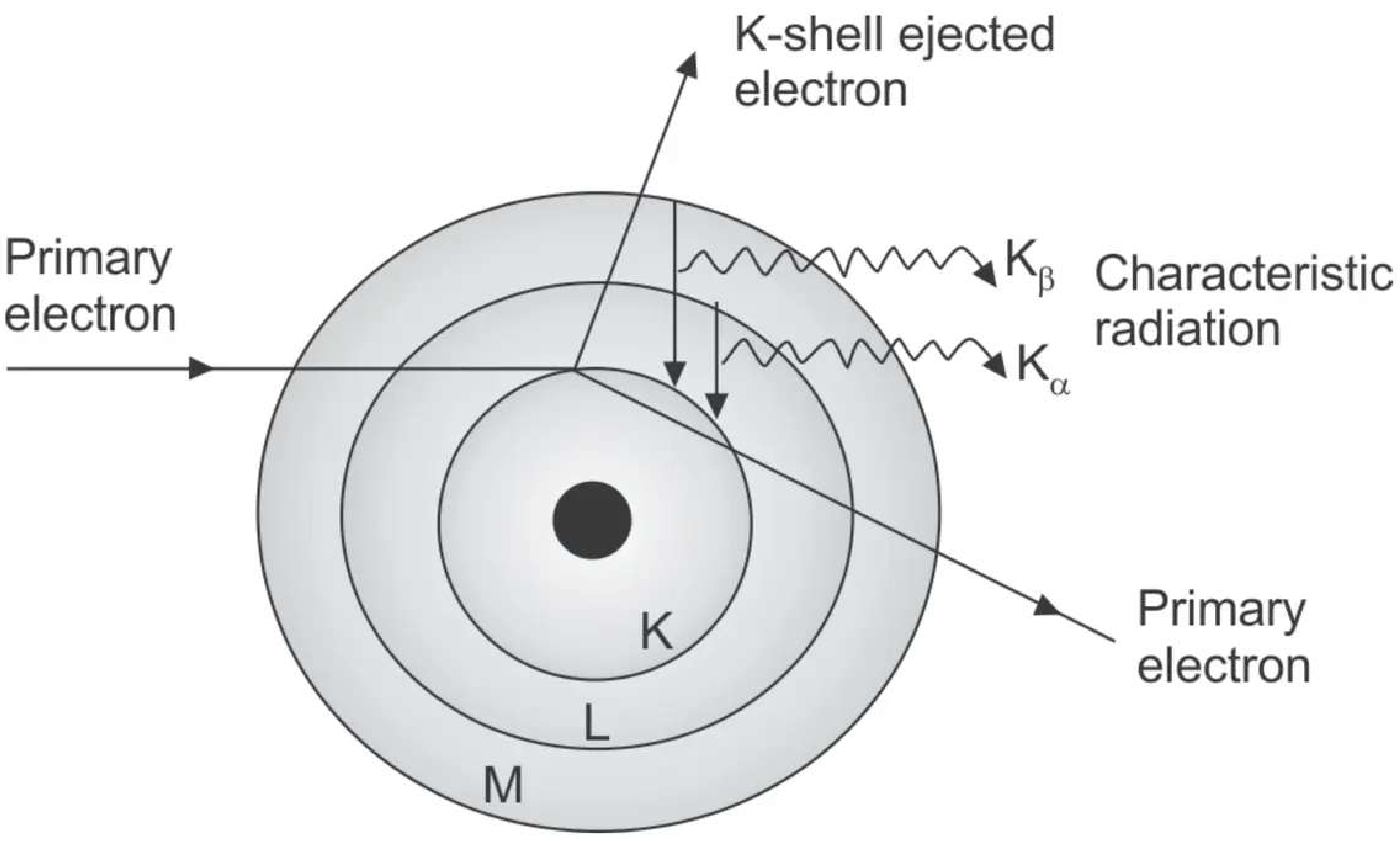


FIG. 3.4: Production of characteristic X-rays

Energy transitions are designated by the shell capturing the electron with a subscript of α or β. The subscript α refers to an adjacent shell transition, e.g. L → K transition is denoted as K_α X-rays. The subscript β refers to a non-adjacent shell transition, e.g. M → K transition is denoted as K_β X-rays. Thus, transition results in fine energy splitting of the characteristic X-rays, due to subshells of the given orbit. Only K characteristic X-rays are very important in diagnostic radiology ($K_{\alpha 1}$, $K_{\alpha 2}$ and $K_{\beta 1}$ transitions). The K-shell characteristic X-rays for various target atoms are given in Table 3.1.

The characteristic X-rays other than K-shell transitions are not important, since they are entirely attenuated by the tube window and filters. K characteristic X-rays are emitted only, if the incident electrons have energies greater than the binding energy of the K-shell electron. Hence, the kilovoltage applied must be greater than 69.5 keV for tungsten,

TABLE 3.1 K-shell characteristic X-rays (keV) and target material

Transition	Tungsten, Z = 74	Molybdenum, Z = 42	Rhodium, Z = 45
$K_{\alpha1}$	59.32	17.48	20.22
$K_{\alpha2}$	57.98	17.37	20.07
$K_{\beta1}$	67.24	19.61	22.72

20 keV for molybdenum and 23.2 keV for rhodium targets respectively, which is called as threshold energy. As the energy of the incident electron increases above the threshold energy, the % of characteristic X-rays also increases. The 100 kV_p X-rays spectrum consists of about only 10% characteristic X-rays.

X-RAY TUBE DESIGN

The production of X-ray needs the following: (i) electron source (cathode), (ii) target to stop the electrons (anode), (iii) high voltage supply to accelerate electrons, (iv) vacuum and (v) tube insert (glass envelope). Electron can be produced either by ionization in gas or by thermionic emission. The electron source acts as a cathode and the target acts as an anode. The high voltage is applied in between the cathode and anode. This voltage accelerates the electrons to a higher velocity; as a result the electron will possess high kinetic energy. When the electrons are stopped by a target, the electron kinetic energy is converted into X-ray energy and thus X-rays are produced. The equipment having all the above requirements is called an X-ray tube.

The tube should be designed in such way that, it should withstand voltages from 20–150 kV and currents up to 1000 mA. In radiography, tube current may vary from 100 to 1000 mA, whereas in fluoroscopy, it is 1–5 mA. In addition, exposure time has to be varied over a wider range.

CATHODE

The cathode is made of tungsten wire in the form of helical filament, surrounded by a focusing cup (Fig. 3.5). Tungsten is used as filament material because of its high melting point, low vapor pressure, good ductility (easily drawn into fine wire) and low work function (4.5 eV). Tungsten exhibits thermionic emission well below its melting point. The filament is made of tungsten wire, about 0.2 mm in diameter, that is coiled to form a vertical spiral about 0.2 cm in diameter and 1 cm in length. The coil format provides large surface area for electron emission.

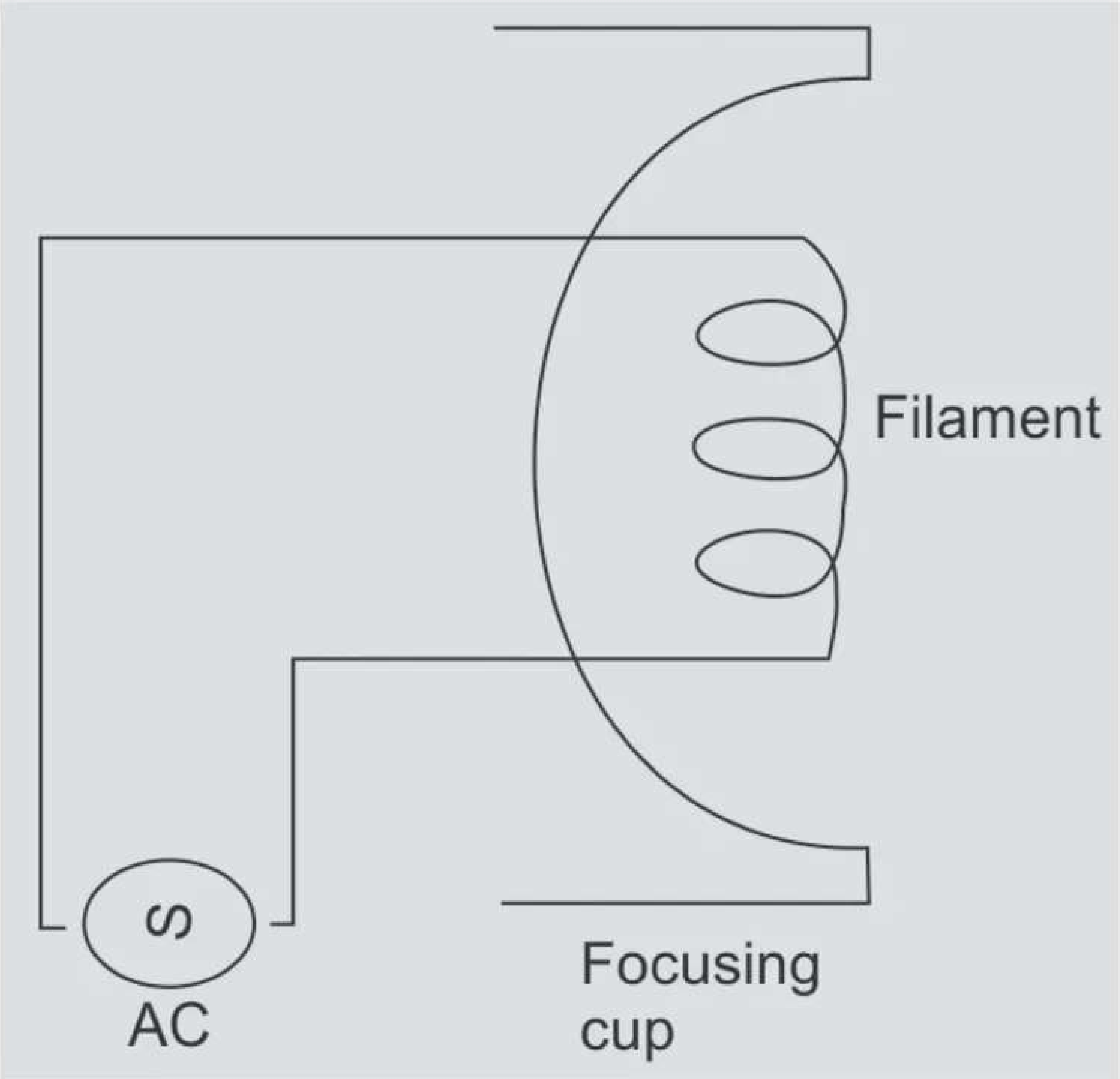


FIG. 3.5. Cathode assembly

The filament circuit supplies a voltage of 8–12 V and selectable filament current of 3–7 amperes. Electrical resistance to electron flow heats the filament to very high temperature, releasing surface electron through thermionic emission process. The rate of emission depends on the temperature and it can be adjusted by the filament current. A trace of thorium in the filament not only increases the efficiency, but also prolongs the filament life. If the applied voltage between anode and cathode is zero, the electrons form a cloud near the cathode, which is called space charge. As the applied voltage increases, the electrons are accelerated towards the anode, helps the production of X-rays.

The focusing cup controls the width of the electron distribution, and directs the electron toward the target. Usually, the focusing cup is at the same potential as the filament, which is called nonbiased X-ray tube. Usually, X-ray tubes are provided with two filaments of different length. Selection of a particular filament determines the focal spot length or area.

SPACE CHARGE EFFECT

To under stand the operation of an X-ray tube, it is essential to know how the tube current depends upon the tube voltage, for a given filament excitation (Fig. 3.6). When the applied kV is zero or small, the electrons surrounding the filament forms a cloud, resulting in space charge effect. These electrons tend to repel electron back into the filament and hence the tube current is very small. As the kV_p is increased, (0–40 kV) the effect of space charge reduces gradually and the tube current also increases. This is called space charge limited region. In this region, the tube current strongly dependent on applied kV, for a constant filament current.

Above 40 $kV_{p,}$ the space charge effect is overcome, and the tube current is controlled by the filament current. This is called the saturation or emission limited region. In this region, the tube current undergoes little change with an increase in tube voltage. The tube current is 5–10 times lesser than the filament current in this region.

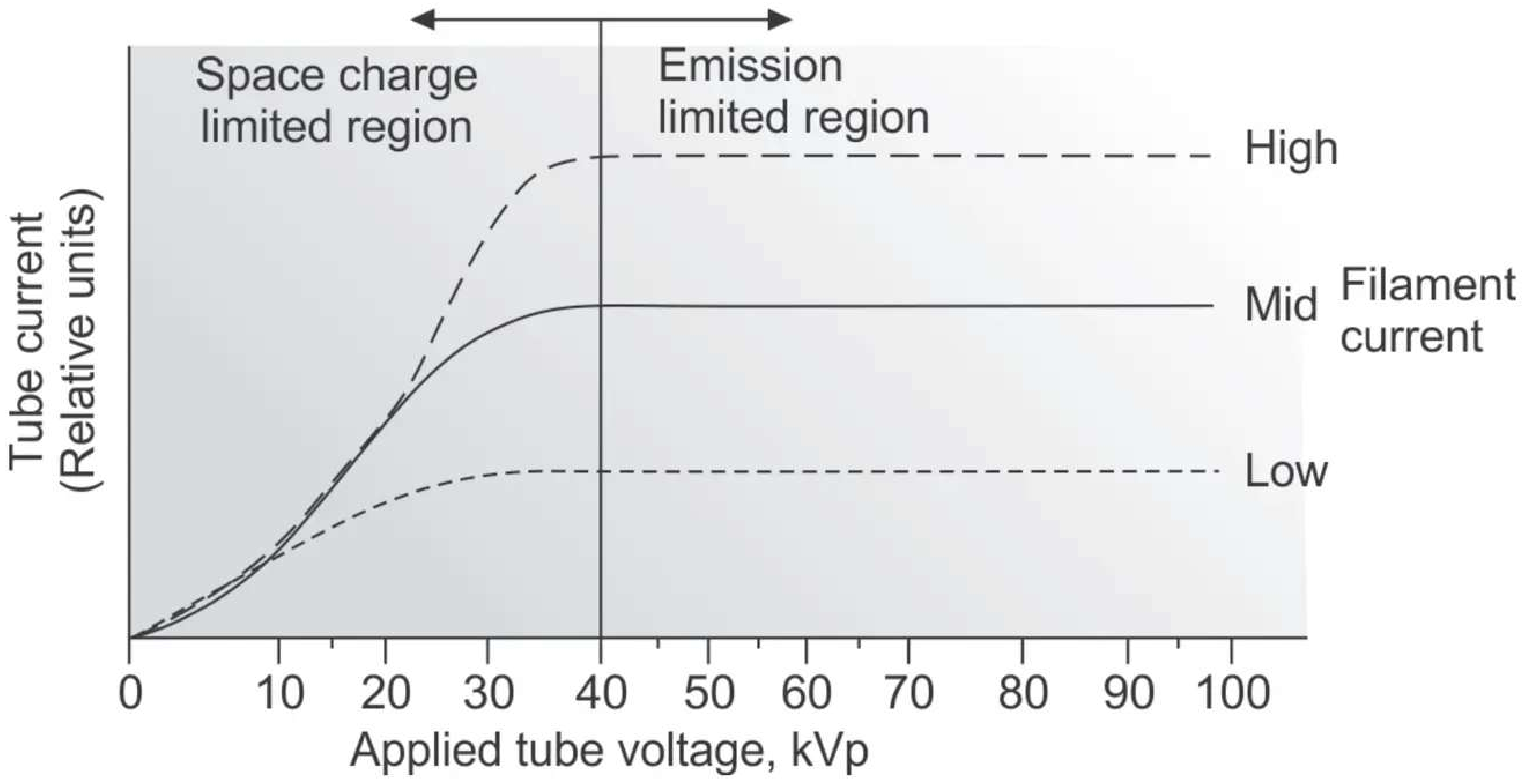


FIG. 3.6: Space charge effect

Most of the X-ray tubes are operating in between the space charge region and saturation region. Thus, the tube current is determined by both kV and filament current. In the space charge region (< 40 kV), the tube current is influenced by the applied voltage only. To deliver the selected tube current, a space charge compensating circuit is used. This circuit also corrects the small increase in tube current, at higher applied voltage (> 40 kV).

The above characteristics of the tube (curves) are depend upon many factors, including the distance between anode-cathode, the configuration of focusing cup, the focal spot size, and the filament temperature. Particularly the change of potential of the focusing cup, will drastically alter the curves.

ANODE

The anode is the target electrode, which is maintained at a positive potential. The target material should possess the following properties: (i) high melting point to withstand high temperature, (ii) high atomic number to increase the X-ray production efficiency, (iii) high thermal conductivity to dissipate heat quickly, (iv) low vapor pressure at high temperature to prevent the evaporation of target material, and (v) easily machined to make smooth surface.

Tungsten (W) is the metal widely used as target because of its high melting point, 3387°C and high atomic number, 74. However, its thermal conductivity is low (174 $Wm^{-1}K^{-1}$) and hence tungsten is embedded over a thick block of copper. The thermal conductivity of copper is 400 $Wm^{-1}K^{-1}$, so that the heat will be removed very quickly to the surrounding. The vapor pressure of tungsten is 5000 kPa, which is low, by which it releases less vapor into the vacuum. In the stationary anode, the tungsten is a square or rectangular plate of 2 or 3 mm thick and dimension greater than 1 cm. However, rotating anode design employs disk of 75–200 mm diameter, with beveled edges. Large diameter anodes are used in CT and fluoroscopy, which increases the heat capacity and heat dissipation. However, they are prone for mechanical damage, which is prevented by making radial slots in the anode. The above type of anode is called stress relieved anodes.

The anode has a tendency to crack under severe stress caused by heating. Therefore, tungsten-rhenium alloy (90% tungsten + 10% rhenium) is always used, which makes the target tougher and reduces surface pitting. Molybdenum (Mo, $Z = 42$) and rhodium (Rh, $Z = 45$) are commonly used as anode materials for mammographic X-ray tubes. These targets are capable of giving characteristic X-rays, suitable for soft tissue contrast studies.

FOCAL SPOT SIZE

The area of target with in which the electrons are absorbed and X-rays are generated is called focal spot or focal area. If the focal area is very small, penumbra will be lesser, and the picture sharpness will be good, but heat removal is difficult. On the other hand, if the focal area is large, heat will be removed quickly, penumbra is larger and the picture sharpness is bad. This can be compromised by careful design of the tube.

Usually, focal spot is defined in two ways namely, actual and effective focal spots. The actual focal spot size is the area on the anode that is struck by electrons. The effective focal spot size is the length and width of the emitted X-ray beam as projected down the central axis of the X-ray tube. The effective focal spot length is always smaller than the actual focal spot. The relation between them is given as follows:

$$\text{Effective focal length} = \text{Actual focal length} \times \sin\theta$$

where, θ is the anode angle. The focal spot size is usually expressed in terms of effective focal spot size, which varies from 0.3 mm to 2 mm square. The focal spot sizes of 0.3 mm, 0.6 mm, 1.0 mm, and 1.2 mm are commonly employed in radiology. The focal spot size has a major effect on spatial resolution, particularly when appreciable magnification of the object occurs. Focal spot size can be measured by using a pinhole camera, slit camera and star pattern.

LINE FOCUS PRINCIPLE

X-ray tube requires a specialized focal area in the target, which is larger in size to spread the heat easily and smaller in size to act as a point source. The point source reduces penumbra effect resulting sharp images. Hence, the target of an X-ray tube is mounted at a very steep angle (θ) with respect to the motion of the incident electrons. The X-rays will appear to come from a small focal area (effective focus), whereas the electrons bombard relatively a larger focal area (actual focus). There fore heat is removed very quickly and also the image sharpness is preserved. This is known as *line focus principle* (Fig. 3.7). Consider the electrons that are made to strike on a target of length ab, width cd and anode angle θ, then

$$\begin{aligned}
\text{effective focus} &= \text{actual focus} \times \text{sin of anode angle}\\
\text{cd} &= \text{ab} \times \sin\theta,\ \text{for example, if } \theta = 17^\circ,\\
&\ \text{cd} = 1\ \text{mm, ab} = 3\ \text{mm, then}\\
\text{effective focus} &= 3\ \text{mm} \times \sin 17^\circ\\
&= 3\ \text{mm} \times 0.2924\\
&= 0.877\ \text{mm}
\end{aligned}$$

In such tubes electrons bombard on a rectangular area of 3 mm × 1 mm, while the X-rays appear to come from an area of ≈ 1 mm × 1 mm.

Now, the loading gain is given by the relation,

$$\text{loading gain} = \frac{\text{actual focal area}}{\text{effective focal area}}$$

$$= \frac{3 \times 1}{1 \times 1} = 3.0$$

If the θ is made smaller the loading gain may be increased, but the angular width of the useful X-ray field is reduced.

ANODE ANGLE

Anode angle is defined as the angle of the target surface with respect to the central ray in the X-ray field as shown in Figure 3.7. It has strong relationship with focal spot size and usable X-ray field size. A small anode angle gives smaller effective focal spot, but its usable X-ray field is limited. Large anode angle gives larger usable X-ray field, but the effective focal spot is larger. To optimize the design, larger anode angle with small filament length is used. This will provide smaller effective focal size, with wide field coverage.

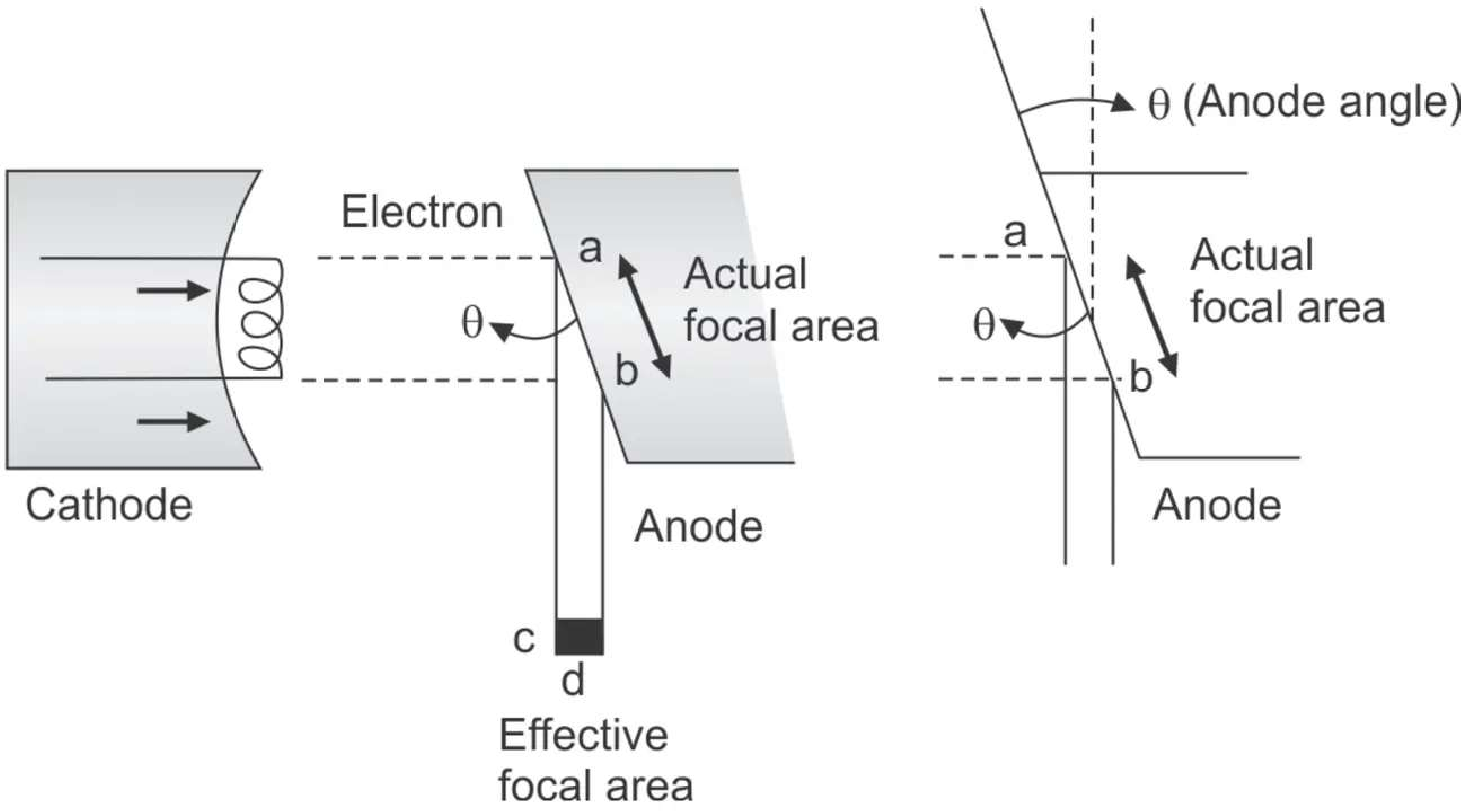


FIG. 3.7: Line focus principle

The optimum choice of anode angle depends on the clinical application. A small anode angle (7–9°) is useful in small field of view (FOV) imaging such as ciniangiography and neuroangiography, where the FOV is limited by image intensifier. Larger anode angles are necessary for general radiographic work to achieve larger FOV coverage at short focus to image distances (FID). Modern X-ray tubes are designed with anode angle of 10°–13° with focal spot sizes of 0.6–1.3 mm.

TUBE INSERT AND VACUUM

The tube insert or envelope is made up of borosilicate glass (Pyrex). The pyrex glass can withstand high temperature and also act as an electrical insulator. It contains vacuum, which support the electrodes.

The tube insert (i) absorbs the X-rays emerging in undesired directions, (ii) maintains the required vacuum, (iii) acts as an electrical insulator and (iv) also contain the cooling system which removes the heat from the target. Glass is not an ideal insert for X-ray tubes since tungsten vapor condenses and forms electrically conducting thin layer. This may lead to arcing and loss of vacuum due to puncture of the glass. Glass is also susceptible to damage from electron bombardment. Hence, metal envelope have been developed with low attenuation beryllium window ($Z = 4$), for X-ray transmission. However, metal may short circuit cathode and anode due to its conductivity. To eliminate this, ceramic or glass insulations are done at the end of the tube. This type of envelope is called metaceramic or metal glass design.

A high vacuum is maintained between the anode and cathode. This is necessary (i) to avoid the collision between electrons and gas molecules, which gives raise to ionization that reduces the kinetic energy of the electrons, (ii) to prevent oxidation of electrodes and (iii) act as an electrical insulator. The required vacuum is less than 10^{-5} mm Hg.

TUBE COOLING

In a X-ray tube, only less than 1% of the electrical power supplied is converted to X-rays. The remaining electrical power (over 99%) is converted into heat. This large amount of heat may melt the target and therefore heat should be removed very quickly from the target. Hence, efficient cooling systems are necessary for the X-ray tube.

In general, targets are made by inserting a layer of tungsten in copper block, and X-ray tubes are usually enclosed in metal cases, which are filled with oil for insulation purpose. The heat produced on the focal area is conducted quickly into the anode disk, stored temporarily, later transferred to the insulating oil by radiation. This oil surrounds the glass envelope as well as copper block (static oil cooling). The heat taken up by the oil is transferred to the housing (metal case) by convection process. In some designs, fan is used to assist the convection process and removes the heat from the housing.

In the case of rotating anode tube, the molybdenum neck is so long and prevents the heat conduction to the rotor. If the anode assembly is coated black, it will promote the heat radiation process. The rate of heat radiation is proportional to fourth power of anode temperature. Hotter the anode, greater the rate of heat dissipation. For prolonged operation, the oil around the tube is connected by two pipes to a oil reservoir with radiator and pump, where the oil is cooled additionally by an air current and water (circulating oil cooling). In X-ray tubes used in CT scan and angiography work, oil is pumped through an external heat exchanger.

In some modern tubes, the anode is earthed and water is allowed to circulate through the anode. Sometimes the water is additionally cooled by Freon gas.

HISTORICAL X-RAY TUBES

GAS TUBE

In the beginning, gas filled tubes were used to produce X-rays. These tubes consist of two electrodes called cathode and anode, kept in a sealed glass envelope, at opposite ends (Fig. 3.8). The cathode is an aluminum stem carrying a concave aluminum disc. The anode or target is tungsten or platinum backed with copper. The radius of concavity of the cathode is such that its center of focus lies on the surface of the target. The face of the target makes an angle 45° with the axis of the cathode neck. A provision is made to evacuate the tube, to different degrees of vacuum. The tube vacuum must be always less than 0.001 mm Hg.

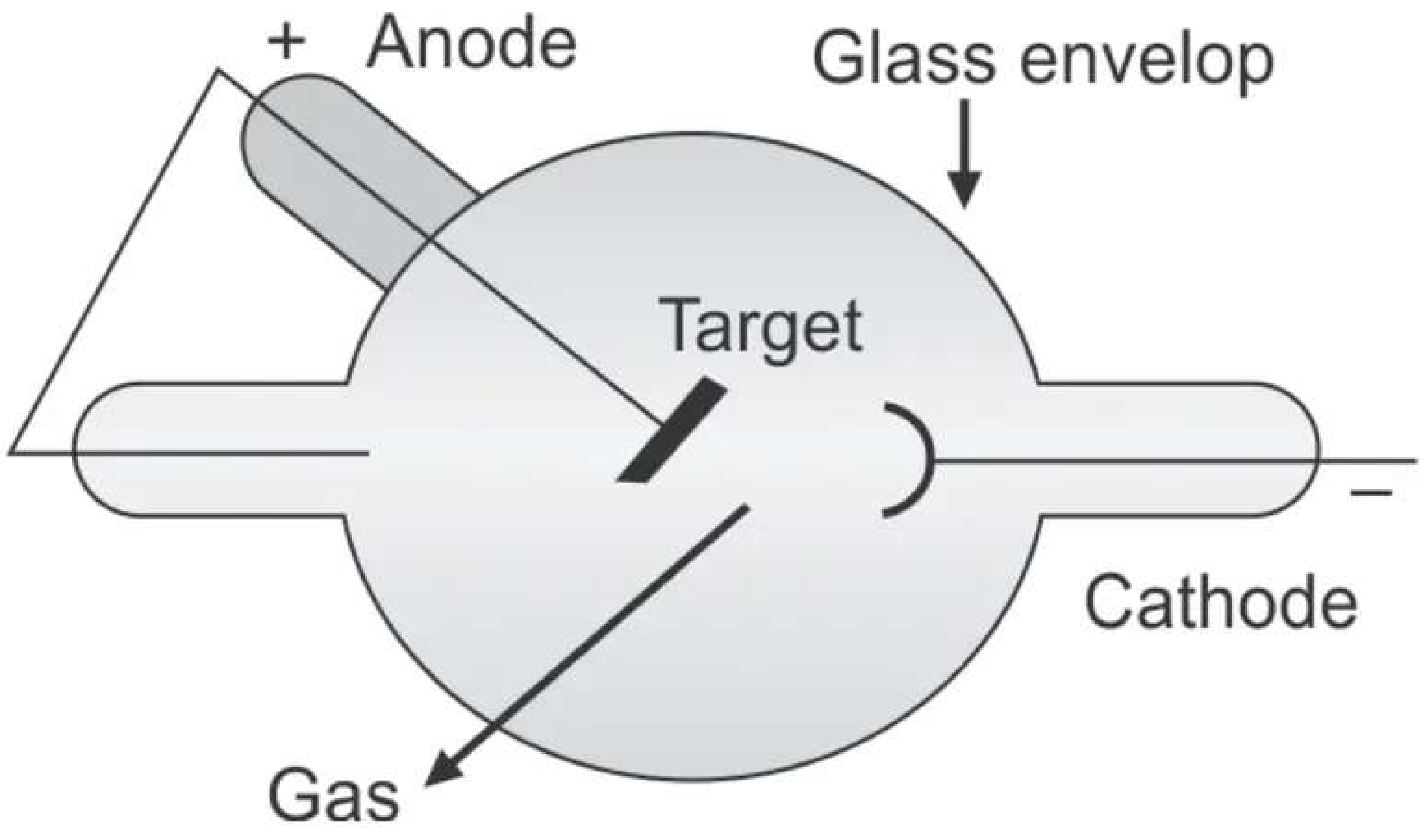


FIG. 3.8: Gas X-ray tube

In a gas tube, a small residue of air is always left. When a high potential is applied between the cathode and anode, the air inside the tube gets ionized and electrons are produced. These electrons move at higher speed towards the anode, and produce an avalanche of electrons by collision with air molecules. The positive ions left are attracted towards the cathode and release many more electrons by its impact.

When the electron stream strikes the target, X-rays are emitted. The relation between the voltage applied to the tube and the minimum wavelength of X-rays emitted are given by the *Duane and Hunt's law*

$$\lambda_{min} = \frac{12.4}{kV_p}$$

The wavelength is expressed in angstrom (Å) units and 1 Å= (10^{-10} m).

Defects of Gas Tubes

i. Ionization potential of the gas depends upon the degree of evacuation of the tube. A tube with much residual gas will produce X-rays at lower voltages. If the voltage increases beyond ionization potential, the tube current increases enormously, and may melt the target. The whole tube may be filled with vapor of the target material, making the tube gassy.

ii. The energy of the X-rays and the intensity of X-rays are interlinked. To increase the penetrating power, evacuation has to be increased, while applying higher voltage. Hence, a vacuum pump is always required through out the operation. Thus, the apparatus require more skill to operate.

iii. As the tube operates, the ions gradually diminishes, resulting higher vacuum. Hence, fresh gas has to be injected into the tube by the use of gas regenerators. Because of these disadvantages, the gas tubes are now practically obsolete.

COOLIDGE TUBE

Flaming and Richardson showed that, when a metal is heated in vacuum to incandescence, it emits large amount of electrons. Such a emission of electrons by the supply of heat is called thermionic emission.

These electrons can be collected by using another electrode, kept at a positive potential. It was proved that all the emitted electrons can be collected at a particular potential called the saturation potential. Further increase of potential does not increase the current flowing between the electrodes.

A new X-ray tube was designed by Coolidge (1913), by using above thermionic emission principle. This was known as hot cathode or electron tube (Fig. 3.9). This tube is completely evacuated, so that there is no production of electrons by ionization. A spiral of wire, which serves as a hot cathode, is heated to incandescence by means of a current of 4 ampere and 10 volts. The filament commonly used is tungsten. The target is placed opposite to the cathode similar to that in a gas tube.

When the high voltage is applied between the cathode and anode, electron current flows from the cathode to anode. As the electron reaches the target, X-rays are produced. These tubes are always operated at saturation potential. The wavelength of the X-rays can be controlled by altering the voltage applied to the tube. The tube current can be varied by altering the temperature of the filament. Thus, the applied voltage and tube current are independent of each other, and can be controlled separately, which is the advantage of this tube. All the modern X-ray tubes are based on the principle of Coolidge tube only.

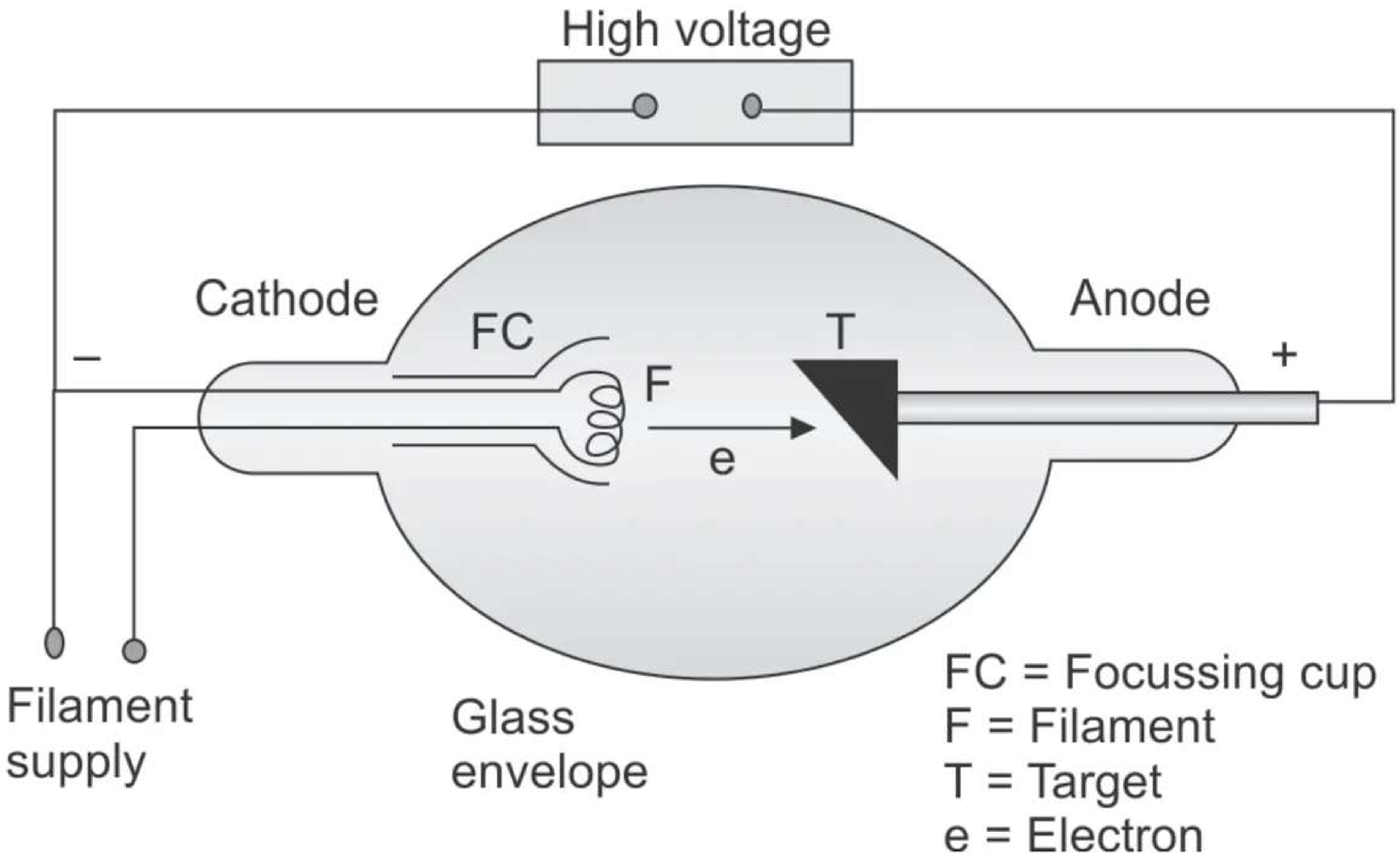


FIG. 3.9: The Coolidge X-ray tube

MODERN X-RAY TUBES

STATIONARY ANODE X-RAY TUBE

In earlier periods, gas tubes were used to produce X-rays. But, these tubes suffered with disadvantages. Hence, Coolidge proposed a prototype X-ray tube based on the thermionic emission principle. On the basis of Coolidge tube, several X-ray tubes have been designed. The stationary anode X-ray tube is one of the modern X-ray tubes in which the anode is stationary.

The stationary anode X-ray tube consists of a cathode and an anode which are kept in a evacuated glass envelope (Fig. 3.10). The cathode consists of a tungsten filament in the form of a coil placed in a shallow focusing cup. The filament is heated by passing an electric current through it from a low voltage supply.

The anode is made of copper block in which a small tungsten plate is embedded. The tungsten plate serves as a target. The target is positioned on line focus principle, in order to increase the ratio of the actual focal area to the effective focal area. The anode angle is usually 15–20°. A high voltage supply is applied between the cathode and

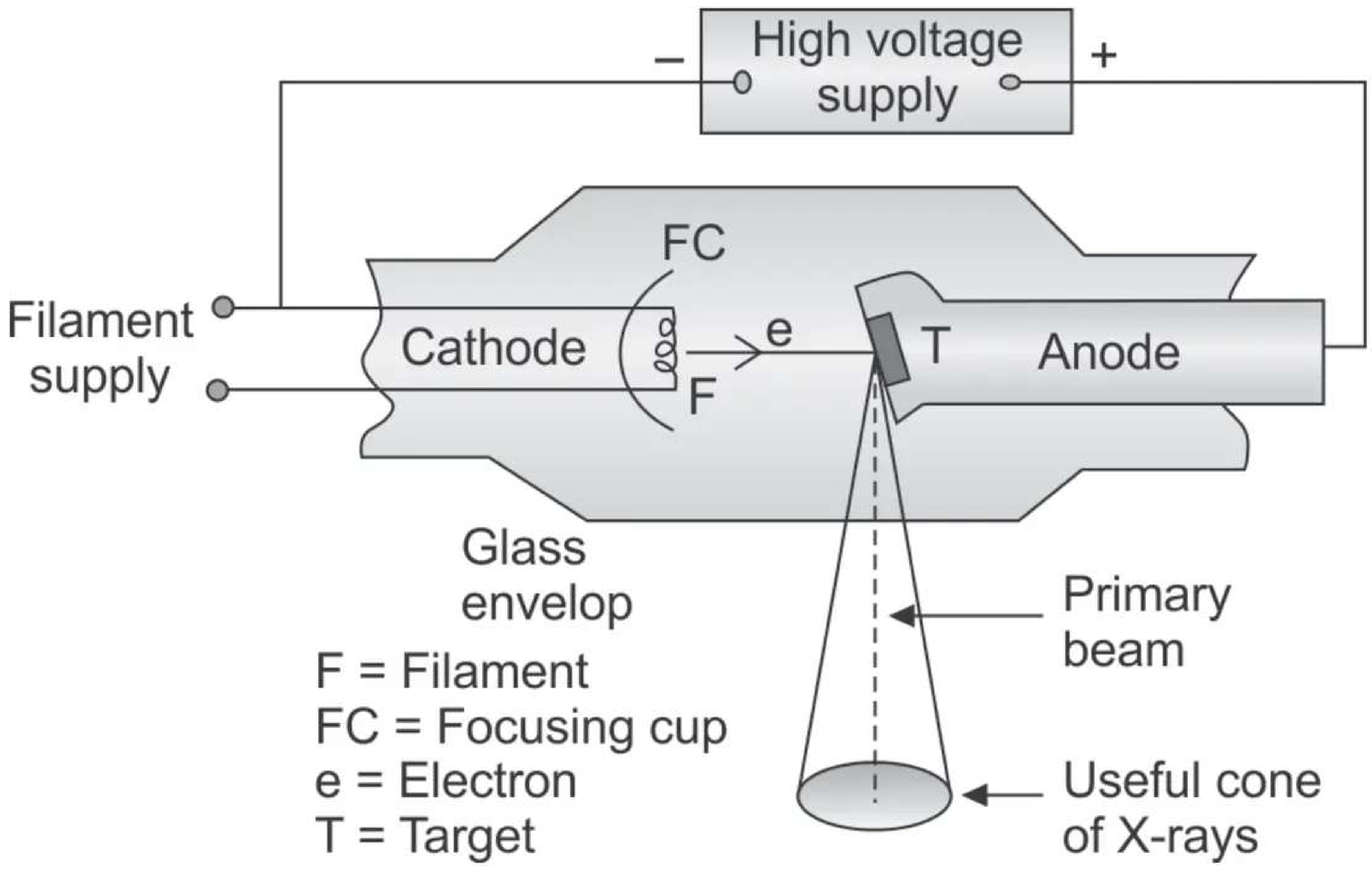


FIG. 3.10: Stationary anode X-ray tube

anode to accelerate the electrons. A vacuum of the order of 10^{-5} mm Hg is maintained in the tube.

When the filament is heated to white light, it emits electrons. The focusing cup (made up of nickel) produces an electric field (negative) that focuses the electron to the focal area. The focusing cup also protects the adjacent parts of the tube wall from damage by electron bombardment. If the anode is made positive with respective to the filament, these electrons will be attracted to the anode. This will constitute an electron current around the circuit in the anticlock wise direction. The tube current is measured by the milliammeter (mA).

Since the space between anode and cathode is a high vacuum, the electrons do not collide with gas molecules in crossing the gap and so acquire very high velocities. The electrons which are accelerated by the applied voltage possess high kinetic energy. When they suddenly stopped in the target, X-rays are emitted in all directions. About one-half of these are absorbed in the target itself. The remaining portion emerges as a useful primary X-ray beam. During the production of X-rays, large amount of heat is produced in the target. The tube is also provided with suitable cooling system to remove the heat very quickly.

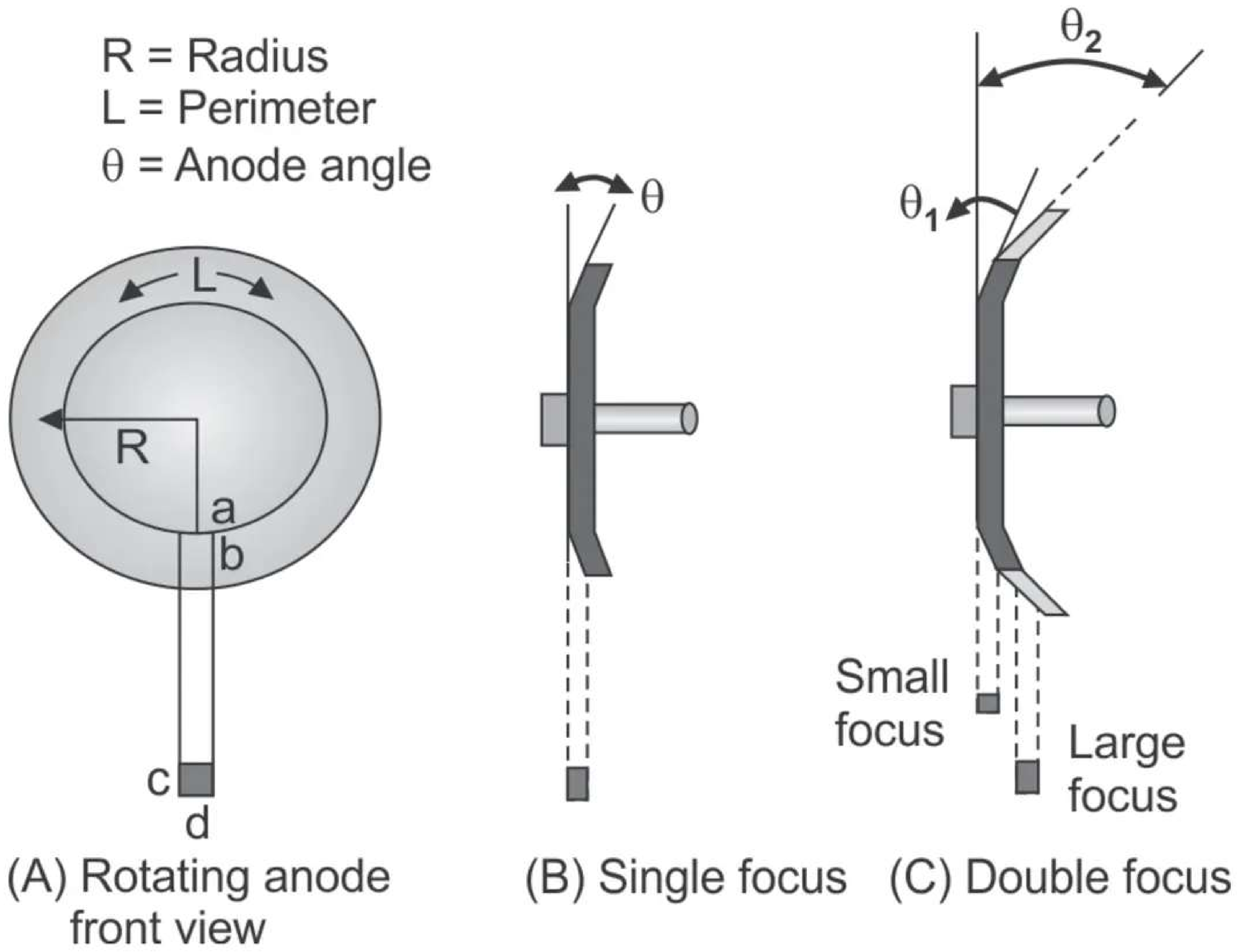
Stationary anode tubes have a small target area that limits the heat dissipation and this limit the X-ray output, but they are small in size and weight. Dental X-ray units (intraoral and ortho-pantomography), portable X-ray units, and portable fluoroscopy systems use stationary anode X-ray tubes.

ROTATING ANODE X-RAY TUBE

In 1933, the rotating anode X-ray tube was invented, in which the anode is made to rotate before the electron is emitted. It was developed to increase the heat loading with higher X-ray output. In these tubes, the electrons transfer their energy over a large area of a rotating target. Rotating anode tubes are larger in size, but the principle and function are similar to that of stationary X-ray tube.

Principle

Consider a rotating anode of radius R and circumference L as shown in the Figure 3.11. The electrons bombard a region of height ab and width cd. The length may range up to the circumference ($L = 2\pi R$) depending on the exposure time. But, the X-rays always appear to come from a focal spot of area cd × cd.



(A) Rotating anode front view (B) Single focus (C) Double focus

FIG. 3.11: Rotating anode assembly: front and side view

Let us consider a stationary anode of actual focal area 7.3 mm × 2 mm, and rotating anode of R = 30 mm and length 7.3 mm, then

$$\text{Loading gain} = \frac{\text{Actual focal area of rotating anode}}{\text{Actual focal area of stationary anode}}$$

$$= \frac{2\ \pi \times 30 \times 7.3}{7.3 \times 2} = 94.2$$

Thus, the rotating anode arrangement helps to increase the loading to a greater extent of the order 100. The construction of such a rotating anode is a remarkable technological development. The diameter of the tungsten disk determines the total length of the target track, and obviously affects the maximum permissible loading of the anode.

Cathode

Rotating anode X-ray tube consists of a cathode and an anode which are kept in a glass bulb (Fig. 3.12). The cathode is a tungsten filament which is offset from the long axis of the X-ray tube to face the target near the periphery of the anode disk. Usually, rotating anode tubes are fitted with two filaments (Fig. 3.13), one larger than the other set side by side in the cathode assembly. One filament is designed to focus the electrons on a larger area of the anode, which require heavy tube loading. The other filament is used to focus the electrons on a

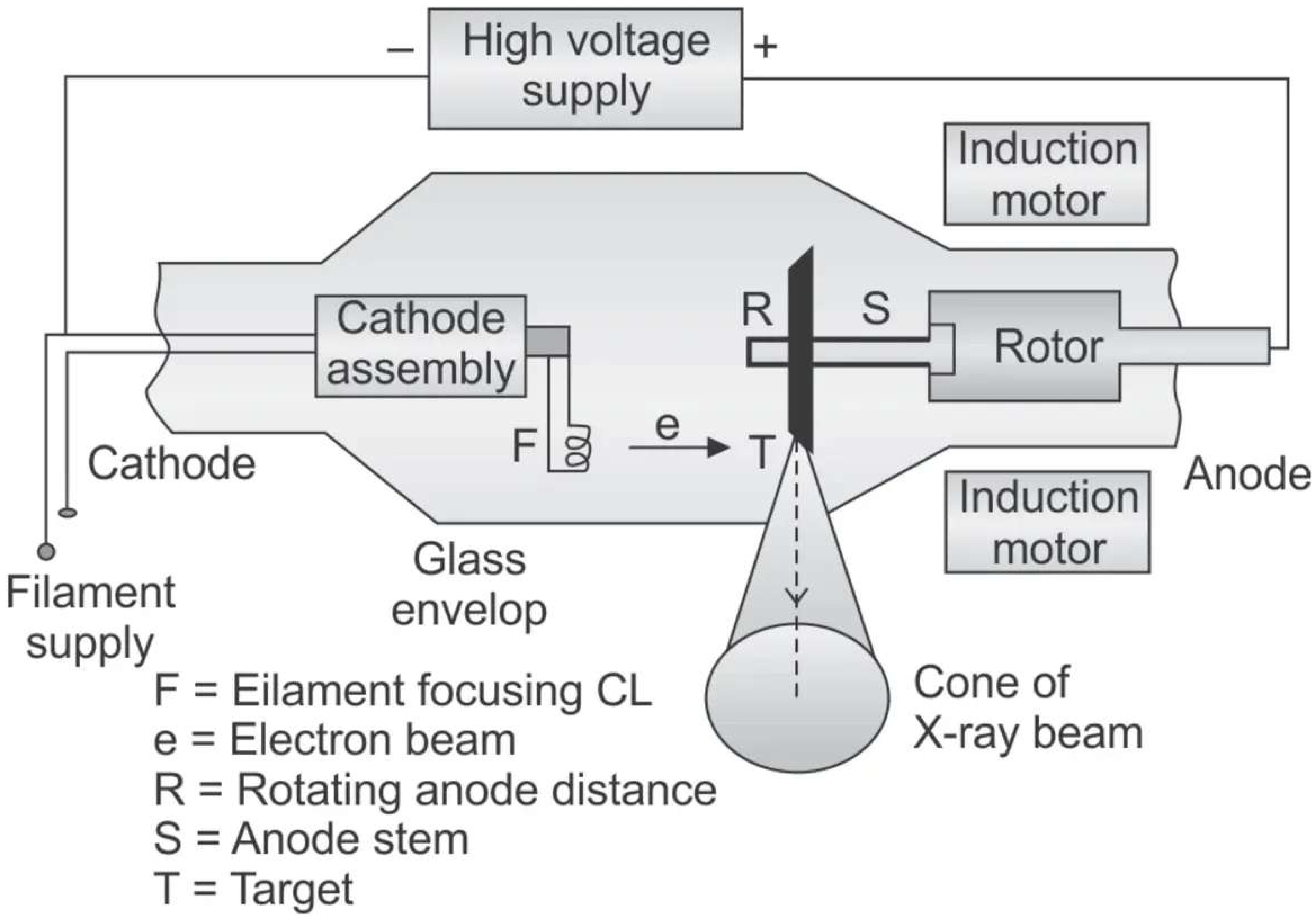


FIG. 3.12: Rotating anode X-ray tube

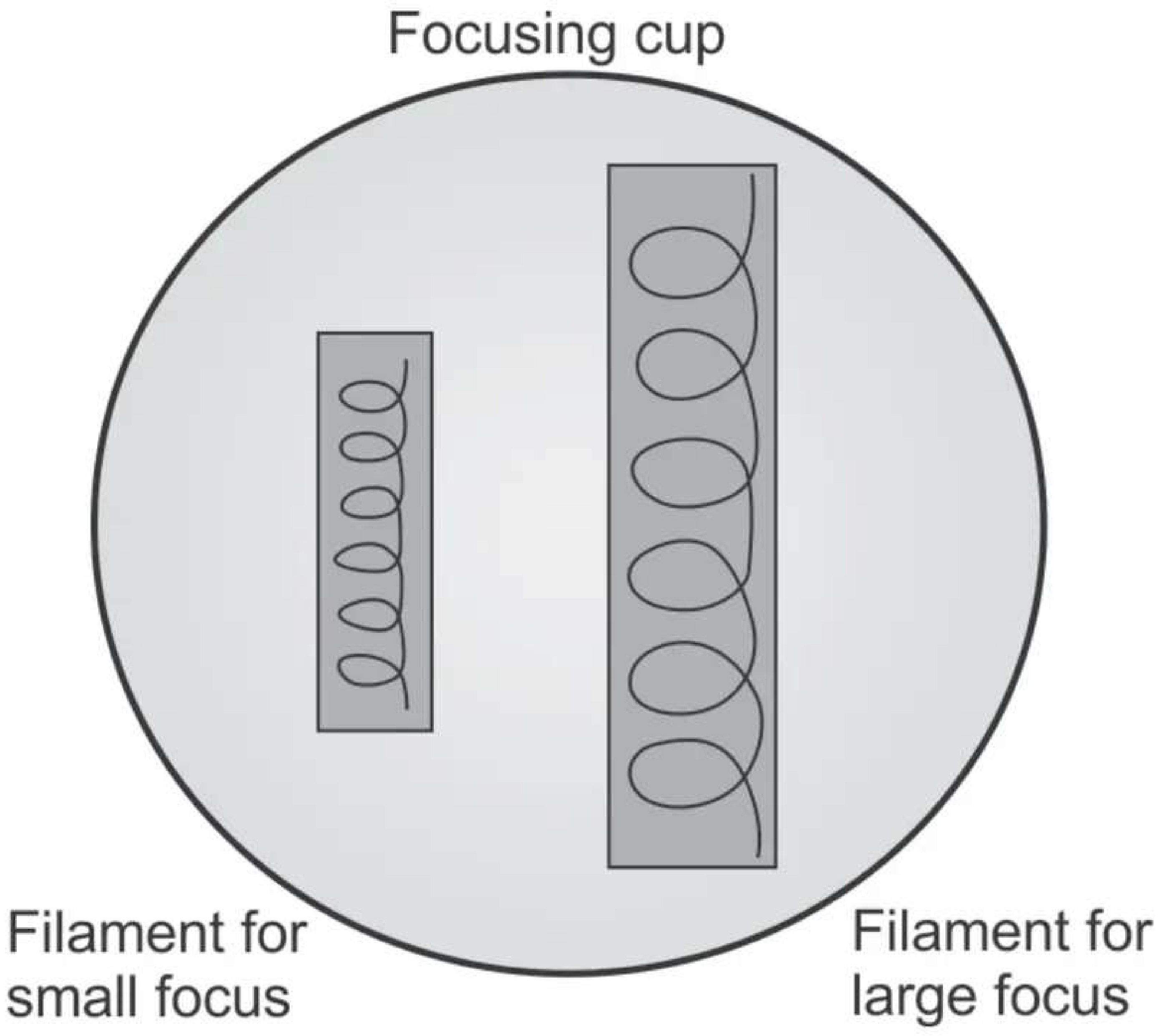


FIG. 3.13: Cathode with dual filament

smaller area of the target. This type is used when high resolution is required. Both filaments should focus the electron on the same part of the anode, so that focal spot is at the same point for both modes of operation. Some tubes provide two target angles for two filaments, so that each filament will have a separate focal spot. Smaller angle is used with the smaller focal spot.

Focusing Cup

The focusing cup (cathode block) surrounds the filament, shapes the electron beam width. It is used to focus the electrons on a small area (focal spot) in the anode. There are two ways by which the focusing cup is energized, namely, unbiased and biased (Fig. 3.14). In unbiased setup, same voltage is applied to both focusing cup and filament. In this type, the electron spread is wider and the focal spot width is larger. In biased X-ray tubes, insulated focusing cups are used and it is given more negative supply (–100 V) than the filament. This creates a tighter electric field around the electron, reduces the electron spread and gives smaller focal spot width. Thus, the focusing cup width determines focal spot width and the filament length determines the focal spot length.

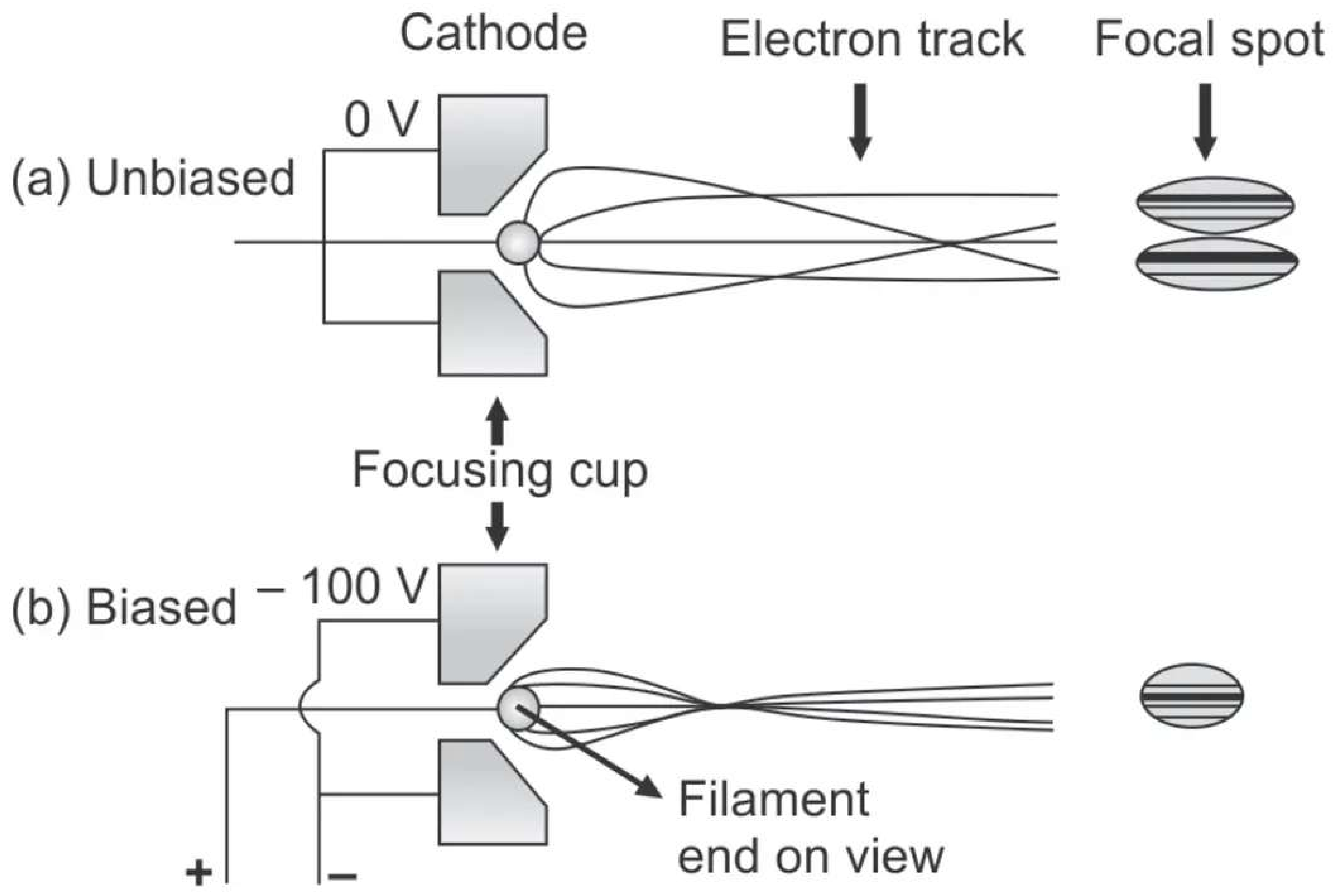


FIG. 3.14: (A) Unbiased focusing cup potential is 0 V, relative to filament, (B) Biased focusing cup, potential is -100 V, relative to filament

Anode

The anode is made in the form of large disk of tungsten, or an alloy of tungsten, which is saucer shaped. The target track is near the periphery of the disk, to maximize the length. The track is a mixture of 90% tungsten and 10% rhenium (Z = 75), which reduces the crazing effect caused by thermal stresses. Modern rotating anodes are made from solid molybdenum onto which a thin tungsten-rhenium focal track is coated. The specific heat capacity of molybdenum is higher than that of tungsten (250 vs 130 J $Kg^{-1}K^{-1}$). The mass of molybdenum anode is also lower due its lower density. Some high output X-ray tubes have radial slots cut into the anode disc to reduce thermal stresses caused by repeated heating and cooling. Heavy duty X-ray tubes have graphite layer (Carbon) in the back of the anode disk. The anode disk has a beveled edge and the angle of the bevel may vary from 6 to 20^o. The bevel is used to achieve the line focus principle.

Anode Stem

The anode disk is mounted on a stem, which is attached to the rotor. The anode assembly rotates with the help of bearings. The stem is made of molybdenum, which is having high melting point (2620°C) and poor heat conduction. The molybdenum stem prevents the flow of heat from the tungsten to the bearings of anode assembly, due its small cross section. Thus, the bearings are protected from heat, which may cause them to expand and bind. Higher the length of the stem, higher the inertia of the tungsten disk, more will be the load on the bearings. Hence, it is desirable to keep the stem as short as possible.

Rotor

The anode disk is connected to a rotor, which is made up of copper bars arranged around a cylindrical iron core. There are electromagnets surrounding the rotor, outside the glass envelope is called stator (Fig. 3.15). Both the stator and rotor is called as an induction motor. When the stator coils are energized, a rotating magnetic field is produced, that induces current in the copper bars of the rotor. This induced current produces an opposing magnetic field that causes the rotor to spin.

The rotor rotates at a speed of about 3000–9000 revolutions per minute (rpm). This will facilitate the electrons to bombard a constantly changing area of the target. Since the electrical conductivity of copper is higher, it will facilitate induction of strong currents from the induction coil supply. The surface of the rotor is blackened to enhance heat dissipation by radiation process. The rotor support is made of steel and the positive high tension supply is made at the end of the rotor support outside the glass envelope.

Low speed rotor operates from 60 Hz power (single phase) and gives rotation of about 3000 rpm. This speed is too slow for short exposure of the order of mill-seconds. High speed rotor operates from

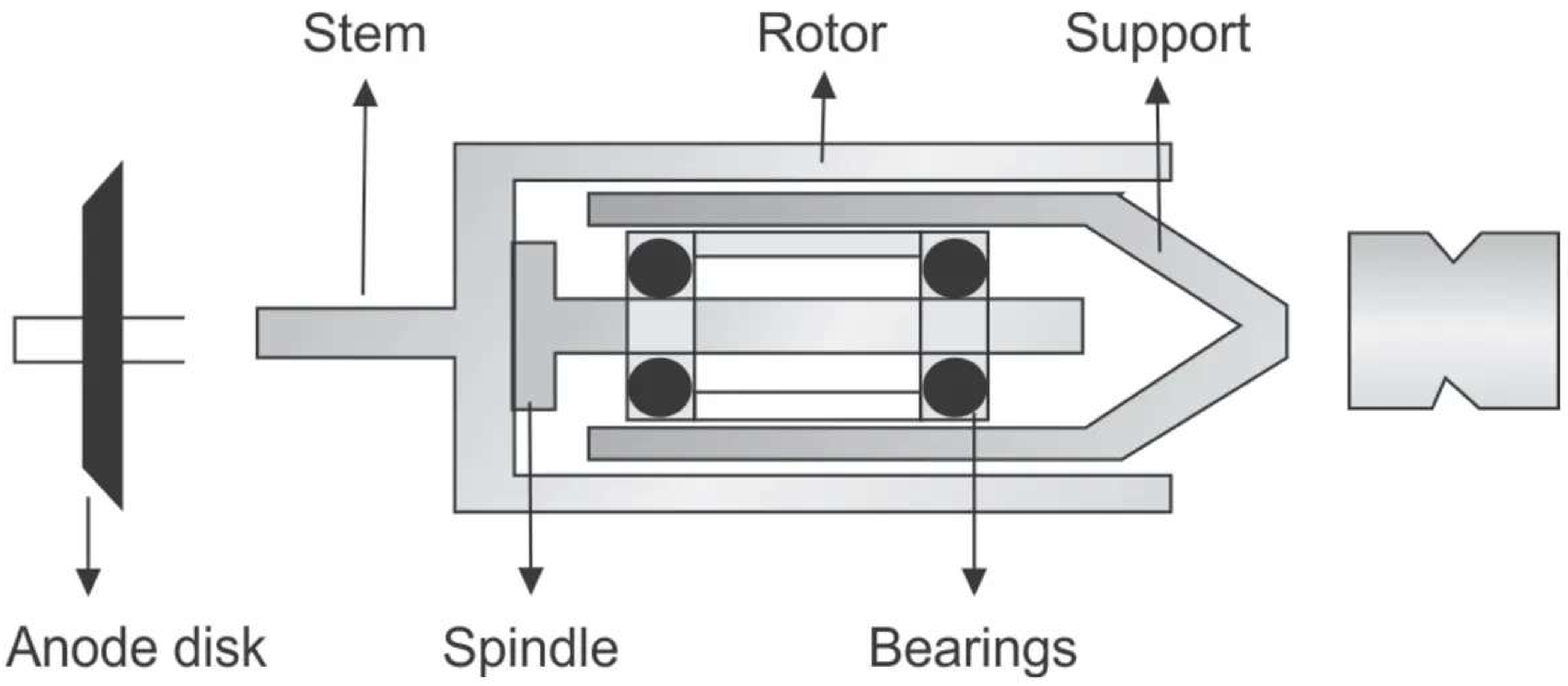


FIG. 3.15: Rotating anode X-ray tube and anode assembly inner view

180 Hz power (3 phase) and gives a rotation speed of 9000 rpm. If the speed of rotation is increased, the heat generated at the focus will be spread over a larger area. Modern X-ray tubes employs higher rotor speeds by increasing the frequency of the stator supply with frequency multiplying circuits. The X-ray machines are designed so that the tube cannot be energized until the anode attains its full speed. This delay time (1–2 s) is incorporated in the exposure buttons. The power supplied to the induction coils, produce eddy current which causes heating of the rotor.

Bearings

The anode assembly is rotated with the help of bearings, which are made of steel ball races. Bearings are in the high vacuum environment and require special heat insensitive, nonvolatile lubricants. The bearings are coated with lead or silver to act as (metallic lubricants) lubricant. Commonly available lubricants such as oil and grease cannot be used, since it will vaporize while heating and destroy the vacuum. Even dry lubricant (graphite) would wear off as a powder and destroy the vacuum.

When the X-ray unit is turned on, the motor alone is energized first for a few seconds until the rotor reaches its operating speed. Then, a high voltage is applied to the tube for the required exposure. After the exposure, the rotor is slowed down quickly by dynamic braking to avoid the wear in the bearings. Since the electrons are striking the whole circumference of the anode, no part of the anode attains very high temperature. The heat from the tungsten disk is dissipated by radiating through the vacuum to the wall of the tube, and then into the surrounding oil and tube housing.

The life of a rotating anode X-ray tube is limited, because of pitting due to continuous electron bombardment on the anode surface.

These changes are due to thermal stress. This pitting reduces the X-ray yield and changes the spectral distribution. The decreased output, results in excessive scattering of X-rays and increased absorption of X-rays by the target itself. A pitted anode will affect the electric field between cathode and anode, so alter the size of the focal spot.

Grid Controlled X-ray Tubes

A grid controlled X-ray tube contains three electrodes, the anode, cathode and the focusing cup. The focusing cup acts as a third electrode (grid), and controls the flow of electrons from the filament to the target. The grid is electrically negative relative to the filament. The voltage across the filament-grid produces an electric field along the path of the electron beam, that pushes the electrons even closer together. If the voltage is made large enough, the tube current may be completely pinched off, and no electrons go from the filament to target. The voltage applied between the focusing cup and filament acts like a switch to turn the tube current on and off. Since the cup and filament are close together, the voltage necessary to cut off the tube current is not very large.

For example, a 0.3 mm focal spot tube operating at 105 kV_p require about -1500 V between the filament and cup. This type of grid controlled X-ray tubes are useful in some procedures involving rapid switching and short exposure times, e.g. cini-angio-cardiography and pulsed fluoroscopy.

HEEL EFFECT

The heel effect refers to the reduced intensity of the X-ray beam towards the anode side of the X-ray field (Fig. 3.16). The X-ray photons that are emitted on the anode side of the field must pass through a greater

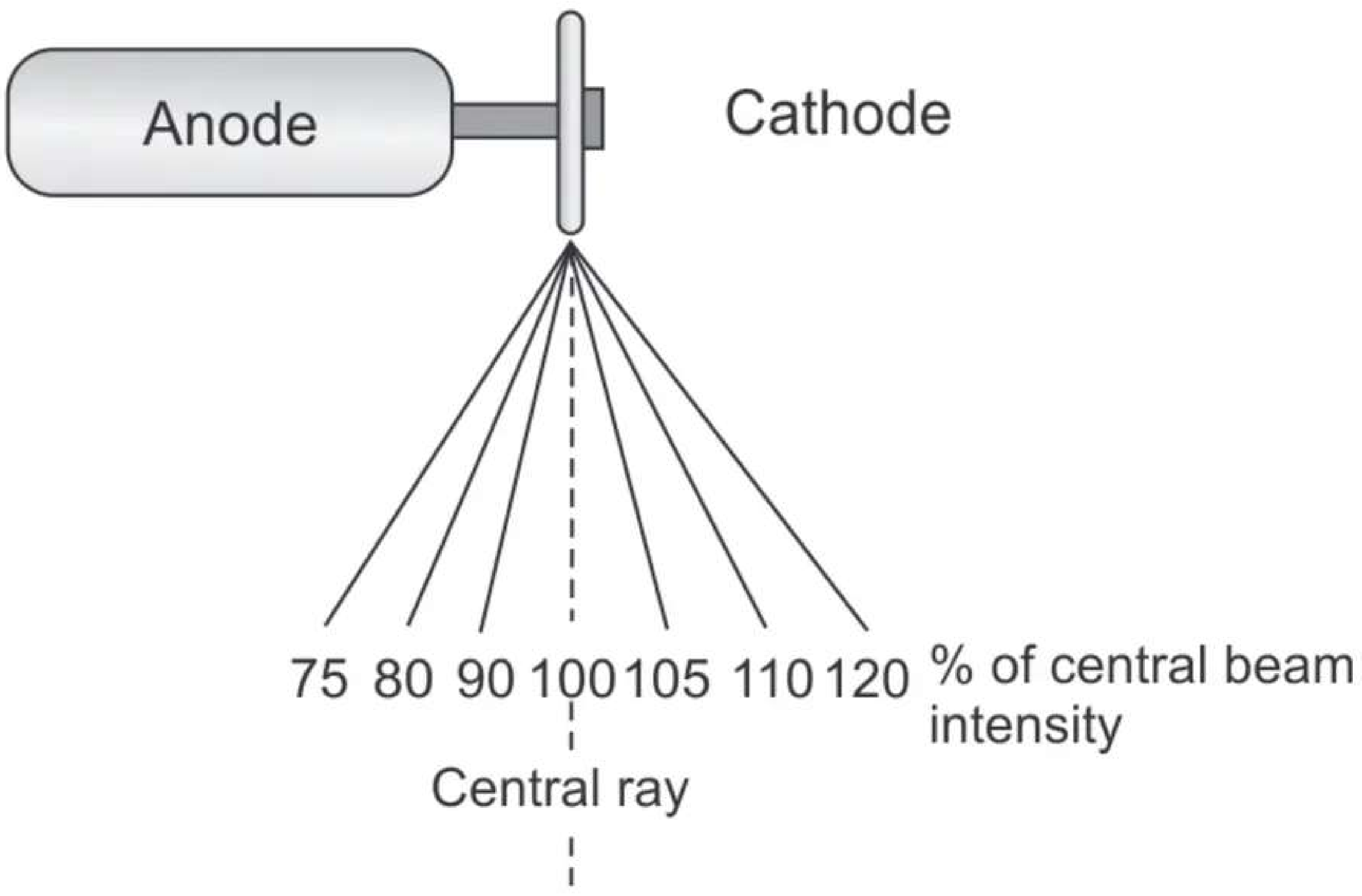


FIG. 3.16: Heel effect

thickness of the anode than those directed toward the cathode side. This results in a reduced intensity on the anode side of the field. The magnitude of the heel effect depends on the anode angle, focus to film distance (FFD) and field size. The heel effect is less important at large FFD, because the film subtends a smaller beam angle. To reduce heel effect, anode angle should be increased and field size should be decreased. For better balance of the transmitted X-rays, the cathode side of the tube is oriented over the thicker parts and anode over the thinner parts of the patient.

OFF-FOCUS RADIATION

Off-focus radiation is produced by an X-ray tube when high speed electron interacts the anode surfaces, other than the focal spot area. The main source of off-focus radiation is scattered electrons at the target. They are accelerated back to the anode, outside the focal spot. They create a low intensity X-rays over the face of the anode. Off-focus radiation increases the patient exposure, geometric blurring and background fog, resulting poor image quality. To reduce the off-focus radiation, small lead collimator may be placed very close to the X-ray tube port. Grounded anode X-ray tubes (anode and metal tube envelopes are given same electrical potential) reduce off focus radiation since the scattered electrons are attracted by the metal envelope. Tubes that are used in mammography also reduce off-focus radiation.

X-RAY TUBE AND HOUSING

The tube housing supports, insulates and protects the tube insert from the environment (Fig. 3.17). The tube housing is internally shielded with lead to attenuate X-rays emitted in other directions except through the window. The shield should perform four functions namely, (i) radiation protection, (ii) electrical protection, (iii) thermal protection and (iv) physical protection. Steel casing is lined with lead to prevent radiation emerging in all directions. The Perspex/beryllium window is convex upwards to reduce filtration of the X-ray beam by oil. To prevent electrical shock, the shield is earthed. Wherever high tension cables enter the shield, insulated sockets are used. The shield is filled with mineral oil, which act as a electrical insulator and prevents sparking across the insert.

The oil also acts as a cooling medium and expands at higher temperatures. The oil expansion activates bellow to operate a micro

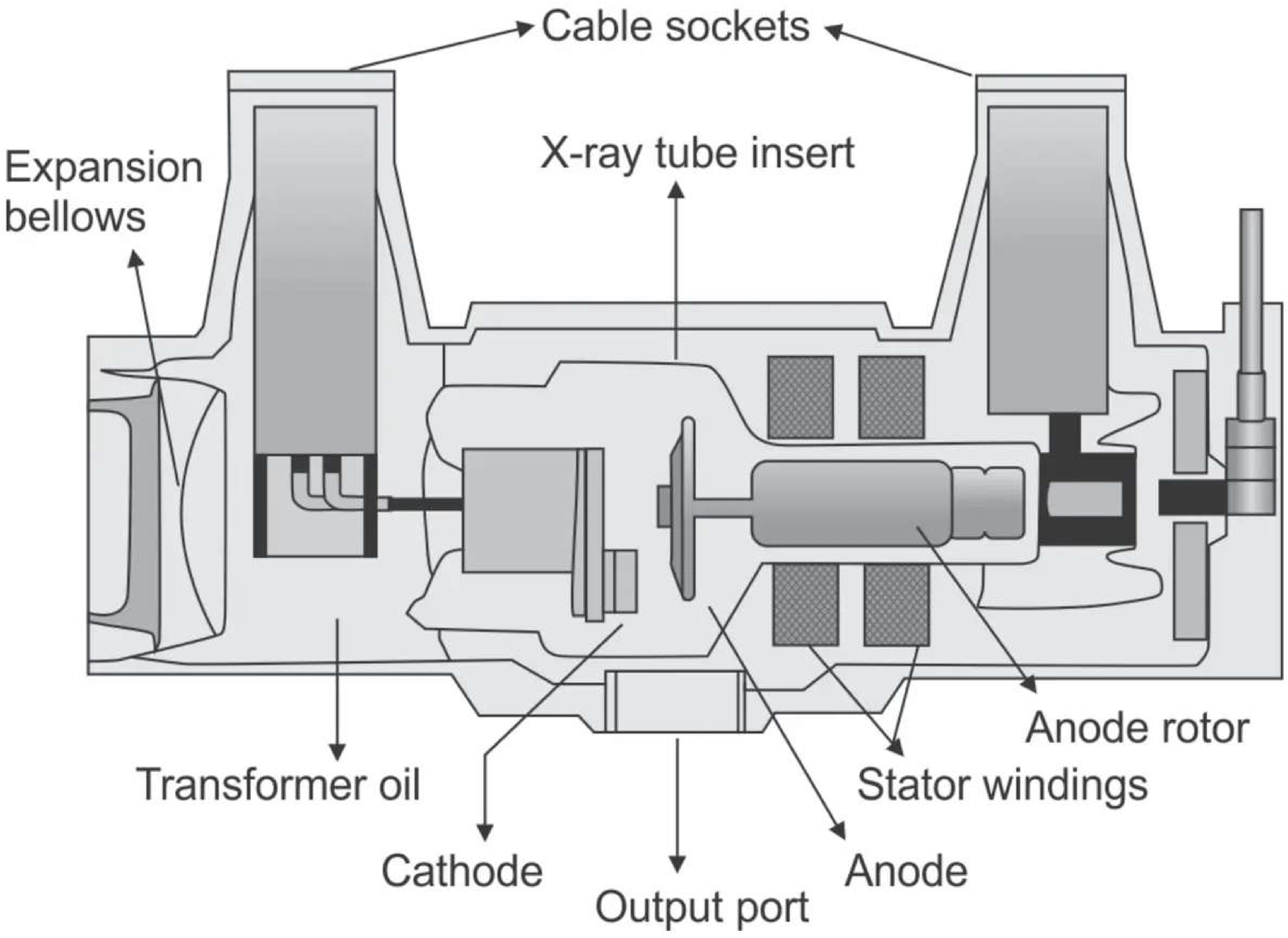


FIG. 3.17: X-ray tube and housing anatomy

switch, so that further use of the tube is prevented. The oil expansion also helps prevent the entry of air into the tube insert. The shield also protects the insert from accidental damage caused by knocks and bumps.

The effectiveness of the tube housing in limiting the leakage radiation must meet the specifications, listed by the Atomic Energy Regulatory Board (AERB). The leakage radiation measured at a distance of 1 m from the source shall not exceed 115 mR (air kerma of 1 mGy) in one hour, when the tube is operating at each of the ratings specified by the manufacturer.

FILTERS

A filter is a metallic sheet introduced in the path of X-rays, in order to reduce the patient dose. Diagnostic X-rays consist of both low energy and high energy X-rays. When X-rays passes through a patient, only high energy X-rays penetrate through the patient and form the radiological image. Whereas, the low energy X-rays are absorbed in the first few centimeter of tissue, thereby increasing the radiation dose. The introduction of filters absorb these low energy X-rays and reduce the patient dose. This process of removing the low energy X-rays, by introducing metallic sheets is called filtration (Fig. 3.18).

Filtration has two components namely, (i) inherent filtration and (ii) added filtration. Filtration resulting from the absorption of X-rays by

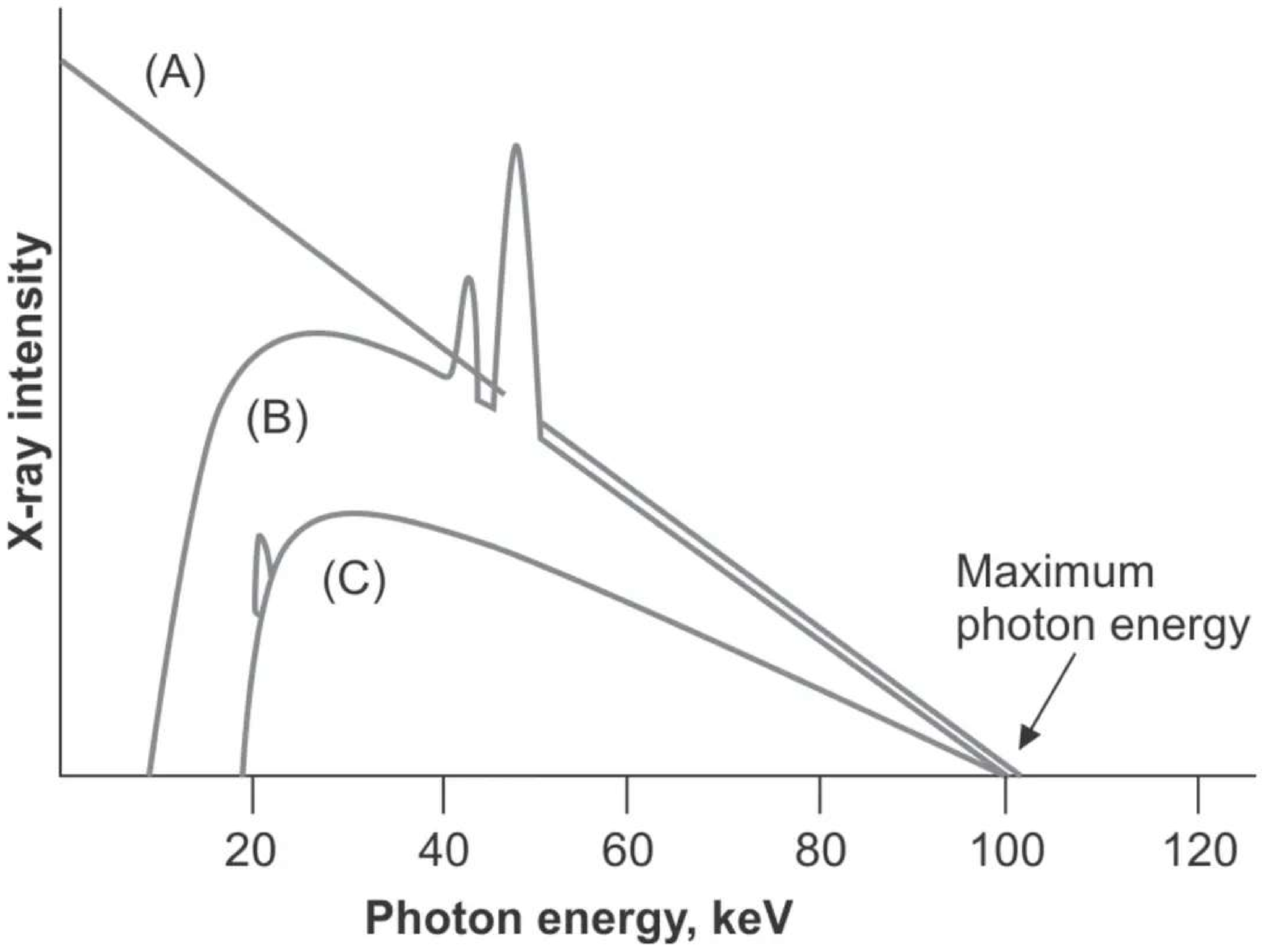


FIG. 3.18: Effect of filter, (A) Unfiltered spectrum, (B) Filtered spectrum with inherent filter, and (C) Filtered spectrum with added filter

the X-ray tube and its housing is called inherent filtration. This usually varies between 0.5 mm and 1.0 mm of Al equivalent. Added filtration results from absorbers placed in the path of the X-ray beam. The sum of the inherent and added filtration gives the total filtration.

Total filtration = Inherent filtration + Added filtration.

Al and Cu are the materials usually used in diagnostic radiology. The thickness of added filter varies from 1.0 mm to 1.5 mm of Al. Aluminum (Z = 13) is an excellent filter material for low energy X-rays. Copper (Z = 29) is a better filter for high energy radiation. Copper is always used in combination with aluminum as a compound filter. A compound filter consists of two or more layers of different metals. The layers are arranged in such a way that the high Z layer always faces the X-ray tube.

The recommended total filtration for diagnostic X-ray unit of > 100 kV_p is 2.5 mm Al. X-ray units with proper filters, reduces the patient dose significantly, up to 80%. Filters are simple and inexpensive. Though filters reduce the intensity of X-ray beam significantly, it does not affect the maximum energy of the X-ray beam spectrum.

Heavy metal filters (Gd, Ho) are also used in general radiography. These filters make use of the K-edge, and offer increased absorption of X-rays, while imaging with contrast agents. They enhance contrast for iodine and barium, reduce patient dose and increase tube loading.

The recommended beam filtration is follows:

i. General radiography
   - 1.5 mm Al below 70 kVp
   - 2.0 mm Al between 70 and 100 kVp
   - 2.5 mm Al above 100 kVp

ii. Mammography
   - Be 1 mm + Mo 0.03 mm (Mo target)
   - Be 1 mm + Rh 0.025 mm (Rh target)

In mammography, Mo target with Rh filter is commonly used. However, Mo cannot be used as filter in mammography X-ray tubes with Rh targets.

SCATTERED RADIATIONS

There are three types of radiation involved in patient imaging, namely, primary, scattered and leakage radiation. Leakage radiation does not contribute to image formation and no discussion is required. However, primary and scattered radiations are responsible not only for image formation but also the degree of image quality. Two vital factors of image quality are spatial resolution and contrast resolution. Spatial resolution is greatly controlled by focal spot, whereas contrast resolution is controlled by scatter radiation or noise. Scatter radiation is produced by Compton interaction, resulting in noise. Hence, scatter radiation needs to be reduced to obtain good quality image. That is why collimators and grids are used in patient imaging.

Scattered radiation mainly depends on kVp, field size and patient thickness. As the kvp increases, the X-ray energy increases. As a result, Compton interaction increases, and photoelectric interaction decreases. Hence, increase of kVp, increases the scatter radiation and reduces image quality. Therefore, X-ray imaging should be done with minimum kVp, with lowest scatter. But, at low kVp, the percentage of transmission may be lesser, which can be compensated with increase of mAs. Increase of mAs may account higher patient dose, hence optimal selection of kVp and mAs is required.

Scattered radiation increases with field size. As the field size increases, scatter radiation also increases, which reduces the contrast of the image. Smaller the field size, lesser the scatter radiation and lesser the optical density. To maintain the optical density, higher exposure techniques are required with smaller field size.

Scatter radiation increases with patient thickness. More scatter radiation is involved with thicker patients or thicker body parts. Mainly muscle, fat, bone and fluid filled cavity (pathology) are the sources of scatter radiation. Abdomen X-ray produces 3 times higher scatter than that of extremity X-rays. Compression will reduce patient thickness and bring the patient closer to the film. It will improve spatial and contrast resolution, with reduced patient dose. Patient thickness cannot be controlled except in mammography, only proper selection of techniques will help to obtain a good quality image.

BEAM RESTRICTORS OR COLLIMATORS

An X-ray beam restrictor is a device that is attached to the X-ray tube housing, to regulate the size and shape of an X-ray beam. They can be classified into three categories, namely, (i) aperture diaphragms (ii) cones and cylinders (Fig. 3.19) and (iii) collimators.

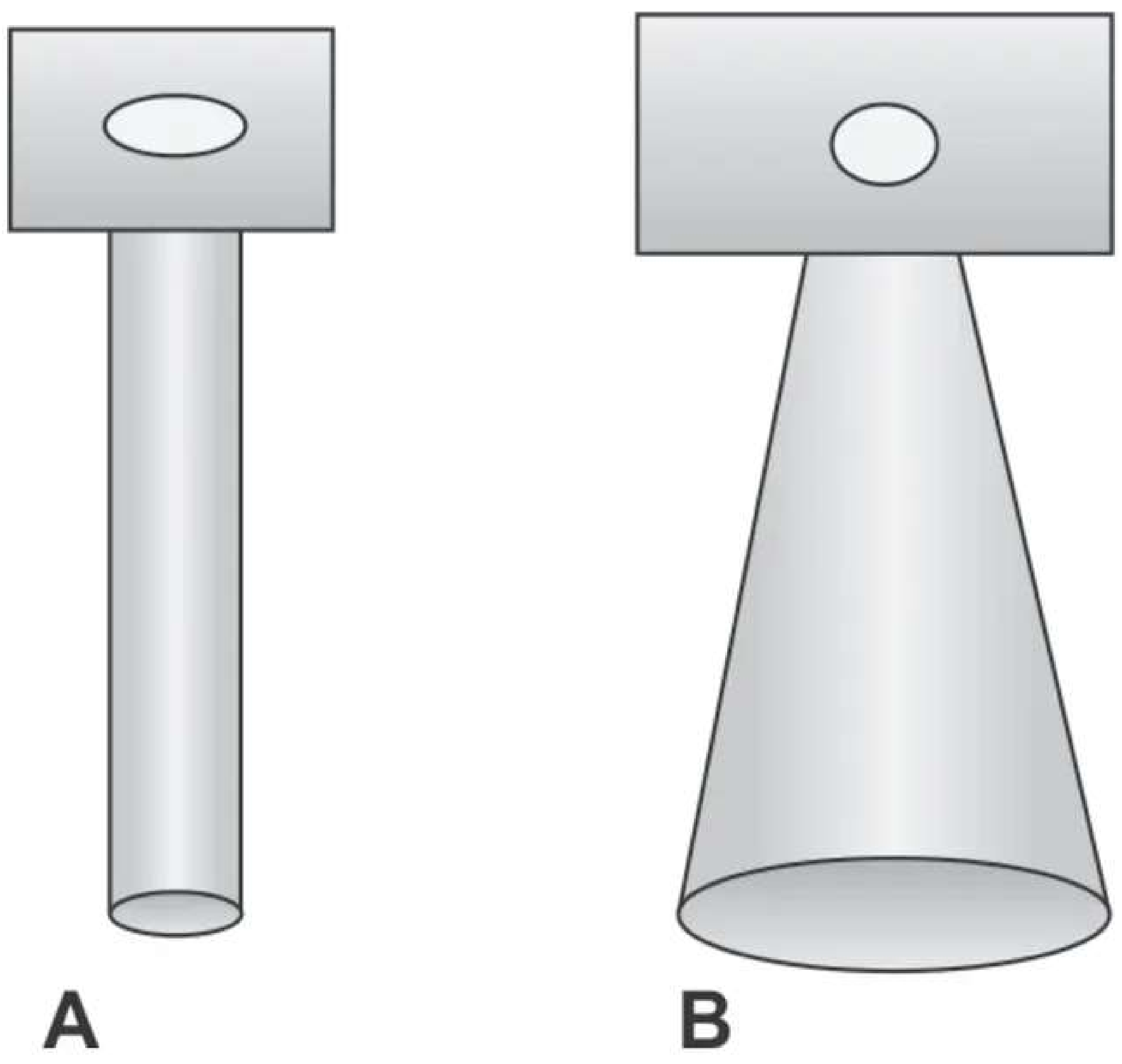


FIG. 3.19: (A) Cylinder and (B) Cone

Aperture diaphragms consist of a sheet of lead with a hole in the center. The size of the hole determine the size and shape of the X-ray beam. It is simple and the aperture can be altered to any size and shape. The disadvantage of an aperture diaphragm is that it produces large penumbra. The penumbra can be reduced by keeping aperture diaphragm far away from the X-ray target. Aperture diaphragms are used in dental radiography with rectangular collimation. In addition, it is used in trauma and chest radiography.

The use of cones and cylinders will reduce the penumbra considerably. Both have extended metal structures that restrict the useful circular beam to the required size. The position and size of the distal end determine the field size. If the X-ray source, cone and film are not aligned properly, then, one side of the film may not be exposed, which is called cone cutting. Cone is a ideal beam restrictor, but the flare of the cone is greater than the flare of the X-ray beam. These systems provide only limited number of field sizes.

The collimator is the best X-ray beam restrictor. It defines the size and shape of the X-ray field that emerges from the X-ray tube.

The collimator assembly is attached to the tube housing at the tube port. A collimator consists of two sets of shutters, which can be moved independently. Each shutter consists of four or more lead plates of 3 mm thick, which can absorb X-rays completely, to provide a well defined X-ray field. When the shutters are closed, they meet at the center of the X-ray field.

The collimator also has a light and mirror arrangement, to illuminate the X-ray field. The light bulb is positioned laterally and the mirror is mounted in the path of the X-ray beam at an angle 45° (Fig. 3.20). The target and the light bulb should be kept at equal distance from the center of the mirror. The collimator provides variety of rectangular X-ray fields and the light beam shows the center of the X-ray field. The light field and radiation field should match exactly with each other. The variation must be with in 4% of TFD. The alignment of light beam and X-ray beam should be checked periodically. A well collimated beam covers lesser area of the patient, giving less patient dose. Also it generates less scatter radiation, which improves the image quality.

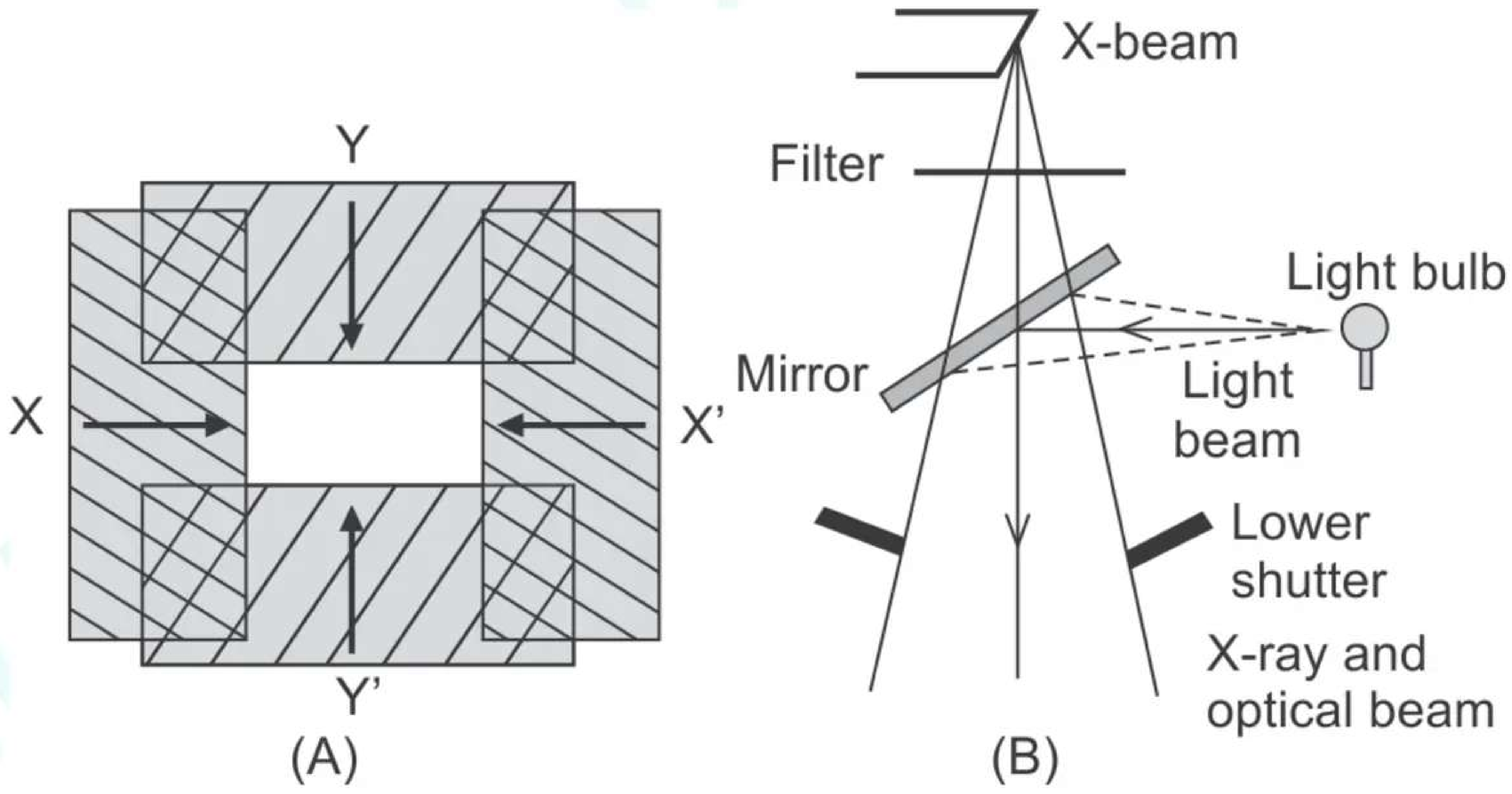


FIG. 3.20: (A) Collimator shutters and (B) Light and mirror arrangement to create radiation and optical field coincidence

Collimators that automatically limit the X-ray field size to the useful area of the detector is also available. These are called positive beam limitation (PBL) collimators. A sensor in the cassette holder, adjust the collimator opening, equal to the cassette dimensions. Thus, PBL collimators limit the irradiated volume and reduce the patient dose.

4

Generation and Control of X-rays

The X-ray generators use transformers and rectifiers to generate suitable DC voltage to the X-ray tube. The generator also has operator console, kV_p and mA controls, exposure time selection, the kV and mA meters, primary and secondary switching, filament transformer, automatic exposure control circuits, space charge and voltage compensation circuit and exposure timer. The types of X-ray generators are single-phase, three-phase, constant potential, and high frequency inverter generators.

TRANSFORMER

The transformer is an electrical device, which can convert electrical energy from one coil to another coil. The transformer is working on the principle mutual induction. The transformer basically consists of two coils, namely, primary and secondary (Fig. 4.1). These coils are wound on a iron core. The alternating voltage, which is to be transferred, is applied in the primary coil as input. This produces a changing magnetic flux in the iron core, which produces an alternating emf in the secondary coil. The induced emf's in the coils are directly proportional to the respective number of turns of the coil.

Let N_p and N_s are the number of turns in the primary and secondary coils respectively. Let V_p and V_s are the voltage in the primary and secondary coils respectively. Let I_p and I_s are the current in the primary and secondary coils respectively, then,

$$V_p \propto N_p$$

$$V_s \propto N_s$$

$$\text{or} \quad \frac{V_p}{V_s} = \frac{N_p}{N_s}$$

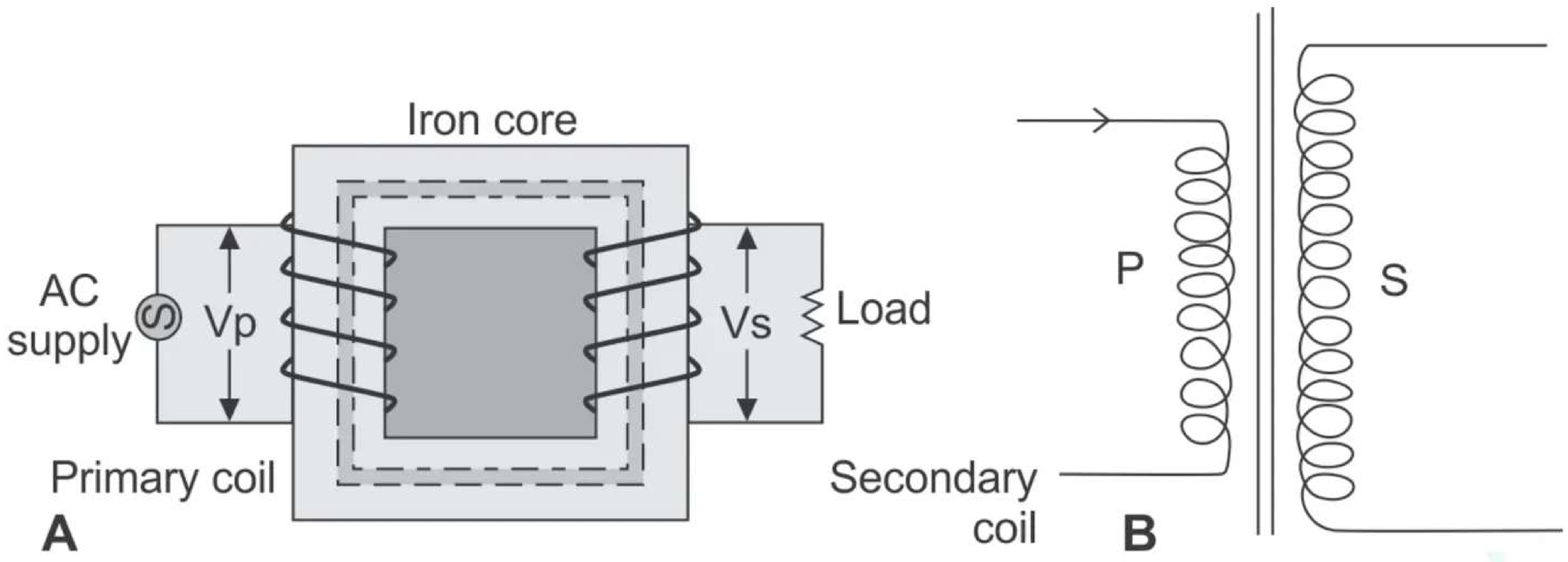


FIG. 4.1: (A) Transformer principle, and (B) Symbol

In a transformer, the turns ratio is equal to the voltage ratio. The power in put in the primary (P_p) = $V_p \times I_p$ and the power output in the secondary (P_s) = $V_s \times I_s$. On the basis of the law of conservation of energy, power input is equal to the power output.

$$V_p \times I_p = V_s \times I_s$$

$$\frac{V_p}{V_s} = \frac{I_s}{I_p} = \frac{N_p}{N_s}$$

This shows that the current in the coils are inversely proportional to the number of turns in the respective coils.

Basically, there are three types of transformers, namely, step up, stepdown and isolation transformers. If a transformer, transfers power of low voltage and high current into power of high voltage and low current, it is called step-up transformer. In this type, the secondary coil will have more number of turns than the primary, i.e. $N_s > N_{p.}$ If a transformer, transfers power of high voltage and low current into power of low voltage and high current, it is called step-down transformer. In this type, the primary will have large number of turns than the secondary, i.e. $N_s < N_p$. If $N_s = N_{p,}$ this results in an isolation transformer.

Efficiency

The efficiency of the transformer is the ratio between the output power and input power.

$$\text{i.e. efficiency} = \frac{\text{output power}}{\text{input power}}$$

$$= \frac{P_s}{P_p} \times 100$$

In actual transformer, the output power is always lesser than the input power due to some energy losses. Hence, the efficiency is always less than <100%.

Transformer Rating

The transformer rating refers the maximum safe output that can be taken from the secondary winding. The ratings are specified in three ways as follows: the highest voltage which the transformer can provide, the maximum current which the transformer can give on continuous running and the maximum current which the transformer can give for a period not exceeding one second.

If the rating is exceeded, the transformer may overheat and burn out its insulation and winding. Usually, it is expressed as the maximum safe output of its secondary winding in kilowatts. For three-phase generators ratings are calculated by the formula,

$$\text{kW} = (\text{kV} \times \text{mA}) \div 1000$$

For example, a three-phase generator operating at 100 kV and 500 mA, will have a rating as follows:

$$\text{Rating} = \frac{(100 \times 500)}{1000} = 50 \text{ kW}$$

For single-phase generators, the formula is, $\text{kW} = (\text{kV} \times \text{mA} \times 0.7) \div 1000$. The factor 0.7 comes from the rms value of the voltage. Kilowatt ratings of X-ray generators are determined, when the generator is under load. Information about ratings are useful to compare X-ray generators.

TRANSFORMER LOSSES

In practice, the output power is always lesser than the input power and hence, the efficiency of the transformer is always less than 100%. This implies that some amount of energy is lost in the form of heat. This energy loss can be considered as copper losses, eddy current losses, hysteresis and flux leakage losses.

Copper Losses

Whenever a current I flows through a resistance R, an amount of power equal to $I^2 \times R \times t$ watt is converted into heat. This can arise in both copper coils and iron core. The copper coil has resistance. If current flows through this coil, electrical energy equal to I^2Rt is converted into heat. To reduce this loss, the current cannot be reduced because the normal operation of the transformer will be affected. Instead, the resistance of the coil must be minimized by using wire of low resistivity. Therefore, thicker wire should be used as transformer coil. The optimum thickness will be decided by comparing the cost, space and saving of power. Copper is the best coil material available to day and hence, it is commonly used.

Eddy Current Losses

The iron core consists of concentric layers of iron, each acts as a circuited single turn coil. Whenever the magnetic field changes, an emf will be induced in the core. The current produced by the induced emf in the core is called eddy current, which will give rise to I^2Rt heat losses. These eddy currents can be eliminated by making the iron core in the form of thin sheet of metal, and each sheet is insulated from its neighbor by a thin layer of paper. This type of core is known as laminated core. The core is usually made up of stelloy, an alloy of steel. Some design employ high resistance ceramics as core material.

Hysteresis Losses

The transformer core is a magnetic material. The core is magnetized twice in each cycle of the alternating voltage. When the direction of AC changes, the magnetization is also gets reversed. During this reversal, some energy is lost due to the molecular friction and the energy appears as heat. The loss of energy by molecular friction is called hysteresis loss. This can be reduced in practice by choosing a suitable magnetic material, such as mu-metal, which has low hysteresis loss. Mu-metal is a ferromagnetic alloy containing 78% nickel, 17% iron, and 5% copper. It has high permeability.

Flux Leakage

All the magnetic flux linked with the primary is not linked with the secondary coil. This is said to be flux leakage, which results in loss of energy. This can be minimized by using good core design like shell type of core.

TRANSFORMER CONSTRUCTION

A practical transformer differs considerably from the ideal transformer. The following points should be considered during the construction of the transformer.

Winding

The transformer is usually made with single primary winding, whereas the secondary will have more than one winding. For example, the primary of a transformer used in control equipment, may be designed for 200 V input. The secondary may be designed with three windings for three out put such as 500 V low current, 50 V low current and 6 V high current. The primary will have a wire of medium thick, whereas the secondary have thin and thick wires. Thicker wire offer lesser resistance and allow flow of high current in the primary. Whereas secondary handle only low current, hence, thin wire with relatively higher resistance is preferred to save cost and power loss.

Core

The transformer cores are always designed so that they form a closed circuit. A core with a closed magnetic circuit has high permeability and is very efficient. At the same time, the core is laminated to eliminate eddy current loses. There are three types of core, namely, (i) core type, (ii) shell type, and (iii) cross type or H type (Fig. 4.2).

In a core type transformer, the primary winding is on one leg and the secondary winding is on other leg. This is easily assembled and has a good cooling surface. Alternatively, both primary and secondary windings are made as two halves. The secondary is wound over the primary winding on each leg. This is the most preferred transformer core type, used in X-ray generators.

In a shell type transformer, the primary and secondary are wound around the central limb, and the magnetic circuit is shorter. Shell type

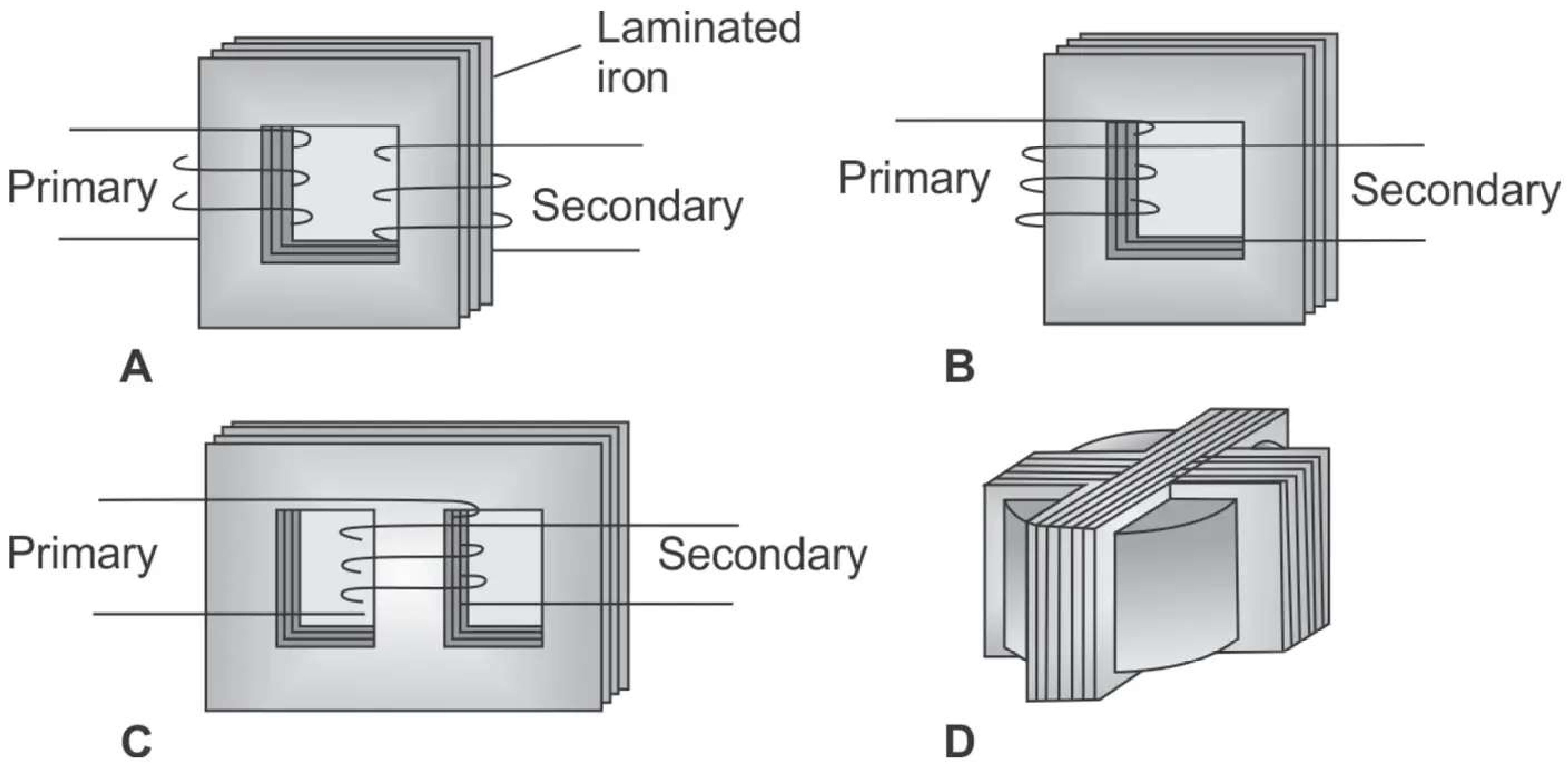


FIG. 4.2: Different types of transformer cores: (A) Core or single window type, (B) Core or single window type, (C) Shell or double window type and (D) Cross or H type

is the most efficient design in terms of energy conservation and efficiency (98%). Hence, it is used most commonly.

The cross or H type core is called modified shell type, since it is a combination of two shell cores set at right angles to each other. In this, the coils are surrounded by four legs. The windings are located over the center core, which is four times the area of the each of the outside legs. This type of core is cooled easily and hence used in large power transformers, where the voltage drop and cost is kept minimum.

Transformer designed for higher output voltages, such as 100 kV, needs special care. The secondary winding must be designed very carefully to avoid electrical break down due to ionization of the surrounding air. Transformers are cooled by oil or forced air, to avoid overheating. Transformers never be immersed in water for cooling. During accidental flooding, if the transformer is immersed in water, immediately the water should be pumped out.

Oil

High voltage transformers are usually enclosed in a metal tank filled with oil. This oil penetrates into the inner spaces of the windings and increases the effectiveness of the insulation. The oil prevents the windings from dust and moisture and also acts as a cooling medium. The oil is a good insulator than air, it avoids electrical short circuiting. Oil also provides effective cooling to the transformer.

Autotransformer

The autotransformer consists of a single winding wound on a laminated iron core and it is working on the principle of self induction (Fig. 4.3). The primary voltage is applied across two of the terminals, and the secondary voltage taken from two terminals, almost always having one terminal in common with the primary voltage. The primary and secondary circuits, therefore, have a number of windings turns in common.

The alternating current applied between the input points will induce a flow of magnetic flux around the core. This magnetic flux will link with all the turns forming the coil, inducing a voltage into each turn of the winding. Since the volts-per-turn is the same in both windings, each develops a voltage in proportion to its number of turns. In an autotransformer, part of the current flows directly from the input to the output, and the other part is transferred inductively, allowing a smaller, lighter, cheaper core to be used as well as requiring only a single winding.

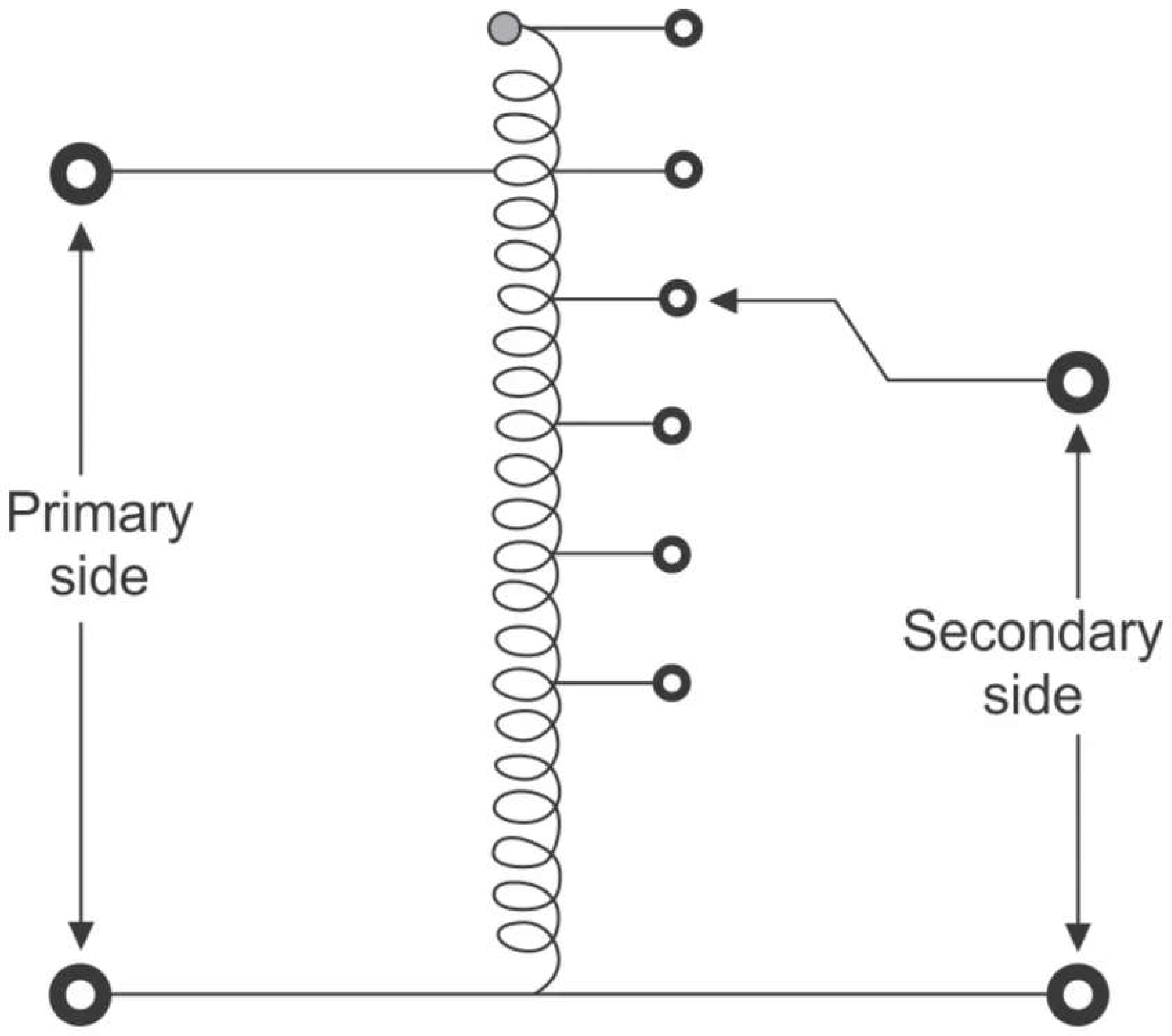


FIG. 4.3: Autotransformer

For example, if 230 V are applied between points A and B (Fig. 4.4), which involves 115 turns of the autotransformer winding, then the volts per turn (230 ÷ 115) will be 2. By a suitable selection of taps, one may select the number of turns to supply the necessary voltage to the other components. A selection of 55 turns will provide voltage of 110 V, while a selection of 160 turns provide 320 V. Thus, an autotransformer can function as a step-up or step-down transformer.

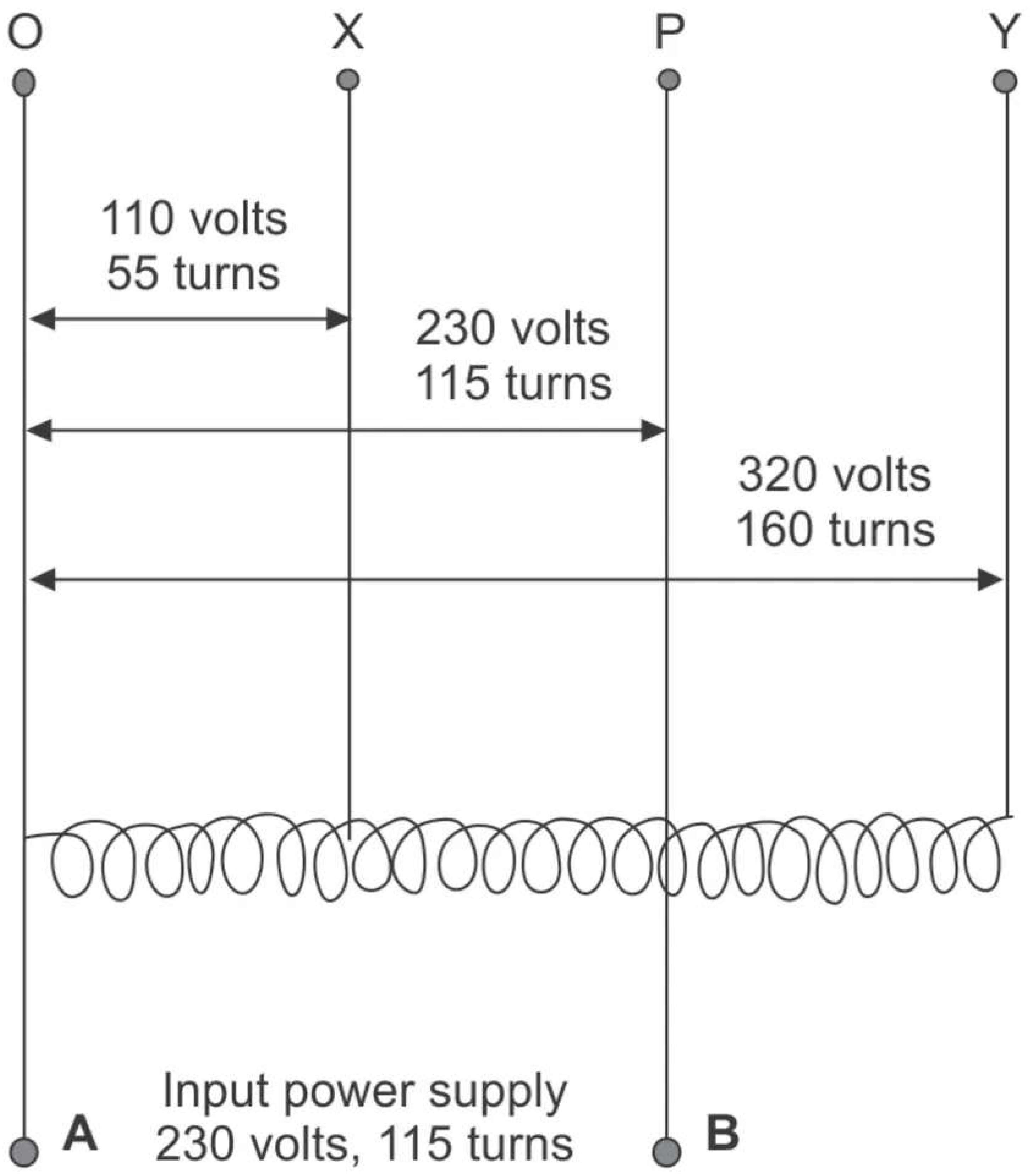


FIG. 4.4: Autotransformer working principle

These transformers are widely used where electrical isolation between primary and secondary is not necessary. Autotransformer occupy very important place in X-ray generator circuits. In the X-ray generator, the autotransformer is used to adjust the voltage applied to the primary of the high voltage transformer with high efficiency and convenience.

An autotransformer does not provide electrical isolation between its windings as an ordinary transformer does. A failure of the insulation of the windings of an autotransformer can result in full input voltage applied to the output. If there is a break in the part of the winding, then the transformer acts as an inductor in series with the load.

HIGH-TENSION TRANSFORMER

The high voltage transformer is used to transfer low voltage into high voltages required to operate X-ray tubes. This is known as high tension generator, which provide voltage from 20–150 kV and current up to 1000 mA for the X-ray tubes. It is a step up transformer with two windings and a shell type core. The number of turns in the secondary is higher than that of primary, and it is decided by the voltage ratio. If 400 volt is to be transformed into 80,000 volts, then the voltage ratio is 80,000/400, requiring 200 turns in secondary per primary turn. Thus primary winding consists of a few hundred turns of thick copper wire, which is well insulated and wound on a cylinder. A thin copper sheet is fitted over the primary winding and it is earthed. This is known as stress shield, which protects the primary circuit during breakdown of the secondary insulation (Fig. 4.5).

The secondary winding consists of about 100,000 or more turns of thin copper wire coated with insulated varnish. This is wound in an insulating cylinder, which is placed over the primary winding. The layers are separated from each other by thin paper prepared with wax for insulation. The voltage difference between any two layers

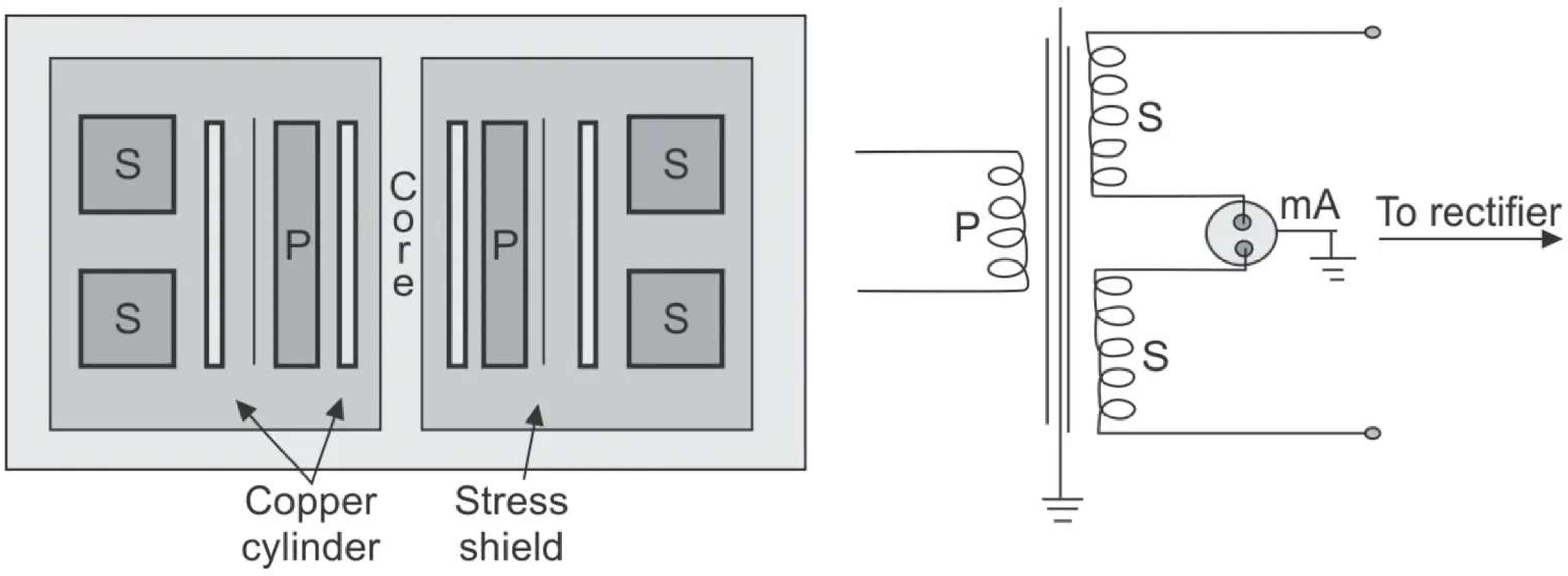


FIG. 4.5: High-tension transformer

is about only 200–300 volts. This method of design reduces the risk due insulation breakdowns. The core of the high tension transformer is rectangular in shape, which is earthed and well laminated.

Usually, the secondary is wound in two equal multiple parts and the center of the winding is earthed through the core. This means that instead of running from 0 to + 150 kV, the two secondary cables run from – 75 kV to + 75 kV. This is to reduce the insulation, size and cost. Since the current measurement in the primary coil is not an accurate representation of the current in the secondary coil, the current must be measured on the secondary side.

A milliameter (mA meter) is connected between the inner ends of the two secondary windings at which the transformer is grounded, which is also the center of the coil. This minimizes the risk of electrical shock to the operator. Though the mA meter is connected at this point, it is placed at remote distance at the control console.

The entire unit is immersed in an earthed metal tank, which is filled with oil. The metal tank is closed with a tight lid. In the case of dental and mobile X-rays, the heat production is very low and hence, oil is not used. Instead of oil, plastic is used as an insulator. The transformer is immersed in plastic when it is in fluid state. Later on, the plastic solidifies and acts like a solid insulator.

RECTIFIER CIRCUIT

RECTIFICATION

Rectification is the process of changing alternating current into direct current. The device that produces the change is called a rectifier. A rectifier allows an electrical current to flow in one direction but does not allow current to flow in the other direction. Rectifiers are connected into the X-ray circuit in series. They are mainly divided into half wave and full wave rectifiers.

If alternating voltage is applied directly to the X-ray tube, the anode will emit electrons, whenever it is negative with respect to cathode. These electrons will travel towards the cathode and bombard the filament and destroy the filament. This is called back projection which is avoided by the supply of rectified DC voltage. Thus, rectifiers play an important role in X-ray production.

HALF WAVE RECTIFIER

Vacuum tube diodes or solid state (semiconductor) diodes can be used for rectification. In a half wave rectifier, a single diode is used, as shown in the Figure 4.6. An alternating voltage is applied to the diode as input. The output is obtained across the resistance R. When the plate is positive, the diode will allow the current to flow. When the plate is negative, the diode will not allow the current. Therefore, the diode will allow the current only during those half cycles when the plate is positive. Hence, the output current is always in one direction. This circuit is known as half wave rectifier and it is mainly used in mobile and dental X-ray units. A single solid state diode cannot prevent reverse current at higher voltages. Hence, many diodes are placed in series in a stick to do rectification.

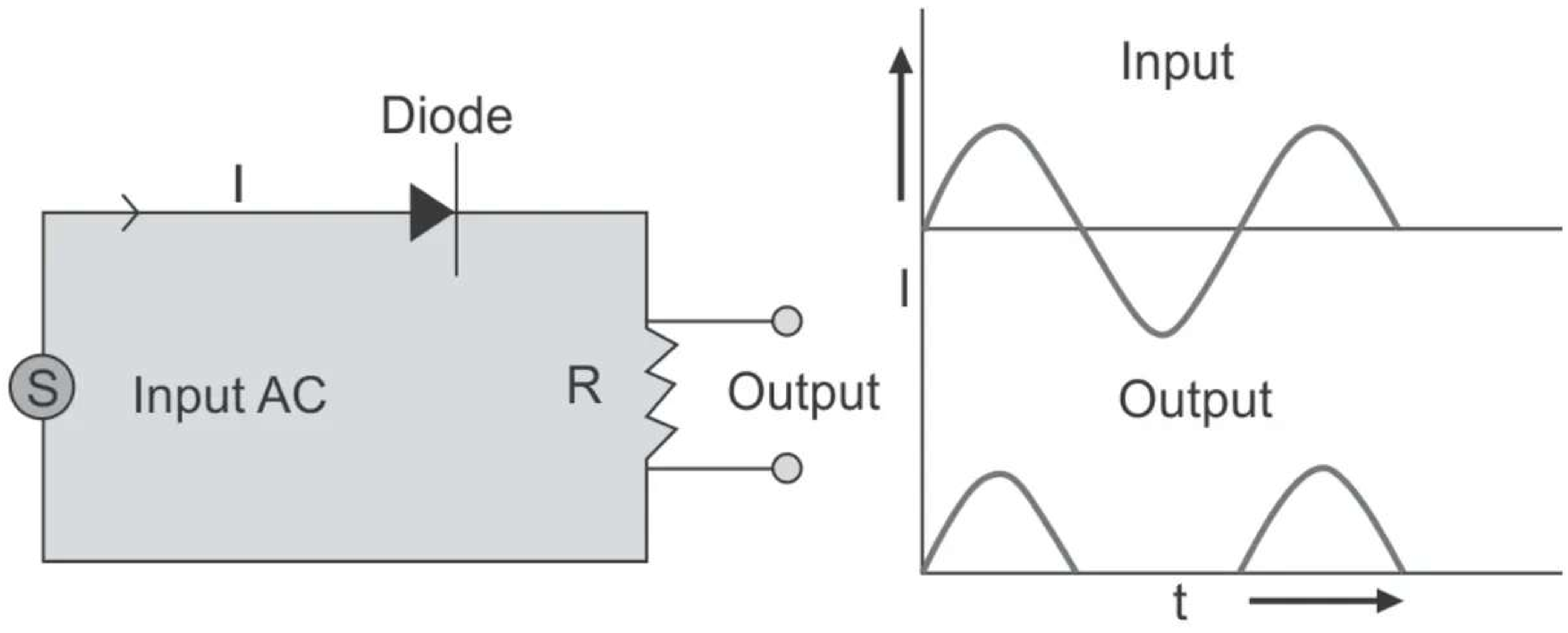


FIG. 4.6: Half wave rectifier

FULL WAVE RECTIFIER

In the half wave rectifier, the input voltage is used only in one half of the cycle. The other half of the cycle is not used. Therefore, there is a need for a rectifier, which will use the full cycle of the input. This is possible by having two or more number of diodes, as shown in the Figure 4.7. The alternating voltage is applied between A and B. The output is obtained across the resistance R.

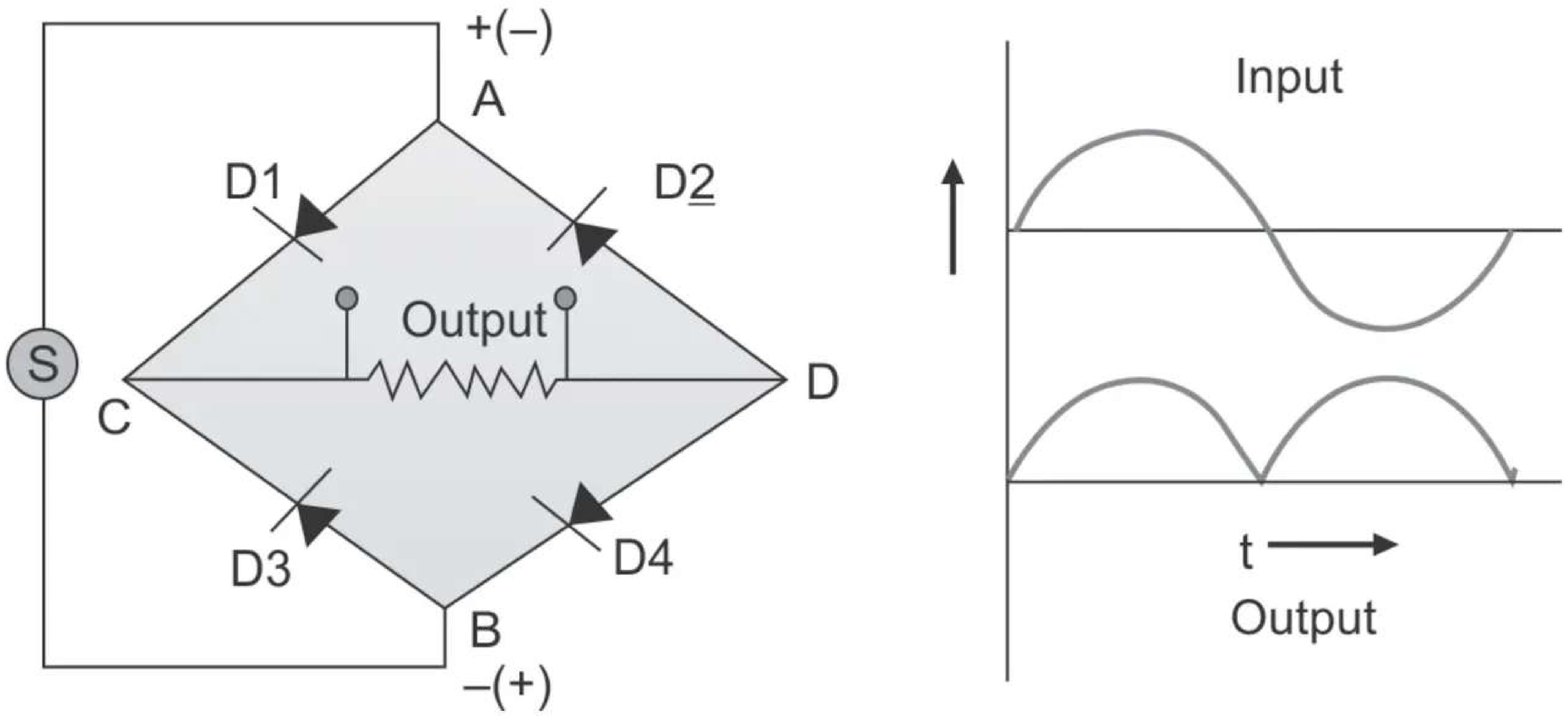


FIG. 4.7: Full wave rectifier

When end A is positive, D1 and D4 will conduct and a current flows through R. During the next half of the cycle end A is negative, and end B is positive. Now, the diodes D2 and D3 will conduct and a current flows through R. Thus, the current flows through the resistance R during full cycle of the input voltage, in the same direction. X-rays are produced in two pulses per cycle, irrespective of the polarity of the transformer. Three phase generator employ multiple rectifiers in the secondary circuit. Full wave rectifiers are used in high end X-ray tubes which employ rotating anode X-ray tubes.

THYRISTOR

A thyristor is a silicon-controlled rectifier which has four layer semiconductors (n-p-n-p). It is used to switch larger currents, which the transistor cannot handle. It has two large terminals, namely, anode and cathode, which connects the main circuit (Fig. 4.8). The third terminal is the gate, which is smaller in size. Initially, the junction J1 and J3 are forward biased and junction J2 is reverse biased. Hence, only small current flows through the circuit and the thyristor is said to be in OFF state.

If a positive voltage is applied in the gate terminal, holes flows through J3 and the barrier across J2 breaks down. This will facilitates movement of electrons across J2 junction and makes the thyristor to ON condition. The conduction continues in the circuit, even after the gate voltage is removed. The conduction ceases only when the potential difference across the anode and cathode falls to zero. Thyristor conduct current only in one direction and can be used to switch the alternating current.

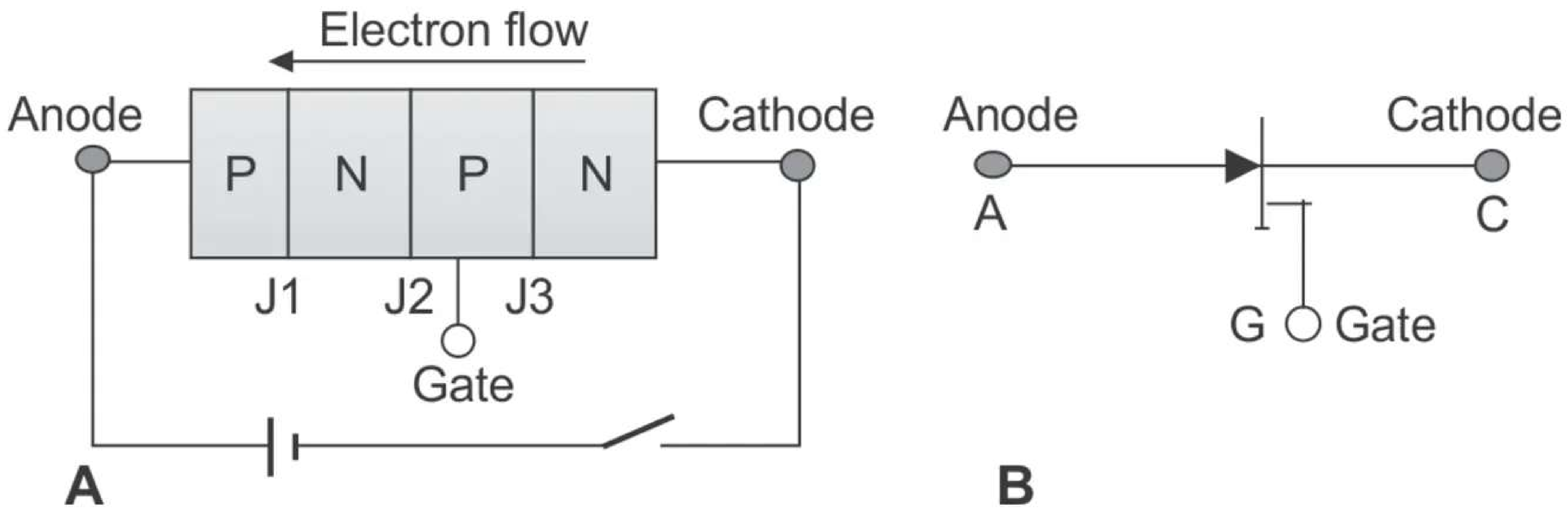


FIG. 4.8: (A)Thyristor rectifier principle and (B) Symbol

HALF WAVE RECTIFICATION X-RAY CIRCUIT

The half wave rectification is the most commonly used circuit. The circuit uses two rectifier stacks connected in series with the X-ray tube, as shown in Figure 4.9. The center point of the secondary winding of the step up transformer is grounded. The electrons flow through the X-ray tube from the cathode to anode in the first half cycle. When the voltage reverses, in the second half cycle, the rectifier stops current flow. Since there are two rectifiers, the circuit is symmetric and each has to withstand only half of the peak voltage (V_p). The anode goes only to $+V_p/2$ at the peak of the conducting cycle and the cathode to $-V_p/2$. The tube voltage, tube current and X-ray pulse are shown as a function of time.

The discontinuous nature of X-ray yield reveals that the tube is inoperative at least half the time. This means that the exposures must be twice as long to get the same X-ray flux. This increases the chance of organ motion during the exposure, with a loss of diagnostic information. The advantage of the half wave rectification is that they protect the X-ray tube from the full potential of the inverse cycle.

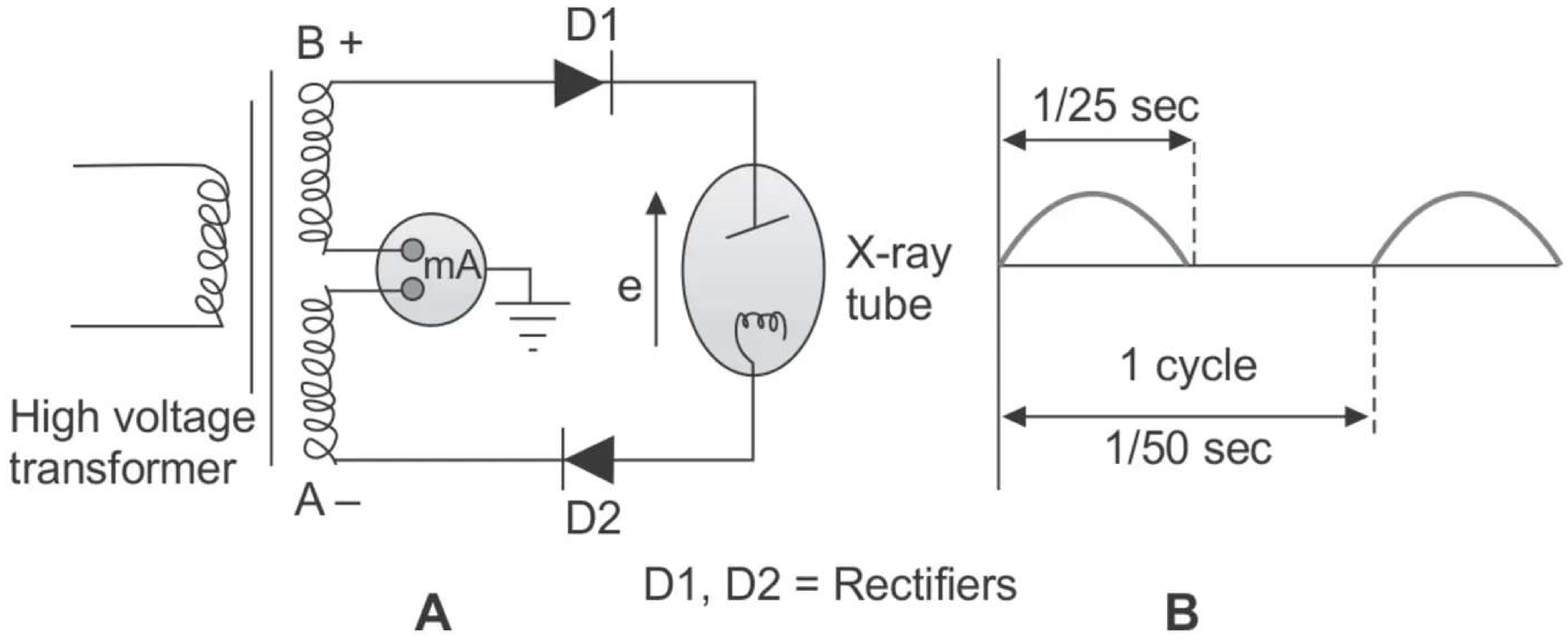


FIG. 4.9: (A)The half wave rectifier X-ray circuit and (B) Rectifier output

FILAMENT CIRCUIT

The tube current can be altered by altering the number of electrons emitted by the filament. The number of electrons can be altered by changing the temperature of the filament. To achieve this, a filament circuit is used, which will regulate current flow through the filament (Fig. 4.10).

The power to heat the filament is provided by a small step-down transformer, called the filament transformer. In addition, the circuit consists of a variable resister network and a focal spot size selector. This transformer has 10–20 times more turns in primary coil, compared to secondary coil. The filament is connected directly to the secondary coil of a step-down transformer. The primary coil of the transformer obtains its voltage from the auto transformer. Usually, the primary voltage will be around 100–200 V, whereas the secondary voltage

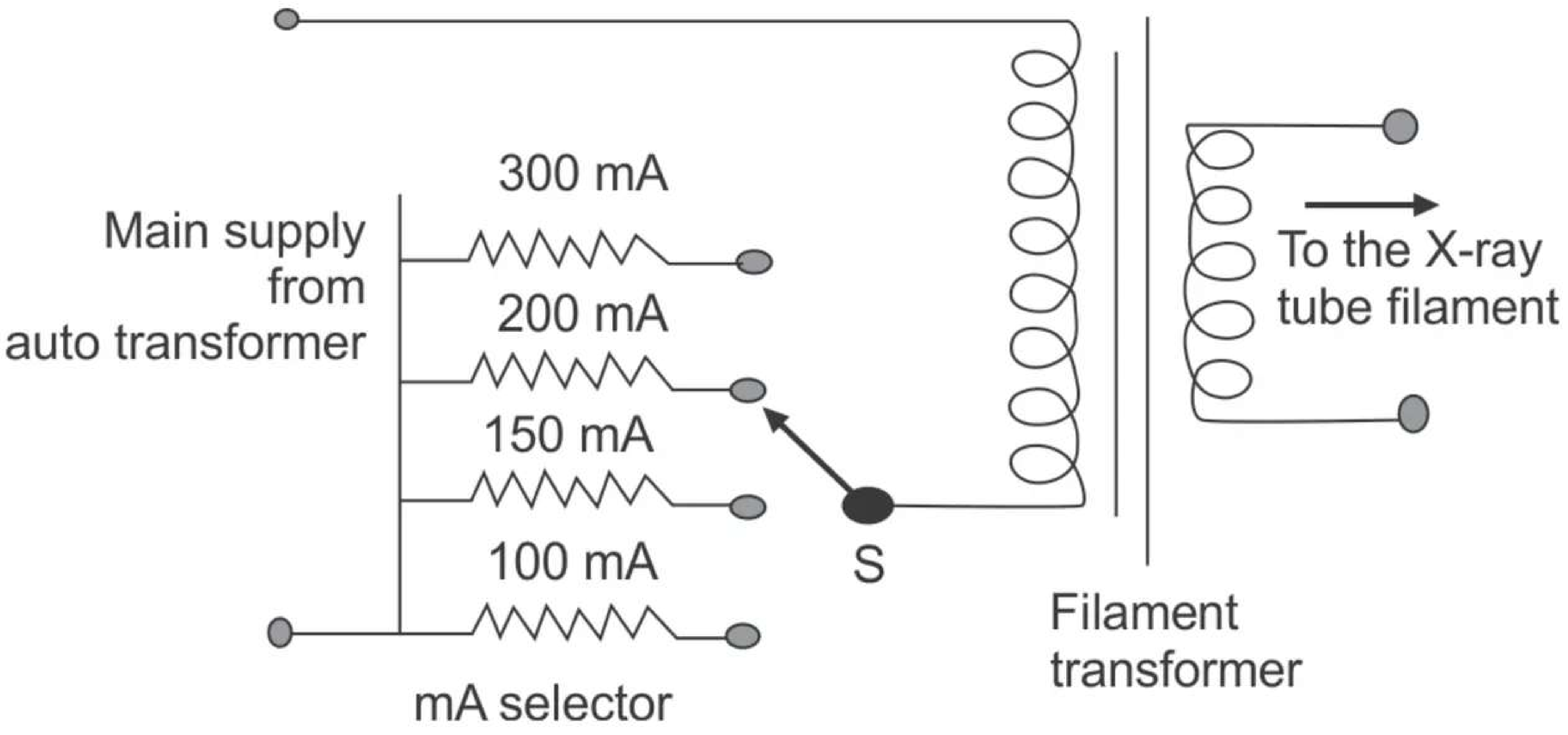


FIG. 4.10: The filament circuit

is around 10 V and current up to 7A. This makes it necessary to provide high voltage insulation between primary and secondary coils. Hence, the filament transformer is placed in the same oil-filled grounded metal tank as the high voltage transformer.

Precise control of filament heating is very essential. A small variation in the filament current results in a large variation in X-ray tube current. A 5% change in filament voltage may bring a change of 20–30% in X-ray tube current. The filament current may be controlled, by altering the voltage to the primary of the step-down transformer, by addition of resisters connected in series. The resisters may be a number of separate resisters or a single variable resister. As the resistance increases, the voltage to the filament decreases. For example, a current of 4 A and a resistance of 1.5 ohms will reduce voltage by 6 V.

When the selector S moves over the resisters, the primary voltage of the transformer is altered. As a result, different values of tube current (mA) are obtained. The selector is either a rotary switch or a push button located on the control panel. The circuit also has other components to stabilize the voltage to the filament transformer that includes a voltage stabilizer and a frequency stabilizer. There is also a circuit that automatically compensates for the space charge effect.

KILOVOLTAGE (KV) CONTROL CIRCUIT

The kilovoltage applied across an X-ray tube determines maximum energy and hence, the penetrating power of the X-rays. To have a wide range of penetrating power of X-rays, the applied kilo voltage must be varied in small steps. By using a kilovoltage circuit, the kilovoltage can be varied in steps of say 2 kV_p. A simplified kilovoltage circuit is shown in Figure 4.11. The circuit has two transformers, namely, an autotransformer and a step-up transformer. The autotransformer is actually the kV_p selector and is located in the control panel. The voltage across the primary coil of the step-up transformer can be varied by selecting the suitable number of turns in the auto transformer.

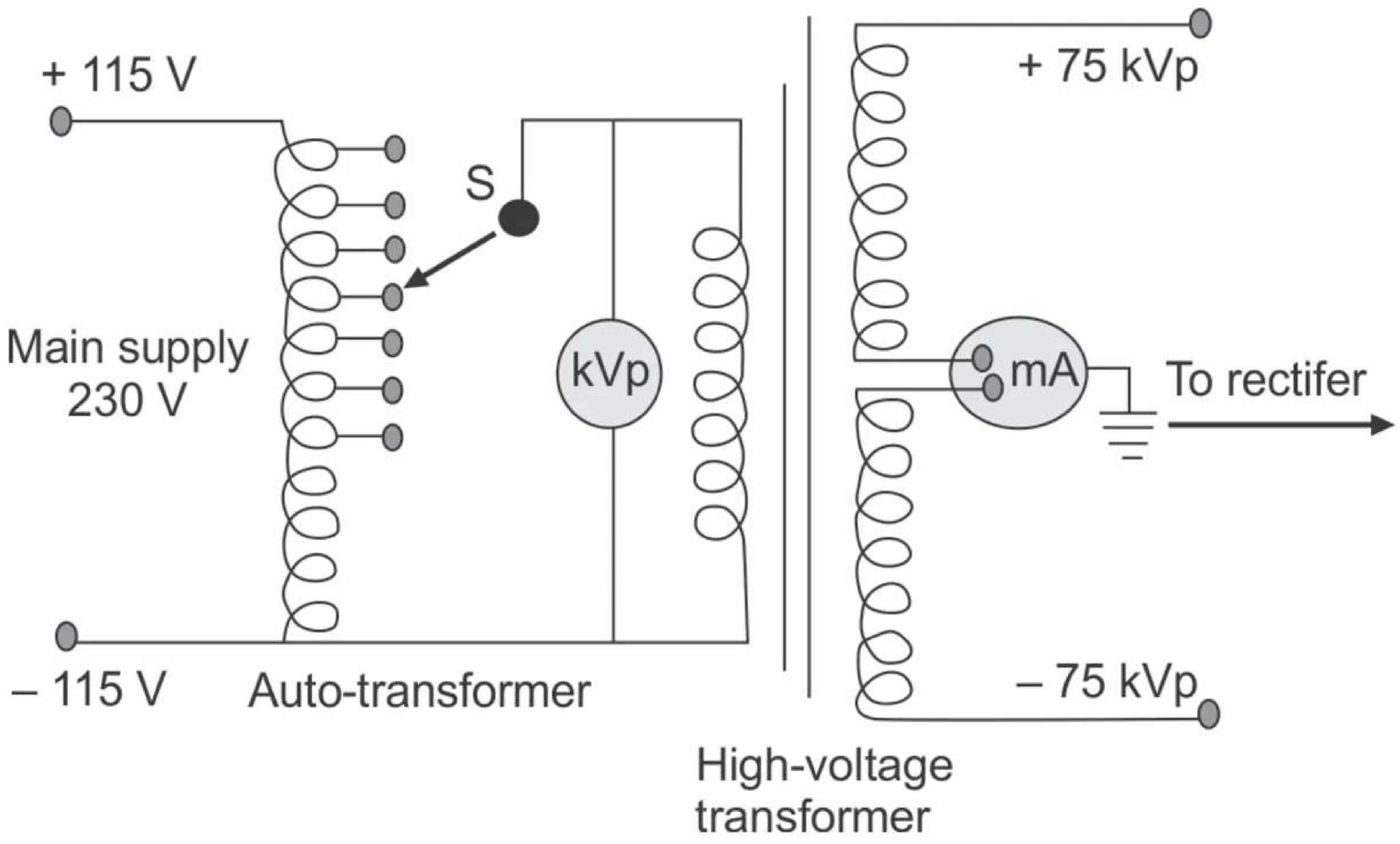


FIG. 4.11: Kilovoltage control circuit

The secondary coil of the step-up transformer has more turns than primary, and increases the voltage by a factor of 600. The potential difference across the secondary coil may be as high as 150,000 V, so the step-up transformer is immersed in oil for maximum insulation. There are two meters in the circuit, one to measure kV_p (voltmeter) and the other to measure mA (ammeter). The meters are located on the control panel, but their connections are in the high voltage circuit. They indicate the potential across the X-ray tube and the actual current flowing through the tube during exposure.

The potential difference across the X-ray tube can be measured indirectly on the low voltage side of the transformer. Therefore, the kV_p meter is placed in the circuit between the autotransformer and step-up transformer. Because the kV_p meter records the selected kV_p before the actual exposure begins, it is usually termed as pre-reading kV_p. If the kV_p meter is properly calibrated, it can directly read the applied voltage across the X-ray tube. Since the voltage in the primary circuit is relatively small, the meter can be placed on the control panel. This requires minimum insulation without any risk of electrical shock.

The connections for the mA meter must be in the secondary winding of the transformer. Since the efficiency of the transformer is less than 1, measurement at primary level is not the true representation of the current in the secondary. Hence, the mA meter is connected at the centre of the secondary coil, at which the transformer is grounded. This will minimize the risk of electric shock to the operator, since the center of the coil is at zero potential. Though the meter is connected at this point, it may be placed at the control panel.

The main supply is applied to the autotransformer. There are number of tapping in the autotransformer. By moving the stud selector over the tapping, the output voltage of the autotransformer can be varied. This variable output voltage is applied to the primary of the high tension transformer. Finally, the kilovoltage across the X-ray tube is varied.

If the range provided by the stud selector is from 40 to 100 kV_p in steps of 2 kV_p, then there must be 31 tapping. Usually, there are two selectors, one is a coarse control giving step of 10 kV_p and the other is a fine control giving steps of 2 kV_p. The kilovoltage can also be continuously varied by using a variance transformer. This type of control is employed in the diagnostic X-ray units, used for fluoroscopy.

SINGLE-PHASE X-RAY GENERATOR

A single-phase X-ray generator utilizes a single-phase AC supply as input. These generators employ full wave rectification, which utilizes the full potential of the electrical supply. Figure 4.12 shows the full wave rectified single-phase generator and its wave form. Both half cycles of the AC is used to produce X-rays. Hence, the X-ray output per unit time is twice as large as that of half wave rectification.

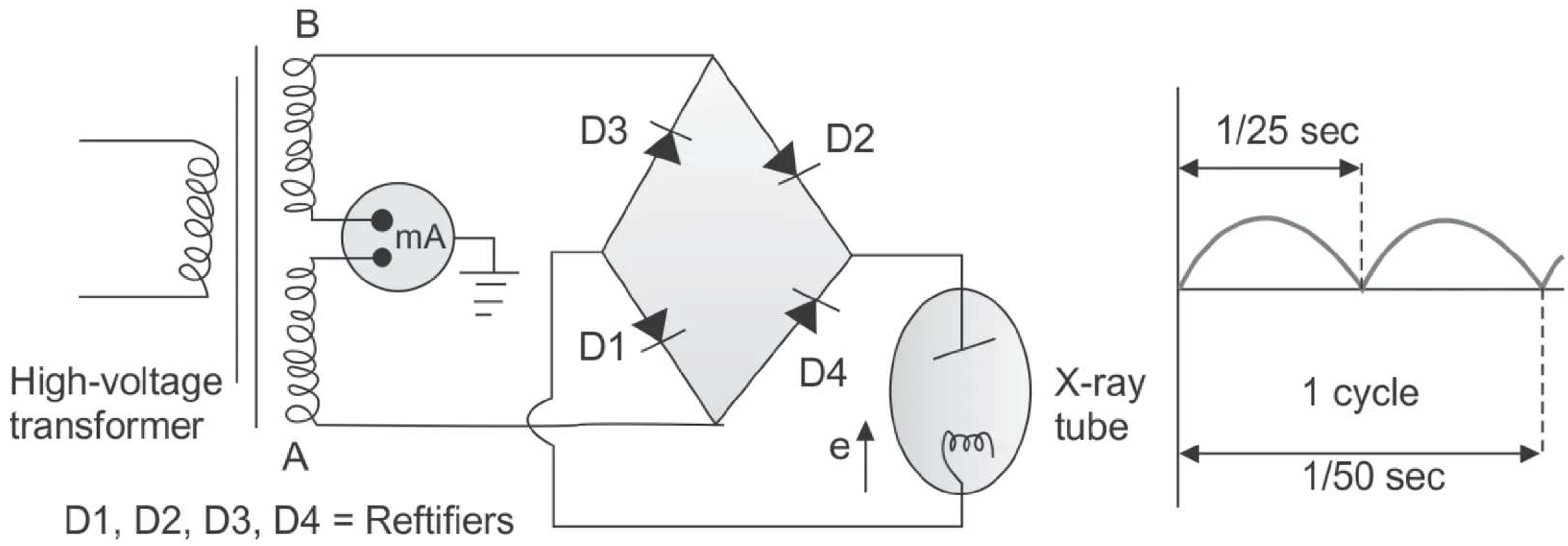


FIG. 4.12: Single phase X-ray generator with full wave rectifier

The voltage across the circuit is supplied by the step up transformer. In the first half cycle (A is negative and B is positive), the electrons will flow from A through the rectifier D1 to the X-ray tube, and return through rectifier D2 to the side B. In the next half cycle (A is positive and B is negative), the electrons will flow from B through the rectifier D3 to the filament and return through the rectifier D4 to side A. Thus, the four rectifiers produce pulsating DC through the X-ray tube and the voltage across the tube fluctuates from zero to maximum.

The generated X-rays have 100 short pulses in one second (2 pulses/cycle, frequency = 50 cycles/sec). The exposure time for each X-ray pulse is 1/100 s = 10 ms. The AC waveform can be easily switched off, when the voltage in the circuit is at zero level. It is at this point, the primary voltage switches can be opened easily. Hence, the timer is calibrated in fractions of seconds in most of the single-phase generators. Most of the X-ray pulses are generated during the peak value of the applied voltage. The tube current follows the kV in a nonlinear way below 40 kV_p due to space charge effect. A typical single-phase X-ray generator circuit design is shown in the Figure 4.13.

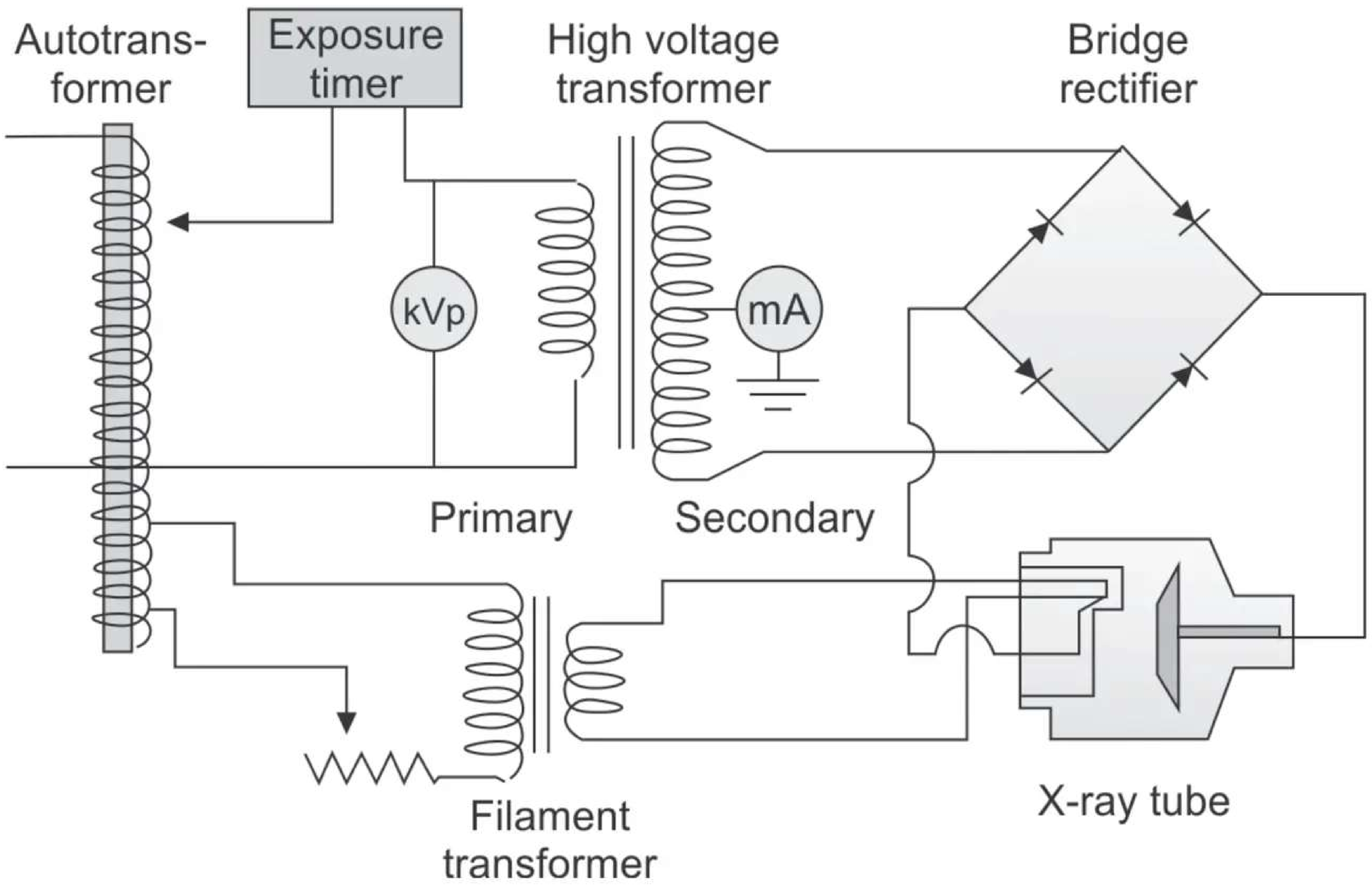


FIG. 4.13: Single-phase X-ray generator circuit

Thus, half wave and full wave rectifier circuits are generating only pulsating potential. The principal disadvantage of pulsed radiation is that a considerable portion of the exposure time is lost while the voltage is in the valley between two pulses. This will enable the low energy electron to bombard with the target, by giving heat and low energy X-rays. These X-rays are absorbed in the patient and raise patient dose.

Hence, there is a need for constant potential circuits, which can give better X-ray output with more penetration. To achieve this, a condenser C is connected parallel to the X-ray tube. As a result, sufficient charge may be stored on it to maintain a constant voltage to the X-ray tube. Alternatively, three-phase generator can be used to produce constant potential across the X-ray tube.

THREE-PHASE X-RAY GENERATOR

The three-phase X-ray generator uses a 3-phase AC line supply. There are three wires, each with a single phase AC sinusoidal wave. Each wave is out of phase with the other two for one-third (120°) of a cycle. A three-phase transformer is used to convert the low voltage AC to high voltage AC. It has three sets of primary and secondary windings. These windings are connected in one of the two configurations, namely, delta and wye (star). Generally, the primary windings are of delta configuration and the secondary is connected with wye configuration.

When the voltage is rectified, the circuit produces two pulses per cycle for each line, resulting six pulses per cycle. Hence, this is named as 3-phase 6-pulse generator. It is also possible, to produce 12-pulse per cycle, by using different configurations of transformers and rectifiers. This is called the 3-phase 12-pulse generator.

SIX-PULSE THREE-PHASE GENERATOR

This type employs a delta-wound primary transformer with a wye-wound secondary transformer. The output of the secondary winding is rectified with six solid state rectifiers. The wye winding and 6 rectifiers are connected together, as shown in Figure 4.14. The rectified output will have six positive maximum voltages per cycle. Suppose, A is negative with respect to B, electron will flow from A, through

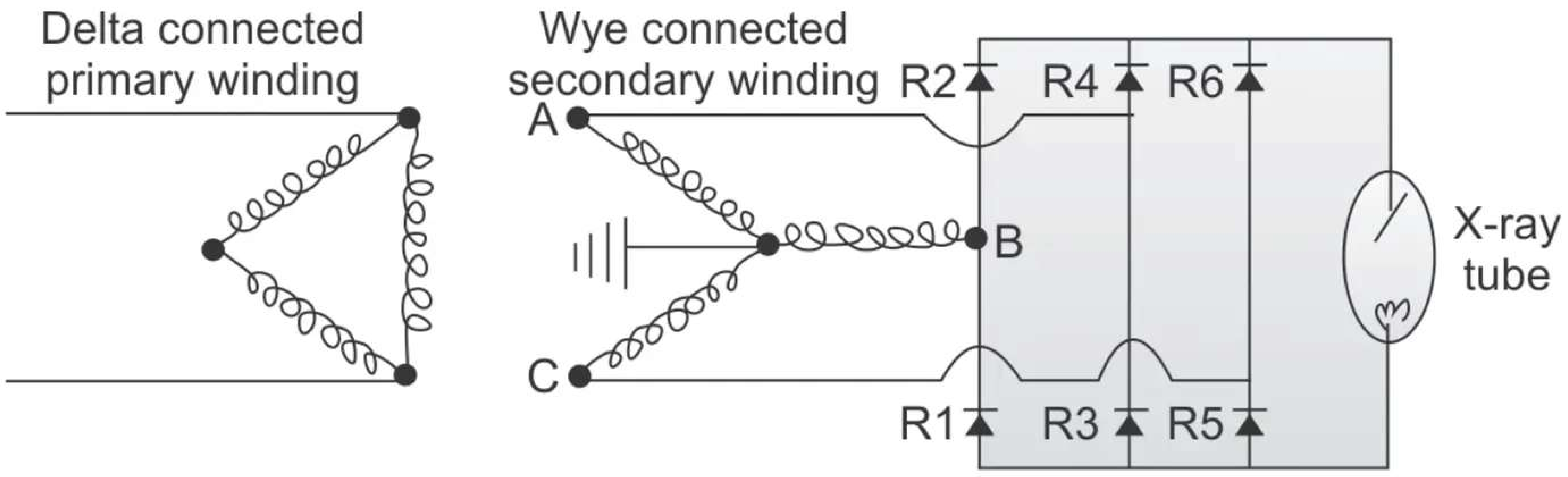


FIG. 4.14: A six-pulse, three-phase X-ray generator circuit

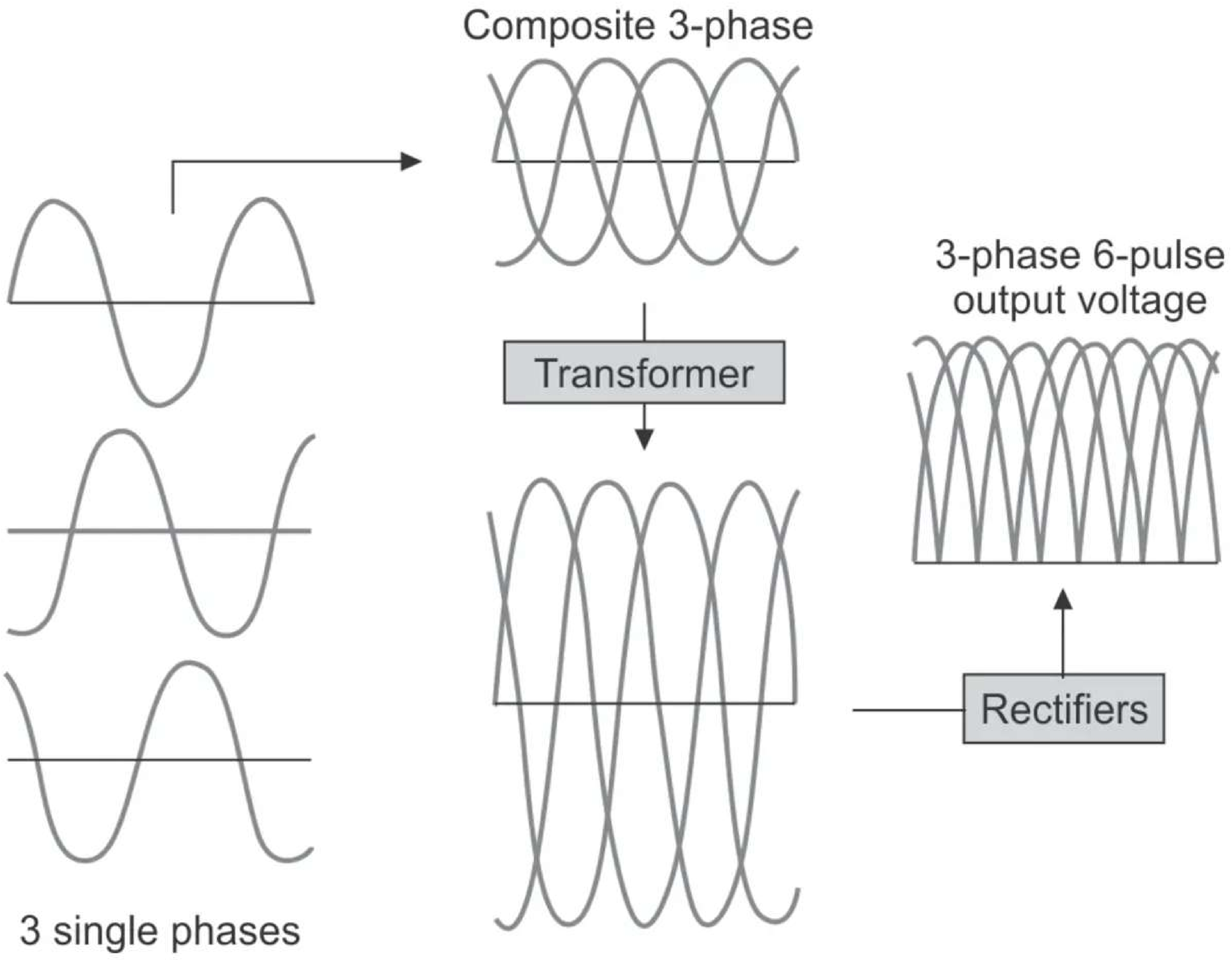


FIG. 4.15: The wave form of 3 phase, 6 pulse X-ray generator

rectifier R3 to the filament of the X-ray tube, then to the target of the tube and through the rectifier R2 and to the coil B. During the next half cycle, B would be negative with respective to A and the electron flow from B, through R1, X-ray tube, through R4 to A. By this method, full wave rectification of all three phases will produce six pulses per cycle.

Since voltage supplied to the X-ray tube never falls to zero, the ripple factor is very low (13.5%), as shown in Figure 4.15. The ripple factor of an DC voltage is the ratio of the difference between the maximum and minimum voltage divided by the maximum voltage.

$$\text{Ripple factor (\%)} = \frac{(\text{Vmax} - \text{Vmin})}{\text{Vmax}} \times 100$$

The ripple factor is the variation of voltage across the X-ray tube expressed as a percentage of the maximum value. For example, a ripple factor of 13.5% means that at 100 kV voltage fluctuates between 86.5 and 100 kV. The single phase X-ray generator ripple factor is 100, but in practice it is less than 100, due to capacitance effect of the cable. It means that the cable offers capacitance, which smoothens the DC voltage. The ripple factor for high frequency and constant potential generators are 4–15% and < 2%, respectively.

Three-phase generators produce a nearly constant potential. This is a major advantage over single-phase generators that produce a