This chapter discusses importance and objective of the work in the field of electron accelerator based research for medical as well as industrial applications. The Race-Track Microtron at Pune University and Linear Accelerator at SAMEER, Mumbai are discussed with their specifications and working principle for production of high energy electrons. Apart from this, an interaction of electrons with matter along with an emphasis on the generation of bremsstrahlung radiation is discussed in great detail. In addition, an interaction of gamma radiation is discussed in view of the generation of neutrons through photo nuclear reactions along with the interaction of neutrons with matter. The Monte Carlo based FLUKA code, has been explained with minute details. Moreover, to set an overview of the thesis, a summary of the thesis is finally incorporated.
1.1 Importance and Objective

Although not published until 1897, J. J. Thomson’s work on cathode rays and consequent discovery of the electron preceded Roentgen’s discovery of X-rays in the November of 1895 - a year before the announcement by the Becquerel of the discovery of radioactivity. The experts were therefore, aware that X-rays had been produced by a primitive electron accelerator. X-rays were immediately applied to diagnosis and therapy in medicine. In 1903, Coolidge developed hot cathode X-ray tube. Since the inception of radiotherapy, the technology of radiation production has first been aimed to get higher photon and electron beam energies and intensities, and more recently towards computerization and intensity modulated beam delivery. During the first 50 years of radiotherapy, the technological progress was relatively slow and mainly based on X-ray tubes, Van de Graaff generators and betatrons. The Co-60 gamma radiation unit was invented by H.E. Johns in Canada in the early 1950s for radiotherapy. The concurrently developed medical linacs, became the most widely used radiation source in modern radiotherapy. With its compact and efficient design, the linac offers excellent versatility for use in radiotherapy through isocentric mounting and provides either electron or megavoltage X-ray therapy with a wide range of energies.

Presently, there are more than ten thousand of accelerators running all over the world. Out of which almost fifty percent are devoted to the medical applications. The main areas of use are radioisotopes production, radiography and conventional radiotherapy with electron and photon beams. Electrons and photons are found to be good members of radiation therapy for treating the cancer, quite years ago. This is because of their high penetrability, low Linear Energy Transfer (LET) to exhibit damage to the normal cell and unique characteristics of dose distribution at depth. With the advent of high energy linear and circular accelerators, electron / photon have become a viable option in treating superficial tumors up to the depth of about 5-10 cm. In such case, the dose of radiation absorbed correlates directly with the energy of the beam and its deposition of
energy in tissues, which results in damage to DNA strands and diminishes the cell’s ability to replicate indefinitely. For low LET radiations, the damage is induced primarily by activated radicals produced from atomic interactions. Over the energy range of therapeutically used X-rays, typically 100 keV to 25 MeV, approximately the same physical dose needs to be delivered at different energies to reach a given biological endpoint, resulting in similar Relative Biological Effectiveness (RBEs). High LET radiations such as protons, neutrons, however, result in biological damage that is generally larger per unit dose than for X-rays, resulting in an elevated RBE.

In case of neutrons, the recoils and nuclear disintegration product contributes to the dose are responsible for a high energy transfer to the biologically active molecules and destroy them in turn. High RBE, LET characteristics and comparatively good dose distribution advantage, are the main attractive feature of the neutron therapy. As the biological effectiveness of neutrons is high, the required tumor dose is about one third the dose required with photons. Therefore, the neutron therapy is presently realized in two versions: Neutron Capture Therapy (NCT) and the Fast Neutron Therapy (FNT). In NCT, the isotope with large absorption cross-section for thermal/epithermal neutrons is introduced into the body mainly through the blood, while FNT uses fast neutron with high penetrability and treats the malignant tumors of the head, neck, dairy gland, osteogenous sarcomas, etc.

In earlier works, the neutrons produced in reactors or through D-T reaction were mainly used to study the nuclear reactions, measurement of cross sections and elemental analysis in different materials because of their high neutron flux. But, recently the attention has been paid to use these neutrons in various fields such as medical, engineering, archaeological, defense, geological and industries. The main stream of these applications are irradiation of biological samples, neutron induced damage in an electronic devices, activation analysis, fissile element content determination, detection of explosive class materials, etc. Moreover, the wide range of applications of neutrons have been covered due to their properties such as being a neutral particle with high penetrating power,
magnetic moment and comparable wavelength with atomic spacing. This helps to investigate not only the nuclear system but also analysis of materials such as reconstructing the magnetic microstructure, determination of crystal structures, etc. However, in recent years, there have been a rapid growth in case of low and medium energy electron accelerator based neutron sources for medical and industrial applications because of their compactness, easy handling, adjustable flux, no radioactive waste, less shielding requirement, etc. The wavelength of fast neutron is too short for investigating the matter and wavelength of 25 meV (thermal) neutron is 1.8 A.U., which is of the same order as typical interatomic distances and is quite suitable for diffraction experiments. Therefore, in the present thesis considering the importance of electron, photon, fast neutrons and thermal neutrons in the medical and industrial field, the actual evaluation and designing aspect of the associated accessories of the sources have been studied thoroughly.

1.2 Electron Accelerators

To perform the accelerator based research, a 6 MeV electron accelerator called Microtron, and 6 MeV, 15 MeV electron accelerator called LINAC (LINear ACcelerator) has been used in the present study. In addition to this the results are also estimated for the energies 9 MeV, 12 MeV and 18 MeV.

1.2.1 6 MeV Race-Track Microtron

In the decade of 80’s, a new type of accelerator called Race-Track Microtron [1] was developed and commissioned at Department of Physics, University of Pune. The Microtron is re-circulating accelerator which produces electron beam in two energy ranges 0.5 – 1 MeV and 6 – 8 MeV. Pierce type diode electron gun and co-axial diode type electron gun can be used in Microtron. The electrons emitted by the electron gun having 25 keV energy is injected into the cavity [2] which is powered by 1 MW pulsed magnetron and gains 1 MeV electron energy. Separate modulators are used for the electron gun and magnetron. The 1 MeV electron beam from cavity enters in to the sector magnets. Instead of one circular magnet, four sector magnets are designed in such way that the
electron beam trace a circular orbit and reached to cavity again as shown in Figure 1.1 of a schematic diagram of the Race-Track Microtron. The accelerating cavity is kept in field free region between the sectors. The time-required for electrons to complete its path in an orbit should be an integral multiple of r.f. period. This is the resonance condition for the Microtron. For electron passing through the cavity, the maximum energy gain per pass through the cavity is 1 MeV energy. In this way the electron beam is repeatedly passed through RF accelerating cavity and gains energy. At present the beam is extracted from the 6th orbit and thereby gives 6 MeV electron beam. Adequate shielding provided with the help of lead bricks and concrete blocks which can be seen in a view of the Race-Track Microtron in Figure 1.2(a).

All the operation parameter of the Microtron such as an injection energy, radio frequency, drift space length and magnetic field in the sector electromagnet are adjusted in such a way that the beam can come out from the extraction port. All these parameters are controlled and monitored from the control console which is shown in Figure 1.2(b). The various parameters/specifications of the
Chapter 1. Introduction

Race-Track Microtron are shown in Table 1.1. Based on pulsed current (1 – 10 mA), pulse width (2 µ sec) and pulse rate (50 PPS) the average current of the electron beam is varying between 0.1 µA and 1 µA.

**Table 1.1:** Specifications of the Pune University Race-Track Microtron.

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<td>1</td>
<td>Beam Particle</td>
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<td>Operating Beam Energy</td>
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<td>Beam Current (peak pulse)</td>
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<td>4</td>
<td>Beam Current (average)</td>
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<td>5</td>
<td>Number of Orbits</td>
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<td>6</td>
<td>Pulse Width</td>
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<td>Maximum Pulse Rate</td>
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<td>R.F.Peak Power</td>
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<td>12</td>
<td>Cavity type</td>
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<td>13</td>
<td>Main Chamber</td>
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<td>Operating Vacuum in the system</td>
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<td>Magnet Type</td>
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<td>Magnetic field Strength at gap</td>
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<td>17</td>
<td>Maximum Gun Voltage</td>
</tr>
<tr>
<td>18</td>
<td>Gun Current</td>
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</table>

1.2.2 **Linear Accelerator**

Society for Applied Microwave Electronics Engineering and Research (SAMEER), Mumbai is a research institute engaged in developing the Linear Accelerator (LINAC) facilities for medical as well as industrial applications. The
technology to develop ‘S’ band compact side coupled standing wave electron linear accelerator is very well established at SAMEER, Mumbai center [3]. Based on this technique 6 MeV to 15 MeV linac are developed at SAMEER, Mumbai.

In linear accelerator, the electrons are accelerated using nonconservative microwave RF fields. A Pierce’s type diode gun is used as an electron source. Waveguides are evacuated or gas filled metallic structures of rectangular or circular cross-section. Two types of waveguide are used in linacs (a) RF power transmission waveguides and (b) accelerating waveguides. The standing wave structure of accelerating waveguide is used in linear accelerator of SAMEER. A schematic diagram of standing wave accelerating waveguide is shown in Figure 1.3. Six cells are brazed together to make a 32 cm long linac tube as shown in Figure 1.4(a) and linac with shielding is shown in Figure 1.4(b).

![Figure 1.3: Schematic diagram of standing wave accelerating waveguide of 6 MeV Linear Accelerator](image)

The linac tube has two buncher cavities and five acceleration cavities. The linac tube is water cooled to maintain the body temperature within 5°C. The electrons are accelerated in the accelerating waveguide by means of an energy transfer from the microwave radiation produced by high power RF fields. The microwave power produced by 2.6 MW magnetron at 2856 MHz frequency is carried to the accelerating waveguide through rectangular uniform S band waveguides that are either evacuated or more commonly pressurized with a dielectric gas (Freon or sulfur hexafluoride, SF6) to twice the atmospheric pressure. The klystron is used as high power microwave amplifier. The high voltage...
(~100 kV), high current (~100 A), short duration (~1 s) pulses required by the RF power source and the electron gun are produced by a pulsed modulator. The electrons are accelerated following straight trajectories in accelerating waveguides. An advantage of linear accelerators is their compact size and potential for high current operation.

The mechanism of operation is such that electrons from electron gun drifted to enter into the first cavity at a proper time according to the phase of the microwave field and is accelerated along the axis of the cavity. The length of the cavities is chosen in such a way that a particle is in proper phase with the electric field in the first cavity propagates into the following cavity in the time equal to the half period of the microwave field. Hence, the particle always encounter the field in each cavity with the same phase as in the preceding cavity, and is accelerated at each cavity where it receives an energy equal to the particle charge multiplied by the voltage drop across the cavity. Electrons after passing through microwave accelerating cavities gains energy and coming out with beam energy of 6 MeV. The parameters of the electron beam are pulsed current 130 mA, pulse width 4.5 µs and pulse rate 150 PPS. Therefore, the average current of the electron beam is 87 µA.
1.3 Interaction of Radiations with Matter

Each radiation behaves differently while passing through the material.

1.3.1 Electrons

In an absorbing material an electron is slowed down and finally brought to rest by the combined action of all four of these elastic and inelastic processes. 

1. Elastic collision with atomic electron

An incident charged particle may be elastically deflected in the field of the atomic electrons of the struck atom. Energy and momentum are conserved and the energy transfer is generally less than the lowest excitation potential of the electrons, so that the interaction is really with the atom as whole. Such collisions are significant only for the case of very low energy (< 100 eV) incident electrons. The cross-section for this process is,

$$\sigma_{\text{electron}} \propto \frac{2z}{\beta^4} \quad (\text{barn/atom}) \quad (1.1)$$

$$\theta \geq 45^0$$

2. Elastic collision with atomic nuclei

The incident particle is elastically deflected in the field of nucleus. It loses only the kinetic energy required for conservation of momentum. This is a radiative free process. The deflection due to nucleus will take place at an angle greater than 90°. Cross-section for this process is very small and is given as

$$\sigma_{\text{nucleus}} \propto \frac{Z^2}{4\beta^4} \quad (\text{barn/atom}) \quad (1.2)$$

$$\theta \geq 90^0$$
3. Inelastic collision with atomic electron

In this mechanism the incident electrons loses their energy while passing through matter. During such inelastic collisions incident electron transfers part of its energy to a bound atomic electron taking it to an unbound state (ionization) or an excited state (excitation). In this type of collision, electron losses its energy in the form of ionization energy loss. The cross-section and energy loss per unit path length of this process is,

\[ \sigma_{ion} \propto \frac{2Z}{\beta^4} \ln \left[ \frac{E \sqrt{2} I}{I} \right] \]  \hspace{1cm} \text{(barn/atom)} \quad (1.3) \]

\[ \left( \frac{dE}{dx} \right)_{ion} = \frac{e^4 nZ}{4\pi\varepsilon_0^2 m_e v^2} \ln \left( \frac{2m_0 v^2}{I} \right) \]  \hspace{1cm} E \leq m_0 C^2 \quad (1.4) \]

\[ \left( \frac{dE}{dx} \right)_{ion} = \frac{e^4 nZ}{4\pi\varepsilon_0^2 m_e v^2} \left[ \frac{1}{2} \ln \left( \frac{E^3}{2m_e v^2 I^2} \right) + \frac{1}{16} \right] \]  \hspace{1cm} E \gg m_0 C^2 \quad (1.5) \]

I = mean excitation energy of the atomic electrons [4].

4. Inelastic collision with atomic nuclei

Incident electron passing through the field of a nucleus experiences a deflection with a resultant emission of radiation. This process is known as bremsstrahlung. This leads to loss of kinetic energy of the incident electron in the form of radiation loss. The rate of energy loss by this interaction is proportional to \( Z^2 \), where \( Z \) is the atomic number of the target atom. The cross-section and energy loss per unit
path length of this process is, [4]

\[ \sigma_{rad} = 4 \left( \ln \frac{2(E + m_0C^2)}{m_0C^2} \right) - \frac{1}{3} \sigma_0 Z^2 \] (1.6) (barn/atom)

\[ \frac{dE}{dx}_{rad} \propto \frac{Z^2 n}{A} \left( E + m_0 C^2 \right) \] (1.7)

The collisional energy loss is predominant for light elements and at low electron energies while radiative losses start becoming comparable only at high electron energies and for heavy targets. When a charged particle is either accelerated or decelerated in an electric field, electromagnetic radiations may be given off. If an electron passes close to nucleus while traversing a substance, the charge \( Z \) on the nucleus will exert a force on the electron. This will cause its path to be bent. During this acceleration, the electron may radiate energy of any amount from zero up to its total kinetic energy \( (E_k) \) in the form of bremsstrahlung. The total bremsstrahlung per atom is roughly proportional to \( (Z/m)^2 \), where \( Z \) is the atomic number of the absorbing matter and \( m \) is the mass of the charged particle. Because of a \( 1/m^2 \) dependence, the amount of bremsstrahlung is almost completely negligible for all particles except electrons, unless the particle energy is in the GeV range.

As a electron traverses matter, it suffers many "soft" or "glancing" collisions with the atoms along its path. At each collision the particle loses energy
and changes its direction slightly. The net result is that the electrons path is very tortuous. The **Range of the particle** \(R\) (gm/cm\(^2\)) is defined as the minimum thickness required of an absorber to stop the particle (electron). The small variations in the range is called **Straggling** of the particle. This is the statistical fluctuations. The **Radiation Length** \(L\) (gm/cm\(^2\)) is the absorber thickness needed to reduce the electron energy by radiation loss to \(1/e\) of its original value. The energy loss per unit path length is known as **Specific Energy Loss** \(dE/dx\) (MeV·cm). The **Stopping Power** \(S\) (MeV·cm\(^2\)/gm) is defined as the average value of specific energy loss of the particle in a given absorber. The **Stopping Cross section** \(\epsilon\) (MeV·cm\(^2\)/atom) is defined as the average energy loss per atom of given absorber for electron.

1.3.2 **Photons**

Different interactions dominate for different photon energies. The main modes of interaction of gamma rays with matter are the photo effect both in its photoelectric and photonuclear forms, Compton scattering and electron positron pair production. To a minor extent photofission, Rayleigh scattering and Thomson scattering also occur.

1. **Photoelectric effect:**

In this process, the photon is absorbed by an atom and expels an electron by losing all its energy in one interaction. The probability of photoelectric absorption is inversely proportional to the gamma photon energy and proportional to atomic number of the atom \(Z^5\). The probability is greater the more tightly the electron. The kinetic energy \(E_e\) of the emitted photo electron is given by \((h\nu - E_\gamma)\) [5].

\[
\sigma_{\text{photoelectric}} \propto \text{Const.} \frac{Z^5}{E^{5.5}} \text{ (barn/atom)} 
\]  

(1.8)
2. Compton scattering:
In this process, the gamma ray interacts with a free or weakly bound electron and transfers part of its energy to electron. The photon is scattered through an angle $\theta$ with an energy $E'$ while the electron recoils with kinetic energy ($E_e$) at an angle $\phi$. The kinetic energy of the electron is equal to the difference of the energy lost by the gamma ray and the electron binding energy. $E_e = h\nu - E'$. The probability for this process is weakly dependent on $E$ and $Z$. The interaction probability depends on the electron density, which is proportional to $Z/A$ and nearly constant for all materials.

$$\sigma_c \sim \frac{\pi r_0^2 Z}{2E_\gamma} \left[ \ln \left( 4E_\gamma + 1 \right) \right] \text{ (barn/atom)} \quad (1.9)$$

$E_\gamma = \text{MeV}, \ r_0 = \text{Classical electron radius}.$

3. Pair production:
In this process, the gamma ray losses all its energy in one interaction. A gamma ray with an energy of at least 1.022 MeV can create an electron-positron pair when it is under the influence of the strong electromagnetic field in the vicinity of a nucleus. A photon cannot create an electron-positron pair in free space, as the process cannot conserve momentum and energy. In this interaction the nucleus receives a very small amount of recoil energy to conserve momentum, but the nucleus is otherwise unchanged and the gamma ray disappears. A heavier nucleus takes less recoil energy. This interaction has a threshold of 1.022 MeV because that is the minimum energy required to create the electron and positron. If the gamma ray energy exceeds 1.022 MeV, the excess energy is shared between the electron and positron as kinetic energy. Above the threshold, the probability of the interaction increases rapidly with energy. The probability of pair production is proportional to the square of the atomic number $Z$ and is significant in
high Z elements [5].

\[ \sigma_{pp} \sim Z^2 \sigma_0 \left( \frac{28}{9} \ln \frac{2E_\gamma}{m_0 c^2} - \frac{218}{27} \right) \]  
\[ \sigma_0 = \frac{1}{137} \left( \frac{e^2}{m_0 c^2} \right)^2 \]  

(1.10)

4. Photonuclear absorption:

It is a form of photoelectric effect where the photon is absorbed in a nucleus. When the energy of the photon is higher than the binding energy of the least bound neutron, photo neutron emission becomes possible. The reaming energy is shared as kinetic energy between the neutron and the residual nucleus. The photoneutron production threshold energy varies in general from 8 to 19 MeV for light nuclei (A < 40) and 6–8 MeV for heavy nuclei [6]. But, for few light elements such as deuterium and beryyllium, threshold energy is 2.226 MeV and 1.666 MeV respectively [7]. The cross section of this process is generally small but peaks in the region of the nuclear “giant resonance”. Neutrons are produced through following different mechanisms based on the incident photon energy as, Giant Dipole resonance \((E_{\text{th(\gamma,n)}} < E < 30 \text{ MeV})\), Quasi-Deuteron Region \((30 \text{ MeV} < E < 200 \text{ MeV})\), Delta Resonance \((E > 140 \text{ MeV})\) and Vector Meson Dominance (In high energy region above delta resonance). The boundaries between the four energy domains are not sharp and depend somewhat on atomic number.
1.3.3 Neutrons

The interaction process of neutrons with matter are fundamentally different from the interactions of photons. Neutrons interact with nuclei through the strong force and are non-ionizing. Because the neutron has no charge, it will not be scattered by the light electron clouds surrounding the nucleus, but will travel straight on to nucleus. Neutrons cross sections not only can vary rapidly with the incident neutron energy, but they vary erratically from one element to another and even between isotopes of the same element. Neutrons while passing through matter interacts by five different processes. The particular effect which occurs depends upon the properties of the substances and the energy of the neutron. In the first two, known as scattering reactions, a neutron elastically and inelastically emerges from the reaction. In the remaining reactions, known as absorption reactions, the neutron is absorbed into the nucleus and something different radiation emerges.

1. Elastic scattering \((n,n)\):

If the kinetic energy of the incident neutron is insufficient to excite the lowest level of the nucleus, the neutron is emitted with approximately the same kinetic energy which it had when it entered the nucleus. Hence this process is called elastic scattering. For fast and intermediate neutrons, elastic scattering is the dominant mode of interaction. This is the most important process for slowing down of neutrons. Light nuclei are the most effective for slowing neutrons. A neutron colliding with a heavy nucleus rebounds with little loss of speed and
transfers very little energy. Total kinetic energy is conserved in this process and the energy lost by the neutron is transferred to the recoiling particle. If the collision of neutron and nucleus is head on, maximum energy transfer occurs. The cross section for this process is depend on energy and material.

2. Inelastic scattering \((n, n'\gamma)\):
A neutron may strike a nucleus and be temporarily absorbed, forming a compound nucleus. This will be in an excited state. It may de-excite by emitting another neutron of lower energy, together with a gamma photon, which takes the remaining energy. This process is called inelastic scattering. In the inelastic scattering process the scattering nuclei are left in an excited state which decay by the emission of gamma rays. It generally happens only when high energy neutrons \((E > 1 \text{ MeV})\) interact with heavy nuclei. Heavy nuclides have lower threshold than light nuclides.

3. Nonelastic scattering \((n, \gamma), (n, \alpha), (n, p)\):

![Diagram of inelastic and nonelastic scattering](image-url)
Differs from inelastic scattering in that a secondary particle emitted is not a neutron. A nucleus may absorb a neutron forming a compound nucleus, which then de-energizes by emitting a charged particle, either a proton or an alpha particle. This produces a nucleus of a different element. Such a reaction is called a transmutation. Transmutation is the transformation of one element into another by a nuclear reaction. Such reactions are generally threshold reactions.

4. Radiative Capture \((n, \gamma)\):
Same as nonelastic scatter, but by definition, neutron capture occurs only at low neutron energies (thermal energy range is \(< 0.025 \text{ eV}\)). The compound nucleus resulting from the capture of neutron has a high energy of excitation. Capture leads to the disappearance of the neutron. The de-excitation of the compound nucleus is accomplished by the emission of gamma rays and the reaction in consequence is known as radiative capture. The production of radioactive nuclide by radiative capture is a consequence of the fact that the prompt emission of gamma rays does not usually remove all of the excitation energy leaving the product nucleus unstable. The excess energy is then dissipated by the familiar processes known collectively as radioactivity. This is the dominant process for thermal neutron.

5. Fission / Spallation \((n, f)\):
Probably the most spectacular effect produced by neutrons when captured in nuclei is nuclear fission. Nuclear fission is a phenomenon in which a heavy nucleus, splits into two smaller nuclei, called fission fragments, mostly one often nearly half the mass as the other, and rarely of equal masses. This reaction gives off a large amount of energy and emits two or more neutrons, and gamma rays. When
a neutron hits a heavy nuclide like U-235, the neutron gets absorbed in the heavy nuclide that gets energetically agitated (or excited). If the new energy state of the heavy nuclide is sufficient for it to split, then it can split to cause fission. The neutrons produced in fission are fast, with an average energy of 2 MeV. This process is important at neutron energies in excess on 100 MeV. (cross sections are higher at 400-500 MeV). Material like Uranium, can cause a nucleus to undergo fission.

\[ \text{Nucleus} \rightarrow \text{Neutron} \rightarrow \text{Fragments} \]

\[ \text{After collision} \rightarrow \text{Before collision} \]

1.4 Monte Carlo Based FLUKA Simulation

The radiation field of electron accelerator includes several components such as bremsstrahlung photons, fast neutrons, positrons, hadrons and muons. The production and transport of all these radiations through different targets are difficult to study theoretically even on the basis of correct experiments. Therefore, simulations with an effective Monte Carlo code are very helpful to get information of all the particles produced in accelerator head and for the formation of accelerator based neutron source. A general purpose Monte Carlo based code FLUKA [8] has been used for the calculations of particle transport and interactions with matter. FLUKA code version 2006 and 2008 has been used to calculate the results published in this thesis. It can simulate of about 60 different particles with high accuracy, including photons, electrons, neutrons, heavy ions and antiparticles. The program can also consider polarized photons (e.g., synchrotron radiation) and optical photons. The lowest transport limit for all particles is $\sim 1$ keV. There are various tools for input geometry visualization and output plotting in two and three dimensions giving a clear picture of the calculations. FLUKA
can handle very complex geometries, using an improved version of the well-known Combinatorial Geometry (CG) package.

1.4.1 Transport

FLUKA uses an original transport algorithm for charged particles, including complete multiple Coulomb scattering treatment. It also uses Bethe-Bloch theory for energy loss mechanism. Delta-ray production via Bhabha and Moller scattering is implemented in FLUKA. The differences between positrons and electrons are taken into account in both stopping power and bremsstrahlung case. For photons; pair production, Compton effect, Photoelectric effect, photonuclear reactions with cross sections for all the elements, emission of fluorescence photons and photon polarization for Compton, Rayleigh and Photoelectric effects are some of the important features implemented. Low energy neutrons are handled in 260 groups with varying group structure prepared from ENDF, JEF and JENDL evaluations. This technique results in faster calculations as compared to using point wise cross sections.

1.4.2 Cross sections

In FLUKA the full set of Seltzer and Berger cross sections [9] of accurate electron-nucleus and electron-electron bremsstrahlung has been tabulated in an extended form [10]. There are significant improvements on the treatments of photonuclear reaction in FLUKA with time [11–13]. The Fasso A. et al. [13] explains in details about the materials for which the photonuclear reactions cross sections are included in FLUKA. The photo nuclear interactions are modeled by Vector Meson Dominance, Delta Resonance, Quasi-Deuteron and Giant Dipole Resonance model over the whole energy range [14]. The photonuclear reactions have been successfully benchmarked with activation and neutron spectrometry experiments.
1.4.3 Scoring

The FLUKA code has numerous options to score the required quantity and has been designed with accelerator applications in mind. The double differential cross sections and yields, region and density independent scoring of energy deposition, residual nuclei formation are some of the features generally not available in other Monte Carlo codes. In addition to these, track length estimator, boundary crossing estimator, collision estimator, event by event information, radioactive decay, etc, are also possible. FLUKA scores fluence and current as a function of energy and angle. It can also score track-length fluence in a binning structure (cartesian or cylindrical) independent of geometry. The fluence and current are two different quantities, for surface crossing estimator current calculated as the number of particle crossing the surface per unit area while fluence calculates the average surface fluence by adding $dt/cos\theta$ for each particle crossing the surface. For parallel beam, current and fluence are same while for isotropic distribution current is half of fluence.

1.4.4 Biasing

The FLUKA code can be run in fully analogue or biased mode. In addition to the usual biasing such as splitting, Russian Roulette, few unique techniques such as biasing the interaction length to statistically enhance the production of secondaries that have low production cross section, biased decay length for increased daughter production etc are also implemented. Sufficient number of primary electrons have been traced in the simulation and the resultant statistical uncertainties of the Monte Carlo results were in the levels of about 1% for bremsstrahlung and 5% for induced photoneutrons, respectively.

1.4.5 Input

FLUKA reads user input from an ASCII ‘standard input’ file with extension .inp, which is in particular format. Typically, an input file begins with a
TITLE card. All ‘events’ or ‘histories’ are initiated by primary particles, therefore a card defining primary particle and its related information is added. The main part of the input is the geometry of the problem. By defining the bodies and boolean operations of subtraction (or complement), intersection and union on these bodies different regions can be formed. The materials defined in the input or predefined materials are used to fill the regions. The production, cut off and transport threshold energies for particles are provided. The detectors are defined in geometry wherever detection has to be done. With the help of available detector cards detection of the particle can be done for various regions. The physical quantity such as dose, fluence, current etc. are detected. To calculate the statistical error of the results, it is necessary to perform other independent runs, each with different initialization. For this random number sequence is input to FLUKA. The completed input file is run with the help of FLUKA executable. The output of the run provides separate file for each detector which has been used in input file. The output file is in unformatted format, which has to convert in formatted form by using codes provided in FLUKA for getting data.

1.5 Radiation units used in FLUKA and experiments

1. **Flux** (particles–cm$^{-2}$–sec$^{-1}$): Flux is a term referring to the number of particles passing through an area over a span of time.

2. **Particle Fluence** ($\Phi$) (particles–MeV$^{-1}$–cm$^{-2}$ per primary particle): The particle fluence is defined as the particle flux integrated over a certain time period and represents the number of particles per unit area that passed during this time.

3. **Particle Current** ($J$) (particles–MeV$^{-1}$–cm$^{-2}$ per primary particle): The particle current is defined as the number of particles crossing an area over a certain time period and represents the number of particles per unit area that passed during this time.
Fluence and Current:

Fluence and Current are two separate quantities which are used in FLUKA simulation for surface crossing estimation. Imagine a surface having an infinitesimal thickness $dt$. A particle incident with an angle $\theta$ with respect to the normal of the surface $S$ will travel a segment $dt/cos\theta$. Therefore, we can calculate an average surface fluence by adding $dt/cos\theta$ for each particle crossing the surface, and dividing by the volume $S.dt$, while the current $J$ will be to count the number of particles crossing the surface divided by the surface area

$$\Phi = \lim_{dt\to 0} \sum_i \frac{dt}{S.dt} \cos\theta_i$$

$$J = \frac{dN}{dS}$$

(1.11)

The fluence is independent from the orientation of surface $S$, while the current is NOT! In an isotropic field it can be easily seen that on a flat surface $J = \Phi/2$.

4. **Yield** (particles−sec$^{-1}$ per primary particle): The total particle coming out from the system per unit time. The particles are measured over a cross sectional area.

5. **Dose** (J/kg, GeV/g, RAD, Gray): It is the amount of energy deposited in a medium by ionizing radiation. It is equal to the energy deposited per unit mass of medium.

6. **Dose Equivalent** (Sievert(Sv), Roentgen Equivalent Man(REM)): The equivalent dose ($H_T$) is a measure of the radiation dose in tissue. Equivalent dose ($H_T$) is calculated by multiplying the absorbed dose to the organ or tissue ($D_T$) with the radiation weighting factor, ($w_R$).
7. **Isocenter**: The radiation isocenter (in contrast to the mechanical isocenter) is the point in space where radiation beams intersect when the Gantry is rotated during beam-on. The placement of the radiation isocenter plays an important role in treatment planning because ideally the isocenter should be placed in the center of the target volume, usually a tumor.

### 1.6 Outline of the Thesis

The thesis is divided into seven chapters.

The first chapter is on "Introduction" is discussed already.

The Chapter second which is on “Design of dual scattering foil for 6 to 20 MeV electron beam Radiotherapy” begins with a literature survey on scattering foil design for electron radiotherapy. The electron beam from the linear accelerator is of size ~2 mm, whereas the size of the electron beam profile required for actual treatment is usually larger than $2 \times 2 \text{ cm}^2$ up to $30 \times 30 \text{ cm}^2$ at the iso-center. Therefore, scattering foils were optimized through two different ways (i) by analytical calculations and (ii) by simulations with FLUKA code. The objective of this chapter is to discuss the designing of the dual scattering foil for 6 to 20 MeV electron beam.

In the present work, it is proposed to use a system with two scattering foils. The first foil called the primary foil which is made of high Z element such as gold, tungsten, tantalum, etc., whereas, the secondary foil is made of low Z element such as Aluminum. Electrons while passing through high Z medium undergo multiple coulomb scattering and therefore, the pencil beam is converted into Gaussian shape. The primary scattering foil was kept to be uniform thickness, whereas the secondary foil was of Gaussian shape with varying thickness; maximum at the center and minimum at the edges. Electrons falling at and around the centroid have experienced maximum scattering events, whereas those falling at the tail of the profile have experienced the minimum scattering events. The Gaussian width and thickness of the secondary foil were optimized such that it should meet the design parameters (Dose at iso-center, beam uniformity, etc.). As a result, the profile of the electron beam is reasonably flat over the
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designated field area of $30 \times 30 \text{ cm}^2$, with sharp fall off at the edges of the field. The thickness and shape of the foils were calculated using FLUKA code as well as through analytical calculations. The simulated results obtained from both the ways were compared, and they are in good agreement.

The third chapter which is on “Characterization of bremsstrahlung radiations for 6 to 18 MeV electron beam from different Z elements: experimental and simulation approach” mainly deals with the study of the exact analysis of bremsstrahlung spectra for different $e^-\gamma$ targets. When high energy electrons pass through a target, it generates a cascade shower of bremsstrahlung radiation with continuous energy spectrum shows an end point equal to the electron kinetic energy. A study of bremsstrahlung spectra from 6 – 18 MeV electron beam were carried out using FLUKA. The study includes different material as bremsstrahlung producing targets ranging from low to high Z elements. The materials are Beryllium, Aluminum, Silicon, Copper, Iron, Molybdenum, Silver, Gadolinium, Bismuth, Tungsten, Tantalum, Lead, Gold, and Uranium. The materials which having higher melting point were selected for $e^-\gamma$ target because when an electron interacts with material, it generates a high amount of heat, which rises the temperature of the target. Bremsstrahlung spectra were estimated at various angles at different target thickness from thin target to the thickness up to range of the target. The requirement of gamma therapy also requires less contribution of other radiations. Therefore, the contribution of other radiations such as electrons, positrons and neutrons were calculated for each case and reported in the thesis. Moreover, the depth dose curve was estimated in water phantom (equivalent to the human body) at 100 cm Source to Surface Distance (SSD) to get an exact idea of dose delivered to the patient body.

It has been observed from the results of bremsstrahlung spectra that initially there is increase in the bremsstrahlung fluence $[(\text{photon-}\text{cm}^{-2})/e^-]$ with target thickness up to certain thickness and further increase in thickness decreases the fluence due to absorption of photons in the material itself. The thickness giving maximum bremsstrahlung fluence is different for different material. From the angular distribution of bremsstrahlung, it is observed that the maximum
bremsstrahlung fluence is in the forward direction (0°). Also, average energy of bremsstrahlung radiation is higher in the forward direction. Moreover, it is also observed that the bremsstrahlung yield (photon/e\(^{-}\)) increases with the increase in incident electron energy. The tungsten found to be good candidate which gives maximum bremsstrahlung fluence. This data will help researchers and medical physicists to take precise right hand data of flux and energies of bremsstrahlung radiations to be used for desire object in radiation therapy.

The experimental results published by D. W. O. Rogers were simulated in FLUKA for the verification of code and subsequently compared. In another case, an experiment performed by Bhoraskar, et al. on measurement of bremsstrahlung spectra from tantalum using 6 MeV Race-Track Microtron was also simulated. In both the cases the simulated results obtained by FLUKA are in good agreement with their experimental results.

The fourth chapter which is on “Estimation of Neutron Production from Accelerator Head Assembly of 15 MV Medical LINAC using FLUKA Simulations” mainly deals with the estimation of neutron contamination in a bremsstrahlung beam from optimized accelerator head assembly of 15 MV medical LINAC. The accelerator operating above 10 MeV can result in the production of neutrons, mainly due to photo nuclear reaction (\(\gamma, n\)) induced by high energy photons in the accelerator head materials. These neutrons contaminate the therapeutic beam and give a non negligible contribution to patient dose.

For production of a clinical photon beam, the design of accelerator head assembly was optimized using 15 MeV electrons. The accelerator head assembly consists of two different collimators. The first one is the primary collimator. The second one is an adjustable rectangular secondary collimator which consists of two upper and two lower independent jaws for producing rectangular and square fields with a maximum dimension of 40 × 40 cm\(^2\) at the linac iso-center. For this purpose high Z materials were simulated for primary collimator. The gamma while passing through such collimators generates neutrons through photo nuclear reaction. The collimators were optimized such that the neutron contamination in the gamma beam was below the allowed limit.
The $e-\gamma$ target, primary and secondary collimator, were designed in Monte Carlo based FLUKA code and the corresponding neutron dose equivalent and gamma dose at the patient plane (in water phantom at 100 cm from $e-\gamma$ target) were estimated. Results were obtained at various field sizes varying from $0 \times 0 \text{ cm}^2$, $10 \times 10 \text{ cm}^2$, $20 \times 20 \text{ cm}^2$, $30 \times 30 \text{ cm}^2$, $40 \times 40 \text{ cm}^2$. The maximum neutron dose equivalent observed near the central axis of $30 \times 30 \text{ cm}^2$ field and has a value 36.6 mSv/min. This is 0.61% of the central axis photon dose rate of 60 Gy/min. The values fall within the allowed limit by International Electrotechnical Commission (IEC). The dimensions of the collimators and filters were optimized in such a way that the neutron dose equivalent estimated is below the allowed limit in the therapy beam.

The Fifth chapter which is on “Measurement of angular distribution of neutron flux for the 6 MeV Race-Track Microtron accelerator based pulsed neutron source” includes the detail discussion about the experimental and simulation results. This source is having applications in an elemental analysis by Delayed Gamma Neutron Activation Analysis (DGNAA) and analysis of short lived activation products. In addition to this, an attempt has been made to use this source for studying the $(n,\alpha)$ reaction. Bremsstrahlung radiation produced through $e-\gamma$ target can be redirected towards a suitable $\gamma-n$ target and produce neutron through photo nuclear reaction. The photo neutron production threshold energy varies in general from 8 – 19 MeV for light nuclei ($A < 40$) and 6 – 8 MeV for heavy nuclei. But, for few light elements such as deuterium and beryllium, threshold energy is 2.226 MeV and 1.666 MeV respectively. These targets are suitable for generating neutrons as far as low energy of the electron beam is concerned. Therefore, beryllium was chosen as the $\gamma-n$ target.

It was observed from the FLUKA simulations that the total neutron fluence is found to be more in cylindrical geometry in comparison to parallelepiped geometry. Therefore, for further studies cylindrical geometry of the target was chosen and the respective thickness was varied. It was also observed that as the target thickness increases, neutron yield increases and saturates beyond the thickness of 4 cm. Using the optimized target, the maximum neutron flux and neutron
yield one can obtain from the Microtron is $1.2319 \times 10^6$ neutron–cm$^{-2}$–sec$^{-1}$ and $4.064 \times 10^8$, neutron–sec$^{-1}$ respectively for 1 $\mu$A current of the electron beam. Integrated neutron flux was also measured experimentally by activation of vanadium at $0^\circ$, $30^\circ$, $60^\circ$, $90^\circ$, $115^\circ$, and $140^\circ$ angles and subsequently compared with the simulated one. The neutron flux was found to be decreased with the increase in angle. The decreasing trend in neutron flux has been observed in the case of simulated results by FLUKA. Our experimental results show good agreement with the simulated results by FLUKA.

The Chapter sixth which is on “Optimization of thermal neutron source based on 6 MeV Linear Accelerator using FLUKA simulation” deals with design of 6 MeV Linear Accelerator based thermal neutron source for elemental analysis. Neutrons produced through photo nuclear reaction in $\gamma – n$ target mainly belongs to high energy range. Therefore, reduction in neutron energies from fast to thermal is possible by neutron interaction with set of low $Z$ materials. Neutrons while passing through a material the flux decreases due to neutron capture, neutron escape and inverse square law $\Phi(r) \sim (1/r^2)$. When designing such thermal neutron source, the challenges were made to bring down the neutron energies to thermal by keeping the neutron economy. In addition, gamma production at the output is to be maintained very low. In design of thermal neutron source, the materials and dimensions of each region were determined using Monte Carlo based FLUKA code. The optimized materials in different regions are Beryllium as a $\gamma – n$ target, polyethylene as a filter, alumina as a reflector and graphite + polyethylene as a moderator using FLUKA.

A prototype experiment was carried out using 6 MeV linac and the integrated neutron flux was measured with activation technique. For the measurement of total (fast + thermal) neutron flux and thermal neutron flux, the vanadium and cadmium covered vanadium was used. To obtain the effective thermal neutron flux, the flux measured by cadmium covered vanadium sample was subtracted from the flux measured by vanadium sample. The total neutron flux and thermal neutron flux were measured at various target thickness of wax material (moderator) from 0 to 16 cm along forward ($0^\circ$), perpendicular ($90^\circ$)
and backward direction (180°) with respect to the incident gamma. The total neutron flux decreases and thermal neutron flux increases up to 4 cm thickness of wax. Further, increase in the wax thickness the contribution of thermal neutron increases. Our experimental results show good agreement with the simulated results by FLUKA.

The chapter seventh which is on “Design and Development of 15 MeV Linear Accelerator based Neutron Radiography facility” mainly deals with the work on design and development of Neutron Radiography facility. Based on the same technique as discussed in chapter sixth, optimization of the thermal neutron facility was carried out for 15 MeV linear accelerator. The major part of the design was to optimize the collimator for neutron beam. The main design parameters for the collimator are collimation ratio, gamma content, neutron flux, cadmium ratio, beam uniformity, etc.

The simulation results on the collimator design show that as an increase in collimation ratio \(\frac{L}{D}\) the image sharpness of radiograph increases due to less scattered neutron beam, but subsequently the neutron flux at the object plane decreases. The collimator was designed with cadmium lining square cone to capture the scattered thermal neutrons. For this purpose, the collimation ratio was optimized \(\frac{L}{D}=18\) and the simulations were carried out to optimize the rest parameters. The gamma contamination in the beam influences the quality of generated neutron radiographs. Therefore, in the simulation a care was taken to minimize the neutron to gamma ratio. The neutron flux of the optimized facility obtained at the object plane is \(1 \times 10^5 \text{n cm}^{-2}\text{sec}^{-1}\) and neutron to gamma ratio is \(1 \times 10^5 \text{n cm}^{-2}\text{mR}^{-1}\).

Moreover, some of the radiographs have also been taken up using the radiography facility of APSARA reactor at BARC, Mumbai for right hand experience and understanding. The samples are aluminum plates filled with boron and lithium chloride, different Z materials having the same thickness, electronic components (MOSFET and IC’s), etc. In addition, some radiographs were also obtained for a silver key chain and plant. All the radiographs were taken by direct techniques using 25 mm Gadolinium screen and D–7 type industrial X-ray film.
Bibliography


