



**BIOLOGICAL SHIELDING CALCULATIONS FOR A 10 MeV
RHODOTRON ELECTRON ACCELERATOR FACILITY**

by

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Declaration

I, Otsile Tikologo, declare that this thesis is my own original work, unless otherwise referenced or acknowledged. It is being submitted for the degree of Master of Science (Physics) in the Botswana International University of Science and Technology and has not been presented nor under consideration for any degree or examination in any other university for a similar or any other degree award.

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1st day of: November 2019

Certification

The undersigned certify that have read and hereby recommend for acceptance by the Faculty of Sciences a dissertation titled: **Biological Shielding Calculations for a 10 MeV Rhodotron Electron Accelerator Facility**, in fulfilment of the requirements for the degree of Master of Science (MSc Physics) of the Botswana International University of Science and Technology.



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Dedication

This dissertation is wholeheartedly dedicated to my beloved family and friends, who have been my source of inspiration and gave me the strength when I thought of giving up, who continually provided their moral, spiritual, emotional, and financial support.

Abstract

This thesis focuses on biological shielding calculations for a 10 MeV Rhodotron electron beam accelerator operating in dual mode to produce a 10 MeV primary electron beam and 7.5 MeV secondary X-rays, generated by hitting an optimized tantalum-73 (^{73}Ta) target with the primary electron beam.

The first part of this thesis describes the Rhodotron electron accelerator and its operating principle. A model is presented for the transverse optics of a TT-100 Rhodotron accelerator. Potential industrial applications of a Rhodotron accelerator for Botswana are highlighted, including sterilization of food products, medical devices, pharmaceuticals, wastewater and sludge treatment, cargo screening and postal mail decontamination. Sterilization of food reduces harmful micro-organisms, thus prolonging shelf-life and minimizing health risks to humans. A particular emphasis is placed on the sterilization of meat for local consumption and export as the meat industry plays an important role in Botswana's economy and represents the country's third main income earner.

The second and main part of this thesis focuses on designing an optimal biological radiation shielding structure for the Rhodotron and irradiation vaults to protect the general public, radiation workers and the environment from unnecessary radiation exposure in compliance with recommendations by the International Commission on Radiological Protection (ICRP).

Two methods of shielding calculations are employed, namely analytical estimates using empirical formulas from the literature and Monte Carlo (MC) predictions based on the FLUKA simulation package. FLUKA has the added advantage that the transport of particles (photons and electrons in this project) and their interactions with matter are included for complex geometrical shielding structures. On the other hand, FLUKA simulations are numerically intensive and require more computational time.

After the primary beam strikes the target, the main biological dose rate is attributed to the secondary photons. The shield is designed to reduce the biological dose equivalent rates to less than $5 \mu\text{Sv h}^{-1}$ during normal operation. The analytic calculations show that an ordinary concrete wall with a thickness of approximately 2.1 m is sufficient to shield the Rhodotron accelerator vault. Using the latter value as the input for FLUKA, the thickness is varied in steps of 0.01 m from a lower limit of 1.9 m until the biological dose rate of $5 \mu\text{Sv h}^{-1}$ is achieved. The FLUKA results show that a 2 m thick ordinary concrete wall, roof and slab are sufficient to shield both the accelerator and irradiation vaults to permissible levels for optimal and safe operation.

Research Output

1. Poster Presentation: “Feasibility study for commissioning a Rhodotron electron beam accelerator facility in Botswana”, at the *Research and Innovation Symposium (RDAIS 2017)*, Botswana International University of Science and Technology; <https://drive.google.com/open?id=12E2AMdnBeczXfsrOGNkbUGq602Tp9qUTtZ2Y5EY1E-U>; accessed on 30th May 2017.
2. Poster Presentation: “Shielding calculations for electron beams as well as secondary X-rays from a 10 MeV Rhodotron accelerator”, at the 5th *South Africa – JINR Symposium, Advances and Challenges in Physics by JINR and South Africa (2018)*, Somerset West, South Africa; <http://theor.jinr.ru/~sajinr18/#index>; accessed on 15th August 2019.
3. Oral Presentation: “Monte Carlo Shielding Calculations for a 10-MeV Electron Accelerator in Botswana”, at the 64th *Annual Conference of the South African Institute of Physics (2019)*, Polokwane, South Africa; <http://events.saip.org.za/conferenceDisplay.py/abstractBook?confId=144>; accessed on 15th August 2019.

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Nomenclature

Acronyms

ASCII American Standard Code for Information Interchange

BIUST Botswana International University of Science and Technology

BMC Botswana Meat Commission

CERN Conseil Européen pour la Recherche Nucléaire

EB Electron Beam

EM Electromagnetic

EU European Union

FLUKA FLUktuierende KAskade

GDP Gross Domestic Product

LABS Laboratory for Accelerator Based Sciences

LHC Large Hadron Collider

LINAC LINear ACcelerator

MC Monte Carlo

MCNP Monte Carlo N-Particle

MeV Mega Electronvolt

NCRP National Council on Radiation Protection and Measurements

nTOF neutron Time-of-flight

RF Radio Frequency

RNA Ribonucleic Acid

Symbols

γ gamma

c Speed of light in vacuum

e Electron charge

Introduction

The establishment of accelerator-based applications and technologies may play a key role in the long term goal of transferring modern accelerator technologies to Botswana for diversifying the economy. A Rhodotron electron accelerator is a relatively new type of electron accelerator which Botswana can acquire for research and industrial applications. Therefore, as a first step towards acquiring a Rhodotron electron accelerator, this project aims to design an optimal biological radiation shielding structure for a 10 MeV Rhodotron electron accelerator. The purpose of designing an optimal shielding structure is to protect radiation personnel as well as the general public from unnecessary radiation exposure.

1.1 Context and Rationale

This project is placed within the context of the sustainable development goals of Botswana which aim to meet and improve the needs of the present generation without compromising the needs of future generations. Moreover, technology transfer is expected from developed countries to Botswana as a roadmap for transforming Botswana's economy from being resource-based to knowledge-based. Being ranked as an upper middle-income country, Botswana's source of income has been largely dependent on non-renewable resources such as diamond mining.

At present, Botswana has put forward a transformational plan termed “Vision 2036” [1], which outlines the country’s goals and ambitions to be achieved by the year 2036. The aim of this plan is to transform the economy from being upper middle-income to a high-income country. The Vision 2036 goals are anchored on the principles of global sustainable development goals and have been mirrored down to four pillars namely: Sustainable Economic Development, Human and Social Development, Sustainable Environment as well as Governance, Peace and Security. It is through these pillars that the Botswana government aims to diversify the economy by moving away from being a resource-based to knowledge-based economy.

To become a knowledge-based economy, the Botswana government will leverage on science, engineering and technology to propel economic diversity. The Botswana International University of Science and Technology is a fully government supported institution with the mandate to drive local and regional industrialization through the development and application of innovative products and services through science, engineering and technology.

This research project is aligned with the Botswana International University of Science and Technology focus area on “Innovative Technological Products and Services for Economic Development” as well as the Vision 2036 pillar of “Sustainable Economic Development”. In particular, this project focuses on laying the foundation for the development of nuclear accelerator-based products and services, presently a multi-billion industry with global impact.

1.2 Project Purpose

There are many types of electron beam technologies with several applications, however, this project focuses on the so-called Rhodotron electron accelerator, a recently developed compact electron beam accelerator that provides a safer, cheaper and more effective method for industrial applications, research and development in diverse sectors of the economy [2, 3]. Furthermore, this technology provides intense radiation beams compared

to other electron accelerators. There are no Rhodotron electron accelerator facilities on the African continent.

Since the Rhodotron is a high intensity accelerator, the main aim of this project is to design an optimal biological radiation shield to protect the radiation workers, general public and the environment against high intensity radiation associated with the operation of this envisaged accelerator. The biological shield should minimize the biological radiation dose rates to internationally acceptable levels.

1.3 Dissertation Outline

The structure of this dissertation is organized as follows:

Chapter 1 introduces the background and motivation for this study. The rationale and the purpose of study are discussed. Chapter 2 describes the Rhodotron electron accelerator, its operating principle and the transverse optics for the envisaged TT-100 Rhodotron are modelled. Secondly, the industrial applications of the Rhodotron accelerator relevant to Botswana are highlighted with appropriate references. Chapter 3 focuses on biological shielding design for the Rhodotron accelerator. The first part of this chapter considers analytic shielding calculations. The second part focuses on Monte Carlo shielding calculations where, the FLUKA package, a Monte Carlo tool for particle transport and interaction, is extensively used. Finally, Chapter 4 summarizes and reflects on the overall research. The Appendices and Bibliography are presented at the end of this thesis.

The Rhodotron Accelerator

As mentioned in Chapter 1, the aim of this project is to perform biological shielding calculations for a 10 MeV Rhodotron electron accelerator with a typical electron beam intensity of 4 mA. The latter specifications are suitable for the industrial applications envisaged for Botswana. In this chapter, the operating principle for the Rhodotron accelerator is described and the transverse optics for the envisaged TT-100 Rhodotron are modelled. In addition, industrial applications of the Rhodotron accelerator relevant to Botswana are mentioned.

2.1 The Rhodotron Accelerator

This section describes the Rhodotron accelerator, its operating principle and the transverse optics for the envisaged TT-100 Rhodotron accelerator is modelled using Microsoft Excel Solver. Furthermore, the advantages of the Rhodotron accelerator over a conventional industrial Linear Accelerator are discussed.

A Rhodotron accelerator, shown in Figure 2.1, is an electron accelerator that re-circulates a beam of electrons in a “rose-shaped” path through a single resonating accelerating cavity within a common axis [4]. The name Rhodotron originates from a Greek word “Rhodo” which refers to a rose, describing trajectories of the electrons, as they travel in the resonant accelerating cavity as illustrated in Figure 2.2 [5]. Jacques Pottier first

proposed in 1989 the original design principle of the Rhodotron by suggesting the use of a half wavelength coaxial cavity [4]. In 1993, a company originating from Belgium called Ion Beam Applications (IBA) built the first Rhodotron accelerator model (TT-200). The Rhodotron accelerator models presently available are listed in Table 2.1 together with model specifications.

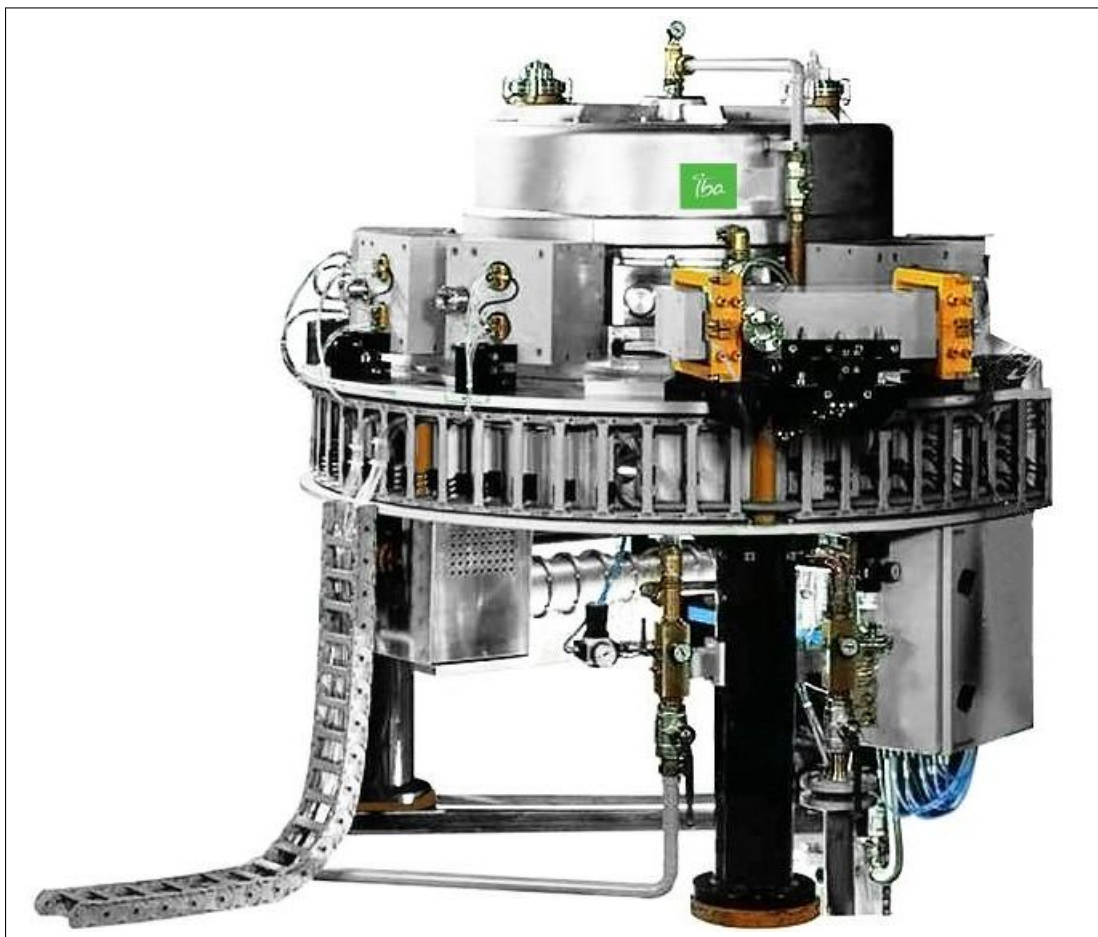


Figure 2.1: *A 10 MeV TT-100 Rhodotron accelerator [6].*

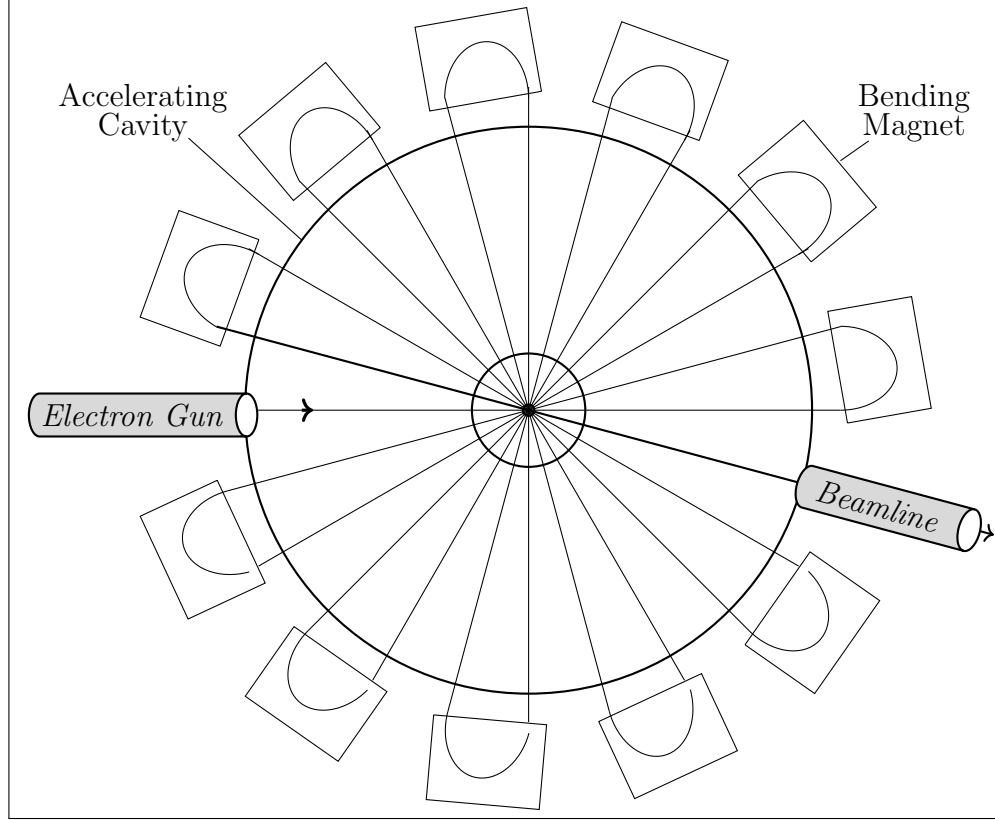


Figure 2.2: A TT-100 Rhodotron electron trajectories from the electron gun through the accelerating cavity, the bending magnets and through beam-line.

Table 2.1: IBA Rhodotron accelerator models and specifications [7].

	TT-50	TT-100	TT-200	TT-300	TT-1000
Energy (MeV)	2–10	2.5–10	2–10	2–10	2–7
Maximum power (kW)	20	40	100	245	560
Maximum current (mA)	2	4	10	35	80
Diameter (m)	1.3	1.6	3	3	3
Height (m)	Adjustable	1.7	2.4	2.4	2.4
Energy gain per pass (MeV)	0.8–1	0.833	1	1	1.166
Number of passes	10	12	10	10	6

For this project, the envisaged Rhodotron accelerator model is the TT-100 which, relative to other models (TT-200, TT-300 and TT-100), is more compact and hence suitable for small scale applications. This study focuses on the TT-100 Rhodotron model taking into account its technical specifications as shown in Table A.1 of Appendix A. Subsection 2.1.2 presents the TT-100 transverse optics modelling calculations.

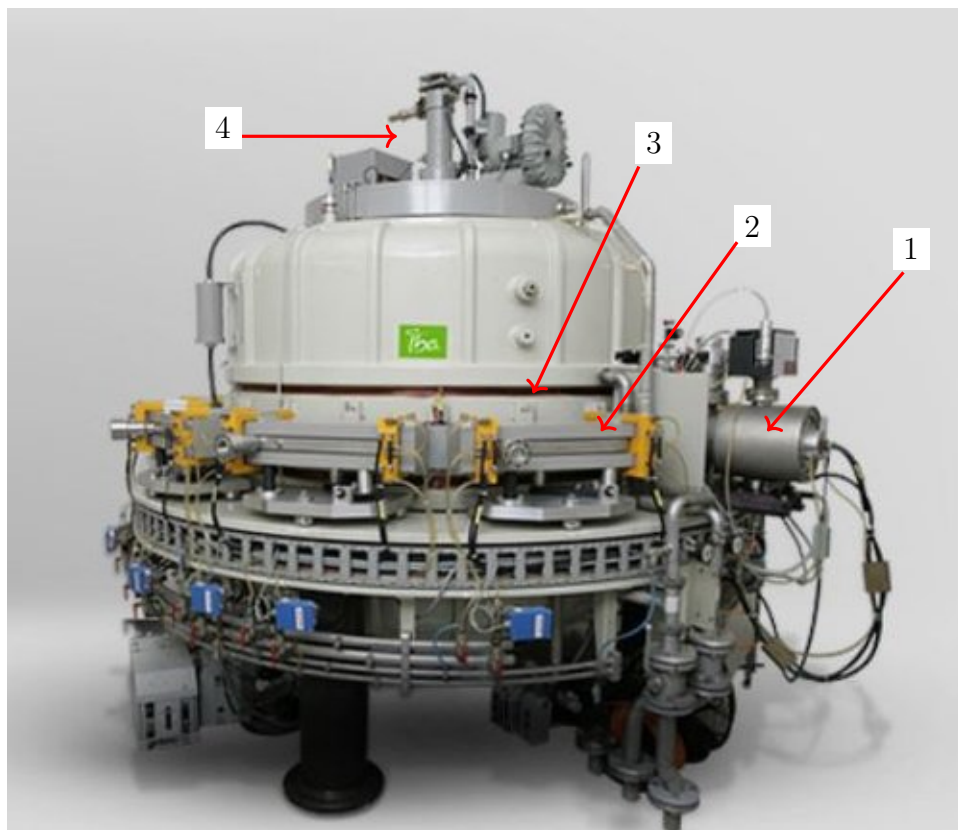


Figure 2.3: A Rhodotron accelerator showing (1) the electron gun, (2) bending magnet, (3) accelerating cavity, (4) Radio Frequency (RF) system [8].

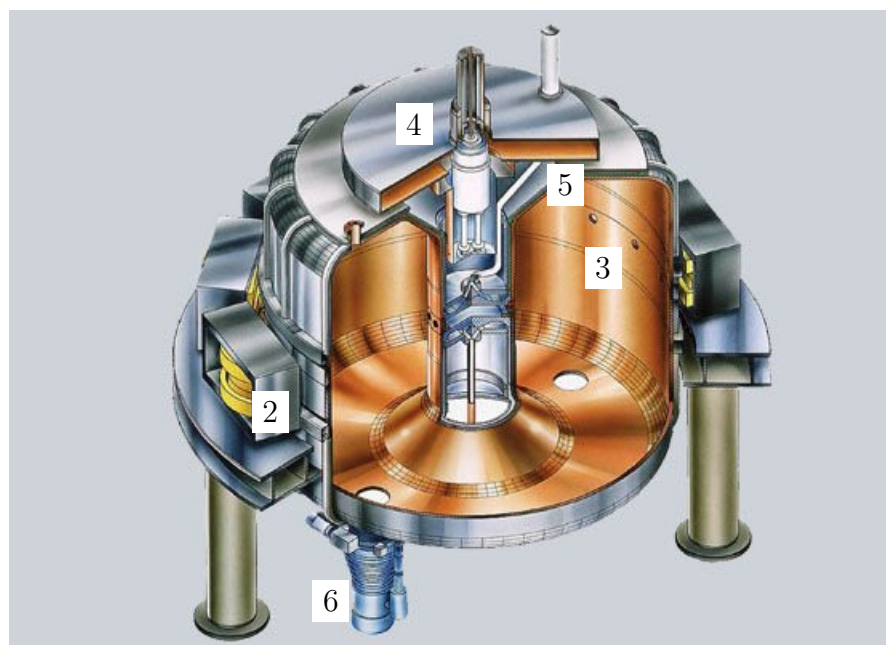


Figure 2.4: A Rhodotron accelerator transverse view showing (2) bending magnet, (3) accelerating cavity, (4) Radio Frequency (RF) system, (5) cooling system, (6) vacuum system [9].

The Rhodotron electron accelerator consists of the following components as shown in Figure 2.3 and Figure 2.4:

Electron Gun- The Rhodotron electron gun is the electron source which is located at the outer wall of the accelerating cavity. It uses the standard cathode and grid assembly system that is commonly used in small Ultra High Frequency (UHF) electron tubes. The electron gun is pulsed at the radio frequency so that the electrons are injected into the accelerating cavity while the electric field is in accelerating mode.

Accelerating Cavity- Rhodotron accelerator cavities are made of electrochemically copper-plated steel shaped as coaxial lines shorted on both ends and resonating in the half-wavelength mode 107.5 or 215 MHz [5].

Vacuum System- The rotary and turbine molecular pumps are used to remove any air molecules (that could generate collisions on the electron path) inside the Rhodotron accelerator and its components, including the beam-line to reach a high vacuum level up to 10^{-5} Pa [10].

Radio Frequency System- Designed to deliver up to 1 MW, the Radio Frequency (RF) system of the Rhodotron accelerator is made up of a voltage controlled oscillator followed by a sequence of amplifiers. Amplification occurs in four stages. First, a small signal is generated by the low-level RF rack. The signal is amplified by the pre-driver and then amplified a second time by the driver amplifier and finally the last time by the final power amplifier that is located on top of the accelerating cavity. This final amplifier is coupled with the accelerating cavity to generate the electric field in the Rhodotron accelerator.

Cooling System- The Rhodotron cooling system is made up of two cooling loops of water illustrated in Figure 2.5. A loop of ionized and a loop of de-ionized water are distributed all over the Rhodotron subsystems depending on the subsystems that need to be cooled. The water of these two closed circuits is cooled down by a chiller or an equivalent system. The heat exchanger dissipates the heat of these subsystems through the water cooled by the secondary cooling system.

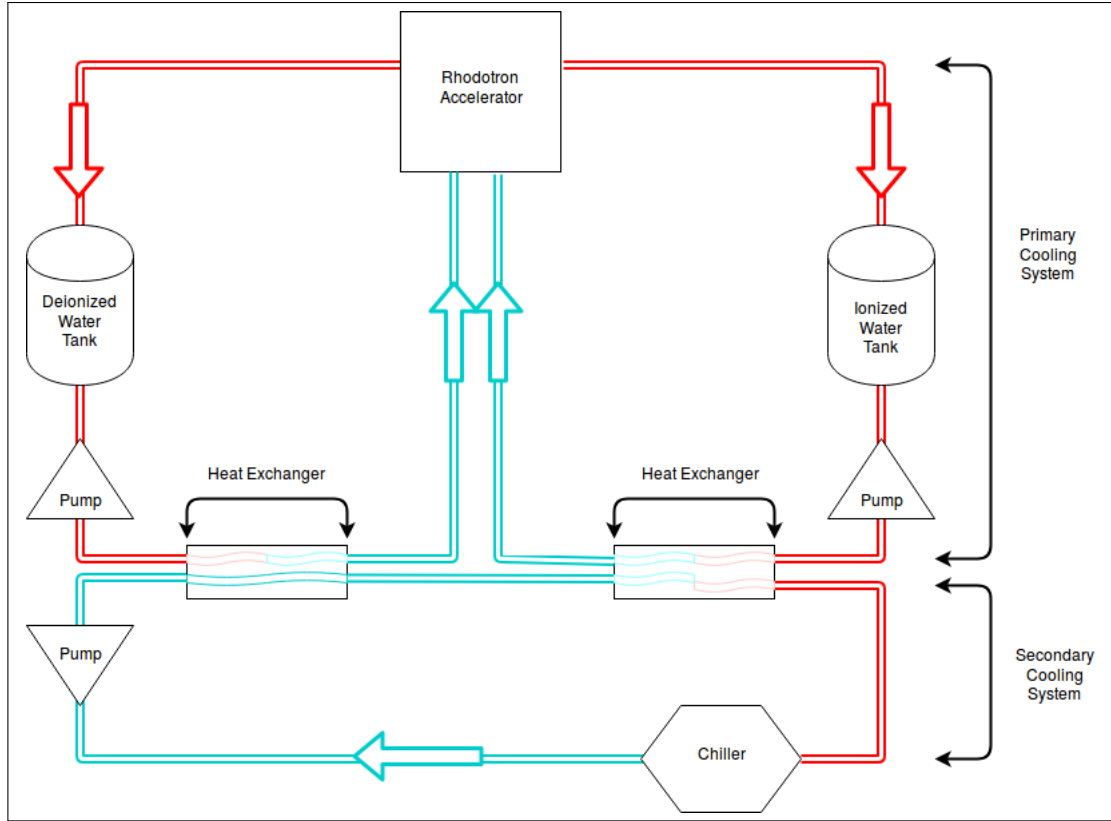


Figure 2.5: *The Rhodotron cooling system. The red arrows show the flow of hot water while the blue arrows show flow of cold water.*

Control System- The Rhodotron accelerator uses a control system that is based on the industrial programmable logic controller (PLC) [4]. This system contains all the software that is necessary for the smooth running of the accelerator.

Transport System- The Rhodotron beam transport system consists of a beam-line with one or two scanning magnets at 100 Hz [4] to allow the electron beam to be scanned across a 100 cm wide band. The other beam-line components include the optical quadrupoles for beam focusing and beam scanning horn.

2.1.1 Operating Principle

The aim of this subsection is to explain the operating principle of the Rhodotron electron accelerator.

Electrons from the ion source are injected into the accelerating cavity at a voltage of about 35 - 40 kV [4]. When electrons reach inside of the accelerating cavity, the RF system produces an electric field between the external wall of the accelerating cavity and the central pillar (which acts as an anode) [11]. The electrons are attracted by the pillar and undergo first acceleration as illustrated by the red shaded area under “region 2” in Figure 2.6. When electrons go through the pillar, the polarity of electric field is reversed in such a way that when travelling in the second part of the accelerating cavity, the electrons are accelerated a second time as represented by the blue shaded area under “region 4”. Under “regions 1, 3 and 5”, electrons do not undergo any acceleration.

After passing through the cavity, electrons are deflected back by the use of bending magnets back to the accelerating cavity for another acceleration process. With each pass, the electrons are accelerated by a fraction of the final energy required. When reaching the final energy, electrons exit the cavity and propagate in a straight line through the beam-line as illustrated in Figure 2.2. The electron beam is of very high quality with low energy spread and low angular divergence, thus simplifying the design and operation of external beam transport and scanning systems [12, 13].

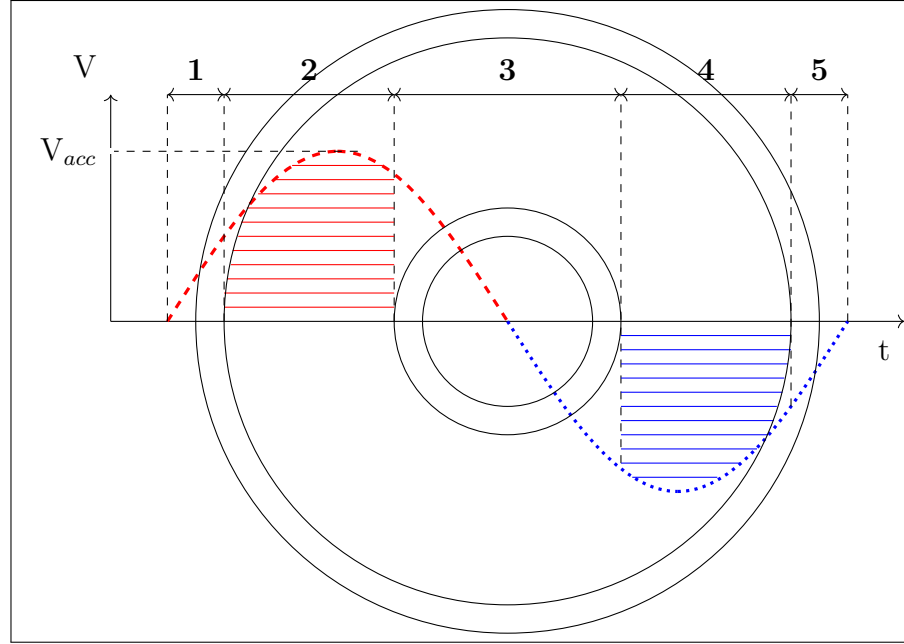


Figure 2.6: A plot of voltage versus time showing a sinusoidal wave for a single period of acceleration. V_{acc} is the accelerating voltage. The inner two inner circles represent the inner conductor (central pillar) and the outer two circles denote the cavity outer conductor.

2.1.2 Modelling Transverse Optics for the Envisaged TT-100

In this subsection, theoretical considerations are presented to model the structure of envisaged TT-100 Rhodotron accelerator. Here, the linear optics calculations support why the Rhodotron accelerator has a compact structure. The envisaged TT-100 is considered on the grounds that it is suitable for medium level irradiation facilities compared to other models which are suitable for high dose and very high throughputs applications [4].

The TT-100 is capable of producing up to 10 MeV beam energy with a maximum current of 4 mA, maximum beam power of 40 kW and operating at an RF of 215 MHz. To synchronize the RF phase with the beam, appropriate bending radius (R_b), maximum inner radius of the cavity (R_1) and the maximum outer radius of cavity (R_2), as shown in Figure 2.7, must be computed [14]. According to N'Guyen et al. [11], for RF phase synchronization the required stability is achieved when the total path λ taken by the electrons passing through the cavity and the bending magnets follow Equation 2.1:

$$\lambda = D + 2R, \quad (2.1)$$

where D represents the distance travelled by electrons inside the bending magnet, and R denotes the distance from cavity center to the bending magnet.

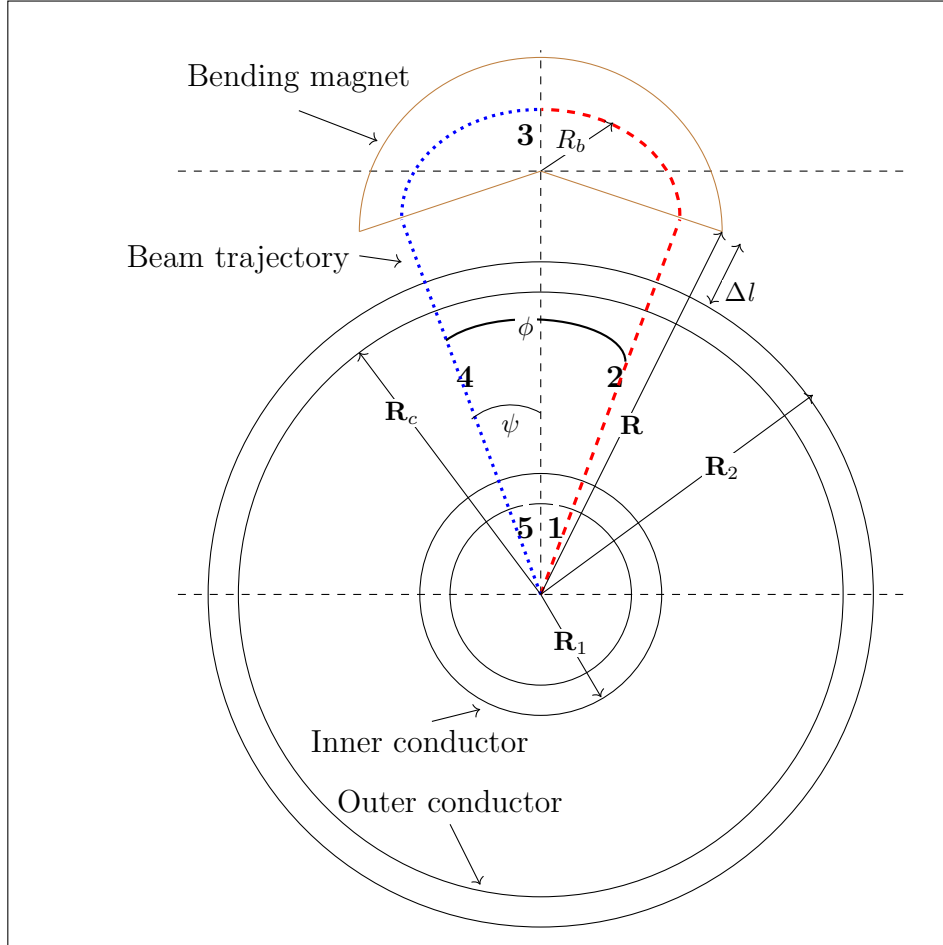


Figure 2.7: Simple geometry of a single period of acceleration.

The angle ϕ , between two paths 2 and 4 is defined as,

$$\phi = 2\psi = \frac{\pi}{n}, \quad (2.2)$$

where n represents the total number of passes in the acceleration cavity. For the TT-100, there are 12 passes and from Equation 2.2, it follows that $\phi = 15.01^\circ$.

Using the well-known relation

$$\lambda = \frac{c}{f}, \quad (2.3)$$

together with the following equation from reference [11]:

$$R = \frac{\lambda}{2 + \frac{n+1}{n}\pi \tan\left(\frac{\phi}{2}\right)}, \quad (2.4)$$

yields

$$R = \frac{c/f}{\left[2 + \frac{n+1}{n}\pi \tan\left(\frac{\phi}{2}\right)\right]}. \quad (2.5)$$

With the TT-100 operating at 215 MHz, the distance R computed from Equation 2.5 was found to be 0.571 m. According to Jabbari et al. [14], the bending radius R_b is determined using Equation 2.6:

$$R_b = R \tan\left(\frac{\phi}{2}\right). \quad (2.6)$$

Following Equations 2.3 - 2.6, the linear optics parameters were computed and recorded in Table 2.2.

Table 2.2: *Computed parameters for the TT-100 Rhodotron accelerator.*

Accelerator cavity voltage, V_{acc}	0.56 kV
Energy gain per pass, $E_{perpass}$	0.833 MeV
Angle between two paths, ϕ (Equation 2.2)	15°
Wavelength, λ (Equation 2.3)	1.395 m
Cavity centre to bending magnet, R (Equation 2.4)	0.571 m
Bending radius, R_b (Equation 2.6)	0.0746 m
Inner radius, R_1 [14]	0.120 m
Outer radius, R_2 [14]	0.554 m
Path length outside cavity, D (Equation 2.1)	0.253 m
Acceleration gap, l	0.41 m

To track the electron beam along acceleration path, the Lorentz factor(γ) was used to relate an electron's rest mass (m_0c^2) with its kinetic energy (T) by Equation 2.7 [15]:

$$\gamma = \frac{T + m_0c^2}{m_0c^2}. \quad (2.7)$$

When electrons become relativistic, the energy increase depends solely on the mass increase. More often it is convenient to use Equation 2.8 [16], to scale energy and momentum of a particle:

$$\beta = \sqrt{1 - \left(\frac{1}{\gamma}\right)^2}, \quad (2.8)$$

where β is the fraction of the speed of light in vacuum (c) at which electrons move.

For electrons accelerated by an electric field, their speed increases significantly at lower energies but does not change much at higher energies. This is because electrons quickly approach the speed of light even at low energies. A relativistic particle moving with velocity v is often characterized by Equation 2.9:

$$\beta = \frac{v}{c}. \quad (2.9)$$

The time taken by electrons (t) in the acceleration gap (l) was determined using equation from basic principles of motion which states that speed equals distance travelled per unit time taken [17],

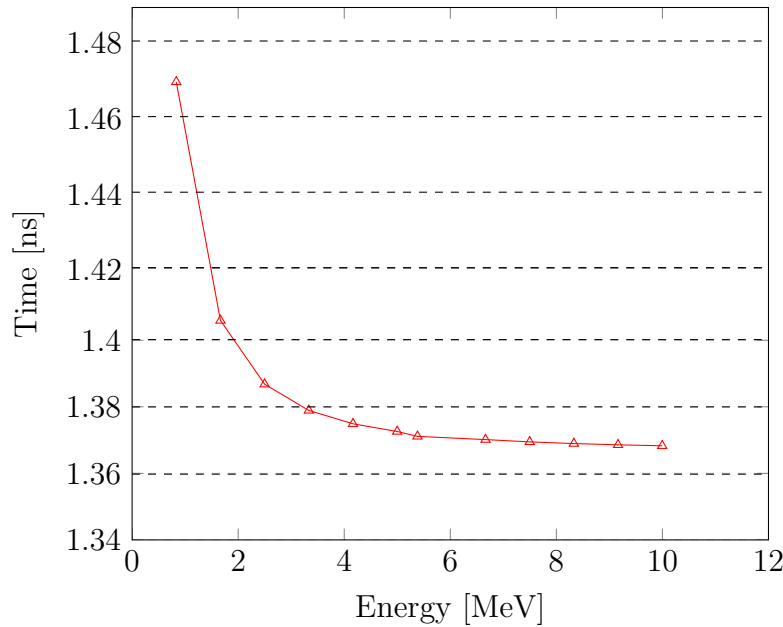
$$v = \frac{l}{t}. \quad (2.10)$$

Following Equations 2.7 - 2.10, for each pass, the parameters γ , β , v and t were calculated for the TT-100 with an acceleration gap l , of 0.41 m and results obtained are shown in Table 2.3.

Table 2.3: *A TT-100 Rhodotron accelerator transverse optics.*

Pass number	T [MeV]	γ	β	$v \times 10^8$ [ms ⁻¹]	t [ns]
1	0.833	2.630	0.924	2.775	1.4776
2	1.666	4.260	0.9720	2.916	1.4059
3	2.499	5.890	0.9854	2.956	1.3867
4	3.332	7.521	0.9911	2.973	1.3789
5	4.165	9.151	0.9940	2.982	1.3749
6	4.998	10.781	0.9956	2.987	1.3725
7	5.831	12.411	0.9967	2.990	1.3711
8	6.664	14.041	0.9974	2.992	1.3701
9	7.497	15.671	0.9979	2.993	1.3694
10	8.330	17.301	0.9983	2.994	1.3689
11	9.163	18.932	0.9986	2.995	1.3685
12	9.996	20.562	0.9988	2.996	1.3682

Using results shown in Table 2.3, a graph of energy against time was plotted as illustrated in Figure 2.8. The graph shows that electrons tend to spend more time in the acceleration gap during the first phases of acceleration. After being accelerated to energies of approximately 4 MeV, electrons become relativistic and spend almost equal time in the acceleration gap until they reach extraction energy. For this reason, there is no need to change the acceleration path length to achieve high energies, thus allowing for compact design of the Rhodotron accelerators.

**Figure 2.8:** *Energy-time graph for the TT-100 Rhodotron accelerator model.*

2.1.3 Advantages of the Rhodotron over LINAC

The aim of this subsection is to discuss advantages of the Rhodotron compared to an industrial electron Linear Accelerator (LINAC). An electron LINAC is a machine that accelerates electrons along a long series of small accelerating cavities.

I. Single large accelerating cavity

Compared to the LINAC with multiple accelerating cavities, the Rhodotron has only a single resonating accelerating cavity [18]. Housing a LINAC requires significant land compared to a Rhodotron accelerator. Furthermore, the large accelerating cavity translates to less heating severity, moreover, ordinary water is used to cool the Rhodotron accelerator [19].

II. Compactness

Some industrial irradiation applications like in-house food sterilization require low-cost small size compact accelerators with high energy and low power. The IBA product line offers these distinctive Rhodotron properties. The Rhodotron accelerator is by far the most compact electron beam accelerator in the industry. This is shown by the latest IBA TT-50 Rhodotron accelerator model. This Rhodotron accelerator model is perfectly suitable for mobile applications. Besides, this compact size reduces shielding expenses.

III. Easy access to the crucial elements

All the Rhodotron crucial elements are situated outside the cavity compared to many other electron beam accelerators. The electron gun, all of the deflecting magnets, amplifiers are attached to the outside of the assembly and therefore this unique design allows for fast and simple repair and exchange of parts.

IV. Non diverging electron beam output

The use of scanning horn system allows the delivery of non-diverging scanned electron beam, hence excellent uniform application of dose to the irradiated products as well as efficient usage of the electron beam. The IBA have recently developed a new

beam scanning system which allows the installation of the Rhodotron accelerator to be on the same level with the conveyor belt system to ensure that all of the beam reaches the product under the same angle [4].

V. Cold start

The Rhodotron accelerator can reach full operational within a few minutes from a “cold start” whereas a LINAC may take up to an hour to warm up. From a “warm start”, the Rhodotron accelerator reaches full operational within a few milliseconds, whereas this may take minutes for LINAC. This fast start up improves production efficiency and safety [19].

VI. No klystron used

The Rhodotron utilizes a cathode driven tetrode rather than a klystron for amplification the RF signal compared to the LINAC [20]. In addition, the tetrode operational life period is 4 times more than that of the klystron thus, cutting down replacements and down time costs [13].

VII. Uniform dose distribution

The continuous wave current of the Rhodotron removes the restriction of narrow scanning frequency [4, 19]. The Rhodotron electron accelerator is scanned at a frequency of 100 Hz or more compared to that of the LINAC of about 5 Hz. This high-frequency scanning capability produces a better uniform dose distribution, for example at very low doses (e.g. at 0.1 kGy), which a LINAC cannot do.

VIII. Reduced fire hazards

Since the Rhodotron does not use a klystron, it eliminates the need for an oil filled “transformer tank” to be housed within the building which is a fire hazard. This reduces insurance costs.

To this end, the main components, operating principle, modelled linear optics of an envisaged Rhodotron accelerator and the advantages over a conventional industrial LINAC have been discussed. Next, potential industrial applications of the Rhodotron relevant to Botswana are briefly highlighted.

2.2 Industrial Applications of a Rhodotron Accelerator

In this section, a literature survey of industrial applications of Rhodotron accelerators is presented. The aim of this section is to highlight potential industrial applications for Botswana.

2.2.1 Sterilization

Electron beam (EB) sterilization is a process of subjecting materials to a controlled amount of energy from a beam of electrons to break the chains of Deoxyribonucleic acid (DNA) in living organisms, such as pathogens and bacteria, leading to microbial death and rendering the space they inhabit sterile [21]. EB sterilization is a safe and cost-effective methods for sterilizing single-use medical devices and pharmaceuticals. EB sterilization permits already-packaged products to be sterilized. The passage of an EB through materials produces ions and free radicals which react with the molecular structure of the material to produce a number of positive or negative effects. EB sterilization inactivates microorganisms by causing microbial death or by an indirect chemical reaction and it is by far the cheapest sterilization technology compared to radioisotope sterilization. EB sterilization is more compatible with a majority of single-use medical devices and pharmaceuticals, including plastic syringes, needles, plastic and rubber catheters, surgical gloves, dressings, surgical blades, razors, various plastic bags and containers.

2.2.2 Postal Mail Decontamination

Postal mail decontamination began shortly after the bioweapon attacks that happened in 2001, the terror sparked by the anthrax causing spores in the United States of America. Gazso and Ponta [22] have indicated that first class postal mails strapped with *Bacillus anthracis* spores were sent to high ranking officials and media resulting in 5 people dead and about 20 severely ill. Following these terrorist actions, the US Federal government found methods to mitigate/prevent the attacks using ionizing radiation to eliminate the *Bacillus anthracis* spores. Here, the IBA was deployed to use EB to help decontaminate first class postal mails [23].

2.2.3 Wastewater, Sludge and Flue Gases Treatment

Waste treatment is a growing problem in the world today. Studies have shown that wastewater can be treated using electron beams [24, 25]. Some applications of EB irradiation on wastewater treatment include treatment of wastewater from textile dyeing industries, wastewater from paper-mills, contaminated underground water, and leachate from the sanitary landfills.

2.2.4 Food Irradiation

Food irradiation is the practice of exposing food products to a controlled amount of ionizing radiation to increase the safety of the food and to extend the shelf life of the food [26, 27]. Food irradiation technology promises to ensure food safety and security. Studies by Farkas and Roberts, refs [27, 28] have emphasized that this process of food irradiation is growing fast, being adopted by more than 55 countries. The use of EB radiation decreases the population of, or prevents the growth of undesirable biological organisms in food. EB irradiation also destroys harmful bacteria such as *Moraxella* and *Escherichia coli* (*E. coli*) which are responsible for spoilage [29–31]. The kinetic energy of the EB produced by the electron accelerators is limited by regulation to 10 MeV for direct electron irradiation to avoid any issues associated with nuclear activation of foods [32].

EB irradiation (up to 10 MeV) has a minimal penetrating power of 5 to 10 cm as shown in Figure 2.9. As a result, most foods are treated from both sides ultimately penetrating up to 8 cm. The use of a conveyor belt with doubled sided irradiation can give a bit more than double the single-sided depth dose because of the way the two depth-dose curves superimpose as showed in Figure 2.10 such that a product thickness of 8 cm is achievable. Each curve in the Figure 2.10 shows the dose distribution for one-sided irradiation; dashed curve, irradiation from the top side; solid curve, irradiation from the bottom side.

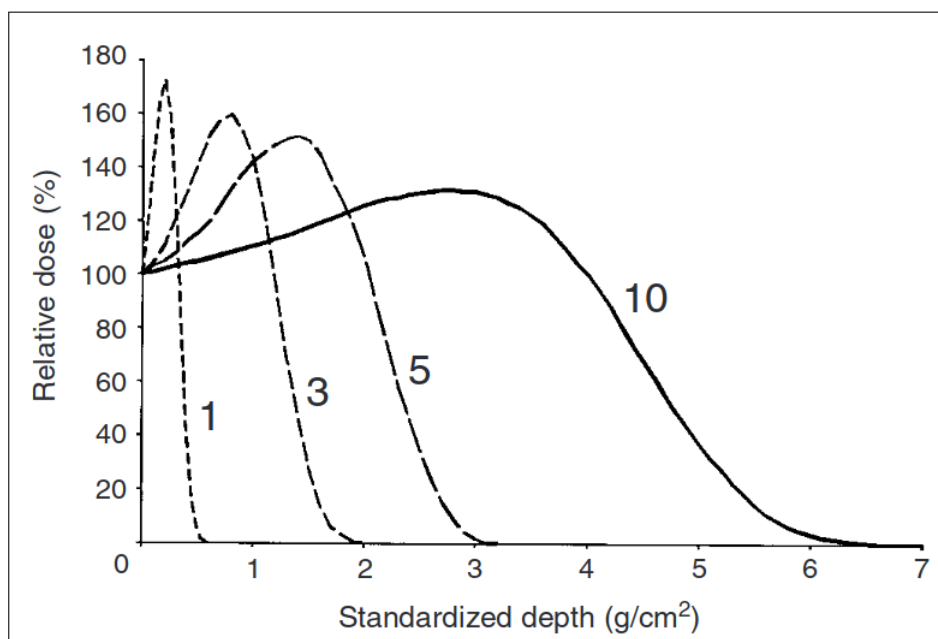


Figure 2.9: Typical standardized depth–relative dose curves for 1, 3, 5 and 10 MeV EB energies applicable to food irradiation [33].

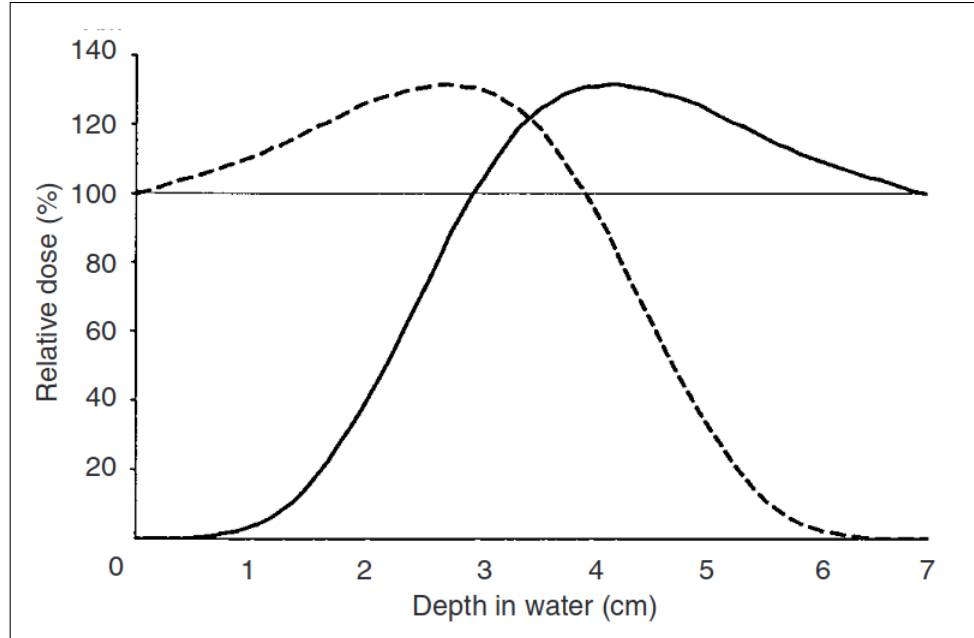


Figure 2.10: *Double-sided 10 MeV EB irradiation depth-dose curves; dashed curve shows irradiation from one side and the solid curve shows irradiation from the other side [33].*

2.2.4.1 Levels of Food Irradiation

In this sub-subsection, internationally permitted levels of food irradiation are defined. Firstly, the concept of absorbed dose commonly used in the context of industrial irradiation is defined.

Absorbed dose: The penetration power of electrons is limited by their kinetic energy and by the mass and density of the absorbing material. The amount of energy of electrons deposited per unit mass of the absorbing material is commonly referred to as the absorbed dose. Absorbed dose is measured in Gray (Gy) and 1 Gy is equivalent to 1 Joule per kilogram (1 Jkg^{-1}). For industrial processing, a unit kiloGray (kGy) ($1 \text{ kGy} = 1 \text{ Jg}^{-1}$) is commonly used.

There are three levels of food irradiation that are accepted as shown in Table 2.4, namely: low dose level, medium dose level and high dose level [28, 32, 34]. Nevertheless, there are a number of food irradiation applications at these three levels, a few of which are described below.

Table 2.4: *Dose levels of irradiation allowed for food use [35].*

Dose Level	Effects	Applications
Low (0.01 - 1 kGy)	Inhibit sprouting	Potato, onion, garlic
	Delay ripening	Bananas
	Pest disinfection	Fresh produce, dried foods
	Parasite inactivation	Pork (trichinella)
Medium (1 - 10 kGy)	Reduce spoilage organisms (extend shelf-life)	Strawberries, mushrooms, dried fish
	Reduce non-sporulating pathogens	Meats, shellfish, spices
High (10 - 100 kGy)	Reduce pathogens to point of sterility	Spices; hospital diets, emergency rations.

I. Inhibit Sprouting

Storage period of considerable months is essential to provide customers with a year-round supply of sprouting vegetables namely potatoes, carrots, onions as well as garlic [36]. In most cases, sprouting can be inhibited by refrigeration and the use of chemicals. Refrigeration is costly whereas the use of chemicals to treat food is comparatively economical and efficient. However, the chemicals retain residues which might pose a health hazard. Under such cases, irradiation becomes a suitable option.

II. Reduction of Food-borne Pathogens and Shelf-life Extension

Medium dose levels are applicable for controlling both food-borne pathogens as well as significant shelf-life extension of food. For example, 2.5 kGy of radiation dose may prolong the shelf-life of meat by over a few weeks [28]. Since this project is partially motivated by a particular interest in sterilization as well as shelf-life extension of meat, an overview of meat irradiation is considered in Subsection 2.2.5.

III. Spice Irradiation

Spices are derived from fresh plants which are almost always contaminated by micro-organisms from the soil, windblown dust, as well as animal and bird droppings. During the drying process, the population of these harmful micro-organisms grow. Irradiation of spices has proved to eliminate these micro-organisms [37, 38].

2.2.4.2 Regulation of Irradiated Food Products

The aim of this sub-subsection is to briefly mention some international regulations governing the use of ionizing radiation to treat meat.

In 1980, a Joint committee of experts on food irradiation called together by the Food and Agriculture Organization (FAO) of the United Nations, IAEA and WHO declared food irradiated with a dose below 10 kGy to be wholesome. “The Committee concluded that the irradiation of any food commodity up to an overall average dose of 10 kGy presents no toxicological hazard; hence, toxicological testing of foods so treated is no longer required” [39]. The Codex Alimentarius Commission approved a regulation to accept foods irradiated lower than 10 kGy in 1983 and further approved foods irradiated at higher than 10 kGy if so necessary in 2003. The United States Food and Drug Administration (FDA) requires that irradiated food must be clearly labelled with the Radura symbol shown in Figure 2.11. This is an international symbol signifying that a food product has been treated with ionizing radiation.



Figure 2.11: *The green Radura symbol that is used to signify irradiated products [40].*

2.2.5 Meat Irradiation

The Botswana beef industry plays an important role in the country's economy and represents the country's third main income earner, after diamond mining and tourism [41]. The beef industry is also important for economic growth in rural areas in Botswana as it provides employment and has been emphasized as a premeditated sector within the country's economic diversification drive. Furthermore, the Botswana economy has been dependent on its beef exports to the countries of Europe. The European Union (EU) market is the most important export market for Botswana beef, given the premium prices it pays. The beef export contributes about 3% of Botswana's Gross Domestic Product (GDP) [42]. The EU however, enforces strict regulations concerning the safety and quality of meat it imports. Therefore, this subsection presents concise survey of meat irradiation, highlighting only concepts applicable within the scope of this study. For further reading, see provided references.

The process of irradiating food is an effective process for reducing harmful micro-organisms in food products like meat. The use of ionizing radiation to preserve meat was approved by the United States FDA in 1997 [43] after several studies [26, 44–49] had shown that EB irradiation of meat is a technology capable of extending the shelf life of meat without compromising its nutritional value. Fresh meat is a profoundly perishable food product because of its dampness and high nutrient contents. Moreover, meat may also be contaminated by different microorganisms such as *E. coli* O157: H7, *Salmonella* and *Listeria*, during slaughter, processing and transportation. The nature and level of microorganism contamination pose a health hazard to the public and reduce the shelf life of meat.

The primary goals of meat irradiation is to improve its safety, reduce the health hazard it may pose to humans upon consumption, and to extend its shelf life. However, the process of irradiating meat has some limitations that may bring negative changes that affect the quality of meat. Below, the effects of irradiation on the quality of meat are discussed.

Colour of the Irradiated Meat: The colour of fresh meat is one of the visual factors influencing the perspective of customers regarding the quality of meat. There are some

pigments (haemoglobin and myoglobin) responsible for the colour of the meat [50]. The content levels of these pigment-containing proteins are the prime factors that dictate the meat colour. A study by Millar et al. [51] indicated that carbon monoxide that is produced during meat irradiation induces changes in the colour of meat. Furuta et al. [52] have indicated that the carbon monoxide that is produced during meat irradiation results from organic compounds such as esters, amides, alcohols, aldehydes, ketones and carboxylic acids. The addition of ascorbic acid during the irradiation process to retain the colour of fresh meat is well reported [53, 54]. On the other hand, a study by Ramamoorthi et al. [55] showed that the use of antioxidants like butylated hydroxytoluene, butylated hydroxyanisole, propyl gallate as well as ascorbic acid during the irradiation helps preserve the colour of meat.

Odour of the Irradiated Meat: Ahn et al. [56] reported that Sulphur containing compounds are the main causes of off-odour in irradiated meat. Propanal, pentanal, hexanal, 1-pentanol and total volatile compounds are reported to highly correlate with Thiobarbituric acid reactive substance (TBARS) of irradiated meat [57]. Nam and Ahn [58] discovered that to reduce the formation of off-odour volatiles in irradiated meat, the use of antioxidants is important.

Flavour of the Irradiated Meat: Flavour is the combination of basic tastes like sour, sweet, bitter, salty and spicy. Irradiated meat can have a different flavour from the meat that is not irradiated. Free radicals produced during the irradiation process has the ability to destroy some antioxidants in meat hence resulting in bad flavour [47].

Effect of Meat Irradiation Temperature: Irradiation of meat in a frozen state provides a room for the reduced generation of off-flavour. Nonetheless, a study by Black [59] showed that EB irradiation of meat at chilled temperatures (4 °C) minimize the multiplication of *E. coli* consequently inhibiting the development of spoilage bacteria.

As pointed out in the introduction of this section, the beef industry adds value to the economy and improve the livelihood of Botswana citizens. Therefore, the above discussed issues on meat irradiation can form a basis for future research Botswana.

To this end, a Rhodotron electron accelerator has been modelled and described in terms of how it works as well as potential industrial applications in Botswana. The next chapter addresses the main aim of this project.

Biological Shielding Calculations

In this chapter, biological shielding calculations for a 10 MeV TT-100 Rhodotron accelerator are presented. The TT-100 Rhodotron accelerator produces high-intensity beams of 4 mA, therefore, extra precautions for shielding must be considered to ensure human safety. The aim is to design optimal biological radiation shielding structures to attenuate dose rates to internationally acceptable levels. The biological shield should be capable of protecting the radiation staff, the public, and equipment used to control the accelerator and environment against unnecessary radiation associated with the operation of an accelerator. Both analytical, as well as Monte Carlo (MC) shielding calculations, are presented. The analytic calculations are used to determine an estimate of the shielding thickness required to reduce the biological radiation dose rates to acceptable levels. The determined shielding thickness is then used as a baseline value in the MC calculations.

3.1 General Considerations

The aim of this section is to highlight general factors that should be taken into consideration when constructing the radiation shielding structure for an electron accelerator. These factors are used in [Section 3.2](#) and [Section 3.3](#) and include:

1. types of radiation produced during operation,

2. the radiation hazard from the maximum beam energy and intensity, average beam power, normal and abnormal beam losses, schedule and modes of operations,
3. dose limits for radiation workers and the members of public,
4. internationally accepted dose levels for radiation workers as well as general public,
5. environmental radiological impact from beam operations,
6. occupancy of the area under consideration.

3.1.1 Types of Radiation from the Rhodotron Accelerator

The aim of this subsection is to highlight types of radiation associated with the operation of a Rhodotron electron accelerator.

As the electron beam from the Rhodotron accelerator interacts with the absorbing matter, ionization and excitation take place, which may lead to the production of secondary radiation that includes fast neutrons, induced activity from the accelerator components, muons (from electron beam energies greater than 500 MeV) and X-rays from the RF systems [60], together with bremsstrahlung radiation (also called braking radiation) production. The characteristics of the secondary radiation are determined by the energy and type of particle accelerated, the beam duty factor, the target material, and shielding around the accelerator [61].

The Rhodotron accelerator produces primary electron beams and secondary bremsstrahlung radiation. Bremsstrahlung occurs where an electron changes direction in the presence of electric field of an atomic nucleus and to a small extent, as shown in Figure 3.1. Such a deflection is regarded as a change in the electric current characterized by that moving electron [60]. Bremsstrahlung radiation is produced predominantly in forward direction of the path of an electron at high energies and it is the prevailing secondary radiation in the materials that absorb the electron beam energy. Secondary radiation exists only when the accelerator is operating, and ceases when the accelerator is turned off [62].

To minimize the bremsstrahlung generation, the shielding material should have a low atomic number (Z) to stop electrons as mentioned by L'Annunziata [63]. Such a shielding material is usually enclosed with a high atomic number material to adequately absorb the radiation [64].

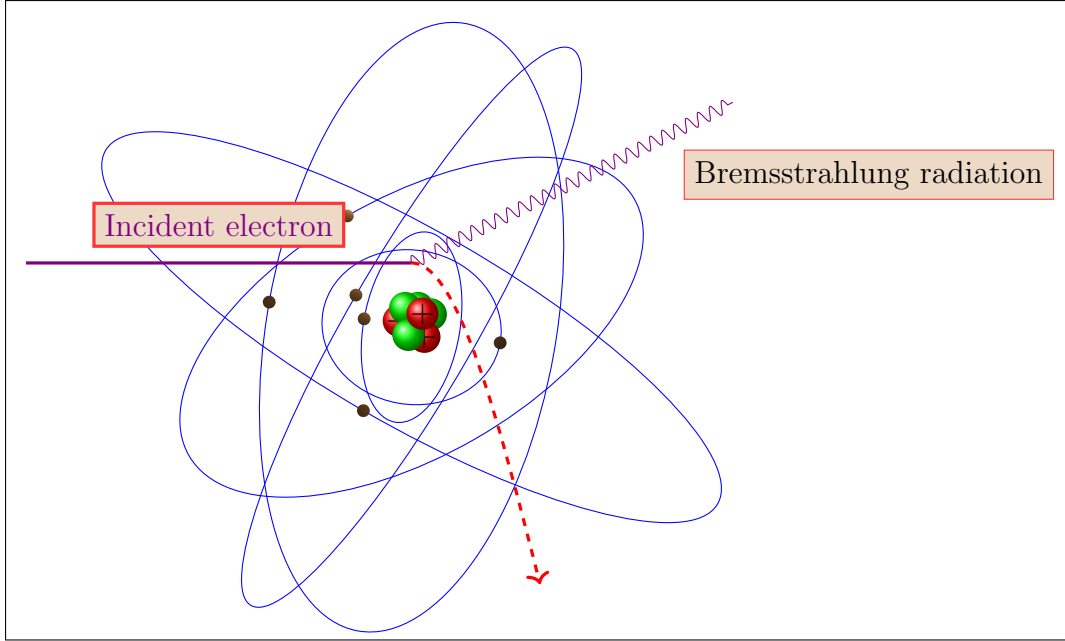


Figure 3.1: *Schematic representation of bremsstrahlung radiation.*

The following empirically determined Equation 3.1 [65], is used in Section 3.2 to estimate the bremsstrahlung produced from electrons:

$$f = 3.5 \times 10^{-4} Z E, \quad (3.1)$$

where f is the fraction of the incident electron energy transformed into photons, Z is the atomic number of the absorbing medium and E is the maximum energy of the electron energy in MeV.

Now, to understand the principle risks the above mentioned types of radiation pose specifically to human health, the following subsection is dedicated to the potential hazards that arising from operation of the Rhodotron accelerator facility.

3.1.2 Evaluation of the Radiation Hazard

The aim of this subsection is to make an estimate of the magnitude of the radiation hazard the TT-100 Rhodotron can pose to human health. From Table 2.1, it is seen that the TT-100 is capable of producing maximum beam energy of 10 MeV when operating at a maximum beam current of 4 mA. Under these two operational conditions, the Rhodotron will produce 40 Joules per second (40 Js^{-1}). One can therefore estimate that if a person with an average body mass of 75 kg was to be in the proximity of the electron beam for 5 seconds and to consequently absorb all the beam energy, the individual will be subjected to an absorbed dose of 2.67 Jkg^{-1} or 2.67 Gy.

To estimate the radiation risk presented by the absorbed dose on the person, the dose equivalent $H_{T,R}$, measured in Sieverts (Sv), is calculated using Equation 3.2:

$$H_{T,R} = W_R D_{T,R}, \quad (3.2)$$

where $H_{T,R}$ is weighed by the absorbed dose $D_{T,R}$ for tissue T with the radiation weighting factor W_R , given in Table 3.1. W_R is an estimate of Relative Biological Effectiveness (RBE), for radiation R.

Table 3.1: *Radiation weighting factors, W_R from NCRP report No. 116 [66, 67].*

Radiation	W_R
X and γ rays, electrons, positrons and muons	1
Neutrons, energy < 10 keV	5
10 keV to 100 keV	10
> 100 keV to 2 MeV	20
> 2 MeV to 20 MeV	10
> 20 MeV	5
Protons other than recoil protons and energy > 2 MeV	2
α -particles, fission fragments and nonrelativistic heavy nuclei	20

If the radiation comprises parts with various weighting factors, the dose equivalent in tissue is calculated as follows:

$$H_T = \sum_R W_R D_{T,R}. \quad (3.3)$$

For a 10 MeV EB, the radiation weighting factor, W_R obtained from Table 3.1, is equal to 1. Using Equation 3.3, the test person in the above scenario would be subjected to a dose equivalent of 2.67 Sv within 5 seconds. From Table 3.2, one can conclude that the radiation dose is enough to kill the body cells (which multiply within a few seconds) of the test person.

Table 3.2: *Effects of specific radiation dose equivalent levels [68].*

Radiation dose	Negative effect
100 mSv	Increase cancer risk.
400 mSv	Results in symptoms of acute radiation syndrome in case of short exposure time.
≥ 2 Sv	Destroys rapidly dividing body cells, including blood as well as the reproductive cells, and damage the nucleic acids of remaining cells.
≥ 4 Sv	Severely serious poisoning of radiation. With timely medical therapy, survival is achievable.
≥ 8 Sv	Radiation dose fatal, even with medical treatment.

Table 3.3 provides the acceptable radiation dose equivalent rate limits to which a radiation worker and the general public may be exposed to. The following assumptions were followed so as to infer and project effective dose rates from Sieverts per year to Sieverts per hour for the radiation workers and the general public(non-radiation workers):

1. 8 working hours of possible exposure in a day,
2. 5 working days in a week,
3. 4 weeks in a month,
4. 12 months per year.

Consequently, the exposure time amounts to a total of 1920 hours per year of possible exposure to radiation. Therefore, for a radiation worker with the dose equivalent rate limit of 20 mSv/year, we convert this value into 20 000 μSvh^{-1} . Using the factor of 1920 hours, the effective dose rate limit becomes 10.42 mSvh^{-1} .

Table 3.3: *Permissible biological dose-rate levels suggested by the International Commission on Radiological Protection [69].*

Category	ICRP dose rate limit [mSv/year]	Projected effective dose rate [μSvh^{-1}]
Radiation workers	20	10.42
Non-Radiation Workers and general Public	1	0.52

3.1.3 Radiation Shielding

This subsection defines some radiation shielding subjects or concepts that are commonly considered when designing a radiation shield.

The National Council on Radiation Protection and Measurements (NCRP) defined radiation shield as “a physical entity interposed between a source of ionizing radiation and an object to be protected such that the radiation level at the position of that object will be reduced” [61]. A single material or a particular combination of materials can be used to attenuate high radiation levels to tolerable levels. Other than the material’s attenuation properties, there are certain factors that dictate the selection of shielding materials as well as their configurations.

These factors include the total cost of installation and maintenance of the material, weighed thickness of the material, possibility of use as shielding for photons and neutrons, consistency, uniformity and homogeneity of the material, possibility of induced radioactivity, and the necessity of the shield design to be incorporated with all other features of an accelerator facility [70].

Before the concept of shielding is discussed, a brief definition some of the concepts that are commonly used in association with radiation shielding are presented. These concepts

will be used in Section 3.2.

I. Radiation Yield

The radiation yield of electrons is described as an a fraction of electron energy radiated as bremsstrahlung in slowing down. As the electron slows down, the relative energy lost through radiation reduces constantly. The radiation yield increases with the electron energy and the atomic number of the shielding material. Estimating radiation yield gives a measure of the possible bremsstrahlung risk from an electron beam accelerator. If an electron beam of initial kinetic energy E in MeV is stopped in an absorber of atomic number Z , the radiation yield is then given approximately by [71]:

$$Y = \frac{6 \times 10^{-4} Z E}{1 + 6 \times 10^{-4} Z E}. \quad (3.4)$$

Table 3.4: Mean atomic mass, mean atomic number, minimum and maximum of effective atomic numbers and minimum and maximum of effective electron density [72].

	$\langle Z \rangle$	$\langle A \rangle$	Z_{efmin}	Z_{efmax}	N_{efmin}	N_{efmax}
1	7.09	13.93	5.68	13.33	2.44E+23	5.76E+23
2	7.09	13.93	5.68	13.33	2.44E+23	5.76E+23
3	7.10	13.93	5.68	13.33	2.44E+23	5.76E+23
4	7.10	13.93	5.68	13.34	2.44E+23	5.76E+23
5	7.10	13.94	5.69	13.34	2.44E+23	5.76E+23
6	7.10	13.94	5.69	13.34	2.44E+23	5.76E+23
10	7.11	13.96	5.70	13.36	2.44E+23	5.76E+23
15	7.11	13.96	5.70	13.36	2.44E+23	5.76E+23
20	7.11	13.97	5.70	13.37	2.44E+23	5.76E+23

The yield of a 10 MeV electron passing through a concrete wall can be calculated using Equation 3.4,

$$Y = \frac{6 \times 10^{-4} \times 13.34 \times 10}{1 + 6 \times 10^{-4} \times 13.34 \times 10} = 7.41 \times 10^{-2}, \quad (3.5)$$

where Z is the average effective atomic number of concrete (13.34), obtained from Table 3.4.

Thus, about 7.4% of the electron kinetic energy is converted into bremsstrahlung radiation as it traverses the concrete wall.

II. Shielding photons (Gamma-rays)

Gamma rays cannot be completely absorbed, but their intensities can be reduced when passing through matter. Considering a mono-energetic gamma radiation, attenuation measurements can be made under conditions of good geometry, i.e. with a well-collimated, narrow beam of radiation, as shown in Figure 3.2, a straight-line relationship between the logarithm of intensity versus the thickness x of the shield is obtained, i.e. [73]:

$$I = I_0 e^{-\mu x}, \quad (3.6)$$

where μ denotes the linear attenuation coefficient, I_0 and I represent the radiation intensity before and after attenuation respectively.

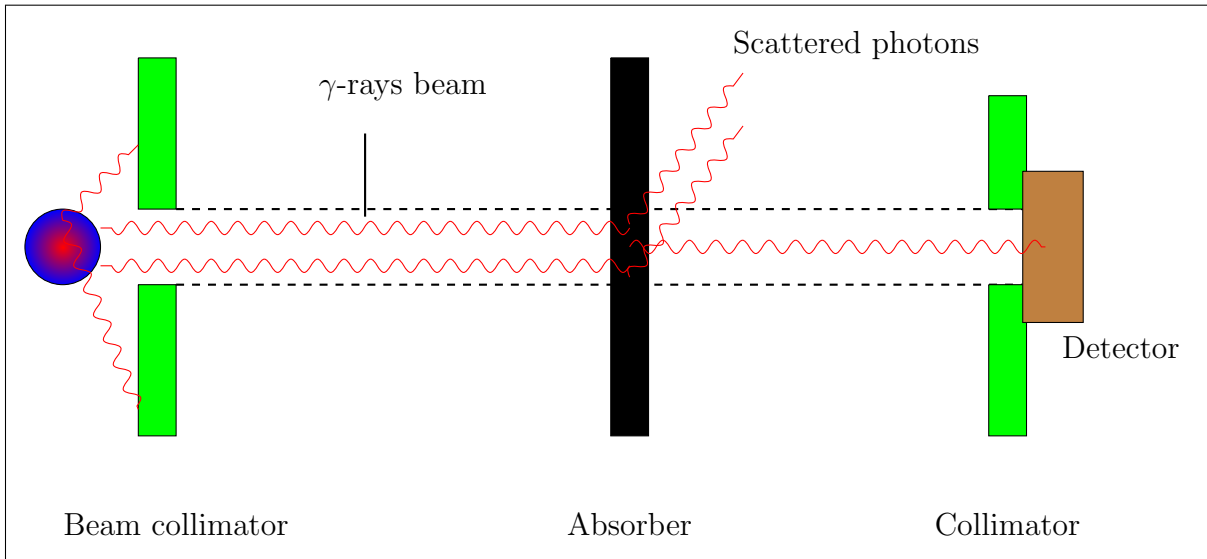


Figure 3.2: A simple model of attenuation of γ -rays under good geometry.

When measuring the exposure rate, Equation 3.6 can be written as following [71]:

$$\dot{X} = \dot{X}_0 e^{-\mu x}, \quad (3.7)$$

where $\dot{X}$ and $\dot{X}_0$ represent the exposure rate with shielding and exposure rate without shielding respectively.

When shielding multiple γ -ray energies, a conservative method is considered whereby calculations are done using the highest of the gamma ray energies. This overestimates the exposure rate and the necessary shielding. This approach might be rational in a scenario where the two gamma rays are of similar energy and contribute approximately equally to the exposure rate. On the other hand, this approach could be a catastrophe for the circumstances where the highest gamma ray energy contributes only a little to the exposure rate. The correct approach is to determine the exposure rate for each γ -ray energy and then determine the attenuation of each gamma ray energy independently. For this study in Section 3.2, the analytic calculations are based on the assumption that the photons are mono-energetic.

III. Shielding of Neutrons

For a primary electron beam energy of 10 MeV, the production of secondary fast neutrons has been reported to be minimal [65]. However, for primary electron beam energies greater than 10 MeV, production of fast neutrons is possible and the following considerations are applicable when shielding these neutrons.

The shielding of neutrons involves three steps, namely: slowing down the fast neutrons, absorbing slowed down neutrons and then absorbing photons. According to Turner et.al [71], neutron shields act to moderate fast neutrons to thermal energies, principally by elastic scattering, and then absorb them. For shielding against neutrons, any material can be used, but hydrogenous materials are most effective (per areal density) because elastic scattering by hydrogen is the most efficient slowing down mechanism for intermediate-energy neutrons [60].

The hydrogen captures thermal neutrons through the reaction ${}^1\text{H}(n,\gamma){}^2\text{H}$ with a cross-section of 0.33 barns. On the other hand, materials like Cadmium, have a very high (n,γ) thermal-neutron capture cross-section (2450 barns) and for that reason are commonly used as neutron absorbers. Hydrogen and Cadmium have the shortcoming of emitting energetic (2.22 MeV and 9.05 MeV) capture γ -rays, which might themselves call for shielding. Other nuclides, such as ${}^{10}\text{B}$ and ${}^6\text{Li}$, capture thermal neutrons through an (n,α) reaction without the release of significant gamma

radiation.

Materials such as wood, paraffin, plastics or water are also effective in capturing thermal neutrons because of their high hydrogen content. However, considerations should also be given to the fire risk represented by some materials, particularly organic liquids [60]. Water shields have the shortcoming of requiring maintenance and evaporation can lead to a potentially hazardous loss of shielding [71].

IV. Concrete Shielding

Concrete is a compound material that is essentially made up of a binding medium, such as a mixture of portland cement and water, within which are embedded particles or fragments of aggregate, usually a combination of fine and coarse aggregate. Concrete has a density range of 2.3 to 2.5 gcm⁻³. Due to its relatively low cost, simplicity to mould it into different shapes, good structural properties to use as both photon and neutron shield [70], concrete is commonly used as shielding material in accelerators. The effective atomic number (Z_{ef}) of the concrete consisting of different elements is based on the total attenuation cross-section for γ -ray interaction and it can be obtained by Equation 3.8, where σ_a and σ_e represent total atomic cross section and total electric cross-section respectively [74]:

$$Z_{ef} = \frac{\sigma_a}{\sigma_e}. \quad (3.8)$$

From research conducted in 2014 by Ipbüker et al. [72], the average Z_{ef} of concrete can be calculated using results in Table 3.4. To account for a worst case scenario, the average effective atomic number is calculated using values of $Z_{ef\max}$. This is because high-energy accelerators are capable of producing radiation fields of high energy and high intensity, mixed with photons and neutrons [70].

So far this chapter has discussed the types of radiation and estimated the radiation hazard associated with the operation of a Rhodotron electron accelerator facility and highlighted some radiation shielding concepts that will be used throughout the rest of this chapter. The next section looks at the analytic approach for shielding the Rhodotron accelerator.

3.2 The Analytic Approach

This section describes analytic approach for shielding calculations where empirical formulas from literature were used. The analytic approach provides a faster and rough means of shielding calculations hence saving computational time. Implementation of this method is based on a simplified approach where the shield assumes a regular and uniform geometry such as rectangular, cylindrical, spherical.

3.2.1 Shielding the Rhodotron Vault

To determine dose rate $\dot{D}_i$ at a distance d due to an electron beam of energy E , the following Equation 3.9 is used [65]:

$$\dot{D}_i = \frac{f \times E[\frac{MeV}{s}] \times 1.6 \times 10^{-13}[\frac{J}{MeV}] \times \mu_m[cm^{-1}] \times 3.6 \times 10^3[\frac{s}{h}]}{\rho_m[\frac{kg}{cm^3}] \times 4\pi d^2 \times 1 \frac{Jkg^{-1}}{Gy} \times 10^{-3}[\frac{Gy}{mSv}]}, \quad (3.9)$$

where, f represents percentage of the electron energy transformed into bremsstrahlung radiation and μ_m represents linear absorption coefficient.

The TT-100 Rhodotron accelerator has 11 bending magnets situated just outside the accelerating cavity. These bending magnets are made from iron (atomic number 26). Because of the maximum probability of electron beam incidence in these 11 bending magnets as well as along the beam-line, the TT-100 Rhodotron is considered to consist of 12 electron point sources with 0.833 – 9.996 MeV energies such that a proportion for individual source is one-twelfth of the entire lost beam particles.

Following Equation 3.9, the dose rate $\dot{D}_i$ due to a bending magnet, a distance 2.6 m away from the Rhodotron, the dose rate for the energy $E = 0.833$ MeV and other beam energies were obtained as follows:

$$\dot{D}_{0.833} = \frac{(3.5 \times 10^{-4} \times 26 \times 0.833) \times 0.1 \times \frac{4 \times 10^{-3}}{1.6 \times 10^{-16}} \times 1.6 \times 10^{-13} \times 0.14112 \times 3600}{1.293 \times 4\pi(2.6)^2 \times 1 \times 10^{-3}} \mu Sv h^{-1}. \quad (3.10)$$

The coefficients used in the calculations for air and concrete are presented in Table B.2 of Appendix B.

To determine final dose rate after the concrete shield $\dot{D}_f$, the following exponential attenuation equation is used [65]:

$$\dot{D}_f = \dot{D}_i e^{-\mu t}, \quad (3.11)$$

where, μ represents linear attenuation coefficient of concrete at specific energy and t denotes shield thickness.

Taking into consideration the values of $\dot{D}_i$ as well as μ at 12 specific energies (0.833 - 9.996 MeV), the concrete shield thickness is determined through trial and error such that the sum of dose rates is equal to the required value. Accordingly, the total biological dose rate is given by:

$$\dot{D} = \dot{D}_1 e^{-\mu_1 t} + \dot{D}_2 e^{-\mu_2 t} + \dots + \dot{D}_{12} e^{-\mu_{12} t} = \sum_{n=1}^{12} \dot{D}_n e^{-\mu_n t}. \quad (3.12)$$

Table B.3 of Appendix B shows the Microsoft Excel sheet formatted shielding calculations for the Rhodotron vault. The value in cell B3 is varied to determine a shield thickness sufficient to attenuate the biological dose rates to $5 \mu\text{Svh}^{-1}$ (cell J15). Table 3.5 presents extracted dose rate results from the calculations. The results show that a concrete shield of thickness 2.1 m attenuates the dose rates to $4.947 \mu\text{Svh}^{-1}$.

Table 3.5: *X-ray dose rate due to deflection magnets ($\dot{D}_i$) and concrete shield ($\dot{D}_f$). This table is extracted from Table B.3 of Appendix B.*

Pass number	Energy [MeV]	$\dot{D}_i[\mu\text{Svh}^{-1}]$	$\dot{D}_f[\mu\text{Svh}^{-1}]$
1	0.833	3.08E05	4.16E-08
2	1.666	1.09E06	4.76E-06
3	2.499	2.26E06	7.40E-05
4	3.332	3.52E06	1.85E-03
5	4.165	5.00E06	1.44E-02
6	4.998	6.70E06	5.91E-02
7	5.831	8.64E06	1.65E-01
8	6.664	1.09E07	2.25E-01
9	7.497	1.34E07	5.94E-01
10	8.330	1.63E07	8.06E-01
11	9.163	1.95E07	1.22E+00
12	9.996	2.23E07	1.86E+00
Total dose		1.10E08	4.947

3.2.2 Shielding the Irradiation Vault

To determine the shield thickness of the irradiation vault, the tantalum target is considered to be a rod source producing a mono-directional beam of X-rays of intensity Θ_0 and energy E_0 , which is incident on the concrete slab shield of thickness a as shown in Figure 3.3. For the concrete shield to adequately attenuate the dose equivalent rate to a tolerable level in a worst-case scenario, the shield thickness is computed considering a case where the maximum dose equivalent rate is produced. Thus, maximum dose equivalent rate is attained in the case of 4 mA current striking a tantalum target.

The dose equivalent rate in the air for unscattered X-rays of energy E_0 is [75]:

$$\dot{X}_0 = 0.0659\Theta_0 E_0 (\mu_a/\rho)_{air} \quad [mRh^{-1}], \quad (3.13)$$

where, $\dot{X}_0$ is the dose equivalent rate in milliRoentgen per hour (mRh^{-1}), Θ_0 is the X-ray flux, E_0 is the X-ray energy in MeV and $(\mu_a/\rho)_{air}$ is the air mass absorption coefficient in cm^2g^{-1} .

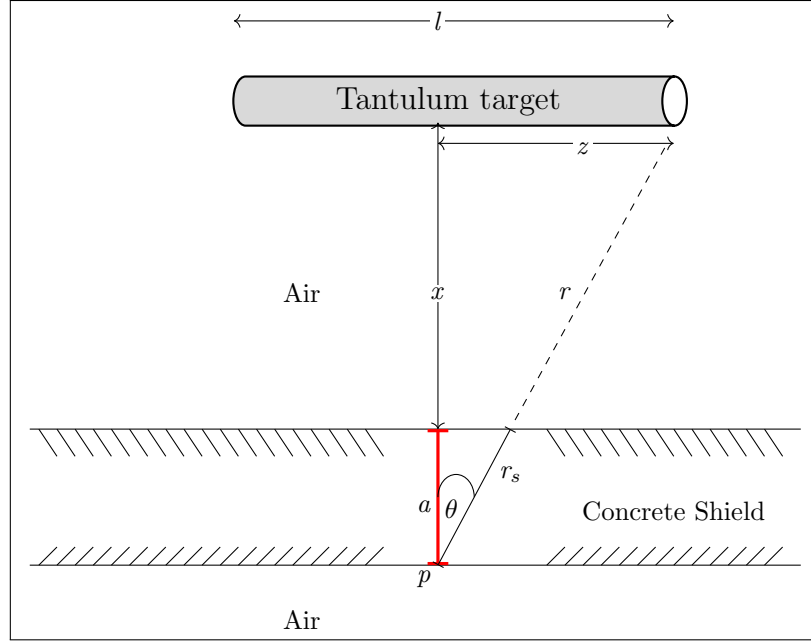


Figure 3.3: A rod target with its shield. The target is made of tantalum and is situated a distance x away from a concrete shield with thickness a .

Since

$$1 \text{ Sv h}^{-1} = \frac{3881}{34} Rh^{-1} [76], \quad (3.14)$$

it follows that:

$$5 \mu \text{ Sv h}^{-1} = 0.57074 [mRh^{-1}]. \quad (3.15)$$

Hence, from Equation 3.13,

$$0.57074 = 0.0659 \times \Theta_0 \times 10 \times 0.0144, \quad (3.16)$$

and the following result is obtained:

$$\Theta_0 = 60.14 [\text{photons/cm}^2 \text{ s}]. \quad (3.17)$$

Therefore, $5 \mu \text{ Sv h}^{-1}$ dose equivalent rate is equal to 60.14 photons/cm²s flux. The thickness of ordinary concrete is designed to attenuate the flux to 60.14 photons/cm²s. The

bremsstrahlung flux produced by a primary electron beam with energy E (in MeV) incident on a target at distance r cm away from the source is given by the Equation 3.18;

$$\Theta = \frac{fE'}{4\pi r^2 E} \left[\frac{\text{photons}}{\text{cm}^2 \text{s}} \right], \quad (3.18)$$

where f is given by Equation 3.1. To obtain photons per unit time, it is convenient to multiply Θ by $4\pi r^2$ and obtain:

$$\Theta_0 = 4\pi r^2 \times \Theta = \frac{fE'}{E} = 60.14 \left[\frac{\text{photons}}{\text{s}} \right]. \quad (3.19)$$

Substituting numerical values, the following is obtained:

$$\Theta_0 = \frac{3.5 \times 10^{-4} \times 73 \times 7.5 \text{ MeV} \times 2.496723 \times 10^{16} \times 7.5 \text{ MeV}}{7.5 \text{ MeV}} \left[\frac{\text{photons}}{\text{s}} \right]. \quad (3.20)$$

Introducing this result into Equation 3.21 gives

$$S = \frac{\Theta_0}{l(\text{hornlength})} = \frac{4.784 \times 10^{15}}{110 \text{ cm}} = 4.349 \times 10^{13} \left[\frac{\text{photons}}{\text{cms}} \right], \quad (3.21)$$

where S is the photon emission rate of the X-ray target considered to be a rod of length l .

To determine build-up photon flux Θ_f at point p , beyond the concrete shield of thickness a , Equation 3.22 is used [75]:

$$\Theta_f = \frac{S}{2\pi(x+a)} \{A_1 F[\theta_1, (1+\alpha_1)\mu_s a] + A_2 F[\theta_1, (1+\alpha_2)\mu_s a]\}, \quad (3.22)$$

where x represents distance of X-ray target to concrete shield of thickness a . Table 3.6 provides coefficients for the exposure build-up factors; A_1 , A_2 , α_1 , α_2 and μ_s for 10 MeV energy obtained from [75].

Table 3.6: Coefficients for the exposure build-up factors [75].

Material	Energy (MeV)	A_1	A_2	$-\alpha_1$	α_2
Concrete	10	4.015	-3.015	0.0288	0.06844

If $\theta < 10^\circ$,

$$F(\theta, y) = \theta e^{-y}, \quad (3.23)$$

hence,

$$\Theta_f = \frac{4.349 \times 10^{13}}{2\pi(400 + 200)} \{4.015 \times F[0.00695, 20.978] - 3.015 \times F[0.00695, 23.08]\}, \quad (3.24)$$

where F is given by Equation 3.23.

Solving Equation 3.24, the following is obtained:

$$\Theta_f = 60.14 \text{ [photons/cm}^2\text{s]}. \quad (3.25)$$

This result indicates that a 2 m thick concrete shield will reduce the photon flux to 60 photons/cm²s. This result satisfies the estimated photon build-up flux obtained in the earlier case (see Equation 3.17). The present result shows that a concrete shield of thickness 2 m proved sufficient to attenuate biological dose rates to 5 μSvh^{-1} . The 2 m thickness will be used as a baseline for estimating the shielding thickness of the FLUKA geometry in the next section.

3.3 Monte Carlo Shielding Calculations

In this section, Monte Carlo (MC) shielding calculations for the 10 MeV TT-100 Rhodotron accelerator are presented. MC is a more rigorous approach in terms of considering a variety of physics issues.

Fermi, Ulam and von Neumann [77] developed the Monte Carlo method in the late 1940s as a technique of particle transport used to solve commonly differing kinds of physical issues. The MC solutions are based on the use of features for generating occurrences using random number generators. In this work, “FLUktuierende KAskade (FLUKA), a fully integrated MC package”, is used to design a biological shielding structure to house the

envisaged Rhodotron. The Rhodotron facility is designed to reduce the biological dose rates to less than $5 \mu\text{Svh}^{-1}$ during normal operation. This level is half the projected level ($10.42 \mu\text{Svh}^{-1}$) mentioned in Subsection 3.1.2.

To help keep this section focused, only important information is discussed to support the arguments. For further reading, detailed information that is not immediately needed, although would be useful to the reader, can be found in Appendix C.

3.3.1 FLUKA

FLUKA [78], is a versatile tool for calculations of particle transport and interactions with matter. It was developed in 1962 by Johannes Ranft when he was working on hadron cascades at the European Organization for Nuclear Research (CERN). There are three FLUKA generations which have been extensively described by Ferrari et.al [78]. The first code was named FLUktuierende KAskade (FLUKA) and it was developed at Rutherford High Energy Lab on the basis of hadron cascades projects. The code was then developed over decades until the third generation was first published in 1989. The third generation is the latest and present FLUKA model that is based on multi-particle transport and interaction.

This study was carried out using the latest FLUKA version 2011.2x.3, which was released on June 19th 2018 and can be downloaded at <http://www.fluka.org/fluka.php>. FLUKA was preferred over other MC packages because it is a free licensed software available online.

3.3.1.1 Physics, structure and capabilities of FLUKA

The aim of this sub-subsection is to present a brief survey of the physics of FLUKA, its structure and capabilities. First, let us look at the physics behind FLUKA in terms of electrons, photons and low neutrons transport and interaction with matter.

(a). Physics

I. Electrons

FLUKA utilizes an algorithm for electron transport problems. According to Kling [79], this algorithm ensures that the Molière theory of multiple scattering is not breached. The lowest transport energy for electrons is 1 keV. For primary electrons, the minimum supported energy is approximately 50 to 100 keV for materials with low atomic number and 100 to 200 keV for materials with high atomic number, except if a single scattering algorithm is utilized. The single scattering algorithm reduces low energy constraints for high atomic number materials at the expense of increasing computer time [78].

II. Photons

The Electro Magnetic FLUKA (EMF) input card is used to activate transportation of not only the photons but also transportation of electrons as well as positrons. FLUKA supports transportation of photons with energies from 100 eV. Nonetheless, the recommended minimum energy for primary photons is set to 100 keV.

Based on Sauter’s fully relativistic theory, the photoelectric effect with real photo-electron angular distribution is computed [61]. Elemental interactions are sampled individually, taking into consideration the fine edge structure. Tabulated photoelectric cross sections include known edges up to $Z = 100$ and down to a few eV [80]. The Compton effect is determined through application Compton data, taking into consideration the nuclear bonds employing inelastic Hartree-Fock form factor, which is really crucial at low energies in high atomic number materials. Pair production has definite angular and energy spectrum of positrons and electron that are accurately reported, with no “fixed angle” or analogous estimation. The approximation is spread up to 1×10^6 GeV.

III. Low Energy Neutrons

In FLUKA, neutrons with energy less than 20 MeV are handled as low-energy neutrons with a special dedicated library. Due to many resonances, this range of neutron energy has complicated interactions with a nucleus and can therefore

not be managed with simple and basic atomic models. Low energy neutron transport in FLUKA is activated by the input card LOW-NEUT.

The point-wise and group wise transport [81], are two main approaches in neutron transport. FLUKA utilizes the group-wise approach to handle transportation of low energy neutrons. The range of energy is split into energy groups within which this approach uses a single cross-section, weighted by fluence. Pignol et al. [82] reported that the fluence is considered to follow a $1/E$ distribution between 1 eV and 1 MeV in this weighting and a lower-energy Maxwell distribution. The errors in this approach are minimized by keeping the group widths small. The group-wise approach is preferred because it is much faster and produces some very good results for most applications. On the other hand, Ballarini et al. [83] mentioned that the multi-group transport is established on evaluated cross section data files inclusive of ENDF/B-VI, JEFF, JENDL and so forth. For low-energy neutrons, these files present neutron cross sections for all channels.

Since the various transport options behind FLUKA have been discussed, now its structure is outlined.

(b). Structure

The FLUKA input file is an ASCII (American Standard Code for Information Interchange) file with extension (.inp). This FLUKA input file is a text file as shown in Appendix D, comprising a series of lines termed cards. Below is a typical FLUKA input file structure :

- Title and comments
- Beam description
- Description of geometry
- Media/material specification
- Material assignment

- Scoring estimators
- Initialisation of the random number sequence
- START
- STOP

FLUKA is a powerful MC package for particle transport and interaction. Next, a summary of FLUKA applications is presented.

(c). Applications

FLUKA is used for a wide range of applications, including:

1. applications in nuclear and high energy physics such as the neutron time-of-flight (nTOF) target design and Large Hadron Collider (LHC) devices for beam interception [84],
2. cosmic ray studies,
3. estimation of radiation dose received by airplane cabin crews,
4. design of detectors and telescopes,
5. heavy ion and proton radiotherapy,
6. labyrinth design for medical accelerators as well as,
7. accelerator shielding.

3.3.2 FLUKA Simulation Results

As mentioned earlier, the aim of this project is to design an optimal biological radiation shielding to house the envisaged Rhodotron accelerator. The aim of this subsection is to present results for the FLUKA shielding calculations.

3.3.2.1 FLUKA Geometry Design

In this sub-subsection, the proposed FLUKA shielding geometry is presented. Basic objects called finite bodies (cylinders, spheres and parallelepipeds) are used to design the facility structure. The structure includes concrete walls and door, labyrinths, air bodies outside and inside the building as well as soil and all the dimensions of this geometry are expressed in centimetres. All the regions corresponding to these bodies were assigned to the corresponding materials for example, the grey region in this diagram represents concrete walls. The elemental composition of the ordinary concrete used in the FLUKA calculations is shown in Table 3.7.

Table 3.7: *The elemental composition of concrete used in the FLUKA simulations [68].*

Element	Composition
Al	4.48%
Ca	10.05%
Co	2.55 ppm
Eu	0.294 ppm
Fe	2.92%
H	0.55%
Mg	2.0%
O	40.91%
Si	31.1%

The proposed biological shielding structure is designed using FLUKA. Figure 3.4 shows a top view layout of the proposed structure plotted at X-Z planes. The X-plane represents the width and the Z-plane denotes the length of the facility relative to the ground level.

Figure 3.5 shows a side view of the proposed design plotted at Y-Z planes.

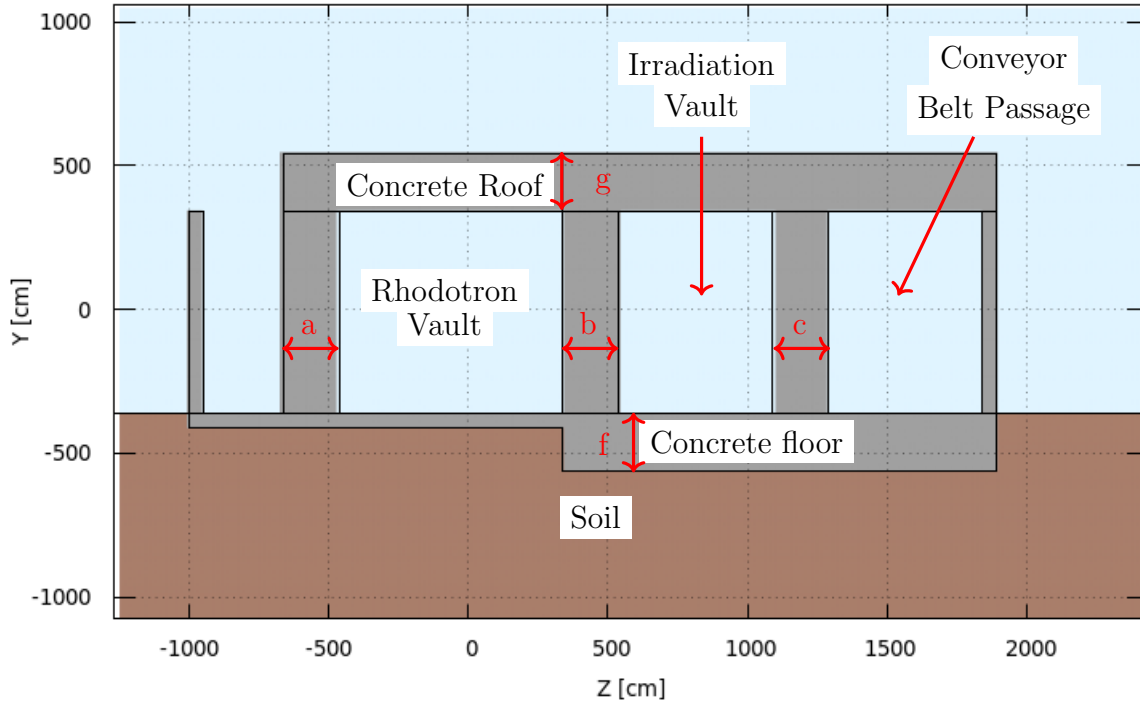


Figure 3.5: Cross-sectional FLUKA geometry layout in the YZ plane. The Y-plane shows height and the Z-plane represents length of the structure. The alphabetic letters a , b , c , g and f denote the shield thickness to be determined.

The Y-plane denotes the height and Z-plane is the length. In this design, the TT-100 Rhodotron accelerator is housed at an elevated height (1 m) above the concrete floor at the centre of the ‘Rhodotron vault’. Access to the Rhodotron accelerator is through the labyrinth and concrete sliding door. This is to ensure that the dose rates outside the Rhodotron vault do not exceed maximum allowed levels.

A horizontal beam-line (not shown in the figure) will run from the Rhodotron accelerator through concrete wall ‘b’ into the irradiation vault. Inside the irradiation vault, a 270° bending magnet will be used to change the beam direction from the horizontal to downward vertical direction.

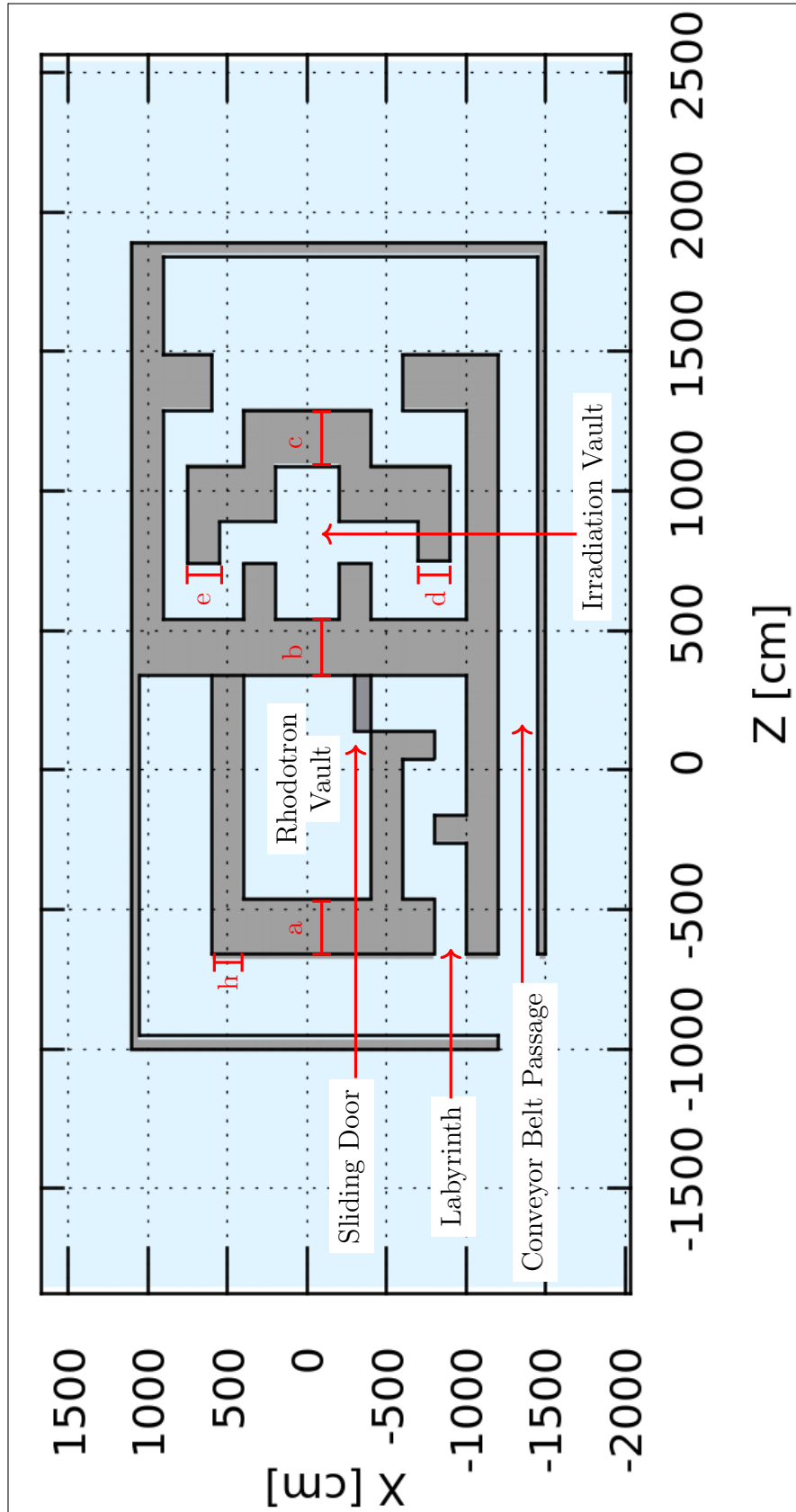


Figure 3.4: FLUKA geometry layout plotted at X-Z planes. X-plane represents the width while Z is length of the structure. The alphabetic letters a, b, c, d, e, and h denote the shield thickness to be calculated.

FLUKA calculations were performed to determine the shield thickness indicated with letters as shown in Figures 3.4 and Figure 3.5. Results from analytic calculations in Section 3.18 were used as baseline to set a rough estimate of thickness in the FLUKA geometry.

3.3.2.2 FLUKA Radiation Level Results

The aim of this sub-subsection is to present the FLUKA radiation field results. The flair USBIN cards are used to present 2-dimensional radiation plots. The simulations took 60 computer minutes consisting of 25 running cycles. One million primary particles were simulated in the run. Furthermore, a scaling factor of 2.497×10^{16} was used to normalize results to the primary beam current (4 mA) of a TT-100 Rhodotron accelerator.

To keep track of the photon distribution in the irradiation vault and the conveyor labyrinth, a 2D plot of the photon distribution projected from the top view as shown in Figure 3.6 was plotted.

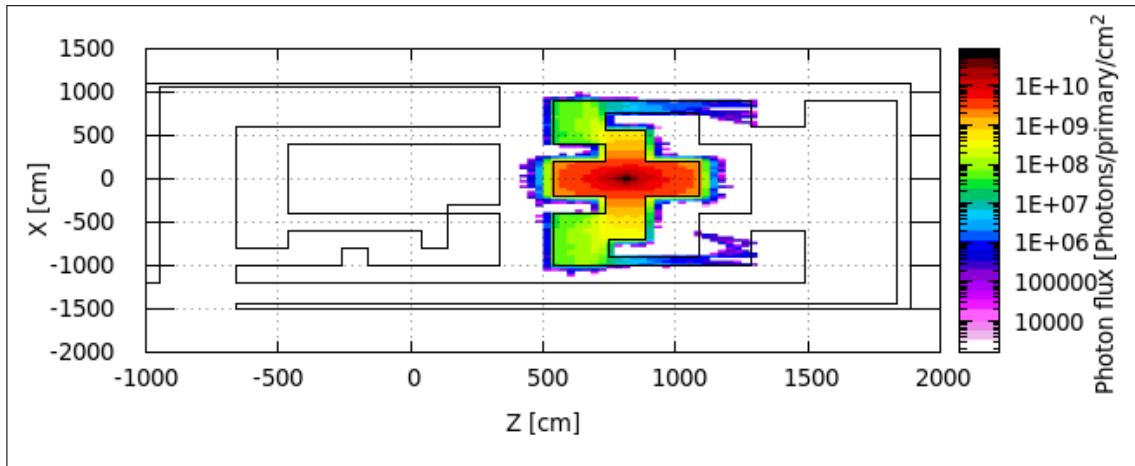


Figure 3.6: *XZ plane showing top view plot of photon flux, Y from -900 to 700 cm.*

Figure 3.7 presents a 2-D side view of the photon flux in the irradiation vault. This plot shows a transverse view of photon distribution.

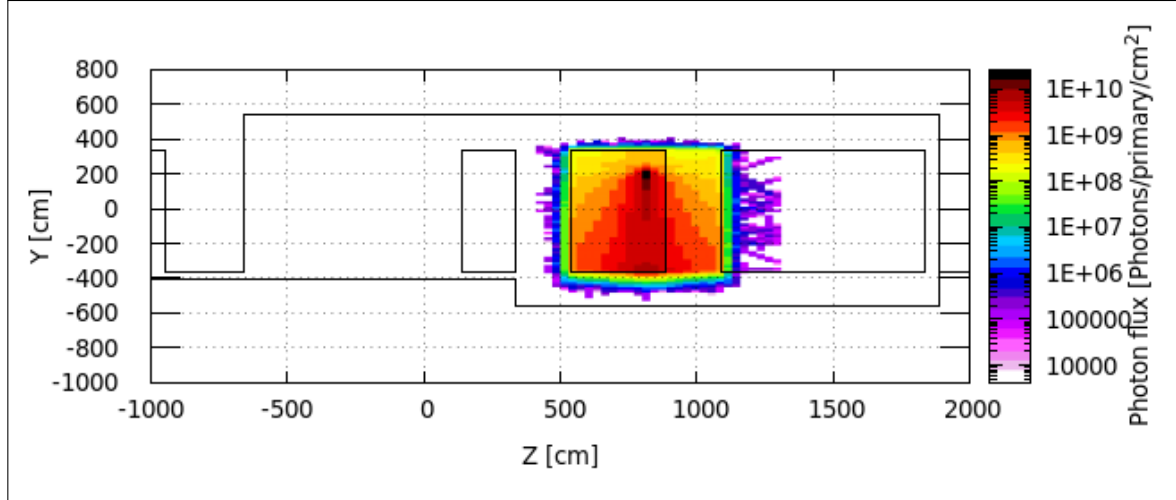


Figure 3.7: *FLUKA* result for photon flux in the *YZ* plane with *X* from -2000-1100 cm.

To evaluate the dose distribution in the irradiation vault and the conveyor labyrinth, a 2D plot of the photon dose distribution projected both from the top view as well as the transverse section as shown in Figure 3.8 and Figure 3.9 were plotted.

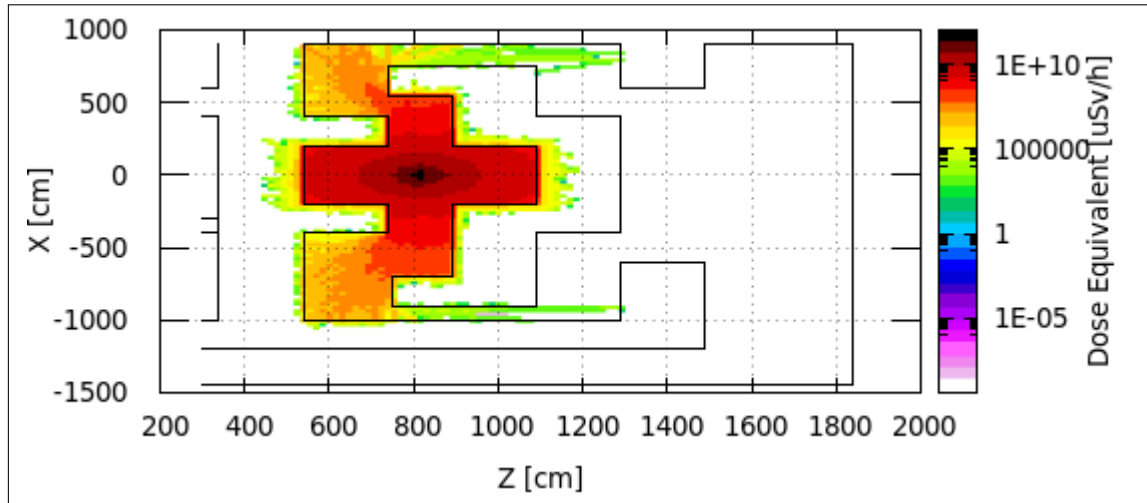


Figure 3.8: *FLUKA* result showing top view photon dose equivalent rate plotted in the *XZ* plane, *Y* from -900 to 700 cm.

3.3.3 Discussion of FLUKA Results

The FLUKA package was utilized to design a biological shielding structure to house an envisaged TT-100 Rhodotron accelerator. In this subsection, the photon flux and dose rate distribution plots are discussed.

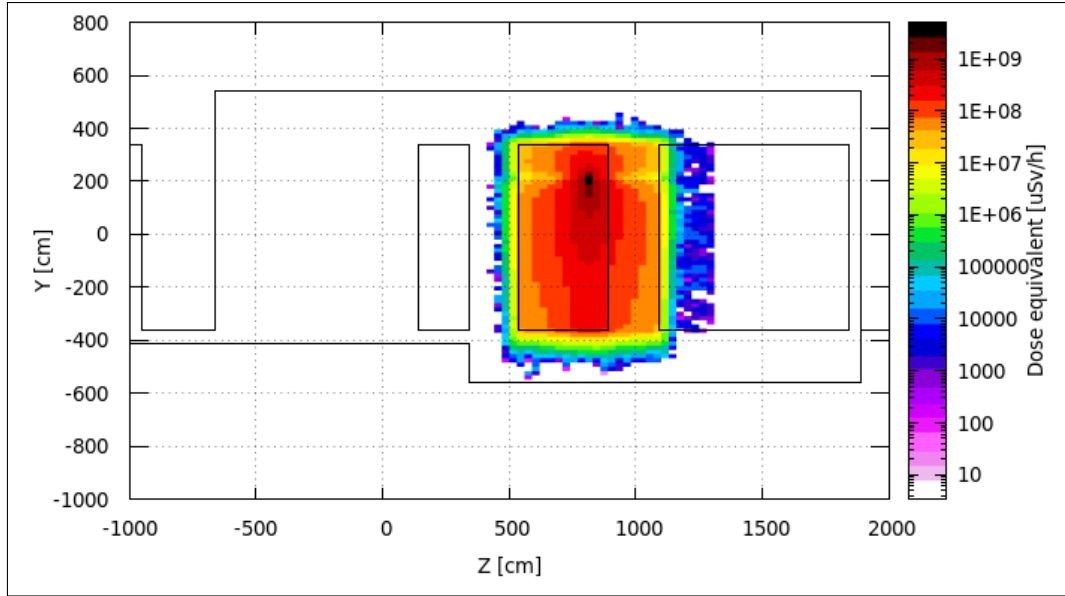


Figure 3.9: *FLUKA* result of photon dose equivalent rate plotted in the *YZ* axis, for *X* ranging from -2000 to 1100 cm.

Figure 3.6 shows a 2D plot of photon distribution projected from a top view. A considerable photon flux was registered around $X = 0$ cm and Z approximately 800 cm. This is true because it is at this location where an X-ray target is located. Furthermore, the result shows that a concrete wall with a thickness of 2 m was sufficient to stop photons from escaping into uncontrolled areas with the public. Some scattered photons leak through the conveyor belt maze, nevertheless, these photons die at some distance. For attenuation of these photons through the concrete roof and floor, a transverse section of the shielding structure projected at *YZ* plane was plotted to show a side view photon distribution. Figure 3.7 indicates that photons do not escape through the concrete roof and floor.

The objective behind designed shielding was to attenuate biological dose rates to levels less than $5 \mu\text{Sv h}^{-1}$. From the dose rate plots obtained, Figure 3.8 shows a top view distribution. The registered dose rates show that the concrete wall of thickness 2 m was sufficient to attenuate dose level to approximately $5 \mu\text{Sv h}^{-1}$ beyond the walls. The dose equivalent rate peak through the shield occurs at $X = 0$ cm and Z approximately 800 cm, which approximates a rough location of the electron to bremsstrahlung conversion consistent with the results shown in Figure 3.9. Nonetheless, this demonstrates that a 2 m concrete floor and roof satisfies the shield design requirements.

Summary, Conclusion and Recommendations

The purpose of this chapter is to give an overall summary and draw conclusion on findings of the study. The aim of this project was to design a biological shielding structure for a 10 MeV Rhodotron accelerator, to minimize the radiation dose rates to the internationally tolerable limits without compromising the intended use of the facility. Firstly, the Rhodotron electron accelerator was introduced. The operating principle of an envisaged TT-100 model was defined, its transverse optics were modelled and advantages of the Rhodotron over LINAC accelerator were discussed. Furthermore, a survey of potential industrial applications for the Rhodotron accelerator for Botswana were described.

To design an optimal biological shielding structure to house the 10 MeV Rhodotron accelerator, two methods of shielding calculations were employed namely analytical estimates using empirical formulas from the literature and Monte Carlo (MC) predictions based on the FLUKA simulation package. The shielding design was to reduce dose rates levels to $5 \mu\text{Sv h}^{-1}$. The analytic calculations used empirical formulas from available literature as a base line to make a theoretical informed consideration for a required shield thickness. On the other hand FLUKA, a Monte Carlo simulation package for particle transport and interaction was used to design the shielding structure.

A worst case scenario where 10% of the electron beam was incidence on bending magnets and beam-line was considered when shielding the Rhodotron vault. Likewise, when deter-

mining shield thickness for the irradiation vault, a worst case scenario was evaluated when the whole electron beam hits a tantalum target for secondary X-ray production. The analytic calculations show that an ordinary concrete wall with a thickness of approximately 2.1 m is sufficient to shield the Rhodotron accelerator vault. Using the latter value as the input for FLUKA, the thickness was varied in steps of 0.01 m from a lower limit of 1.9 m until the biological dose rate of $5 \mu\text{Svh}^{-1}$ was achieved.

The FLUKA results show that a 2 m thick ordinary concrete wall, roof and slab are sufficient to shield both the accelerator and irradiation vaults to permissible levels for optimal and safe operation for a 10 MeV TT-100 Rhodotron electron accelerator. Future work could consider using another Monte Carlo package called Monte Carlo N-Particle Transport Code (MCNP) for comparison with FLUKA shielding calculations.

Appendix A

Table A.1: *The TT-100 Rhodotron technical specifications*[4, 7].

Beam energy	Standard	10 MeV
	Energy gain	0.833 MeV per pass
	Optional second output	2.5 - 6.6 MeV
Beam power	Guaranteed	40 kW
Beam current	4 mA	
Beam orientation	Vertical or Horizontal	
Power consumption	Stand by	< 10 kW
	At 45 kW beam power	< 210 kW
RF system	Mode	Continuous wave
	Frequency	215 MHz
Dimensions	Cavity height	0.75 m
	Cavity thickness	5 mm
	Total height	1.75 m
	Cavity outer diameter	1.05 m
	Total diameter	1.60 m
	Weight	2500 kg
Electrical power	400 VAC, 50 Hz	3 phases + neutral + ground ($\pm 5\%$)
	250 kVA	Voltage to be nominal ($\pm 5\%$)
Scanning horn	Length	1.00 m
	Frequency	100 Hz ($\pm 5\%$)
	Uniformity	$\pm 5\%$
	Range	30 to 100% of scanning length
Control system	PLC	Siemens S7
	User interface	User friendly PC based interface
Building requirements	Vault	4 m x 4 m x 3.5 m
	Power supply and control rooms	5 m x 4.5 m x 3 m
	Power supplies weight	2500 kg
Secondary water cooling system	Flow	22 m ³ /h (DP: 0.5 Bars)
	Temperature Power to be removed	Maximum 15 °C <200 kW including beam stopping power

Appendix B

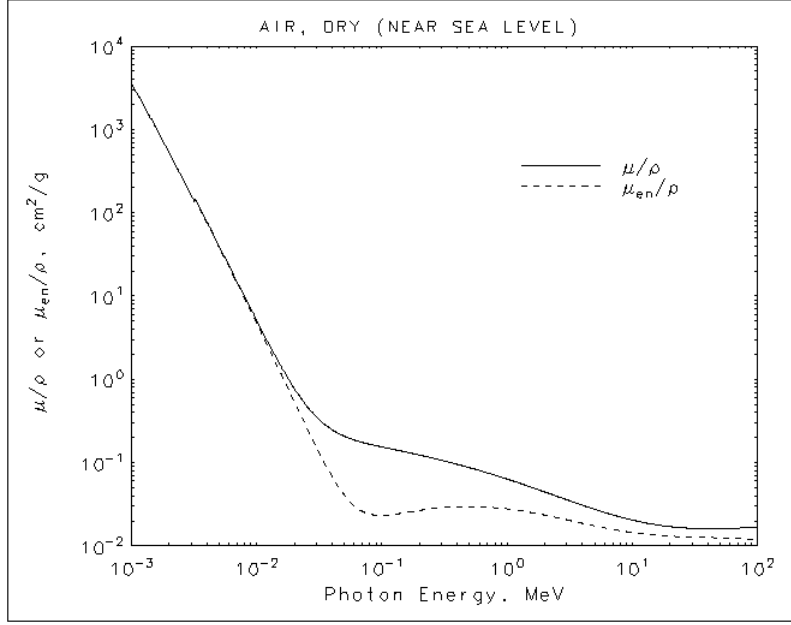


Figure B.1: Graphs of mass attenuation coefficient, μ/ρ and mass energy-absorption coefficient, μ_{en}/ρ as function of photon energy for air [85].

Table B.1: Air Mass-Energy Attenuation Coefficients, μ_{en}/ρ and Linear Attenuation Coefficients, μ for specific energies.

Beam Energy (MeV)	μ_{en}/ρ (cm^2g^{-1})	μ (cm^{-1})
0.833	0.02882	3.726×10^{-5}
1.666	0.02547	3.293×10^{-5}
2.499	0.02345	3.032×10^{-5}
3.332	0.02057	2.659×10^{-5}
4.165	0.01870	2.417×10^{-5}
4.998	0.01740	2.249×10^{-5}
5.831	0.01647	2.129×10^{-5}
6.664	0.01585	2.050×10^{-5}
7.497	0.01549	2.000×10^{-5}
8.330	0.01525	1.971×10^{-5}
9.163	0.01508	1.950×10^{-5}
9.996	0.01450	1.874×10^{-5}

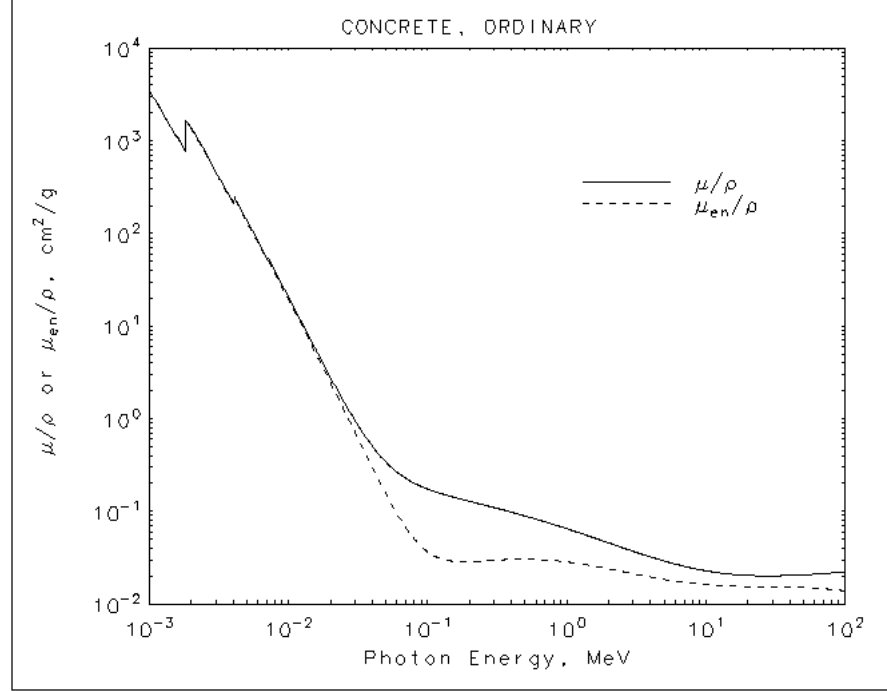


Figure B.2: Graphs of mass attenuation coefficient, μ/ρ and mass energy-absorption coefficient, μ_{en}/ρ as function of photon energy for ordinary concrete [85].

Table B.2: Ordinary Concrete Mass-Energy Attenuation Coefficients, μ_{en}/ρ and Linear Attenuation Coefficients, μ for specific energies.

Beam Energy (MeV)	μ_{en}/ρ (cm ² g ⁻¹)	μ (cm ⁻¹)
0.833	0.02940	0.141
1.666	0.02595	0.124
2.499	0.02395	0.114
3.332	0.02120	0.101
4.165	0.01951	0.093
4.998	0.01840	0.088
5.831	0.01763	0.085
6.664	0.01755	0.084
7.497	0.01680	0.082
8.330	0.01669	0.080
9.163	0.01646	0.079
9.996	0.01617	0.077

Table B.3: Analytic shielding calculations for the TT-100 Rhodotron accelerator vault; imported Microsoft Excel sheet.

	A	B	C	D	E	F	G	H	I	J
1	$Z_{concrete}$	13.34	E [MeV]	μ_{air} [m ⁻¹]	$\mu_{concrete}$ [cm ⁻¹]	$\mu_{concrete}$ [m ⁻¹]	D_i [mSvh ⁻¹]	μ_{Svh}^{-1}	D_f [mSvh ⁻¹]	μ_{Svh}^{-1}
2	Z_{Fe}	26	0.83	3.73E-03	1.41E-01	14.11	3.08E2	3.08E5	4.16E-11	4.16E-08
3	Shield t [m]	2.1	1.67	3.29E-03	1.25E-01	12.46	1.09E3	1.09E6	4.76E-09	4.76E-06
4			2.50	3.03E-03	1.15E-01	11.50	2.26E3	2.26E6	7.40E-08	7.40E-05
5	I [A]	4.00E-03	3.33	2.66E-03	1.02E-01	10.18	3.52E3	3.52E6	1.85E-06	1.85E-03
6	e	1.60E-19	4.17	2.42E-03	9.36E-02	9.36	5.00E3	5.00E6	1.44E-05	1.44E-02
7	ρ_{Air} [gcm ⁻³]	1.29E-03	5.00	2.25E-03	8.83E-02	8.83	6.70E3	6.70E6	5.91E-05	5.91E-02
8	Rt [m]	0.554	5.83	2.13E-03	8.46E-02	8.46	8.64E3	8.64E6	1.65E-04	1.65E-01
9	d [m]	4	6.66	2.05E-03	8.42E-02	8.42	1.09E4	1.09E7	2.25E-04	2.25E-01
10	$\rho_{Concrete}$ [kgm ⁻³]	[gcm ⁻³]	7.50	2.00E-03	8.06E-02	8.06	1.34E4	1.34E7	5.94E-04	5.94E-01
11	2400	4.8	8.33	1.97E-03	8.01E-02	8.01	1.63E4	1.63E7	8.06E-04	8.06E-01
12			9.16	1.95E-03	7.90E-02	7.90	1.95E4	1.95E7	1.22E-03	1.22E00
13			10.00	1.87E-03	7.76E-02	7.76	2.23E4	2.23E7	1.86E-03	1.86E00
14										
15						SUM	1.10E5	1.10E8	4.95E-03	4.95E00

Formulas for some selected cells:

Cell G2: $=((0.00035 * C2 * B2) * (0.1 * (B5 / B6) * C2) * 0.00000000000016 * D2 * 3600) /$
 $(1.293 * 4 * PI()) * (2.6 * 2.6) * 0.001)$

Cell H2: $=G2 * 1000$

Cell I2: $=G2 * EXP(-(F2 * B3))$

Cell J2: $=I2 * 1000$

Cell G15: $=SUM(G2:G13)$

Cell J15: $=SUM(J2:J13)$

Appendix C

The main aim of this Appendix is to provide additional technical FLUKA informational that may be useful to the reader.

C1 Physical units

The units commonly used in FLUKA input and output files are given in Table C.1 below:

Table C.1: *Units used in FLUKA input and output files.*

Quantity	Unit
Distance	cm
Energy	GeV
Momentum	GeVc ⁻¹
Temperature	degree Kelvin
Solid angle	sr
Magnetic field	T
Electric field	kVcm ⁻³
Time	s
Activity	Bq
Linear Energy Transfer (LET)	keV/ (μm gcm ⁻³)
Dose equivalent	pSv

C2 Beam definition

The primary beam is specified by the BEAM and BEAMPOS cards. The BEAM card defines primary beam particle (e.g. ELECTRON), beam energy (e.g. 0.01 GeV) while the BEAMPOS card specifies the beam starting position (X,Y,Z) and its direction.

C3 Geometry definition

Complex geometries and tracking of charged particles are manipulated and handled with a package called Combinatorial Geometry (CG) [86]. The CG package has a unique ability of handling charged particles in the existence of fields. Bodies as well as regions are fundamental concepts in the present CG package. Bodies are convex solid bodies including infinite circular cylinders and planes while regions are described as bodies combined using “boolean operations” such as intersection, subtraction and union.

C4 Material definition

In FLUKA geometric regions are supposed to be filled with vacuum, or with blackhole, or with a homogeneous material. The material blackhole is used to stop particle trajectories. Materials can either be simple elements (natural composition or consisting of an atom) or compounds (mixture or alloy) of known compositions. The material name, density and isotope specifications (compound) are properties that define the material card.

C5 Material assignment

The ASSIGNMA card is used to describe the correlation of material indices and regions. This card assign materials to the specific regions, for example, the material blackhole “BLCKHOLE” is assigned to region blackbody “BLCKBODY”.

C6 Scoring

In FLUKA, scoring refers to a measurement of a physical quantity under investigation. FLUKA has an intrinsic generic scoring alternatives that distinguish it from several programs in which end-users are expected to create their own provisional scoring methods for a specific assignment. Scoring cards are used to detect and measure the specified quantity e.g. the USRBDX and USRBIN cards which were used in this study. The USRBDX card describe a detector for estimating current as well as boundary fluence. The USRBIN scoring card is used to specify a detector measuring quantities such as dose, dose rate, as well as dose equivalent and the results

are plotted in 2-dimensional grids. For further reading, the following references provide more details on scoring: [\[78, 87, 88\]](#).

C7 Flair

FLUKA uses Flair as a graphical user interface (GUI) for composition and editing of FLUKA input files provided in Appendix [D](#), code application and display of the output data [\[89\]](#). The user interface is shown in Figure [C.1](#).

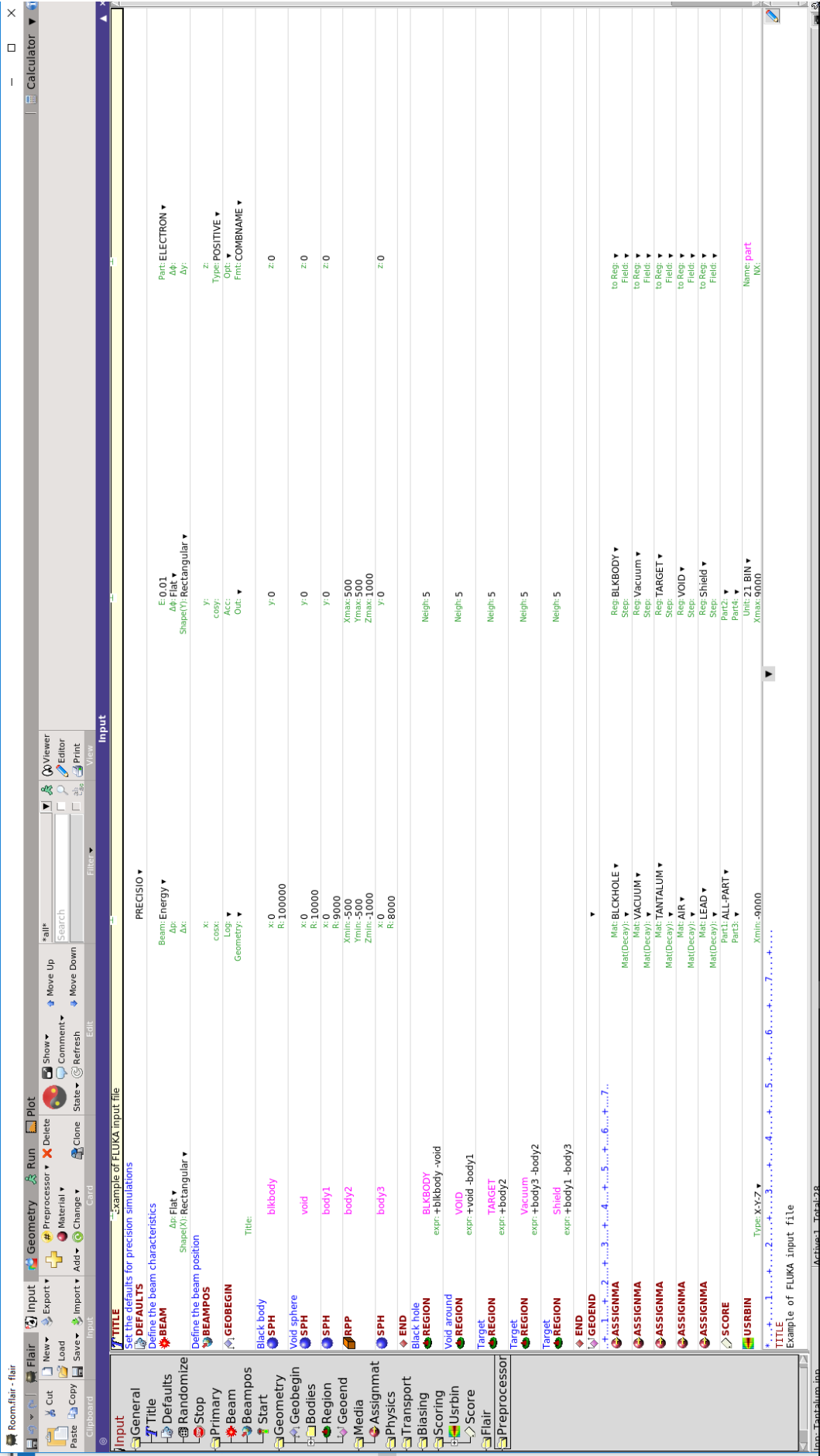


Figure C.1: Flair graphic user interface.

Appendix D

In this Appendix, the input text file for the FLUKA shielding simulations carried out in this research project is provided. The file contains all the data cards which are a sequence of option lines that were used for specific options requested.

```

TITLE
FLUKA shielding simulations for a 10 MeV Rhodotron accelerator facility.
DEFAULTS                                     EM-CASCA
* Beam specs
BEAM          -0.01                0.0      45.      0.0      -1.ELECTRON
* Beam position
BEAMPOS        0.0      250.      814.                -1.
GEOBEGIN                                     COMBNAME
0      0
* Geometry definition
RPP body1      -3000. 2000. -2011. 2989. -2061. 2939.
RPP body2      -5000. 4000. -6000. 5000. -4000. 5000.
RPP body3      400. 600. -361. 339. -461. 339.
RPP body4      -800. 600. -361. 339. -661. -461.
RPP body5      -600. -400. -361. 339. -461. 139.
RPP body6      -800. -600. -361. 339. 39. 139.
RPP body8      -1200. 1100. -361. 339. 339. 539.
RPP body9      -1200. -1000. -361. 339. -661. 1289.
RPP body10     -1000. -800. -361. 339. -261. -161.

```

```

RPP body11      900. 1100. -361. 339. 539. 1839.
RPP body14      -1450. 1100. -361. 339. 1839. 1889.
RPP body15      -1500. -1450. -361. 339. -661. 1889.
RPP body17      -1500. 1100. -561. -361. 339. 1889.
RPP body21      -1200. 1100. 339. 539. 339. 1889.
RPP Door        -400. -300. -361. 339. 139. 339.
RPP BoxX1       -400. 400. -361. 339. 1089. 1289.
RPP BoxX2       -700. -200. -361. 339. 889. 1089.
RPP BoxX3       200. 750. -361. 339. 889. 1089.
RPP body12      -1200. -600. -361. 339. 1289. 1489.
RPP body16      -600. 600. 339. 539. -661. 339.
RPP body7       200. 400. -361. 339. 539. 739.
RPP body13      -400. -200. -361. 339. 539. 739.
RPP body18      600. 900. -361. 339. 1289. 1489.
RPP body19      -900. -700. -361. 339. 749. 1089.
RPP body22      550. 750. -500. 500. 739. 889.
RPP body20      1050. 1100. -361. 339. -1000. 339.
RPP body23      -1200. 1050. -361. 339. -1000. -950.
RPP body24      -1500. 1100. -411. -361. -1000. 339.
RPP body25      -3000. 2000. -2011. -361. -2061. 2939.
RPP body26      -2.5 2.5 219.9 219.95 769. 859.
RPP body27      -45. 45. 219.7 219.9 769. 859.
RPP body28      -45. 45. 219.5 219.7 769. 859.
YCC body29      814. 0.0 45.
YZP body30      0.0
RPP body31      -45. 45. 235. 242. 769. 859.
RPP body32      -2.5 2.5 235. 242. 769. 859.
END

* Definition of Regions
*
* Black hole
BLKBODY        5 +body2 -body1

```

```

Wall          5 +body3 | +body4 | +body5 | +body6
!@alpha=100

Air           5 +body1 -BoxX1 -BoxX2 -BoxX3 -Door -body10 -body11 -body14
             -body15 -body17 -body21 -body3 -body4 -body5 -body6 -body8 -body9 -body12
             -body16 -body7 -body13 -body12 -body18 -body19 -body22 -body20 -body23
             -body24 -body25 -body26 -body27 -body28-body31
             | +body31 +body32

Slab          5 +body17
             | +body24

Roof          5 +body21

Door          5 +Door

LabrWall      5 +body3 +body4
             | +body10
             | +body12
             | +body9
             | +body11
             | +body14
             | +body15
             | +body8
             | +body7
             | +body13
             | +body18
             | +body20
             | +body23

Roof2         5 +body16

Shield        5 +BoxX1
             | +BoxX2
             | +BoxX3
             | +body19
             | +body22

Soil          5 +body25 -body24 -body17

TargReg1      5 +body26

```

```

TargReg2      5 +body27
TargReg3      5 +body28
COLLI         5 +body31 -body32
END
GEOEND

* Definition of Materials
*
* Concrete
MATERIAL              2.4                      CONCRETE
MATERIAL      63.      5.2443                      Europium
MATERIAL      27.      8.9                        Cobalt
COMPOUND      -0.0055 -HYDROGEN -2.94E-07 -Europium  -0.489  -OXYGENCONCRETE
COMPOUND      -2.55E-06  -Cobalt  -0.02 -MAGNESIU  -0.0448 -ALUMINUMCONCRETE
COMPOUND      -0.311  -SILICON  -0.0292  -IRON  -0.1005  -CALCIUMCONCRETE
* Soil
MATERIAL              2.65                      SOIL
MATERIAL      16.      32.06      2.                      SULFUR
MATERIAL      19.              0.862                      POTASSIU
MATERIAL      55.              1.873                      CESIUM
COMPOUND      0.42      OXYGEN      0.21  SILICON      0.135      IRONSOIL
COMPOUND      0.05  MAGNESIU      0.04  CALCIUM      0.08  POTASSIU
COMPOUND      0.005  CESIUM      0.03  SULFUR                      SOIL
* Material Assignment
ASSIGNMA      AIR      Air
ASSIGNMA      BLCKHOLE  BLKBODY
ASSIGNMA      CONCRETE  Wall
ASSIGNMA      CONCRETE  Roof
ASSIGNMA      CONCRETE  Door
ASSIGNMA      CONCRETE  Slab
ASSIGNMA      CONCRETE  LabrWall
ASSIGNMA      CONCRETE  Roof2
ASSIGNMA      CONCRETE  Shield

```

```

ASSIGNMA      SOIL      Soil
* Target
ASSIGNMA      TANTALUM  TargReg1
ASSIGNMA      WATER    TargReg2
ASSIGNMA      ALUMINUM  TargReg3
ASSIGNMA      BLCKHOLE   COLLI
* Importance Biasing
#if
BIASING        0.0              1.  BLKBODY      Air      PRINT
BIASING        2.              4.      Air
BIASING        2.              16.     Slab
BIASING        2.              32.     Soil
#endif
* Estimators/Scoring Cards
SCORE          BEAMPART    PHOTON  DOSE-EQ    DOSE
USRBIN         10.  BEAMPART    -40.     1100.     700.     2000.BeamPart
USRBIN        -2000.     -900.   -1000.     100.     100.     100. &
USRBIN         10.  PHOTON      -41.     1100.     700.     2000.PhotDist
USRBIN        -2000.     -900.   -1000.     100.     100.     100. &
USRBIN         10.  DOSE-EQ     -42.     1100.     700.     1400.DoseEq
USRBIN        -2000.     -900.     300.     100.     100.     100. &
AUXSCORE       USRBIN    PHOTON              DoseEq              AMB74
USRBIN         10.  DOSE-EQ     -43.     900.     700.     1840.PhotonDE
USRBIN        -1500.   -1000.     300.     100.     100.     100. &
AUXSCORE       USRBIN    PHOTON              DoseEq              AMB74
USRBIN         10.  DOSE        -44.     1100.     700.     2000.Dose
USRBIN        -2000.     -900.   -1200.     100.     100.     100. &
USRBDX         101.  PHOTON      -45.  TargReg3      Air      PhotFL
USRBDX         0.008  2.5E-11    200.              200. &
USRBDX         101.  PHOTON      -46.      Air  LabrWall      PhotFL
USRBDX         0.008  2.5E-11    200.              200. &
USRBIN         10.  ENERGY     -47.      2.5     220.     860.EnerDep

```

```
USRBIN      -2.5      219.6      770.      200.      400.      200. &
AUXSCORE    USRBIN    PHOTON                      EnerDep
* Set the random number seed
RANDOMIZ      1.
* Set the number of primary histories to be simulated in the run
START        100000.                                3600.
STOP
```

Bibliography

- [1] Republic of Botswana, “Government portal.” <http://www.gov.bw/en/Ministries--Authorities/Ministries/Ministry-of-Local-Government-MLG1/News/VISION-2036-Prosperity-for-all-/>, 2019. [Online; accessed 28-August-2019].
- [2] J. Pottier, “A new type of RF electron accelerator: the Rhodotron,” *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, vol. 40, pp. 943–945, 1989.
- [3] Y. Jongen, M. Abs, S. Zaremba, T. Delvigne, and A. Herer, “Realignment of a diverging electron beam: a new beam delivery system for rhodotrons,” in *Proceedings of the 1997 Particle Accelerator Conference (Cat. No. 97CH36167)*, vol. 3, pp. 3857–3859, IEEE, 1997.
- [4] Y. Jongen, M. Abs, T. Delvigne, A. Herer, J. Capdevila, F. Genin, and A. Nguyen, “Rhodotron accelerators for industrial electron-beam processing: a progress report,” *Proceedings of the EPAC, Bristol, UK*, pp. 2687–2692, 1996.
- [5] B. P. Fairand, *Radiation sterilization for health care products: x-ray, gamma, and electron beam*. CRC Press, 2001.
- [6] IBA Industrial, “Rhodotron and Dynamitron documents and descriptions.” <http://www.iba-industrial.com/downloads>, 2018. [Online; accessed 28-October-2018].

-
- [7] IBA Industrial, “Second Generation Rhodotron E-beam Accelerator.” <https://www.iba-industrial.com/downloads#modal.download>, 2017. [Brochure].
 - [8] W. Kleeven, “Design and Simulation Tools for the High-Intensity Industrial Rhodotron Accelerator,” 2017.
 - [9] A. Poursaleh, I. Jabbari, and H. Khalafi, “Design and construction of multi-port solid state structure for the Rhodotron accelerator,” *Journal of Instrumentation*, vol. 12, no. 04, p. P04001, 2017.
 - [10] A. Telnov, “Status report of development of high power beam cw electron accelerator,” in *26th Russian Particle Accelerator Conf.(RuPAC’18), Protvino, Russia, 1-5 October 2018*, pp. 72–74, JACOW, Geneva, Switzerland, 2018.
 - [11] A. N’guyen and J. Pottier, “Electron accelerator with coaxial cavity,” Apr. 21 1992. US Patent 5,107,221.
 - [12] M. Van Lancker, A. Herer, M. R. Cleland, Y. Jongen, and M. Abs, “The IBA Rhodotron: an industrial high-voltage high-powered electron beam accelerator for polymers radiation processing,” *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, vol. 151, no. 1-4, pp. 242–246, 1999.
 - [13] D. Defrise, M. Abs, F. Genin, and Y. Jongen, “Technical status of the first industrial unit of the 10 MeV, 100 kW Rhodotron,” *Radiation Physics and Chemistry*, vol. 46, no. 4-6, pp. 473–476, 1995.
 - [14] I. Jabbari, A. M. Poursaleh, and H. Khalafi, “Design study of double-layer beam trajectory accelerator based on the Rhodotron structure,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 828, pp. 72–80, 2016.
 - [15] J. Forshaw and G. Smith, *Dynamics and Relativity*. Manchester Physics Series, Wiley, 2014.

-
- [16] D. Bohm, *The special theory of relativity*. Routledge, 2015.
- [17] K. Mohindroo, *Basic Principles of Physics*. Pitambar Publishing, 1997.
- [18] A. Nassiri, B. Chase, P. Craievich, A. Fabris, H. Frischholz, J. Jacob, E. Jensen, M. Jensen, R. Kustom, and R. Pasquinelli, “History and technology developments of radio frequency (rf) systems for particle accelerators,” *IEEE Transactions on Nuclear Science*, vol. 63, no. 2, pp. 707–750, 2015.
- [19] IBA Industrial, “Practical Advantages of the Rhodotron.” https://www.iba-industrial.com/downloads#modal_download, 2017. [Whitepaper].
- [20] M. Cleland, A. Herer, Y. Jongen, M. Abs, J. Meissner, D. Kerluke, A. Winter, and R. Zlousic, “A Rhodotron electron beam facility for pre-treatment of cellulosic pulp,” in *AIP Conference Proceedings*, vol. 475, pp. 953–956, AIP, 1999.
- [21] A. Nor Rul Hasma, *Electron beam sterilization*. PhD thesis, University Malaysia Pahang, 2004.
- [22] L. Gazso and C. Ponta, *Radiation Inactivation of Bioterrorism Agents*. NATO Science Series, IOS Press, 2005.
- [23] M. Desrosiers, B. Coursey, S. Seltzer, L. Hudson, J. Puhl, P. Bergstrom, F. Bateman, S. Cooper, D. Alderson, G. Knudson, *et al.*, “Irradiation decontamination of postal mail and high-risk luggage,” in *Radiation Inactivation of Bioterrorism Agents. NATO Science Series I: Life and Behavioural Sciences*, vol. 365, pp. 115–126, IOS Press The Netherlands, 2005.
- [24] H.-S. Shin, Y.-R. Kim, B. Han, I. E. Makarov, A. V. Ponomarev, and A. K. Pikaev, “Application of electron beam to treatment of wastewater from papermill,” *Radiation Physics and Chemistry*, vol. 65, no. 4-5, pp. 539–547, 2002.
- [25] B. Han, J. K. Kim, Y. Kim, J. S. Choi, and K. Y. Jeong, “Operation of industrial-scale electron beam wastewater treatment plant,” *Radiation Physics and Chemistry*, vol. 81, no. 9, pp. 1475–1478, 2012.

-
- [26] K. E. Nanke, *Effects of ionizing radiation on pork, beef, and turkey quality*. PhD thesis, Iowa State University, 1998.
- [27] J. Farkas, “Irradiation as a method for decontaminating food: a review,” *International journal of food microbiology*, vol. 44, no. 3, pp. 189–204, 1998.
- [28] P. B. Roberts, “Food irradiation is safe: Half a century of studies,” *Radiation Physics and Chemistry*, vol. 105, pp. 78–82, 2014.
- [29] R. M. Grodner and L. S. Andrews, “Irradiation,” in *Microbiology of marine food products*, pp. 429–440, Springer, 1991.
- [30] T. M. Arthur, T. L. Wheeler, S. D. Shackelford, J. M. Bosilevac, X. Nou, and M. Koohmaraie, “Effects of low-dose, low-penetration electron beam irradiation of chilled beef carcass surface cuts on escherichia coli o157: H7 and meat quality,” *Journal of food protection*, vol. 68, no. 4, pp. 666–672, 2005.
- [31] S. Lewis, A. Velasquez, and S. Cuppett, “Effect of electron beam irradiation on poultry meat safety and quality,” *Poultry science*, vol. 81, no. 6, pp. 896–903, 2002.
- [32] FOOD AND AGRICULTURE ORGANIZATION, WORLD HEALTH ORGANIZATION, “Codex General Standard for Irradiated Foods and Recommended International Code of Practice for the Operation of Radiation Facilities used for the Treatment of Food,” *Codex Alimentarius*, vol. 15, 1984.
- [33] IAEA, “Dosimetry for food irradiation,” tech. rep., International Atomic Energy Agency, 2002.
- [34] B. Kalyani and K. Manjula, “Food irradiation-technology and application,” *Int. J. Curr. Microbiol. App. Sci*, vol. 3, no. 4, pp. 549–555, 2014.
- [35] H. A. Mostafavi, H. Fathollahi, and F. Motamedi, “Food irradiation: Applications, public acceptance and global trade,” *African Journal of Biotechnology*, vol. 9, no. 20, 2010.

-
- [36] T. Kume, M. Furuta, S. Todoriki, N. Uenoyama, and Y. Kobayashi, "Status of food irradiation in the world," *Radiation Physics and Chemistry*, vol. 78, no. 3, pp. 222–226, 2009.
- [37] S. E.-D. A. Farag, N. H. Aziz, and E.-S. A. Attia, "Effect of irradiation on the microbiological status and flavouring materials of selected spices," *Zeitschrift für Lebensmittel-Untersuchung und Forschung*, vol. 201, no. 3, pp. 283–288, 1995.
- [38] M. Al-Bachir, "The irradiation of spices, packaging materials and luncheon meat to improve the storage life of the end products," *International journal of food science & technology*, vol. 40, no. 2, pp. 197–204, 2005.
- [39] INTERNATIONAL ATOMIC ENERGY AGENCY, *Use of Mathematical Modelling in Electron Beam Processing: A Guidebook*. No. 1 in IAEA Radiation Technology Series, Vienna: INTERNATIONAL ATOMIC ENERGY AGENCY, 2011.
- [40] D. A. Ehlermann, "The RADURA-terminology and food irradiation," *Food control*, vol. 20, no. 5, pp. 526–528, 2009.
- [41] G. Mwakikagile, *Botswana Since Independence*. New Africa Press, 2009.
- [42] K. Dizyee, D. Baker, and K. M. Rich, "A quantitative value chain analysis of policy options for the beef sector in Botswana," *Agricultural Systems*, vol. 156, pp. 13–24, 2017.
- [43] C. Sommers and X. Fan, *Food Irradiation Research and Technology*. Institute of Food Technologists Series, Wiley, 2008.
- [44] R. Maxcy and N. Tiwari, "Irradiation of meats for public health protection," in *Radiation preservation of food*, International Atomic Energy Agency, 1973.
- [45] A. BRYNJOLFSSON, "Wholesomeness of irradiated foods: a review," *Journal of Food Safety*, vol. 7, no. 2, pp. 107–126, 1985.
- [46] J. Diehl, *Safety of irradiated foods*. Food science and technology, CRC Press, 1990.

-
- [47] D. W. THAYER, “Extending shelf life of poultry and red meat by irradiation processing,” *Journal of Food Protection*, vol. 56, no. 10, pp. 831–833, 1993.
- [48] Z. Derakhshan, G. O. Conti, A. Heydari, M. S. Hosseini, F. A. Mohajeri, H. Gheisari, S. Kargar, E. Karimi, and M. Ferrante, “Survey on the effects of electron beam irradiation on chemical quality and sensory properties on quail meat,” *Food and chemical toxicology*, vol. 112, pp. 416–420, 2018.
- [49] H.-M. Lung, Y.-C. Cheng, Y.-H. Chang, H.-W. Huang, B. B. Yang, and C.-Y. Wang, “Microbial decontamination of food by electron beam irradiation,” *Trends in Food Science & Technology*, vol. 44, no. 1, pp. 66–78, 2015.
- [50] S. Brewer, “Irradiation effects on meat color—a review,” *Meat Science*, vol. 68, no. 1, pp. 1–17, 2004.
- [51] S. Millar, B. Moss, and M. Stevenson, “The effect of ionising radiation on the colour of leg and breast of poultry meat,” *Meat Science*, vol. 55, no. 3, pp. 361–370, 2000.
- [52] M. Furuta, T. Dohmaru, T. Katayama, H. Toratani, and A. Takeda, “Detection of irradiated frozen meat and poultry using carbon monoxide gas as a probe,” *Journal of agricultural and food chemistry*, vol. 40, no. 7, pp. 1099–1100, 1992.
- [53] J. Bauernfeind and D. Pinkert, “Food processing with added ascorbic acid,” in *Advances in food research*, vol. 18, pp. 219–315, Elsevier, 1970.
- [54] B. Demos, D. Gerrard, R. Mandigo, X. Gao, and J. Tan, “Mechanically recovered neck bone lean and ascorbic acid improve color stability of ground beef patties,” *Journal of food science*, vol. 61, no. 3, pp. 656–659, 1996.
- [55] L. Ramamoorthi, S. Toshkov, A. Stetzer, E. Tucker, and M. S. Brewer, “Effects of antioxidants on irradiated beef color,” *Journal of food quality*, vol. 33, no. 3, pp. 283–298, 2010.
- [56] D. Ahn, C. Jo, M. Du, D. Olson, and K. Nam, “Quality characteristics of pork patties irradiated and stored in different packaging and storage conditions,” *Meat Science*, vol. 56, no. 2, pp. 203–209, 2000.

-
- [57] D. Ahn, J. Sell, C. Jo, X. Chen, C. Wu, and J. Lee, “Effects of dietary vitamin e supplementation on lipid oxidation and volatiles content of irradiated, cooked turkey meat patties with different packaging,” *Poultry science*, vol. 77, no. 6, pp. 912–920, 1998.
- [58] K. Nam and D. Ahn, “Use of antioxidants to reduce lipid oxidation and off-odor volatiles of irradiated pork homogenates and patties,” *Meat science*, vol. 63, no. 1, pp. 1–8, 2003.
- [59] J. Black and J. Jaczynski, “Temperature effect on inactivation kinetics of *Escherichia Coli* 0157: H7 by electron beam in ground beef, chicken breast meat, and trout fillets,” *Journal of food science*, vol. 71, no. 6, pp. M221–M227, 2006.
- [60] W. P. Swanson, “Radiological safety aspects of the operation of electron linear accelerators,” *International Atomic Energy Agency*, 1979.
- [61] A. Fassò, “Radiation protection for particle accelerator facilities,” *Health Physics*, vol. 88, no. 2, p. 175, 2005.
- [62] K. H. Darby, T. C. Mcclanaha, A. Moore, C. T. Crutcher, and M. A. Megonigal, *Accelerator Facility Shielding Design*. PhD thesis, University of Tennessee, 2015.
- [63] M. L’Annunziata, *Handbook of Radioactivity Analysis*. Elsevier Science, 2012.
- [64] M. G. Stabin, *Radiation protection and dosimetry: an introduction to health physics*. Springer Science & Business Media, 2007.
- [65] H. Cember and T. E. Johnson, *Introduction to health physics*. McGraw-Hill Companies, Inc, 2009.
- [66] National Council on Radiation Protection and Measurements and Meinhold, C.B., *Limitation of Exposure to Ionizing Radiation: Recommendations of the National Council on Radiation Protection and Measurements*. NCRP report, NCRP, 1993.

-
- [67] J. Valentin, *The 2007 recommendations of the international commission on radiological protection*. Elsevier International Commission on Radiological Protection, 2008.
- [68] N. R. Mantengu, “Radiation Shielding Calculations using the FLUKA transport code for a Radioactive-ion Beam facility at iThemba LABS,” Master’s thesis, University of Zululand, 2016.
- [69] International Commission on Radiological Protection, “ICRP publication 103: the 2007 recommendations of the international commission on radiological protection,” *Ann. ICRP*, vol. 37, no. 2–4, pp. 116–117, 2007.
- [70] S. H. Rokni, J. D. Cossairt, J. C. Liu, *et al.*, “Radiation shielding at high-energy electron and proton accelerators,” tech. rep., Stanford Linear Accelerator Center (SLAC), 2007.
- [71] J. E. Turner, *Atoms, radiation, and radiation protection*. John Wiley & Sons, 2008.
- [72] C. Ipbüker, H. Nulk, V. Gulik, A. Biland, and A. H. Tkaczyk, “Radiation shielding properties of a novel cement–basalt mixture for nuclear energy applications,” *Nuclear Engineering and Design*, vol. 284, pp. 27–37, 2015.
- [73] A. Chao, H. Moser, Z. Zhao, and O. Association, *Accelerator Physics, Technology and Applications: Selected Lectures of OCPA International Accelerator School 2002, Singapore*. World Scientific, 2004.
- [74] S. G. Prasad, K. Parthasaradhi, and W. Bloomer, “Effective atomic numbers for photoabsorption in alloys in the energy region of absorption edges,” *Radiation Physics and Chemistry*, vol. 53, no. 5, pp. 449–453, 1998.
- [75] J. R. Lamarsh, *Introduction to nuclear reactor theory*, vol. 3. Addison-Wesley Reading, Massachusetts, 1966.
- [76] H. Khalafi, A. Ghane, S. S. Arshi, and F. Tabakh, “Biological shield design for a 10 MeV Rhodotron,” *Annals of Nuclear Energy*, vol. 50, pp. 111–116, 2012.

-
- [77] N. Metropolis and S. Ulam, “The Monte Carlo Method,” *Journal of the American statistical association*, vol. 44, no. 247, pp. 335–341, 1949.
- [78] A. Ferrari, P. R. Sala, A. Fasso, and J. Ranft, “FLUKA: A multi-particle transport code (Program version 2005),” tech. rep., CERN, 2005.
- [79] A. Kling, F. J. Barao, M. Nakagawa, L. Tavora, and P. Vaz, *Advanced Monte Carlo for Radiation Physics, Particle Transport Simulation and Applications: Proceedings of the Monte Carlo 2000 Conference, Lisbon, 23–26 October 2000*. Springer Science & Business Media, 2014.
- [80] E. Storm and H. Israel, “Photon cross sections from 0.001 to 100 MeV for elements 1 through 100,” 1 1967.
- [81] E. Cuccou, A. Ferrari, and G. Panini, “A group library from JEF 1.1 for flux calculations in the LHC machine detectors,” *fluka.org*, 1991.
- [82] J.-P. Pignol, P. Cuendet, N. Brassart, G. Fares, F. Colomb, C. M’Bake Diop, R. Sabattier, A. Hachem, and G. Prevot, “Combined use of fluka and mcnp-4a for the monte carlo simulation of the dosimetry of neutron capture enhancement of fast neutron irradiations,” *Medical physics*, vol. 25, no. 6, pp. 885–891, 1998.
- [83] F. Ballarini, G. Battistoni, M. Brugger, M. Campanella, M. Carboni, F. Cerutti, A. Empl, A. Fasso, A. Ferrari, E. Gadioli, *et al.*, “The physics of the fluka code: Recent developments,” *Advances in Space Research*, vol. 40, no. 9, pp. 1339–1349, 2007.
- [84] G. Battistoni, F. Broggi, M. Brugger, M. Campanella, M. Carboni, A. Empl, A. Fassò, E. Gadioli, F. Cerutti, A. Ferrari, *et al.*, “Applications of fluka monte carlo code for nuclear and accelerator physics,” *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, vol. 269, no. 24, pp. 2850–2856, 2011.
- [85] J. Hubbell and S. Seltzer, “Tables of x-ray mass attenuation coefficients and mass energy-absorption coefficients 1 keV to 20 MeV for elements $z = 1$ to 92 and 48 addi-

- tional substances of dosimetric interest,” tech. rep., National Institute of Standards and Technology, 1995.
- [86] M. Emmett, “MORSE Monte Carlo radiation transport code system,” tech. rep., Oak Ridge National Lab., TN (USA), 1975.
- [87] T. Ronaldo, “General solution to Bateman’s differential equations with direct index notation,” *International Journal of Pure and Applied Mathematics*, vol. 93, pp. 879–883, 2014.
- [88] D. Peter, B. Mimi, and L. L, *Mc 93 - Proceedings Of The International Conference On Monte Carlo Simulation In High Energy And Nuclear Physics*. World Scientific Publishing Company, 1994.
- [89] V. Vlachoudis *et al.*, “FLAIR: a powerful but user friendly graphical interface for FLUKA,” in *Proc. Int. Conf. on Mathematics, Computational Methods & Reactor Physics (M&C 2009), Saratoga Springs, New York, 2009*.

