Development of a Low Energy Electron Accelerator System for Surface Treatments and Coatings

Nuttapong Phantkankum

Kent State University

Author Note

Nuttapong Phantkankum, College of Applied Engineering, Sustainability & Technology, Kent State University.

Correspondence concerning this thesis should be addressed to Nuttapong Phantkankum, College of Applied Engineering, Sustainability & Technology, Kent State University, Kent, OH 44240.

Contact: nphantka@kent.edu
REPORT OF THESIS FINAL EXAMINATION

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Name of Candidate  Phantikankum Nuttapong

Local Address  636 Walters St. Kent Ohio 44240

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Signatures of examining committee:

Name (typed or printed)  Signatures  Pass  Fail

Roberto M. Urbe, Ph.D.  [Signature]  [Check mark]

Advisor
Darwin Boyd, Ph.D.

John Duncan, Ph.D.

Michael Fisch, Ph.D.

Shin-Min Song, Ph.D.

FINAL RESULT:  Pass   Fail

*Attach comments or specified conditions if student fails.

John C. Duncan  Graduate Program Coordinator

[Signature]  [Signature]

Chair/Director

College Dean

Registrar
College
Student
Department/School

2/05
Preface

Treatment with ionizing radiation can modify the physical, chemical or biological properties of materials. By using this method one can obtain many beneficial effects. “High – energy ionizing radiations used to initiate radiation-chemical reactions include radiation from natural and artificial radioisotopes (i.e., $\alpha$, $\beta$, and $\gamma$ radiation), x rays, neutron beams, and beams of charged particles, the latter including both electron beams and beams of positively charged particles. Of these, $\gamma$ radiation and electron beams are employed most frequently in radiation processing applications.”[1]. Thousands of industrial processes use electron accelerators – from the facilities that produce integrated circuits (ICs) to the cross-linking of plastic materials and beyond. Electron-beam applications focus on the modification of material properties such as the reduction of contaminants in surface treatment, the development of new coating materials, the alteration of plastics, medical sterilization [2], and the treatment of food by ionizing radiation [3]. Electron Beam Accelerators are durable and reliable equipment for these applications.

This thesis focuses on designing an electron accelerator system for irradiation of thin samples using a 125 keV electron emitter, high voltage cables, and a power supply obtained through a donation to KSU. To introduce the concept of a low energy electron accelerator, the following is a brief summary of the topics that are covered in each chapter.

Chapter 1 presents the background information such as characteristics of electron accelerators, how to use them, why they are important in industries, their types, their energy levels, and applications.
Chapter 2 introduces quantities and units used in a low energy electron accelerator technology for radiation processing. To build an optimal low energy electron accelerator, many possible designs and simulations were calculated with appropriate quantities and units.

Chapter 3 covers radiation processing and dose requirements. To realize the true potential added value of radiation processing to products, it is very important that radiation processing give more advantages than disadvantages with particular doses. For example, when comparing radiation processing with chemical processing for the property improvements of plastics it can be determined which approach gives more benefit at the same cost.

Chapter 4 introduces low energy electron accelerators, and then describes the 125 keV electron accelerator which is the main topic of this work. In particular, the chapter describes how the high voltage and beam current are produced and how the electrons are extracted from the emitter unit into the air.

Chapter 5 deals with system requirements including safety requirements – shielding requirement (radiation safety), ozone production removal, mechanical safety, and utility requirements (electrical, water, and air). Before the low energy electron accelerator was designed, system requirements were a crucial condition to build the unit appropriately.

Chapter 6 explains the design of the unit. For the radiation safety and dose calculations, PENELOPE Monte Carlo Code simulations were performed to determine the appropriate material for the accelerator enclosure, the amount of shielding material, and the dose received by a sample under different operation conditions of the unit. For the mechanical design, Inventor drawings and simulations were performed to determine the structure of the whole unit.
Chapter 7 covers results and conclusions. According to the purposes of the thesis, the results from Chapter 6 were discussed and conclusions were drawn to ensure that the design is valid and reliable.
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Chapter 1

Background information of an electron accelerator

Particle accelerators are very common and benefit many fields. Electron accelerators are devices that produce a directional stream of electrons. There are two kinds of electron accelerators. A circular electron accelerator is a device that uses an electromagnetic field to bend the particle (electron) path so that the electron beam passes repeatedly through the accelerating structures. A linear electron accelerator is designed to produce a beam of electrons in a single line and the beam usually passes only once through the accelerating field [4].

Generally, an electron accelerator consists of a source, a vacuum chamber, magnets, accelerating structures, cooling systems, and beam diagnostics (controllers). The source is a device that produces the charged particles (in the case of this thesis, electrons) that will be accelerated. The vacuum chamber provides a space for the charged particles to move without interference from other particles like gas molecules and prevents loss of energy due to collisions with gas molecules. Magnets are used to keep the particles concentrated in a narrow beam or to make them move in a circular path. Accelerating structures producing electrical fields are used to accelerate the particles. Cooling systems, either air or water, remove heat generated in the accelerator. Controllers provide information about the state of the beam and accelerator such as energy, beam current, and a speed of the platform. Controllers also allow the operator to adjust parameters of the accelerator.

To use an electron accelerator, the user should first determine the objective of the application. For example, the user needs to consider the type of materials or samples, the dosage, and the expected results. Second, the user must be aware of the safety considerations. Next, the
user needs to prepare the accelerator and samples. For example, parameters such as beam current, energy, and speed of the platform for the accelerator must be input into the controller. At this point, the user places the samples on the sample tray or platform and passes the sample through the beam area. Finally, the user extracts the sample and analyzes the results.

Electron accelerators are used in many applications in industry. They can be used to improve the physical and chemical properties of materials, especially in the plastic industry. The properties of plastic that can be improved include strength, melting point, and durability. Electron accelerators can also be used to reduce undesirable contaminants. For example, domestic and industrial wastewater contains substances that are toxic, and electron accelerators can be used to reduce the toxins in the wastewater.

In general, industry relies on electron beam energies ranging from 75 keV to 10 MeV. The energy levels of electron accelerators are from 75 keV to 300 keV for low-energy accelerators, 400 keV to 5 MeV for mid-energy accelerators and 5 MeV to 10 MeV for high-energy accelerators.

High-energy electron accelerators have been designed in two types, microwave linear accelerators (linacs) and the radiofrequency Rhodotron. For industry, linacs are suitable because of the extensive previous use of linacs in research and in medical therapy. In 1985, the food industry began using linacs for food irradiation and, in 1987, linacs began to be used for medical device sterilization [5, 6]. High-energy electron accelerators are also used in crosslinking plastic and polymers.

Mid-energy electron accelerators have a range of energy from 400 keV to 5 MeV and are able to provide high beam currents suitable for industrial use. These high beam currents provide
high dose-rates that are needed for industrial production. These mid-voltage and high-current electron accelerators are used frequently in the wire, cable, heat-shrinkable tubing, and tire industries.

The use of low-energy electron accelerators in industry has grown quickly in recent years. These accelerators are sufficiently low energy so they can be shielded with high density metal like lead, or even steel. These units use little plant floor space, and can be used when applying coating and surface treatments. There are also many applications such as curing or crosslinking of inks and adhesives that can be applied with low-energy electron accelerators.
Chapter 2

Quantities and Units of Radiation Processing

Quantities and units used in low energy electron accelerator technology are very important for calculating and designing an optimal low energy electron accelerator. The main quantities or parameters to control an electron beam accelerator are the energy, current, and the speed of the platform or line speed of the process.

Generally, The SI unit of energy is the joule (J), however, the electron volt (eV) is more frequently used in radiation technology. One electron volt is the energy gained by one electron when accelerating through a potential difference of 1 Volt. This follows from the relationship

\[ E = qV \]

where \( E \) is the energy, \( q \) is the charge, and \( V \) is the voltage. So, for one electron, the conversion factor is \( 1 \text{eV} = 1.6 \times 10^{-19} \text{ J} \) and \( q = 1.6 \times 10^{-19} \text{ Coulomb (C)} \) is the charge of an electron. Energies in radiation processing are usually in the MeV (\( 10^6 \text{ eV} \)) or keV (\( 10^3 \text{ eV} \)) range.

Another key parameter is current and that is a measure of the number of electrons being produced in a given amount of time usually measured in milliamps (mA). The number of electrons passing through a product relates directly to the energy the product receives. The average beam current can be expressed in terms of the number of electrons emitted by using the following equation:

\[ I_{beam} = \frac{qeN}{t} = \frac{qeN}{l \nu} \]

In an electron accelerator the current is formed by \( N \) electrons with a charge \( q \) per unit of time \( t \) or unit of length \( l \) and average velocity or speed of an electron \( \nu \).
There is one more characteristic of an electron accelerator called power usually measured in watts (W). The greater the power of an electron accelerator, the higher the throughput can be. Power is obtained from the accelerating high-voltage and beam current as:

\[
\text{Power} = \text{Current} \times \text{Energy} \quad \text{or} \quad P = IE
\]

For example, if an electron accelerator is operating at 5 MeV, and the maximum current capability is 20 mA, then its beam power is 100 kW.

The use of ionizing radiation in any process depends on the transfer of energy from the radiation beam to the material being processed. The quantitative measurement of this transferred energy is called the dose. Dose is related to the energy absorbed by the material or product, not what is emitted by the radiation source. The dose depends on energy, current, and the speed – the speed at which the product passes through the shower of electrons is usually measured in meters per second (m/s) or feet per minute (f/m) and the type of material where the energy is absorbed. The energy and the current are proportional with the dose. In other words, the higher the energy or the current for a given platform speed, the higher the dose delivered. The speed is inversely proportional to the dose, or the higher the speed the lower dose delivered, when all else is equal.

Dose in general terms is used to express how much energy from radiation exposure materials receive. Since the fraction of the energy in a radiation field that is absorbed by the body (a person or other materials) is energy dependent, it is necessary to distinguish between exposure and radiation absorbed dose.
Exposure

The exposure unit is based on the ionization of air because of the relative ease with which radiation-induced ionization can be measured. For external radiation of any given energy flux, the exposure to any point within an organism depends on type and energy of the radiation. One exposure unit is defined as a quantity of X-ray or gamma radiation that produces ions carrying 1 coulomb (C) of charge per kilogram of air (1X unit = 1C/kg air). This unit has replaced the roentgen. Before the SI system was introduced, the unit of X-ray exposure was called the roentgen (R). The roentgen was defined as a quantity of X-ray or gamma radiation that produces ions carrying 1 sC of charge of either sign per cubic centimeter of air at 0° C temperature and 760 mmHg pressure, so 1R = 1sC/cm³.

Absorbed Dose

The fundamental quantity for describing the effects of radiation in tissue, organs, or materials is the absorbed dose. Absorbed dose is the energy deposited in a small volume of matter by the radiation beam passing through the matter divided by the mass of the matter. Therefore, absorbed dose is measured in terms of energy deposited per unit mass of material. Absorbed dose is the most important specification for irradiation process. The quantitative effects of the process are related to the absorbed dose. Electron beam dose or radiation dose is measured and is being used officially today in most scientific and technical papers, in terms of a unit called the gray. For the radiation absorbed dose, the gray (Gy) is the unit in the International System of quantities and Units. It is defined as:

“One gray is an absorbed radiation dose of 1 joule per kilogram, or 1 Gy = 1J/kg [7]”
This unit replaced the old unit of absorbed dose, the rad (Radiation Absorbed Dose) which is defined as

“One rad is an absorbed radiation dose of 100 ergs per gram, or 1 rad = 100 ergs/g

Since \(1 \text{ joule} = 10^7 \text{ ergs}\), and since \(1 \text{ kg} = 1000 \text{ g}\), then \(1 \text{ Gy} = 100 \text{ rads}\) [7]”

The rad unit is still used widely, even though the gray is the newer unit and has replaced the rad.

Equal doses of all types of ionizing radiation are not equally harmful. For example, neutrons have been found more effective than X-rays in producing cataracts, and alpha radiation has been found to be more toxic per unit absorbed dose than beta or gamma radiation. In comparing the relative toxicity or damage producing potential of a given absorbed dose of various radiations, it is found that the higher the rate of linear energy transfer (LET) – linear energy transfer is defined as the linear rate of loss of energy (locally absorbed) by an ionizing particle traversing a material medium [8] – of the radiation, the more effective it is in producing biological damage. To account for this difference, radiation dose is expressed as an equivalent dose in units of Sievert (Sv). The dose in Sieverts is equal to “absorbed dose” multiplied by a “radiation weighting factor (\(W_R\))” and this factor was referred to as quality factor (QF). Both \(W_R\) and QF are given in Table 2.1 below.

Equivalent dose is often referred to simply as dose in everyday use of radiation terminology. The old unit of dose equivalent was the rem, with the dose in rem equal to the dose in rad multiplied by QF.
Table 2.1 Quality and radiation weighting factors for various radiations

<table>
<thead>
<tr>
<th>Radiation</th>
<th>QF</th>
<th>W_R</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-ray, gamma, beta</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Neutrons</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>0.01 MeV</td>
<td>2.5</td>
<td>10</td>
</tr>
<tr>
<td>0.1 MeV</td>
<td>7.5</td>
<td>10</td>
</tr>
<tr>
<td>0.5 MeV</td>
<td>11</td>
<td>20</td>
</tr>
<tr>
<td>&gt;0.1 MeV – 2 MeV</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>&gt;2 MeV – 20 MeV</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Unknown energy</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>High-energy protons</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>Alpha particles, fission fragments, heavy nuclei</td>
<td>20</td>
<td>20</td>
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</table>

Various safety organizations have made recommendations related to the exposure of workers to radiation. “On the principle that the risk of a stochastic effect should be equal whether the whole body is uniformly irradiated or whether the radiation dose is non-uniformly distributed, the International Commission on Radiological Protection (ICRP) introduced the concept of effective dose equivalent in the 1977 review of its radiation safety recommendations, and recommended that, in order to control stochastic effects, the effective dose equivalent for occupational exposure be limited to 50 mSv (5 rems) in 1 year. [7]”. The Threshold Limit Values (TLVs) introduced by the American Conference of Governmental Industrial Hygienists
(ACGIH) are used in many jurisdictions; the occupational exposure limit is 20 mSv TLV for average annual dose for radiation worker over five years.

**Engineering Factors of Electron Accelerators**

There are a number of engineering factors which require consideration in the evaluation of any electron beam process. In particular one must be able to estimate whether a given electron accelerator can run the process at the needed rates of production. To obtain this information requires not only knowledge of the dose but the knowledge of the product, its material and density, and the geometry of the system to be used. Aside from the dose necessary and the other factors listed as necessary for the evaluation, this chapter is concerned with how electron beams penetrate into materials.

**Electron Penetration**

The total distance which electrons can penetrate into a given material, at a given or machine voltage, is a smooth and more or less linear function of the energy of the electron. All of the energy of the electrons which make up that beam will be deposited within that medium and within that range or distance. However, the dose, ionization, or radiation effect is not uniform within that range or distance. For a beam in which all the component electrons have the same energy the radiation effect varies approximately with depth in accordance with a curve known as the depth-dose curve.
Depth-Dose Characteristic

Depth-dose curves are an indication of how energy is deposited into a material. They show the relative absorbed dose at a particular point as a function of the penetration. “The shape of the depth-dose plot depends on the nature of the radiation, the energy of the photons or particles, and the source-sample geometry.” [1]. A typical depth dose curve for electron irradiation in materials is shown in Figure 2.1 below.

![Depth Dose Curve](image)

Figure 2.1 Electron beam energy deposition in materials, accessed from “UV+EB Technology”, the official publication of RadTech International North America

Figure 2.1 illustrates the gradual buildup and decline of absorbed dose as the distance below the irradiated surface is increased.

The absorbed dose distribution in a material (absorber) can be estimated using computer programs. Computer modeling of depth dose data can be done using a Monte Carlo method in which the histories of a large number of randomly selected particles (electrons, photons, and positrons) are calculated individually using energy loss data [1]. Then the individual histories are combined to give a picture of the distribution of absorbed dose through the irradiated material.
Chapter 3

Radiation Processing

Radiation processing is the controlled application of the energy of ionizing radiation to materials. It includes gamma rays, X-rays, and electrons applied to have a desired effect on a product. Radiation processing utilizes radiation energy to treat a material in the form of gas, liquid, or solid. Radiation treatment can initiate biological and chemical changes in a material when the energy from the radiation is absorbed by the product.

Types of Radiation

There are two types of radiation used to produce chemical and physical changes in materials: non-ionizing and ionizing radiation. Non-ionizing radiation is radiation that does not have enough energy to ionize atoms. Ionizing radiation is radiation that has sufficient energy to ionize atoms or molecules. Ionizing radiation eventually leads to chemical and biological reactions. This project focuses on ionizing radiation because it relates to an electron accelerator.

Type of Ionizing Radiation

There are many types of ionizing radiations. First, gamma rays and X-rays are short wavelength forms of photon or electromagnetic radiation. A gamma ray is produced in a nuclear interaction but an X-ray originates from atomic or charged particle collisions. The interaction with matter of gamma rays and X-rays are identical. Because both of them are photons and have no mass, they are lightly ionizing and have high penetration power in an irradiated material.

Second, alpha particles are the nuclei of helium atoms which have a mass of 4 and a positive charge of 2 units. They interact strongly with matter and produce heavy ionization. Their
energy is normally of several MeV. Because they have a lot of mass, they have low penetrating power and travel in straight lines.

Next, beta particles, or electrons, have smaller mass than alphas. With their small size and charge, they penetrate matter more easily than alpha particles but they are more easily scattered. They are lightly ionizing because they travel with very high velocity, normally close to the speed of light.

**Source of Ionizing Radiation**

The source of radiation used in radiation processing application and radiation chemical studies can be obtained for two different sources, those employing natural or artificial radioactive isotopes, and those that employ some form of particle acceleration or electrical discharge instrumentation. The first group consists of the classical radiation sources radium and radon, and artificial radioisotopes such as cobalt-60 and cesium-137, which are the most common radioisotopes used. The second group includes electron accelerators, X-ray machines, and accelerators such as the Van de Graaff accelerator and cyclotron used to generate beams of positive ions. Nuclear reactors also have been used as radiation sources, normally as sources of neutron beams. The most widely used radiation sources currently are cobalt-60 and electron accelerators.

**Radioisotope Sources**

Radioisotopes, radioactive isotopes, or radionuclides occur naturally and also can be produced artificially in a nuclear reactor. All of them are unstable elements with an excess energy or an excess of neutrons in their nuclei, so they need to release excess energy by emitting alpha (α), beta (β), and gamma (γ) radiation as they spontaneously disintegrate or decay to a
stable state. The time that radioisotopes take to decay to the level of radioactivity that is one half of what was originally present is known as their half-life ($t_{1/2}$), and half-life is specific for each radioisotope of a particular element. In other words, radioactive decay refers to the process of a radioisotope emitting radiation to become more stable. There are a lot of practical applications of this type of radiation, especially cobalt-60. Cobalt-60 is the most popular radioactive source of gamma radiation for uses such as sterilizing medical products, herbs, cosmetic items, food preservation, decontamination of sewage sludge or waste water, and other applications where the greater penetration of gamma radiation offers an advantage.

**Electron Radiation**

Electrons are produced by natural radioisotopes or man-made instrumentation such as the electron accelerators described above. In natural activities, electrons are produced by a process called beta decay. Beta decay can be viewed as the conversion of a neutron inside the radioactive nucleus into a proton, an electron, and an antineutrino. Since the electron cannot exist inside the nucleus, it is ejected as soon as it is created. The most common way to produce electrons by man-made instrumentation is through an electron accelerator. In an electron accelerator, the electrons are first emitted from a hot filament by the Joule effect. Once the electrons are free from the filament they can be accelerated by the use of an electric force produced by a high voltage terminal or the production of electromagnetic fields inside the beam tube.

The Joule effect is the production of heat as a consequence of the flow of current through a conductor. If the current is very high it can produce incandescence of the conductor, liberating electrons from the material. Once the electrons are free they can be accelerated inside a vacuum tube.
Electron Accelerator

Several electron accelerator designs have been adapted to create machines suitable for routine irradiation of materials ranging from thin films (e.g. paints and varnishes, plastic films) to bulkier samples (e.g. wire and cable insulation, medical supplies, foodstuffs) [9, 10]. An electron accelerator is the preferred radiation source for cross-linking or curing polymer-based materials such as plastic films, heat shrink tubes, wires, and cable. Because electron accelerators give higher radiation intensities but less penetrating radiation compared to radioisotope sources, electron accelerators are well suited for the high speed irradiation of films and the surface layers of thicker materials, but less well adapted to the irradiation of bulky samples.

Electron accelerators are manufactured in various types and can be designed to produce electron beams with the range of energy from 80 keV to 10 MeV for commercial applications. Types with beam powers ranging from a few kilowatts to 300 kW are currently available.

Linear Electron Accelerator

The linear electron accelerator is a traveling wave accelerator in which electrons are injected in pulses into a straight, segmented waveguide and accelerated by the electric field of an electromagnetic wave that travels down the waveguide. Electron energy of the order of several hundred MeV is employed for studies in nuclear physics and radiation chemical research and applications.

Febetron

The Febetron is a commercial electron accelerator which is based on a series of condenser modules that are charged in parallel and discharged in series, with the 1-2 MeV pulse
generated being applied to the cathode of a field emission tube to give a pulse of electrons. This system is capable of producing a very high beam current which is well adapted to pulse radiolysis studies.

**Van de Graaff Accelerator**

In the Van de Graaff accelerator an electrostatic charge, either negative or positive, is carried to a high voltage electrode by means of a moving belt and the potential difference between the electrode and the ground is used to accelerate electrons or positive ions to high velocities. The Van de Graaff accelerator is able to accelerate electrons or positive ions to any energy within the range of the machine, usually between 1 and 5 MeV.

**Low Energy Electron Accelerator**

In most low energy electron beam accelerators, electrons are emitted from heated tungsten filaments. Then the electrons are focused into a beam with an extraction electrode. Next, electrons are accelerated within an evacuated space with a strong electric field. Finally, electrons pass through a thin titanium foil window into air. This thesis is focused on a low energy electron accelerator produced by Advanced Electron Beams, Inc. It will be explained in more detail in the next chapter.

**Interaction of Electrons with Matter**

Once electrons are produced either by a radioisotope or an electron accelerator, they interact with matter by a number of processes, namely inelastic and elastic collisions, and the emission of electromagnetic radiation. The relative importance of those processes varies strongly with the energy of the incident electron and with the nature of the absorbing material. In electron
radiation processing with energy less than 10 MeV, the major mechanism of electron energy transfer to a material is inelastic collisions, and by a lesser amount the emission of electromagnetic radiation (bremsstrahlung). Elastic scattering (change in the direction of motion without conversion of kinetic energy to any other form of energy) is of greatest importance at low energies [11]. In the following paragraphs these mechanisms are described in more detail.

**Elastic Scattering**

In this mechanism the charged particles are deflected by the Coulomb (electrostatic) field of an atomic nucleus. The electric field produced by the nucleus interacts with the electric charge of the particle, producing only a change in direction, and there is no energy transferred from the incoming particle to the atom in the material. This is particularly important in the case of electrons. Since electrons have a small mass, they frequently experience such elastic scattering. Scattering is greatest for low electron energies and for high atomic number materials.

**Inelastic Scattering**

During inelastic scattering, the incoming charged particles will transfer part of their energy and momentum to the atom with which it interacts through Coulomb interactions with atomic electrons of the stopping material. Interacting in this way, the atom will be ionized or its electrons will be excited to a higher energy state, leading to a reduction in the incoming particle speed.

In this case, the energy is deposited in the material, which is going to be the main process for the calculation of the energy absorbed in the material. The energy loss per unit path length due to inelastic collisions is known as the specific energy loss or stopping power. This is the function of the electron velocity and changes as the electron is slowed down.
Energy Loss by Radiation (Bremsstrahlung)

High speed charged particles passing close to the nucleus of an atom may be decelerated and will radiate electromagnetic energy (Bremsstrahlung). In the case of electrons, when fast electrons are stopped in matter, part of their initial energy is converted into electromagnetic radiation, and the intensity of the radiation emitted will depend on the energy of the electrons and the atomic number of stopping material. For electrons, bremsstrahlung emission is negligible below 100 keV but increases rapidly with increasing energy, becoming the predominant mode of energy loss at electron energies between 10 and 100 MeV (the exact energy depends on the stopping material). The effect also increases with the atomic number of the interacting material [11].

Comparing the energy loss between collision and radiation, the ratio of the energy loss by radiation ($\frac{dE}{dx}_{rad}$ sub-index) to the loss by collision ($\frac{dE}{dx}_{col}$ sub-index) is given approximately by

$$\frac{(dE/dx)_{rad}}{(dE/dx)_{col}} \approx \frac{EZ}{700}$$

Where $E$ refers to the energy of the electron in MeV and $Z$ is the atomic number of the absorbing material.

From this equation, the energy loss due to bremsstrahlung is going to be more important for high energy electrons as well as for high atomic number absorbing materials as stated above.
Consequences of Interaction of Electrons with Matter

Electrons can be deflected with large scattering angles. They can lose up to 50% of their energy in a single inelastic collision, and their range is much longer than the range of heavy charged particles of similar energy. Electrons produce more Bremsstrahlung than heavy charged particles.

The last two effects, inelastic scattering and Bremsstrahlung, lead to the deposition of energy from the electrons in the interacting material. In inelastic scattering, this occurs by collisions with the atoms and electrons of the material. In Bremsstrahlung, this occurs by the conversion of electron energy into electromagnetic radiation, which is then followed by the interaction of this radiation with the material by photoelectric, Compton, and pair production effects.

Application and Dose Requirement of Radiation Processing

The following table list some applications widely used in radiation processing, along with their dose requirements:
Table 3.1 Applications and dose requirements of radiation processing [12]

<table>
<thead>
<tr>
<th>Type of radiation processing</th>
<th>Applications</th>
<th>Dose (kGy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biological</td>
<td>- Disinfecting consumer products</td>
<td>0.1 - 3</td>
</tr>
<tr>
<td></td>
<td>- Pasteurizing and preserving foods</td>
<td>1 - 5</td>
</tr>
<tr>
<td></td>
<td>- Sterilizing medical products</td>
<td>15 - 30</td>
</tr>
<tr>
<td>Modifying polymeric materials</td>
<td>- Curing monomers and oligomers</td>
<td>10 - 30</td>
</tr>
<tr>
<td></td>
<td>- Grafting monomers onto polymers</td>
<td>25 - 50</td>
</tr>
<tr>
<td></td>
<td>- Crosslinking polymers</td>
<td>50 - 150</td>
</tr>
<tr>
<td></td>
<td>- Degrading polymers</td>
<td>500 - 1500</td>
</tr>
<tr>
<td>Environment</td>
<td>- Wastewater decontamination</td>
<td>2 - 70</td>
</tr>
<tr>
<td></td>
<td>- Sewage sludge treatment</td>
<td>2 - 10</td>
</tr>
<tr>
<td>Solid state devices</td>
<td>- Modifying semiconductors</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>- Coloring gemstones</td>
<td>&gt; 1500</td>
</tr>
</tbody>
</table>
Surface Decontamination

An electron beam accelerator can get rid of substances or kill germs. For example, Cheddar cheese slices, surface-inoculated with either *Penicillium cyclopium* or *Aspergillus ochraceus* spores, were vacuum packaged and irradiated using an electron beam accelerator. Following treatment at .21 and .52 kGy, the shelf-life of cheese containing *P. cyclopium* was extended by 3 and 5.5 days, respectively, in comparison with inoculated, untreated samples [13].

Surface Modification

An electron beam accelerator can modify or improve physical properties of some materials such as strength and lifetime of the materials. Electron radiation is a new technology for surface modification of metallic materials based on the use of original sources of low-energy, high-current electron beams. For example, when a metallic material was treated with electrons of energies 10–40 keV, the results of the experiment found that it was possible to improve substantially the electrochemical and strength properties of the surface layers. It has been established that the deformation processes occurring in the near-surface layers have the result that the thickness of the modified layer with improved strength properties is significantly greater than that of the heat-affected zone [14].

Coatings

Coatings are often applied on a variety of materials to extend the life of components under severe thermal, corrosion, wear, and oxidation environments. The role of coatings is significant in the advancement of technologies for applications in the optics, auto, and aerospace industries. Industrial coating techniques can be broadly classified into three groups: physical vapor deposition (PVD), chemical vapor deposition (CVD), and spray processes. All three
processes have some disadvantages, for example, a disadvantage of the spray processes is the inability to obtain homogenous, high-quality, and dense coatings. The disadvantages of the CVD process are that they often require high-deposition temperatures (>1000°C), they produce chemical waste such as acids that is environmentally unacceptable, and deposition rates are usually slow for high-quality coatings. The main disadvantages of PVD processes are the low deposition rates (1-5 pm per hour) and the difficulty in applying oxide coatings efficiently. The electron beam-physical vapor deposition (EB-PVD) process has overcome some of the difficulties associated with the CVD, PVD, and metal spray processes. The EB-PVD process offers extensive possibilities for controlling variations in the structure and composition of condensed materials. Coatings produced by the EB-PVD process usually have a good surface finish and a uniform microstructure. The microstructure and composition of the coating can be easily altered by manipulating the process parameters and ingot compositions [15].

**Adhesives**

Adhesive bonded composite joints and repairs are increasingly being used for high performance structures in the aerospace, civil and marine industries providing lighter weight, smoother skin surfaces, higher fatigue resistance, and lower fabrication costs. The adhesives are typically cured by heating for several hours in large autoclaves, presses or heat blankets. This results in high processing costs in terms of equipment and labor costs. In addition, the use of high temperature adhesive curing causes thermal residual stresses to build up in the components that are bonded together due to differences in their coefficients of thermal expansion. These stresses tend to weaken the adhesive bond and increase its susceptibility to stress-corrosion. All of these factors tend to limit the performance of high temperature cured adhesive joints and repairs.
Electron beams (EB) have the ability to deposit large amounts of energy on the substrates, and offer benefits for adhesive curing. The most attractive feature is that with electron beams as sources of energy, curing can be achieved at ambient temperatures and contact pressure in very short time periods. As a result residual thermal stresses which usually accompany high temperature curing can be eliminated, thereby ensuring longer life of adhesive bonded components. Other benefits of electron beam curing include simplified processing methods, higher energy efficiency due to the elimination of autoclaves and heat blankets, better shelf life of electron beam curable adhesives, and environmental friendliness due to low volatile emissions. Because of these advantages, a number of efforts have been made in the present decade to apply the EB in this manufacturing process [16].
Chapter 4

Low-Energy Electron Accelerator

An electron accelerator is a device that uses electromagnetic fields to propel electrons to high speeds and to contain them in well-defined beams. In this chapter, a low energy electron accelerator is reviewed. A low-energy electron accelerator has an energy between 125 and 300 keV and beam current ranging from 10 – 25 mA. In this case we are referring to an instrument with energy of 125 keV. This chapter also provides a description of the components of the accelerator, which consists of an emitter, high voltage power supply (HVPS), and high voltage (HV) cable.

High Voltage Power Supply

The 125 kV high voltage power supply (HPVS) consists of two enclosures, the HVPS converter and the HVPS rectifier. The HVPS converter is mounted in a 48.26 cm (19 in.) rack and requires a 91.44 cm (36 in.) deep rack. The HVPS rectifier is not rack mountable. The converter and rectifier should be mounted with less than 17.78 cm (7 in.) between the top of one and the bottom of the other. The HVPS requires an input voltage of 3 phase 208 VAC ± 10%, 50/60 Hz, and consume 5 kW at 25 mA [17].

To get adjustable high voltage, the HVPS converter converts low voltage from the power outlet, described above, into adjustable AC at a particular frequency by using an LC oscillator. Then, a step-up transformer will be used to get high voltage AC output of several kilovolts. After that, the HVPS rectifier acts as a voltage multiplier which has the input AC voltage from the HVPS converter. The circuit uses the principle that the capacitors are charged in series alternatively. The circuit consists of two stacks of capacitors connected in series, $C_1, C_2, C_3$, etc.,
and $C'_1, C'_2, C'_3$, etc., and a set of rectifiers $D$ connecting the two stacks, as shown in the Figure 4.1. During each AC cycle voltage in the first rectifier ($D'_n$) changes from 2 to 2V, where $V$ is the peak voltage of the AC source. From this type of circuit, the output voltage form HVPS rectifier is about 125 kV.

![Figure 4.1 Voltage multiplier circuit diagram](image)

**High Voltage Cable**

The High Voltage (HV) cable is a cable that is connected between the HVPS rectifier and an emitter for transferring the power from the HVPS to the emitter. The HV cable has a 2.03 cm (0.8 in.) cable diameter, and a 8.89 cm (3.5 in.) bend radius. It weighs 0.3 pound per foot [17].
The HV cable is usually thick because it has a shield layer. If an unshielded insulated cable (core cable) contacts with earth or a grounded object, the electrostatic field around the conductor will be concentrated at the contact point, resulting in corona discharge, and eventual destruction of the insulation. Moreover, leakage current and capacitive current through the insulation presents a danger of electric shock. Although the HV cables do not produce any significant heat on their own, the cable should be routed to ensure it does not contact the emitter side wall or any other sources of significant heat.

**Emitter**

The emitter connects to a high voltage power supply via a high voltage power cable. One end of the HV cable connects to the HVPS rectifier, and the other end connects to the top of the emitter. The emitter is a hermetically sealed vacuum unit that produces an electron beam. The filament consists of a cylindrical shape tungsten wire 25.40 cm (10 in.) long, emitting electrons when heated. Then, a high voltage accelerates the electrons, forming an electron beam aimed at a window in the emitter enclosure. After that, the electrons pass from the inside of the emitter, through a thin foil of titanium, into the air, and then to a sample [17].

![Figure 4.2 A 10 inch hermetically sealed vacuum emitter that produces an electron beam](image-url)
The emitter from Figure 4.2 was produced by Advanced Electron Beam Inc. It is 27.43 cm (10.8 in.) wide and 33.66 cm (13.25 in.) high and weighs 12.7 kg (28 pounds). The emitter has a mechanical interface consisting of eight \( \frac{1}{4} - 20 \) tapped holes used to mount the emitter and four water port holes located on the same mounting surface. These holes provide cooling for the foil. Water flows along each of the long sides of the foil. The electrons accelerated in the emitter unit exit the system through a thin titanium foil (exit window). This foil is 6 µm thick and is bonded to a support grid that will produce mechanical stability when under vacuum. The support grid is provided with a surface that has contours, typically being smooth recessed surfaces that the foil can lie against once enlarged as the vacuum pulls the foil against the grid. The window has to be a perfect thickness. If the titanium window is too thick, the electrons that pass through will lose a substantial amount of energy in it. If the window is too thin, the differential pressures inside and outside of the vacuum chamber can cause the titanium window to collapse.

**Operational System**

Normally, the HVPS is connected to the HVPS rectifier, the HVPS rectifier is connected with the HV cable, and the HV cable is connected to the emitter. To control system parameters such as beam current, energy, and the power of the beam, a controller should be provided and connected to the HVPS converter. In other words, a system that has an HVPS converter, HVPS rectifier, HV cable, and controller is called a closed loop system. Without the controller, the system could not control any system parameters. For this reason, this project studied the system behavior without the controller, or an open loop system. This was accomplished by investigating how the system behaves at any particular energy and beam current using PENELOPE Monte Carlo Code simulations.
Chapter 5

System Requirements

This chapter covers the hazards present during normal operation of Advanced Electron Beam (AEB) components consisting of electrical, radiation, chemical and mechanical systems. For designing these systems, PENELOPE Monte Carlo Code and Autodesk Inventor were used.

Autodesk Inventor

Autodesk Inventor is a 3D mechanical solid modeling design software developed by Autodesk to create 3D digital prototypes. It is used for mechanical design, communication design, tooling creation, and product simulation. This software enables users to produce accurate 3D models to aid in designing, visualizing and simulating products or models before they are built. This program was used for designing safety systems and also simulating the structure of the unit enclosure to ensure that the design was strong enough.

Electrical Safety

Lethal voltages with potential up to 150 kV are present in some components. Therefore, people who work with or near high voltage equipment should be thoroughly familiar with emergency equipment, procedures and resuscitation methods. They must understand safe electrical work practices and procedures for controlling hazardous energies.

Radiation Safety

The AEB unit generates high voltage to accelerate electrons. When electrons collide with any material, ionizing radiation in the form of X-rays is produced. To prevent radiation leakage (electron and photon), the system design must enclose the entire emitter and processing zone.
Electron beams and X-rays can cause immediate injury and long term effects, so the unit’s shielded enclosure must prevent the electrons and X-rays from escaping.

Electron beams have a range in air, depending on the voltage level in effect. Electron beams are effectively absorbed along the product path, which is the path of a sample moving through the exposure area. X-rays have a longer range and they attenuate when they strike metal. A shielded enclosure reduces radiation levels to an acceptable level during normal operation. The range and attenuation of both the electron beams and X-rays were simulated by the PENELOPE program. After that, Autodesk Inventor was used for creating the 3D modeling for the unit enclosure. The results from both programs are shown in detail in the next chapter.

Safety considerations include four doors, one used for the sample compartment and the others to access and service different parts of the unit, all with limit switches to shut off the operation of the accelerator when any one of the doors is opened. Radiation detectors will shut down the system when radiation exposure exceeds the maximum thresholds.

**Chemical Safety**

The system may produce chemicals that are extremely hazardous substances. The type and amount of hazardous substances created will vary depending on the use of the system. The chemical of most concern is Ozone (O₃). Ozone is a by-product of the electron beam treatment that occurs when oxygen is present in the reaction chamber. Ozone is produced when electrons interact with an oxygen molecule. During the interaction, the oxygen molecule is divided into two radical oxygen atoms by the electrons. Each radical oxygen atom then recombines with other molecules of oxygen, resulting in an ozone molecule. Ozone is a poisonous gas and an oxidizer. It is lethal at low concentrations and is incompatible with all oxidizable materials. It will
accelerate combustion and increase the risk of fire and explosion in combustible, flammable, and oxidizable materials. To remove the ozone from the reaction chamber, this design provided inlet and outlet ducts with an electric fan, referred to as the air cooling system. The air cooling system was designed using the Autodesk Inventor program, and will be explained in more detail in the next chapter.

**Thermal Safety**

The emitter has four areas of heat management that must be considered: emitter water cooling, convective foil cooling, reaction chamber cooling, and emitter housing cooling.

**Emitter Water Cooling**

Water cooling of the copper around the emitter foil, which is located at the exit window of the emitter, is required for all applications to provide proper cooling of the emitter’s copper base. The temperature of the cooling water must be kept above the dew point of the ambient air near the foil to avoid any condensation. Water flow through the emitter must be interlocked. The power supply will shut off when the water flow rate drops or temperature exceeds the parameter ranges, which are $1.5 - 2.5$ gpm ($5.7 - 9.7$ lpm) flow rate, $75 - 85$ °F ($25 - 29$ °C) water inlet temperature. This corresponds to the necessary thermal load to remove $2.5$ kW per emitter. The mineral content of the supply water from a closed circulating system must not exceed $40$ ppm and the water must be algae free [17].

**Convective Foil Cooling**

The emitter window is a thin titanium foil over a copper grid, through which the electrons travel. The water that circulates through the copper, described above, will adequately remove the
heat from the copper and foil. However, in most instances conductive water cooling (emitter water cooling) is not adequate to sufficiently cool the foil and convective cooling is also required. For the emitter that is described in the previous chapter, the maximum operating current with no foil cooling is 10 mA at 125 kV, and the maximum operating current with foil cooling is 25 mA at 125 kV. The emitter foil must be cooled by a gas flowing uniformly across the emitter foil. This will dissipate the heat that is not removed by the water flowing through the copper. Gas flow through the emitter must be interlocked such that the power supply is disabled if the gas flow rate drops below the minimum rate defined. The minimum actual flow rate is 10 scfm, the gas inlet temperature must be less than 75 °F (<25 °C), and thermal load that must be removed is 0.5 kW per emitter [17]. This system has been designed using Autodesk Inventor and the results are shown in the next chapter.

**Reaction Chamber Cooling (Process Zone Cooling)**

The emitter’s electron beam energy will deposit into any material, including air, which falls in its path. The thermal energy from the decelerating electrons has to be considered when designing the structure or material handling equipment directly in front of the emitter foil. The thermal load in this area can be up to 1.0 kW which is above the 0.5 kW thermal load removed at full power by the convective gas flow. The system structure or material handling equipment will heat up if any part is located in the electron beam path.

The product and product handling equipment could also have an effect on the foil heating. It is important to consider the backscatter of electrons, from both the product and handling equipment, back into the emitter foil window. If the product material handling equipment or structure is located within 2.54 cm (1 in.) of the emitter foil, a non-planar surface
must be used to reduce direct reflection of the electron back into the emitter foil. Keeping the product and handling equipment at a distance greater than 2.54 cm (1 in.) from the foil will avoid interference with the convective foil gas flow and prevent stagnation zones of the gas flow [17]. This system has been designed in conjunction with the design of the air cooling system above by using Autodesk Inventor and the result is shown in the next chapter.

**Emitter Housing Cooling**

The emitter housing is the area around the main body of the emitter. This housing should be large enough to facilitate the installation and removal of the emitter without causing damage to the emitter foil. The volume inside the emitter housing must be cooled by replacing the heated air inside this volume with cool dry air from the outside. The maximum heat load that needs to be removed is 0.5 kW per emitter, and the air temperature within the volume should not exceed 100 °F (38 °C) [17]. Maintaining this temperature is important to prevent arcs from occurring between the emitter and HV cable. This part of the system also has been designed by using Autodesk Inventor and the result is shown in the next chapter.
Chapter 6

Design and Simulation

This chapter will cover the simulations that were performed to evaluate radiation safety and dose amounts on the accelerator described in this thesis. PENELOPE Monte Carlo simulations were used to determine an appropriate shielding material type and amount, as well as the expected dose under several conditions. Autodesk Inventor was used to create drawings and simulations for the mechanical design.

PENELOPE Monte Carlo Code

Monte Carlo methods are well known computational algorithms that rely on repeated random sampling to obtain numerical results. “The computer code system PENELOPE performs Monte Carlo simulation of coupled electron-photon transport in arbitrary materials for a wide energy range, from a few hundred eV to about 1 GeV. Photon transport is simulated by means of the standard, detailed simulation scheme. Electron and positron histories are generated on the basis of a mixed procedure, which combines detailed simulation of hard events with condensed simulation of soft interactions. A geometry package called PENDING permits the generation of random electron-photon showers in material system consisting of homogeneous bodies limited by quadric surfaces, i.e. planes, spheres, cylinders, etc.” [18].

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1 Results from this chapter were presented at the 23rd Conference on Applications of Accelerators in Research and Industry (CAARI-2014), that took place in San Antonio TX on May 25-30, 2014; and the 23rd meeting of the Council on Ionizing Radiation Measurements and Standards (CIRMS), that took place at the NIST campus in Gaithersburg MD, on April 27-29, 2015
Simulations and Conceptual Design

The simulations were performed by using accelerator parameters for which the emitter head consists of a cylinder that is 27.43 cm (10.8 in.) in diameter, 33.66 cm (13.25 in.) in height, and the electron emitter filament is a 25.40 cm (10 in.) long wire. The accelerator has a maximum beam energy of 125 keV, and a maximum beam current of 25 mA. The emitter is a hermetically sealed vacuum unit that produces an electron beam. A high voltage accelerates the electrons making an electron beam aimed at a window in the emitter enclosure. After that, the electrons pass from the inside of the emitter, through a thin foil, into the air, and then to a sample. All simulations were performed for a minimum of $3 \times 10^6$ electron histories.

The sample conveyer system consists of an aluminum plate on top of a platform. The sample plate is moved by a stepper motor. The platform is 63.50 cm (25 in.) wide, 185.42 cm (73 in.) long, and it rests on four adjustable legs ranging in height from 12.70 cm (5 in.) to 25.40 cm (10 in.) from the floor. The speed of the platform can be continuously changed from 0 to 25.40 cm/s (0 to 50 fpm).

Unit Prototype

The first unit prototype was designed based on the dimensions of the emitter and the platform. The emitter enclosure is a 1.27 cm (0.5 in.) thick, 50.80 cm (20 in.) wide, 50.80 cm (20 in.) long, and 48.26 cm (19 in.) high aluminum box as shown in Figure 6.1. The reaction chamber enclosure is a 1.27 cm (0.5 in.) thick, 76.20 cm (30 in.) wide, and 254 cm (100 in.) long aluminum box as shown in Figure 6.1. This project was evaluated using aluminum for shielding because it is readily available, inexpensive, easy to machine, and a non-toxic material.
From Figure 6.1, the height of the reaction chamber enclosure is 30.48 cm (12 in.) because the platform can adjust the height from 12.70 cm (5 in.) to 25.40 cm (10 in.), and the sample should not be located closer than 2.54 cm (1 in.) from the titanium window of the emitter to avoid overheating from backscatter electrons, as mentioned in the previous chapter.

The emitter shielding box was designed to be located at the middle of the reaction chamber enclosure, to allow for the sample to move past the emitter two times in one process. Therefore, the sample will receive twice the dose when moving forward and backward to the loading position.
Physical Parameters

Simulation Geometry and Energy Spectrum of 125 keV Electrons

Figure 6.2 shows the conceptual design used to simulate the interaction of the electrons with the titanium window of the emitter to obtain from that the energy spectrum and angular distribution of electrons and photons coming out of the accelerator.

![Simulation geometry of 125 keV electrons interacting with titanium](image)

Figure 6.2 Simulation geometry of 125 keV electrons interacting with titanium

For the simulation it was assumed that the electrons come from a point source with an initial energy of 125 keV, travel 5 cm in a vacuum, and then go through the titanium window. The electron spectrum was obtained assuming that the detector is titanium.

From the PENELLOPE program, was used to obtain the energy spectrum of the electrons and photons coming out of the emitter and their angular distributions. Figure 6.3 and 6.4 show the results for electrons. Figure 6.5 and 6.6 show the results for photons.
These figures show that most of the electrons emerge from the titanium window with an energy equal to 125 keV and at 0 degrees with respect to the Z-axis, gradually decreasing to zero for an angle of 80 degrees. This is because the initial direction of the electron particles is sampled uniformly within a cone of semi-aperture $\alpha = 0.5^\circ$ with respect to the initial direction in which electrons are emitted ($\alpha = 0.5^\circ$).
These figures show that for the photons most of them emerge from the titanium window with an energy equal to 5 keV and at 0 degrees with respect to the Z-axis, and there are some photons that emerge close to 180 degrees due to backscattering, caused by their interaction with the titanium window.
Depth Dose of 125 keV Electrons in Water

The next simulation investigated the way in which the energy of the 125 keV electrons is absorbed in a detector made out of water as a function of the penetration. To do this it was assumed that the electrons come from a point source with an initial energy of 125 keV, and travel directly to the water which is 0.03 cm thick, 30 cm wide, and 30 cm long. This is shown in Figure 6.7

![Figure 6.7 Simulation geometry of 125 keV electrons interacting with water](image)

Figure 6.7 Simulation geometry of 125 keV electrons interacting with water

![Figure 6.8 Depth dose distributions of 125 keV electrons in water at the central Z axis](image)

Figure 6.8 Depth dose distributions of 125 keV electrons in water at the central Z axis

Figure 6.8 shows the depth dose distribution obtained from the simulation for electrons with an energy of 125 keV interacting with water. The result is that, as the distance below the
irradiated surface is increased, the energy deposited results in an absorbed dose that gradually builds up, then declines.

**Depth Dose for a Line Source in Three Layers of Absorption Material**

The simulation geometry for this simulation is shown in Figure 6.9. Because the emitter’s filament is a cylindrically shaped tungsten wire 25.40 cm (10 in.) long, the source of energy changed from point source to line source with a length of 25.40 cm (10 in.), an energy of 125 keV, and an aperture of 0.25° ($\alpha = 0.25^\circ$). The distance between the line source and the titanium window is 5 cm potential. Three layers of absorption materials consist of 6 $\mu$m of titanium, 3 cm of air, and 100 of $\mu$m water, with all layers being 30 cm wide and 30 cm long. In the PENEOLOPE program, the user needs to choose one of the layers (or bodies) in the geometry file [18] to specify that an analysis result is calculated for this layer. In this section, the detector for absorption is the water layer.

![Simulation geometry for a line source in three layers of absorption material](image)

Figure 6.9 Simulation geometry for a line source in three layers of absorption material
The results from this simulation are presented in Figures 6.10 and 6.11 below. The first figure shows the energy distribution on top of the water layer used as the energy detector during the simulation and the second one the angular distribution of emerging electrons leaving this detector.

Figure 6.10 Two dimensional dose distribution in the middle of the top surface of the water layer

Figure 6.11 Angular distributions of emerging electrons from the detector for a line source in three layers of absorption material
Figure 6.10 shows that the dose distributions in the water layer (detector) has a similar shape as with the line filament. Figure 6.11 shows that most electrons emerge at 0 degrees with respect to the Z-axis, and gradually decrease to 90 degrees. This is because the initial direction of the electron particles is sampled uniformly within a cone of semi aperture \( \alpha = 0.25^\circ \) with respect to the initial direction in which electrons are emitted (\( \alpha = 0.25^\circ \)). There are some electrons that emerge at 180 degrees due to backscattering, caused by their interaction with the detector.

Figure 6.12 Dose distributions at the central X axis for a line source in three layers of absorption material

Figures 6.12 and 6.13 show the dose distribution on the top surface of the water layer at the central X axis and Y axis respectively, which corresponded with the line source of energy. Figure 6.14 shows the dose distribution at the central Z axis, where \( z = 0 \), corresponds to the surface of the titanium layer, which decreases gradually with the depth along the Z axis.
Figure 6.13 Dose distributions at the central Y axis for a line source in three layers of absorption material

Figure 6.14 Dose distributions at the central Z axis for a line source in three layers of absorption material
Dose on One Detector in the Central Axis of the Beam and One off Axis

In this section, simulation parameters depended on the simulation geometry which is shown in Figure 6.15. Again the filament consists of a line source with a length of 25.40 cm (10 in.), an energy of 125 keV, and aperture of 0.25 degrees ($\alpha = 0.25^\circ$). The distance between the line source and the titanium window is 5 cm. There are four layers of absorption materials:

- First, the titanium layer, which is 6 $\mu$m thick, 10.29 cm wide, and 27.42 cm long.
- Second, the air layer, which is 3 cm thick, 73.66 cm wide, and 254 cm long.
- Third, the water layer, which is 12.5 $\mu$m thick, 73.66 cm wide, and 254 cm long.
- Last, the aluminum, which is 0.64 cm thick, 73.66 cm wide, and 254 cm long.

All four layers’ dimensions corresponded with the design of the actual unit, explained in Chapter 4. The shielding wall thickness is 1.27 cm. Additionally the simulation included two energy detectors:

- The first detector consisted of small volume of water, which is on the center of the emitter, and is 12.5 $\mu$m thick, 1 cm wide, and 1 cm long.
- The second detector is at 24.63 cm off center (at the edge of the emitter enclosure), and is equal to the first detector.
For this simulation, the results show that at the first detector experiences 95.2 eV and no energy is deposited at the second detector. The output file from the simulation is included in the Appendix 1 of this thesis.
Dose Calculation

Dose Calculation for Typical Accelerator Parameters

To obtain the results in this section, simulation parameters depended on the simulation geometry shown in Figure 6.16. Because of the emitter’s filament, the source of energy is a line source with a length of 25.4 cm (10 in.), an energy of 125 keV, and an aperture of 0.25 degrees ($\alpha = 0.25^\circ$). The distance between the line source and titanium is 5 cm. There are four layers of absorption materials:

- First, a titanium layer that is 6 $\mu$m thick, 10.29 cm wide, and 27.42 cm long.

- Second, an air layer that is 3 cm thick, 73.66 cm wide, and 254 cm long.

- Third, a water layer that is 12.5 $\mu$m thick, 73.66 cm wide, and 254 cm long.

- Last, an aluminum layer that is 0.64 cm thick, 73.66 cm wide, and 254 cm long.

All four layers dimensions’ correspond with the actual unit explained in Chapter 4. The shielding wall thickness is 1.27 cm.

An energy detector was also simulated to account for the deposited energy from the electron beam in a dosimeter:

- This detector consists of water located on the center of the emitter, and is 12.5 $\mu$m thick ($d$), 1 cm wide ($b$), and 30 cm long ($c$)).

Additionally two particle detectors were simulated with the purpose of finding the fraction of the electron particles in the first particle detector to those in the second particle detector.
- The first detector, on the center of the emitter, is water (12.5 \( \mu \text{m} \) thick, 1 cm wide, and 30 cm long).

- The second is the whole water layer (12.5 \( \mu \text{m} \) thick, 73.66 cm wide, and 254 cm long).

![Diagram of electron acceleration system](image)

Figure 6.16 Simulation geometry for a line source in four layers of absorption material with an energy detector and two particle detectors

The result of this simulation shows that the deposited energy at the energy detector was 502 eV per electron. The number of particles in the first particle detector was 3,670 particles, and the number of particles in the second particle detector was 89,400 particles. Therefore, the fraction of particles in the first particle detector to those in the second particle detector was 0.04 \((f_I = 0.04)\). Output files from these simulations are included in Appendix 2 at the end of this thesis.
PENELOPE has given the surface density of deposited energy $F(x,y)$ per primary electron. This is shown in Figure 6.17

![Image of 2D dose distribution](image)

**Figure 6.17 Surface density of electron energy in the second particle detector**

A dosimeter will collect the energy deposited in detector 1 as it is moved by the platform from one end to the other end of this detector with a speed $v$.

The total energy collected by the dosimeter, in the $x$ direction will then be given by

$$E = \int_{-c/2}^{+c/2} \int_{-b/2}^{+b/2} F(x, y) \, dx \, dy$$

The simulation has already given us $E$ as the energy collected in the energy detector.

Then the dose can be calculated as:
\[ D = \frac{EN_e}{\rho bcd} \]

Where \( N_e \) is the number of electrons being collected by the first detector, \( \rho \) is the density of the dosimeter material, \( b \) is its width, \( c \) is its length, and \( d \) its thickness.

\( N_e \) can readily be obtained from the irradiation parameters using the following procedure:

\[ N_e = \frac{f_l I_b c}{v(1.6 \times 10^{-19})} \]

Where \( f_l \) is the fraction of particles, \( I_b \) is the beam current of the accelerator, \( v \) the speed of the sample under the beam and the quantity in parentheses is the charge of one electron. Then the dose will be:

\[ D = \frac{E f_l I_b}{\rho bcd v} \text{ (Gy)} \]

Figure 6.18 a) Schematic diagram of the geometry used to determine the dose, with the beam at its central position. b) Diagram showing the dosimeter and the area covered when it moves relative to the static beam, with the velocity \( v_x \).

By using the values given above and assuming that the platform is moving with a speed of 0.51 m/s, a dose value of 3.98 kGy was obtained.
Dose Calculation for Different Energies

Simulations of the dose for different energies using the simulation geometry from Figure 6.16 were performed. The simulation was run under the same conditions as those used to determine the energy absorbed in a detector for electrons with an energy from 125 keV to 300 keV. The results are shown in Table 6.1

Table 6.1 Dose in particular energy sources

<table>
<thead>
<tr>
<th>Energy Sources (keV)</th>
<th>Dose (kGy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>125</td>
<td>3.98</td>
</tr>
<tr>
<td>150</td>
<td>3.60</td>
</tr>
<tr>
<td>300</td>
<td>1.8</td>
</tr>
</tbody>
</table>

Dose Calculation for Different Air Gaps

Simulations were run to find the dose for different air gaps using the simulation geometry from Figure 6.16. The simulation was run under conditions in which the energy source was 100 keV, the beam current was 12.6 mA, and the sample speed was 0.51 m/s. The results are shown in Figure 6.19.
Figure 6.19 and 6.20 show that from the simulation using an air gap of about 5 cm, a beam current of 12.6 mA, and a sample speed of 0.51 m/s, the dose at the detector is about 2.7 kGy, which matches the manufacturer data sheet.
X-ray Production

For radiation safety purposes, the average incoming energy of x-rays produced by the electrons interacting with the metal parts of the enclosure box of the unit was calculated. To calculate the amount of the photon energies leaving the unit a water detector was placed under the aluminum box. In this section, the simulation geometry is shown in Figure 6.21

Figure 6.21 Simulation geometry for a line source in five layers of absorption material with two energy detectors

The energy absorbed in the second detector was used to determine the equivalent dose produced by the unit outside of the enclosure box. This simulation was run using the same simulation parameters from the previous section, with an electron energy of 150 keV and a beam current of 25 mA, the first energy detector is the whole water layer (12.5 µm thick, 73.66 cm
wide, and 254 cm long) above the aluminum layer, and the second energy detector is the whole water layer (that is 0.635 cm thick, 73.66 cm wide, and 254 cm long) under the aluminum layer.

The results show that the average incoming energy from electrons at the first detector is 89.4 keV per electron, but no energy from electrons is detected at the second detector. For photon or X-rays, the average incoming energy at the first detector is 93.44 eV, and 24.04 eV per photon at the second detector.

The simulation results found that the aluminum enclosure can absorb all electrons’ energies, but could not absorb all photons or X-rays which are produced when electrons interact with the aluminum by the Bremsstrahlung effect. In this section the amount of lead necessary to reduce the amount of dose equivalent to a level smaller than the maximum permissible value proposed by the National Council on Radiation Protection (NCRP), is calculated. The effective dose equivalent for occupational exposure must be less than 50 mSv (5 rems) in 1 year [7] or 5.71 μSv per hour.

In the worst case scenario for radiation exposure, the emitter can produce a maximum beam current 25 mA with energy 150 keV.

So

\[ I_{\text{max}} = 25 \text{ mA} \text{ or } I_{\text{max}} = 25 \frac{mc}{s} \]

And

\[ 1C = (q_{e^-})(#e^-) \]

Where

\[ q_{e^-} = 1.6 \times 10^{-19} C \text{ and } #e^- \text{ is the number of electrons} \]
Therefore the number of electrons emitted by the accelerator per unit time will be,

\[ \frac{#e^-}{s} = \frac{25 \times 10^{-3} \text{C/s}}{1.6 \times 10^{-19} \text{C/e^-}} = 15.625 \times 10^{16} \frac{e^-}{s} \]

Or the emitter can produce $15.625 \times 10^{16}$ electron per second at the maximum beam current

Next, the amounts of X-rays that this emitter can produce when the electrons interact with the aluminum depend on the stopping power ratio or radiation yield, explained in Chapter 3, and the energy of the electron. The radiation yield of the aluminum at 150 keV (maximum energy of the emitter) is $1.816 \times 10^{-3}$, obtained from the stopping power and range tables for electrons [19].

So \[ \frac{#X-ray}{s} = \left( \frac{#e^-}{s} \right) \text{(radiation yield)} \]

Where \(#X-ray\) is the number of photons or X-rays

And \[ \frac{#X-ray}{s} = (15.625 \times 10^{16})(1.816 \times 10^{-3}) = 28.375 \times 10^{13} \frac{X-ray}{s} \]

So there will be $28.375 \times 10^{13}$ photon per second emitted from the enclosure at the maximum beam current.

From simulation, the amount of photon energy that needs to be reduced is 24 eV per X-ray or $38.4 \times 10^{-19} \frac{J}{X-rays}$, so the energy of the X-rays per unit of time can be obtained by the expression below

\[ \dot{E} = (38.4 \times 10^{-19})(28.375 \times 10^{13}) = 1089.6 \times 10^{-6} \frac{J}{s} \]
And the volume of the second detector (the last water layer) is 0.012 m$^3$, so the mass of the water is 0.012 kg

Therefore, the dose rate or equivalent dose that the emitter can produce outside the shielding aluminum box is obtained by the expression below:

$$\dot{D} = \frac{\dot{E}}{m} = \frac{1089.6 \times 10^{-6}}{0.012} = 90,800 \times 10^{-6} \frac{J}{kg \cdot s} \text{ or } 90,800 \frac{\mu Gy}{s}$$

Where $m$ is the mass of the second detector.

Or $$\dot{D} = 326.88 \frac{Gy}{hour} = 326.88 \frac{Sv}{hour}$$

The effective dose equivalent for occupational exposure should be limited to 5.71 $\mu$Sv per hour, so the amount of lead thickness to reduce the equivalent dose from 326.88 $\frac{Sv}{hour}$ to 5.71 $\frac{\mu Sv}{hour}$ can be determined by using the approach below:

For a narrow beam of mono-energetic photons, the change in x-ray beam intensity at some distance in a material can be expressed in the form of an equation as:

$$I = I_0 e^{-\mu x}$$

Where $I$ = the intensity of photons or X-rays transmitted across some distance $x$

$I_0$ = the initial intensity of photons or X-rays

$\mu$ = the linear absorption coefficient of the material

$x$ = absorber thickness
Since a linear absorption coefficient is dependent on the density of a material, the mass absorption coefficient is often reported for convenience [20].

So \( \mu = (\mu/\rho)\rho \)

Where \( (\mu/\rho) \) is the mass absorption coefficient

\( \rho \) is the density of the material

Therefore,

\[
I = I_0 e^{-((\mu/\rho)\rho)x}
\]

Where \( (\mu/\rho)_{Pb} \), the mass absorption coefficient of the lead at 150 keV, is 1.056 \( \text{cm}^2/\text{g} \), obtained from the table of X-rays mass attenuation coefficient [21], and \( \rho_{Pb} \), the density of the lead, is 11.34 \( \text{g/cm}^3 \).

Where \( I = 5.71 \mu\text{Sv/hour} \) (the intensity of X-rays transmitted across some distance \( x \)) and

\[
I_0 = 326.88 \frac{\mu\text{Sv}}{\text{hour}} \text{ (the initial intensity of photons or X-rays)}
\]

So \( \frac{I}{I_0} = \frac{5.71 \times 10^{-6}}{326.88} = 1.75 \times 10^{-8} \text{ or } \frac{I}{I_0} \approx 10^{-9} \text{ in the worst case scenario} \)

Therefore,

\[
x = \frac{9\ln10}{(\mu/\rho)_{Pb} \rho_{Pb}} = \frac{20.72}{(1.056)(11.34)} = 1.73 \text{ cm}
\]

So the lead thickness to reduce the intensity of X-rays from 326.88 Sievert per hour to 5.71 micro-Sievert per hour is 1.73 cm
**Hardware Design**

This part of the project focuses on the design and construction of the hardware and safety devices of the unit. The entire unit enclosure will be built using aluminum and lead. The electron-emitter support will be built using extruded aluminum profiles inside the enclosure to ensure that it can support the 16 kilogram weight of the emitter. A controller will be provided to control the speed of the platform that can move the sample to the beam exposure area. The controller will also control the power supply to get an appropriate high voltage and beam current from the electron emitter. The heat generated by the electrons passing through the window foil will be removed by a cooling system. The temperature of the window foil as well as of the sample platform will also be measured as part of the safety considerations of the whole unit. The overall hardware design is shown in Figure 6.22.
Stress Analysis

Stress analyses were performed on the support and shielding frame by using Autodesk Inventor to ensure that it could safely support the unit. The stress analyses were performed using a static analysis with a gravity load, assuming the unit enclosure sits on a flat area. The results are shown in Figure 6.23 and 6.24.
Emitter Support Frame Stress Analysis

Figure 6.23 Displacement and safety factor of the emitter support frame

Figure 6.23 shows that the emitter support frame has a maximum displacement of 0.41 mm (0.016 in.) and a minimum safety factor of 6.26, so the frame will safely support the emitter.
Shielding Frame Stress Analysis

Figure 6.24 shows that the shielding frame has a maximum displacement of 0.08 mm (0.003108 in.), and a minimum safety factor of 1.18, so the frame will safely support the load.
Window Cooling System

A window cooling system was designed because the water cooling that is part of the emitter to help provide cooling to the copper base is not sufficient for irradiation conditions at maximum beam power. Therefore, convective cooling of the titanium window is required. This system forces pressurized air over the window, providing convective cooling to the window. This system is shown in Figure 6.25

![Window Cooling System](image)

Figure 6.25 Window cooling system

The maximum thermal energy that the emitter can generate is 1.0 kW. The conductive water cooling can remove heat up to about 0.5 kW, so the remaining heat will need to be removed by the convective foil cooling.
Air Cooling System

An air cooling system was designed for the irradiation chamber. The system consists of an open inlet duct and an outlet duct with an electric fan at the end of the duct. The chamber requires at least 10 CFM of airflow for cooling, since the emitter can generate a maximum heat of 1 kW. To prevent the temperature in the chamber from exceeding 50 centigrade, the fan should be capable of producing a minimum flow of 70 CFM, which obtained by using \( Q_{(CFM)} = \frac{1.76 \times P}{\Delta T_C} \), where \( P \) is internal heat dissipation and \( \Delta T_C \) is allowable temperature rise in °C [22]. The fan also extracts ozone, a harmful byproduct of the interaction of the electrons with air. This system is shown in Figure 6.26

![Air Cooling System](image)

Figure 6.26 Air cooling system, with electric fan (A) to remove air from the irradiation chamber.

The fan is 12 cm wide and 12 cm long, fits the dimensions of the air cooling system, and can provide a minimum flow of 70 CFM.
Sample Platform System

This system is shown in figure 6.27 the platform system is used to move the sample into and out of the chamber.

![Sample Platform System](image)

Figure 6.27 Sample platform system

Simulations were performed to estimate the dose for different platform speeds using the simulation geometry from Figure 6.16. The simulations were run using an energy source of 100 keV, a beam current of 12.6 mA, and an air gap of 3 cm. The results are shown in figure 6.28 by using $D = \frac{E f t b}{\rho bdv}$ to calculate the dose in gray.

![Dose vs Speed Graph](image)

Figure 6.28 Doses for different speeds of the platform
Chapter 7

Conclusion

The work described in this thesis was concerned with the simulation and design of the enclosure of a low energy electron accelerator. The focus of this work was on determining the construction of an appropriate enclosure for the accelerator, as well as determining and obtaining the appropriate dose in a sample. First, general information of the electron accelerator was studied and presented. To clarify how the design calculations were optimized for a low energy electron accelerator, the main quantities and units such as energy, beam current, power, and dose were reviewed. In order to obtain a more clear understanding of this thesis, radiation processing and how it can initiate biological and chemical changes in a material was studied and presented. These details were used in the simulation and design of the unit, and allowed for the correct parameters to be used when determining the appropriate enclosure properties and dose delivery. The hazards present during normal operation of the unit, which contribute to the requirements of the project, are also important. These were studied before simulating and designing the enclosure. PENELOPE Monte Carlo simulations were used to determine an appropriate shielding material type and its appropriate amount, as well as the expected dose under several conditions. Autodesk Inventor was used to create drawings and simulations for the mechanical design. The results can be summarized in the two paragraphs below:

The simulations show that:

- The 0.635 cm (0.25 in.) of aluminum can absorb all electrons with an initial energy of 125 keV, and 1.73 cm of lead will be needed to reduce the intensity of X-rays produced by those electrons to a level less than the maximum permissible value suggested (5.71 μSv/hour) by the
National Council on Radiation Protection (NCRP). The lead thickness required to reduce the intensity of X-rays from 326.88 Sievert per hour (the maximum dose equivalent that the electron accelerator can produce) to 5.71 micro-Sievert per hour (the maximum permissible value) is 1.73 cm.

- At the edge of the emitter enclosure the dose obtained by the simulation was negligible as compare to the dose at the center of radiation field.

- By using an air gap of about 5 cm, a beam current of 12.6 mA, and a sample speed of 0.51 m/s, we obtained a dose at the detector of 2.7 kGy. The manufacturer data sheet lists the expected dose as 2.75 kGy, which represents a 1.8 % difference.

Analysis for the hardware design demonstrates that the unit is safe:

- The stress analysis shows that the structure is robust. The emitter support frame has a maximum displacement of 0.41 mm (0.016 in.) and a minimum safety factor of 6.26, and the shielding frame has a maximum displacement of 0.08 mm (0.003108 in.), and a minimum safety factor of 1.18.

- A window cooling system was designed to help provide cooling to the copper base, which is not sufficiently cooled for irradiation conditions at maximum beam power. The maximum thermal energy that the emitter can generate is 1.0 kW. The conductive water cooling can remove heat up to about 0.5 kW, so the remaining heat will need to be removed by this system.
- The cooling system was designed to provide sufficient cooling as well as remove ozone from the system. By installing a fan with a minimum flow of 70 CFM at the outlet duct, the system can prevent the temperature in the chamber from exceeding 50 centigrade.

- By controlling the platform speeds, the radiation dose can also be controlled by using the equation

\[ D = \frac{E_t I_b}{\rho b d v} \]

to calculate the dose in gray. The speed of the platform can vary the dose, so the appropriate speed will depend on the desired dose.

**Future Work**

Although the results presented here have satisfactory outcomes, the accelerator must be built to bring the project to completion. Once an actual unit has been built, the results from the experiment, such as dose calculation, radiation safety, and mechanical design, can be compared with the results from the simulations that have been done in this thesis to confirm that the results from this thesis are useful and practical.

There is clearly much work to be done in the hardware design. Perhaps the most direct extension of this work is to determine the budget for the construction of a unit. This would require analyzing the cost of the new electron accelerator unit and comparing this to the cost of the accelerator that is described in this thesis. This will involve finding the total cost, including the materials to build the enclosure, the controller, and facilities, and comparing this with the cost of a new unit. If these materials have a lower cost than the new unit then the accelerator described in this thesis represents a superior course of action. After determining the cost of building the accelerator, the construction and assembly of the hardware will be undertaken, which will require gathering additional information and using other technical skills.
The minimum safety factor for the shielding frame found in this work was low. The minimum safety factor for the shielding frame can potentially be increased by reevaluating the amount of lead needed for shielding. This can be done by adjusting the expected dose equivalent to account for the fact that an operator would only be exposed to radiation from the accelerator during a work shift, typically eight hours a day. The calculations done in this thesis assumed that an operator would work with the unit for 24 hours a day. Thus, this reduction in exposure time would allow for a thinner layer of lead to be used to maintain the expected dose equivalent at the maximum allowable level. As a result, the mass of the shielding would be reduced, and the minimum safety factor of the shielding frame would be increased.
References


APPENDIX
Appendix 1
**[Simulation File]**

**TITLE** simulation of a 125 keV electron beam going through titanium and air with Line - Source
  . (the dot prevents editors from removing trailing blanks)

  >>>>>>>> Source definition.

  **SKPAR** 1        [Primary particles: 1=electron, 2=photon, 3=positron]
  **SENERG** 1.25e5           [Initial energy (monoenergetic sources only)]
  **SPOSIT** 0 0 -5                             [Coordinates of the source]
  **SBOX** 25.4 0 0                               [Source box dimensions]
  **SPYRAM** 0 0.125 0 360                      [Rectangular beam; angles in deg]

  >>>>>>>> Material data and simulation parameters.

  Up to MAXMAT materials; 2 lines for each material.

  **MFNAME** titanium                       [Material file, up to 20 chars]
  **MSIMPA** 1.0e3 1.0e3 1.0e3 0.0 0.0 1e3 1e3  
      [EABS(1:3),C1,C2,WCC,WCR]

  **MFNAME** air                            [Material file, up to 20 chars]
  **MSIMPA** 1.0e3 1.0e3 1.0e3 0.05 0.05 1e3 1e3  
      [EABS(1:3),C1,C2,WCC,WCR]

  **MFNAME** water                          [Material file, up to 20 chars]
  **MSIMPA** 1.0e3 1.0e3 1.0e3 0.02 0.02 1e3 1e3  
      [EABS(1:3),C1,C2,WCC,WCR]

  **MFNAME** aluminum                       [Material file, up to 20 chars]
  **MSIMPA** 1.0e3 1.0e3 1.0e3 0.02 0.02 1e3 1e3  
      [EABS(1:3),C1,C2,WCC,WCR]

  >>>>>>>> Geometry definition file.

  **GEOMFN** Test4L2D.geo              [Geometry definition file, 20 chars]
  **DSMAX**  3 1.0e-5                  [KB, maximum step length in body KB]

  >>>>>>>> Interaction forcing.

  **IFORCE** 1 1 3 -100. .5 1               [KB,KPAR,ICOL,FORCER,WLOW,WHIG]

  >>>>>>>> Emerging Particles. Energy and angular distribution

  **NBE** 1E3 1.25E5 100
  **NBANGL** 90 45 100

  >>>>>>>> Energy-deposition detectors 1

  **ENDETC** 1e3 1.25e5 50  
      [Energy window and number of bins]
  **EDSPC** pm-spc-enddet-01.dat     [Output spectrum file name, 20 chars]
  **EDBODY** 3                        [Active body; one line for each body]

  >>>>>>>> Energy-deposition detectors 2

  **ENDETC** 1e3 1.25e5 50  
      [Energy window and number of bins]
  **EDSPC** pm-spc-enddet-02.dat     [Output spectrum file name, 20 chars]
  **EDBODY** 4                        [Active body; one line for each body]

  >>>>>>>> Dose distribution.

  **GRIDX** -28 28                 [X coordinates of the enclosure vertices]
  **GRIDY** -20 20                 [Y coordinates of the enclosure vertices]
  **GRIDZ** 3.0006 3.00185         [Z coordinates of the enclosure vertices]
  **GRIDBN** 50 50 50                          [Numbers of bins]
>>> Job properties.
RESUME dump1.dat  [Resume from this dump file, 20 chars]
DUMPTO dump1.dat  [Generate this dump file, 20 chars]
DUMPP 120        [Dumping period, in sec]
NSIMSH 1e9       [Desired number of simulated showers]
TIME 1e9         [Allotted simulation time, in sec]
END
This is an example of a geometry for electrons interacting with water after going through titanium and air.

**SURFACE ( 0)** plane, bottom of aluminum plate $z=-0.6344$
- **INDICES** = ( 0, 0, 0, 0, 0)
- **AZ** = ( 1.000000000000000E+00, 0)
- **A0** = ( 6.344000000000000E-01, 0)

**SURFACE ( 1)** plane, bottom of titanium window $z=0$
- **INDICES** = ( 0, 0, 0, 0, 0)
- **AZ** = ( 1.000000000000000E+00, 0)
- **A0** = ( -6.000000000000000E-04, 0)

**SURFACE ( 2)** plane, top of titanium window $Z=0.0006$
- **INDICES** = ( 0, 0, 0, 0, 0)
- **AZ** = ( 1.000000000000000E+00, 0)
- **A0** = ( -3.000600000000000E+00, 0)

**SURFACE ( 3)** plane, bottom of water $Z=3.0006$
- **INDICES** = ( 0, 0, 0, 0, 0)
- **AZ** = ( 1.000000000000000E+00, 0)
- **A0** = ( -3.001850000000000E+00, 0)

**SURFACE ( 4)** plane, top of water $Z=3.00185$
- **INDICES** = ( 0, 0, 0, 0, 0)
- **AZ** = ( 1.000000000000000E+00, 0)
- **A0** = ( -3.001850000000000E+00, 0)

**SURFACE ( 5)** plane, top of aluminum $Z=3.63685$
- **INDICES** = ( 0, 0, 0, 0, 0)
- **AZ** = ( 1.000000000000000E+00, 0)
- **A0** = ( -3.636850000000000E+00, 0)

**SURFACE ( 6)** PAIR OF 2 PLANES, $X=+/- 13.716$ CM
- **INDICES** = ( 1, 0, 0, 0, -1)
- **X-SCALE** = ( 1.371600000000000E+01, 0)

**SURFACE ( 7)** PAIR OF 2 PLANES, $Y=+/- 5.1435$ CM
- **INDICES** = ( 0, 1, 0, 0, -1)
- **Y-SCALE** = ( 5.143500000000000E+00, 0)

**SURFACE ( 8)** PAIR OF 2 PLANES, $X=+/- 0.5$ CM
- **INDICES** = ( 1, 0, 0, 0, -1)
- **X-SCALE** = ( 5.000000000000000E-01, 0)

**SURFACE ( 9)** PAIR OF 2 PLANES, $Y=+/- 0.5$ CM
- **INDICES** = ( 0, 1, 0, 0, -1)
- **Y-SCALE** = ( 5.000000000000000E-01, 0)

**SURFACE ( 10)** PAIR OF 2 PLANES, $X=+/- 2.25$ CM
DEVELOPMENT OF A LOW ENERGY ELECTRON ACCELERATOR SYSTEM

INDICES=( 1, 0, 0, 0,-1)
X-SCALE=( 2.250000000000000E+00,   0)
0000000000000000000000000000000000000000000000000000000000000000
SURFACE ( 11)  PAIR OF 2 PLANES, Y=+/- 0.2 CM
INDICES=( 0, 1, 0, 0,-1)
Y-SCALE=( 2.000000000000000E-01,   0)
0000000000000000000000000000000000000000000000000000000000000000
SURFACE ( 12)  PAIR OF 2 PLANES, X=+/- 36.83 CM
INDICES=( 1, 0, 0, 0,-1)
X-SCALE=( 3.683000000000000E+01,   0)
0000000000000000000000000000000000000000000000000000000000000000
SURFACE ( 13)  PAIR OF 2 PLANES, Y=+/- 127 CM
INDICES=( 0, 1, 0, 0,-1)
Y-SCALE=( 1.270000000000000E+02,   0)
0000000000000000000000000000000000000000000000000000000000000000
SURFACE ( 14)  PAIR OF 2 PLANES, X=+/- 38.1 CM
INDICES=( 1, 0, 0, 0,-1)
X-SCALE=( 3.810000000000000E+01,   0)
0000000000000000000000000000000000000000000000000000000000000000
SURFACE ( 15)  PAIR OF 2 PLANES, Y=+/- 128.27 CM
INDICES=( 0, 1, 0, 0,-1)
Y-SCALE=( 1.282700000000000E+02,   0)
0000000000000000000000000000000000000000000000000000000000000000
SURFACE ( 16)  plane, Y=-24.13
INDICES=( 0, 0, 0, 0, 0)
   AY=( 1.000000000000000E+00,   0)
   A0=( 2.413000000000000E+01,   0)
0000000000000000000000000000000000000000000000000000000000000000
SURFACE ( 17)  plane, Y=-25.13
INDICES=( 0, 0, 0, 0, 0)
   AY=( 1.000000000000000E+00,   0)
   A0=( 2.513000000000000E+01,   0)
0000000000000000000000000000000000000000000000000000000000000000
BODY    (   1)  titanium foil
MATERIAL(   1)
SURFACE (  1), SIDE POINTER=(   1)
SURFACE (  2), SIDE POINTER=(-1)
SURFACE (  6), SIDE POINTER=(-1)
SURFACE (  7), SIDE POINTER=(-1)
0000000000000000000000000000000000000000000000000000000000000000
BODY    (   2)  air column
MATERIAL(   2)
SURFACE (  2), SIDE POINTER=(   1)
SURFACE (  3), SIDE POINTER=(-1)
SURFACE ( 12), SIDE POINTER=(-1)
SURFACE ( 13), SIDE POINTER=(-1)
0000000000000000000000000000000000000000000000000000000000000000
BODY    (   3)  detector 1
MATERIAL(   3)
SURFACE (  3), SIDE POINTER=(   1)
SURFACE (  4), SIDE POINTER=(-1)
SURFACE (  8), SIDE POINTER=(-1)
SURFACE (  2), SIDE POINTER=( 1)
SURFACE (  4), SIDE POINTER=(-1)
SURFACE ( 13), SIDE POINTER=( 1)
SURFACE ( 14), SIDE POINTER=(-1)
SURFACE ( 15), SIDE POINTER=(-1)
0000000000000000000000000000000000000000000000000000000000000000
END 0000000000000000000000000000000000000000000000000000000000000000
Appendix 2
TITLE simulation of a 125 keV electron beam going through titanium and air with Line - Source
               (the dot prevents editors from removing trailing blanks)
               >>>>>>>> Source definition.
SKPAR 1 [Primary particles: 1=electron, 2=photon, 3=positron]
SENERG 1.25e5 [Initial energy (monoenergetic sources only)]
SPOSIT 0 0 -5 [Coordinates of the source]
SBOX 25.4 0 0 [Source box dimensions]
SPYRAM 0 0.125 0 360 [Rectangular beam; angles in deg]

               >>>>>>>> Material data and simulation parameters.
Up to MAXMAT materials; 2 lines for each material.
MFNAME titanium [Material file, up to 20 chars]
MSIMPA 1.0e3 1.0e3 1.0e3 0.0 0.0 1e3 1e3 [EABS(1:3),C1,C2,WCC,WCR]
MFNAME air [Material file, up to 20 chars]
MSIMPA 1.0e3 1.0e3 1.0e3 0.05 0.05 1e3 1e3 [EABS(1:3),C1,C2,WCC,WCR]
MFNAME water [Material file, up to 20 chars]
MSIMPA 1.0e3 1.0e3 1.0e3 0.02 0.02 1e3 1e3 [EABS(1:3),C1,C2,WCC,WCR]
MFNAME aluminum [Material file, up to 20 chars]
MSIMPA 1.0e3 1.0e3 1.0e3 0.02 0.02 1e3 1e3 [EABS(1:3),C1,C2,WCC,WCR]

               >>>>>>>> Geometry definition file.
GEOMFN Test4L2D.geo [Geometry definition file, 20 chars]
DSMAX 3 1.0e-5 [KB, maximum step length in body KB]

               >>>>>>>> Interaction forcing.
IFORCE 1 1 3 -100. .5 1 [KB,KPAR,ICOL,FORCER,WLOW,WHIG]

               >>>>>>>> Emerging Particles. Energy and angular distribution
NBE 1E3 1.25E5 100
NBANGL 90 45 100

               >>>>>>>> Impact detectors 1.
IMPDET 0 1.25e5 50 1 2 [E-window, no. of bins, IPSF, IDCUT]
IDSPC pm-spc-impdet-01.dat [Spectrum file name, 20 chars]
IDPSF pm-psf-impdet-01.dat [Phase-space file name, 20 chars]
IDFLNC pm-fln-impdet-01.dat [Fluence spectrum file name, 20 chars]
IDBODY 3 [Active body; one line for each body]
IDKPAR 1 [Kind of detected particles, one line each]

               >>>>>>>> Impact detectors 2.
IMPDET 0 1.25e5 50 1 2 [E-window, no. of bins, IPSF, IDCUT]
IDSPC pm-spc-impdet-02.dat [Spectrum file name, 20 chars]
IDPSF pm-psf-impdet-02.dat [Phase-space file name, 20 chars]
IDFLNC pm-fln-impdet-02.dat [Fluence spectrum file name, 20 chars]
IDBODY 5 [Active body; one line for each body]
IDKPAR 1 [Kind of detected particles, one line each]

               >>>>>>>> Energy-deposition detectors 1
ENDETC 1e3 1.25e5 50 [Energy window and number of bins]
EDSPC pm-spc-enddet-01.dat [Output spectrum file name, 20 chars]
EDBODY 3 [Active body; one line for each body]

>>> Energy-deposition detectors 2
ENDETC 1e3 1.25e5 50 [Energy window and number of bins]
EDSPC pm-spc-enddet-02.dat [Output spectrum file name, 20 chars]
EDBODY 4 [Active body; one line for each body]

>>> Dose distribution.
GRIDX -28 28 [X coordinates of the enclosure vertices]
GRIDY -20 20 [Y coordinates of the enclosure vertices]
GRIDZ 3.0006 3.00185 [Z coordinates of the enclosure vertices]
GRIDBN 50 50 50 [Numbers of bins]

>>> Job properties.
RESUME dump1.dat [Resume from this dump file, 20 chars]
DUMPTO dump1.dat [Generate this dump file, 20 chars]
DUMPP 120 [Dumping period, in sec]

NSIMSH 3e6 [Desired number of simulated showers]
TIME 1e9 [Allotted simulation time, in sec]
END
This is an example of a geometry for electrons interacting with water after going through titanium and air.

SURFACE (0) plane, bottom of aluminum plate z=-0.6344
INDICES=(0, 0, 0, 0, 0)
AZ=(1.000000000000000E+00, 0)
A0=(6.344000000000000E-01, 0)

SURFACE (1) plane, bottom of titanium window z=0
INDICES=(0, 0, 0, 0, 0)
AZ=(1.000000000000000E+00, 0)
A0=(-6.000000000000000E-04, 0)

SURFACE (2) plane, top of titanium window Z=0.0006
INDICES=(0, 0, 0, 0, 0)
AZ=(1.000000000000000E+00, 0)
A0=(-3.000600000000000E+00, 0)

SURFACE (3) plane, bottom of water Z=3.0006
INDICES=(0, 0, 0, 0, 0)
AZ=(1.000000000000000E+00, 0)
A0=(-3.001850000000000E+00, 0)

SURFACE (4) plane, top of water Z=3.00185
INDICES=(0, 0, 0, 0, 0)
AZ=(1.000000000000000E+00, 0)
A0=(-3.636850000000000E+00, 0)

SURFACE (5) plane, top of aluminum Z=3.63685
INDICES=(0, 0, 0, 0, 0)
AZ=(1.000000000000000E+00, 0)
A0=(-3.636850000000000E+00, 0)

SURFACE (6) PAIR OF 2 PLANES, X=+/- 13.716 CM
INDICES=(1, 0, 0, 0, -1)
X-SCALE=(1.371600000000000E+01, 0)

SURFACE (7) PAIR OF 2 PLANES, Y=+/- 5.1435 CM
INDICES=(0, 1, 0, 0, -1)
Y-SCALE=(5.143500000000000E+00, 0)

SURFACE (8) PAIR OF 2 PLANES, X=+/- 0.5 CM
INDICES=(1, 0, 0, 0, -1)
X-SCALE=(5.000000000000000E+00, 0)

SURFACE (9) PAIR OF 2 PLANES, Y=+/- 36.83 CM
INDICES=(0, 1, 0, 0, -1)
Y-SCALE=(3.683000000000000E+01, 0)

SURFACE (10) PAIR OF 2 PLANES, X=+/- 2.25 CM
DEVELOPMENT OF A LOW ENERGY ELECTRON ACCELERATOR SYSTEM

INDICES = (1, 0, 0, 0, -1)
X-SCALE = (2.250000000000000E+00, 0)
SURFACE (11) PAIR OF 2 PLANES, Y=+/− 0.2 CM
INDICES = (0, 1, 0, 0, -1)
Y-SCALE = (2.000000000000000E-01, 0)
SURFACE (12) PAIR OF 2 PLANES, X=+/− 36.83 CM
INDICES = (1, 0, 0, 0, -1)
X-SCALE = (3.683000000000000E+01, 0)
SURFACE (13) PAIR OF 2 PLANES, Y=+/− 127 CM
INDICES = (0, 1, 0, 0, -1)
Y-SCALE = (1.270000000000000E+02, 0)
SURFACE (14) PAIR OF 2 PLANES, X=+/− 38.1 CM
INDICES = (1, 0, 0, 0, -1)
X-SCALE = (3.810000000000000E+01, 0)
SURFACE (15) PAIR OF 2 PLANES, Y=+/− 128.27 CM
INDICES = (0, 1, 0, 0, -1)
Y-SCALE = (1.282700000000000E+02, 0)
SURFACE (16) plane, Y=-24.13
INDICES = (0, 0, 0, 0, 0)
AY = (1.000000000000000E+00, 0)
A0 = (2.413000000000000E+01, 0)
SURFACE (17) plane, Y=-25.13
INDICES = (0, 0, 0, 0, 0)
AY = (1.000000000000000E+00, 0)
A0 = (2.513000000000000E+01, 0)
BODY (1) titanium foil
MATERIAL (1)
SURFACE (1), SIDE POINTER = (1)
SURFACE (2), SIDE POINTER = (-1)
SURFACE (6), SIDE POINTER = (-1)
SURFACE (7), SIDE POINTER = (-1)
BODY (2) air column
MATERIAL (2)
SURFACE (2), SIDE POINTER = (1)
SURFACE (3), SIDE POINTER = (-1)
SURFACE (12), SIDE POINTER = (-1)
SURFACE (13), SIDE POINTER = (-1)
BODY (3) detector 1
MATERIAL (3)
SURFACE (3), SIDE POINTER = (1)
SURFACE (4), SIDE POINTER = (-1)
SURFACE (8), SIDE POINTER = (-1)
DEVELOPMENT OF A LOW ENERGY ELECTRON ACCELERATOR SYSTEM

SURFACE ( 9), SIDE POINTER=(-1)
BODY ( 4) detector 2
MATERIAL( 3)
SURFACE ( 3), SIDE POINTER=( 1)
SURFACE ( 4), SIDE POINTER=(-1)
SURFACE ( 8), SIDE POINTER=(-1)
SURFACE (16), SIDE POINTER=(-1)
SURFACE (17), SIDE POINTER=( 1)
MODULE ( 5) water foil
MATERIAL( 3)
SURFACE ( 3), SIDE POINTER=( 1)
SURFACE ( 4), SIDE POINTER=(-1)
SURFACE (12), SIDE POINTER=(-1)
SURFACE (13), SIDE POINTER=(-1)
BODY ( 3)
BODY ( 4)
BODY ( 6) aluminum
MATERIAL( 4)
SURFACE ( 4), SIDE POINTER=( 1)
SURFACE ( 5), SIDE POINTER=(-1)
SURFACE (14), SIDE POINTER=(-1)
SURFACE (15), SIDE POINTER=(-1)
BODY ( 7) aluminum
MATERIAL( 4)
SURFACE ( 0), SIDE POINTER=( 1)
SURFACE ( 2), SIDE POINTER=(-1)
SURFACE ( 6), SIDE POINTER=( 1)
SURFACE (14), SIDE POINTER=(-1)
SURFACE (15), SIDE POINTER=(-1)
BODY ( 8) aluminum
MATERIAL( 4)
SURFACE ( 0), SIDE POINTER=( 1)
SURFACE ( 2), SIDE POINTER=(-1)
SURFACE ( 7), SIDE POINTER=( 1)
SURFACE (14), SIDE POINTER=(-1)
SURFACE (15), SIDE POINTER=(-1)
BODY ( 9) aluminum
MATERIAL( 4)
SURFACE ( 2), SIDE POINTER=( 1)
SURFACE ( 4), SIDE POINTER=(-1)
SURFACE (12), SIDE POINTER=( 1)
SURFACE (14), SIDE POINTER=(-1)
SURFACE (15), SIDE POINTER=(-1)
BODY (10) aluminum
MATERIAL( 4)
SURFACE (  2), SIDE POINTER=(  1)
SURFACE (  4), SIDE POINTER=(-1)
SURFACE ( 13), SIDE POINTER=(  1)
SURFACE ( 14), SIDE POINTER=(-1)
SURFACE ( 15), SIDE POINTER=(-1)
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