

SIMULATION OF THE EFFECT OF DEE RADIUS ON THE KINETIC ENERGY OF A CYCLOTRON ACCELERATOR USING PYTHON PROGRAMMING AS A STUDY OF PROTON THERAPY

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Abstract

Cancer is a dangerous disease and one of the leading causes of death worldwide. One of the treatments for cancer is radiotherapy. Proton radiotherapy has been widely developed due to its advantage of reducing damage to healthy tissue surrounding the cancer. The source of proton radiotherapy comes from an accelerator, and currently, the most commonly developed type is the cyclotron. This study aims to simulate and analyze the effect of the dee radius on the kinetic energy produced by the cyclotron. The research was conducted using an in silico method with the Python programming language. Based on the simulation results, the kinetic energy produced by the cyclotron for dees radii of 0.2 m, 0.25 m, 0.3 m, 0.35 m, and 0.4 m are 1.644 MeV, 2.639 MeV, 3.941 MeV, 5.462 MeV, and 7.246 MeV, respectively. Therefore, the larger the dee radius used, the greater the kinetic energy of the proton produced. This occurs because a larger dee radius allows the proton to pass through the gap between the dees more frequently. When the proton crosses the gap between the dees, its velocity increases due to acceleration caused by the potential difference between the two dees, resulting in higher kinetic energy.

Keywords: *Cancer; Proton Therapy; Cyclotron; Python*

INTRODUCTION

Cancer is one of the leading causes of death worldwide (Pichaiavel, M., et al., 2022). Based on data from The International Agency for Research on Cancer (IARC, 2024), in 2022 there were approximately 408,661 new cancer cases in Indonesia. IARC predicts that this number will continue to increase by 2030. One of the methods used for cancer treatment is radiotherapy. Radiotherapy is a medical treatment that uses high-energy radiation to destroy cancer cells. The most widely used radiotherapy at present employs X-ray radiation (Fitriatuzzakiyyah, N., et al, 2027). X-ray radiation has proven effective in killing cancer cells; however, it also damages surrounding healthy tissue. This occurs due to the nature of X-ray interaction with the medium it passes through, namely the exponential decrease in intensity caused by energy absorption in the medium. As a result, the greatest damage occurs in tissue areas near the skin, which poses a problem if the cancer is located deep inside the body (Sulistya, E., et al., 2014).

In addition to X-ray radiotherapy, proton radiotherapy is currently being extensively developed. Proton radiotherapy is a radiation therapy that destroys cancer cells using high-energy proton particles. Protons are charged particles with a relatively high mass, giving their interactions with the medium different characteristics compared to X-rays. As protons enter the medium, their velocity decreases; this reduction in velocity increases the number of interactions between the protons and the medium, causing a sharp rise in ionization known as the Bragg Peak, followed by a rapid drop to zero when the ions stop (Sulistya, E., et al., 2014). This property is advantageous because healthy tissue traversed by the proton beam undergoes minimal ionization, whereas the cancer tissue receives a high level of ionization (Dewi, R. A., et al., 2023). The source of radiation for proton therapy comes from positively charged particles (protons) accelerated in a vacuum chamber known as an accelerator (Rochette, L., et al., 2021). Currently, the accelerators commonly used include LINAC, cyclotrons, and synchrotrons (Otto, T., 2021). For medical purposes, cyclotrons are more often used due to their better cost-to-performance ratio (Mayles, P., et al.,

2007). In a cyclotron, the ion source injects protons into the center of the machine, which is positioned between two hollow semicircular electrodes called “dees.” These two dees are connected to a high alternating voltage (AC) source. When protons are in the electric field between the dees, the negative polarity sector exerts an attractive force, causing the protons to accelerate. A magnetic circuit and a set of coils generate a strong magnetic field perpendicular to the particle path. When the protons enter the cavity of the electrodes (dees), no electric force acts on them. The magnetic field B bends the path of a charged particle q moving at velocity v into a circular trajectory with radius r . The protons then re-emerge into the space between the dees precisely when the electric field has reversed its direction, accelerating them again and causing them to follow a circular path with a larger radius, and so on, until higher energies are achieved (Das, B. K., 2015).

Although cyclotrons are not yet widely used, they are currently being developed extensively due to their favorable performance-to-cost ratio compared to other accelerators (Mayles, P., et al., 2007). In Indonesia, there are currently no healthcare facilities utilizing proton radiotherapy as a cancer treatment modality. However, Gatot Soebroto Army Hospital in Jakarta has announced plans to build a proton radiotherapy facility equipped with a cyclotron (PTCOG, 2024). Designing a cyclotron requires specifications for parameters such as the size of the dee radius, the strength of the magnetic field, and the electric potential to achieve the desired energy level. Many studies on cyclotrons have been conducted, one of which is through the in silico method. The in silico approach can be implemented in various ways, one of which involves numerical analysis using Python programming. Numerical analysis is advantageous in handling large systems of equations, nonlinearity, and complex geometries that are often impractical to solve analytically in engineering applications (Maharani, S., & Suprpto, E., 2018). In this study, the authors employed Python to simulate the effect of variations in dee radius on the energy produced by a cyclotron. Python is a simple, script-based computer programming language capable of performing data analysis, executing complex statistical computations, generating data visualizations, implementing machine learning algorithms, and manipulating data. Python was chosen in this research due to its ease of use and its ability to produce more accurate and efficient results (Surbakti, N. M., et al., 2024). Considering the significant benefits of proton therapy for cancer treatment, and the fact that cyclotrons are among the most commonly used sources for proton therapy, further research is needed on the influence of cyclotron parameters. This study aims to simulate and analyze the effect of dee radius on the kinetic energy generated by a cyclotron using Python programming

LITERATURE REVIEW

A proton is a positively charged particle located in the nucleus of an atom, possessing a charge of $q = 1.602 \times 10^{-19}$ Coulomb and proton mass of $m = 1.672 \times 10^{-27}$ kg, which is approximately 1,800 times heavier than the mass of an electron (Irawan et al., 2024). A cyclotron is a type of particle accelerator that can accelerate charged particles, such as protons, by utilizing both magnetic and electric fields, thereby producing high kinetic energy. Cyclotrons can be applied in proton radiotherapy. Proton radiotherapy has the advantage of delivering a maximum dose to tumor tissue while significantly reducing the dose received by the surrounding healthy tissue, due to the presence of the Bragg Peak (Fitriatuzzakiyyah et al., 2017). The Bragg Peak occurs when the specific ionization increases proportionally with the charge of the charged particle, as a higher charge generates a stronger Coulomb field. As the charged particle loses energy, its velocity decreases, resulting in a longer interaction time and a sharp increase in ionization just before the particle comes to a complete stop (Hazem, 2023).

Inside a cyclotron, there are two D-shaped electrodes known as *dees*. These *dees* are connected to an oscillator, producing an alternating current (AC) in the gap between them. The *dees* are positioned within a magnetic field oriented perpendicular to their plane. Between the two *dees* lies an ion source, which generates protons and injects them into the gap between the *dees*. When a proton is injected into the gap between the *dees*, it is accelerated toward one of the *dees* by the electric field. Once inside a *dee*, the electric field becomes zero, and the proton's trajectory is bent into a semicircle by the magnetic field, directing it back toward the gap. At that moment, the potential between the *dees* reverses, accelerating the proton toward the opposite *dee*. Each time the proton crosses the gap, its velocity increases, which in turn increases the radius of its circular path, forming a spiral trajectory. When the proton's path reaches the outer edge of the *dees* or when there is no more space to increase its radius, the proton has achieved its maximum energy and is then extracted through the window (Das, 2015).

METHOD

This study employed the in silico method using the Python programming language, written in the Integrated Development Environment (IDE) Jupyter Notebook. In this research, simulations and analyses were conducted to

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examine the effect of variations in dee radius on the kinetic energy of protons produced by a cyclotron. The variables used in this study were as follows:

- Independent variable: dee radius with values $r = 0.2$ m, 0.25 m, 0.3 m, 0.35 m, and 0.4 m.
- Control variables: proton charge $q = 1.6 \times 10^{-19}$ C, proton mass $m = 1.67 \times 10^{-27}$ kg, voltage between dees $V = 100$ kV, and magnetic field strength $B = 1$ T.
- Dependent variables: proton position and kinetic energy.

The simulation was executed using Python on a laptop with the brand HP, equipped with a 12th Gen Intel® Core™ i5-1235U processor and 8 GB RAM. The workflow of this research is illustrated in the flowchart shown in Image 1.

RESULTS AND DISCUSSION

The particle used in this study is a proton, which has a charge of $q = 1.6 \times 10^{-19}$ C dan a mass of $m = 1.67 \times 10^{-27}$ kg. In the simulation, the cyclotron operates with a magnetic field of 1 T, a distance between dee plates of $d = 0.0005$ m and an electric potential difference between the dees of $V = 100$ kV.

After conducting simulations and computational calculations using Python, the relationship between radius, velocity, and kinetic energy was obtained, as shown in Table 1.

Table 1. Simulation results of proton motion in a cyclotron at $B = 1$ T, $d = 0.0005$ m, and $V = 100$ kV.

r (m)	v (m/s)	E_k (MeV)
0.2	1.774×10^7	1.644
0.25	2.246×10^7	2.639
0.3	2.741×10^7	3.941
0.35	3.223×10^7	5.462
0.4	3.707×10^7	7.246

Based on Table 1, it can be seen that the energies produced by the cyclotron for dee radii of 0.2 m, 0.25 m, 0.3 m, 0.35 m, and 0.4 m are 1.644 MeV, 2.639 MeV, 3.941 MeV, 5.462 MeV, and 7.246 MeV, respectively. Thus, the larger the dee radius used, the greater the proton kinetic energy produced by the cyclotron, as shown in Image 2. This occurs because a larger dee radius allows protons to complete more revolutions and more frequently cross the gap between the dees. Each time a proton crosses the gap, its velocity increases due to acceleration caused by the potential difference between the two dees, thereby increasing the resulting kinetic energy. The simulation results shown in Image 3 through 7 also confirm this finding.

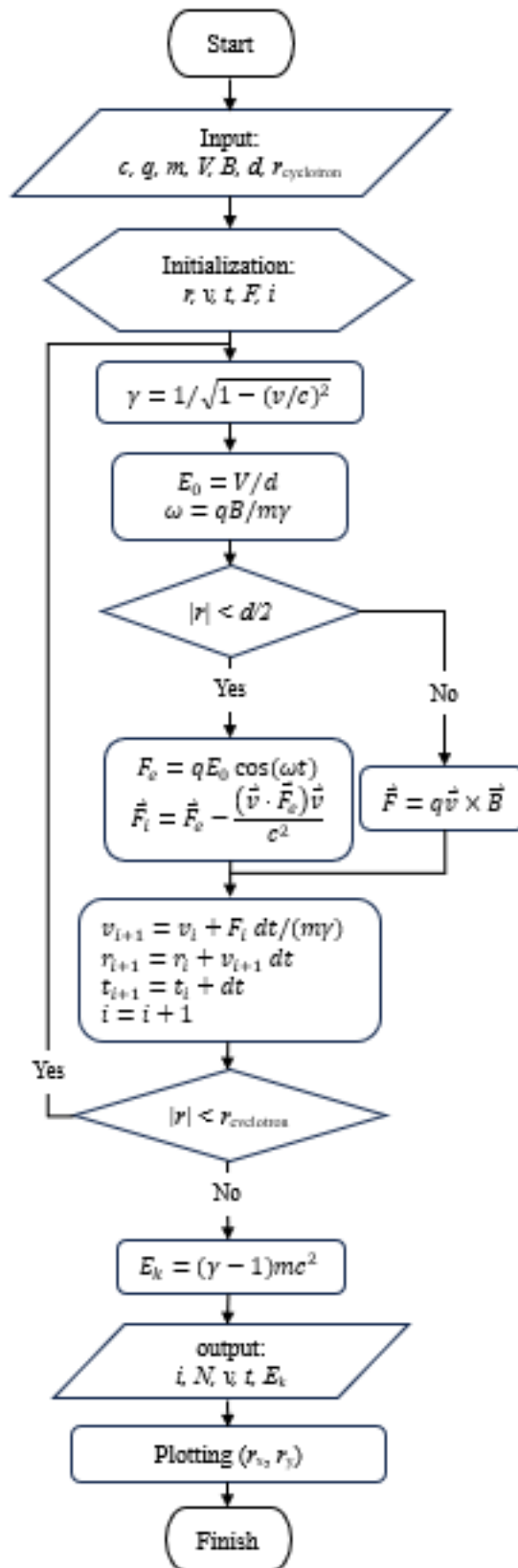


Image 1. Flow chart.

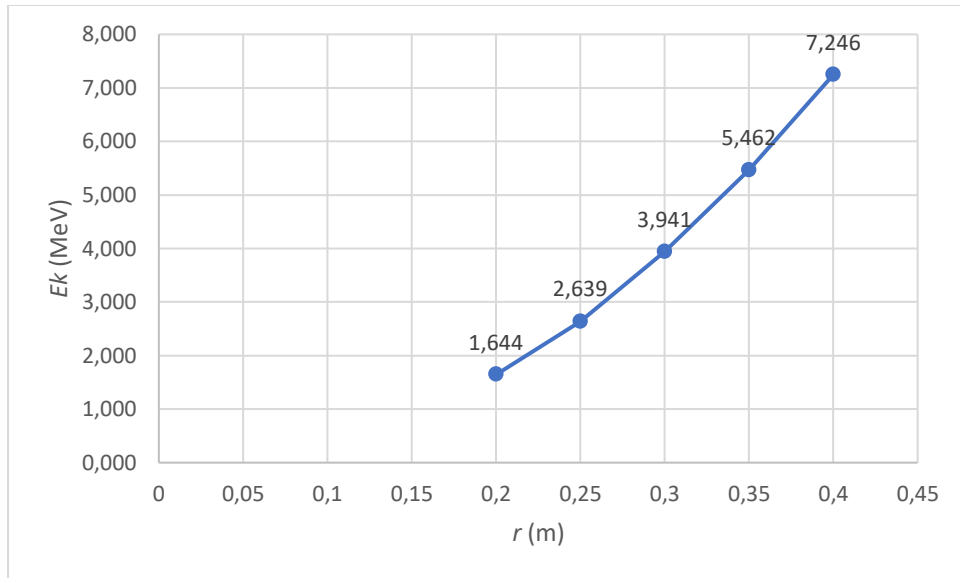


Image 2. The Effect of Dee Radius on Energy in a Cyclotron.

The simulation results using Python for dee radii of 0.2 m, 0.25 m, 0.3 m, 0.35 m, and 0.4 m, as shown in Image 3 to 7, indicate that the larger the dee radius, the greater the number of proton revolutions in the cyclotron, thereby increasing the frequency with which protons cross the gap between the dees.

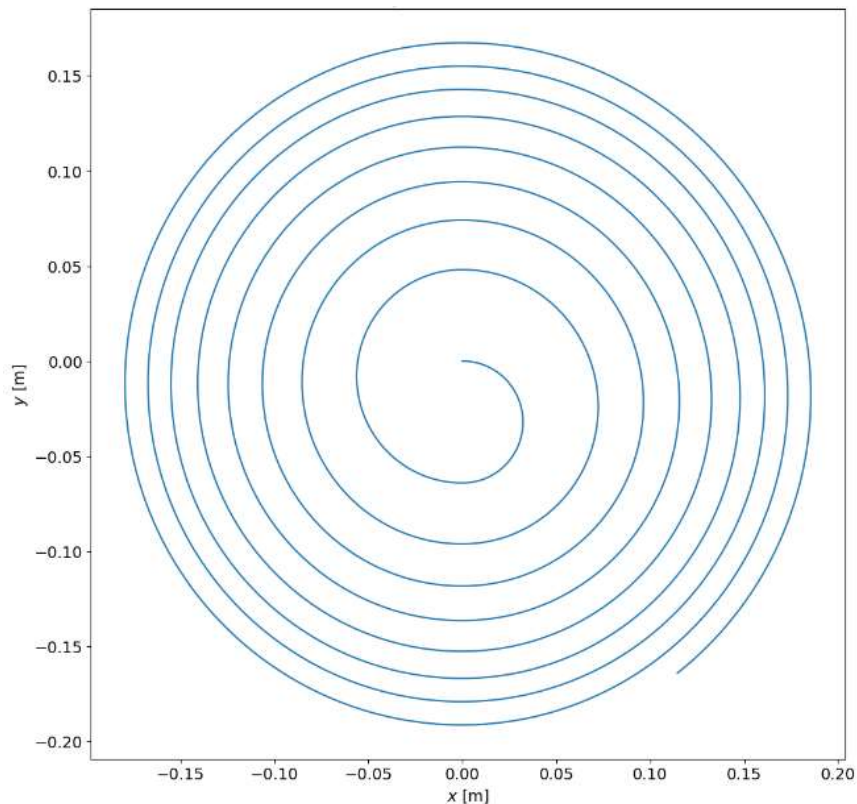


Image 3. Simulation of proton motion at $r = 0.2$ m.

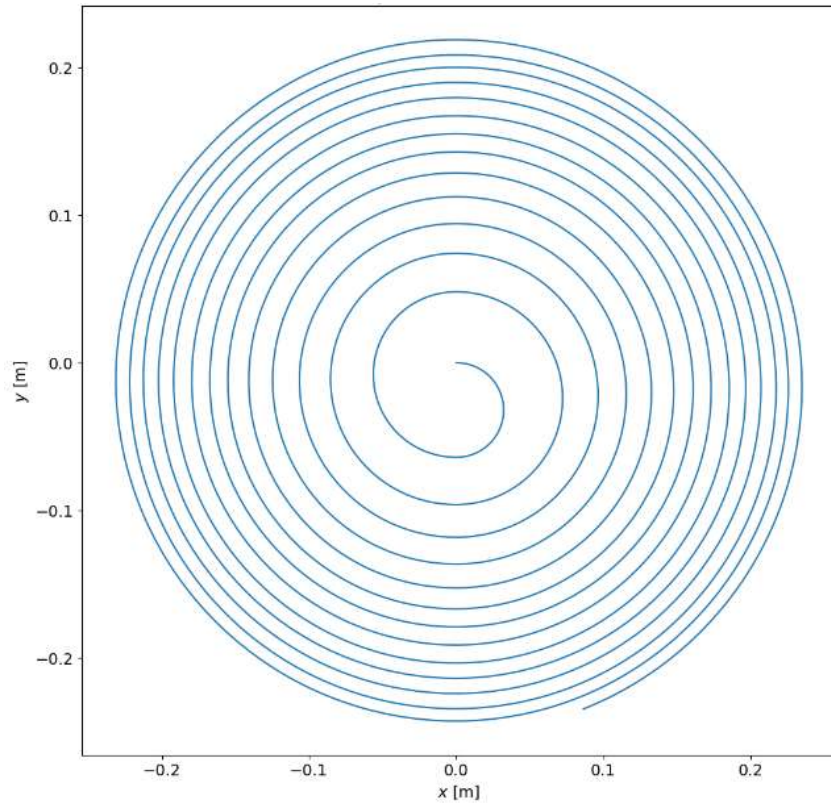


Image 4. Simulation of proton motion at $r = 0.25$ m.

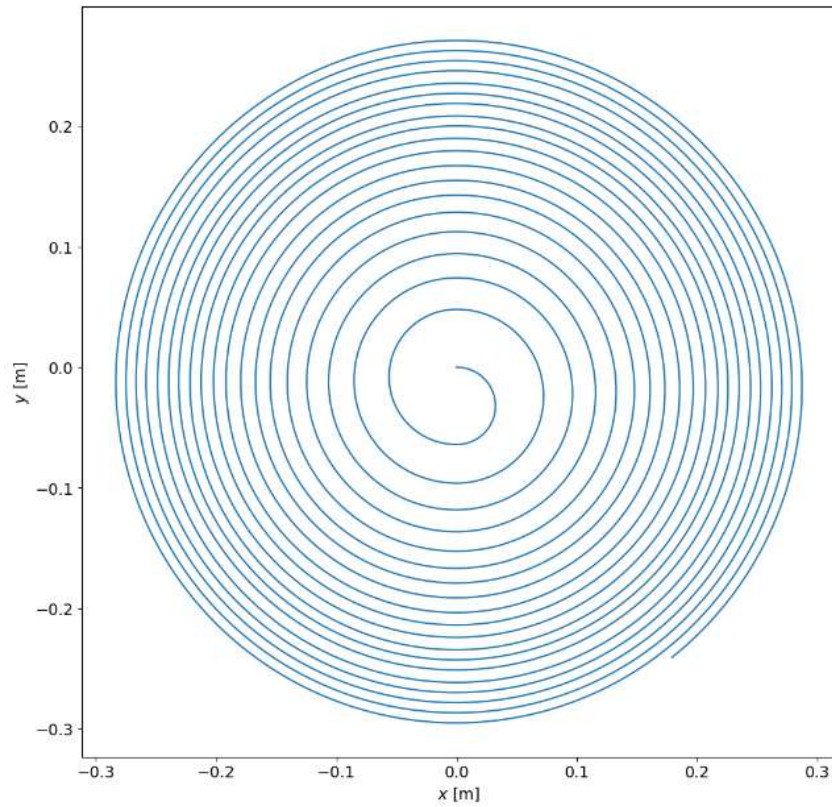


Image 5. Simulation of proton motion at $r = 0.3$ m.

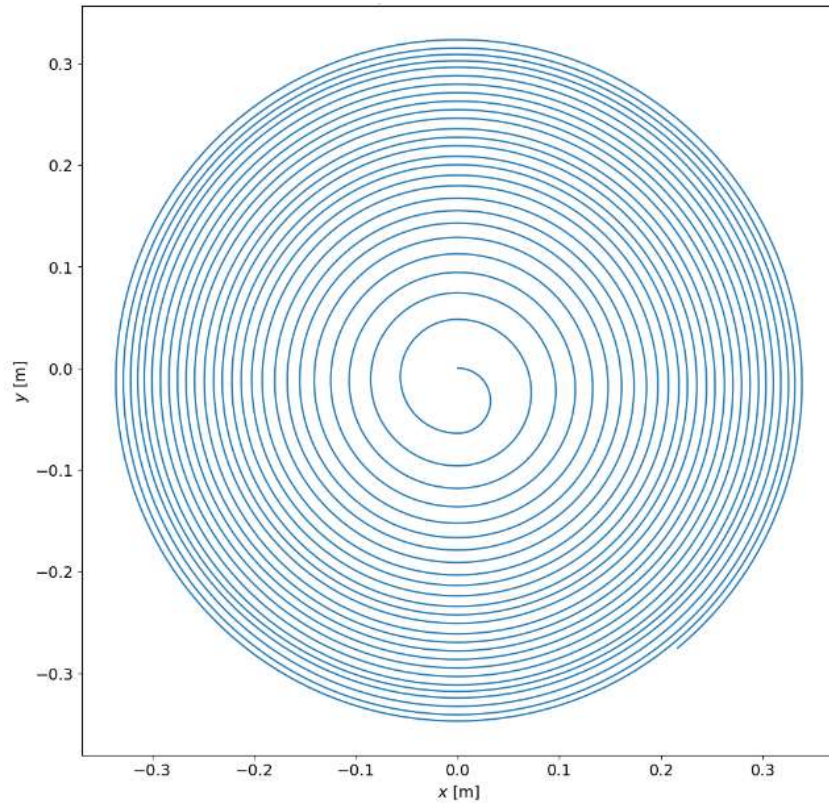


Image 6. Simulation of proton motion at $r = 0.35$ m.

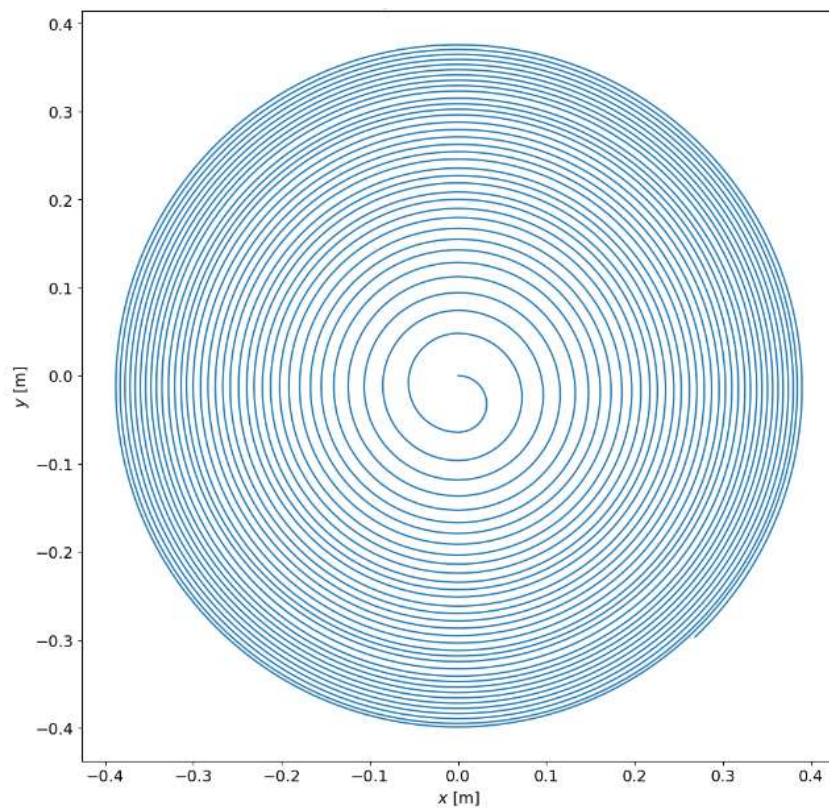


Image 7. Simulation of proton motion at $r = 0.4$ m.

When a proton crosses the gap between the dees, its velocity increases due to acceleration, thereby increasing its kinetic energy. This is in accordance with the working principle of a cyclotron, in which, as the proton moves

toward one of the dees, a change in polarity produces an attractive force that pulls the positively charged proton toward the negatively charged dee. This change in polarity is generated by an RF oscillator that produces an alternating electric field, such that when the proton is inside one of the dees, the oscillator switches the polarity of the other dee to negative, enabling the proton to move toward it. The relationship between the electric field and force is expressed by the following equation (Halliday, D., et al., 2014):

$$F = qE \quad \text{with} \quad E = \frac{V}{d}$$

$$F = q \frac{V}{d}$$

Each time a proton crosses the gap between the dees, it gains an electric potential (V) that increases the electric field (E). An increase in the electric field (E) leads to an increase in force (F). According to Newton's Second Law ($F = ma$), the presence of a force (F) causes the proton to accelerate (a), which in turn increases the particle's velocity (v). As the velocity of the proton increases, its kinetic energy also increases, and the radius of its circular path grows with each pass across the gap between the dees. Therefore, the larger the dee radius in the cyclotron, the greater the proton kinetic energy produced.

$$\vec{F}_L = q(\vec{v} \times \vec{B})$$

In this study, the proton velocity (v) is directed along the \hat{i} and \hat{j} directions, while the magnetic field (B) is oriented along the \hat{k} axis, perpendicular to the velocity. Consequently, the resulting Lorentz force acts along the \hat{i} and \hat{j} directions. The Lorentz force serves only to bend the proton's trajectory without increasing its velocity. However, it is known that when the proton is influenced by a magnetic field, it exhibits a cyclotron motion frequency that indicates how quickly the particle moves along its circular path due to the magnetic force. This proton motion frequency must match the RF oscillator frequency to achieve resonance. When resonance is achieved, the electric field can exert maximum force on the proton, thereby increasing its velocity and kinetic energy. The motion of the proton under the influence of both the electric and magnetic fields in the cyclotron occurs repeatedly, causing the proton to move progressively faster while tracing a spiral path that gradually expands. Thus, the diameter of the dees influences the number of proton revolutions. The larger the dee radius, the more revolutions the proton completes, resulting in more frequent crossings of the gap between the dees, which in turn increases its velocity. As the proton velocity increases, its kinetic energy also increases.

This finding is consistent with the research of Dewi Sri (2010), entitled "*Simulasi Lintasan Partikel Bermuatan (Proton) di dalam Cyclotron*" in which it was stated that the greater the energy produced, the faster the particle moves. However, the acceleration imparted to the particle never allows it to reach the speed of light. Furthermore, the characteristic RF frequency during particle motion in the field must match the constant RF frequency of the electric oscillator (i.e., the frequencies must remain stable). This study is also supported by Power et al. (2024) in the book "The Current State of Proton Radiotherapy," in which it is stated that as the proton radius increases, the energy produced also increases, indicating that the energy output of the cyclotron depends on the radius and its maximum resonance. According to the authors, the size of the dee radius in a cyclotron affects the level of kinetic energy produced. The larger the dee radius, the greater the kinetic energy generated by the cyclotron; thus, the dee radius can be adjusted according to the desired energy requirements. Moreover, a cyclotron can produce higher energies of up to 11.1 MeV compared to X-ray radiotherapy, which generates energies of 6 MeV and 10 MeV.

CONCLUSION

Based on the simulation and computational calculations using Python, with a proton charge $q = 1.6 \times 10^{-19}$ C and proton mass $m = 1.67 \times 10^{-27}$ kg, a cyclotron magnetic field of 1 T, a distance between dee plates $d = 0.0005$ m, and an electric potential between dees of 100 kV, it was found that the energies produced by the cyclotron for dee radii of 0.2 m, 0.25 m, 0.3 m, 0.35 m, and 0.4 m were 1.644 MeV, 2.639 MeV, 3.941 MeV, 5.462 MeV, and 7.246 MeV, respectively. Thus, the larger the dee radius used in the cyclotron, the greater the proton kinetic energy produced. This occurs because a larger dee radius allows the proton to cross the gap between the dees more frequently. Each time the proton crosses the gap, its velocity increases due to the acceleration caused by the potential difference between the two dees, thereby increasing the resulting kinetic energy.

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