Simulating the trajectory of differently charged particles in cyclotron using GNU Octave

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Simulating the trajectory of differently charged particles in cyclotron using GNU Octave

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Abstract

Computer simulation is essential to experimental physics research, as well as to the design, commissioning and operation of particle accelerators. In this work, we have tried to simulate the particle trajectories for different input values. From the simulation, we can observe the radius of that particle trajectory. Largely, we have considered Electron, Helium atom, Proton, Tritium atom, and Deuteron atom and obtained their corresponding trajectories. The whole process is carried out in GNU Octave.

Keywords: Cyclotron, Simulation, GNU Octave

1 Introduction

Particle Physics had its growth after the discovery of particle detectors which showed the presence of nucleus from *Rutherford's Gold foil experiment* [1]. Even though, we were not able to accelerate charges to attain relativistic velocities. 1929, Ernst Lawrence designed and operated the first cyclotron which opened a new era of doing experiments in particle physics [4]. So, understanding the foundation of experimental physics was our motivation to simulate the motion of charged particle inside the cyclotron designed by Lawrence [4]. A cyclotron accelerates a charged particle beam using a high frequency which is applied between two metal electrodes inside a vacuum chamber. The electrodes are located between the poles of a large electromagnet which applies a static magnetic field B perpendicular to the electrode plane [2].The magnetic field causes the particles path to bend in a circle due to the Lorentz force perpendicular to their direction of motion. The cyclotron was an improvement of the linear accelerators also called as *LINACs* [5].

The cyclotron was being more cost- and space-effective due to the iterated interaction of the particles with the accelerating field. In the 1920s, it was not possible to generate the high power, high-frequency radio waves [5] which are used in modern LINACs . As such, impractically long LINAC structures were required for higher-energy particles. The compactness of the cyclotron reduces other costs as well, such as foundations, radiation

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shielding, and the enclosing building. Cyclotrons have a single electrical driver, which saves both money and power. Furthermore, cyclotrons are able to produce a continuous stream of particles at the target, so the average power passed from a particle beam into a target is relatively high [1].

The spiral path of the cyclotron beam can only "sync up" with klystron-type voltage sources [2] if the accelerated particles are approximately obeying Newton's laws of motion. If the particles become fast enough that relativistic effects become important, the beam becomes out of phase with the oscillating electric field, and cannot receive any additional acceleration [9]. The classical cyclotron is therefore only capable of accelerating particles up to a few percent of the speed of light [5]. To accommodate increased mass the magnetic field may be modified by appropriately shaping the pole pieces as in the isochronous cyclotrons, operating in a pulsed mode and changing the frequency applied to the dees as in the synchro-cyclotrons, either of which is limited by the diminishing cost effectiveness of making larger machines [4]. Cost limitations have been overcome by employing the more complex synchrotron or modern, klystron-driven linear accelerators, both of which have the advantage of scalability, offering more power within an improved cost structure as the machines are made larger [2].

2 Cyclotron - An overview

A cyclotron accelerates a charged particle beam using a high frequency alternating voltage which is applied between two hollow "D"-shaped sheet metal electrodes called "dees" inside a vacuum chamber [6]. The dees are placed face to face with a narrow gap between them, creating a cylindrical space within them for the particles to move. The particles are injected into the center of this space. The dees are located between the poles of a large electromagnet which applies a static magnetic field B perpendicular to the electrode plane [7]. The magnetic field causes the particles' path to bend in a circle due to the Lorentz force perpendicular to their direction of motion.

If the particles' speeds were constant, they would travel in a circular path within the dees under the influence of the magnetic field [6]. However a radio frequency alternating voltage of several thousand volts is applied between the dees. The voltage creates an oscillating electric field in the gap between the dees that accelerates the particles. The frequency is set so that the particles make one circuit during a single cycle of the voltage [8]. To achieve this, the frequency must match the particle's cyclotron resonance frequency, The centripetal force that makes the particles in curved path is,

$$F_c = \frac{mv^2}{r}$$

where m - mass of the particle, r - radius of the path and v is the velocity. The force is provided by lorentz force of the magnetic field [7],

$$F_B = vqB$$

where q is the charge of the particle. Thus we get the path of the charged particle as,

$$r = \frac{mv}{qB}$$

The simulation would be carried out for the path of the charged particle.

$$f = \frac{qB}{2\pi m} \quad (1)$$

where B is the magnetic field strength, q is the electric charge of the particle and m is the relativistic mass of the charged particle. Each time after the particles pass to the other dee electrode the polarity of the RF voltage reverses. Therefore, each time the particles cross the gap from one dee electrode to the other, the electric field is in the correct direction to accelerate them [8]. The particles' increasing speed due to these pushes causes them to move in a larger radius circle with each rotation, so the particles move in a spiral path outward from the center to the rim of the dees. When they reach the rim a small voltage on a metal plate deflects the beam so it exits the dees through a small gap between them, and hits a target located at the exit point at the rim of the chamber, or leaves the cyclotron through an evacuated beam tube to hit a remote target. Various materials may be used for the target, and the nuclear reactions due to the collisions will create secondary particles which may be guided outside of the cyclotron and into instruments for analysis [8]. It is very expensive to build a cyclotron particularly due to its gigantic structure and the precision required in its engineering. So it is no surprise that there are very few operational cyclotrons in the world. The largest cyclotron is the 17.1 m (56 ft) multimagnet TRIUMF accelerator at the University of British Columbia in Vancouver, British Columbia, which can produce 520 MeV protons. Close to 1500 cyclotrons are used in nuclear medicine worldwide for the production of radionuclides [3]. We have listed a few below.

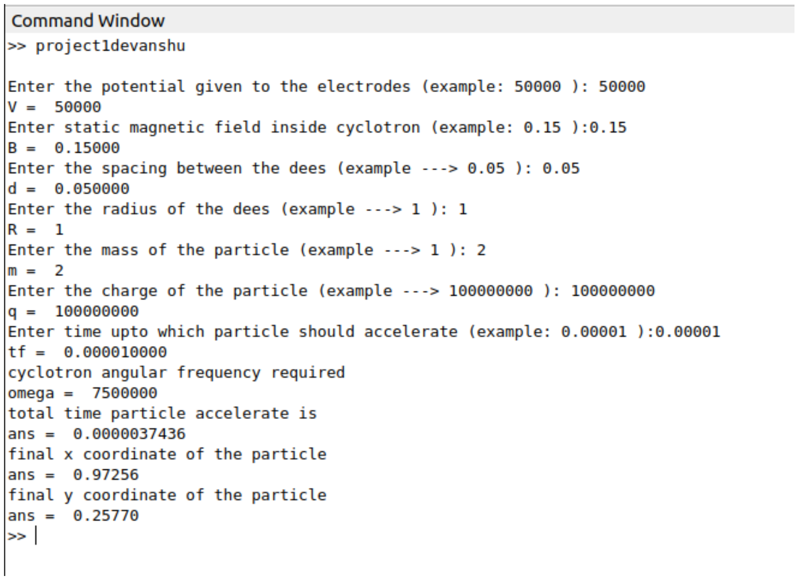
Country	***Institution***	***Machine Name***
Switzerland	Paul Scherrer Institute	Philips Cyclotron Injector I
Russia	Petersburg Nuclear Physics Institute	Gatchina Isochronous Cyclotron
India	Variable Energy Cyclotron Centre	Variable Energy Cyclotron
USA	Michigan State University	K1200
USA	Lawrence Berkeley National Lab	88 Inch Cyclotron
Germany	Institute for Nuclear Physics	JULIC
Poland	University of Warsaw	U-200P
Canada	TRIUMF	TRIUMF Cyclotron
China	Institute of Modern Physics	HIRFL
Japan	Tohoku University	CYRIC AVF Cyclotron

3 Simulating the trajectory of different charged particles

The cyclotron simulation is carried out using GNU Octave by differing the mass and charges of different particles. The particles that are taken into account are: **Electron, Proton, Helium atom, Deuterium atom and Tritium atom**. The output would be displayed and an interpretation is given with respect to the radius obtained. The details regarding the relativistic corrections would be also accounted in the interpretation. Neutral particles cannot be accelerated through cyclotron and it can be used in the radio therapy in the treatment of cancer [3].

3.1 Electron

The corresponding code can be obtained here.



```
Command Window
>> project1devanshu

Enter the potential given to the electrodes (example: 50000 ): 50000
V =  50000
Enter static magnetic field inside cyclotron (example: 0.15 ):0.15
B =  0.15000
Enter the spacing between the dees (example ---> 0.05 ): 0.05
d =  0.050000
Enter the radius of the dees (example ---> 1 ): 1
R =  1
Enter the mass of the particle (example ---> 1 ): 2
m =  2
Enter the charge of the particle (example ---> 100000000 ): 100000000
q =  100000000
Enter time upto which particle should accelerate (example: 0.00001 ):0.00001
tf =  0.000010000
cyclotron angular frequency required
omega =  7500000
total time particle accelerate is
ans =  0.0000037436
final x coordinate of the particle
ans =  0.97256
final y coordinate of the particle
ans =  0.25770
>> |
```

Figure 1: Input values to generate the simulation

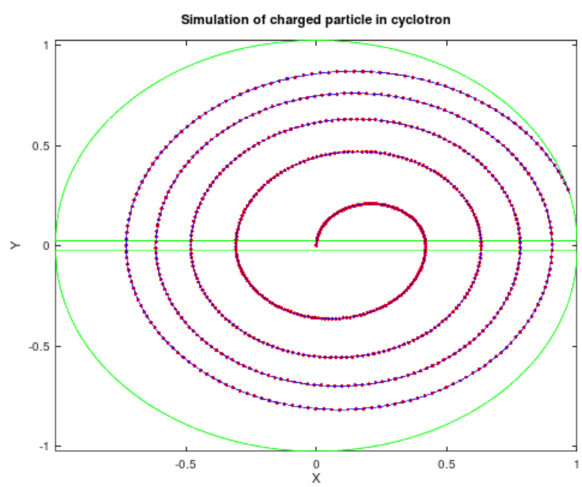
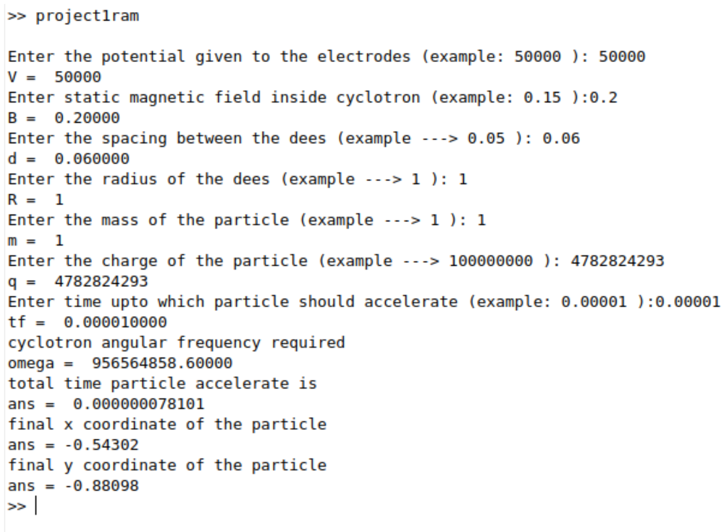


Figure 2: Simulating the trajectory of electron

3.2 Helium atom

The corresponding code can be obtained here.



```
>> project1ram

Enter the potential given to the electrodes (example: 50000 ): 50000
V =  50000
Enter static magnetic field inside cyclotron (example: 0.15 ):0.2
B =  0.20000
Enter the spacing between the dees (example ---> 0.05 ): 0.06
d =  0.060000
Enter the radius of the dees (example ---> 1 ): 1
R =  1
Enter the mass of the particle (example ---> 1 ): 1
m =  1
Enter the charge of the particle (example ---> 100000000 ): 4782824293
q =  4782824293
Enter time upto which particle should accelerate (example: 0.00001 ):0.00001
tf =  0.000010000
cyclotron angular frequency required
omega =  956564858.60000
total time particle accelerate is
ans =  0.000000078101
final x coordinate of the particle
ans = -0.54302
final y coordinate of the particle
ans = -0.88098
>> |
```

Figure 3: Input values to generate the simulation

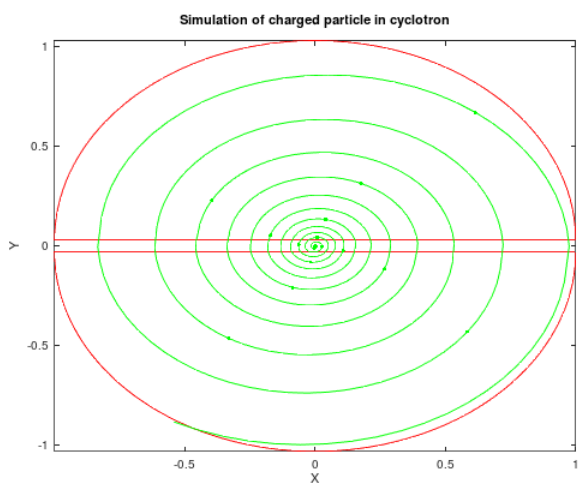


Figure 4: Simulating the trajectory of Helium

3.3 Proton

The corresponding code can be obtained here.

```
>> project1suraj

Enter the potential given to the electrodes (example: 50000 ): 49000
V =  49000
Enter static magnetic field inside cyclotron (example: 0.15 ):0.221
B =  0.22100
Enter the spacing between the dees (example ---> 0.05 ): 0.477
d =  0.47700
Enter the radius of the dees (example ---> 1 ): 1.23
R =  1.2300
Enter the mass of the particle (example ---> 1 ): 1
m =  1
Enter the charge of the particle (example ---> 100000000 ): 9578834096
q =  9578834096
Enter time upto which particle should accelerate (example: 0.00001 ):0.00001
tf =  0.000010000
cyclotron angular frequency required
omega =  2116922335.21600
total time particle accelerate is
ans =  0.000000032800
final x coordinate of the particle
ans = -1.1249
final y coordinate of the particle
ans = -0.88441
>> |
```

Figure 5: Input values to generate the simulation

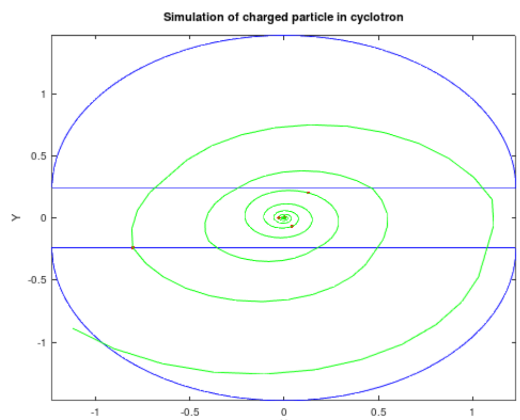


Figure 6: Simulating the trajectory of Proton

3.4 Deutron atom

The corresponding code can be obtained here.

```
>> project1akash

Enter the potential given to the electrodes (example: 50000 ): 45000
V =  45000
Enter static magnetic field inside cyclotron (example: 0.15 ):0.15
B =  0.15000
Enter the spacing between the dees (example ---> 0.05 ): 0.04
d =  0.040000
Enter the radius of the dees (example ---> 1 ): 1.2
R =  1.2000
Enter the mass of the particle (example ---> 1 ): 1
m =  1
Enter the charge of the particle (example ---> 100000000 ): 191576881
q =  191576881
Enter time upto which particle should accelerate (example: 0.00001 ):0.00001
tf =  0.000010000
cyclotron angular frequency required
omega =  28736532.15000
total time particle accelerate is
ans =  0.0000055697
final x coordinate of the particle
ans =  1.1426
final y coordinate of the particle
ans =  0.38680
>> |
```

Figure 7: Input values to generate the simulation

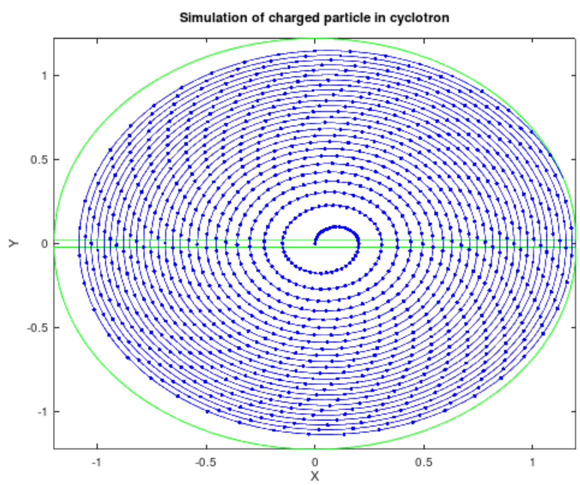


Figure 8: Simulating the trajectory of Deutron

3.5 Tritium atom

The corresponding code can be obtained here.

```
Command Window
>> project1meet
Enter the potential given to the electrodes (example: 50000 ): 60000
V =  60000
Enter static magnetic field inside cyclotron (example: 0.15 ):0.2
B =  0.20000
Enter the spacing between the dees (example ---> 0.05 ): 0.01
d =  0.010000
Enter the radius of the dees (example ---> 1 ): 0.5
R =  0.50000
Enter the mass of the particle (example ---> 1 ): 1
m =  1
Enter the charge of the particle (example ---> 100000000 ): 2873650229
q =  2873650229
Enter time upto which particle should accelerate (example: 0.00001 ):0.00001
tf =  0.000010000
cyclotron angular frequency required
omega =  574730045.80000
total time particle accelerate is
ans =  0.00000011510
final x coordinate of the particle
ans =  0.49388
final y coordinate of the particle
ans =  0.088076
>> |
```

Figure 9: Input values to generate the simulation

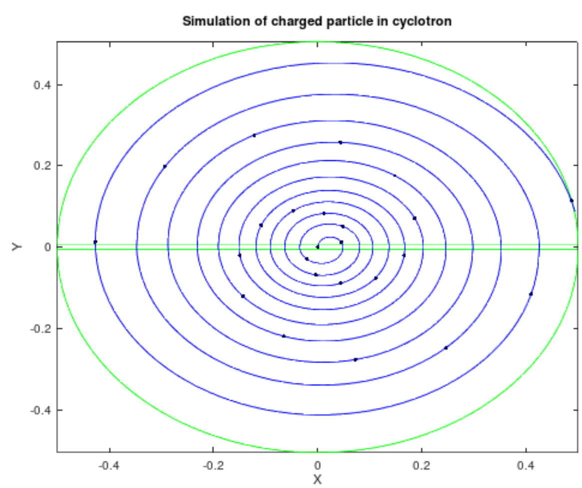


Figure 10: Simulating the trajectory of Tritium

4 Conclusion

The simulation of the cyclotron model that was simulated through the GNU Octave clearly shows that the mass varies directly with that of the radius of the path traced by the particle. The radius of the particles can be written as follows, Helium atom >Tritium atom > Deuterium atom > Hydrogen > Proton > Electron. Electron having the smaller mass would have the smallest radius where as the Helium atom having the larger mass would trace the trajectory over a large radius for the given frequency and the applied fields. The radius of the electron is very small and the scale was minimised for the clarity as it would appear like a dot if the scale that was used for Helium atom. The further approach of this problem can be used in studying the relativistic corrections of electron. This is the main reason that electrons cannot be accelerated through the cyclotron. This property of the electron in cyclotron can be studied with respect to the simulations that are obtained via GNU Octave. Further, the simulation can also be studied in real world applications such as the Radio therapy treatment for calculating the trajectories of the particles with the given radio active source. Thus the simulation would be helpful in deciding the suitable radio active source in order to facilitate the treatment of cancer [3].

5 Declaration

The authors have equal contributions.

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References

[1] Edwards, D A., Syphers, M J. (1993) *An introduction to the physics of high energy accelerators*, New York: Wiley. 1, 2

[2] Kondo, M., and Joho, W. (1975). *Proceedings of the 7th International Conference on Cyclotrons and Their Applications*, Zurich, Switzerland, 1975. 1, 2

[3] Muramatsu, M., and Kitagawa, A. (2012). *A review of ion sources for medical accelerators.* Review of Scientific Instruments, 83(2), 02B909. 3, 9

[4] Lawrence, E. O., and Edlefsen, N. E. (1930). *On the production of high speed protons.* Science, 72(1867), 376. 1, 2

[5] Conte, M., and MacKay, W. W. (2008). *Introduction To The Physics Of Particle Accelerators*, An. World Scientific Publishing Company. 1, 2

[6] Bethe, H. A., and Rose, M. E. (1937). *The maximum energy obtainable from the cyclotron.* Physical Review, 52(12), 1254. 2

[7] Schlyer, D. J., Van den Winkel, P., Ruth, T. J., Vora, M. M., Pillai, M., and Haji-Saeid, M. (2008). *Cyclotron produced radionuclides: Principles and practice.* IAEA Technical Reports Series, 465. 2

[8] Grillenberger, J., Baumgarten, C., and Seidel, M. (2021). *The high intensity proton accelerator facility.* SciPost Physics Proceedings, (5), 002. 2, 3

[9] Blosser, H. (2005). *30 years of superconducting cyclotron technology.* 2