SG2 – Particle Accelerators

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Kinetic Energy Conservation

- Conservation of Kinetic Energy

In a perfectly elastic collision no kinetic energy is lost.

\[ m_1 = \text{mass of incident (blue) ball.} \]

\[ m_2 = \text{mass of target (red) ball.} \]

\[ u_1 = \text{initial velocity of incident ball.} \]

\[ v_1 = \text{final velocity of incident ball.} \]

\[ v_2 = \text{final velocity of target ball.} \]

Conservation of kinetic energy gives,

\[ \frac{1}{2} m_1 u_1^2 = \frac{1}{2} m_1 v_1^2 + \frac{1}{2} m_2 v_2^2 \] (1)

Remember that the target (red) ball is stationary at first and so has zero initial velocity.
Cyclotron in 3D Model

written by Fu-Kwun Hwang and Loo Kang Wee

This simulation illustrates the operation of a cyclotron, showing a charged particle moving through combined magnetic and electric fields. The particle, started near the center of the cyclotron, accelerates when passing through the gap between the electric electrodes and is turned by a perpendicular magnetic field. The geometry of the cyclotron, the magnitude of the electric and magnetic fields, and the properties of the charge are all adjustable. This page includes links to information on the operation of cyclotrons.

Please note that this resource requires Java Applet Plug-in.


1 supplemental document is available

1 source code document is available

**Subjects**
- Electricity & Magnetism
- Electric Fields and Potential
- Electric Field
- Magnetic Fields and Forces
- Force on Moving Charges
- Magnetic Fields

**Levels**
- Lower Undergraduate
- High School
- Informal Education
- Upper Undergraduate

**Resource Types**
- Instructional Material
- Activity
- Demonstration
- Interactive Simulation
- Model
- Simulation

**Supplements**
- Shared Folders (2)

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**Related Materials**
- Is Based On
  - Easy Java Simulations Modeling and Authoring Tool
- Is Based On
  - Charge in Magnetic Field Model

**Similar Materials**
Interactive animation
Cyclotron Model Simulation

The charged particles, injected near the center of the magnetic field B_z, accelerate only when passing through the gap between the electric field E_y electrodes with increase in kinetic energy. The perpendicular magnetic field B_z bends moving charges into a semicircular path between the magnets with no increase in kinetic energy. The magnetic field causes the charge to follow a half-circle that carries it back to the gap. While the charge is in the gap the electric field E_y is reversed, so the charge is once again accelerated across the gap. The cycle continues with the magnetic field in the dees continually bringing the charge back to the gap. Every time the charge crosses the gap it picks up speed. This causes the half-circles in the dees to increase in radius, and eventually the charge emerges from the cyclotron at high speed. The combined motion is a result of increasing energy of the particles in electric field E_y and the magnetic field B_z forces the particles to travel in an increasing radius of the circle after each entry into the other magnetic field. This results in a spiral path of which the particles then emerge at a higher speed than when it was injected into the center of the magnetic field B_z.

For several decades, cyclotrons were the best source of high-energy beams for nuclear physics experiments; several cyclotrons are still in use for this type of research. Cyclotrons can be used to treat cancer. Ion beams from cyclotrons can be used, as in proton therapy, to penetrate the body and kill tumors by radiation damage, while minimizing damage to healthy tissue along their path.

The cyclotron was an improvement on the linear accelerator.
Exercises

1. Explore the simulation, this simulation is designed with a charge particle in a system of magnetic fields in \( z \) direction.
   - 2. The play button runs the simulation, click it again to pause and the reset button brings the simulation back to its original state.
   - 3. Select \( B_x = 0 \) (key in the value \( 0 \)) follow by enter on keyboard, \( E_y = 0 \), \( v_y = 60 \), and play the simulation. Notice that the path of the particle in a straight line in the \( y \) direction. What is the physics principle simulated here?
     - Hint: Newton's 1st law
   - 4. Reset the simulation.
   - 5. Using the default value \( B_z = 0, E_y = 0, v_y = 60 \) play the simulation. What did you observe? Explain the motion in terms of the influence of magnetic field (assume gravitational effect can be neglected).
   - 6. Explore the slider \( x \), \( y \), and \( z \), what do these sliders control?
   - 7. Explore the slider \( v_x \), \( v_y \), and \( v_z \), what do these sliders control?
   - 8. By leaving the cursor on the slider tips will appear to give a description of the slider. You can try it the following sliders such as the charge \( q \), mass \( m \), radius of dee (magnets) \( R \).
   - 9. There are some values radius of circular path \( r \), kinetic energy of particle \( KE \), resultant velocity \( v_r \) and resultant force \( F \) on the m.
   - 10. Vary the simulation and get a sense of what it does.

11. Reset the simulation.
12. Using the values \( B_z = 1, E_y = 0, v_y = 60, E_y = 10 \), observe the difference in the introduction of \( E_y \) in the gaps.
13. Notice that the \( E_y \) field is alternating, explain the purpose of this \( E_y \) in this simulation.
14. Propose the logic deployed by this simulation to time the switching of \( E_y \). Can you think of other switching logic?
15. Note the first time the charge crosses the whole gap its kinetic energy increases by an amount \( \Delta KE \). Determine this value from looking at the value bar of \( KE \), you may select the checkbox to view the scientific graph of \( KE \) vs \( t \).
16. What is the change in kinetic energy associated with just moving in each half-circle in a dee (the magnetic field).
17. Note the first time the charge crosses the gap its kinetic energy increases by an amount \( \Delta KE \) say 400 J. Assuming the electric field in the gap is the same magnitude at all times but in opposite direction to earlier time, what is the change in kinetic energy the second time the charge crosses the gap?

18. Hint: Look at the value bar of \( KE \), you may select the checkbox to view the scientific graph of \( KE \) vs \( t \).
19. Explain why this it is so?
20. Hint: In the dee (magnetic field) the force on the charge comes from the magnetic field, so the force is perpendicular to the velocity. The speed, and hence the kinetic energy, stays constant, so the change is zero.
21. The force first time the charge crosses the gap its kinetic energy increases by an amount \( \Delta KE \) say 400 J. Assuming the electric field in the gap is the same magnitude at all times but in opposite direction to earlier time, what is the change in kinetic energy the second time the charge crosses the gap?

22. Elaborate
23. Suggest with reason why the values for 15 and 17 are not exactly the same
24. Hint: Look at the value of \( v_x \)
25. Explain the exiting from magnetic field causes the \( v_x \) to be slightly bigger than \( 0 \), thus the resultant velocity is increased very slightly.
26. Elaborate
27. Suggest with reason why the values for 15 and 17 are not exactly the same
28. Hint: Look at the value of \( v_x \)
29. Explain the exiting from magnetic field causes the \( v_x \) to be slightly bigger than \( 0 \), thus the resultant velocity is increased very slightly.

30. A scientist asks a question: "To increase the speed of the particles when they emerge from the cyclotron. Which is more effective, increasing the electric field \( E_y = -v_y/dy \) across the gap or increasing the magnetic field \( B_z \) in the dee?"
31. Play the simulation for different initial conditions and design an experiment with tables of values to record systematically, determine what is the more effective method. State your assumptions made.
32. Hint: Assumption is made the physical radius of dee = \( R \) is fixed.

Note that whatever the magnitudes of the fields the final half-circle the charge passes through in the dee has a radius approximately equal to \( R \), the radius of the dee itself. The radius of the circular path of a charged particle in a magnetic field is:

\[ r = \frac{2 \mu_0 q E}{m} \]

\[ r = \frac{mv^2}{Bq} \]

In this case the speed of the particle is \( Rq/m = v \)

Therefore the final kinetic energy is:

\[ KE = \frac{1}{2} m v^2 \]
Features
Proton beam therapy is being introduced in the UK as a new cancer treatment. A beam of protons is accelerated by a cyclotron to an energy of 23 MeV and is then focused onto a tumour.

* Explain how the cyclotron produces the high-energy proton beam.
Build up your own accelerator by placing the cubes on a tabletop, and then bring it to life using the acceleratAR app!
the particle source
a little dispersion
The Salad Bowl Accelerator

https://www.cockcroft.ac.uk/archives/4941
The Salad Bowl Accelerator

https://www.youtube.com/watch?v=uN2kxNKDdxM&feature=youtu.be
The Salad Bowl Accelerator

Problem Based Learning
How to build it, isolate different variables:

dish or bowl?
slope of the border aluminium strips: which kind? Kitchen? Sticky?

Ball: which kind?
Which conductive painting to be used?

Which forces make the ball run? Electric field... Bending force...
Similarities and differences with particle accelerator. Ball vs particles....charges....
Cathode Ray Tube

- Vacuum
- Energy
- Lenses
- Focus and defocus

Cathode Ray Tube

What is the speed of electrons that have been accelerated with 250 V at the cathode ray tube?
What is the speed of electrons that have been accelerated with 90 kV at the first electrostatic accelerator of the LHC (located inside the proton source)?

2. Kinetic energy of the electrons:
\[ E = 250 \text{ eV} = 4 \cdot 10^{-17} \text{ J} \]

\[ v = \sqrt{\frac{2 \cdot E}{m_e}} = 9.38 \cdot 10^6 \text{ m/s} \]

3. Energy of the protons:
\[ E = 90 \text{ keV} = 1.44 \cdot 10^{-14} \text{ J} \]

\[ v = \sqrt{\frac{2 \cdot E}{m_p}} = 4.15 \cdot 10^6 \text{ m/s} \]

*Consequences for particle physics:*
Though protons are accelerated with 90 kV at the CERN proton source, they do not even reach the speed of the electrons accelerated with only 250 V at the Braun’s tube. The reason is the high mass of the protons. In fact, proton accelerators like the LHC need much more energy to accelerate particles to high speed.

Cathode Ray Tube

- Vacuum
- Energy
- Lenses
- Focus and defocus

Cathode Ray Tube

- Vacuum
- Energy
- Lenses
- Focus and defocus

\[
\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 f_2}.
\]

\[
\frac{1}{F} = \frac{d}{f_1^2}
\]

S.Gilardoni, Introduction to accelerators, lecture slides during HST2014 CERN

Quadrupoles with GEOMAG
Quadrupoles with GEOMAG

GEOMAG™ Paradoxes
Silvia Defrancesco, Fabrizio Logliurato, and Grzegorz Karwasz

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Quadrupoles with GEOMAG

Fig. 2. (a) When the opposite poles of the two magnets face each other, they induce a magnetization in the same direction in the sphere; the resultant field of the sphere is similar to a dipole. (b) On the contrary, when the facing poles are similar, the induced magnetization in the sphere is similar to a quadrupole. The orientation of some elementary dipoles within the sphere is shown. In the upper figures the direction of the field lines inside the sphere is illustrated.
Your smartphone can do Physics!

Collider is a mobile application that lets you view high energy particle collisions directly from the Large Hadron Collider, making it simple to understand what's going on at a glance.
Your smartphone can do Physics!

**LHSee** grabs live collision events from the underground detectors in Geneva, and beam them direct to your own device.  
Variety of educational resources.  
Collision events in full 3D graphics.  
Learn how to identify different types of collision.  
"Hunt the Higgs" game.
Your smartphone can do Physics!
Your smartphone can do Physics!
Content and Language Integrated Learning
'CLIL refers to situations where subjects, or parts of subjects, are taught through a foreign language with dual-focused aims, namely the learning of content, and the simultaneous learning of a foreign language'.

Examples

https://stfc.ukri.org/files/educational-publications/big-questions-big-experiments-the-large-hadron-collider/
Exercise 1. With your partner, consider the gaps in the text below. Try to put the right word in each gap.

The words are the following:


**Cyclotron**

A cyclotron is a machine used to __________ charged particles to high energies. The first cyclotron was built by E. O. Lawrence and his graduate student, M. S. Livingston, at the University of California, Berkeley, in the early 1930's.

A cyclotron consists of two D-shaped ________ sandwiched between two electromagnets. A radioactive source is placed in the center of the cyclotron and the electromagnets are turned on. The radioactive source emits ___________ particles. It just so happens that a magnetic field can ________ the path of a charged particle so, if everything is just right, the charged particle will circle around inside the D-shaped cavities. However, this doesn't accelerate the particle. In order to do that, the two D-shaped cavities have to be hooked up to a radio wave ________. This generator gives one cavity a positive charge and the other cavity a negative charge. After a moment, the radio wave generator ________ the charges on the cavities. The charges keep switching back and forth as long as the radio wave generator is on. It is this switching of charges that accelerates the particle.

Let's say that we have an alpha particle inside our cyclotron. Alpha particles have a charge of +2, so their paths can be bent by ________ fields. As an alpha particle goes around the cyclotron, it crosses the ________ between the two D-shaped cavities. If the charge on the cavity in front of the alpha particle is negative and the charge on the cavity in back of it is positive, the alpha particle is ____________ (remember that opposite charges attract while like charges repel). This just accelerated the alpha particle! The particle travels through one cavity and again comes to the gap. With luck, the radio wave generator has changed the charges on the cavities ________, so the alpha particle once again sees a negative charge in front of it and a positive charge in back of it and is again pulled forward. As long as the ________ is right, the alpha particle will always see a negative charge in front of it and a positive charge in back of it when it crosses the gap between cavities. This is how a cyclotron accelerates particles!

Unfortunately, there's one more thing to worry about. The faster a charged particle moves, the less it is affected by a magnetic field. So, as particles speed up in a cyclotron, they spiral outwards. This makes it easy to get the particles out of the cyclotron, but also puts a limit on the amount of acceleration they can ________.

https://image.slidesharecdn.com/cyclotron-140912090543-phpapp01/95/cyclotron-10-638.jpg?cb=1410512821
Examples

The Large Hadron Collider

Exercise 2. Match the words with the definitions.

a Big Bang  b beam  c collide  d intersect  e magnet  

f mass  g matter  h quark  i subatomic particle

1 line of light or other form of energy ___________________________
2 tiny part of matter that forms part of an atom or is smaller than an atom ___________________________
3 very small unit of matter that the particles of an atom consist of ___________________________
4 the amount of matter that something contains ___________________________
5 an explosion that some scientists believe happened 15 billion years ago and started the universe ___________________________
6 crash into each other ___________________________
7 piece of metal that can make iron or steel objects come to it so that they seem to stick to it ___________________________
8 to join or cross each other ___________________________
9 the physical substance that everything in the world is made of ___________________________

Exercise 3. Complete the text with words and expressions from Exercise 1.

How it works

The Large Hadron Collider (LHC) is a very big machine that makes hadrons. It works like this:
(1) ___________________________, made up of tiny (2) ___________________________, accelerate in two (3) ___________________________ of light, which rotate in opposite directions. When the particles reach their maximum speed (almost the speed of light), they are made to (4) ___________________________ with each other with the help of (5) ___________________________. This occurs at four points where the two rings of the LHC (6) ___________________________. Scientists record and measure the results of these collisions and try to identify and track the behaviour of the new particles which they produce.

What it can be used for

The purpose of the LHC is to develop our understanding of physics. The LHC will be able to simulate the conditions just after the (7) ___________________________, when our universe was created, improving our understanding of the origins of the universe and the basic structure of (8) ___________________________ and its (9) ___________________________.


https://apod.nasa.gov/apod/image/1112/atlas_cern_3008.jpg
Thank you for listening.