MAKIN' IT ROUND THE BEND: QUALITATIVE
TEACHER NOTES

DESCRIPTION

This set of three classroom activities allows students to explore some basic physics at the heart of particle physics accelerator design. The activity can serve as a review of concepts in classical mechanics as well as electricity and magnetism. The activity may be done with a qualitative (continue with these instructions) or quantitative approach (Open *Makin' It Round the Bend: Quantitative*) depending on time constraints and the level of your students. Students study how electric and magnetic fields accelerate, turn and focus the electrically charged particles in the Large Hadron Collider (LHC) beam.

STANDARDS ADDRESSED

Next Generation Science Standards

Science and Engineering Practices

4. Analyzing and interpreting data
5. Using mathematics and analytical thinking
6. Constructing explanations
7. Engaging in arguments from evidence

Crosscutting Concepts

1. Observed patterns . . . guide organization and prompt questions.
2. Cause and effect . . . investigating and explaining causal relationship

Common Core Literacy Standards

Reading

9-12.4 Determine the meaning of symbols, key terms . . .
9-12.7 Translate quantitative or technical information . . .

Common Core Mathematics Standards

MP2. Reason abstractly and quantitatively.
MP5. Use appropriate tools strategically.
MP6. Attend to precision.

AP Physics 1 Standards

EK 3.A.2: Forces are described by vectors.
EK 3.B.1: If an object of interest interacts with several other objects . . .
EK 3.C.3: A magnetic force results from the interaction of a moving . . .

AP Physics 2 Standards

EK 1.E.6.a: Magnetic dipole moment is a fundamental source . . .
EK 3.A.2: Forces are described by vectors.
EK 3.C.3: A magnetic force results from the interaction of a moving . . .

IB Physics Standard 1: Measurement and Uncertainty

1.2.6 Describe and give examples of random and systematic errors.
1.2.8 Explain how the effects of random errors may be reduced.
1.2.11 Determine the uncertainties in results.

IB Physics Standard 5: Electricity and Magnetism

5.1 Electric Fields

Aim 7: Use of computer simulations would enable students to measure microscopic interactions that are typically very difficult in a school laboratory situation.

5.4 Magnetic Effects of Electric Currents

Aims 2 and 9: Visualizations frequently provide us with insights into the action of magnetic fields; however, the visualizations themselves have their own limitations.

6.1 Circular Motion

Aim 7: Technology has allowed for more accurate and precise measurements of circular motion, including data loggers for force measurements and video analysis of objects moving in circular motion.

ENDURING UNDERSTANDINGS

Scientists can use data to develop models based on patterns in the data.

LEARNING OBJECTIVES

Qualitative Treatment:

As a result of this investigation, students will know and be able to:

- Describe the direction of motion of an electrically charged particle when interacting with an electric field.
- Describe the direction of motion of an electrically charged particle when interacting with a magnetic field.
- Describe the conditions needed for an electrically charged particle to travel through a region of crossed electric and magnetic fields with velocity unchanged.
- Describe the path traveled by an electrically charged particle entering a region of magnetic field.
- Describe how the right-hand rule can predict the curvature of an electrically charged particle in a magnetic field.

PRIOR KNOWLEDGE

Students must be able to:

- Define the types of electrically charged particles as positive or negative.
- Define the types of magnetic poles as north and south.
- Apply the right-hand rule in situations described by vector cross products.

BACKGROUND MATERIAL

When an electrically charged particle interacts with an electric field, the particle accelerates in the direction of the electric field vector. The equation $\mathbf{F_e} = q\mathbf{E}$ describes this interaction. When an electrically charged particle interacts with a magnetic field, the particle travels in a circular path. The right-hand rule determines the direction of the magnetic force of interaction. The equation for this interaction, $\mathbf{F_m} = q\mathbf{v} \times \mathbf{B}$, is a cross product, so the direction of the force is determined by using the right-hand rule; sweep the **v** vector into the **B** vector direction, and the thumb represents the direction for the magnetic force. The more momentum a particle has, the larger the force needed to turn it. Large magnetic fields create larger forces on moving particles. For a review of the use of the right-hand rule in magnetism, see the activity *Mapping the Poles*.

Particles in the CERN accelerators move inside beam pipes about the size of your index finger. Magnets in the curved segments of these accelerators send the particles around the bend. Each revolution of the ring increases the momentum of the particles; each momentum increase requires a stronger turning force; these stronger forces come from adjusting the field of the bending magnets. Electromagnets can do this—sending more current through one of these magnets increases the magnetic field.

RESOURCES/MATERIALS

The links below provide useful background material.
https://home.cern/about/how-accelerator-works
http://lhc-machine-outreach.web.cern.ch/lhc-machine-outreach/components/magnets.htm
http://www.lhc-closer.es/taking_a_closer_look_at_lhc/0.magnetic_multipoles

IMPLEMENTATION

Each part below will use the *Makin' it Round the Bend* simulation. Open the simulation to introduce your students to the features of the simulation. Along the bottom are buttons for *Play, Pause, Step left (Step <<), Step right (Step >>),* and *Reset*. There is no *Stop* button so the students must use *Pause* to stop the simulation. There are three tabs along the very bottom of the simulation. Each tab opens the simulation for that part.

1. *Accelerator*
   - Along the bottom are values for t in x10^{-6} s, x in mm, and v_x in km/s. Below the parallel plates are sliders to select *Electric field* in N/C, and *mass/charge ratio* in x10^{-9} kg/C.
2. *Velocity Selector*
   - Along the bottom are values for t in x10^{-6} s. Just under the parallel plates are values for x in mm, y in mm, v_X in km/s and v_Y in km/s. Below the parallel plates are sliders to select *Electric field* in N/C, *Magnetic field* in mT, Charge Attributes: *mass/charge ratio* in x10^{-9} kg/C, and *Initial* v_x in km/s.
3. *Mass Spectrometer*
   - Under the velocity selector plates are values for t in x10^{-6} s, values for x in mm, y in mm, v_X in km/s and v_Y in km/s. The sliders control each region of the mass spectrometer:
     - *Velocity Selector* Controls: *Electric field* in N/C, *Magnetic field* in mT
     - *Mass Deflector* Controls: *Magnetic field 2* in mT
     - *Charge Attributes*: *mass/charge ratio* in x10^{-9} kg/C
     - *Initial* v_x in km/s

In each section, the force vector resulting from the interaction between the electrically charged particle and the field is the same color as the field vector.

PART 1: PICKING UP SPEED

Select the tab *1. Accelerator* to begin this activity. Make sure that students know how to start and stop the simulation to collect data for change in velocity and change in time. With these data students can determine the acceleration of the electrically charged particle for a chosen setting of the *Electric field* slider.

<u>Qualitative Treatment</u>:

Students should gather evidence to answer the following questions:

- Does the electrically charged particle change motion in the electric field? What evidence from the data supports your claim?
- Does the electrically charged particle speed up, slow down or have constant velocity? What evidence from the data supports your claim?
- What is the direction of motion of the electrically charged particle compared to the direction of the electric field vector? What evidence from the data supports your claim?

- If the electric field strength is increased, does the electrically charged particle speed up more, slow down more or continue to travel with the same velocity? What evidence from the data supports your claim?

Ask the students to use their answers to these questions to make claims about the relationship between the electric field strength and the acceleration of the electrically charged particle. Be sure they support their claim with evidence from the data and the reasoning for how the evidence leads to the claim.

PART 2: CHOOSE YOUR RACER
Select the tab *2. Velocity Selector* to begin this activity. The initial setting results in the electrically charged particle traveling straight through the region of crossed electric and magnetic fields.

Qualitative Treatment:
Students gather evidence to answer the following questions:

- What is the test, using the meters just below the parallel plates, to determine if the electrically charged particle is traveling straight through the plates? What evidence from the data supports your claim?
- What is the relationship between the electric field vector and the magnetic field vector when the electrically charged particle passes straight through the crossed electric and magnetic fields? What evidence from the data supports your claim?
- If the initial velocity in the x direction is changed with no change to the electric field strength or the magnetic field strength, does the electrically charged particle continue to travel straight through? What evidence from the data supports your claim?
- Select a new initial velocity in the x direction. What adjustments must be made to the electric field strength and magnetic field strength to once again make the electrically charged particle travel straight through the crossed electric and magnetic fields? What evidence from the data supports your claim?

Ask the students to use their answers to these questions to make claims about the relationship between the electric field strength and the magnetic field strength to ensure that an electrically charged particle passes in a straight line through crossed electric and magnetic fields. Be sure they support the claim with evidence from the data and the reasoning for how the evidence leads to the claim.

PART 3: MAKIN' IT ROUND THE BEND
Select the tab *3. Mass Spectrometer* to begin this activity. The values for the Charge Attributes, mass/charge ratio and Initial v_x, can be set at the beginning of each run. Notice that the initial setting of v_x allows the electrically charged particle to travel straight through the *Velocity Selector* when the *Electric field 1* and *Magnetic field* sliders are set appropriately. The electrically charged particle then enters the Mass Deflector which is controlled by *Magnetic field 2*.

Qualitative Treatment:
Students gather evidence to answer the following questions:

- What is the relationship between the magnetic field strength in the mass spectrometer and the radius of curvature of the particle path? What evidence from the data supports your claim?
- What is the relationship between the mass/charge ratio and the radius of curvature of the particle path? What evidence from the data supports your claim?

- What is the relationship between the velocity of the particle as it enters the mass spectrometer and the radius of curvature? What evidence from the data supports your claim?
- What mathematical model can describe the radius of curvature of the particle path based on these relationships? What evidence from the data supports your claim?

Ask the students to use their answers to these questions to make claims about the relationship among the mass-to-charge ratio, the magnetic field strength and the velocity of the particle as it enters the mass spectrometer to predict the radius of curvature of the particle path. Be sure they support the claim with evidence from the data and the reasoning for how the evidence leads to the claim.

ASSESSMENT

You might ask students the following questions:

<u>Qualitative Treatment</u>:

Students gather evidence to answer the following questions:

<u>Part 1</u>:

- Does the electrically charged particle change motion in the electric field? What evidence from the data supports your claim?
    - *The value of v_x increases over time as the particle travels across the parallel plates when the electric field is greater than zero. Therefore, the electric field causes the electrically charged particle to change motion—in this case, speed up.*
- Does the electrically charged particle speed up, slow down or have constant velocity? What evidence from the data supports your claim?
    - *The value of v_x increases over time as the particle travels across the parallel plates when the electric field is greater than zero. Therefore, the electric field causes the electrically charged particle to change motion—in this case, speed up.*
- What is the direction of motion of the electrically charged particle compared to the direction of the electric field vector? What evidence from the data supports your claim?
    - *Since the electrically charged particle is speeding up as it travels across the parallel plates, the direction of motion of the particle is to the right. The electric field is directed to the right as shown by the black arrows between the plates. Therefore, the direction of motion of the electrically charged particle is in the same direction as the electric field.*
- If the electric field strength is increased, does the electrically charged particle speed up more, slow down more or continue to travel with the same velocity? What evidence from the data supports your claim?
    - *I paused the simulation just as the particle was passing out of the parallel plate region. As the electric field was increased, the velocity of the particle as it was leaving the parallel plates also increased. Therefore, increasing the electric field value caused the electrically charged particle to speed up more.*

Ask the students to use their answers to these questions to make claims about the relationship between the electric field strength and the acceleration of the electrically charged particle. Be sure they support the claim with evidence from the data and the reasoning for how the evidence leads to the claim.

<u>Part 2</u>:

- What is the test, using the meters just below the parallel plates, to determine if the electrically charged particle is traveling straight through the plates?

- *The electrically charged particle passes straight through the parallel plates when v_y is zero.*
- What is the relationship between the electric field vector and the magnetic field vector when the electrically charged particle passes straight through the crossed electric and magnetic fields?
  - *The electric force on the particle must be equal and opposite to the magnetic force on the particle. The evidence is that the electric force arrow points to the bottom of the screen and is the same length as the magnetic force vector which points to the top of the screen.*
- If the initial velocity in the x direction is changed with no change to the electric field strength or the magnetic field strength, does the electrically charged particle continue to travel straight through?
  - *When the initial velocity is changed, the electric force does not change. When the initial velocity is increased, the magnetic force arrow gets longer, and the particle curves upward. When the initial velocity is decreased, the magnetic force arrow gets shorter, and the particle curves upward. The test for traveling straight through is that the electric force arrow and magnetic force arrow must be the same length, changing only the initial velocity causes the electrically charged particle to curve and not pass straight through the parallel plates.*
- Select a new initial velocity in the x direction. What adjustments must be made to the electric field strength and magnetic field strength to once again make the electrically charged particle travel straight through the crossed electric and magnetic fields?
  - *When the initial velocity is changed, the magnetic field value must be adjusted to make the magnetic force arrow be the same length as the electric force arrow OR the electric field value must be adjusted to make the electric force arrow the same length as the magnetic force arrow. When the magnetic force arrow and the electric force arrow are the same length, the electrically charged particle passes straight through the parallel plates.*

Ask the students to use their answers to these questions to make claims about the relationship between the electric field strength and the magnetic field strength to ensure that an electrically charged particle passes in a straight line through crossed electric and magnetic fields. Be sure they support the claim with evidence from the data and the reasoning for how the evidence leads to the claim.

<u>Part 3</u>:

- What is the relationship between the magnetic field strength in the mass spectrometer and the radius of curvature of the particle path?
  - *To test this relationship, I held everything constant except for magnetic field strength. When the magnetic field strength is increased, the radius of curvature decreased; therefore, the magnetic field strength is inversely related to the radius of curvature.*
- What is the relationship between the mass/charge ratio and the radius of curvature of the particle path?
  - *To test this relationship, I held everything constant except for the mass/charge ratio. When the mass/charge ratio is increased, the radius of curvature increased; therefore, the mass/charge ratio is directly related to the radius of curvature.*

- What is the relationship between the velocity of the particle as it enters the mass spectrometer and the radius of curvature?
    - *To test this relationship, I held everything constant except the initial velocity. When the initial velocity was increased, the radius of curvature increased; therefore, the initial velocity is directly related to the radius of curvature.*
- What mathematical model can be used to describe the radius of curvature of the particle path based on these relationships?
    - *To determine mathematical models, if the relationship is direct, the variable must be in the numerator and if the relationship is inverse, the variable must be in the numerator. From the tests above the results are:*
        - *Magnetic field is inversely related to the radius of curvature, so magnetic field is in the denominator.*
        - *Mass/charge ratio is directly related to the radius of curvature, so mass/charge ratio goes in the numerator.*
        - *Initial velocity is directly related to the radius of curvature, so the initial velocity must go in the numerator.*

    Therefore, the equation for the radius of curvature is:

$$r = \frac{m}{q}\frac{v}{B}$$

Ask the students to use their answers to these questions to make claims about the relationship among the mass-to-charge ratio, the magnetic field strength, and the velocity of the particle as it enters the mass spectrometer to predict the radius of curvature of the particle path. Be sure they support the claim with evidence from the data and the reasoning for how the evidence leads to the claim.