MAPPING THE POLES
TEACHER NOTES

DESCRIPTION

Magnets are at the heart of particle accelerators including the Large Hadron Collider (LHC). This set of three qualitative classroom activities allows students to explore some basic physics of magnetic fields. This activity can serve as an introduction to the right-hand rule, which is foundational to the study of magnetism and its effect on electrically charged particles. Students study how magnetic fields can turn and focus the electrically charged particles in the LHC beam.

STANDARDS ADDRESSED

Next Generation Science Standards

Science and Engineering Practices

2. Developing and Using Models
4. Analyzing and interpreting data
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 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 5: Electricity and Magnetism

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.

ENDURING UNDERSTANDINGS

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

LEARNING OBJECTIVES

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

- Plot magnetic field vectors for both dipole and quadrupole configuration using a magnetic compass.
- Describe how the right-hand rule determines the direction of the force on an electrically charged particle in motion in a magnetic field.
- Apply the right-hand rule to predict the changes in motion of an electrically charged particle in a region of a magnetic field.

- Explain how dipole magnets interact with electrically charged particles in motion to cause the electrically charged particles to move in a circular path.
- Explain how paired quadruple magnets focus electrically charged particles in motion.
- Describe the role of each magnet type in the LHC.

Prior Knowledge

Students must be able to:

- Define electrically charged particles as positive or negative.
- Use the model of electric current as moving positive charges.
- Define the magnetic poles as north and south.
- Use a magnetic compass to determine the location of the magnetic poles on a magnetized object.
- Represent magnetic fields using vector arrows.

Background Material

Particles move inside accelerator beam pipes about the size of your index finger. Dipole magnets bend a particle beam into circular paths. Quadrupole magnets focus the beam into a tight bundle to increase the chance of collisions inside the detectors.

Resources/Materials

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

Implementation

This activity is done best in groups of two. Each group need several blank sheets of paper, one small magnetic compass and four rectangular bar magnets. Neodymium magnets are too strong and make the lab difficult to perform.

Sources for Materials:

- Find appropriate magnetic compasses by searching on the Internet for *small magnetic compasses*.
- Find appropriate bar magnets by searching on the Internet for *flat rectangular magnets*.

Many vendors carry these items.

Before the investigation begins, determine which direction is geographic north in your classroom. You may want to make a sign for easy viewing around the room. **The definition of a north pole is the pole of the compass that points in the north direction.** Magnetic compasses often become remagnetized when used near strong magnetic fields. It is important that your students realize the compass is not "broken" if the painted end of the compass no longer points towards the north wall. It is also important that your students correctly identify the north pole of their compass. To do this, your students should identify the north pole of their compass by periodically setting their compass far from the magnets to identify which end of the compass needle points towards the magnetic north.

Encourage the students to move a magnetic compass around a permanent magnet and observe the deflection of the compass needle. Point out that the end of the needle will always point to one magnetic pole and away from the other. Then students can identify which pole of the magnet is the north pole and which pole of the magnet is the south pole.

The LHC is a large circular machine in which the paths of electrically charged particles are bent using uniform magnetic fields. **Dipole magnets keep** the protons in the circular beam pipe.

Part 1: Dipole Mapping

Direct the students to place two magnets, as shown in the diagram A below, about 15 cm apart on a sheet of paper. Make sure the students outline the positions of the magnets on their paper. Move the compass to many locations around and between the bar magnets. At each compass position, lift the compass and make a small arrow on the paper showing the compass needle direction. They should mark at least 30 locations on paper above, below, and in between the magnets.

Task A, below, is a representation of a dipole magnet which demonstrates attraction. The attraction sets up the magnetic field shape that bends particle paths in the LHC. Tasks B and C demonstrate repulsion which is not useful in the LHC. As the students work, you can walk around asking questions to help students improve their observation skills. It is important for students to observe the following patterns:

- The magnetic field is represented by arrows.
- The magnetic field vectors point away from north poles and towards south poles.
- When the poles are unlike or opposites, the magnetic field vectors seem to connect the two poles.
- With like poles, the magnetic field vectors seem to push away from the poles.

A.

Repeat the procedure with the situations shown in Diagrams B and C below.

B.

C.

When the mapping is complete, ask each group to share their results with another group. These two groups then report their findings to the class. Encourage them to make clear statements of claim, evidence and reasoning.

Part 2: The Right-Hand Rule

Gravitational and electrical interactions cause the motion of the particle to change in the direction of motion, resulting in the particle speeding up or slowing down. Magnetic interactions are very different. The magnetic field vectors in between the magnetic poles determine how an electrically charged particle will be affected by the magnetic field. Magnetic interactions can be thought of as a sideways force, perpendicular to the direction of motion, causing a change in the direction of the velocity of electrically charged particles in motion BUT NOT the magnitude of the velocity.

Therefore, using the maps made in *Part 1*, the most important region of the diagrams is the region between the poles as shown in Figure 1 below.

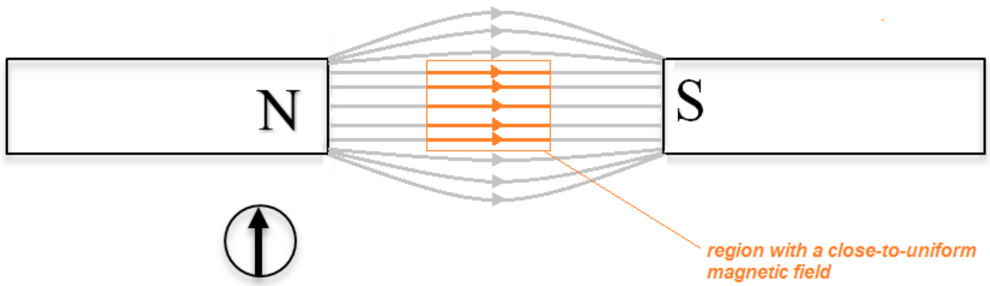


Figure 1. Location of region with uniform magnetic field•.

In Figure 1 above, the uniform magnetic field region is directed to the right. Figure 2 below shows how to represent arrows that point into the page **(X)** and arrows that point out of the page **(•).**

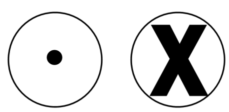


Figure 2. Representing the magnetic field direction.
https://vt-s3-files.s3.amazonaws.com/uploads/problem_question_image/image/24022/electrons_in_out_page.PNG

The right-hand rule allows us to determine the direction of the force acting on electrically charged particles entering a region of uniform magnetic field. Figure 3 below shows the resulting direction of the magnetic force in this case.

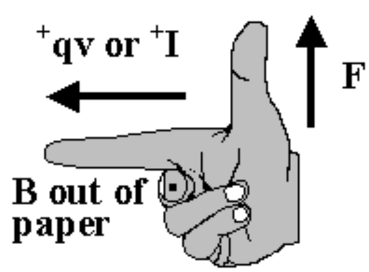


Figure 3. Right-hand rule for magnetic interactions.
https://www.engineering.com/Portals/0/library/articles/right-hand-rule/right-hand-rule.gif

There are a few things to notice in Figure 3. All of the direction arrows are at right angles. This is why the magnetic force, **F**, can be considered a sideways force acting perpendicular to the plane containing the moving positively charged particle, q**v**, and the magnetic field vector, **B**. In Figure 3, the positive charge motion is also labeled **I** for electric current. Remember that electric current is defined as positively charged particles in motion. An important thing to notice is that if the magnetic field, **B**, is parallel to q**v**, then the moving electrically charged particle does not interact with the magnetic field **B** and the motion of the particle does not change.

The next question is what happens to electrically charged particle moving through the regions between the poles? That is where the right-hand rule comes in. Figure 4 shows a wire with current in a region of uniform magnetic field.

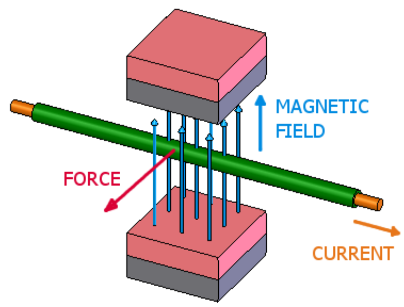


Figure 4. Magnetic force on current in a uniform magnetic field.
https://www.kjmagnetics.com/images/blog/forcediagram1.png

Use the right-hand rule, as shown in Figure 3, to convince yourself that the magnetic field pushes the positively charged particles in the direction shown in Figure 4.

Instruct your students to identify and draw a box around the magnetic field vectors in the region between the poles for Diagrams A, B, and C above as illustrated in Figure 1 above. They should notice that only Diagram A has a region of uniform magnetic field between the poles. Therefore, Diagram A, the dipole representation, represents poles that are attracted. The region between the poles for like poles has magnetic field vectors that seem to bend away from each other as if pushing the poles apart. Magnetic field vectors in the region between like poles represents repulsion.

For the identified region in Diagrams A, have students:

1. Label the direction of the magnetic field vector, **B,** between the poles of the magnets.
2. Draw and label the direction of motion, **v**, for a positively charged particle traveling into the page in the region between the poles.
3. Use the right-hand rule to determine the direction of the magnetic force. Draw and label the magnetic force vector, **F** for the region between the poles.
4. Repeat steps 2–4 for a positively charged particle traveling out of the page.

Repeat steps 1–5 for Diagram B for the region in the very middle where there are no magnetic vector field arrows.

Repeat steps 1–5 for Diagram C for the region in the very middle where there are no magnetic vector field arrows.

It is important for students to make the following observations:

- Electrically charged particles moving through a region of uniform magnetic field vectors that is perpendicular to the direction of motion experience a magnetic interaction which pushes the charged particle sideways.
- Electrically charged particles moving through a region in which the uniform magnetic field vectors are parallel to the direction of motion experience no magnetic interaction.
- Electrically charged particles moving through a region in which there is no magnetic field experience no interaction and the motion is not changed.

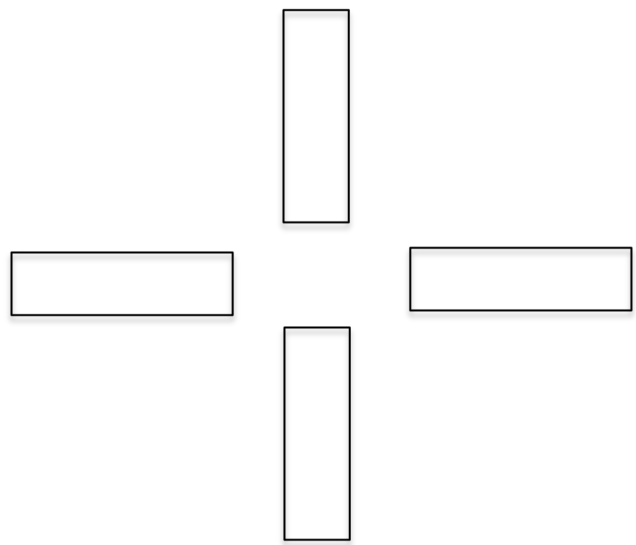
- The sideways magnetic force causes the positively charged particles to travel in a circular path.

The LHC is a large circular machine in which the paths of electrically charged particles are bent using uniform magnetic fields. **Quadrupole magnets** focus the beam keeping the protons in a tight bundle.

Part 3: Quadrupole Mapping

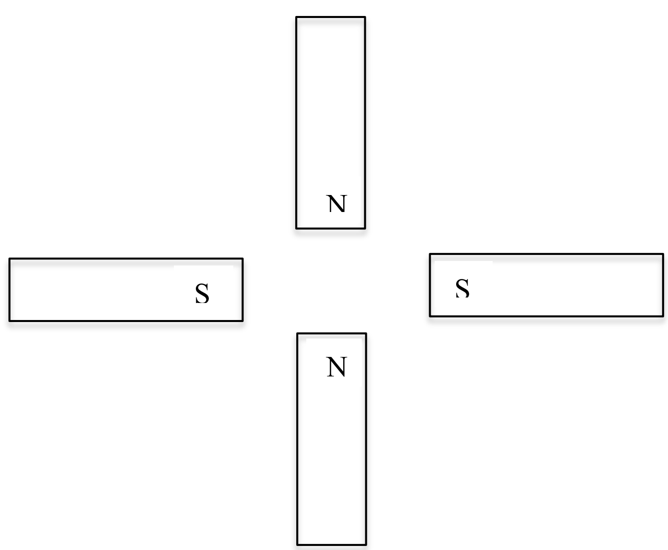
1. Repeat this mapping procedure from *Part 1* for any arrangement of four magnets as shown in Figure D. Students select the orientation of the poles facing the center region for these magnets: NNNN, SSSS, NSNS, SNSN, NSSS, etc. Encourage students to select an orientation different from the groups around them. As the students work, you can ask questions to help students improve their observation skills.

D.



2. Repeat this mapping procedure for an arrangement of four magnets as indicated in Figure E.

E.



3. Identify the region in the center of the map. Since the magnetic field is not uniform in this region, the students will need to draw tangent lines at a point for the magnetic field direction. Tell the students to repeat the process in *Part 2* and determine the direction of the force for several locations, especially locations between the poles.

   It is important for students to make the following observations:

   - The center of the space between the magnets has no magnetic field vector.
   - The paths of the electrically charged particles near but not in the center of the quadrupole magnet are bent.
   - The force vectors point toward the center of the beam in two opposite sides of the magnet and point away from the center of the beam on the other two sides of the magnet. In Figure 5, the arrangement of four magnets is called a magnetic quadrupole. The red arrows represent the direction of the magnetic force in the regions between the poles of the quadrupole magnet.

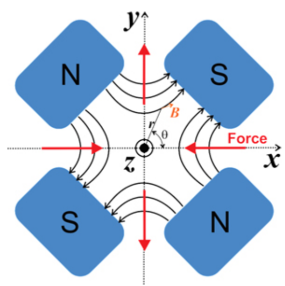


Figure 5. Magnetic force direction in a quadrupole magnet.
http://cdn.iopscience.com/images/books/978-1-6817-4076-8/live/bk978-1-6817-4076-8ch2f4_online.jpg

This result suggests that if the purpose of the quadrupole magnet is to focus the beam into the center of the beam pipe, one quadrupole magnet is not enough. At the LHC, the quadrupoles are always placed in pairs where the second quadrupole is oriented 90° about the z axis from the first. This pushes most of the protons into a tight bundle as they circle the ring and enter the detector.

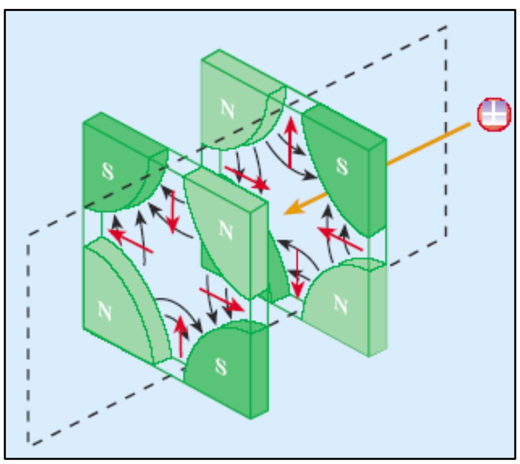


Figure 6. Focusing the proton beam using a pair of quadrupole magnets.
http://www.lhc-closer.es/webapp/files/1435504123_b887b3b5c6aab9b0259320ea21935bbd.png

In Figure 6, the direction of motion of the protons is represented by the yellow arrow; the black lines represent the magnetic field and the red arrows show the direction of the force in the region between the poles. The proton is moving in the z direction; the first quadrupole squeezes the protons toward the center in the x direction and causes them to diverge in the y direction. The second quadrupole does the opposite. This results in a net squeezing of the beam towards the center of the beam pipe.

4. Discussion: You can ask students to explain the purpose of the quadrupole magnets in the LHC.

ASSESSMENT

The assessment for this activity may be formative or summative. Students can be evaluated on the clarity of their presentations and their use of complete statements of claim, evidence and reasoning. The statements in italics represent answers to the prompts. These do not represent every correct answer.

Part 1

Examples of possible assessment questions:

- Work with your partner to develop claims based on the evidence.
    - *A possible claim is that the dipole configuration can be used to bend the electrically charged particles into a circular path with evidence from their mapping and clear reasoning to support the claim. Other claims can be acceptable if there is clear evidence in their mapping to support the claim.*
- Which configuration represents a magnetic dipole? Explain your reasoning.
    - *The N–S pair of magnets represents a magnetic dipole because in between the poles is a region of uniform magnetic field.*

Part 2

Consider the diagram shown in Figure 5 (from the student pages) in which electrons enter a region of uniform magnetic field from the blue region in the diagram.

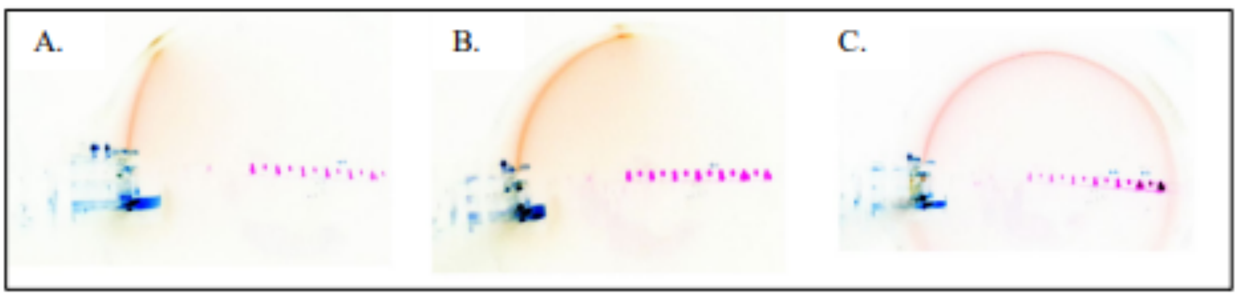


Figure 5. Electron paths entering regions of uniform magnetic field. (Images taken from an e/m apparatus at the University of Notre Dame.)

Answers to the student questions:

- If you assume that the particles are protons, what is the direction of the uniform magnetic field given the curvatures shown in Figure 5?
    - *The magnetic field in Figure 5 is directed into the page. Imagine for a moment that the particle is a* proton with a positive charge. *As the proton enters the region, the velocity vector is directed towards the top of the page. The right thumb must be pointed to the right towards the center of the circular path. Using the righthand rule, the magnetic field must then be pointed out of the page.*
- The particles are actually electrons; therefore, what is the direction of the uniform magnetic field that results in the curvatures shown in Figure 5?
    - *Since the particles in Figure 5 are* negatively charged electrons*, the magnetic field that makes these curvatures is opposite or* into the page.

- Rank the diagrams based on the speed of the electrons from greatest to least. Explain your reasoning.
    - *The speed of the electron is greatest when the radius of the circular path is greatest. Therefore, the ranking is A, B, C. The force points towards the center of the circular path; therefore, the motion is determined by centripetal acceleration. When the force is constant and towards the center, the greater the velocity, the greater the radius of curvature.*
- Explain why the magnetic force can be considered a sideways force. Use evidence to support your claim.
    - *Using the right-hand rule, the magnetic interaction pushes the particle in a direction perpendicular to the velocity direction. The magnetic field that results in this curvature is oppositely directed for electrons and protons, but both magnetic fields are perpendicular to the plane of the circular path. This results in the "sideways" force. The pictures in Figure 5 clearly show the particles pushed into a circular path in the plane of the page.*
- Based on the evidence from this activity, explain how the protons in the LHC are maintained in a large circle.
    - *There are many reasonable answers to this question. One possible answer is the dipole magnets provide a uniform field which bends the path of the protons as they pass through, resulting in a circular path.*

<u>*Part 3*</u>

Examples of possible assessment questions are:

- When protons enter the center of a quadrupole perpendicular to the plane of the quadrupole, is there a pattern in the direction of the force arrows? Make a claim about the effect of the quadrupole on the paths of the protons. Explain your reasoning based your mapping results.
    - *When protons enter the center of a quadrupole perpendicular to the plane of the quadrupole, the force vectors point toward the center of the beam in two opposite sides of the magnet and point away from the center of the beam on the other two sides of the magnet. This can be seen in the mapping diagram.*
- Make a claim about the effect of the paired quadrupoles on the paths of the protons. Explain your reasoning using your conclusions from question above.
    - *One possible claim is that the quadrupole configuration can be used to focus the electrically charged particles into a tight configuration only when two quadrupoles are rotated 90° from each other about the z axis. From the mapping, it is shown that when a proton enters the quadrupole along the z axis, the protons are pushed towards the center in the x-direction and pushed away from the center in the y-direction. The next quadrupole will push the protons away from the center in the x-direction and push the protons toward the center in the y-direction. The net effect is that most of the protons end up focused into the center of the beam pipe.*
- Based on the evidence gathered from this activity, explain the purpose of the quadrupole in the LHC.
    - *While the protons travel along the beam pipe, they spread out a bit. As they approach the detector, it is important for the protons to be bunched together in the center of the detector. The pairs of quadrupoles provide the focusing effect to keep the protons in a tight bunch.*