MAPPING THE POLES
STUDENT GUIDE

DESCRIPTION

Magnets are at the heart of the Large Hadron Collider (LHC). You will explore magnetic fields around bar magnets and the effect of these magnetic fields on moving electrically charged particles such as the protons in the LHC. You will learn about the two main types of LHC magnets and the function of these magnets to ensure that the protons collide inside a detector.

PART 1: MAPPING DIPOLES

This activity is done best in groups of two. You will need several blank sheets of paper, one small magnetic compass, and four rectangular bar or dipole magnets. (Dipole magnets have opposite poles on opposite sides.) As you do each part, work with your partner to make observations and claims based on the evidence provided by your investigation.

- Check to see which end of your compass needle points towards the north wall of your classroom. That end of the compass needle represents the arrow head of the magnetic field vector.
- Place two magnets, as shown in the Diagram A, about 15 cm apart on a sheet of paper. Outline the positions of the magnets on your 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. Remember the compass needle points away from north poles and towards south poles.
- Mark at least 30 locations on your paper above, below, and in between the magnets.

A.

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

B.

C.

1. What Do You Think?

- Work with your partner to develop claims based on the evidence.
- Which configuration represents a magnetic dipole? Explain your reasoning.
- Share your claims with another group.
- Be prepared to present your claims to the class.

PART 2: RIGHT-HAND RULE

In the maps you made in *Part 1*, the most important region of a map is the region between the poles as shown in Figure 1 below.

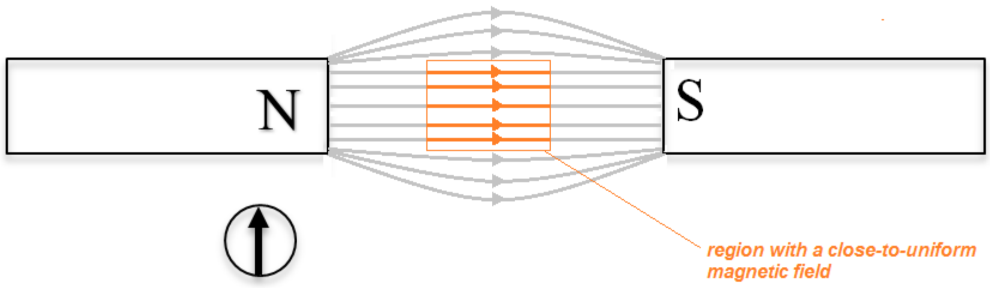


Figure 1. Location of region with uniform magnetic field•.

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

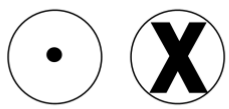


Figure 2. Representing the magnetic field direction.
https://vt-s3-files.s3.amazonaws.com/uploads/problem_question_image/image/24022/electrons_in_out_page.PNG

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

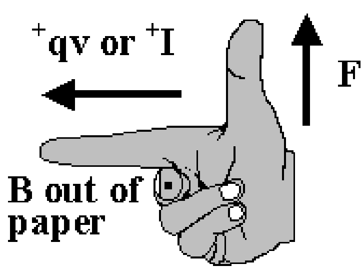


Figure 3. Right-hand rule for magnetic interactions.
https://www.engineering.com/Portals/0/library/articles/right-hand-rule/right-hand-rule.gif

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**, the moving electrically charged particle does not interact with the magnetic field **B** and the motion of the particle does not change.

What happens to electrically charged particles 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.

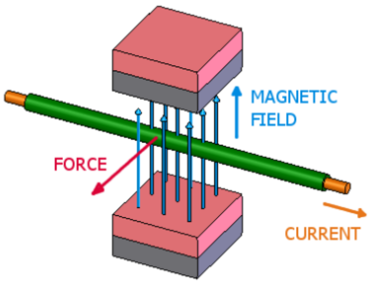


Figure 4. Magnetic force on current in a uniform magnetic field.
https://www.kjmagnetics.com/images/blog/forcediagram1.png

- **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.
- **Identify and draw** a box around the magnetic field vectors in the region between the poles for Diagrams A, B, and C.
- For the identified region in Diagram A:
    1. **Label** the direction of the uniform magnetic field vector, **B**.
    2. **Draw and label** the direction of motion, **v**, for a positively charged particle traveling into the page.
    3. **Use the right-hand rule** to determine the direction of the magnetic force. Draw and label the magnetic force vector, **F**.
    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.

2. What Do You Think?

Consider the diagram shown in Figure 5 in which electrons enter a region of uniform magnetic field from the blue region in the diagrams. The yellow arcs represent particle paths.

Figure 5. Electron paths entering regions of uniform magnetic field.

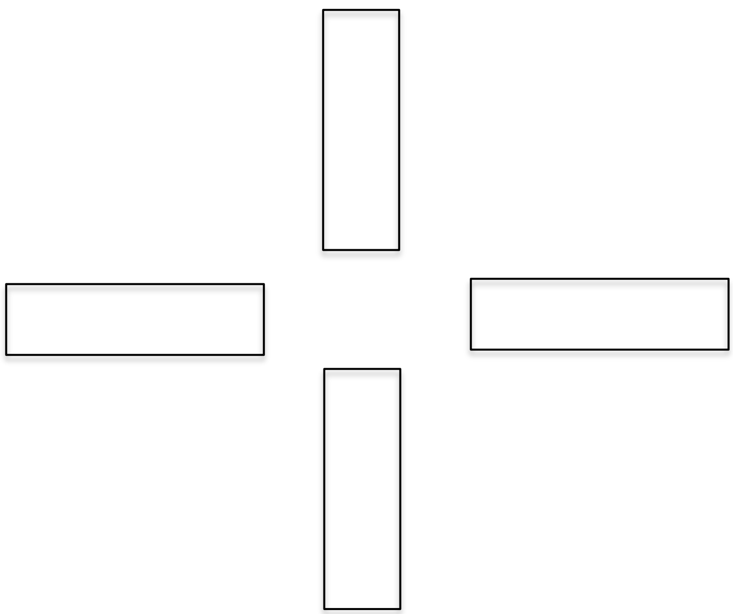
- If you assume that the particles are protons, what is the direction of the uniform magnetic field given the curvatures shown in Figure 5?

- The particles are actually electrons; therefore, what is the direction of the uniform magnetic field that results in the curvatures shown in Figure 5?
- Rank the diagrams based on the speed of the protons from greatest to least. Explain your reasoning.
- Explain why the magnetic force can be considered a sideways force. Use evidence to support your claim.
- Based on the evidence from this activity, explain how the *protons* in the LHC are maintained in a large circle.

PART 3: MAPPING THE QUADRUPOLES

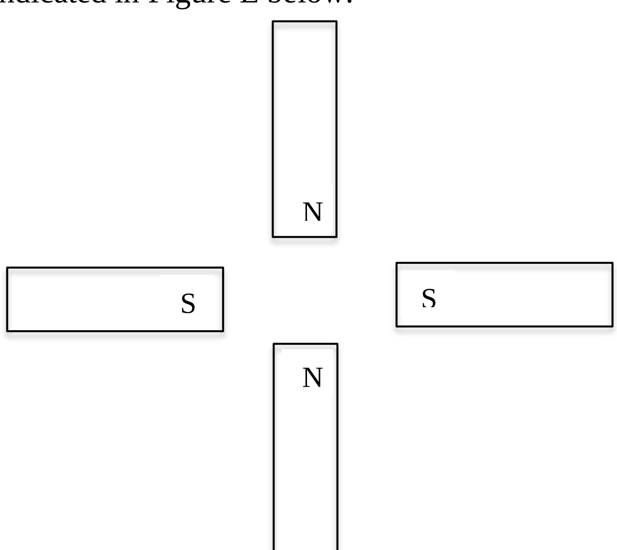
1. Make an arrangement of four magnets as shown in Figure D below.
2. You select the orientation for these magnets: NNNN, SSSS, NSNS, SNSN, NSSS, etc.
3. Make sure your orientation is different from that of neighboring groups.
4. Repeat the mapping procedure from Part 1 for the center region of the magnets.

D.



5. Repeat this mapping procedure for an arrangement of four magnets, referred to by physicists as a quadrupole, as indicated in Figure E below.

E.



6. Identify the region in the center of the map. Since the magnetic field is not uniform in this region, you will need to draw tangent lines at a point for the magnetic field direction.
7. Repeat the process in *Part 2* and determine the direction of the force for several locations, especially locations between the poles.
8. Is there a pattern in the direction of the force arrows? If the protons enter the quadrupole through the center region and perpendicular to the plane of the quadrupole, make a claim about the effect of the quadrupole on the paths of the protons. Explain your reasoning based your mapping results.
9. At the LHC, the quadrupoles are always placed in pairs where the second quadrupole is oriented 90° from the first quadrupole.
10. In Figure 6, the direction of motion of the protons is represented by the yellow arrow, the black lines are the magnetic field, and the red arrows are the direction of the force in the region between the poles.

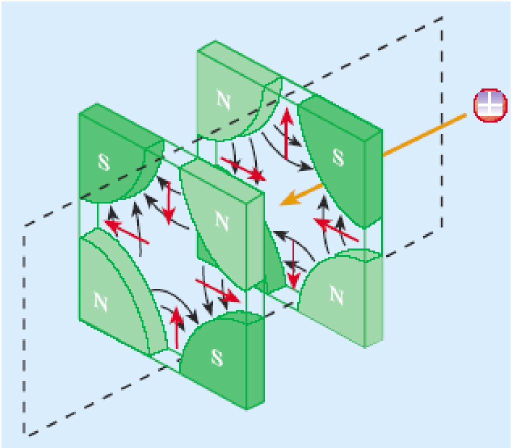


Figure 6. Focusing the proton beam using a pair of quadrupole magnets.
http://www.lhc-closer.es/webapp/files/1435504123_b887b3b5c6aab9b0259320ea21935bbd.png

11. Does the direction of the red magnetic force arrow follow the right-hand rule?
12. Make a claim about the effect of the paired quadrupoles on the paths of the protons. Explain your reasoning using your conclusions from question 8.
13. Based on the evidence gathered from this activity, explain the purpose of the quadrupole in the LHC.