Teaching electromagnetism to high-school students using particle accelerators

D A Sinflorio[1], P Fonseca[2], L F S Coelho[2] and A C F Santos[2]

[1] Instituto Superior de Educação do Rio de Janeiro, R Mariz e Barros, 273, 20270-003, Rio de Janeiro, RJ, Brazil
[2] Instituto de Física, Universidade Federal do Rio de Janeiro, Caixa Postal 68528, 21941-972, Rio de Janeiro, RJ, Brazil

Abstract
In this article we describe two simple experiments using an ion accelerator as an aid to the teaching of electromagnetism to high-school students. This is part of a programme developed by a Brazilian State funding agency (FAPERJ) which aims to help scientifically minded students take their first steps in research.

Introduction

A programme was developed in 1999 by a Brazilian State funding agency (FAPERJ) for students interested in natural sciences, with the aim of introducing them to the daily activities of scientists in universities and research institutes. The students are selected from public schools in the State of Rio de Janeiro and led to take their first steps in research. The objectives are twofold: at an individual level to stimulate the scientific development of the students and to identify new vocations in science; and at a more general level to contribute to the diffusion of scientific knowledge, the demystification of science and the explanation of research and teaching.

During the last hundred years accelerators have played a significant part in training scientists and technologists, as much of our knowledge about the atomic nature of matter comes from experiments using accelerators. A page from the doctoral thesis of Marie Curie in 1904 offers a vivid example, where she shows the behaviour of distinct types of atomic radiation in a magnetic field (figure 1). This is also illustrated by papers which describe the use of accelerators in undergraduate physics laboratories, by conferences on the applications of accelerators to teaching and research, and by textbooks [1, 2].

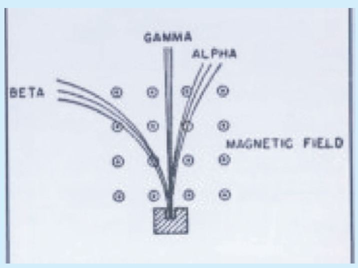

Figure 1. Marie Curie's representation of alpha, beta and gamma rays coming from a radioactive material placed in a narrow but deep cavity in a block. The whole setup is in the presence of a magnetic field perpendicular to and out of the plane of the figure. (Figure adapted from www.vigyanprasar.gov.in/dream/apr2001/RADIOACTIVITY.htm.)

The aim of this article is to describe physical experiments in which high school students

Figure 2. The 1.7 MV accelerator.

may become involved. The objective of the experiments, which are suitable for senior high-school students, is to demonstrate the principles of electromagnetism. Here we describe two such experiments, requiring the use of the 1.7 MV Pelletron accelerator (figure 2). Both experiments explore the Lorentz force (figure 3)

$$\boldsymbol{F} = q(\boldsymbol{v} \times \boldsymbol{B} + \boldsymbol{E}) \tag{1}$$

and demand prior knowledge of vectorial algebra.

Velocity selector

The velocity selector is a device in which mutually perpendicular electric and magnetic fields are produced, forming a right angle with the ion flight path [3]. There is a specific velocity v such that the ions will feel the magnetic and electric forces equally in modulus and in opposite directions, and will consequently travel in a straight line with a constant velocity. In most velocity selectors the magnetic field is supplied by a pair of permanent magnets and the electric field is produced by a pair of parallel conductors, separated by a distance d, where an electric potential difference V is applied. Even in the non-ideal case (conductor length and width not much larger than the distance d) the electric field lines are parallel close to the centre of the conductor gap. The $\boldsymbol{E} \times \boldsymbol{B}$ velocity selectors allow separation of the ion beams by mass and charge state. Charged particles passing through orthogonal electric ($\boldsymbol{E}$) and magnetic ($\boldsymbol{B}$) fields are deflected unless their velocity is given by

$$v = \frac{E}{B}$$

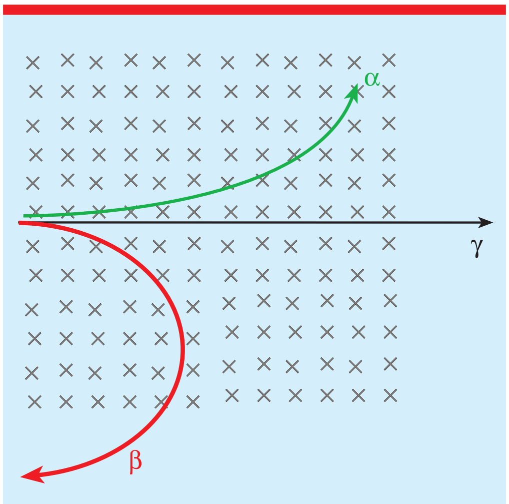

Figure 3. Deflection of alpha, beta and gamma rays in a magnetic field due to the Lorentz force. The uniform magnetic field is directed into the paper.

or, using the fact that $E = V/d$,

$$v = \frac{V}{Bd}.$$

One can also scan the mass spectrum of ions entering the filter by varying V. Let us assume that all ions possess a kinetic energy K, obtained after being accelerated from rest by an electric potential V_0. When these ions enter the selector, only ions with a well-defined mass-to-charge ratio will be transmitted. The mass of these transmitted ions is

$$m = \frac{2KB^2d^2}{V^2}.$$

Then a plot of the mass of the ions as a function of $1/V^2$ is a straight line as shown in figure 4.

Switching magnet

The switching magnet (figure 5) selects the momentum of a particle. The deflection of ions in a perpendicular magnetic field is proportional to the momentum of the particle per unit charge. As the magnetic force is orthogonal to the particle velocity, the velocity modulus remains constant, though its direction changes in response to the sideways deflecting force of the magnetic field. If the particle velocity is $\boldsymbol{v}$ at right angles to $\boldsymbol{B}$, the particle will exhibit a circular motion of radius R at constant speed. The centripetal force mv^2/R is

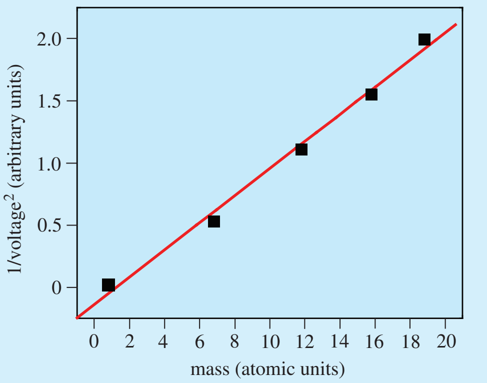

Figure 4. Calibration of a Wien filter.

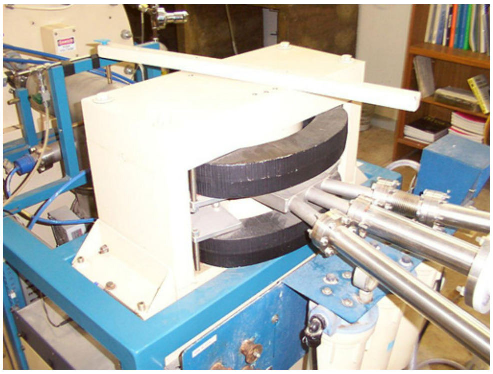

Figure 5. The switching magnet.

provided by the magnetic force:

$$qvB = \frac{mv^2}{R}$$

or, in terms of the particle's kinetic energy,

$$B = \sqrt{\frac{mK}{q^2R}}.$$

A plot of the square of the magnetic field as a function of mK/q^2 should then be a straight line, and this is shown to occur in figure 6.

Conclusions

The experiments performed using the accelerator succeed in giving students an excellent follow-

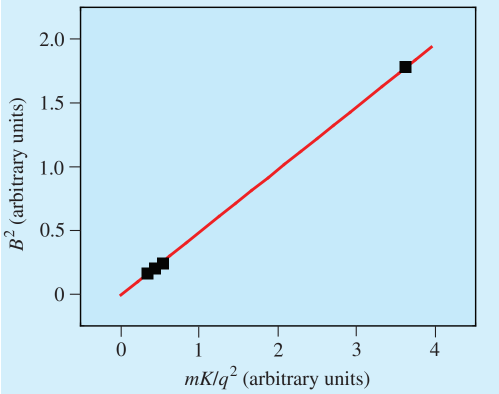

Figure 6. The magnetic field in the switching magnet as a function of mK/q^2.

up to the preparation they were given in high school. They are complemented at university during undergraduate studies in physics.

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Debby Sinflorio is a high-school student. She was awarded a Young Talented scholarship from a Brazilian funding agency (FAPERJ). She is applying for a physics college.

Paulo Fonseca is a freshman student of physics at UFRJ. He was awarded a PIBIC-CNPq scholarship.

Felipe Coelho has been an Associate Professor of Physics at UFRJ for 25 years, working with atomic collisions.

Toni Santos is also an Associate Professor of Physics at UFRJ. He specializes in inelastic collisions involving positrons, electrons, photons and ions with atoms and molecules.