Minicourse on Experimental techniques at the NSCL **Fragment Separators**

Thomas Baumann

National Superconducting Cyclotron Laboratory
Michigan State University
e-mail: baumann@nscl.msu.edu

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1 Introduction

Fragment separators are used for the in-flight separation of reaction products. Separation in this context is the spatial separation depending on specific properties of the reaction products (e.g. mass, charge, momentum). If the fragments are spatially separated, slits or the limited acceptance of the separator can be used to stop the unwanted beam particles.

A more specialized purpose of fragment separators is the isotopic separation of secondary beams for the production of rare isotope beams, and this is what I will focus on in this lecture.

2 Production of rare isotope beams

There are different ways to produce a rare isotope beam (RIB): one can either fragment target nuclei and try to extract them from the target, or one fragments the projectile, with the projectile fragments passing through the target. Other ways to create rare isotopes are through fission or fusion.

In the *projectile fragmentation*, parts of the projectile are removed when it hits a target nucleus. For projectiles that can undergo *fission*, like some uranium isotopes, the interaction with the target can cause an excitation above the fission barrier. The products of fission are neutron rich and for some isotopes this method can offer higher yields as compared to the fragmentation. A *fusion* only occurs if the projectile is within a narrow energy window. This method is used to produce super-heavy elements.

The two main methods used for the RIB separation are the Isotope Separation On-Line (ISOL) and the In-Flight Separation. A schematic sketch of the two is shown in Fig. 1.

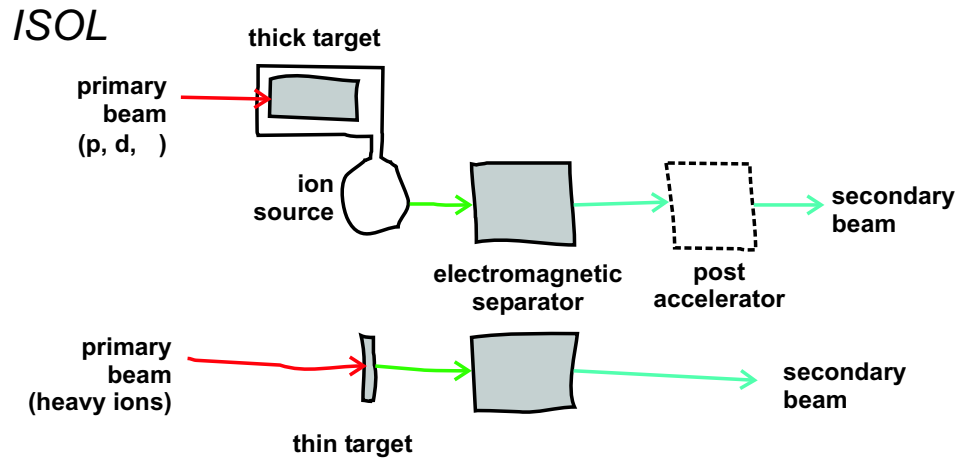

Figure 1: Basic layout of an ISOL facility (top) and In-Flight-Separation (bottom).

In the ISOL layout, a primary beam of protons, deuterons, or alpha particles is usually stopped in a thick target. The projectiles cause the target nuclei to fragment or fission. The reaction products then have to be extracted from the thick target via diffusion. This step of the process depends on the properties of the target material and can already be selective. The ISOL target is integrated into an ion source from which the reaction products are transported through an electro-magnetic separator for selection of the wanted isotope. Due to the low energies of up to 100 keV, a post accelerator is needed if the rare isotope beam should be used for secondary reactions.

In the In-Flight Separation technique, a thin target is used and the primary beam is not stopped in the target. In this case, the projectile nuclei are fragmented by the target nuclei. The projectile fragments are emitted from the target with almost the velocity of the primary beam and can be separated in an electro-magnetic separator directly following the production target. Because the projectile fragments already have high energies, a post accelerator is not needed.

3 Elements of electro-magnetic fragment separators

Electro-magnetic separators employ the Coulomb and Lorentz forces to deflect ions:

$$\vec{F} = \frac{d\vec{p}}{dt} = q\,(\vec{E} + \vec{v} \times \vec{B})\,. \tag{1}$$

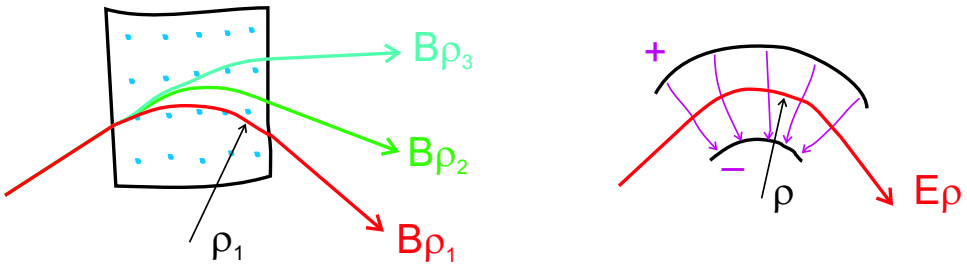

Figure 2: Illustration for the magnetic rigidity (left) and the electric rigidity (right).

If you know the electric field $\vec{E}$, the magnetic field $\vec{B}$, the ion's velocity $\vec{v}$, and it's charge q, you can calculate it's trajectory.

For special cases we define the *magnetic rigidity*

$$B\rho = \frac{p}{q} = \frac{\gamma m_0 v}{q} \,, \tag{2}$$

and the *electric rigidity*

$$E\rho = \frac{pv}{q} = \frac{\gamma m_0 v^2}{q} \,. \tag{3}$$

These formulas are valid for a homogeneous magnetic field that is perpendicular to the ion's movement, and a radial electric field, respectively (see Fig. 2). Here, ρ is the radius of the circle the ion travels on. The unit for the magnetic rigidity is Tesla-meter (Tm).

An electro-magnetic separator consists of different basic elements, the most common ones are the magnetic dipole (see Fig. 3), the magnetic quadrupole (Fig. 5), multipoles of higher order (sextupoles, octupoles, etc.), and solenoids. The velocity filter, a combination of electric and magnetic fields, is also used in some separators.

A dipole magnet can be used for two purposes, one is to just bend a beam around a corner in order to transport the particles to a certain location. The other is to disperse the particle beam and select only a beam within a limited range of magnetic rigidities. This is the key element of the $B\rho$ analysis or a $B\rho$ separation.

Quadrupole magnets are necessary to focus the beam. A single quadrupole as depicted in Fig. 5 can only focus the beam in one direction, in order to achieve a focusing in both, the x- and y-plane, at least a doublet of quadrupoles is needed. Many separators employ quadrupole triplets for this purpose.

Multipole magnets of higher orders are needed to correct ion optical aberrations. A multipole will only affect the beam optics of the same order and higher. So if second order effects are to be corrected, sextupole magnets have to be employed, for third order effects octupoles are needed.

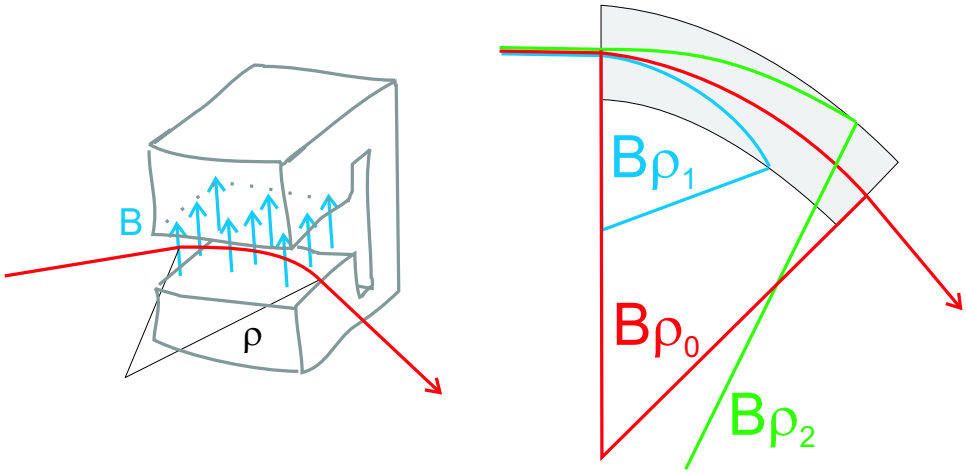

Figure 3: The dipole magnet selects a beam within a certain range of magnetic rigidities.

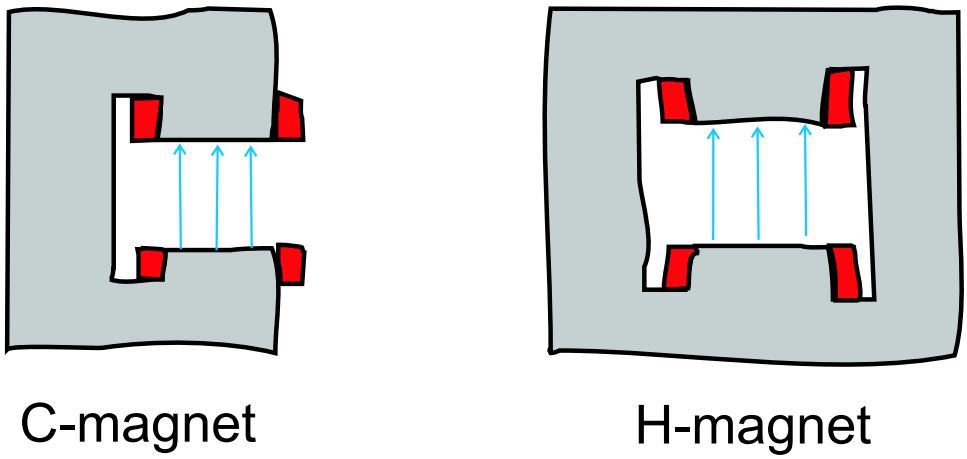

Figure 4: The two common designs of dipole magnets are the C-magnet and the H-magnet. The yokes are pictured in grey, while the red boxes indicate the position of the coils.

A solenoid can also be used for focusing if the beam passes through it along it's axis. The rare isotope facility GANIL uses a pair of solenoids around the production target to focus reaction products. This is the SISSI device which enhances the angular acceptance of the separator. But the focusing strength of a solenoid is a second order effect and it is inversely proportional to the beam energy squared, therefore solenoids are only useful at lower beam energies.

The technical limitation in the strength of electric fields also makes their use for beams of high electric rigidity difficult, therefore separators for higher energy beams commonly only use magnetic elements.

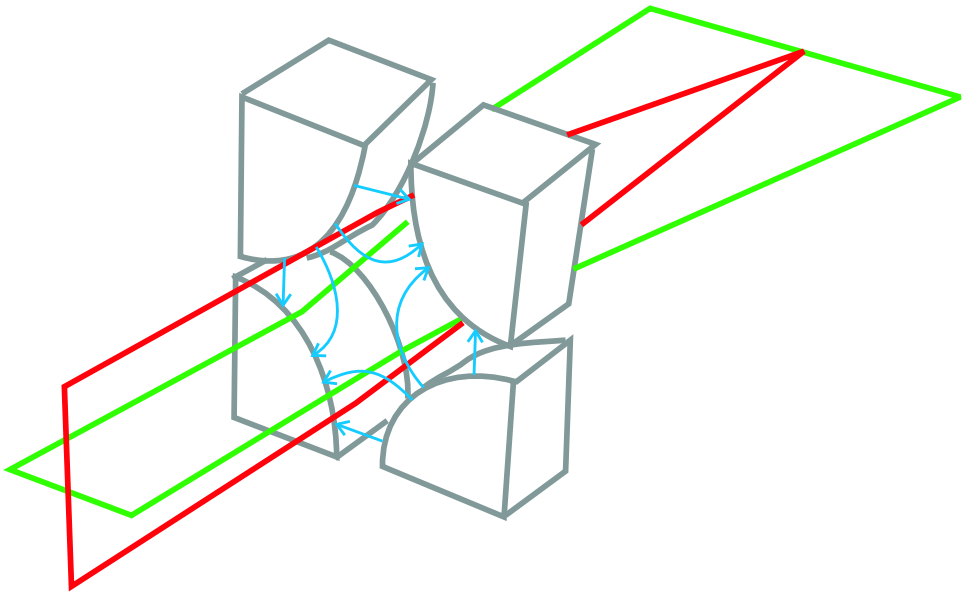

Figure 5: Quadrupole magnet. This one focuses the beam in the vertical direction and defocuses it in the horizontal plane.

A Wien-filter is a combination of electrical and magnetic field that acts as a velocity filter. If you cross an electric and magnetic field and have ions enter this field perpendicular to the field lines, the Coulomb and Lorentz forces in Eq. 1 can exactly compensate for one specific velocity. This kind of velocity filter in realized at the end of the LISE spectrometer at GANIL and at the RPMS (Reaction Products Mass Separator) at the NSCL.

4 The achromatic magnetic separator

A fragment separator has to offer more than just a $B\rho$ separation in order to be useful for the production of secondary beams. The projectile fragmentation yields reaction products that are emitted with an angular and energy spread due to the nuclear reactions in the production target. Because the most interesting rare isotopes are also the ones that have the smallest production cross sections, the separator must be able to capture a large fraction of the angular and energy range of the selected fragment. This is only possible if the selected fragment is focused back to a small area. To achieve a $B\rho$ separation at the same time, most fragment separators consist of two dispersive stages, where the second stage counteracts the dispersion of the first stage. The limited $B\rho$ acceptance of the first stage does the selection, while the second stage focuses the transmitted fragments back. Figure 6 shows the basic principle of the achromatic separator in an ion optics sketch. The projectile fragments origin from a small beam spot at the target (position

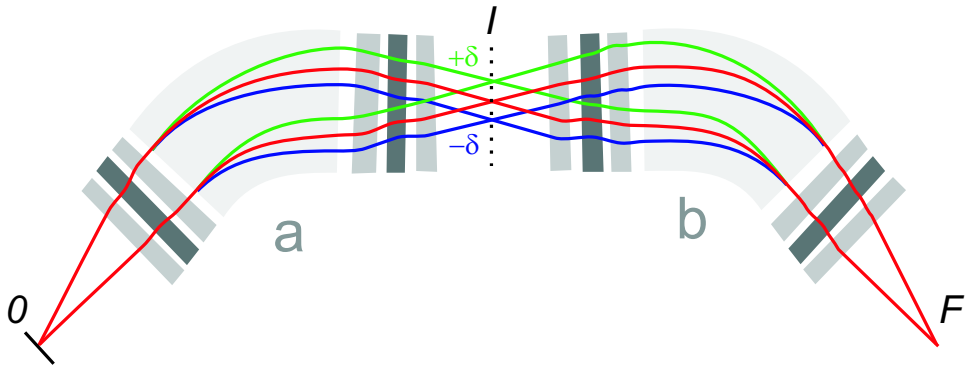

Figure 6: Ion optics of an achromatic magnetic separator.

0). The red lines indicate the angular cone in which the fragments leave the target. The momentum spread of the fragment ($+\delta$ and $-\delta$) is dispersed in position at the intermediate focus (I), while the angular spread is focused back to a point. So the position in x at the intermediate focus only depends on the fractional momentum deviation δ. Looking at the transfer matrix in first order

$$\begin{pmatrix} x \\ \theta \\ y \\ \phi \\ s \\ \delta \end{pmatrix} = \begin{pmatrix} (x|x) & (x|\theta) & 0 & 0 & 0 & (x|\delta) \\ (\theta|x) & (\theta|\theta) & 0 & 0 & 0 & (\theta|\delta) \\ 0 & 0 & (y|y) & (y|\phi) & 0 & 0 \\ 0 & 0 & (\phi|y) & (\phi|\phi) & 0 & 0 \\ (s|x) & (s|\theta) & 0 & 0 & 1 & (s|\delta) \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_0 \\ \theta_0 \\ y_0 \\ \phi_0 \\ s_0 \\ \delta \end{pmatrix} ,$$

we see that due to the point-to-point imaging in x between target and intermediate focus, the term $(x|\theta)$ is zero, and the position x_I can be expressed as

$$x_I = (x|x)_a x_0 + (x|\delta)_b \delta \ .$$

Here the subscript a denotes the matrix elements that correspond to the first separator stage.

The x position at the final focus F is consequently

$$x_F = (x|x)_b (x|x)_a x_0 + (x|x)_b (x|\delta)_a \delta + (x|\delta)_b \delta \ .$$

If we want a system where x_F does not depend on the momentum deviation δ (in first order), we have to choose

$$(x|x)_b (x|\delta)_a = -(x|\delta)_b \tag{4}$$

i.e. the dispersion of the second stage must compensate the dispersion of the first stage times the magnification of the second stage. Equation 4 is the *achromatic condition*.

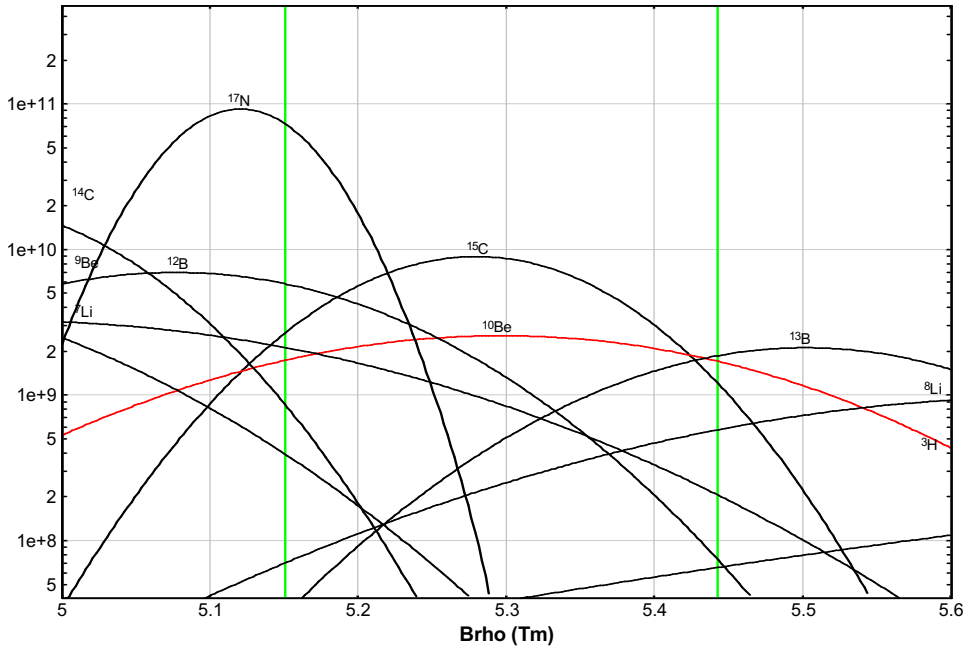

Figure 7: This is a LISE calculation of the $B\rho$ distribution of projectile fragments behind the production target. In this example, a ^{18}O primary beam of 200 MeV/nucleon is fragmented in a 500 mg/cm^2 beryllium target. The ^{10}Be distribution is centered around 5.3 Tm. Because ^{15}C has the same A/Z ratio, it's $B\rho$ distribution also peaks at 5.3 Tm. The green lines indicate the momentum acceptance of the separator. In this case, ^{10}Be and ^{15}C can not be separated, and there are a lot of contaminants from the wings of the $B\rho$ distributions of other fragments.

Slits at the intermediate focus can be used to limit the transmitted momentum width. Thus an achromatic magnetic separator can perform a p/q selection of the reaction products with a certain acceptance in momentum width $\delta = \Delta p/p_0$. This corresponds to an m/q selection if all reaction products have similar velocities. If they are fully ionized, this is equivalent to an A/Z selection.

5 Isotopic separation using a wedge degrader

As shown above, the magnetic separator can not separate different isotopes with the same A/Z ratio. To achieve this, a degrader has to be used. A degrader is just a piece of matter that the beam has to pass. Because the atomic slowing down of the ions is roughly proportional to Z^2/v^2, different isotopes with different Z will have different velocities after passing through the degrader. This change in velocity causes the isotopes with the same A/Z ratio to be separated in the second dispersive stage. Figures 8 and 9 illustrate this.

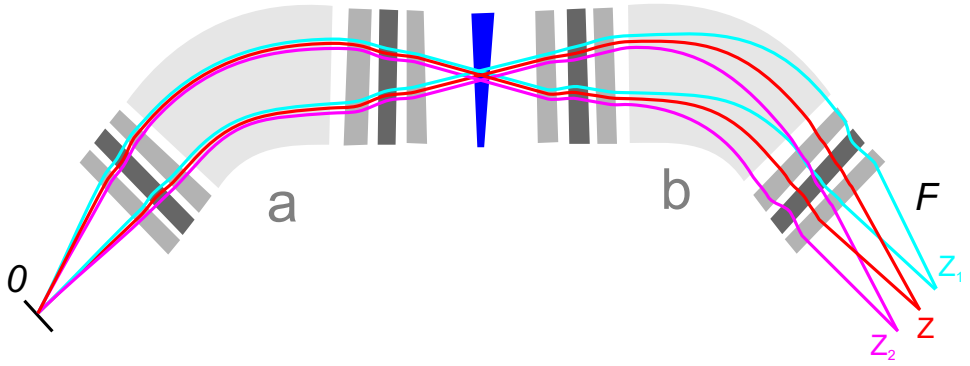

Figure 8: Fragment separation using a wedge degrader. Three different isotopes with the same m/q ratio and the same velocity pass through the first spectrometer stage. A degrader at the intermediate plane slows the beam particles down depending on their charge. Due to the velocity difference, the different isotopes are now separated in the second stage.

The degrader is wedge shaped because you want to keep the achromatic condition for the selected isotopes. Because the energy loss in the degrader also depends on the particle velocity, different thicknesses are needed at the dispersive plane, a thicker degrader at the high velocity side and a thinner degrader at the lower velocities. A degrader that is shaped accordingly is called *achromatic degrader*.

Because the degrader slows all particles including the selected isotope down, the $B\rho$ setting of the magnetic elements following the degrader have to be adjusted accordingly.

As the isotopes with the same A/Z become more separated, other contaminants might be shifted further into the acceptance window. This has to be checked when selecting a wedge degrader in order to reach the optimum parameters.

Appendix: $B\rho$ formula

Sometimes the units used in nuclear physics can become pretty confusing. Therefore I give an example how to derive a formula for the magnetic rigidity of a beam in which you can enter the energy in MeV/nucleon, the mass number in atomic mass units, and the charge in proton number (or charge state if not fully ionized).

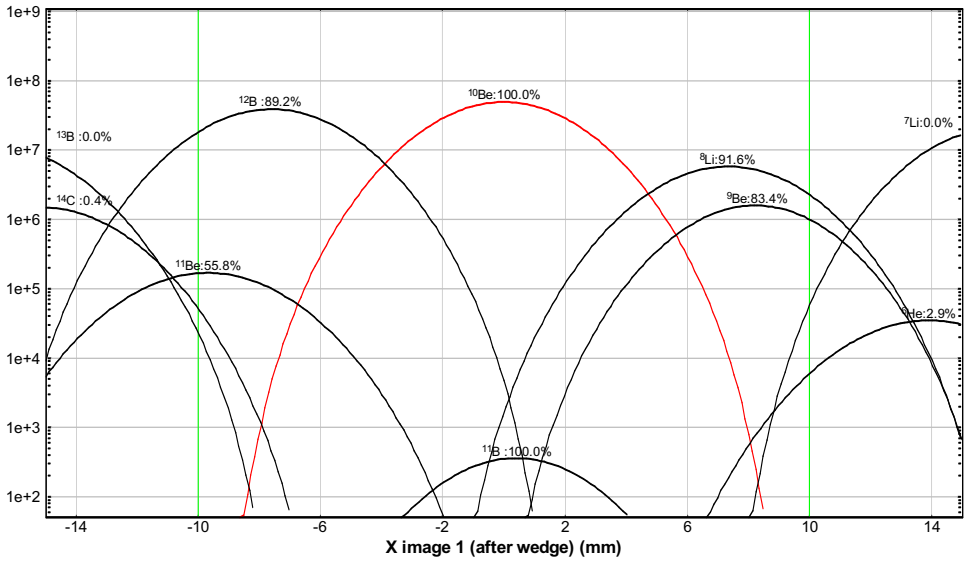

Figure 9: A wedge degrader (achromatic) was added to the LISE calculation shown in Fig. 7. Plotted here are the position distributions in x of the various isotopes at the final focus. The ^{15}C is now completely removed from the ^{10}Be distribution. The use of slits can further cut down on the remaining contaminants.

We start with

$$\begin{aligned} B\rho &= \frac{p}{q} \\ &= \frac{\gamma m_0 v}{q} \\ &= \frac{m_0 c}{q}\,\beta\gamma\ , \end{aligned} \tag{5}$$

with $\beta = v/c$ and the speed of light c. Using the relativistic energy relation

$$\begin{aligned} E^2 &= m_0^2c^4 + p^2c^2 \\ &= m_0^2c^4 + (\beta\gamma)^2 m_0^2c^4\ , \end{aligned}$$

we will attempt to replace the $\beta\gamma$ term in Eq. 5.

Resolving for $\beta\gamma$ yields

$$\begin{aligned} \beta\gamma &= \sqrt{\frac{E^2 - m_0^2c^4}{m_0^2c^4}} \\ &= \frac{1}{m_0c^2}\sqrt{(E_{\rm kin} + m_0c^2)^2 - m_0^2c^4} \\ &= \frac{1}{m_0c^2}\sqrt{E_{\rm kin}^2 + 2E_{\rm kin}m_0c^2}\ . \end{aligned}$$

Equation 5 then can be written as

$$B\rho = \frac{m_0 c}{q} \frac{1}{m_0 c^2} \sqrt{E_{\mathrm{kin}}^2 + 2E_{\mathrm{kin}} m_0 c^2}$$
$$= \frac{1}{qc} \sqrt{E_{\mathrm{kin}}^2 + 2E_{\mathrm{kin}} m_0 c^2} \; .$$

Now we introduce the mass number A with the relation $Au = m_0$. Here u is the atomic mass unit, $u = 931.49432\mathrm{MeV}/c^2$. The speed of light is $c = 299792458$ m/s. Note that A is just a number and does have the unit 1. Replacing the energy with E_{kin}/A, m_0 with Au, and q with Ze, we get

$$B\rho = \frac{A}{Zec} \sqrt{(E_{\mathrm{kin}}/A)^2 + 2(E_{\mathrm{kin}}/A)uc^2}$$

Now we only need to check the units!

$$\frac{1}{e\,\mathrm{m/s}}\,\mathrm{MeV} = 10^6\,\frac{\mathrm{Vs}}{\mathrm{m}} = 10^6\,\mathrm{Tm}\;.$$

Entering the energy per nucleon in MeV, the mass number A and the proton number Z (or charge state), this formula yields the magnetic rigidity in 10^6 Tm. The electron charge e drops out in the units.

References

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