SEPARATION AND MATCHING OF ION BEAMS BETWEEN SOURCES AND ACCELERATORS

H. WOLLNIK*

Oak Ridge National Laboratory, Oak Ridge, TN 37830, USA

Possibilities for an effective separation of short lived nuclei are discussed using magnetic sector field analyzers. Here it is accepted that neighboring mass ions are produced with considerably different efficiencies and that at the end only low mass cross contaminations are acceptable. Discussed are also considerations about bunching properties of the separator that may assist the purity of postaccelerated ion beams.

KEY WORDS: Isotope separator, double stage, sector magnet, mass cross contamination, prebunching

1 INTRODUCTION

For radioactive ion beam (RIB) facilities that provide accelerated ions of short lived nuclei it is essential that the produced short-lived nuclei of interest are ionized and delivered most efficiently to the postaccelerator. Equally important is, however, that isotopes of neighboring isobars and of neighboring elements within the same isobar are eliminated as effectively as possible. This is difficult to achieve, especially if the nuclei of interest are produced by spallation or by fission reactions since those reactions are not very specific and usually produce neighboring isobars and elements at intensities that often exceed considerably the produced intensities of the nuclei of interest.

For this reason very efficient separation techniques are required. Such techniques make use of differences in chemical properties and ionization probabilities of the atoms in question in the target ion source.[1] Most importantly, however, such ions of different mass-to-charge ratios are accelerated by the same potential difference (perhaps 60 kV) and passed through large magnetic dipole fields that deflect ions differently if they have different momentum-to-charge ratios.

2 ELECTROMAGNETIC ISOTOPE SEPARATORS

Since for the ions of interest in most cases a high ionization efficiency is mandatory, the target ion source usually is only able to achieve a modest attenuation of the undesired species

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*Permanent address: Physikalisches Institut, Universität Giessen, 35439 Giessen, Germany

except if laser ionization by specific light wave lengths can be used[2] or surface ionization. The main attenuation thus must be obtained by deflecting ions of different mass-to-charge ratios m/q differently by one or by several magnetic sector fields.[3,4,5,6] Note here that because of the desired high ionization efficiencies in most any case only singly-charged positive or singly-charged negative ions are used with q=±1.

Though such separation methods by magnetic sector fields are quite effective, there are limits[4] to how well ions of an undesired mass m_1 can be separated from the desired ions of mass m_0 after both had been accelerated to energies K_0 of perhaps K_0=60 kV.

1. In a magnetic separator of a few meters path length several percent of the ions are scattered at residual gas atoms if the vacuum in that system is $\approx 10^{-7}$ mbar. Some of the ions of the undesired mass m_1 here are scattered such that they pass through the separator exit slit that was positioned as to transmit only ions of mass m_0. If the separator is designed to have a mass resolving power $R = M/\Delta M$ of about 2000, this contamination by ions of mass m_1 amounts to a few ppm of the overall intensity of the ions of mass m_1.[a]

    This contamination reduces if the masses m_1 and m_0 differ more and more. However, this drop off is usually not as rapid as one would hope, so that contamination levels of a few ppm persist also if m_1 and m_0 differ by several percent. A much more drastic reduction in contamination levels is achieved, however, if two separator stages are placed in series since in this case the attenuation factors of the first and of the second stage multiply so that usually less than 10^{-9} of the ions of mass m_1 are scattered into the beam of ions of mass m_0.[4,5,6]

2. In most any ion source the gas pressure is relatively high which causes also a reasonable high gas pressure in the acceleration region, perhaps 10^{-4} mbar. After some of the abundantly available ions of mass m_1 had been accelerated to perhaps $\bar{K} \approx 100$ eV they may thus collide with residual gas atoms of mass m_1 and transfer their charges. The newly formed ions of mass m_1 then are accelerated by the left over part of the acceleration voltage. Besides the common 60 keV ions of mass m_1 there thus will be some ions of mass m_1 accelerated to K_0 - $\bar{K} \approx 59.9$ keV. Since this charge exchange can take place at any potential $\bar{K}q$ in the acceleration region, the ions of mass m_1 can have quite different energies $K_0 - \bar{K}$ and thus also that of $K_0 - \bar{K} = K_0 m_0/m_1$. This energy would make the momentum of an ion of mass m_1 equal to the momentum $m_0 K_0$ of an ion of interest of mass m_0, which two momenta can not be distinguished by magnetic field arrangements.[4,5]

    Although this contamination of the ions of mass m_0 is about a few ppm of the intensity of the ions of mass m_1, it can be reduced only by using some electrostatic fields that can distinguish ions of different energies K_0 and $K_0 - \bar{K}$. In a radioactive ion beam facility such a separation is advantageously achieved by placing the two magnetic separator stages (postulated above in point 1) on two different electrostatic potentials.[6] This procedure, however, requires that the energy spread of the ions under consideration is very small as compared to the energy of the ions. An energy analysis

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[a] Note here that the intensity of ions of mass m_1 may exceed the intensity of ions of mass m_0 by many orders of magnitude.

by electrostatic sector fields, however, would be feasible as well and if combined with the momentum analyzing capabilities of the discussed sector magnets could even allow for an energy focusing[7,8] so that ion sources with large energy spreads would not have to be excluded.

3. For ions of different elements that belong to the same isobaric chain the differences in their masses, i.e. the Q_β-values, are so small that only isotope separators of mass resolving power $R \geq 10^4$ can separate them from each other. Such isotope separators can be built,[5] but they require a careful correction of their image aberrations.[6,7,9]

3   THE LAYOUT OF AN ISOTOPE SEPARATOR

Isotope separators are usually considered to be inseparable from their ion sources. Thus, only if the combined systems are optimized, one can expect a high performance isotope separation. This finding is mainly due to the fact that small changes in the gas pressure or the potential distribution in the ion source or even the temperature of the source change the optical properties of the extracted ion beam.

In order to at least relieve this close tie, one can place a fousing device between the ion source and the entrance slit of the actual isotope separator.[3,5,6,8,9] If in this arrangement the ion source properties change a little — the reason for which may only become obvious later — one may restore the deteriorated beam properties to what they had been before by slightly changing the optical properties of the fosusing device. In doing so one has effectively decoupled the beam forming properties of the ion source from its properties to generate ions.

This prefocusing device can be an electrostatic round lens, however, it is much more advantageous to use an astigmatic device,[b] instead. In this case namely it is possible to match the ion beam optimally to the optics of the sector magnet that performs the momentum analysis. A very good way to do this is[9] to make the sector magnet point-to-point focusing not only in the plane of deflection, i e. the x-direction, but also in the perpendicular direction, i.e. the y-direction, for instance by using a homogeneous sector magnet with inclined pole-face boundaries. As a second step one then may adjust the astigmatic prefocusing device so that the beam has an x-image at the entrance slit but not a y-image. At this position the beam should rather be more or less parallel as far as the y-direction is concerned. Automatically then there is an x-image at the separator exit slit and the beam is again more or less parallel as far as the y-direction is concerned. As a consequence of this, the ion beam (see Figure 1) is rather wide in x-direction — perhaps ± 100 mm — but rather narrow in y-direction — perhaps ± 5 mm — in the middle of the sector magnet whose optic axis may be a circle of perhaps $\rho_0 = 2000$ mm radius.

Such a design of an isotope separator equipped with a pefocusing device[9] has several advantages as compared to a separator in which the ion source sends the beam directly into the sector magnet:

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[b] Such an astigmatic prefocusing device could consist of for instance 3 or better 4 electrostatic or magnetic quadrupole lenses. In the latter case then a variation of only the strengths of the 4 quadrupoles would allow to adjust all important four first-order elements of the transfer matrix in question to desired values, i.e. (X,X), (X,A), (Y,Y), (Y,B).
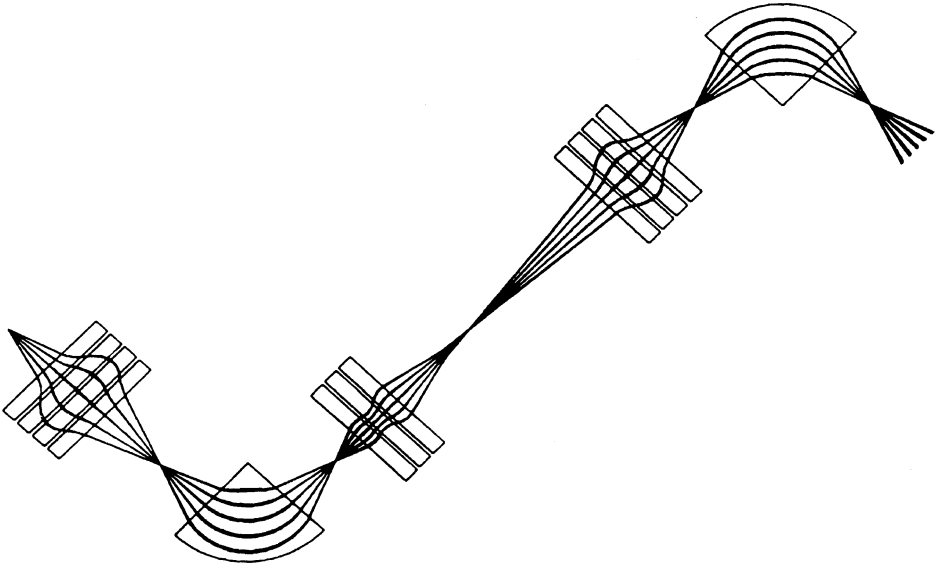
FIGURE 1:   A two-stage sector magnet separator that separates charged particles according to their momentum-to-charge ratios mv/q. Note that the two separator stages are at different electrostatic potentials so that in the second stage the ions have been accelerated by perhaps 250 kV relative to the first stage. Note also that each sector magnet is preceded by an astigmatic focusing device that ensures that the beam is focused to the respective entrance slits but is more or less parallel in the perpendicular direction.

1. The position of the x-image of the ion source can be adjusted to be exactly at the position of the entrance slit by changing the lens strengths of the prefocusing device. Thus small changes of the optics of the ion source can be counterbalanced without deterioration of the separator performance.

2. A sector magnet can be used that has only a small magnet air gap, perhaps $\pm G_0 = \pm 25$ mm for a sector field of radius $\rho_0 = 2000$ mm. This fact can be rather important since the costs for a sector magnet usually increase more than linearly with an increase in $\pm G_0$.

3. A good correction of image aberrations of second order can usually be achieved already by a slight curvature of one or two of the field boundaries. This is so since the largest aberrations of a sector magnet are in most any case the aperture aberrations $(X,AA)a_0^2 + (X,BB)b_0^2$ with $a_0 \approx dx/dz$ and $b_0 \approx dy/dz^7$ and since in our case we have $a_0 \approx 20$ mrad and $b_0 \approx 2$ mrad. Thus we really need to correct only (X,AA) by curving one or two field boundaries without worrying too much about the magnitude of (X,BB) which inevitably will increase by achieving $(X,AA)=0$ because $(X,AA) + (X,BB) = $ const for a stigmatic focusing separator stage postulated above.

4. If the space charge of the initial ion beam should not be negligible the proposed design is quite favourable since it ensures that until into the sector magnet the ion beam cross

section at no position is very small. Thus space charge forces are kept within limits everywhere.

4   BUNCHED BEAMS

In principle there is no need to require the ion beams in a RIB facility to be bunched in order to achieve a good mass separation. However, there are advantages in postulating the beam to be bunched at different positions in the system.

1. Part or all of the ion beam transport system can be used as a time-of-flight mass analyzer[10] whose separating power provides an additional means of purifying the beam of ions of mass m_0. Such a purification would be especially effective since it would differentiate not between ions of slightly different momenta as does any one of the assumed sector magnets, but of ions of slightly different velocities.

2. Providing a bunched beam to the postaccelerator allows for an easier coupling of the ion beam to any RF-device and thus in most cases for a more efficient beam capture and smaller emittance growth.

3. Though accelerators for stable ion beams are built to provide DC beams whenever possible, so that coincidence experiments become easier, there are advantages for accelerators for unstable ion beams if they are built to provide ions only during short periods. The reason is that very often there are only a few ions available to be accelerated. Thus, very often the question is not how many ions are accelerated in one bunch but rather whether in one accelerator bunch there is one ion or none. In this case the signal to noise ratio for an experiment increases if it does not have to wait for an event to happen at an arbitrary time, but if it can expect this event to happen only during short time windows.

The bunching for the first two points should be done before the beam is entered into the postaccelerator either by an in-line or an orthogonal-acceleration bunching devise as shown in Figure 2. The bunching for the third point should be done after or in the postaccelerator.

Since any bunching device induces beam losses of an incoming DC beam, it is quite advantageous that it seems possible[12] to extract a pulsed beam from a good ion source with little or no intensity losses as compared to a DC extraction.[c]

5   MATCHING AN ION BEAM TO THE ACCEPTANCE OF AN ACCELERATOR

To enter an ion beam into an accelerator structure one must preaccelerate the ions properly. In case of an electrostatic accelerator the ion energy should always be the same, while the ion velocity should always be the same in an RF accelerator. In the second case thus the ion

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[c] As compared to a DC beam it was possible in the case of ref. 11 to extract more than 5 times higher currents during each pulse if only during 20% of the time ions were extracted. The overall extracted beam current thus was greater or equal than the initial DC beam.
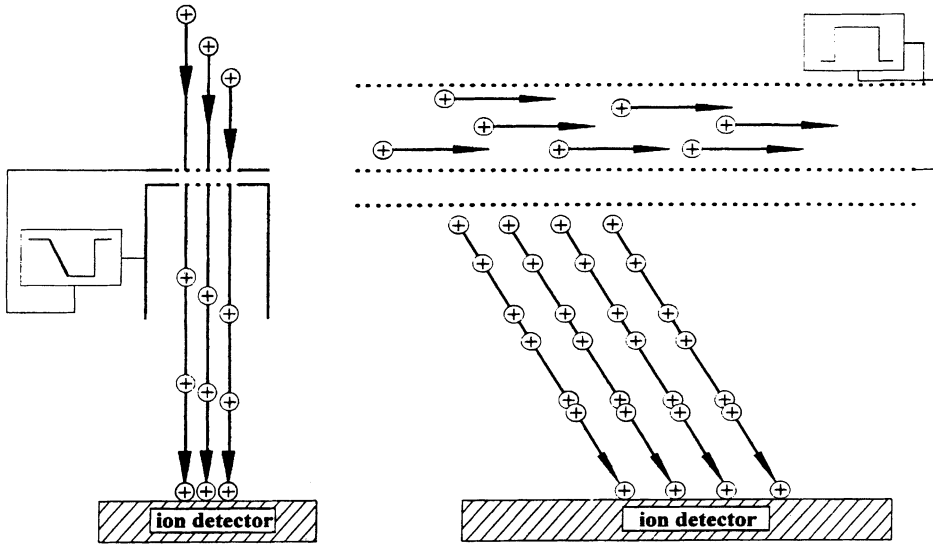
FIGURE 2: Two designs of ion bunchers are indicated. The first buncher decelerates the first of a group of ions and accelerates the last so that after some time they arrive simultaneously at some plane. The corresponding acceleration gap must be powered by some sawtooth generator which usually is approximated by some sinusoidally varying voltage. The second buncher accelerates the ions by a field perpendicularly to the initial direction of the ions. This buncher requires the ions to have rather low initial energies, for instance 10 eV. Here the ions that have a longer distance to go get a higher energy so that after some specified flight distance they all can catch up with each other. In this buncher the main accelerating field is a DC field with only its first portion being pulsed. The pulsed field requires only a simple square pulse with rather modest rise times. For this device it is very useful to make the incoming ion beam as parallel as possible by, some lens, so that the ions have only a very small energy spread in the final direction of the ions.[12]

energy must linearly increase with the ion mass. Consequently the isotope separator system should feature several potentials:

1. V_0 the ion source potential.

2. V_1 the potential of the first stage of the isotope separator, with $V_0 - V_1 \approx 60$ kV.

3. V_2 the potential of the second stage separator with $V_1 - V_2 \leq 100$ kV.

4. V_3 the potential of the entrance to the ion postaccelerator with $V_3 - V_0 = K_r(m_0/m_r)$ where K_r, is the energy that makes an ion of mass m_r, move with the correct velocity into the postaccelerator.

Obviously there is only one potential arbitrary and one should choose it such that the overall sum of technical difficulties becomes smallest.[6] In most cases this leads to making $V_2 = 0$. This would allow to keep the rather large second stage separator at ground potential and at the same time all parasitic experiments that may want to use a well mass analyzed beam of short lived nuclei. This would require, however, the accelerator entrance to be not at ground potential.

Additional to this requirement of a proper ion velocity at the entrance of the accelerator one needs to postulate that the ion beam does not exceed the acceptance phase space of the accelerator, i.e., the lateral phase space in x,a and y,b but also in the longitudinal phase space in δ_t, δ_K with $\delta_t = T/T_0\text{-}1$ and $\delta_K = K/K_0\text{-}1$ describing relative time and energy deviations.

6 CONCLUSION

To mass separate and match beams of ions of short lived nuclei to a postaccelerator seems very well possible. The isotope separator in question, however, becomes rather elaborate consisting of at least two large magnetic separator stages that analyze and transport the ion beam to the postaccelerator. As an additional means of purification one may employ a time-of-flight mass analyzer after the ion beam has been bunched to very short pulses. Since the accelerator requires all entering ions of mass m_1 to have a certain velocity $v_0 \propto \sqrt{K_0/m_0}$ the potential difference K/q between the ion source and the accelerator must attain a certain value $K = K_0 m_0/m_1$. Thus different parts of the system must be at considerably different electrostatic potentials for ions of different masses m_1.

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