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PRINCIPLE OF A NEW KIND OF
LARGE ACCEPTANCE MASS SEPARATOR.

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GANIL-B.P.5027-F14021 CAEN-CEDEX.

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We propound the principle of a new kind of mass separator devoted to the selection of a given ion species (a given $\epsilon = q/m$ ratio) mixed in a composite beam of large emittance. The numerical simulation of the simplest design we can think about is presented and discussed to illustrate our proposal.

1. Introduction : principle of the mass separator.

Radioactive ion beams produced either by fragmentation or using the ISOL method always have to be purified as they are composed of different kinds of ions. Such a selection can be performed using either magnetic spectrometers (if the energy is high enough, a thick target can be placed in front, thus taking advantage of the energy loss differences between ions of different elements), or the accelerator mass-spectrometry method, or a radiofrequency spectrometer. A velocity filter can eventually be added.

In these spectrometers, the mass resolution is most often obtained at the price of a drastic limitation of the transverse emittance or of the longitudinal one, if not both. The new kind of mass analyser which is proposed seems to present some advantages. Its principle is illustrated on the figure 1.

Such a spectrometer essentially includes three successive sections, each one fulfilling a given function :

- in the first section the various kinds of ions are bunched in the same phase widths around mean phases depending on the charge over mass ratios. This section includes a buncher and a transfer line equipped with the suitable transverse focusing elements.

- the second section just includes a debuncher which transforms the mean phase shifts into mean energy shifts while minimising the energy spread of each component. As can be seen on the figure 1, the $w-\phi$ correlation which is given at the entrance of the debuncher is of prime importance.

- in the third section a magnetic analyser transforms the mean energy shifts into mean radial position shifts while minimizing the radial width of each component. A radial slit at the image point of the system selects the required ions.

This kind of spectrometer allows a good control of the transverse beam behaviour all along its path. We will see that the mass resolution is related to the longitudinal beam emittance (this is already obvious from the scheme of figure 1).

Considering its simplicity, its easy tuning, its wide transverse acceptance and the resolution it can afford for a given longitudinal emittance, it seemed to us that it was worth thinking about this new kind of mass separator.

Figure 1 : The principle of the mass separator and the notations used in the text.

2. Simplified theory.

Before entering the system, particles have of course been accelerated and, having different ϵ values, each kind of ions has a different central initial velocity $\beta_0(\epsilon)$. In this paper we suppose that the ions are accelerated through the same static potential V_0 so that, in the non relativistic approximation, we have : $2\delta\beta/\beta_0 = \delta\epsilon/\epsilon_0$.

2.1-First order approximation :

We suppose that there is no coupling between the transverse and the longitudinal phase spaces and for the sake of simplicity we assume a c-w achromatic beam at the entrance of the system. The buncher and the debuncher are supposed to work on the same frequency, both giving a linear voltage $V(\phi)$ over the phase width $\Delta\phi_0$. Under these assumptions (see figure 1 for notations) :

- the longitudinal emittance remains constant : $(V_0 = w_0)/\epsilon_0$

$$\Delta\phi_0 (\Delta w_0/w_0) = \Delta\phi_f (V_r/V_0) = \Delta\phi_c (\Delta w_c/w_0) \quad 1$$

- the bunching occurs over the bunching length L_e :

$$\Delta\phi_c = \pi \left| (L_e/\beta\lambda)(V_r/V_0) - \Delta\phi_0/\pi \right| \quad 2$$

- the various ion species are shifted in phase over the geometrical real length L_r :

$$\delta\phi = \pi (L_r/\beta\lambda)(\delta\epsilon/\epsilon_0) \quad 3$$

Two kinds of ions are obviously separated in energy if :

$$|\delta\phi(\delta\varepsilon)| > |\delta\phi_{\min}| = 2 \Delta\phi_l \iff |\delta w(\delta\varepsilon)| > |\delta w_{\min}| = 2 \Delta w_c \quad 4$$

Moreover, if we want to remain in the linear part of the debuncher voltage $\Delta\phi_0$, we must also satisfy the relation :

$$|\delta\phi(\delta\varepsilon)| < |\delta\phi_{\max}| = \Delta\phi_0 - \Delta\phi_c \quad 5$$

Using 1, 2, 3 we obtain from 4 and 5 :

$$2 \frac{\Delta\phi_0}{\pi} \frac{\Delta w_0}{w_0} \frac{V_0}{V_r} \frac{\beta\lambda}{L_r} \leq \left| \frac{\delta\varepsilon}{\varepsilon_0} \right| \leq \left\{ \frac{\Delta\phi_0}{\pi} - \left| \frac{L_e}{\beta\lambda} \frac{V_r}{V_0} - \frac{\Delta\phi_0}{\pi} \right| \right\} \frac{\beta\lambda}{L_r} \quad 6$$

We now take into account the radial emittance E_x of the beam and the magnetic analyser characterised, at its image point, by a momentum dispersion coefficient C_d and an achromatic radial half beam width e_0 . Two species, both having the energy dispersion $\Delta w_c/w_0$, are radially separated if their mean energy difference δw is such that :

$$|\delta w/w_0| > \left((4e_0/C_d)^2 + (2\Delta w_c/w_0)^2 \right)^{1/2} \quad 7$$

This is a more restrictive condition than the left side of 7 so that using the two obvious relations :

$$\delta w/w_0 = (V_c/V_0)(\delta\phi/\Delta\phi_0) ; \quad V_c/V_r = \Delta\phi_0/\Delta\phi_c \quad 8$$

we obtain :

$$\frac{\left\{ \left[\frac{4e_0}{C_d} \left(\frac{L_e}{\beta\lambda} \frac{V_r}{V_0} - \frac{\Delta\phi_0}{\pi} \right) \right]^2 + \left[2 \frac{\Delta\phi_0}{\pi} \frac{\Delta w_0}{w_0} \right]^2 \right\}^{1/2}}{\frac{L_r}{\beta\lambda} \frac{V_r}{V_0}} \leq \left| \frac{\delta\varepsilon}{\varepsilon_0} \right| \leq \frac{\frac{\Delta\phi_0}{\pi} - \left| \frac{L_e}{\beta\lambda} \frac{V_r}{V_0} - \frac{\Delta\phi_0}{\pi} \right|}{\frac{L_r}{\beta\lambda}} \quad 9$$

This relation gives the mass range which can be analysed as a function of the initial longitudinal emittance of the beam $\Delta\phi_0 \cdot \Delta w_0/w_0$, of the characteristics of the spectrometer ($L_r/\beta\lambda$, $L_e/\beta\lambda$, C_d) and of the radial emittance through e_0 .

The analysed mass range is defined around a succession of masses ε_i such that :

$$\delta\phi_i = 2k_i \pi \implies \varepsilon_i = \varepsilon_0 \left(1 + 2k_i / (L_r/\beta\lambda) \right) \quad 10$$

and, as a consequence, a first analysis within this mass interval could be required.

From 9, we find the extreme values of $\delta\varepsilon/\varepsilon_0$:

$$\left| \frac{\delta\varepsilon}{\varepsilon_0} \right|_{\max} = \frac{\Delta\phi_0}{\pi} \frac{L_r}{\beta\lambda} \quad 11$$

obtained with : $(L_e/\beta\lambda)(V_r/V_0) = \Delta\phi_0/\pi$ 12

$$\left| \frac{\delta\varepsilon}{\varepsilon_0} \right|_{\min} = 2 \frac{\Delta w_0}{w_0} \frac{L_e}{L_r} \frac{4e_0}{C_d} \left[\left(\frac{4e_0}{C_d} \right)^2 + \left(2 \frac{\Delta w_0}{w_0} \right)^2 \right]^{-1/2} \quad 13$$

obtained with : $\frac{L_e}{\beta\lambda} \frac{V_r}{V_0} = \frac{\Delta\phi_0/\pi}{(4e_0/C_d)^2 + (2\Delta w_0/w_0)^2}$ 14

For small energy dispersions we will have $\Delta w_0/w_0 \ll 2e_0/C_d$ and :

$$|\delta\epsilon/\epsilon_0|_{\min} \implies 2 (L_e/L_r)(\Delta w_0/w_0) \quad 15$$

which only depends on the energy dispersion and not on the analyser.

In the opposite case of a large energy dispersion $\Delta w_0/w_0 \gg 2e_0/C_d$ and :

$$|\delta\epsilon/\epsilon_0|_{\min} \implies 4 (L_e/L_r)(e_0/C_d) \quad 16$$

which only depends on the initial radial emittance (e_0) and of the analyser (C_d).

On the other hand, the final energy dispersion of the beam which is separated depends only on the product $(L_e/\beta\lambda)(V_r/V_0)$; it rises very sharply as $L_e/\beta\lambda \Rightarrow \Delta\phi_0/\pi$:

$$\Delta w_c/w_0 = (\Delta\phi_0/\pi)(\Delta w_0/w_0) / |(L_e/\beta\lambda)(V_r/V_0) - \Delta\phi_0/\pi| \quad 17$$

In a real system, these performances will be reduced, due to :

- the departure from perfect linearity and the limited stability of the buncher and debuncher voltages, the transit-time factors and the phase tails if not cured by a chopper;
- the geometrical aberrations in the transfer line which always increase the length of the trajectories for non axial particles;
- the geometrical and magnetic aberrations of the analyser which increase the radial beam width at the slit : a sextupole can afford a rather good compensation;
- space charge effects (transversal and longitudinal) if any.

2.2-The choice of the transfer line :

We can imagine various transfer line configurations, the two extreme cases being :

- a straight drift (in this case $L_e = L_r = L$). More generally we can consider in this first category any achromatic transfer line, the beam itself being achromatic at its entrance : a line with $L_e/L_r < 1$ is of course very interesting;

- an isochronous transfer (in this case $L_e = 0$), for instance the $n-1$ first periods of a n sector isochronous ring. In this case the initial beam has to be bunched in a phase width $\Delta\phi_c < \Delta\phi_0 - \delta\phi$. It has also to be correctly matched and correlated at the entrance of the system. This special case is not considered in this paper, but the related formulae are easy to find.

2.3- First order results :

The first order results, for the simplest case of a straight transfer line $L_e = L_r = L$, are illustrated by the curves on figure 2. All these curves are related to the same longitudinal emittance : $\Delta\phi_0/\pi = 0.75$ (which corresponds to the linear part of the buncher and debuncher voltages : $\Delta\phi_0 = 135^\circ$) and $\Delta w_0/w_0 = 2.10^{-4}$. The ratio $e_0/C_d = 4.10^{-4}$ corresponds for instance to an analyser characterized by $C_d = 2$ m and to a value $e_0 = 0.8$ mm for $E_x = 30 \pi$ mm.mrad.

Figure 2 : First order characteristics of a $L_e = L_r = L$ separator.

$|\delta E / \epsilon_0|_{\min}$ for $e_0 / C_d = 0, 4, 8 \cdot 10^{-4}$, $|\delta E / \epsilon_0|_{\max}$ for $L / \beta \lambda = 50, 100, 150, 200, 250$ and $\Delta w_c / w_0$ versus $(L / \beta \lambda)(V_r / V_0)$: $\Delta \phi_0 / \pi = 0.75$, $\Delta w_0 / w_0 = 2 \cdot 10^{-4}$.

It is obvious that the values $(L / \beta \lambda)(V_r / V_0) > \Delta \phi_0 / \pi$ are favoured. The working point should in fact be chosen around $(L / \beta \lambda)(V_r / V_0) = 1.5 \Delta \phi_0 / \pi$, then the lowest mass difference which can be analysed will be very close to the value given by 15, about $2\Delta w_0 / w_0$, and the energy dispersion after analysis will not be too high.

The smallest $L / \beta \lambda$, the largest the mass range which can be analysed, but also the higher the voltages to be applied on the buncher and the debuncher.

3. Simulation of the simplest scheme of a straight drift.

As an exemple we performed the simulation of the simplest case of a straight drift ($L_e = L_r = L$), the initial achromatic c-w beam being characterized by :

$$\epsilon_0 = 0.25 \quad ; \quad w_0 = 6.25 \text{ KeV/u} \quad (V_0 = 25 \text{ KV})$$

3.1- The components of the spectrometer :

- The transfer line : we choose a $L = 3 \text{ m}$ straight drift from the buncher to the debuncher centers, the transverse focusing being achieved using 2 magnetic quadrupole doublets placed either between the buncher and debuncher or better, outside of these elements, in order to minimise the geometrical aberrations. This symmetrical system has been optimised using the first order code GALOPR¹⁾. For transverse emittances $E_{x0} = E_{y0} = 30 \pi \text{ mm.mrad}$, the beam half widths at the focal points have been chosen equal to $\Delta x = e_0 = 0.75 \text{ mm}$, $\Delta y = 4.5 \text{ mm}$ and in the simulation will be homothetically varied according to the E_{x0} and E_{y0} values.

The results of GALOPR are shown on figure 3 for the two configurations.

Figure 3 : the 2 versions of mass separator as seen by GALOPR.

(buncher (b) and debuncher (db) either inside or outside the 2 doublets. Horizontal and vertical beam envelopes for an emittance of $30 \pi \text{ mm}\cdot\text{mrad}$ in each plane)

- The buncher and debuncher are supposed to be similar to the ATLAS gridded gap, 4 harmonic buncher where the voltage

$$V = V_m (\sin\phi - 0.4 \sin 2\phi + 0.18 \sin 3\phi - 0.06 \sin 4\phi) \quad 18$$

is practically linear over $\Delta\phi_0 = 135^\circ$. The common frequency has been chosen equal to 50 MHz very close to the one of ATLAS ²⁾).

- The analyser is a double focusing sector magnet characterized by $C_d = 2 \text{ m}$ ($\rho = 50 \text{ cm}$, 90° bending angle, 26.5° rotated faces, $n = 0$, $B = 910 \text{ Gauss}$). Its magnification is -1 between the object and image points located 1 m from the mechanical pole faces. The sector aberrations are corrected by a 0.1 m long sextupole located 0.5 m upstream.

In these conditions $\beta\lambda = 22 \text{ mm}$, $L/\beta\lambda = 136.6$ and choosing (see figure 2) :
 $(L/\beta\lambda)(V_r/V_0) = 0.91 \implies V_r/V_0 = 6.66 \cdot 10^{-3}$ and $V_m = 135 \text{ Volts}$
 we should obtain for $e_0 = 0.75 \text{ mm}$, $\Delta w_0/w_0 = 2 \cdot 10^{-4}$ and $\Delta\phi_0 = 135^\circ$:
 $3.9 \cdot 10^{-4} < |\delta\epsilon/\epsilon_0| < 4.3 \cdot 10^{-3}$, $\Delta\phi_c = 29^\circ$, $\Delta w_c/w_0 = 9.4 \cdot 10^{-3}$

3.2- The conditions of the simulation :

We use our 3D multiparticle code SOSO in the following conditions :

- the initial c-w beam is simulated using test particles uniformly distributed first in a 5D ellipsoid (x, x', y, y', w) and then on the 6th dimension ϕ . In our results the beam half width Δx on a given axis x is always defined as equal to $2\sigma_x$ of the projection of the 6D distribution on this axis,
- the equations of motion are integrated step by step in the field of the dipole which is given on a polar mesh in the median plane, the field components outside of this plane being deduced to first order. In the simulation, the field in the analyser is the one measured on an identical dipole used in the low energy beam line of GANIL,
- the transfers through the quadrupoles and the sextupole are performed using the well known second order matrixes corresponding to thick elements (as given in TRANSPORT³⁾),
- the buncher and debuncher are considered as thin lenses without any transverse effect, this approximation being well justified for gridded gaps.

3.3- The results of the simulation.

3.3.1- The second order effects:

The second order effects due to E_x , E_y on the longitudinal emittance together with the corresponding numerical values are shown on figure 4. The figure displays at the exit of the debuncher and for the two configurations shown on figure 3, the ϕ - w projections of 2000 test particles injected without energy dispersion ($\Delta w_0/w_0 = 0$) in a half-phase width $\Delta\phi_0 = 132.5^\circ$ (linear part of the buncher and debuncher voltages) and with transverse emittances equal to 0, 30, 60, 90 $\pi \text{ mm.mrad}$ in each plane.

These results, which also illustrate the linearity of a voltage as given by 18, show that the effect occurs mostly when crossing the doublets : in fact, the phase width is almost unaffected, it is the energy dispersion which is drastically increased. Moreover, the trajectories of non-axial ions being always longer than the one of the axial particles, the phase of these ions and as a consequence the mean phase ϕ of the bunch are always shifted on the same side as compared to the phase of axial particles.

Since the single-gap gridded buncher and debuncher do not require to be located at a beam waist, they should obviously be placed between the focusing elements, which determines the geometry used in this study.

Figure 4 : effect of the transverse emittance on the longitudinal one. Buncher and debuncher located either between (a) or outside (b) the focusing doublets.

3.3.2- The mass analysis :

Figure 5 displays the ϕ - w projections of the 1000 test particles just after the debuncher action for three beams characterized by $\delta\epsilon/\epsilon_0 = 0$ and $\pm 10^{-3}$. As we do not use any chopper and suppose an initial c-w beam, the effect of the phase tails is well illustrated. This figure also displays the x - x' projections of these beams just in front of the radial slit located at the image point of the spectrometer and here again we see the background due to the phase tails.

Figure 6 gives the mass resolution obtained behind a ± 1.5 mm slit for various initial beam emittances : the parts of the phase tails around $\Delta w/w = 0$ are responsible for the background (2 %) and obviously a chopper would be necessary to obtain a pure beam within the theoretical mass separation.

Figure 5 :The mass separation of c-w initial beams.

$E_{x0} = E_{y0} = 30 \pi \text{ mm.mrad}$, $\Delta w_0 / w_0 = 2.10^{-4}$, 1000 test particles

a) ϕ - w projection just after the debuncher action

b) x - x' projection just in front of the analysing slit

Figure 6 : Number of particles behind a $\pm 1.5 \text{ mm}$ slit for initial c-w beams simulated by

1000 test particles in various emittances as a function of their $\delta \epsilon / \epsilon_0$:

a) $\Delta w_0 / w_0 = 2.10^{-4}$; $E_{x0} = E_{y0} = 0, 30, 60, 90 \pi \text{ mm.mrad}$

b) $E_{x0} = E_{y0} = 30 \pi \text{ mm.mrad}$; $\Delta w_0 / w_0 = 0, 2, 4, 6.10^{-4}$

3.4- Discussion of the results :

3.4.1- The first order theory results compared to the simulation :

In order to make a clear comparison we have introduced a hypothetical chopper selecting an initial $\Delta\phi_0 = 135^\circ$ (75% transmission). In this way the phase tails are eliminated and the beam characteristics obtained at the object and image points of the analyser, before and after the ± 1.5 mm slit, are given in table 1.

$\Delta\phi_0 = 135^\circ$, $\Delta w_0/w_0 = 210^{-4}$, $\delta\epsilon/\epsilon_0 = 0$			
$E_x = E_y$	0	30π mm.mrad sextupole ON	30π mm.mrad sextupole OFF
Δx_{object}	0	0.75	0.75
$\Delta\phi_{\text{object}}$	$39^\circ 86$	$40^\circ 38$	$40^\circ 38$
$(\Delta w/w)_{\text{object}}$	$1.17 \cdot 10^{-3}$	$1.18 \cdot 10^{-3}$	$1.18 \cdot 10^{-3}$
Δx_{image}	1.16 mm	1.46 mm	2.42 mm
slit transmission	98.48 %	96.55 %	78.51 %
$(\Delta w/w)_{\text{after slit}}$	$1.11 \cdot 10^{-3}$	$1.09 \cdot 10^{-3}$	$1.07 \cdot 10^{-3}$
$(\Delta x)_{\text{after slit}}$	1.10 mm	1.33 mm	1.44 mm

Table 1.

At the image point, in front of the slit, the comparison is perfect. For $C_d = 2$ m an energy dispersion $(\Delta w/w)_0 = 1.17 \cdot 10^{-3}$ gives a chromatic dimension $\Delta x_i = 1.17$ mm (compared to 1.16) which, quadratically added to the object $\Delta x_0 = 0.75$ mm, results in a first order chromatic dimension at the image point $\Delta x_i = 1.39$ mm (compared to 1.46 when using the sextupole). The sextupole being off we obtain $\Delta x_i = 2.42$ mm, its effect is very important as it gives an almost perfect compensation of the non linear effects.

Behind the ± 1.5 mm slit, the transmission is almost 100 %. We must notice that the slit is larger than $2\Delta x_i = 4\sigma_{x_i}$, this is of course because some ions of the distribution lie at x values greater than 2σ . This effect is still more sensitive on the energy dispersion or on the Δx after the slit which are significantly reduced as can be seen in table 1.

For $E_{x0} = E_{y0} = 30 \pi$ mm.mrad, all the ions having :

$$\delta\epsilon/\epsilon_0 > 5 \cdot 10^{-4} \quad \text{or} \quad \delta\epsilon/\epsilon_0 < -5.6 \cdot 10^{-4}$$

are eliminated. These numbers are to be compared to the first order approximation which predicts a mass selection of $\pm 3.9 \cdot 10^{-4}$.

We can conclude that, for the transfer line and the analyser we have simulated, the first order theory and the simulation are in good agreement.

3.4.2-Interest and limitations of this new kind of mass separator.

On figure 7 we compare the mass selection as given by the system just described to the one obtained when the buncher and debuncher voltages are set to 0, i.e. using only the same analysing magnet. On this figure we also display the results obtained if one uses a pure sine wave on the debuncher.

Figure 7 : Number of ions behind the ± 1.5 mm slit versus their difference in charge over mass ratio $\delta E / \epsilon_0$ (1000 test ions injected, $E_{x0} = E_{y0} = 30 \pi$ mm.mrad, $\Delta w_0 / w_0 = 2.10^{-4}$)

— : buncher and debuncher ON, voltages as given by 18
 — : " " " " , pure sine voltage
 - - - : " " " OFF

On this figure we clearly see the gain obtained when using the proposed system : a factor 5 is obtained for the initial beam considered. If the initial beam emittance increases, the selection which is given by a pure magnetic analyser decreases, in this system it remains almost constant as can be seen on figure 6.

The necessity of a prior rough analysis is also evident as, already mentioned, the selection is obtained around discrete values of ϵ_i . In fact, the working range is restricted to the linear part of the buncher voltage ($\Delta\phi_0 = 135^\circ$ corresponds to $|\delta E / \epsilon_0| \approx 5.10^{-3}$ in our case). We also see that the phase shift between two successive ϵ_i is lower than 2π , this is related to the mean energy difference of these two components which has also to be compensated by the debuncher.

The system which is proposed presents the following characteristics :

- it is very simple and should not be too expensive,
- it has a wide transverse acceptance, up to 100π mm.mrad,

- its tuning is quite simple and just moving the phase of the debuncher voltage (this is better than changing the magnetic field of the analyser), one can bring in front of the slit the successive kinds of ions,

- at the output of the system the beam is bunched and radially dispersed, a second magnet identical to the analyser can make again the beam achromatic, that is, well suited to the injection line of a radiofrequency accelerator (cyclotron or linac). Of course the beam energy dispersion is increased, but just as it would be for bunching in the same phase width using a conventional bunching system, and the transmission is not worst than the capture. In the case of a variable frequency cyclotron (or linac), the buncher and debuncher have to be operated at the same frequency as the accelerator or at a subharmonic. Variable frequency linear bunchers are proposed by Texas A&M ⁴⁾ and Lanzhou ⁵⁾,

- it is well suited to beams having a small energy dispersion and, in the version which has been analysed, to rather low energies (the voltages to be applied on the buncher and debuncher increase with the energy, we can also play with the frequency, if not determined by an accelerator, or with the length of the drift). Such a device should be quite efficient with a large emittance ion source especially when producing radioactive ions using the ISOL method,

- as already explained it may require a crude ϵ analysis in front,

- the problem of the tails has to be solved, but, it is not worse than in the other kinds of spectrometers.

4. Conclusion.

We have proposed a new kind of wide acceptance mass separator. In the simplest version which has been analysed in this paper, it seems to be very competitive as compared to the other systems used today.

As already mentioned, it should be interesting to study more sophisticated transfer lines such that $L_e < L_f$ and even an isochronous transfer ($L_e = 0$).

In SPIRAL, the radioactive ion beam facility under construction at GANIL ⁶⁾, we propose to use such a mass separator between the E.C.R radioactive ion source and the injection line of the post accelerator (a variable energy compact cyclotron). It will allow :

- to be sure that the required ions are produced in the target-E.C.R system, to be able to optimise the yield and to monitor the production using a spare high intensity ion species,

- to inject into the very low energy injection line and in the postaccelerator as clean as possible a beam, thus reducing many problems related to the tuning of a composite beam and to the distributed losses of unwanted particles,

- if required, to feed a very low energy experimental site with another kind of spare ions.

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