BEAM STRIPPING EXTRACTION FROM THE VINCY CYCLOTRON

by

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Received on March 2, 2006; accepted in revised form on April 7, 2006

The extraction system of a cyclotron guides an ion beam from a spiral acceleration orbit, through an extraction trajectory, into a high energy transport line. The two methods commonly used to direct an ion into the extraction path are deflection, by the electric field of an electrostatic deflector, and ion stripping, by a thin carbon foil. Compared to the electrostatic deflector system, the stripping extraction provides a fast and easy change of the extracted ion energy and is easier to manufacture, operate, and maintain. However, the extraction trajectory and dynamics of an ion beam after stripping are highly dependant on the ion energy and specific charge. Thus, when a multipurpose machine such as the VINCY Cyclotron is concerned, it is far from easy to deliver a variety of ion beams into the same high energy transport line and at the same time preserve a reasonable compactness of the extraction system. The front side stripping extraction system of the VINCY Cyclotron provides high (~70 MeV) and mid (~30 MeV) energy protons, as well as a number of heavy ions in broad energy ranges. The back side stripping extraction system extracts low energy protons (~18 MeV) and enables their simultaneous use with high energy protons at the front side of the machine.

Key words: cyclotron, extraction system, ion beam, cyclotron design

INTRODUCTION

Ion beams are extracted from a multipurpose cyclotron using one of the two devices: an electrostatic deflector or a thin foil. In an electrostatic deflector, a strong electric field deflects a beam from its cyclic acceleration orbit into an extraction orbit which then takes the beam out of the cyclotron. The deflecting electric field, *i. e*. the voltage on the electrostatic deflector electrodes, is adjusted according to the energy of the passing beam; therefore, the device is applicable only if the last two accelerating turns with energy difference corresponding to energy gain per turn do not overlap. However, at large radii, accelerating turns usually overlap. Thus, the design of the extraction system with the electrostatic deflector must include turn separation prior to the extraction.

When passing through a thin foil, an ion looses some of its electrons. Thus, after the foil, positive ions have larger specific charge, while negative ions change the sign of their charge and become positive. In a magnetic field, the change of the ion's sign changes the direction of the rotation, while the increase of the specific charge is manifested as a decrease of the rotation radius (see fig. 1).

In a cyclotron, the interaction between an ion beam and a foil takes place in the magnetic field which provides the rotational component of the accelerating orbit. Due to the presence of the magnetic field, the change of the specific charge of the ion caused by the foil results in the change of the ion orbit after the foil, as illustrated in fig. 1. This effect is used to extract an ion beam from a cyclotron. After the foil, a negative ion leaves the cyclotron because of the change of the direction of its rotation. A positive ion has a smaller orbit radius after the foil than before it, and therefore, before exiting the cyclotron, makes at least one more loop (see fig. 2). Ions are defined as positive or negative according to their sign before the interaction with the foil.

Scientific paper
UDC: 539.1.06:621.384.6
BIBLID: 1451-3994, *21* (2006), 1, pp. 21-28

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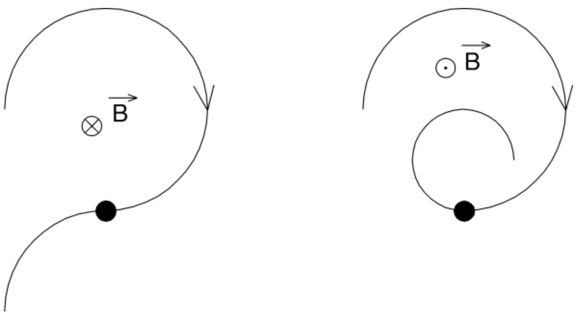

Figure 1. Interaction between ion and foil in homogeneous magnetic field

A negative ion (left) after the interaction with a foil becomes positive and changes the direction of its rotation. The specific charge of a positive ion (right) is larger after the foil than before the foil. Consequently, the radius of the ion rotation is smaller after the foil than before the foil

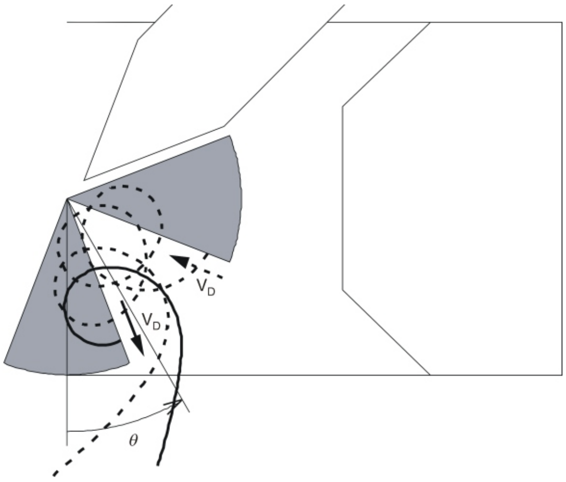

Figure 2. Positive ion interaction with a foil in cyclotron

The magnetic field of a cyclotron is not homogeneus, therefore the ion behavior after its interaction with the foil depends on the foil position. The sector edge gradient causes outward (solid line) or inward (dashed line) drift of a loop V_D. Consequently, after the interaction with the foil, an ion makes one or more loops before it exits the cyclotron. If the foil is placed at small θ's, the outward drift helps the extraction and an ion makes a single loop. For foil positions at large θ's, the inward drift acts on the first loop and causes the appearance of the second loop. If the foil is positioned at even larger θ's, the inward drift acts on the second loop as well and an ion makes the third loop (dashed line). The zero and the positive direction of the azimuthal coordinate shown are used throughout the paper. Due to the axial symmetry, only a half of the yoke, one radiofrequency resonator and two sectors of the VINCY Cyclotron are shown

BEAM EXTRACTION FROM A CYCLOTRON

A stripping foil is commonly used to extract a negative ion beam from commercial cyclotrons, as well as from machines intended primarily for scientific researches [1, 2, 3]. Compared to the electrostatic deflection method, ion stripping extraction has several advantages. The stripping foil extraction, unlike the extraction with the electrostatic deflector, does not require the separation of the last two acceleration turns prior to the extraction. The energy of the extracted beam is easily changed simply by adjusting the parameters of the stripping extraction system, while all other operating parameters of the machine remain unchanged. Beam energy is decreased by decreasing the radial position of the stripping foil. This method can be used to continually change the extracted beam energy, or to extract two beams with different energies, corresponding to the two stripping foils placed at proper radial positions. The efficiency of the negative ion beam's extraction can be as high as 99.9 %.

The specific charge of a positive ion beam after its interaction with the foil is not unique. The distribution of the ion specific charge after the foil depends on ion energy and atomic mass [4, 5]. Ions with different specific charges are spread in space due to the magnetic field influence, thus only a part of the beam corresponding to a single charge state can be extracted from a cyclotron. It is to be expected that the quality of an extracted positive beam will deteriorate along the loops the beam makes after the foil, since the magnetic field of a cyclotron is not designed for such motion. The extraction of a beam that makes more than one loop after the foil should be avoided. The interaction between the beam and the electric field of the acceleration gaps after the foil is also to be avoided, since the beam and the electric field are synchronized only during acceleration. To avoid acceleration gaps after the foil, the loop after the foil must have a sufficiently small radius. Parameter K, defined as the ratio between the ion orbit radius before and after the foil, *i. e.* the ratio between the specific charge of the ion after and before the foil, must be larger than 2. Therefore, the stripping extraction of positive ions from a cyclotron is applicable to heavy ions whose charge before the foil is not larger than approximately $A/2$, where A is the ion atomic number. Regardless of the mentioned disadvantages, the stripping extraction of positive ions is particularly useful for multipurpose cyclotrons.

EXTRACTION SYSTEM

The stripping extraction system of a cyclotron consists of the foil, mechanism for foil positioning and exchange and magnetic elements for the focusing and bending of the extracted beam. The foil is usually made of carbon and its size is of the order of 2 2 cm. Foil thickness and lifetime depend on the type and energy of the ion beam that is being extracted by the foil.

Each of the desired ion beams has a corresponding foil position which takes the beam out of the cyclotron. The operating area of the mechanism for foil positioning and exchange should cover, if not all, than as many as possible foil positions corresponding to the desired ion beams. The construction of the stripping foil mechanism is usually complicated by the operating conditions of the mechanism (vacuum, cooling) and geometric limitations inside and outside the cyclotron (placements and sizes of sectors, valleys, beam orbits, correction coils power connections, vacuum chamber, magnetic structure of the cyclotron, radiofrequency resonators, *etc.*)

Magnetic elements are usually passive elements placed inside a cyclotron or active electromagnets positioned outside the vacuum chamber of a cyclotron. In the case of a multipurpose machine, it is better to use active elements, because their focusing and bending characteristics can be adjusted to different ion beams. During the designing of the extraction system, each of the magnetic elements used must be defined by its dimensions, placement and range of the focusing magnetic field gradient, *i. e.* bending magnetic field.

DESIGN PROCEDURE

The optimization of a beam extraction system is based on the study of the quality dependence on the parameters that define the system. The parameters that define a system are the required operating area of the stripping foil positioning and exchange mechanism and the parameters of the magnetic elements between the foil and the beginning of the high-energy transport line. A magnetic element is defined by its position, size, maximal bending and maximal focusing characteristics. It can be shown that all the parameters that define a system directly or indirectly depend on the azimuthal coordinate of the beam's exit from the cyclotron's vacuum chamber, θ_e [6]. This parameter is thus refered to as the key system parameter.

The quality of an extraction system is defined by the parameters of the extracted beams. The parameters in question are beam losses, emittances and beam directions at the point of exit from the cyclotron. It would be desirable that no beam losses between the foil and the beam exit from the cyclotron exist. Beam emittances at the exit from the cyclotron define the focusing strength of the magnetic elements, thus they should be as small as possible. Also, in order to avoid losses along the transport line, beam emittances should be smaller than the high-energy transport line acceptances. The angular spread of the desired beams at their point of exit from the cyclotron defines the bending power of the magnetic elements. If the direction of the high-energy transport line is not preset, this angular spread is used to define the optimal direction of the transport line.

The above mentioned beam parameters indirectly define the quality of the extraction system, thus their dependence on the constructional parameters of the system should be investigated. The study of these dependencies and resulting conclusions based on optimal solutions are significantly simplified if the constructional parameters used as arguments are properly chosen. It can be shown that the best choice for an argument is a single constructional parameter of the system – the key system parameter, θ_e [6].

The suggested method of beam extraction system optimization consists of the following three steps. First, the range of possible beam exit point positions is defined for each of the desired beams. The exit points are then weighed by the quality of the extracted beams they provide. Finally, for the determined optimal exit point, the optimal direction of the transport line is determined. In all graphical representations of the dependencies used to illustrate this procedure, the VINCY Cyclotron is used as an example [7, 8].

The radial coordinate of the beam exit point from the cyclotron is defined by the vacuum chamber size and is 1.6 m. Therefore, the beam exit point from the cyclotron is uniquely defined by its azimuthal coordinate, θ_e. When beam extraction from a cyclotron by a stripping foil is concerned, different beams behave approximately the same if their K parameters and mean orbit radii before the foil, R_m are equal [6]. Thus, these two values divide the desired beams into classes that are each represented by a single test beam. Figures 3 and 4 give the dependence of the beam's exit point on the position of the stripping foil for different beam classes. Similarly to the beam's exit point, the stripping foil position is also uniquely defined by its azimuthal coordinate, θ_f. The foil is placed along an equilibrium orbit which is defined by beam energy, *i. e.* the mean radius of the orbit.

Figure 3 shows the dependence of the beam's exit point on the stripping foil position for different values of parameter K. The mean radius of the orbit along which the foil is positioned is the same for all four curves and is equal to the maximal value of 86 cm. For negative ion beams ($K = -1$), the shown dependence increases. For positive beams, the dependence is more complex and has local maxima. The number of local maxima on the curves increases with the increase of K. The "hoops" on a curve correspond to different number of loops an ion makes after the foil, before exiting the cyclotron. The most left "hoop" on a curve corresponds to a single loop extraction. Each consecutive "hoop" corresponds to the number of loops increased by one. The position and the width of a "hoop" depend on sector width [6].

The dependence of the beam exit point on foil position for different mean orbit radii, *i. e.* ex-

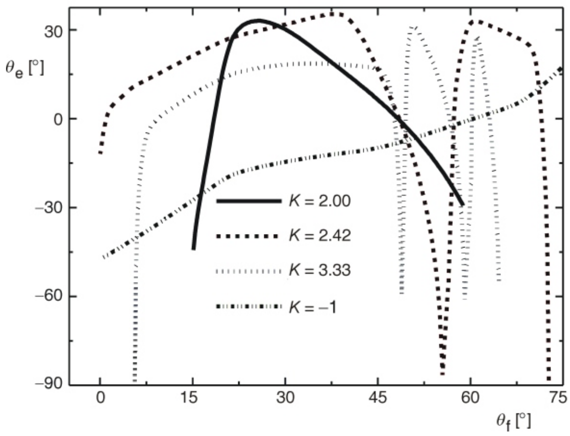

Figure 3. Extraction of beams with maximal energy

For each value of K there is an upper limit for the azimuthal position of the beam exit point, θ_e, defined by the maximum of the corresponding curve. In a given exit point, a beam with a desired value of K can arrive from more than one foil positions, θ_f. For example, for $\theta_e = 0$ a beam with K = 3.33 can have one of the six values of the foil positions. Since larger values of θ_f correspond to multiple ion loops after the foil, only the stripping foil positions with the two lowest values of θ_f should be considered

tracted beam energies, is shown in fig. 4. The example shown corresponds to all ion beams whose specific charge ratio value after and before the foil is $K = 3$.

Mechanical and geometric limitations must be taken into account when defining the position of the beam exit point from a cyclotron. In figs. 3 and 4 these limitations can be represented as restricted zones for foil position, as well as for the exit point position. For example, in the case of the VINCY Cyclotron, the exit point position is limited to the range $\theta_e \in [-17.5°, 17.5°]$ defined by geometric limitations, *i. e.* by the placements and dimensions of the cyclotron magnetic yoke, radiofrequency resonators and the vacuum chamber door. The limiting vertical space between sectors makes the construction of foil positioning and exchange mechanism difficult, so some or all of the foil positions that are placed over a sector may be unavailable. Therefore, the areas that should be entered with caution coincide with the angular spread of the sectors, that is $\theta_f \in [-21°, 21°]$ and $\theta_f \in [69°, 111°]$.

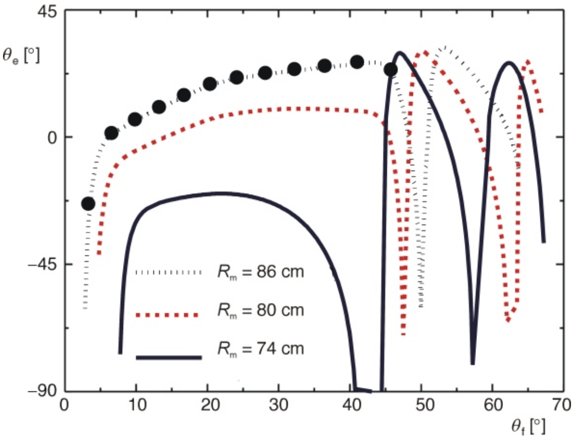

Figure 4. Extraction of positive ions with energies smaller than the maximal

The local maximum corresponding to a single loop extraction decreases with the decrease of the mean orbit radius, i. e. ion energy. The example corresponds to K = 3. The data points on the curve corresponding to the largest mean orbit radius are used as input parameters for beam extraction simulations. The results of the beam dynamics simulations are shown in fig. 5

Results shown in figs. 3 and 4 are obtained by the simulation of test ions trajectories. To study the quality, *i. e.* the efficiency of beam extraction, the dynamics of a test beam instead of a test ion should be simulated. The initial position of the central ion in a beam, used as an input data in these simulations, corresponds to the foil positions marked with dots in fig. 4. As a measure of the quality of an extracted beam, squared emittance, ε^2, defined as a product of horizontal and vertical beam emittances at the exit from the cyclotron, $\varepsilon^2 = \varepsilon_h \varepsilon_z$, is used. In fig. 5, the dependence of this variable on the beam exit point position is shown.

The dependencies shown in figs. 3, 4, and 5 reveal that beam dynamics in the extraction region of a cyclotron also impose limitations on beam exit point positions. The upper limit for θ_e is defined by the local maximum corresponding to the extraction with a single loop after the foil (see figs. 3 and 4). If a beam makes more than one loop after its interaction with the foil, beam losses are large, *i. e.* extraction efficiency is small, which therefore signals that multi-loop extraction should be avoided. Some beams need to be extracted from a cyclotron not only without losses, but with small exit emittance as well. The dynamics of these beams determine the minimal value of θ_e (fig. 5).

The increase of square emittance for two to three orders of magnitude shown in fig. 5 is the consequence of the sector edge defocusing effect illustrated in fig. 6. Thus, the loop a beam makes after the foil should be placed away from the sector edges. Negative ion beams extracted from the maximal radius and radii close to the maximal radius travel only a short distance between the foil and the exit point. Along this distance, they experience the influence of the pole edge magnetic field gradient, which in this case has a focusing effect. The quality of these beams is good and does not depend on the mean orbit radius; therefore, the beam dynamics study for high-energy negative ions is not shown.

The shape of the curves shown in fig. 4 indicates that geometric limitations also define the minimal obtainable energy of a positive ion beam

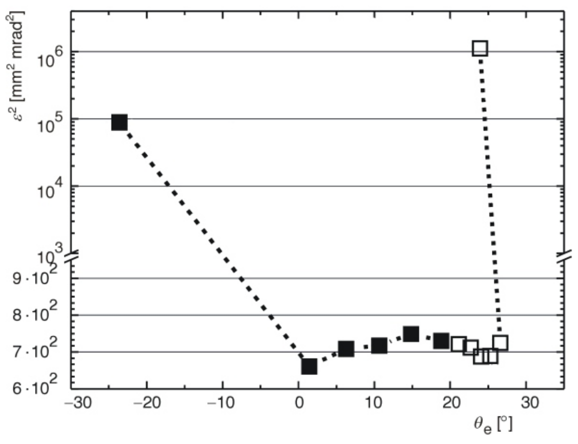

Figure 5. Square emittance

The abrupt deterioration of the beam quality manifested as the increase of the square emittance is caused by the magnetic field gradient at the sector edges [6]. The value of the square emittance between the sudden increases does not depend much on the K parameter, while the width of this region decreases with the decrease of K. The solid symbols correspond to the foil positions over the sector, while the open symbols depict foil positions in the valley. The example corresponds to $K = 3$ *and* $R_m = 86$ *cm*

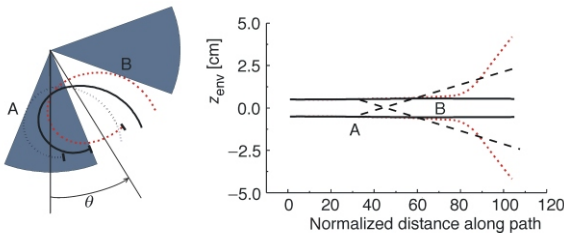

Figure 6. Defocusing by sector edges.

If a beam travels along a sector edge, the magnetic field gradient present in this region acts upon the envelope of the beam. In region A, the direction of the test beam trajectory and the sector edge gradient are such that the resulting effect on the vertical beam envelope, z_{env}*, is focusing. However, the remaining length of the trajectory before the exit from the machine is long and focusing becomes over focusing. Along the sector edge B, the vertical beam envelope is defocused*

through the lower limit of the beam extraction point position. The monotonous growth of the curve corresponding to a negative ion beam in fig. 3 suggests that, for a negative ion beam, there is no lower limit for extracted ion energy. This implies that the stripping foil method can successfully be used to simultaneously extract high energy ions from the maximal mean orbit radius on one side of the cyclotron and low energy ions from a low mean orbit radius on the other side of the machine. The operating regime of the machine remains the same, while the desired beam is chosen simply by inserting the stripping foil to the proper position. The accelerated negative ion beam is H^- and the two extracted beams are proton beams. Figures 7 and 8 illustrate the study of low energy negative ion extraction.

For the small values of parameter K, the radius of the loop a positive beam makes after the foil is too large and sector edges can not be avoided. If such a beam is among the required beams, the focusing magnet should be placed as close as possible to the defocusing region along the beam trajectory, which corresponds to the beam's exit point. When a multipurpose cyclotron is concerned, there is usually more than one beam that requires focusing at the exit point, thus the focusing magnet must have an adjustable magnetic gradient.

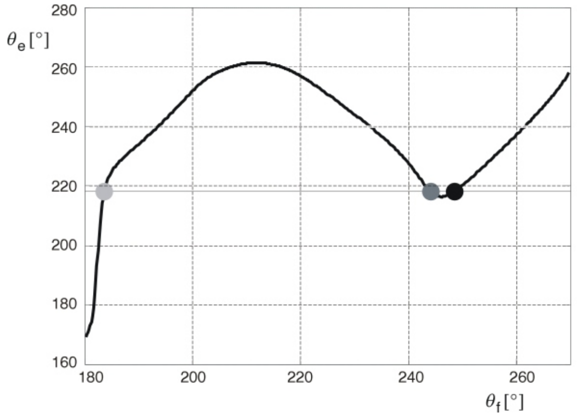

Figure 7. Negative ion extraction from low mean orbit radius

The monotonous growth of the exit point position dependence on stripping foil positions for ion energies and extraction radii close to their maximal values, changes into the shown dependence for small extraction radii. The local maximum and minimum for the range of exit point positions between them provide three foil positions corresponding to a single exit point position. The beam path between the foil and the exit point is not short as was the case for high-energy beams, so the beams may encounter negative influence of sector edges. The quality of the beam and the dependence shown can impose an upper or a lower limit on the exit point position. To clear up the uncertainty about beam quality, three test trajectories corresponding to the exit point position of 218° are shown in fig. 8. The shade of the data point and the corresponding test trajectory in fig. 8 is the same

Beams extracted from a multipurpose cyclotron at an exit point have different exit directions. Nevertheless, they should all continue to travel through the same high-energy transport line. This is achieved by adding an adjustable bending component to the magnet, positioned at the beam's exit point from a cyclotron. A magnetic element with adjustable focusing and bending characteristics is called a combined magnet, because the bending magnetic field and the focusing magnetic field gra-

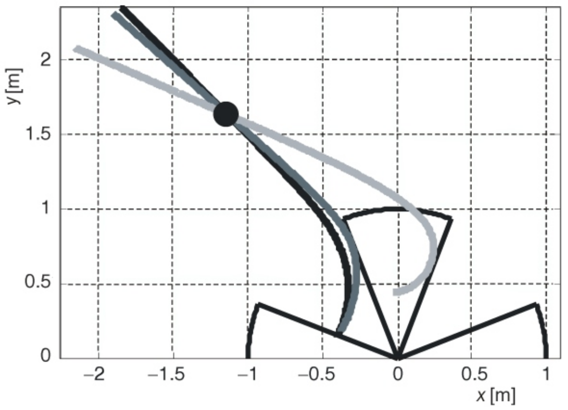

Figure 8. Test trajectories of negative ions extracted from low radius

The test trajectories depicted in light-gray and dark-gray travel along a sector edge, their envelopes are defocused and thus the foil positions corresponding to them are not a good choice. The use of the foil position corresponding to the black test trajectory and the like introduces a lower limit to the exit point position for a given test ion energy (see fig. 7). Once the exit point position is fixed, it sets the lower limit for the obtainable energy of the extracted beam

dient are combined and adjusted to successfully manage each of the required beams. The introduction of the combined magnet significantly improves the quality of the extracted beams and the compactness of the extraction system. It enables unidirectional stripping extraction and decreases the number of magnetic elements needed in an extraction system [9]. If the direction of a high-energy transport line is not predefined, the angular spread of the beams' directions at the exit point is used to determine the optimal direction of the transport line. The transport line direction is optimized by minimizing the required bending magnetic field using the equation $B_b = \text{const}\,\Delta\varphi/K$, where B_b is the bending magnetic field needed for a particular beam and $\Delta\varphi$ is the difference between the beam direction and the transport line direction at the exit point.

All the examples shown are the results of test ion trajectories and test beams dynamics studies. The simulations of test ion trajectories and ion beam dynamics were performed using VINDY, a self-made software package [10].

RESULTS

The described procedure of the stripping extraction system design and optimization has been applied to the VINCY Cyclotron. The machine has two foil stripping extraction systems – the front and back ion beam extraction systems [10]. The front side system enables the extraction of light and heavy ions that have a low charge state during acceleration. These beams are further transported to channels for the production of radioisotopes and for radiation research. The test beams for the front extraction system are the 65 MeV proton beam accelerated as the H^- beam, the 30 MeV proton beam obtained as a result of the interaction between the foil and the H_2^+ beam, the 28 MeV $^4He^{2+}$ beam obtained from the $^4He^+$ beam and the 120 MeV $^{40}Ar^{15+}$ beam obtained from the $^{40}Ar^{6+}$ beam. The operating regime of the machine is adjusted so that the beams reach the required energies at the radius of 84 cm. The acceleration regime corresponding to the 65 MeV H^- beam is also used to obtain 15 MeV protons at the back side of the machine, using the back side extraction system. This beam is used to produce the radioisotope ^{18}F in the shielding vault of the machine. Among the beams required at the front side, protons originating from H_2^+ and $^4He^{2+}$ originating from $^4He^+$ have $K = 2$. The loop these beams make after the foil is large, defocusing by sector edges can not be avoided, and they, therefore, require immediate focusing after they leave the cyclotron. Also, the direction of each of the four test beams has to be adjusted to the preset transport line direction. Thus, the magnetic element placed at the beam's exit point is the combined magnet, because it must have focusing as well as bending capabilities.

The geometry of the machine restricts the placement of the beam's exit point to the region $\theta_{ef} \in [-17.5°, 17.5°]$ and $\theta_{eb} \in [213°, 220°]$ for the front and back side, respectively. The study of beam quality sets the positions of beam exit points to $\theta_{ef} = 9.5°$ and $\theta_{eb} = 215.5°$. The simulations of the test beams dynamics define the parameters of the combined magnet. The effective size of the magnet is $D_h = 260$ mm, $D_z = 120$ mm and $L = 1000$ mm, where D_h, D_z, and L are the horizontal and the vertical aperture, and the length of the magnet. For test beams, the required bending component of the magnetic field is ±200 mT. The maximal value of the required focusing gradient is 1.1 T/m. The required operating areas of the stripping foil mechanism are defined by the corresponding radial and azimuthal ranges $\Delta R_{ff} \in [800\text{ mm}, 860\text{ mm}]$, $\Delta\theta_{ff} \in [12°, 52°]$, and $\Delta R_{fb} \in [390\text{ mm}, 470\text{ mm}]$, $\Delta\theta_{fb} \in [245°, 255°]$, for the front and back side, respectively. The scheme of the machine and the extraction systems, as well as the test ion beams, are shown in fig. 9.

CONCLUSION

While designing a complex system, methods of linear and non-linear programming are often not sufficient for finding the optimal solution. The number of requirements and limitations, as well as the number of complex relations between them, is large; some of them can not be quantitatively described by a variable and the introduction of weighing coefficients in order to rank them by importance is not easy.

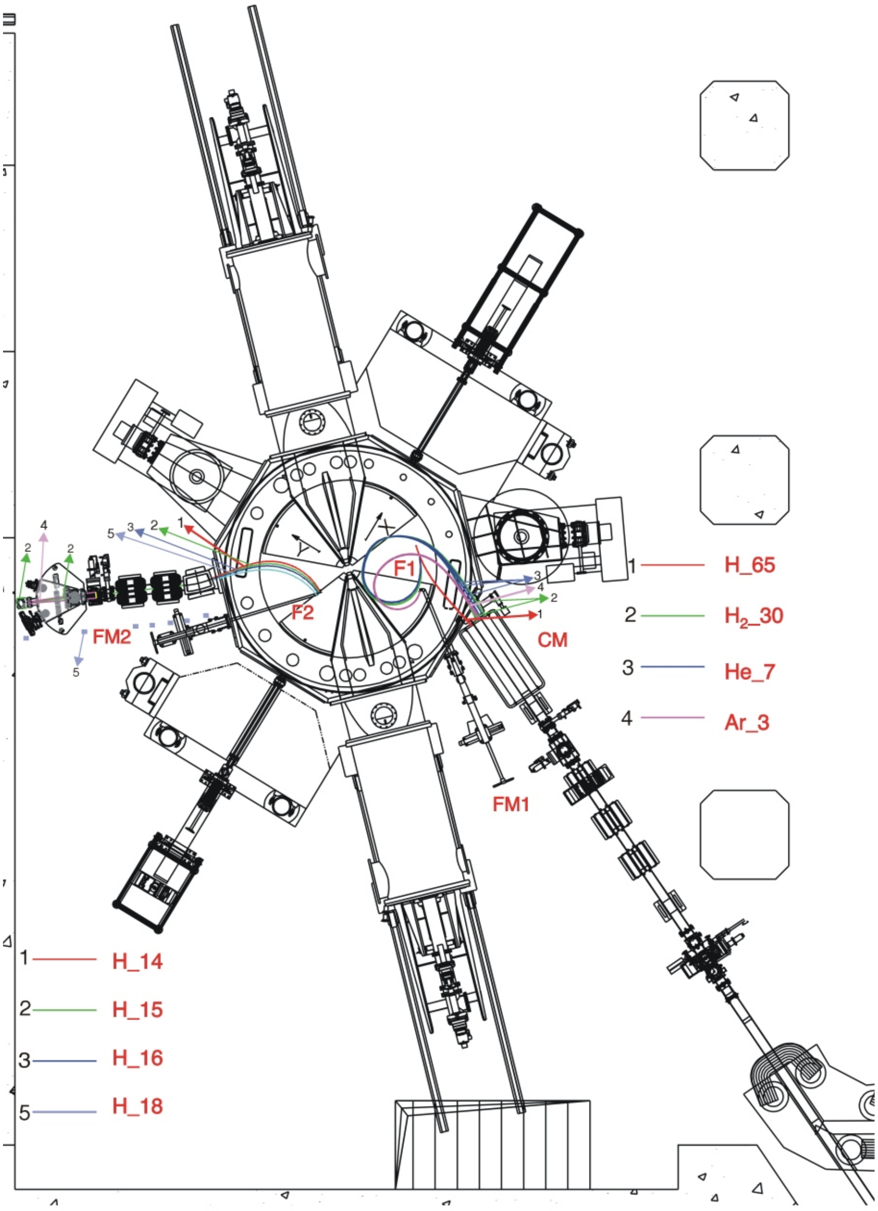

Figure 9. Scheme of the VINCY Cyclotron stripping extraction systems

The front side extraction system: stripping foil, F1, stripping foil mechanism, FM1 and combined magnet, CM. The back side extraction system: stripping foil, F2, stripping foil mechanism, FM2. Also shown are the test beams. On the front side 65 MeV per nucleon H, 30 MeV per nucleon H_2*, 7 MeV per nucleon He, and 3 MeV per nucleon Ar extracted from the equilibrium orbit with* $R_m = 84$ *cm are shown. As expected, the test beams originating from* H_2^+ *and* $^4He^+$ *ions behave similarly because they have the same value of* $K = 2$*. On the front side, the adjustment of the extracted ion energy by the stripping foil position is illustrated. Trajectories of the four test H ions with energies 14, 15, 16, and 18 MeV per nucleon are shown*

The suggested method of optimization for the stripping foil extraction system consists of three steps. Firstly, the range of possible values of the key parameter – the beam's exit point from a cyclotron, θ_e, is determined for each of the desired beams. Results similar to those shown in figs. 3 and 4, as well as geometric and mechanical limitations, restrict the foil and exit point positions. Exit point positions are then associated with a quality measure that serves to choose the optimal exit point. The beams must be extracted from the cyclotron with high efficiency; therefore, after the interaction with the foil, they should make only one loop before they exit the cyclotron. Similarly, the upper limit of θ_e is determined by the minimal of the local maxima corresponding to a single loop extraction. For some of the beams, the quality criterion is not only high extraction efficiency, but small exit emittance, as well (fig. 5). Finally, for the chosen optimal beam exit point, the optimal direction of the transport line is determined. Test ion trajectories and beam dynamics simulations used during the designing process were performed with a self-made software package, VINDY.

The suggested method has been applied to the designing of the two stripping extraction systems of the VINCY Cyclotron – the front and back side extraction systems. The compactness of the front side extraction system and the quality of the beams it extracts are significantly improved by introducing the combined magnetic element.

The front side system is designed to accommodate the extraction of light, as well as heavy ion beams. The two systems enable simultaneous use of the same operating regime of the machine, corresponding to high energy H$^-$ for the extraction of high energy protons at the front side and low energy protons at the back side of the machine.

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ИЗВОЂЕЊЕ СНОПА ИЗ ЦИКЛОТРОНА VINCY УЗ ПОМОЋ ФОЛИЈЕ

Екстракциони систем циклотрона води јонски сноп од убрзавајуће орбите кроз екстракциону путању до високоенергетске транспортне линије. Два уобичајена метода за увођење снопа у екстракциону путању су скретање електричним пољем електростатичког дефлектора и љушћење електронског омотача јона уз помоћ танке фолије од угљеника. У поређењу са системом са електростатичким дефлектором екстракциони систем са фолијом омогућава брзу и лаку промену енергије изведеног снопа, лакше га је направити, њиме руковати и одржавати га. Међутим, екстракциона трајекторија и динамика јонског снопа после фолије веома зависе од енергије и специфичног наелектрисања јона. Зато у случају вишенаменске машине каква је Циклотрон VINCY није нимало лако спровести различите јонске снопове у исту високоенергетску транспортну линију и у исто време обезбедити да систем за извођење буде компактан. Предњи екстракциони систем са фолијом Циклоторна VINCY изводи протоне високих (70 MeV) и средњих (~ 30 MeV) енергија као и читав спектар тешких јона из широког енергетског опсега. Задњи екстракциони систем са фолијом изводи нискоенергетске протоне (~18 MeV) и омогућава њихово истовремено коришћење са високоенергетским протонима изведеним са предње стране машине.

Кључне речи: циклотрон, екстракциони систем, јонски сноп, пројект циклотрона