MOTION OF CHARGED PARTICLES THROUGH A BARRIER CREATED BY NON-UNIFORM MAGNETIC FIELD WITH AND WITHOUT RADIAL ELECTRIC FIELD

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By numerical calculation a motion of one charged Ar, Kr, Xe ions through the magnetic field barrier was studied ($H_{max} \sim 1\,kG$). It was shown that propagation and reflection of the ions is determined by the initial transverse energy of the ions and their masses. Ranges of change of transverse velocities for the particles with different masses that pass through the barrier were evaluated. The influence of direction of a radial electric field that was applied in the region occupied by the linearly decreasing magnetic field, on the particle motion was investigated. It was shown that radial deviation of particles from the axis of symmetry was essentially increased or decreased in comparison to zeroth electric field case depending on the electric field direction. After the particle leaves the crossed-field region the magnitude of its axial velocity can be 1.5...2 times more compared to the starting velocity when the electric field was directed along the radius. Obtained results can be used to minimize the losses of the ions from a particle source by a proper disposition it in the magnetic field and to determine parameters which notably influence beam formation.

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1. INTRODUCTION

Possibility of application of the magnetic field for isotope separation was studied since 1940's. Systems where they are used – electromagnetic separators – permitted to separate isotopes nearly all elements of Mendeleyev's table with proper resolution [1]. In subsequent years regions of application such systems have studied more thoroughly. Electromagnetic separators have widely used for production the high-enriched isotopes of elements with great atomic weights and those which were difficult or impossible to receive by another ways. However, imperfections of electromagnetic separators such as bulkiness, small productivity it has make to search the ways for an improvement their construction and possibilities. The region of application of magnetic fields was broadened in connection with development of plasma methods for isotopes separation [2-7]. Since in plasma a restriction on current magnitude connected with space charge of a beam in vacuum was removed it was expected that these methods along with the proper mass resolution will provide high enough productivity. The magnetic fields that are usually used in such construction are produced by a current flowing in a single coil with multi turn windings or by solenoid. Obtained in such a way axially symmetric configurations of the magnetic field are similar to those for plasma confinement (the magnetic field of mirror trap, picket fence, etc). In present paper the configuration of magnetic field that was shown in [2] will be considered with some simplification (Fig.1). General principles of calculation the magnetic fields like this can be found in books on electron and ion beams [8] (ICR) [5].

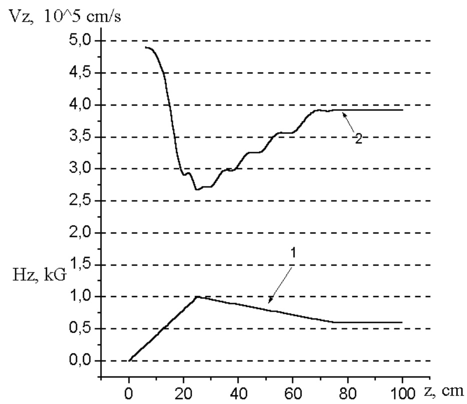

Fig.1. *1 – distribution of H_z component of the magnetic field versus z coordinate. 2 – velocity of v_z – component of Ar ion that pass the magnetic field barrier versus coordinate*

For the calculation of magnetic field and particle motion in this field, as a rule, a cylindrical system of coordinate (r, φ, z) is chosen. This permits to use some advantages of axial symmetry of a given configuration. In the regions where the magnetic field

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rises and falls there are two field-components H_z and H_r. When the distribution of H_z- component on the axis along z coordinate is known one can calculate the components of magnetic field in neighborhood of axis using derivatives of this distribution. In similar configuration different possibilities of isotope separation and selection of single elements were considered (centrifugal separation of elements) because of rotation magnetized plasma column, selective heating isotopes by ion cyclotron resonance.

In [5] an attention was paid that the region with lowered magnetic field permits to increase the efficiency of ICR-apparatus for isotopes separation. Requirements to characteristic of the particle flow sharply differ depending on methods of separation which are used. Therefore, number of questions arise as to an injection of particles in this configuration of the magnetic field, passing the particles through the magnetic field barrier, the influence of the electric field on the motion of particles. The purpose of this work was to investigate the possibilities of the system under consideration for selection the single elements. Similar task arises, for example, during processing of spent nuclear fuel where the elements of some practical interest can be found. In connection with solution of these tasks a mathematical model including a system of equations of motion and the magnetic barrier of a given form was constructed and some calculations of trajectories of particles passing the barrier were done.

2. FORMULATION OF THE TASK

It is supposed that particle start in the region occupied by the magnetic field. The strength of magnetic field at the particle starting position can be changed by displacement the particle source relative to the barrier so that profile of magnetic field was left without change. The system of equations of charged particle motion in axially-symmetric field can be written in a form:

$$\begin{cases} \ddot{r} - r\dot{\varphi}^2 = er\dot{\varphi}H_z/Mc\,, \\ (1/r)\frac{d}{dt}(r^2\dot{\varphi}) = e(\dot{z}H_r - \dot{r}H_z)/Mc\,, \\ \ddot{z} = -er\dot{\varphi}H_r/Mc \end{cases}$$

with the following initial conditions at $t = 0$, where t is a time, $z = z_0$ is the position of a plane from where the particle start, $r = r_0$ is initial radial displacement of particle from axis of symmetry, $z = \dot{z}_0$, $\dot{r}_o$ and $\dot{\varphi}_o$ are the initial axial, radial and azimuthal components of velocities respectively.

The H_z-component of the magnetic field was approximated by linearly changing functions within zones that were defined in this way:

$$H_z = \begin{cases} 0\,, & if \quad z \le 0\,; \\ H_0 \cdot z/L\,, & if \quad 0 < z \le L\,; \\ H_0(6L - z)/5L\,, & if \quad L < z \le 3L\,; \\ 0.6H_0\,, & if \quad z \ge 3L\,. \end{cases}$$

L is the length of the zone where the magnetic field rises. H_r – component of magnetic field was determined by a condition $div\vec{H} = 0$, with the assumption that H_z – component does not depend on r coordinate like in the case [2]. The distribution of magnetic field that was written above gives possibility to consider particle motion in neighborhood of axis of symmetry first of all.

The system of equations was sold numerically after its transforming into dimensionless form. As the references values were taken: $\nu_0 = \sqrt{2eU_0/M}$ is the axial velocity of particle, where U_0 is an electric potential, e and M are charge and mass of ion respectively, L is the length of the region occupied by linearly increasing magnetic field along z coordinate. The magnetic field rise at the length equal to $25\,cm$ (in some cases $50\,cm$) to maximal value then it fall to nearly half of its maximal value and further stayed constant. Besides, one can change the length of that part of barrier where magnetic field lowed by properly choosing coefficients in distribution of magnetic field (2). After passing the barrier the particle continued its motion in the uniform magnetic field. The motion Ar, Kr, and Xe ions were considered through this barrier. The stable isotopes of these elements with atomic weights $Ar = 40$, $Kr = 84$, $Xe = 129$ were chosen for calculation. Since for the selection of elements it had to process the vast quantities of mixture of elements an energetic expenditure on production of charged components should be diminished. The value of a dimensionless parameter of the system of equations $lt = Mc\nu_0/eH_oL$ was evaluated for ions energy which was equated to $5\,eV$ for every element. This energy is typical for the isotope separation by a plasma centrifuge method, for example. The maximal value of the magnetic field of barrier was equal to $1\,kG$. Cyclotron radii of one charged ions were calculated using initial axial velocity and maximal magnitude of the magnetic field and are equal $r_{Ar} = 2.02\,cm$, $r_{Kr} = 2.94\,cm$, $r_{Xe} = 3.65\,cm$.

A transverse dimension of an experimental chamber where particles are moving is equal $2R \sim 30...40\,cm$. It was assumed that the particle is moving near the axis of symmetry if its displacement relative to the axis is several times less then the radius of the chamber. To satisfy the condition $r_c/R < 1$, where r_c is cyclotron radius of particle, R is radius of chamber, the starting radii of particles were taken in the ranges from $2\,cm$ to $3.5\,cm$. For more precise study the motion of particle near an outer electrode it is necessary to have more detailed distribution of the magnetic field in that region. It was assumed that the transverse energy of particle may reach one half or more of energy of the axial motion ($\varepsilon_\perp \sim \varepsilon_\parallel$). The space charge of ions flowing from the source was neutralized by electrons and collisions in the flow are absent. In next section some results of calculation of the trajectories and velocities of particles different masses will be shown depending on different conditions.

3. THE RESULTS OF CALCULATION OF THE MOTION OF ONE CHARGED IONS THROUGH MAGNETIC BARRIER

The distribution of axial velocity of Ar ion (curve 2), starting from the position $z_0 = 6.25\,cm$ with transverse velocity not equal zero, passing the magnetic field barrier (curve 1) was shown on Fig.1. As can be seen the axial particle velocity is decreasing in the region where magnetic field rises and further the velocity begin to restore in that part of the barrier where the magnetic field was lowered. In uniform magnetic field the particle is moving with constant velocity the value of which was established before its entering the uniform magnetic field. Though a decreasing of transverse dimension of particle orbit moving in increasing magnetic field takes place the rise of the field to a considerable extent is compensated by increasing of the radial velocity. In fact, the distribution of axial velocity is typical for all region of changes of parameters used for calculation. In calculation the starting position of particle (r_0, z_0), the value and direction of initial radial velocity $\pm\dot{r}_0$, a form of barrier were changed. The differences of separate runs only the minimal and settled in uniform magnetic field magnitude of the axial velocity are concern. Variation of ν_z- component of velocity for Ar, Kr, Xe ions passing barrier was shown on Fig.2.

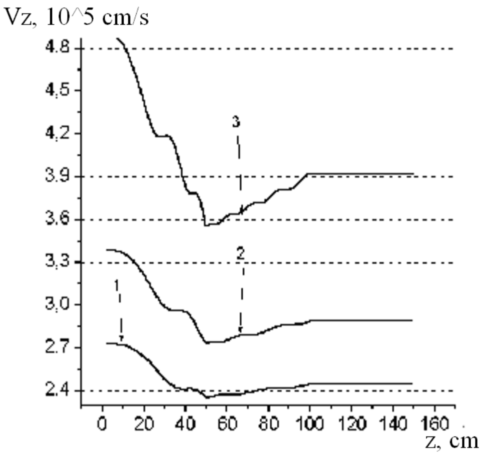


Fig.2. *The velocities of elements 1 – Xe, 2 – Kr, 3 – Ar that pass the magnetic field barrier versus z-coordinate. The initial energy is* $\varepsilon_{\|} = 5\,eV$. *The length of region of increasing magnetic field* $L = 50\,cm$

The length of region with increasing magnetic field was equal $L = 50\,cm$. It follows from the results of calculation that if the initial radial velocities are small (the transverse energy is of the order of a few tenth of one eV) then all elements, which are considered, pass the barrier with small changes of their velocity. In the Table 1 the magnitudes of the least axial velocity of particles starting from the position $r_0 = 0.1$, $z_0 = 0.1$, with the energy of axial motion $5\,eV$, radial velocity $\nu_r = 0.24\nu_0$, passing the barrier, and the velocity settled in the uniform magnetic field was shown.

The magnitudes of least and steady velocity

Element	$V_{min}, L = 1$	$V, L > 3$
Ar	0.87	0.93
Kr	0.89	0.95
Xe	0.91	0.96

The strength of the uniform magnetic field was equal $0.6H_0$. The dimensions which characterize the position of particle and the value of velocity for dimensionless quantities were written. The particle is decelerated considerably more if initial radial velocity is increased and it is reflected at some value of radial velocity in increasing magnetic field of barrier. After a reflection the direction of velocity is changed and the particle begin to accelerate toward the source. In some cases the most part of initial energy of radial motion is transformed into axial energy. The particles with the least mass (in our case Ar ion) begin to reflect the first. The particle usually several radial oscillations to the point of reflection does. The Kr, Xe ions reflect with relatively greater radial velocities. The change of axial component of velocity (curve 1) and radial position (curve 2) along z-coordinate for reflected Ar ion when the value of initial radial velocity was positive and equal 0.55 was shown in Fig.3. The particle started from the position $z_0 = 0.1, r_0 = 0.14$. The calculation with different initial radial velocities shows that there is a limitation on those for passing particles which are differ for each element of given energy.

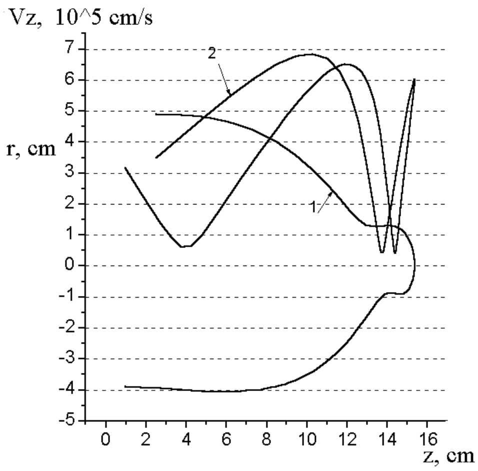


Fig.3. *1 – the velocity change of Ar ion reflected from magnetic barrier with* $L = 25\,cm$. *2 – radial position of Ar ion reflected from magnetic barrier versus coordinate.* $r_0 = 0.14$, $z_0 = 0.1$, $\nu_{z0} = 0.55$

The Ar ions pass through considered barrier if their initial velocities lay within the ranges $-0.7 < \dot{r}_0 < 0.4$, and those for ions of Xe are within the ranges $-0.8 < \dot{r}_0 < 0.55$. From this calculation one should be expect that if an injected flow of particles had initially some spread of the radial velocities then concentration of particles with different atomic weights that were passed through barrier will be differed from their initial content In the case of need to inject through barrier particles with small losses it should be increased the magnetic field in the plane of injection. When particle is injected from the position $z_0 = 0.4$, where the magnetic field is greater, along with Kr, Xe ions begin to pass and Ar ions with $\dot{r}_0 = 0.7$. It is necessary to mark that after passing the barrier the particle continues its motion without circling around axis of symmetry though for particles with great initial radial velocities the minimal deviation of particle trajectory from axis sharply diminishes. Maximal deviation of particle from axis may reach 5...7 cm depending on the initial radial velocity and mass of element.

As the value of the radial component of magnetic field depend on radius decelerating force acting on the particle in the region of non-uniform magnetic field is stronger at the greater radius then near the axis. Therefore, axial particle velocity is non uniformly changed as in linearly increasing magnetic field so in the region where the magnetic field is falling. If the initial radial velocity is great enough (compared with axial one) then after passing the barrier axial velocity is not restore to primary one and the transverse particle energy is increased. For example, for Ar ion starting with initial axial energy $\varepsilon_{\parallel} = 5\,eV$ and transverse energy $\varepsilon_{\perp} = 5\,eV$ after passing the barrier the axial energy was $2\,eV$ and transverse energy was $5.5\,eV$. So the barrier assist to redistribution of axial and transverse energies in the direction of increasing transverse energy. There is also a dependence on the direction initial radial velocity. The value of axial velocity that is settled after passing the barrier is differed for particles starting from the same radius with equal but oppositely directed velocities. In fact, the particles are moving on different trajectories which are not overlapped. Projections of trajectories for two particles (only part of trajectory was taken) were shown in Fig.4.

The value of axial velocity that is settled after passing the barrier in uniform magnetic field depends on the length of zone within of which the magnetic field is reduced to the given quantity. For Ar ion starting with initial velocity $4.9 \cdot 10^5\,cm/s$ in the increasing magnetic field its value was reduced to $1.8 \cdot 10^5\,cm/s$ and after passing the zone of the same length where the magnetic field fall to $0,6H_0$ and further stays constant the velocity is increased to $3.25 \cdot 10^5\,cm/s$. If the magnetic field was reduced more smoothly (the length of zone of decreasing magnetic field was 2...3 times more) the axial velocity was settled $3.67 \cdot 10^5\,cm/s$ and $3.64 \cdot 10^5\,cm/s$ respectively. When magnetic field was reduced to $0.4H_0$ the velocity was settled $4.24 \cdot 10^5\,cm/s$. It is followed from this that by choosing a strength and gradient of the magnetic field one can adjust the value of steady state velocity.

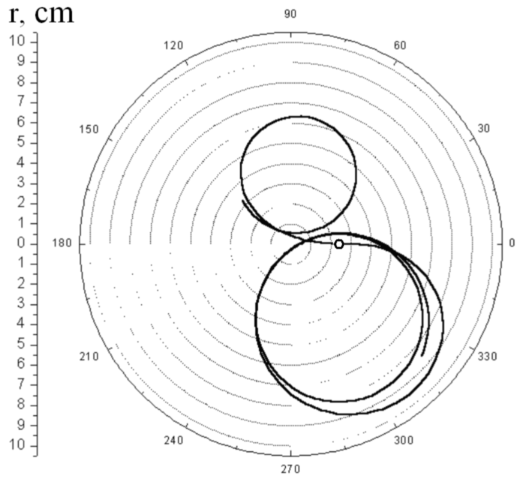


Fig.4. *The projection of a part trajectory of Xe ions, that pass the magnetic barrier with equal initial radial velocities oppositely directed.* $\circ$ *– starting position*

The variation of starting radius in the ranges of $r_0 \sim 2...3\,cm$ do not lead to notable changes in the motion of particles. The differences concerned only the boundary values of radial velocity permitting the particle still to pass the barrier. Difficulty arises when the motion of particles, starting from small radius ($r_0 < 1\,cm$) with great radial velocity, is calculated. The particle passes too close near the axis of the system and it is necessary to improve an accuracy of calculation that lead to increasing of duration of calculation. The strength of the magnetic field at the starting position influenced more noticeably on the ranges of radial velocities that permit the particle to pass the barrier. When the magnetic field is increased the ranges of velocities are widened. A more smooth increase of the magnetic field influences in a similar way. For barrier with magnetic field increasing according $\sin(\pi z/2L)$ $(z < L)$ the Xe ion with initial radial velocity -1 passed. Some notion of the motion of particles with equal masses but different initial radial velocities or particles with different masses and equal initial velocities was shown on Fig.5 for Xe ions and Fig.6 for Ar, Xe ions respectively. In Figs.5 and 6 the region of increasing of magnetic field $L = 25\,cm$ and the region of decreasing is equal $2L$.

The least radial extension of the region where Xe ions were moving is at a location of the magnetic field maximum. The radial extension of the region of particle motion with different radial velocities is growing wider in the uniform magnetic field. As can be seen from Figs.6,a,b the maximal deviation from the axis Ar and Xe ions with equal initial velocities noticeably differ. The value of radial velocity $\dot{r}_0 = 0.5$ for Ar ions starting from $z_0 = 0.1$ position is close to the limit after exceeding of which the ions begin to reflect. When the adiabatic conditions $r_l dH/H_0 dz << 1$ are well satisfied the energy of axial particle motion in non homogeneous magnetic field is defined by a following relation: $\varepsilon_{\|} = \varepsilon_{\|0} - \varepsilon_{\perp 0}(H/H_{st} - 1)$, where H is the magnetic field of barrier, H_{st} is the magnetic field in starting position, and it not depends on mass and gradient of magnetic field.

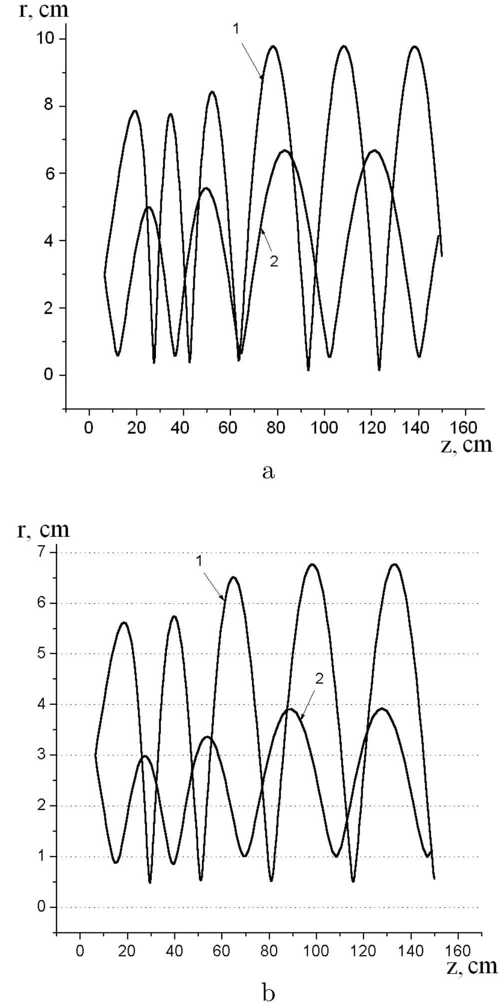


Fig.5. *Radial position Xe ion with different initial radial velocities passing the magnetic barrier:*
a)1 – $\nu_r = 0.5$, 2 – $\nu_r = -0.5$; b) 1 – $\nu_r = 0.3$, 2 – $\nu_r = -0.3$

As it follow from the expression the strength of the magnetic field, that is needed for the particle reflection ($\varepsilon_{\|} = 0$), is defined only by the initial axial and radial energies.

The calculation that was carried out show that for the given barrier and quantities of mass the passing and reflection of particles depends from mass and gradient of magnetic field. One may conclude that for given configuration the adiabatic conditions are badly fulfilled. Summarizing, it should be note that the calculation permitted to find the most important parameters to adjust by the flow of particles passing through barrier. They are the lengths of increasing and falling parts of the magnetic barrier, the relation between the initial radial and axial velocities, the starting position of particles. A new possibility appears to adjust by flow of particles when the external radial electric field is applied.

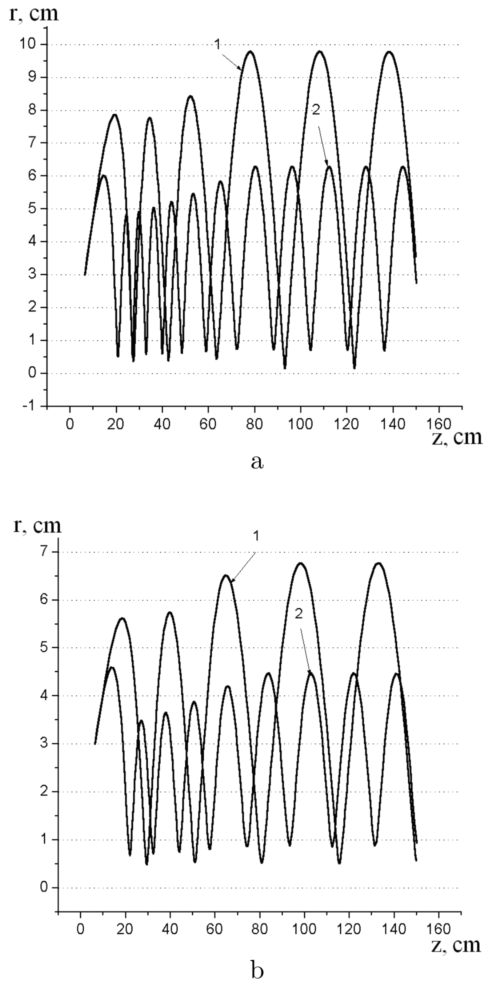
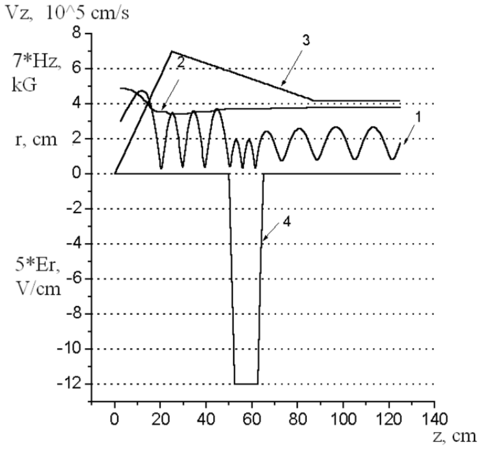


Fig.6. *Radial position Ar and Xe ions passing the magnetic barrier and in uniform magnetic field:*
a)1 – $\nu_{rXe} = 0.5$, 2 – $\nu_{rXe} = -0.5$; b) 1 – $\nu_{rAr} = 0.5$, 2 – $\nu_{rAr} = -0.5$

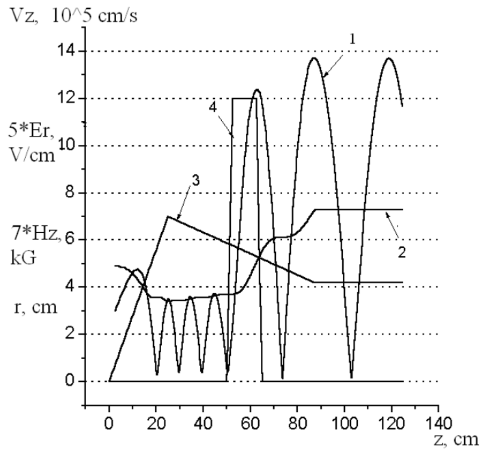
4. THE PARTICLE MOTION PASSING THE MAGNETIC FIELD BARRIER WITH APPLIED THE RADIAL ELECTRIC FIELD

The motion of the particles in crossed electric and axially symmetric magnetic fields was analyzed in [9]. The possible trajectories of particle motion were considered and a division of trajectories and the direction of particle motion depending on magnitude of electric field was done. Some mechanisms of particle separation were analyzed. In the present paper the passing of particles through the magnetic barrier with applied radial electric field in the limited region of barrier where the magnetic field is falling was studied. For simplification, the electric field was taken to be constant ($E_r = const$). The length of the region with constant electric field was equal $0.45L$, The lengths of rising and falling parts of the field were equal $0.1L$. A decreasing the transient length of the region, where electric field was settled, several times did not influenced noticeably on the results of further motion of particle. The differences in the values of velocities and deviations from the axis do not exceeded 1...2%.

The obtained results are markedly differed when direction of electric field are changed (Figs.7,a,b).



a



b

Fig.7. *The projections of trajectories – 1 in (r, z) plane Ar ions and velocity ν_z – 2 passings the magnetic barrier – 3 with applied electric field – 4.* *a) $E_r < 0$, b) $E_r > 0$. The starting radius is equal $3\,cm$. For convenience the curve of the magnetic field H_z was plotted with coefficient 7 and radial electric field E_r with coefficient 5*

The electric field directed to the axis of symmetry ($E_r < 0$), deviate the trajectory in the direction of smaller radii (see Fig.7,a). In a neighborhood of the axis the particle begin to drift in azimuthal direction. While the particle passes the region of the crossed fields it turns relative axis at a certain angle and after leaving this region continuous its motion along the magnetic field on trajectory displayed relative initial one. For the strength of electric field used in calculation ($1...3\,V/cm$) the axial velocity of particle entering the uniform magnetic field always stays less then initial velocity. The deviation of particle in the direction of greater radius is considerably increased (see Fig.7,b) if the electric field is directed along the radius ($E_r > 0$).

The transverse dimension of orbit is increased 5...6 times compare to orbit with opposite direction of the electric field. After particle is leaving the region of crossed magnetic field its axial velocity may exceed 1.5...2 times the starting velocity (Fig.8).

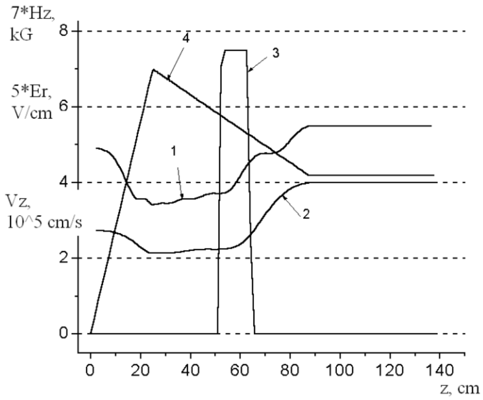


Fig.8. *The axial velocities Ar ions – 1 and Xe ions – 2 passings the magnetic barrier–4 with applied electric field – 3. For convenience the curve of the magnetic field H_z was plotted with coefficient 7 and radial electric field E_r with coefficient 5*

The value of velocity of particle entering the uniform magnetic field depends upon the value and the direction of radial velocity which the particle had before entering the region with crossed magnetic field, and the length of the region where the electric field is differed from zero.

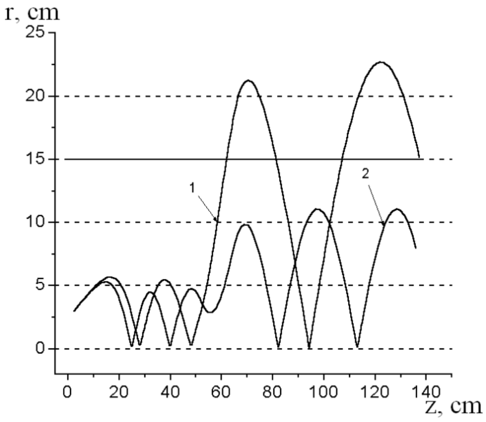


Fig.9. *The projections of trajectories 1 – Xe ion and 2 – Kr ion in (r, z) plane. The boundary of the chamber was shown by horizontal solid line. $z_0 = 0.1$, $\nu_r = 0.25$*

At Fig.9 the projections of trajectories in the plane (r, z) for Kr and Xe ions passing the magnetic barrier with applied electric field E_r are shown. As the calculations show the deviation of particle starting from the positions of $r \sim 2...3\,cm$ is compared with transverse dimension of a chamber. The particles will reach the wall (Xe–curve 1) or will pass the system (Ar–curve 2) depending on relation between axial and radial velocities. As can be seen from a comparison of Figs.5,6 and Fig.9 the application of radial electric field promotes the better stratification in radial direction the mixture of elements with different masses into layers of equal masses. For more precise calculation it is necessary to have more detailed information about the distribution of the magnetic field near the outer wall of the chamber.

5. CONCLUSIONS

In this work, the trajectories of the charged particles of different masses in non-uniform magnetic field were calculated. It was shown that propagation of particle of given energy through magnetic field barrier or its reflection from barrier depends on the initial radial velocity and mass. In the most cases, while passing the barrier, a redistribution between the components of particle velocity occurs in a way that axial velocity is diminished and radial velocity is increased. In uniform magnetic field after passing the barrier, the transverse dimension of particle orbit is increased because of the greater radial velocity and the less strength of magnetic field which can be in this region several times lower compare to its maximal value. The similar character of particle motion assists to divide in radial direction the mixture of particles of different masses into layers of equal masses. The external radial electric field of positive direction ($E_r > 0$, directed along radius) that is applied in the region of falling magnetic field much more increases the differences in the dimensions of orbits of different elements and assists to stratification of particles on masses. And this allows to select the single elements from many component mixture. Besides, the calculation of this kind gives the opportunity to choose the optimal position of the particle source.

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ДВИЖЕНИЕ ЗАРЯЖЕННЫХ ЧАСТИЦ СКВОЗЬ БАРЬЕР, СОЗДАВАЕМЫЙ НЕОДНОРОДНЫМ МАГНИТНЫМ ПОЛЕМ С И БЕЗ РАДИАЛЬНОГО ЭЛЕКТРИЧЕСКОГО ПОЛЯ

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Численным методом рассмотрено движение однозарядных ионов Ar, Kr, Xe сквозь барьер, создаваемый неоднородным аксиально-симметричным магнитным полем ($H_{max} \sim 1\,\textit{кГс}$). Показано, что прохождение и отражение ионов зависит от начальной поперечной энергии частиц и их массы. Приведены оценки для граничных значений начальной поперечной скорости проходящих частиц. Показано, что наложение радиального электрического поля в области спадающего магнитного поля заметно влияет на радиальное смещение частиц разной массы и величину продольной скорости частиц. Полученные результаты могут быть использованы для минимизации потерь ионов, вылетающих из источника путем выбора места расположения источника, и позволяют оценить параметры, наиболее существенно влияющие на формирование потока частиц.

РУХ ЗАРЯДЖЕНИХ ЧАСТИНОК КРІЗЬ БАР'ЄР, ЩО СТВОРЮЄТЬСЯ НЕОДНОРІДНИМ МАГНІТНИМ ПОЛЕМ З ТА БЕЗ РАДІАЛЬНОГО ЕЛЕКТРИЧНОГО ПОЛЯ

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Чисельним методом розглянуто рух однозарядних іонів Ar, Kr, Xe крізь бар'єр, що створюється неоднорідним аксіально-симетричним магнітним полем ($H_{max} \sim 1\,кГс$). Показано, що проходження і відбиття іонів залежить від початкової поперечної енергії частинок та їх маси. Приведені оцінки для граничних значень початкової поперечної швидкості частинок, що проходять. Показано, що накладення радіального електричного поля в області спадаючого магнітного поля помітно впливає на радіальне зміщення частинок різної маси та величину поздовжньої швидкості частинок. Отримані результати можуть бути застосовані при мінімізації втрат іонів, що вилітають з джерела, шляхом вибору місця розташування джерела і дозволяють оцінити параметри, які найсуттєвіше впливають на формування потоку частинок.