# DEVELOPMENT AND CREATION OF THE ELECTROMAGNETIC SEPARATOR FOR ISOTOPE SEPARATION IN THE SYSTEM OF OPPOSING AXISYMMETRIC MAGNETIC FIELDS WITH TWO FIELD REVERSES

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The paper reports the results of work on creation of a setup for isotope separation in the system of opposing axisymmetric magnetic fields with two field reverses. Consideration is given to a real possibility of improving the efficiency of the electromagnetic separator and its resolving power in the double-reverse magnetic field system. It is demonstrated that the use of the opposing axisymmetric field system may substantially reduce the energy consumption during the process of isotope separation. The estimated magnetic field of the facility attests to a possibility of molybdenum isotope separation and isolation of high-purity $^{98}Mo$ and $^{100}Mo$ isotopes required for production of the $^{99}Mo/^{99}Tc$ generator, most widely used in modern medicine.

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The isotope separation is a vital issue, which is of great scientific and practical importance. This importance is determined above all by the needs of nuclear physics and technology. There exist a number of techniques for isotope separation. All of them are based on differences in the properties of isotopes and their compounds attributed to difference in their atomic masses. The isotope separation efficiency is characterized by the separation factor. For most techniques its value is only slightly greater than unity. And only at electromagnetic separation the separation factor varies between 10 and 1000 per separation cycle. The electromagnetic method makes it possible to separate any combination of isotopes.

Along with large electromagnetic separation plants for isotope industry, laboratory separators have found wide use, as their separation factors are 10 to 100 times higher. The main field of their application is the production of small amounts of pure isotopes for obtaining radioactive isotopes, which are necessary for nuclear medicine, for studies of ion interaction with solids (at ion implantation), etc.

One of the drawbacks of the electromagnetic method is a low productivity, which is determined by both the ion current value and the ion trapping efficiency.

In order to attain a high spatial separation of isotopes, and also, to raise the electromagnetic separator efficiency, we have developed a setup, which is supposed to separate isotopes using the system of opposing axisymmetric magnetic fields with two reverses of the direct-axis component of field.

A high efficiency of the isotope separation technique in the system of opposing axisymmetric magnetic fields, as well as the possibility of attaining a higher spatial isotope separation with the system as compared to other methods, were demonstrated in refs. [1]-[2]. This magnetic system [3] provides an efficient separation of isotopes that may have both small and rather large (about 200) atomic masses. Besides, the system makes it possible to separate quite a few isotopes simultaneously, this being undoubtedly of practical interest.

The electromagnetic separators with opposing axisymmetric magnetic fields are simple and low-cost facilities as compared with electromagnetic separators of "Calutron" type [2],[3]. The major drawback of opposing-field separators is their low productivity because of the use of a point isotope source that has a small emitting surface. As is known [7], the productivity and efficiency of the isotope separation procedure are directly dependent on the ion current generated in the process of isotope separation, and the ion current losses due to a variety of reasons.

Our calculations have shown that if the ion source is displaced by 90°...180°, we shall obtain similar

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ion trajectories from different positions of the source. This points to the fact that the ion current can be significantly increased if a source of hollow ion beams is used.

So, if the magnetic system with two magnetic field reverses is used, then, as it follows from ref. [4], with an increase of ion current in the proposed manner, the electromagnetic separator efficiency can be appreciably increased. Besides, it has been indicated in [4] that after the ions undergo two reverses an additional increase in the isotopic-radius spatial separation is observed with the result that isotopes of different masses become much better separated in space as compared to the case of ion motion in a single-reverse system.

In view of the above, with an aim to attain a high spatial separation of isotopes and to increase the electromagnetic separator efficiency, we have developed a setup, which is supposed to separate isotopes with the use of the system of opposing axisymmetric magnetic fields with two reverses of the direct-axis component of field. To this end, we have assembled a magnetic system consisting of five water-cooled electromagnetic coils, equally spaced on a stainless steel tube (1), which is about 1 m in length, 0.2 and 0.21 $m$ in inner and outer diameters, respectively. The coils are grouped into three solenoids according to the following scheme: $1^{st}$ solenoid - one coil (2); $2^{nd}$ solenoid - three coils (3); $3^{rd}$ solenoid (4) - one coil. In the first and third solenoids the electric current directions are coincident, while the current in the second solenoid has an opposite direction (Fig. 1). The schematic diagram of the facility is presented in Fig. 1.

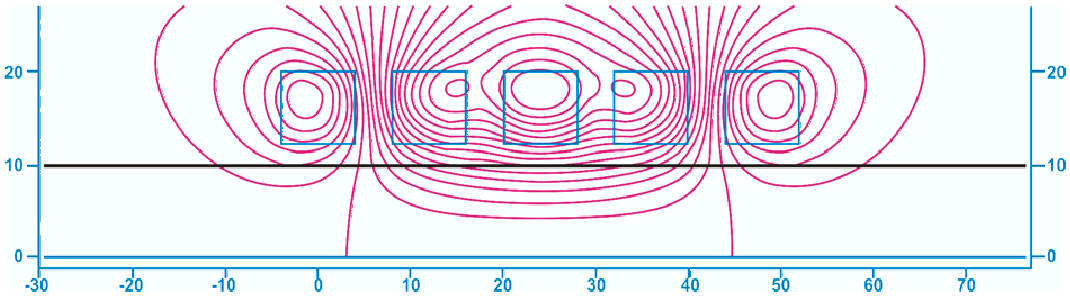


***Fig. 1.*** *Schematic diagram of isotope separation facility*

The magnetic field of the coil system was calculated with the use of the SuperFish program. The computed distribution of magnetic field induction on the axis is shown in Fig. 2.

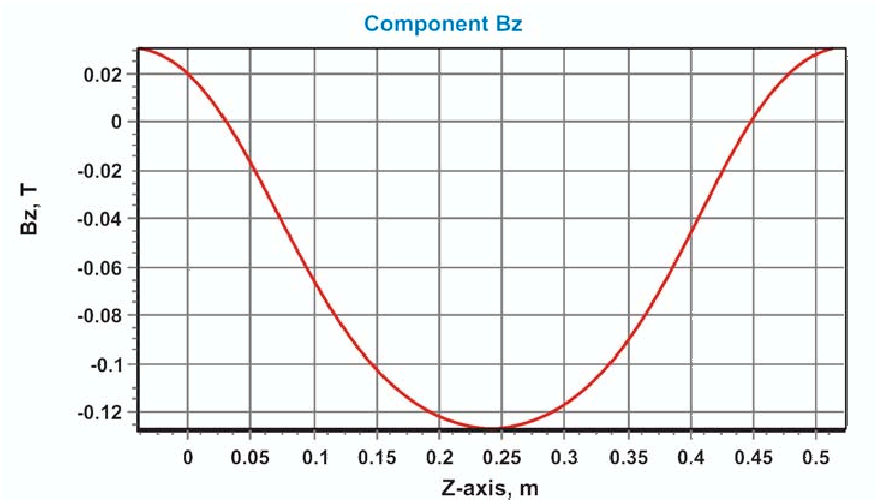


***Fig. 2.*** *Magnetic field induction versus longitudinal coordinate Z*

The coils had the following dimensions: 240 $mm$ and 400 $mm$ for inner and outer diameters, respectively; coil length 80 $mm$. The spacing between the coils was chosen to be 40 $mm$. The coils were powered from a stabilized dc source.

In the given case the coil current was equal to 80 $A$. It can be seen from the plot that the peak value of the magnetic field induction reached $> 0.12\,T$.

The increase in the electromagnetic separator efficiency and a search for possibilities to reduce the costs (especially energy cost) of isotope separation provide a way for electromagnetic separator upgrading. Considering that during separation of isotopes, which have mass numbers of about 200, in the separator with a nonuniform axisymmetric magnetic field 3/4 of power consumption go for magnetic field excitation (see ref. [6]), the reduction in this part of energy demands is most essential.

The use of opposing axisymmetric magnetic fields in our case will enable us to reduce substantially the weight of the magnetic system. Hence, the quantity of copper, iron needed for the system will be lowered by factors of tens to hundreds. As a result, the chamber volume will be also substantially reduced. All these factors will appreciably contribute to cost saving of the whole separator, and also, to the decrease in energy demands for the isotope separation. The cost of isotope separation work will be in this case an order of magnitude lower than that obtained with other methods (see ref. [2]).

The analysis of isotope production with electromagnetic separators during the period of 1980 to 1990 has shown that separation of thallium, zinc, nickel and calcium isotopes was done most frequently. The first two among them are widely used in medicine [7]. Our setup is intended to separate molybdenum isotopes to produce stable molybdenum-100 and molybdenum-98 isotopes. Among isotope generators it is the $^{99}Mo/^{99m}Tc$ generator that is used most extensively in nuclear medicine. Over 90% of all diagnostic studies in medical settings are carried out with the use of $^{99m}Tc$ radioisotope [8].

The $^{99}Mo$ isotope is generally produced in reactors. In recent years, alternative methods of its production have appeared. The $^{99}Mo$ and $^{99m}Tc$ isotopes can be produced in the nuclear reactions $^{98}Mo(p,\gamma)^{99m}Tc$ and $^{100}Mo(p,2n)^{99m}Tc$ at the cyclotron [8]. The $^{99m}Tc$ isotope can be also produced by the photonuclear method using the reaction $^{100}Mo(\gamma,n)^{99}Mo\rightarrow^{99m}Tc$.

For nuclear medicine applications, of vital importance is the purity of the radioisotopes employed for direct introduction into the human body. The current technologies of molybdenum production through its extraction from the fuel in nuclear reactors are unable to separate a certain molybdenum isotope in its pure form without any other isotopic impurities. In this connection, for isotope separation and production of pure radioisotopes it appears currently central to use electromagnetic separators that have opposing electromagnetic fields with two field reverses, as proposed in this work. As is shown in ref. [4], the magnetic system of the separator consists of three solenoids (see Fig. 1). In the middle solenoid, the current flows in the direction opposite to the current directions in the other solenoids, and has the configuration of the magnetic mirror-type, used in magnetic traps for plasma confinement. Under certain conditions, the charged particles moving in the trap reflect from the "mirrors" [10]. In the electromagnetic separator, by choosing appropriate ion injection energy of the isotopes it is possible to create such a situation, at which the ions having a lower mass than the lightest isotope has (from among the target isotopes) will reflect from the "mirror" and won't be able to settle on the collector. This provides a high purity of the isolated isotopes in comparison with the purity provided by other separation methods. The electromagnetic separator under development is supposed to be used for separating molybdenum isotopes. The trajectory calculation of these isotopes shows the possibility of simultaneous separation of molybdenum-98 and molybdenum-100 isotopes in their pure form, because the isotopes having a lighter mass will reflect from the first "magnetic mirror".

It has been indicated in ref. [9] that the enriched $^{100}Mo$ target, $2\,cm$ in diameter and $2\,cm$ in thickness, will weigh about $60\,g$. The world market price of $1\,g$ $^{100}Mo$ amounts to 1000 dollars [9], the price of the isotope produced in Russia is somewhat lower. This fact is one of the main disadvantages of $^{99m}Tc$ isotope production. The estimates of $^{100}Mo$ production during separation of molybdenum isotopes in our electromagnetic separator through the use of opposing axisymmetric magnetic fields with two field reverses encourage us to predict a lower price for $1\,gramme$ of molybdenum-100.

By our estimates, the magnetic field generated in our system under creation may attain $0.12\,T$, this being sufficient for $^{100}Mo$ production.

The use of enriched isotopes in various fields of science and engineering demands a rather high economical efficiency in each case. However, their application will be substantially restricted by their high cost [6].

## CONCLUSIONS

The undertaken studies lead to the conclusion that the proposed scheme of the electromagnetic separator using opposing axisymmetric magnetic fields with two field reverses can provide a more efficient separation of isotopes. The application of the proposed ring-shaped ion source will substantially increase the productivity of the electromagnetic separator.

The use of opposing axisymmetric magnetic fields will make it possible to reduce considerably the magnetic system weight.

All the above will appreciably reduce the total cost of the separator, and also, will reduce power consumption for the isotope separation work, and consequently, will decrease the cost of the isotope separation labor. The reported data demonstrate a real possibility of creating efficient laboratory separators, which are necessary for production of high-purity isotopes in small amounts for nuclear spectroscopy, for studies on interactions between ions and solids, and also, for nuclear medicine.

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## РАЗРАБОТКА И СОЗДАНИЕ ЭЛЕКТРОМАГНИТНОГО СЕПАРАТОРА ДЛЯ РАЗДЕЛЕНИЯ ИЗОТОПОВ В СИСТЕМЕ ВСТРЕЧНЫХ АКСИАЛЬНО-СИММЕТРИЧНЫХ МАГНИТНЫХ ПОЛЕЙ С ДВУМЯ РЕВЕРСАМИ ПОЛЯ

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Приводятся результаты работ по созданию установки для разделения изотопов в системе встречных аксиально-симметричных магнитных полей с двумя реверсами поля. Обсуждается реальная возможность повышения производительности электромагнитного сепаратора и его разрешающей способности в системе магнитного поля с двойным реверсом. Показано, что использование системы встречных аксиально-симметричных полей даст возможность существенно снизить энергозатраты в процессе разделение изотопов. Приведенная оценка магнитного поля на установке свидетельствует о возможности разделения изотопов молибдена и выделения изотопов $^{98}Mo$ и $^{100}Mo$ высокой чистоты, необходимых для получения наиболее применяемого в современной медицине генератора $^{99}Mo\,/\,^{99}Tc$.

## РОЗРОБКА І СТВОРЕННЯ ЕЛЕКТРОМАГНІТНОГО СЕПАРАТОРА ДЛЯ РОЗДІЛЕННЯ ІЗОТОПІВ У СИСТЕМІ ЗУСТРІЧНИХ АКСІАЛЬНО-СИМЕТРИЧНИХ МАГНІТНИХ ПОЛІВ З ДВОМА РЕВЕРСАМИ ПОЛЯ

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Наводяться результати робіт по створенню установки для розділення ізотопів у системі зустрічних аксіально-симетричних магнітних полів з двома реверсами поля. Обговорюється реальна можливість підвищення продуктивності електромагнітного сепаратора і його роздільної здатності в системі магнітного поля з подвійним реверсом. Показано, що використання системи зустрічних аксіально-симетричних полів дасть можливість істотно знизити енерговитрати в процесі розділення ізотопів. Наведена оцінка магнітного поля на установці свідчить про можливість розділення ізотопів молібдену і виділення ізотопів $^{98}Mo$ і $^{100}Mo$ високої чистоти, необхідних для отримання найбільш вживаного в сучасній медицині генератора $^{99}Mo\,/\,^{99}Tc$.