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NEW POSSIBILITIES OF THE FLNR ACCELERATOR COMPLEX FOR THE PRODUCTION OF TRACK MEMBRANES

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1. INTRODUCTION

Research on radiation effects in condensed matter exposed to heavy ions is of special interest for fundamental radiation physics of solids. One of the promising trends of such investigations is research on generating tracks in polymeric materials.

2. ECR - HEAVY ION SOURCE

In the last 10-15 years the ion sources of high-discharge ions have been in progress. Their operation is based on the electron cyclotron resonance principle. In the early days the majority of heavy ion accelerators in the leading research centres (USA, France, Japan) utilized other types of the ion sources. For example, at the FLNR/JINR the accelerators U-200, U-300 (later re-designed and known as U-400M) and U-400 applied the ion sources of a Penning type. This ion source allowed obtaining the average charge ions (the charge of the ions was ranging within $Z = 2 - 8$) with quite high intensity at the whole number of disadvantages. In particular, in order to obtain ejected high energy ion beams, high-charge ions were required from the ion source. That allowed one to obtain high energy heavy ions with no change of accelerator's parameters (of sizes of the so-called pole magnetic tips) or increase of the magnetic field's value in the margin of accelerating. However, increasing the charge of the ions extracted from the Penning source resulted in a considerable decrease of the ion beam intensity. Besides, the source operated in a pulsed mode, and in the course of the depleting of the elements a frequent change of the old source for a new one was required.

The ECR - ion source provides a way for extracting high-charged ions in a wide range over the charges ($Z = 10 - 20$) practically with no decrease of the ion beam intensity. Fig.1 gives a comparison of the characteristics of the ion beam intensity of the U-400 cyclotron with ECR-source and the Penning source depending on the mass of the accelerated ions for two energies of ion beams 5 MeV/amu (Fig.1a) and 18 MeV/amu (Fig.1b). Clearly, for intermediate energy ions the U-400 cyclotron with the Penning source provides much high intensity as compared to the ECR - ion source for the ion mass less than 40 amu. There is a sharp change of the situation at obtaining high energy ions, and here the ECR - ion source has a doubtless advantage. It can be seen from Fig.1b.

The main advantages of this heavy ion source type are as follows: high intensity ion beams in the range of high charge of the extracted heavy ions; long time exploitation with high stability ion beam in a continuous mode of operation (up to one month), possibility of relatively fast change from one ion charge to another; small expenditure of the substance from which the required ion type is produced - this is of particular importance for using the very rare and expensive isotopes, for example, $^{48}Ca^{+5,+6}$ for synthesis of superheavy elements.

For the last two years the FLNR/JINR cyclotrons have been equipped with ECR-heavy ion sources: U-400M-ion source DECRIS-14-2 designed at the Laboratory, and U-400 - with the ECR-4M source designed at the accelerator centre of heavy ions in GANIL (France). Fig.2 shows ion spectra from the ECR-4M ion source optimized for accelerating ^{86}Kr ions (Fig.2a) and ^{209}Bi (Fig.2b) of various charges depending on current of the magnet under analysis.

One can see that practically for all range of the accelerated ions charges the intensity does not change considerably. This allows one to use ^{86}Kr ions of charges $Z = +7$, +8, +9 practically without decrease of their intensity and to obtain ions with the charges up to $Z = +11$, +12 and more. For ^{209}Bi ions the intensity of the ions with a charge ranging from +16 to +22 changes from 30 to 100 mA. This provides a way for obtaining Bi ions of GeV energies at quite a high intensity of ion beams.

3. SYSTEM of EXTERNAL INJECTION of LOW ENERGY IONS onto a MEDIAN PLANE of the CYCLOTRON .

When operating the cyclotrons U-400 and U-400M with an ion source of a Penning type, the gas discharge chamber of the ion source practically reached the central part of the cyclotron. And vacuum in this area appeared to be bad enough (of about 10^{-4} Torr). This resulted in essential loss of the ion beam intensity depending on the accelerating radius at the expense of scattering ions on the residual gas. The up-to-date accelerators of heavy and light ions apply, including the FLNR/JINR, systems of external injection of small energy ion beams (100 - 500 keV) from ECR-ion sources to the centre of the accelerator. Fig.3 shows a scheme of an external line of injection to the U-400 cyclotron which includes the following elements: an ECR-ion source, a beam-bending magnet, an analysing magnet, a quadrupole lens, a beam bending magnet, three solenoids and four cryogenic pumps.

Due to the fact that the ions transported through the external injection line, have relatively small energy, the 50 - 200 μA ion beam intensity at a high charge a spatial electric charge begins manifesting itself which leads to some Coulomb repulsion and loss of ions on the transport channel's walls.

That's why the U-400 and U-400M accelerators have been equipped with two bunchers per each of sinusoidal and saw-tooth voltage of power supply. These devices allow one to stretch the bunch of ions vertically and, thus, to minimize the influence of the space electric charge at passing from the bending magnet to the core and then to form a short bunch from the ion bunch stretched in length. The inflector located in the core deflects the ion beam onto a horizontal plane (the median plane of the accelerator), and finally, the ion accelerating mode starts.

Extraction of ions from the cyclotron is performed by scattering the ions on a thin carbon foil resulting in additional loss of electrons by ions. Changing the position of scattering foil along the accelerator's radius allows one to change the energy of the extracted beam as ion energy (E) is proportional to square of the extracted radius (R).

4. MODERN HEAVY ION TRANSPORT BEAM LINE for IRRADIATION of POLYMERIC and OTHER MATERIALS on U-400 ACCELERATOR

Fig.4 gives a scheme of a channel for irradiation of polymeric and other materials at the heavy ion accelerator U-400. The irradiation channel consists of the following components: magnetic lens for ion beam focusing, deflecting stirrings in vertical and horizontal directions, a block of scattering foils with semiconducting detectors for measuring energy of the ion beam E and a diagnostics block where a break pneumatic gate valve is installed, pneumatic Faraday cup for ion beam intensity control when tracing the ion beams and the scanners of distributing the ion beam in the vertical and horizontal directions. Both distributions are transferred to the cyclotron's control panel in order to control a position and a distribution of the beam in the cross-section.

Behind the diagnostics block there are two systems of scanning in vertical and horizontal directions. The scanning systems are based on two mutually exclusive operational principles, i.e. either one system or the other one works and is assembled. The former (electrostatic) represents a flat capacitor with 1.2 meter plates and a distance between the plates $H \cong 4.5$ cm with an applied linear saw-tooth voltage of U_{max} amplitude. The saw-tooth voltage amplitude can be calculated from the expression:

$$U_{max} = 2*E*d*H/[(L - l)*Z*e_0*l]. \qquad (1)$$

Here E - ion energy, H - a distance between the capacitor's plates, L is a distance from the entrance to the capacitor's plates (along the beam), Z is a charge of the accelerated ion, e_0 - an elementary electric charge, l - a capacitor's plates' length, d - max deflection of the ion beam's centre from the axis of the ion beam line at the distance L, i.e. in the area under irradiation. Due to expression (1), irradiation channel parameters (L, d) as well as charge of the accelerated ion and its energy, one can calculate the value of U_{max}.

In the U-400 channel the scanning systems were calculated to provide a deflection of 430 MeV ^{86}Kr and ^{136}Xe ion beams from the axis of the beam line at a distance of $d = \pm 30$ cm at a distance $L = 11$ m. The parameters of the horizontal and vertical scanning systems have the following values in our case: scanning frequency - $f_G = 4 - 6$ kHz with the amplitude $U_{max}^G = \pm 45$ kV, and $f_V = 2 - 4$ kHz with the amplitude $U_{max}^V = \pm 25$ kV, respectively.

The scanning systems are intended for obtaining a homogeneous, as to the irradiation area (see Section 5), distribution of an ion beam at the cyclotron operating in a pulsed mode. At the pulsed mode of the U-400 cyclotron operation the pulse repetition frequency of the beam is $f_{acc} = 150$ Hz. Therefore, the condition:

$$f_{V,G} >> f_{acc} \qquad (2)$$

is fulfilled. To irradiate polymeric films over the length, as a rule, the relationship of the values from expression (2) of the following order $f_{V,G}/f_{acc} = 10$ looks sufficient. This allows a multiple scanning of the ion beam by the same pulse along the same film area at its moving. Here the maximum film moving velocity (V_{max}) can be estimated with the simple relation:

$$V_{max} \leq h*f_{V,G}/K, \qquad (3)$$

where h is a window height in the irradiation area, and the parameter takes $K = 5 - 10$.

The second principle (magnetic) is grounded on using coaxially winded coil with no use of a magnetic iron core, to which a rectangular impulses of current is fed and then transformed on the capacity and the inductivity of the coil into a saw-tooth alternating magnetic field. The amplitude of the saw-tooth magnetic field B_{max} can be estimated from the expression:

$$B_{max} = 45.7*d*(A*E)^{1/2}/(Z*l*L). \qquad (4)$$

In relation (4) B_{max} is measured in kGs, d - in cm, ion mass A - in mass units, ion energy E - in GeV, coil length l - in cm, and the distance between the coil and the irradiated area L - in m. Due to inductivity in the coil, the amplitude of the magnetic field B_{max} begins its quick decreasing as the magnetic field change frequency f_M increases. Thus, it is rather difficult to obtain f_M exceeding 200-300 Hz.

Calculations by formula (4) for the same values of L and d as in the case of the electrostatic scanning system for 0,75 GeV ^{136}Xe ions have shown that the magnetic field amplitude should be B_{max} = 0,300 kGs. It is the variant of the scanning magnetic systems which is realized at the U-400 cyclotron channel with the following parameters:
B_{max}^G = 0,350 kGs and B_{max}^V = 0,200 kGs with changed scanning frequency $f_{G,V}$ = 100 - 200 Hz. These scanning systems can only be applied to a continuous operation of the cyclotron in accord with the ideas mentioned above (see condition (2)). Here condition (3) is transformed into as follows:

$$V_{max} \leq h * f_{G,V}/K \,. \qquad (5)$$

Comparing the V_{max} obtained from (3) and (5), one can see that both types of the scanning systems provide practically similar maximal velocities of irradiation of the polymeric films.

The main advantages of the scanning magnetic systems, as compared to the electrostatic ones, are as follows. Use of electrostatic scanning systems causes a necessity of minimizing, as far as possible, the distance between the capacitor's plates in order to increase the deviation from the axis of the ion beam line d on the length of the beam line L, because, as one can see from formula (1), d is in inverse proportion to the distance between the plates H. Besides, decreasing H also decreases amplitude U_{max} for obtaining d. However, decreasing H naturally requires to minimize the size of the diaphragms in front of the scanning systems. This leads to deterioration of passing the ion beam and imposes more severe requirements upon vacuum in the spot of the places' location due to increasing possibility of electric break downs and, thus, to decreasing stability of the ion beam in the irradiated zone. The magnetic scanning systems are insensitive to vacuum where they are located, because they are outside the vacuum space, and the ion conducting cross-section of beam channel can be rather large and thus makes the ion beam passage better. The U-400 cyclotron through cross-section of beam channel is of 76 mm diameter. Fig.5 presents some pictures of the magnetic scanning systems in the irradiation channel.

The vertical scanning system allows one to receive a homogeneous distribution of the ion beam flux density (J) in the window height in the irradiated zone h. This naturally allows decreasing parameter K in expressions (3) and (5) and, therefore, increasing the film rewinding velocity. Another important feature of the vertical scanning system will be discussed in Section 5.

The horizontal and vertical scanning systems allow obtaining a homogeneous distribution of the ion beam in the irradiated zone of sizes of 60 cm x 8 cm and homogeneity not worse than $\Delta J/J \leq 5\%$ (Here J is the flux density of ions).

5. ION IRRADIATION of POLYMERIC FILMS and OTHER MATERIALS

The ion beam channel (beam line) represents a set of sections of various sizes. The sections are of 10 cm in diameter before the scanning systems, where the beam cross-section is still having sizes in diameter which do not exceed 2 cm. After the scanning systems the beam channel expands horizontally up to 40 cm at the 10 cm height, and then the next sections are of 70 cm in horizontal size at the 10 cm height. This allows scanning the ion beam in the irradiated zone up to 65 cm width. The beam channel ends with a specially designed unique separating electrical gate valve with a cross-section of 70 cm and 10 cm in size. Fig.6 gives a picture of the wide part of the ion beam line with a separating gate.

Behind the gate valve there is a specialized vacuum chamber for irradiating polymeric films and other materials. The chamber represents a cylindrical vacuum volume of D = 120 cm diameter and of 100 cm width. The vacuum chamber is connected with the separating gate valve.

In the chamber there was installed a rewinding machine (Web transport machine) for polymeric films of a maximum width up to 65 cm. The rewinding machine without vacuum in chamber (when air in) can be removed with the help of special rails out of the chamber to install a new film roll. This mechanism represents a three-motors "tape recorder" consisting of the following elements: a shaft rotating with a permanent velocity with compressing rubbered rollers for dense compression of the polymeric film when rewinding, two rollers for fixing a initial roll with a film and bobbin for winding the irradiated film as well as a system of rollers to provide a proper rewinding of the film. The rollers on which the film rolls are placed, are equipped with frames controlling the rotating velocity. It is necessary since in the course of rewinding the film from one bobbin to the other one their radiuses change, one decreases and the other increases. The rotation rate is determined by formula $V = \omega * R$, where ω - angular rotation rate, and R - roll radius. Therefore, in order to provide a permanent rate and proportional tension of the film, it is necessary to change the angular rotation rate. Fig.7 gives a picture of the irradiation chamber with the removed film rewinding machine.

The rewinding mechanism allows irradiation of polymeric films with various rates step by step: 0,05 m/s; 0,10 m/s; 0,20 m/s; 0,40 m/s; 0,80 m/s.

Another important peculiarity of the vacuum irradiation chamber is that the volume where the film rolls are placed as well as the irradiated zone - irradiating roller through which the film passes, are divided by a vacuum separating partition. This partition provides a differential pumping out of the space directly connected with the beam channel (region of high vacuum, of the order of $(2\text{-}3)*10^{-6}$ Torr) and the volume where the film rolls are placed (the region of low vacuum, of the order of $(2\text{-}5)*10^{-4}$ Torr). As well known, when producing polymeric films in the form of tightly winded rolls, one sorbs water vapours and atmosphere air, so at their fast rewinding in vacuum there is a gas - and vapour secretion that makes vacuum worse. Without some additional efforts this can lead to ion beam scattering on remainder gas and as a result to essential loss of intensity.

The irradiation of the polymeric film is performed in several modes:
1) irradiation of the film on a 10 cm diameter cylindrical roller limited by a diaphragm of a size of up to 60 cm in vertical and up to 8 cm in horizontal directions. This permits to have the angles of entering the ions into the film along its length up to $\alpha = \pm 53^{\circ}$. To obtain a sufficiently homogeneous distribution in angles, it is necessary to use vertical scanning systems;
2) irradiation of the polymeric film in the course of its moving in a vertical direction from the bottom upwards or quite reverse. Here a parallel distribution of tracks with a changeable angle of entering into the film up to a perpendicular one can be reached.

To irradiate nonpolymeric materials without rotation, the following mode is used. The cover of the vacuum chamber with the rewinding machine is removed out of the chamber, and the vacuum chamber is closed with a another vacuum dense cover and the inner volume of vacuum chamber becomes empty. On the back wall of vacuum chamber the special small chamber for the irradiation of samples is installed and is separated with a gate valve from the main cylindrical vacuum chamber. Here the cylindrical chamber is some sort of a continuation of the beam channel, and the ion beam can pass it free and enter the chamber for the sample irradiation. This chamber is isolated electrically from the main chamber and beam channel, i.e. it is a Faraday cup itself. This allows quite a precise measuring of ion beam current on the irradiated target.

6. MEASURING SYSTEMS for IRRADIATION CHANNEL

The measuring system includes: 1) a unit for measuring ion beam energy; 2) Faraday measuring cup; 3) scanners of distributing ion beam in cross-section in the diagnostics block. 4) in a wide part of the beam channel there is a specialized Faraday's cup with sizes of 37 cm and 9 cm intended for measuring ion beam current without scanning and with scanning at a full width of the beam line (the width is 40 cm where it is located); 5) to determine a homogeneity distribution at a full-width scanning (60 cm), there is a wire coordinate detector used at adjustment and then removed from the irradiation zone, as it leaves wire traces at irradiating samples. 6) There are five measuring sections (per three Faraday cups in the vertical direction) among them two stationary sections and three ones which can be removed out of the irradiation zone, if required) for permanent control of distribution the ion beam outside the irradiation zone. 7) Three blocks with scattering foils and semiconductor detectors for measuring the number of scattered ions, were installed to control low density ion beams in the beam channel.

These elements provide a way for tracing the beam from the accelerator to the target to provide the adjustment (the focused beam in the centre of the target and its top intensity at minimal loss). The measurement accuracy is around ±5%.

To irradiate polymeric materials, there are used the following types of ion beams: ^{86}Kr of $Z = +8, +9, +12, +13$ and energy 250, 350, 430, 750 MeV, respectively, as well as 430 MeV ^{136}Xe ions with $Z = +14$. This set of ions and energies first allows one to obtain TM of the width of more than 100 μm.

7. VACUUM SYSTEM of the ION CHANNEL

The vacuum system is based on turbo-molecular pumps of two types: TMP-500 and TMP-1500. This can prevent getting vacuum oil on the polymeric film or the irradiated targets. Three high vacuum pumps TMP-500 are placed in a 10 cm part of the beam line as it is senseless to install more powerful pumps because of a falling rate of vacuum pumping out (evacuating) at the expense of the small cross-section. The pumps are placed in accordance with the calculations at a distance of approximately 5 m one after another.

The wide part of the ion beam channel has 4 turbo-molecular pumps TMP-1500 each 3-4 m for increasing the pumping out rate - it is necessary because of a large internal vacuum space.

Two TMP-1500 were installed in the front part of the irradiation cylindrical chamber (high vacuum) and one TMP-1500 was installed in the back part of the chamber.

The lines of pumping out the atmospheric pressure down to 10^{-2} Torr of the ion beam line, of the cylindrical chamber and the irradiation chamber are based on two vacuum pumps BL-90 (pumping rate - 25 l/s) allowing one to reach this vacuum for 10-15 minutes.

Two pumping out lines of high vacuum pumps (TMP pumps) are independent of the similar vacuum lines of the accelerator and include

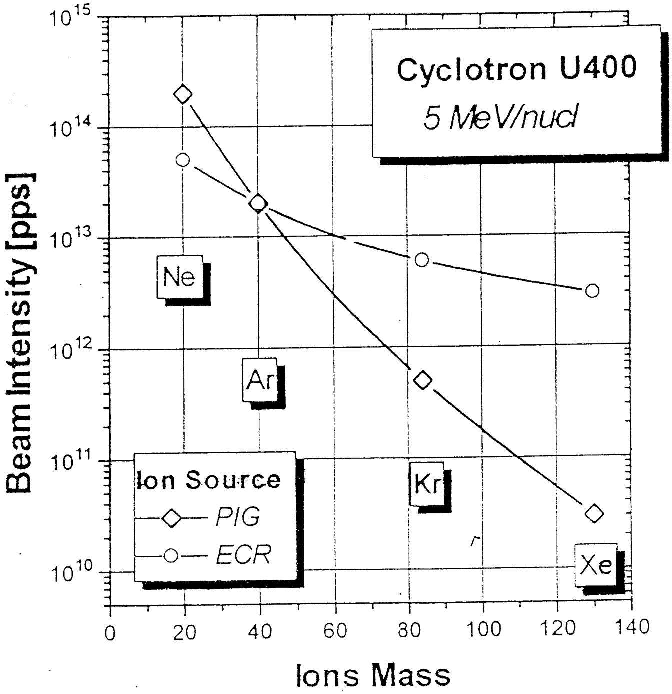


Fig.1a. Intensity of the ion beams from the ECR-ion source of the U-400 cyclotron and from the Penning source for 5 MeV/amu ions (comparison).

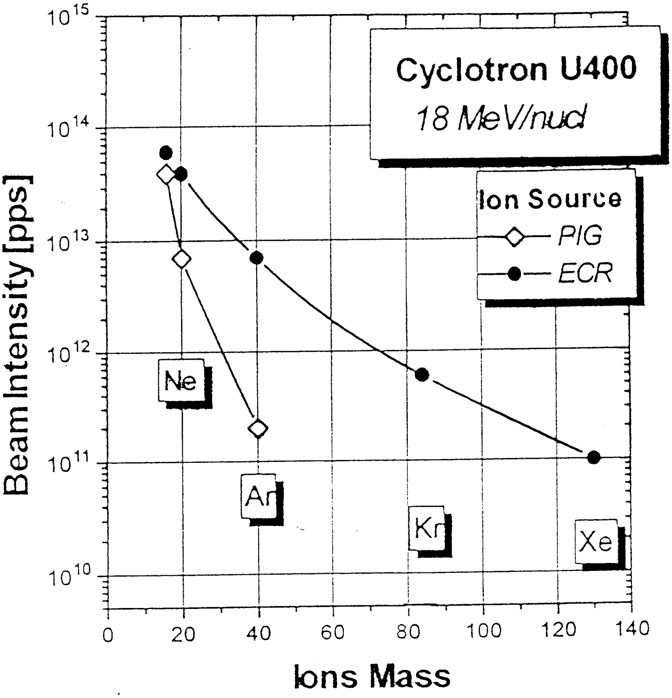


Fig.1b. Intensity of the ion beams from the ECR-ion source of the U-400 cyclotron and from the Penning source for 18 MeV/amu ions (comparison).

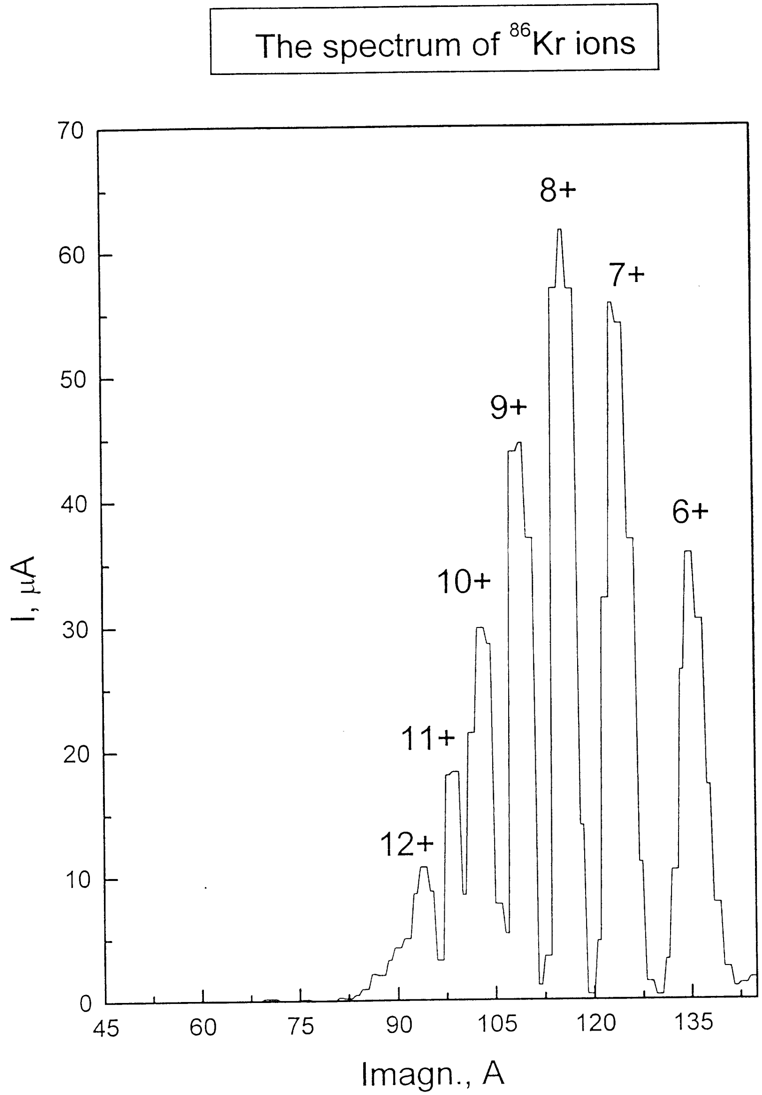
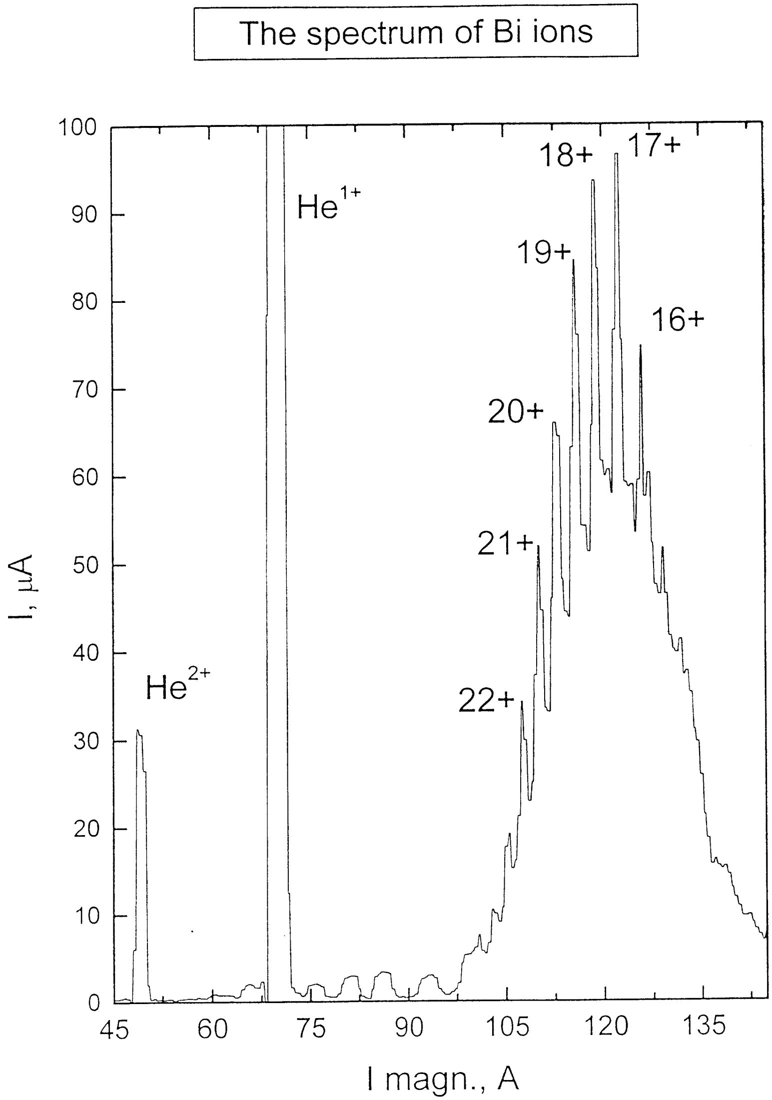


Fig.2a. Spectrum of ^{86}Kr ions of various charges depending on current of the separating magnet.



The spectrum of Bi ions

Fig.2b. Spectrum of ^{209}Bi ions of various charges depending on current of the separating magnet.

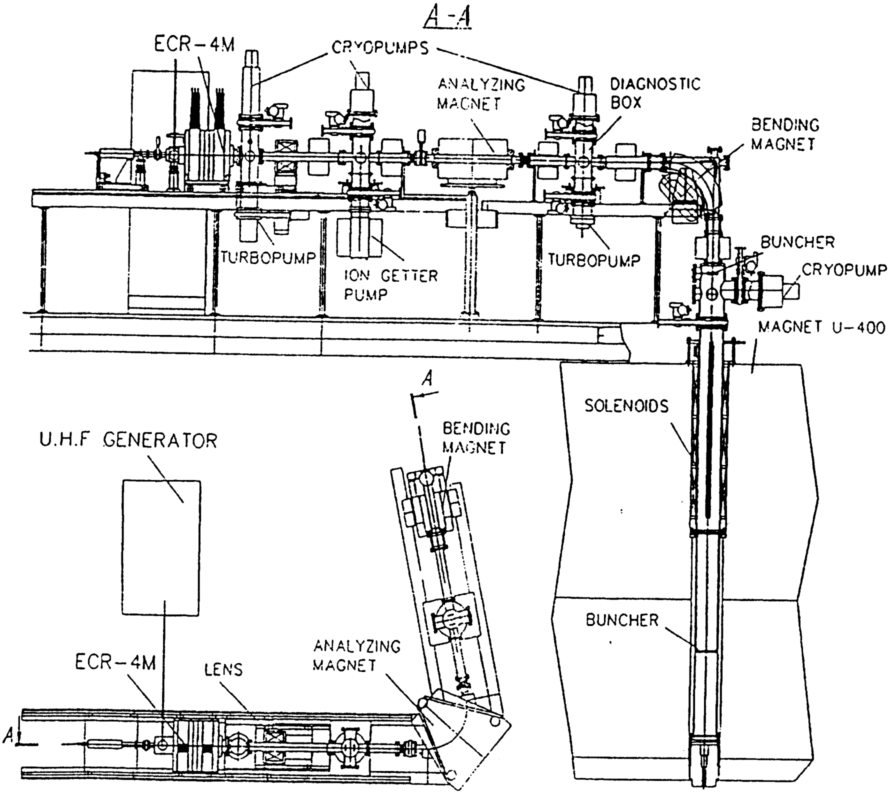
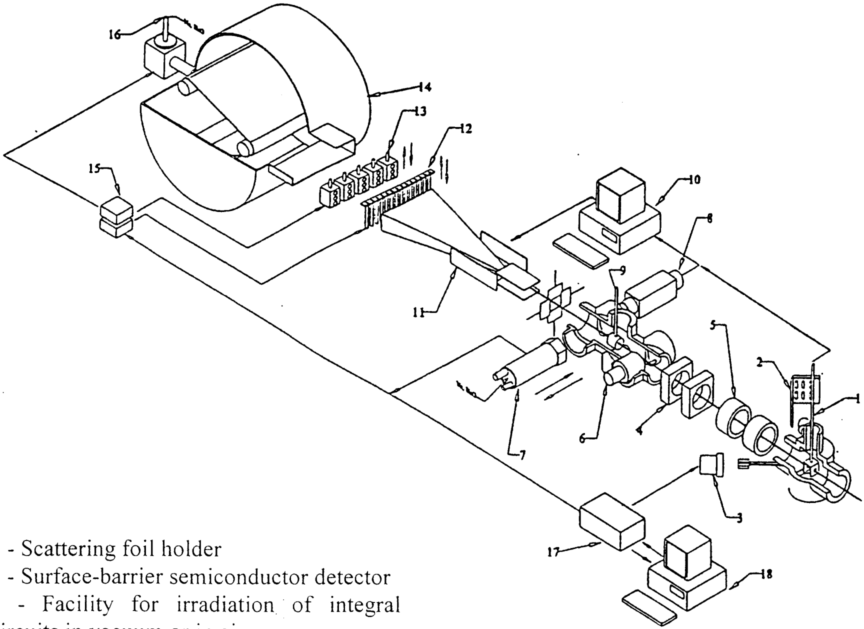


Fig.3. Channels of external injection with the ECR4M-heavy ion source at the cyclotron U-400.



1 - Scattering foil holder
2 - Surface-barrier semiconductor detector
3 - Facility for irradiation of integral circuits in vacuum or in air;
ion beam intensity here can be varied from 10^{-1} to 10^{3} cm^{-2} c^{-1}
4 - Duplet of quadrupole focusing lens
5 - Ion beam deflection magnets
6 - Movable Faraday cup
7 - Water or liquid nitrogen cooled sample holder for high ion fluence irradiation
8 -Rotating wire detector for monitoring of a profile of ion beam cross-section
9 - Quartz window with monochromator for luminescence measurements and other optic studies
10 - Standard CAMAC equipment and a personal computer
11 - Electromagnetic scanning systems
12 - Wire detector of horizontal ion beam distribution
13 - A set of Faraday cups
14 - Vacuum chamber for irradiation of large area (65 x 8 cm^{2}) polymeric materials ion beam intensity is from 10^{5} to $5*10^{11}$ $cm^{-2}c^{-1}$
16 - Relatively small sample holder

Fig.4. Channel of irradiating materials at the U-400 cyclotron.

Fig.5. Horizontal and vertical magnetic scanning systems.

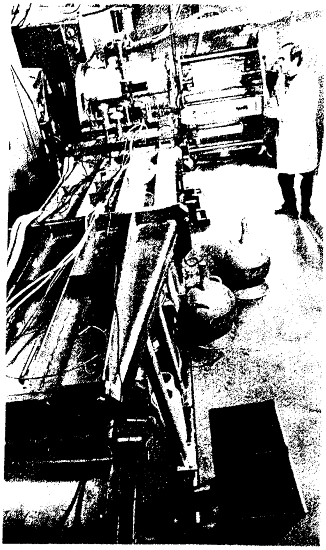


Fig.6. Wide section of the part of the beam channel with a separating gate valve.

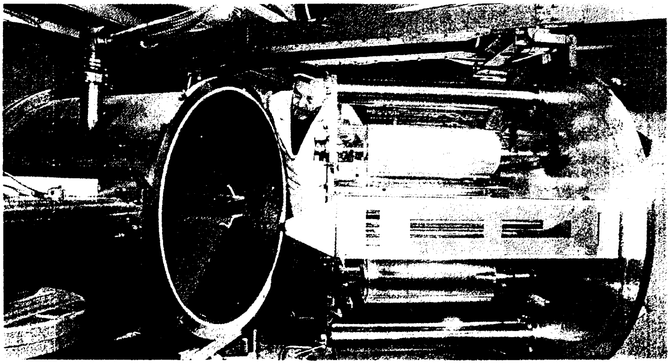


Fig.7. Irradiation chamber with a removed film rewinding machine and with a separating vacuum partition.

also 3 pumps BL-90. One of the lines only serves for the beam channel's pumps, and the second one - only TMP-1500 in the low vacuum region.

To increase the pumping out rates, all high-vacuum pumps in the wide part of the beam line are equipped with nitrogen traps. This requires a constant addition of liquid nitrogen while operating.

At irradiation, the vacuum is not worse than (4 - 5)$*10^{-6}$ Torr in the beam channel and in the high vacuum region, and (2-5)$*10^{-4}$ Torr - in the low vacuum region.

CONCLUSION

The essential modernization of the U-400 cyclotron as a basic set-up for TM production together with the new transport beam channel provides a unique way for irradiating and manufacturing TM with improved parameters and on an industrial scale. The comparison of the ion beam parameters (mass and energy range of the accelerated ions, ion beam intensities) and the irradiation conditions for polymeric materials (maximum width and length of polymeric films, rewinding rate at irradiation) with the analogous parameters of other centres dealing with heavy ions such as GANIL (France), Broohaven (USA), WIKSI and Darmstadt (Germany), Looven (Belgium) allows one to make a conclusion that the TM production complex created at the FLNR/JINR is much better than those in other research centres.

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Новые возможности ускорительного комплекса
Лаборатории ядерных реакций им. Г.Н.Флерова
в производстве трековых мембран

Приведено описание основных систем модернизированного ускорителя тяжелых ионов У-400 Лаборатории ядерных реакций им. Г.Н.Флерова, включающее в себя ЭЦР-источник тяжелых ионов, канал внешней инжекции в медианную плоскость ускорителя и основные параметры для получения ускоренных тяжелых ионов, начиная с криптона и более тяжелых. Приводятся также структура и характеристика нового ионного канала с вакуумной камерой облучения полимерных и других материалов на модернизированном циклотроне У-400.

Обсуждаются новые возможности по производству трековых мембран с уникальными свойствами.

Работа выполнена в Лаборатории ядерных реакций им. Г.Н.Флерова ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна, 2000

Oganessian Yu.Ts. et al. E13-2000-40

New Possibilities of the FLNR Accelerator Complex
for the Production of Track Membranes

The description of the main systems of modified heavy ion accelerator U-400 of the Flerov Laboratory of Nuclear Reactions is presented including the ECR ion source, system of external injection of low energy ions onto median plane. The characteristic parameters for obtaining of accelerated heavy ions from krypton ions to more heavier ones also are presented. The structure and parameters of new beam line and vacuum chamber for irradiation of polymeric and other materials on modified cyclotron U-400 are presented too.

The new possibilities for the production of unique track membrane are discussed.

The investigation has been performed at the Flerov Laboratory of Nuclear Reactions, JINR.

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