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AXIAL INJECTION SYSTEM FOR THE U-400M CYCLOTRON WITH AN ECR ION SOURCE

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The results of calculation, design and construction of the axial injection system for the U-400M cyclotron with an ECR heavy ion source are presented. The U-400M cyclotron and ECR ion source combination allows one to increase the heavy ion beam intensity and expand the range of the accelerated ions at the U-400M cyclotron. The technical data for the axial injection system parts and the DECRIS-14 ion source test results are given.

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

Система аксиальной инжекции циклотрона У-400М с ЭЦР-источником ионов

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В статье представлены результаты расчетов, проектирования и создания аксиальной инжекции тяжелых ионов в циклотрон У-400М из источника типа ЭЦР. Комбинация циклотрона У-400М с ЭЦР-источником ионов позволяет увеличить интенсивность пучков тяжелых ионов и расширить диапазон ускоряемых ионов на циклотроне У-400М. Приведены технические параметры отдельных систем аксиальной инжекции и результаты стендовых испытаний ЭЦР-источника DECRIS-14.

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Introduction

The isochronous cyclotron U-400M was started in 1991 with an internal PIG ion source, and internal beams of accelerated ions were obtained. The parameters of the internal beams produced with the PIG ion source are listed in Table 1. Accelerated ion beams in the mass range from He up to Ar are produced [1]. In 1993, the first physical experiments using 4π spectrometer FOBOS were carried out on the extracted $^{7}Li^{2+}$ beam. For this moment we have reached the limit of the PIG ion source possibilities in the production of the highly charged ions. We are limited by the source itself and by vacuum losses of the accelerated beam due to the gas loading of the vacuum system by the gas flow from the source. The main disadvantage of PIG ion source is the AC mode of operation. So, further development of the U-400M is connected with the use of an ECR ion sources with an axial injection

Table 1. Ion beam parameters of U-400M

Ions	Energy MeV/n	U-400M + PIG Intensity, pps	U-400M + ECR Expected intensity, pps
$^{4}He^{1+}$	30	$1.0\cdot10^{14}$	
$^{6}Li^{2+}$	50	$1.0\cdot10^{13}$	
$^{7}Li^{2+}$	44	$6.0\cdot10^{13}$	$6.0\cdot10^{12}$
$^{12}C^{3+}$	30	$2.0\cdot10^{13}$	
$^{12}C^{4+}$			$5.0\cdot10^{13}$
$^{12}C^{6+}$			$2.0\cdot10^{11}$
$^{14}N^{3+}$	26	$2.0\cdot10^{13}$	
$^{14}N^{4+}$	40	$2.0\cdot10^{12}$	
$^{14}N^{5+}$	60	$5.0\cdot10^{11}$	$5.0\cdot10^{13}$
$^{16}O^{3+}$	15	$2.0\cdot10^{13}$	
$^{16}O^{4+}$	30	$3.0\cdot10^{12}$	
$^{16}O^{5+}$	48	$2.0\cdot10^{12}$	$2.0\cdot10^{13}$
$^{20}Ne^{2+}$	6	$5.0\cdot10^{13}$	
$^{20}Ne^{4+}$	20	$5.0\cdot10^{12}$	
$^{20}Ne^{5+}$	30	$3.0\cdot10^{12}$	
$^{20}Ne^{6+}$	46	$1.0\cdot10^{12}$	$2.0\cdot10^{13}$
$^{40}Ar^{4+}$	6	$2.0\cdot10^{13}$	
$^{40}Ar^{5+}$	10	$1.0\cdot10^{13}$	
$^{32}S^{10+}$	49		$4.0\cdot10^{12}$
$^{48}Ca^{14+}$	44		$1.0\cdot10^{12}$
$^{84}Kr^{17+}$	22		$6.0\cdot10^{11}$
$^{129}Xe^{26+}$	22		$6.0\cdot10^{11}$
$^{181}Ta^{29+}$	15		$8.0\cdot10^{10}$
$^{238}U^{24+}$	6		$4.0\cdot10^{11}$

system. In Table 1, expected beam intensities in combination ECR + U-400M at an efficiency of beam transmission of 20% are presented. The use of an ECR ion source will allow us to increase the reliability of the cyclotron and to run RF in DC mode with the use of stabilization systems and produce a continuous beam.

ECR Ion Source

Designing of the electron cyclotron resonance ion source DECRIS-14 was started in the beginning of 1990 [2]. ECR ion sources provide the ion beam with a higher charge and a lower emittance (100 π mm.mrad) in comparison with a PIG ion source. With the use of gaseous working substances an ECR ion source has a practically unlimited service life. The consumption of working substances for an ECR ion source (about 0.05 cm^3/min for gaseous) is substantially lower than for a PIG source (about 0.2 cm^3/min for Xe). This advantage of an ECR ion source is very important for use of the rare enriched isotopes as a working substance. For example, the consumption of ^{48}Ca is 0.25—0.4 mg/h for an ECR ion source and 4—10 mg/h for a PIG source. The total power consumption for an ECR ion source is within the range 50—150 kW. The scheme of the DECRIS-14 ion source is shown in Fig.1. It consists of two stages. Both the stages have a magnetic mirror configuration. Axial magnetic field is produced by water cooled coils which consume a power of about 130 kW. The minimum **B** configuration at the second stage is produced by a superposition of an axial mirror field and a radial hexapole field.

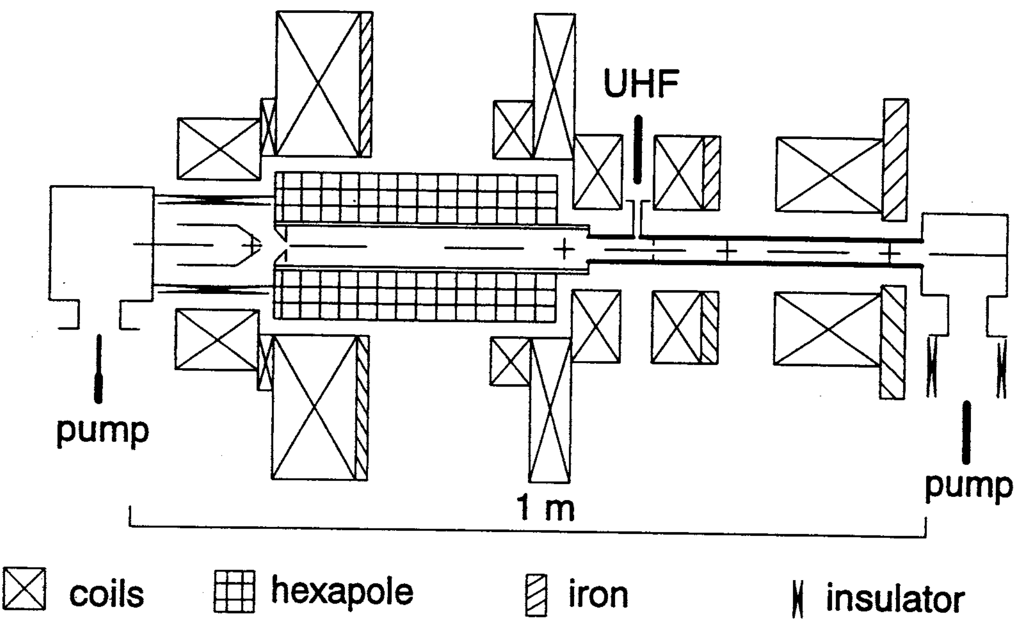


Fig.1. The scheme of the DECRIS-14 ion source

Table 2. Some multiply charged ion current from the DECRIS

Ion/charge	4^+	5^+	6^+	7^+	8^+	9^+	11^+	Support gas
N	270	92	17					
O		160	87	26				
Ar					70	24		...
Ar				120	110	70	15	oxygen

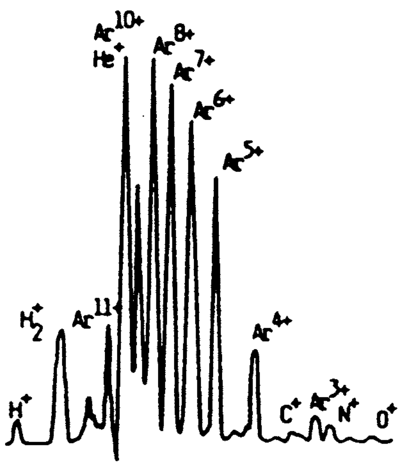


Fig.2. The charge-state distribution of Ar ions

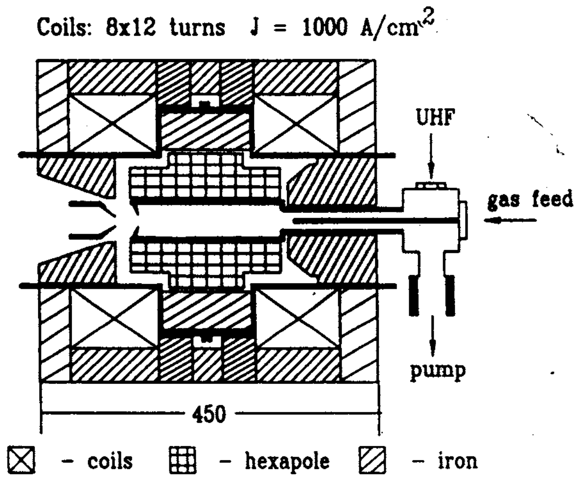


Fig.3. The scheme of the magnetic structure of the new, more compact ion source

The NdFeB hexapole has a magnetic flux concentration geometry. A turbomolecular pump provides $2\cdot10^{-5}$ Pa background pressure through the injection and extraction sides of the source. The whole source body including the plasma chamber and the hexapole are insulated up to 25 kV and connected to a high voltage power supply, except for the solenoids, vacuum pumping, and the beam line. A commercial UHF generator working in the frequency range of 14—14.5 GHz with a maximum output microwave power up to 2.2 kW is used. The generator is connected to the ion source through a high voltage insulator and a tight BN window. Some multiply charged ion currents from the DECRIS are listed in Table 2. The charge state distribution of Ar ions is shown in Fig.2. The new, more compact ECR ion source is now under test. The scheme of the magnetic structure of this ion source is shown in Fig.3. The axial magnetic field is formed by water cooled coils and soft iron yoke. In collaboration with GANIL group the ECR4M ion source is being developed now. The magnetic structure of the source is designed to provide the operation in a frequency range 14—28 GHz, aiming to increase the intensity of Ca^{14+} beam up to 10^{13} pps. GANIL will deliver to the FLNR the ion source equipped with a beam analysis line. The scheme of

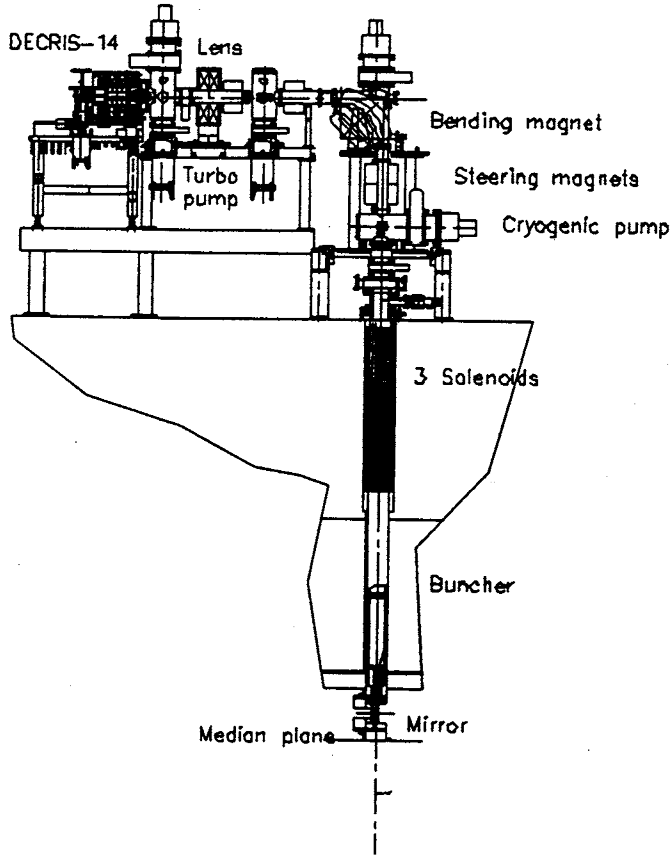


Fig.4. DECRIS-14 ion source injector ELEV

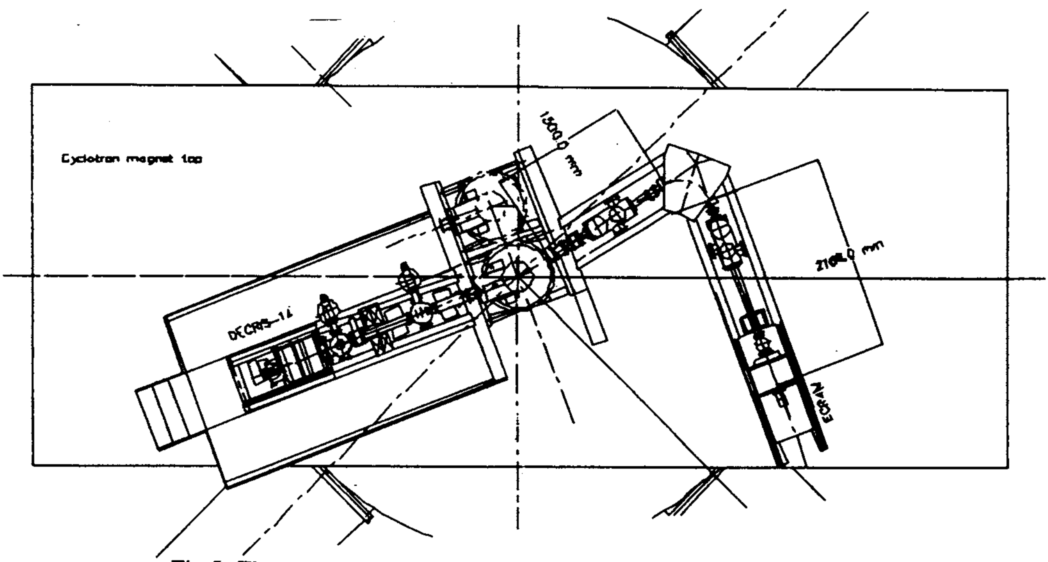


Fig.5. The plan view of ECR4M (GANIL) and DECRIS-14 injector

the GANIL injector and the DECRIS injector disposition on the top of the cyclotron magnet are shown in Figs.4 and 5, respectively.

Magnetic and Focusing Elements

Several configurations of the axial injection system were considered. We chose the shortest beam line with a minimum number of optical elements which is necessary to provide the required degrees of freedom. The beam line consists of short solenoid (lens) in the horizontal part, which is located at 210 mm away from the ECR ion source, three long solenoids in the axial magnet hole; and a bending magnet is located at 1.22 m away from the lens, which carries out two functions:

1. Beam momentum analysis,
2. Beam bending into the vertical channel.

The lens focuses the extracted beam at the entrance slit of the analysing magnet. The slit is located at 42 cm after the lens and 80 cm before the analysing magnet. A nominal beam size of 15 mm has been assumed at the entrance slit of analysing magnet. Charge state selection is provided by a 90° vertical bending magnet running up to 1.4 kG. For $Z/A =$ $= 0.5$ and 25 kV injection voltage, we need 0.89 kG of magnetic field. The main parameters of the analysing magnet are listed in Table 3. The second slit is situated at 80 cm after the bending magnet. At the second slit position, the ion beam dispersion is 1.6 cm/ %. First order calculations have been performed using TRANSPORT code. The optical parameters of the elements provide transmission of the beam with the emittance of $\varepsilon = 150\,\pi$ mm.mrad. As an example, the envelopes of the ion beam with $Z/A = 0.5$ are shown in Fig.6. The fringing magnetic field in the axial hole, which is plotted in Fig.7, was represented by a number of short solenoids with a corresponding strength of magnetic fields.

Table 3. The main parameters of the bending magnet

Magnet radius	400 mm
Wedge angles	26.5°
Dispersion	1.62 cm/ %
Vertical gap	80 mm
Maximum current	22 A
Maximum volt	48 V
Water flow rate	4 L/M
Temperature rises	70°C

Table 4. The main parameters of the lens and solenoids

Parameters	Solenoids	Lens
Maximum axial magnetic field	1 kG	4.9 kG
Effective length	42 cm	12.6 cm
No. of turns	80	256
Iron-yoked thickness	1 cm	1 cm
Solenoid length	50 cm	20 cm
Unner diameter	195 mm	106 mm
Conductor dimensions	11.5 × 11.5 mm	11.5 × 11.5 mm
Maximum current	500 A	321 A
Power consumption	3.15 kW	5.78 kW
Water flow rate	0.67 l/min	2.4 l/min
Temperature rise	8 degrees	34 degrees

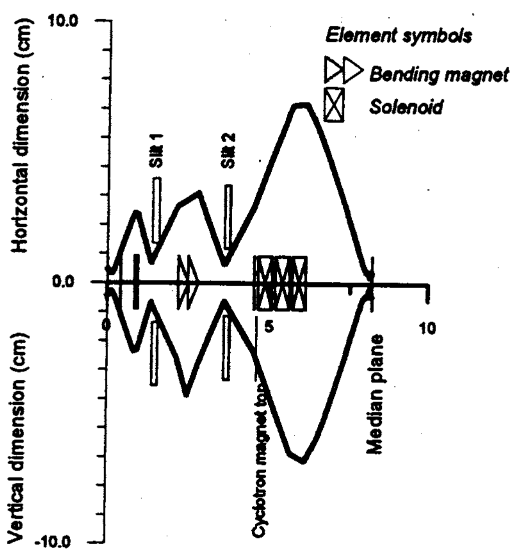
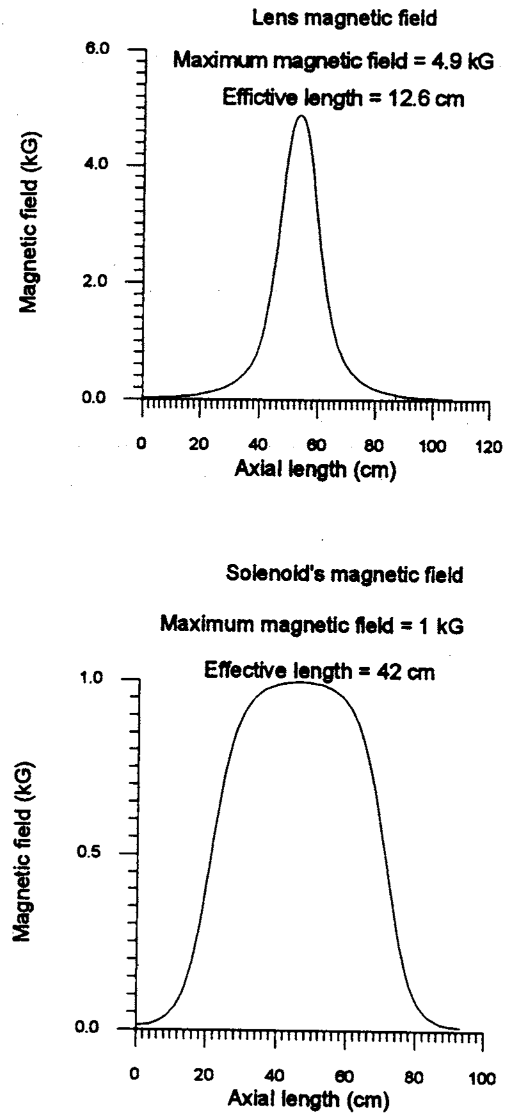


Fig.6. The beam envelope through the transmission line for $Z/A = 0.5$



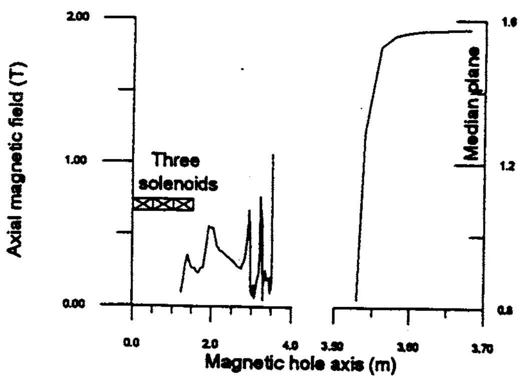


Fig.7. The axial magnetic field in the cyclotron axial hole

Fig.8. The axial magnetic fields for the lens and the solenoids

The main parameters of the solenoids and the lens are listed in Table 4. The solenoids, lens, and bending magnet designs were done with Poisson program. The axial magnetic fields of the lens and the solenoids are plotted in Fig.8. The transverse distribution of the magnetic field of the bending magnet is plotted in Fig.9. The beam is focused after the solenoids by the fringing magnetic field. To get beam dimension less than 1 cm (at the

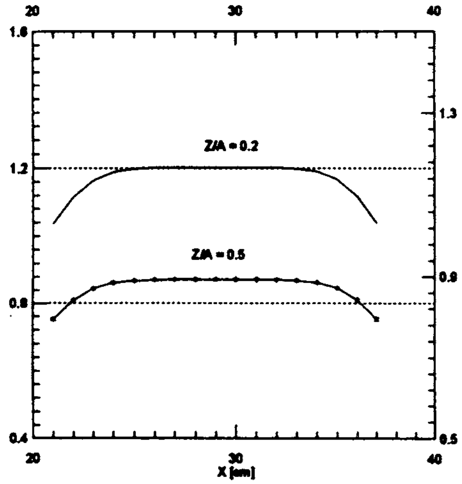


Fig.9. The magnetic field distribution (in kG) of the bending magnet

mirror entrance) we need not more than 0.9 kG. in any solenoid. The short beam line allows us to reduce the vacuum demands. To increase the vacuum conductivity of the vertical channel, we increased the inner diameter of the beam guide pipe inside the axial hole up to 150 mm, thus we enlarged the diameter of the axial hole up to 300 mm.

Vacuum

The losses due to residual gases in transmission line are calculated for some ion beam to get the pressure needed inside the ion guide pipe. In order to get the charge exchange cross section in this range of energies, we used Müller and Salzborn formula [3]. Nitrogen is considered as a residual gas. The transmission efficiency with respect to the pressure in Torr is plotted in Fig.10. We chose 10^{-7} Torr as working pressure inside ion pipe guide. To provide a vacuum of 10^{-7} Torr differential pumping is used. The gas flow from the ion source is evacuated in the horizontal line part which is separated from the main line by a diaphragm. This part is pumped by a turbopump and a cryopump with a pumping speed 500 l/s and 3200 l/s, correspondingly. At a gas flow of 0.05 cm^3/min the vacuum 10^{-7} Torr will be provided. The main part of the channel is pumped by two cryopumps with a total pumping speed of 6400 l/s. The preliminary vacuum is provided by a turbopump. The inner surface of the beam guide pipe was specially treated to reduce the outgasing flow.

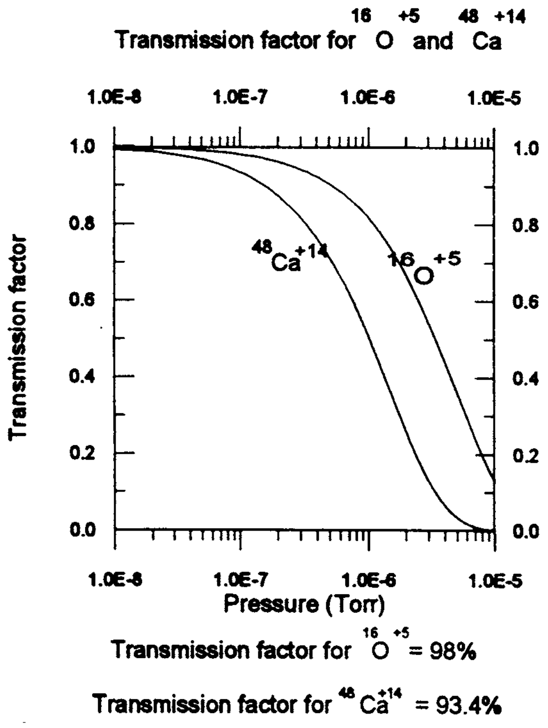


Fig.10. Some ion beam losses due to pressure

Inflector and Central Region

The main feature of the axial injection system, which was taken into account during the central region calculation, is the injection voltage from 16 to 25 kV, which is low comparing with the voltage of four dees from 140 to 200 kV. The optimum initial radius of the central ray at the first gap is 50 mm, which is determined from the optimum centring and first turn energy gain conditions. An electrostatic mirror has been considered [4] in order to have the smallest inflector, well shielded against the RF voltage, and be able to inject the beam into the maximum radius. The mirror is centred on the axis of the cyclotron. The calculations for such a mirror were done analytically. Mirror parameters have been chosen by taking as reference case the $Z/A = 0.5$ ion injected at 25 kV in the magnetic field 1.45 T with a corresponding magnetic radius 22 mm. The mirror structure consists of an electrode, a grid, and an outer cooled copper shell at ground potential. The gap between this shell and the high voltage electrode is 7 mm. The main parameters are obtained:

1. the angle of the mirror grid with the median plane = 47°,
2. mirror voltage $V = 23.6$ kV,
3. distance from the cyclotron axis to the exit point projected in the median plane = 14.6 mm,
4. distance between the electrode and the grid = 9.2 mm,
5. maximum applied electric field between the electrode and the grid = 25.6 kV/cm.

We couldn't increase the angle between the mirror and the median plane more than 47° to get bigger radius because of increasing the mirror dimensions. The maximum injection voltage of ion source is 25 kV for $Z/A = 0.5$ and the second harmonic, and according to the constant orbit principle, the injection voltage will be decreased with decreasing Z/A up to 0.2 for the second harmonic. The central ray trajectory in the magnetic field map was obtained by integrating the Lorentz equations. A grounded slit was placed at 40 mm away from the cyclotron center. The improvement of beam centering during the acceleration was performed by adjusting the direction of the electric field of the first acceleration gap and its geometry. The particle trajectory centers for 40° of RF phase and up to 2 turns are plotted in Fig.11. The central ray will pass through the puller center. The electric field between the dees and the dummy-dees is considered as a Gaussian distribution [5]. In our simulation of the central region, we changed the maximum voltage of the dees from 140 kV up to 200 kV to know the mechanical boundaries and the minimum permissible voltage of the dees with taking into account the electric charge between dees and grounded surfaces. The particle trajectories for 5 particles and 40° of the RF phase

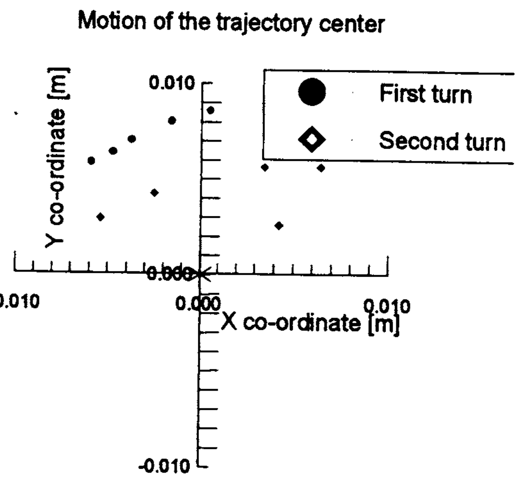


Fig.11. Particle trajectory centers with a dee voltage 170 kV and for 40 degrees of the RF phase

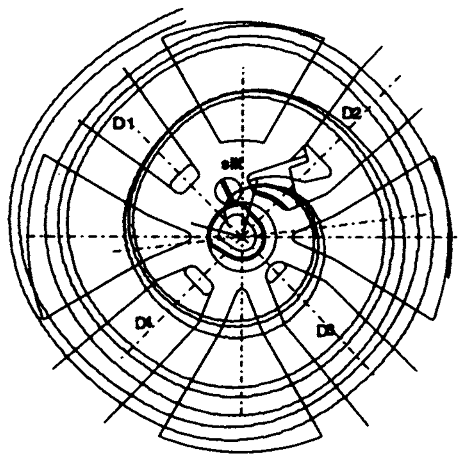


Fig.12. Particle trajectories with dee voltages 140, 150, and 170 kV

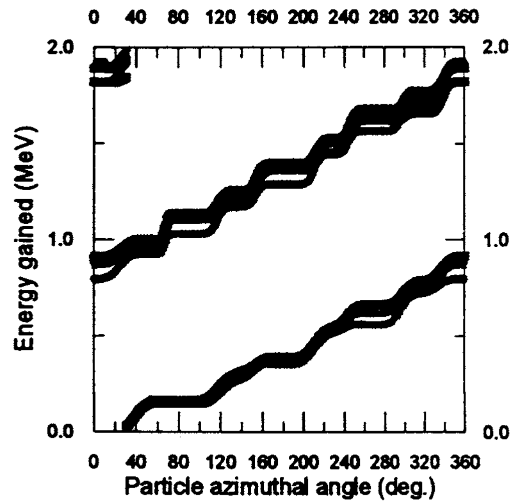


Fig.13. Energy gained with 170 kV of dee voltages

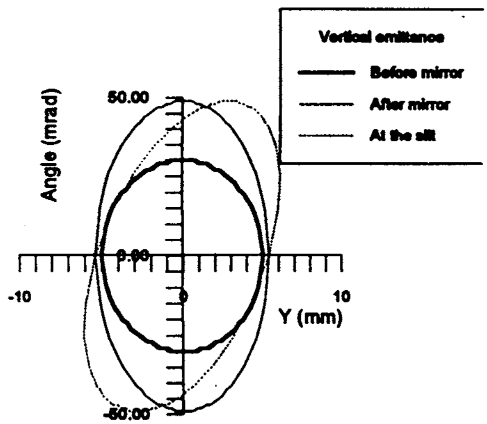


Fig.14. Vertical emittance before and after mirror and at the grounded slit

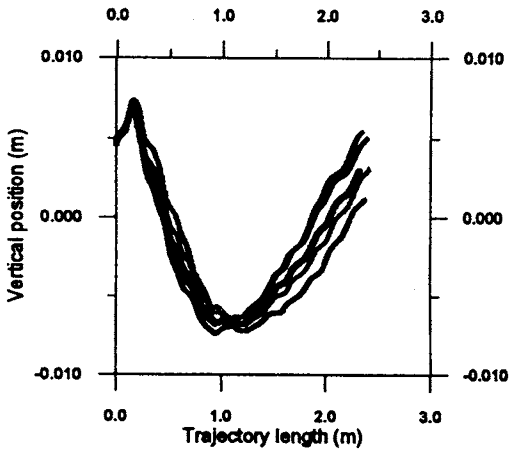


Fig.15. The particle vertical motions for 40 degrees of the RF phase

with 170 kV of dee voltages are shown in Fig.12. The energy gained for 5 particles and 40° of RF phase with 170 kV of the dee voltages in shown in Fig.13. In all cases, the vertical dimension of the beam will be not more than 20 mm up to two turns according to the output emittance of the inflector. Vertical emittances through the inflector are shown in Fig.14. The vertical gaps of the dees are 24 mm in the center. The vertical trajectories for 5 particles in RF phase range 40° with maximum initial vertical position and maximum initial vertical angle at the slit are plotted in Fig.15.

Buncher

A simple grided double gap Klystron-type buncher will be placed 1 m away from the median plane. This buncher consists of a cylindrical electrode, with length 20 mm and a diameter 150 mm, and two accelerating gaps of 3 mm. The step between the grid wires is about 5 mm. The distance between the median planes of the accelerating gaps is 23 mm and the voltage amplitude, which is applied on the electrode is in the range from 300 up to 450 V. The relation between the cyclotron RF phase acceptance and buncher efficiency is shown in Fig.16. The results of these calculations were done without taking into account the space charge effect.

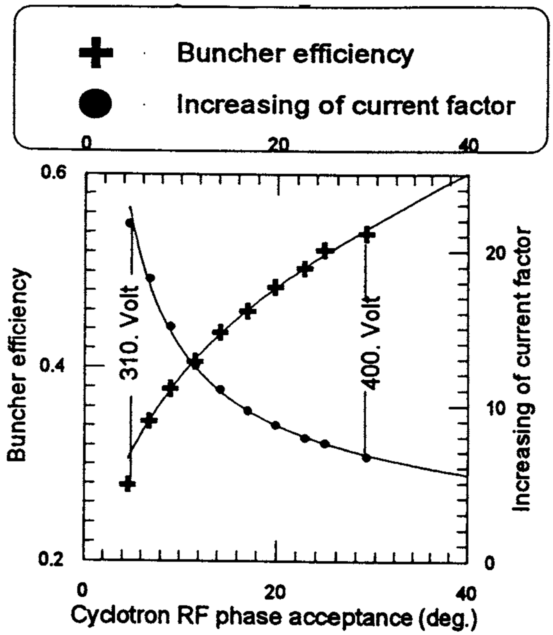


Fig.16. Buncher efficiency

Table 5. The main parameters of the axial injection system of the U-400M cyclotron

Ion Source	DECRIS-2 (Dubna) 1994 ECR-4M (GANIL) 1995
Max.injection voltage	25 kV
Beam line length	8,2 m
Focusing element	Solenoid — 4 units
Analysing magnet	$R = 40$ cm
Resolution	80
Steering magnet	4 units
Vacuum	1.0×10^{-7}: 3×10^{-7} Torr
Pumping speed	7.5×10^{3} l/s
Type of pumps	Cryogenic — 3 units Turbopump — 2 units
Buncher	2 gaps (600 V)
Distance between buncher and median plane	1 m
Inflector	Mirror 1994 Spiral 1996
Diagnostics	Faraday cup — 3 units Collimator — 2 units

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