RECENT DEVELOPMENTS AT DUBNA U400 AND U400M CYCLOTRONS

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At the Flerov Laboratory of Nuclear Reactions there are four heavy ion cyclotrons (U-400, U-400M, U-200 and IC-100) used for physical investigations and applied research. In 1995-1996 the U-400 and U-400M were equipped with modern ECR ion sources (14.5 GHz). At present the U-400 cyclotron is used for a long experiment with ^{48}Ca. Low consumption of working substance (0.4 mg/hr) was reached in the ion source for injection of a 100 μ A beam. Physical experiments at the U-400M are carried out using Li, B, C, O, N, Ar beams with ions of 30 - 55 MeV/nucleon. There are a few large physical facilities at the cyclotron: FOBOS 4π detector, COMBAS fragment separator, ACCULINNA, BGO ball. ^{6}He and ^{8}He beams were obtained on a high resolution beam line created for generation of radioactive beams.

1. Introduction

The development of FLNR's accelerators is determined by the physical research performed at the Laboratory. The Laboratory carries out research in three main directions of heavy ion physics. They include the synthesis of heavy and exotic nuclei with ion beams of stable and radioactive isotopes, studies of nuclear reactions, studies of interaction of matter with heavy ions and applied research.

To carry out the Laboratory's scientific programme, there are four isochronous heavy ion cyclotrons: CI-100, U-200, U-400, U-400M and the MT-25 electron accelerator. During the last two years the U-400 and U-400M cyclotrons have been upgraded through supplying them with ECR ion sources and axial injection systems.

2. The U-400 cyclotron and the production of intense ^{48}Ca beams

2.1 The U-400 cyclotron

The U-400 isochronous heavy ion cyclotron has been in operation for 20 years. Until 1996 the accelerator operated with an internal PIG type ion source, which enabled to achieve high intensities of ion beams up to Kr (for example, $1.5*10^{14}$ pps for Li, $6*10^{13}$ pps for Ne, $1.2*10^{13}$ pps for Ar, $1*10^{12}$ pps for Kr) [1].

The main experiments on the cyclotron include synthesis of new elements. The synthesis of a superheavy element with Z=114 has set a task of producing ^{48}Ca beams with an energy of about 5 MeV/n and an intensity of about $2*10^{12}$ pps. One of the main disadvantages of the PIG type ion source was its huge consumption of working substance: about 10 mg/h, which made it impossible to carry out long experiments. Therefore in 1996 the cyclotron was upgraded. It was equipped with an ECR source, created at GANIL [2], and an axial injection system (Fig. 1). The ECR source was specially modified by FLNR ECR group to produce ^{48}Ca beam at low substance consumption.

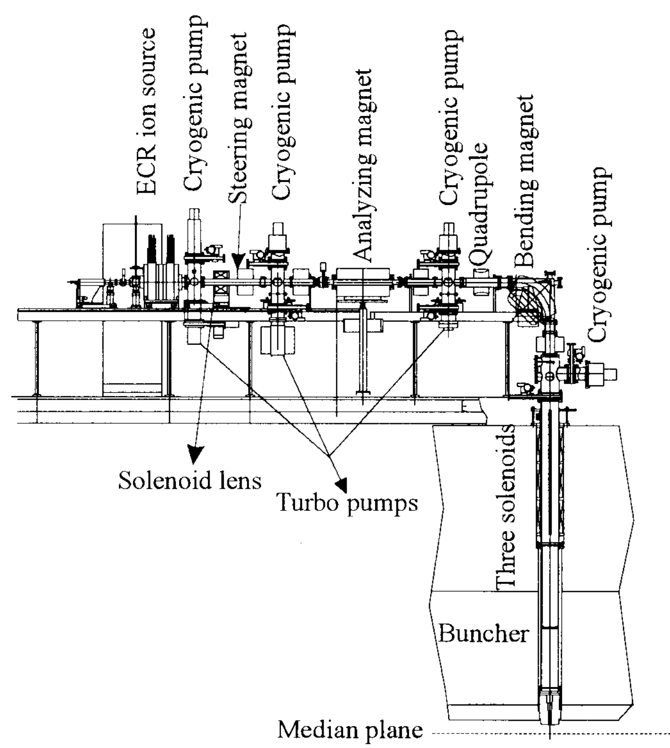

Fig. 1. The axial injection system of the U-400 cyclotron

2.2 Production of solid ion beams with the ECR4M

A new method using a combination of a microoven with a hot tantalum sheet inside the discharge chamber was used at the ECR4M for the production of intense beams of metallic ions with a relatively low melting point such as Mg and Ca.

After the first experiments using CaO+Al as working substance, metallic calcium was used to provide intense ion beams of ^{48}Ca. To ensure optimal consumption of ^{48}Ca during long experiments the intensity of the $^{48}Ca^{5+}$ beam from the ECR4M was set at a level of 30-50 μAe. A typical Ca spectrum is shown in fig. 2

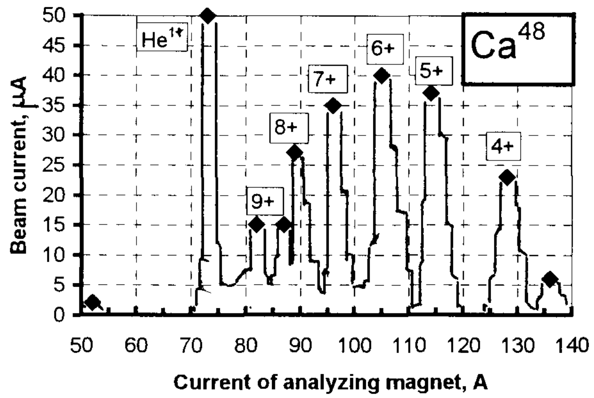

Fig.2. Spectrum of ^{48}Ca from ECR4M optimized for $^{48}Ca^{5+}$.

In this case the oven and screen temperature of about 400°C was supplied. The efficiency of $^{48}Ca^{5+}$ production was about 4%. The average consumption rate of metallic calcium without collection and regeneration can be evaluated as 0.4 mg / hour. The efficiency of ^{48}Ca ion beam production by a new ECR4M ion source is more then 25 times higher compared to the PIG ion source at the U-400.

2.3 Transportation of the beam along the axial injection channel and its acceleration in the cyclotron

The ECR source and the components of the axial injection system are located on the cyclotron magnet. There are two magnets in the transportation channel: AM-102, used to analyze and separate the beam injected from the ECR source, and AM-90, used to bend and guide the beam to the vertical part of the channel. Beam focusing was provided by two lenses installed in the external part of the channel and three long solenoides installed in the channel of the cyclotron magnet, which along with the fringing magnetic field in the channel focus the beam on the cyclotron center. The working vacuum in the channel ($2*10^{-7}$ Torr) is provided by cryogenic and turbomolecular pumps. Transportation of the beam from the source to the cyclotron centre results in the beam vacuum losses of no more than 10% for all types of ions [3].

The beam is turned from the vertical channel to the median plane by a spiral inflector. The start radius of the beam is 34 mm, which ensures its optimal motion in the centre. Hence, the injection voltage varies from 12 to 25 kV depending on the ion mass-to-charge ratio.

The phase capture of the cyclotron is 20-25°. To increase the capture efficiency, the axial injection system is equipped with a buncher, which operates on the first harmonic of the RF generator. The axial injection channel design provides for installation of a buncher at distances of 4 m and 1.1 m from the median plane. Fig. 3 shows the efficiency of beam capture at acceleration with the buncher and without buncher. The capture efficiency depends on the beam current. The longitudinal space charge decreases the bunching effect. If the buncher is placed to the 4 m position, the bunching effect tends to have a fall, when injected beam current is above 10 mkA. For the position of 1.1 m, practically no influence of the space charge was observed up to current value of 60 mkA.

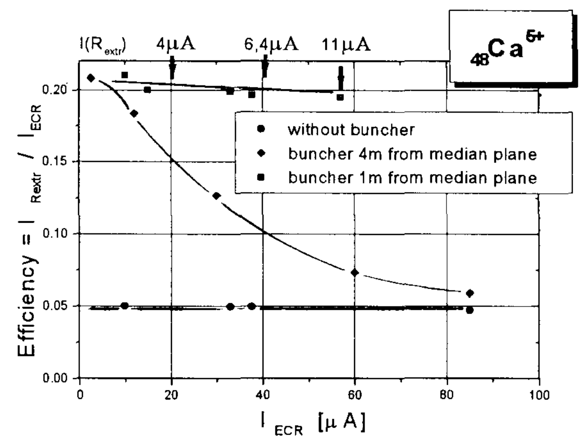

Fig.3. Efficiency of phase capture and acceleration in the cyclotron U-400 without buncher and with buncher installed in 1.1m and 4m from the median plane. ($I_{R\,extr}$ - accelerated beam current at the final radius, I_{ECR} - injected beam current)

The operating vacuum in the cyclotron chamber is $3*10^{-7}$ Torr. The beam is extracted from the cyclotron by using a thin stripping foil, the extraction efficiency due to the charge dispersion is about 40%. The transportation along the channel to the physical target provides 93% efficiency. Table 1 presents the intensities and factors of transporting a $^{48}Ca^{5+}$ beam from the ECR source to physical target.

Table 1:Efficiency of transporting a $^{48}Ca^{5+}$ beam from the ECR source to the physical target

Measuring point	Beam intensity		Ion
ECR source, after separation	57 μAe	$6.8*10^{13}$ pps	$^{48}Ca^{5+}$
Cyclotron centre	12 μAe	$1.4*10^{13}$ pps	$^{48}Ca^{5+}$
Extracting radius	8.8 μAe	$1*10^{13}$ pps	$^{48}Ca^{5+}$
Extracted beam	12 μAe	$4.2*10^{12}$ pps	$^{48}Ca^{18+}$
Target	11 μAe	$3.7*10^{12}$ pps	$^{48}Ca^{18}$

During the experiments there was a need to vary the energy of $^{48}Ca^{5+}$ ions smoothly in a range of 215 to 261 MeV, which was done in two ways: by changing the radial position of the extracting foil and by changing the level of the cyclotron magnetic field. The maximum intensity of the ^{48}Ca beam on the target was $3.7*10^{12}$ pps, the average intensity for a long period (about a month) being $2*10^{12}$ pps.

3. U-400M Cyclotron

The ECR source and the axial injection system of the U-400M [4] were put into operation in 1995. The design of the axial injection system of the U-400M cyclotron (Fig. 4) is similar to that of the U-400 cyclotron, but there is only one bending magnet, which is used both to analyze and separate the beam.

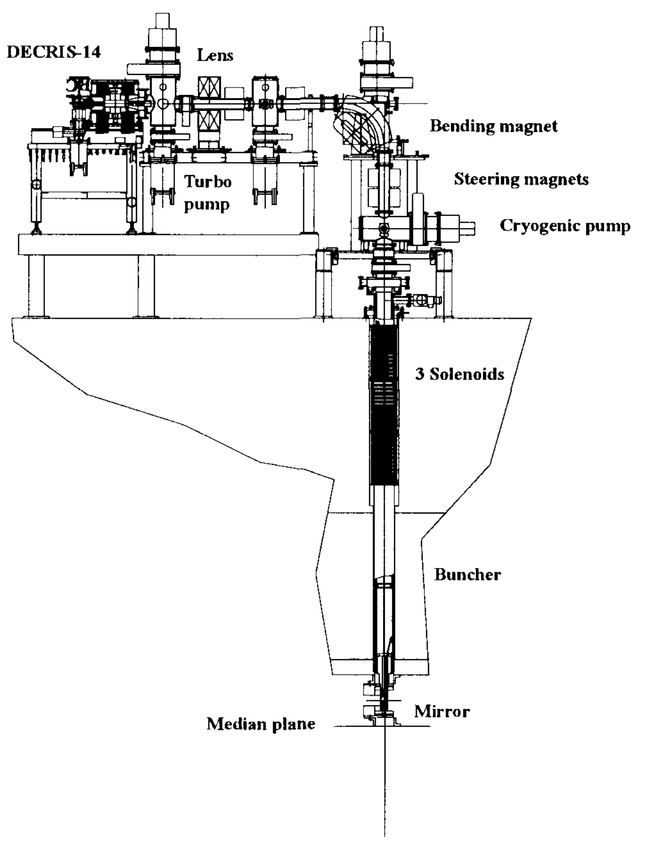

Fig. 4. The axial injection system of the U-400M cyclotron.

The DECRIS-14 (Dubna ECR Ion Source) installed at the cyclotron is created at the FLNR [5]. The beam is focused by a lense and three solenoids placed in the axial channel. The channel is pumped out by two turbomolecular and three cryogenic pumps, which provide vacuum of $2.5*10^{-7}$ Torr.

While the axial injection system was created, the cyclotron centre presented the largest difficulties. The cyclotron has 4 dees, there is no possibility of installing an inflector remotely. The voltage on the dees is high - about 150 kV. At present, an electrostatic inflector-mirror is used, which ensures the maximum start radius. Special orientation of accelerating gaps allows the beam to be adequately centred (Fig. 5).

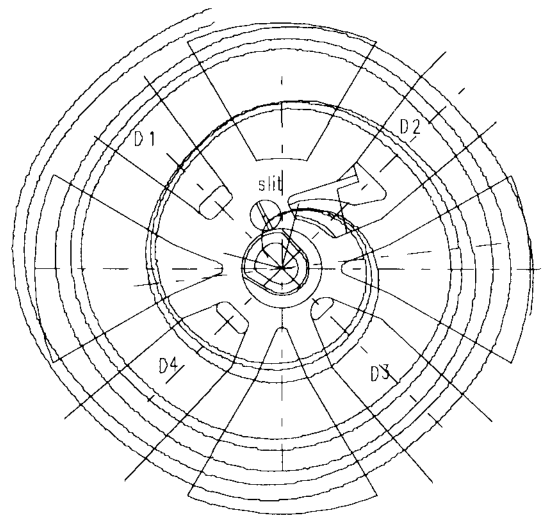

Fig.5. Diagram of the central region of the U-400M cyclotron and the trajectories of ions at dee voltage equal to 140, 150 and 170 kV.

Due to good vacuum in the cyclotron chamber (better than $1*10^{-7}$ Torr) and high acceleration rate, the beam loss during the process of acceleration up to the final radius is no more than 10%.

The beam is extracted from the cyclotron by a stripping on a thin foil. The beam extraction system (Fig. 6) allows the beam to be extracted with a stripping ratio $Z_{int}/Z_{ext} = 1.4 \div 1.7$ (Z_{int} - the charge of ions of the internal beam, Z_{ext} - the charge of ions of the extracted beam). The foil positioning mechanism allows the foil to be moved within the required zone. The passive focusing channels FC-1 and FC-2 focus the beam and match it to the acceptance of the transportation channel of the extracted beam. The modernized this year extraction system provides a beam extraction efficiency of 70-80%.

Until 1998 the beam of the U-400 cyclotron had been mainly used by the FOBOS 4π-detector, which required low intensity and high quality beams, provided by separating properties of the cyclotron-FOBOS beam transportation channel. A beam with the following parameters was produced at the target:

ion - $^{14}N^{5+}$
energy - 50 MeV/nucl
energy spread - 0.3%
intensity - 1 nA
duration of microbunch - 0.6 ns

At present a number of new set-ups have been mounted, including the ACCULINNA channel, intended for the production of radioactive ion beams. To carry out these experiments, the ECR source has been specially adjusted, which has enabled the production of high intensity beams of light ions both of gaseous and solid materials.

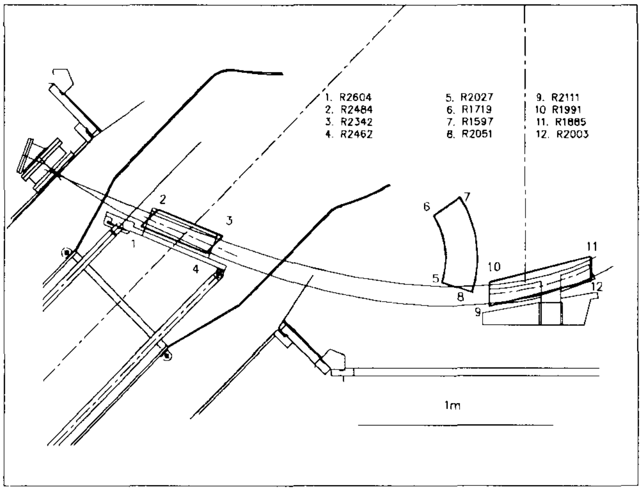

Fig. 6. Lay-out of the components of the beam extraction system and the beam trajectory.

3.1 Production of light ion beams from the DECRIS-14

The results of ion yields for light ion beams of Li, B, N, O are summarized in table 2.

Table 2.
Yields (eμA) for light ions from the DECRIS-14. The ion source was optimized for marked (*)charge states.

Charge	1+	2+	3+	4+	5+	6+	7+	Notice
^{7}Li	15	50	25					no screen
^{7}Li	138	290*	50					with screen
^{11}B	20	55	100	50				no screen
^{14}N				570	640*	70		no screen
^{16}O				340	660*	203	68	no screen

It is important to underline that the DECRIS-14 (Dubna Electron Cyclotron Ion Source, 14 GHz) was optimized only for charge states required for acceleration. For the production of high intensity ion beams a negatively biased electrode was used.

Significant progress in Li ion beam production was made by using a new microoven for the evaporation of metal samples and a screen which was thermally isolated from the discharge chamber walls. Helium was used as the support gas. The oven worked for about 300 hours without any failures. Since the screen is thermally isolated from the walls, it is sufficient to provide microwave power of 200 - 300 W to achieve the screen temperature exceeding the working substance evaporation temperature. A typical Li spectrum with He as support gas, SHF power of 220 W, extracted voltage of 16.8 kV is presented in figure 7.

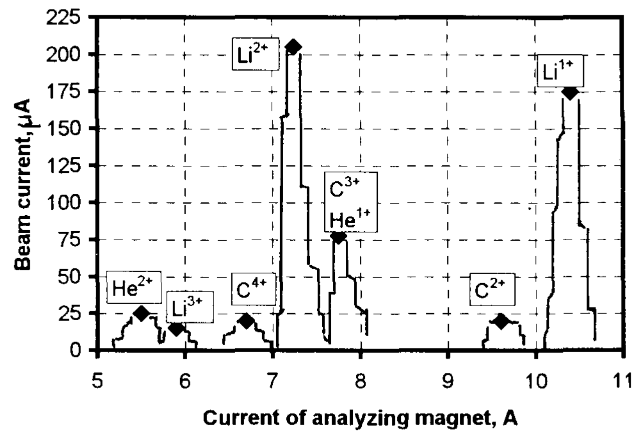

Figure 7. Li spectrum optimized on the maximum current of Li $^{2+}$ beam required for acceleration.

The intensity of beams of light ions in the range from Li to Ne with an energy of 30÷50 MeV/nucl was $3\div5*10^{12}$ pps. This was achieved without using a buncher. We hope to put the bunching system into operation in the coming months and to increase the intensity of the beam by a factor of 3÷5. Table 3 shows the efficiency of the beam transportation from the ECR source to the physical target obtained for $^{13}C^{4+}$.

Table 3.
Efficiency of the $^{13}C^{4+}$ beam transportation
from the ECR source to the physical target without the bunching system

I_{ECR}	I, in the center	I, at final radius	I, extracted	I, on the target
$^{13}C^{4+}$	$^{13}C^{4+}$	$^{13}C^{4+}$	$^{13}C^{6+}$	$^{13}C^{6+}$
90 μA	5.5 μA	5 μA	5.5 μA	4.5 μA
$1.4\cdot10^{14}$ pps	$8.3\cdot10^{12}$ pps	$7.5\cdot10^{12}$ pps	$5.5\cdot10^{12}$ pps	$4.5\cdot10^{12}$ pps
6%				
	90%			
		73%		
			82%	
		3.2%		

A series of experiments on the production of radioactive ion beams from Li to O with an energy of 30÷50 MeV/nucl was carried out at the ACCULINNA facility [6]. On the focal plane of the facility spots of ^{6}He, ^{8}He, ^{11}Li, ^{12}Be beams were about 10 mm diameter, the ion energy spread - ΔE/E = 5%. The obtained results are presented in Table 4.

Table 4.
Radioactive ion beams produced by ACCULINNA facility at the Be target (primary beam intensity - $6.25 \cdot 10^{12}$ pps).

RIB, E_{RIB}	Yields, pps	Reaction
^{6}He (25 MeV/A)	$9.0 \cdot 10^5$	Be + ^{7}Li (32 MeV/A)
^{8}He (25 MeV/A)	$2.5 \cdot 10^3$	Be + ^{13}C (43 MeV/A)
^{11}Li (35 MeV/A)	$2.6 \cdot 10^2$	Be + ^{15}N (47 MeV/A)
^{12}Be (27 MeV/A)	$1.3 \cdot 10^4$	Be + ^{18}O (35 MeV/A)

Conclusions

The last three years have been devoted to the development of FLNR's accelerators. The U-400 and U-400M cyclotrons were equipped with ECR ion sources and axial injection systems. This made it possible to accelerate heavier ions as well as to produce more intense ion beams of high energy.

With the ECR sources, ion beams of solid material were produced comparable in intensity with beams of gaseous materials. Low consumption of working substance allowed long physical experiments to be started on beams of rare isotopes, for example of ^{48}Ca.

At present the main direction of the development of FLNR's accelerators involves efforts to achieve high efficiency of transporting the beam from the ECR source to a physical target mainly by improving the bunching system.

It is planned that in 1998, the U-400 and U-400M cyclotrons will work for physical experiments for 6,000 hours.

Acknowledgment

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