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DEVELOPMENT OF JINR FLNR HEAVY-ION ACCELERATOR COMPLEX IN THE NEXT 7 YEARS

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Plan for seven-year accelerator development and operation is presented.

Представлены статус и план развития ускорительного комплекса ЛЯР ОИЯИ.

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INTRODUCTION

At the present time four isochronous cyclotrons: U400, U400M, U200 and IC-100, are under operation at JINR's FLNR. Total operation time is about 10 000 hours per year. The U400M is a primary beam generator and U400 is used as postaccelerator in RIB (DRIBs) experiments to produce and accelerate exotic nuclides such as ^{6}He, ^{8}He, etc. Layout of FLNR accelerator complex is presented in Fig. 1 [1].

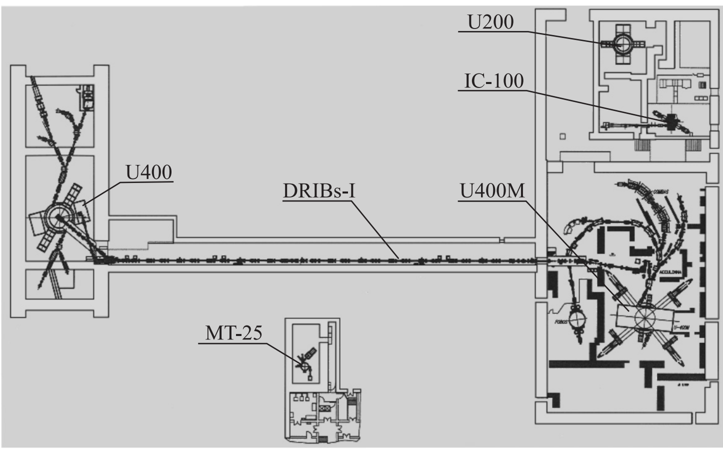

Fig. 1. Layout of the JINR FLNR accelerator complex

1. U400 → U400R CYCLOTRON

The cyclotron U400 (pole diameter 4 m) has been in operation since 1978 [2, 3]. In 1996, the ECR-4M ion source (GANIL) was installed at the U400. The axial injection system with two bunchers (sine and linear) and a spiral inflector was created to inject ions into cyclotron (Fig. 2). From 1997 to the present time, U400 has worked in total 64 000 h. About 66% of the total time was used for acceleration of $^{48}Ca^{5+,6+}$ ions for synthesis of new superheavy elements. Within the mentioned period elements, with $Z = 113, 114, 115, 116, 118$ were synthesized. Chemical properties of $Z = 112$ were studied. The ^{48}Ca beam intensity on the target is $8 \cdot 10^{12}$ pps (1.2 pμA) at ^{48}Ca substance consumption of 0.4 mg/h. Extraction efficiency of ^{48}Ca beam by stripping is at a level of 40% only. The U400 → U400R modernization is planned to start in 2010 and finish in 2011. The aims of the modernization are:

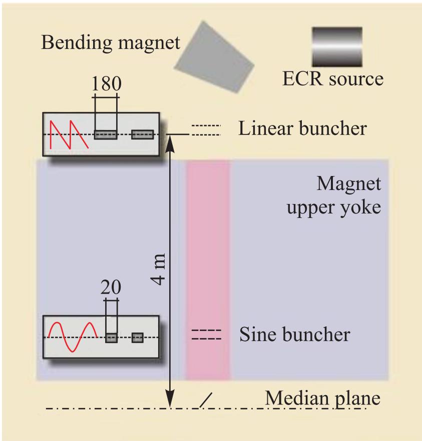

Fig. 2. Scheme of the beam bunching system

— increasing ^{48}Ca, ^{50}Ti, ^{54}Cr, ^{58}Fe, ^{64}N beam intensity on the target up to 2.5–3 pμA;

— providing the fluent ion beam energy variation by factor 5 by magnetic field variation from 0.8 up to 1.8 T instead 1.93–2.1 T now;

— improvement of the energy spread in the ion beam at the target up to 10^{-3};

— improvement of the ion beam emittance at the target up to 10 $\pi \cdot$ mm $\cdot$ mrad.

The project of modernization intends changing axial injection system, magnetic structure, vacuum system, RF system, power supply system, beam diagnostic system and additionally

Table 1. **Comparative parameters of U400 and U400R**

Parameters	U400	U400R
A/Z range	5–12	4–12
Magnetic field, T	1.93–2.1	0.8–1.8
K factor	530–625	100–500
RF modes	2	2, 3, 4, 5, 6
Injection voltage, kV	10–20	10–50
Ion energy range, MeV/nucleon	3–20	0.8–27
Number of sectors	4	4
Number of dees	2	2
Flat-top system	–	+
Beam extraction	Stripping	Stripping, deflector
Power consumption, MW	~ 1	~ 0.4

electrostatic deflector positioning. The main comparative parameters of U400 and U400R are presented in Table 1. The working diagram of the U400R cyclotron with intensities of ^{48}Ca beams is presented in Fig. 3. Parameters of U400 and U400R typical ion beams are presented in Table 2.

Table 2. **Parameters of U400 and U400R ion beams**

U400			U400R (expected)		
Ion	Ion energy, MeV/u	Output intensity	Ion	Ion energy, MeV/u	Output intensity
$^{4}He^{1+}$	—	—	$^{4}He^{1+}$	6.4–27	23 pμA
$^{6}He^{1+}$	11	$3{\cdot}10^7$ pps	$^{6}He^{1+}$	2.8–14.4	10^8 pps
$^{8}He^{1+}$	7.9	—	$^{8}He^{1+}$	1.6–8	10^5 pps
$^{16}O^{2+}$	5.7; 7.9	5 pμA	$^{16}O^{2+}$	1.6–8	19.5 pμA
$^{18}O^{3+}$	7.8; 10.5; 15.8	4.4 pμA	$^{16}O^{4+}$	6.4 ÷ 27	5.8 pμA
$^{40}Ar^{4+}$	3.8; 5.1	1.7 pμA	$^{40}Ar^{4+}$	1–5.1	10 pμA
$^{48}Ca^{5+}$	3.7; 5.3	1.2 pμA	$^{48}Ca^{6+}$	1.6–8	2.5 pμA
$^{48}Ca^{9+}$	8.9; 11; 17.7	1 pμA	$^{48}Ca^{7+}$	2.1–11	2.1 pμA
$^{50}Ti^{5+}$	3.6; 5.1	0.4 pμA	$^{50}Ti^{10+}$	4.1–21	1 pμA
$^{58}Fe^{6+}$	3.8; 5.4	0.7 pμA	$^{58}Fe^{7+}$	1.2–7.5	1 pμA
$^{84}Kr^{8+}$	3.1; 4.4	0.3 pμA	$^{84}Kr^{7+}$	0.8–3.5	1.4 pμA
$^{136}Xe^{14+}$	3.3; 4.6; 6.9	0.08 pμA	$^{132}Xe^{11+}$	0.8–3.5	0.9 pμA

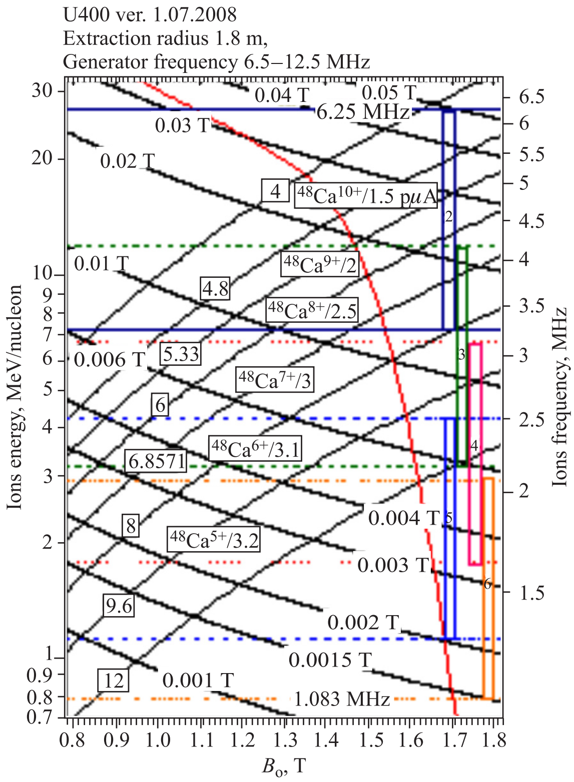

Fig. 3. Operating chart of the U400R cyclotron

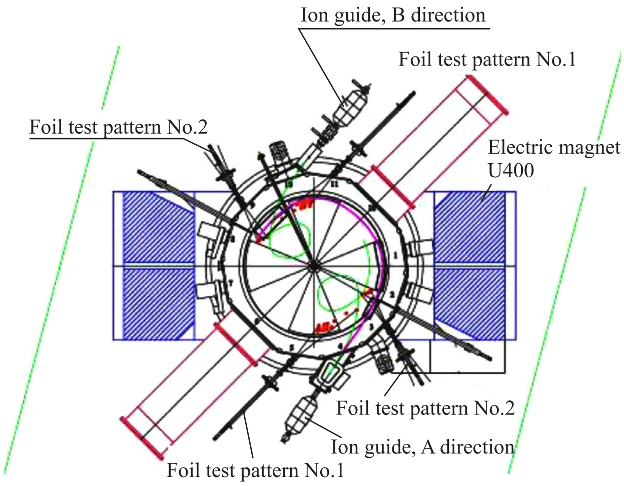

Fig. 4. Scheme of the beam extraction from U400R in two directions

Scheme of the ion beam extraction from U400R by stripping foils in two opposite directions A and B and by deflector in direction A is presented in Fig. 4.

2. U400M CYCLOTRON

The 4-sector and 4-dee cyclotron U400M has been in operation since 1991 [3]. The cyclotron was originally intended for ion beam acceleration with $A/Z = 2{-}5$ at energies of 20–100 MeV/nucleon. The ion beams are extracted from cyclotron by stripping with stripping ratio $Z_2/Z_1 = 1.4{-}1.8$ and therefore energy range of extracted beams is from 30 up to 50 MeV/nucleon. The light ion beams from U400M are used for radioactive beams production. The intensity of light ion beams such as ^{7}Li or ^{11}B on the targets is $(3 \div 5) \cdot 10^{13}$ pps. Tritium ions are accelerated as molecular $(DT)^{1+}$ with intensity $6 \cdot 10^{10}$ pps and energy 18 MeV/nucleon. The generation of $(DT)^{1+}$ ion is in special RF ion source. In 2008 the

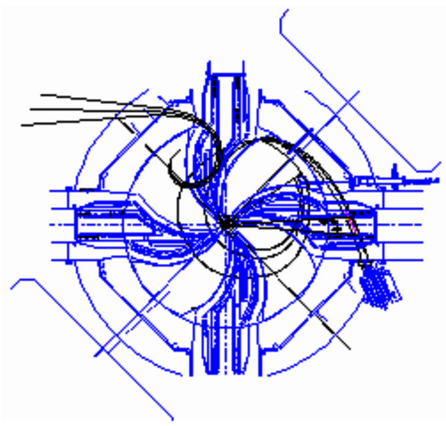

Fig. 5. Scheme of beam extraction from U400M

U400M possibilities have been extended by addition of ion beams with $A/Z = 5{-}10$ at energies of $4.5{-}20$ MeV/nucleon. The low-energy ions such as ^{48}Ca will also be used for synthesis and study of new elements. Scheme of low- and high-energy beam extraction from U400M in two opposite directions is presented in Fig. 5.

3. U200 CYCLOTRON [5]

The 2-m, 4-sector and 2-dee U200 cyclotron has been in operation more than 40 years. At present the accelerator is used for isotope production with 36 MeV ^{4}He beam. In the next year we are going to install an ECR ion source at U200.

4. IC-100 [6]

The 1-m pole diameter, 4-sector, 2-dee cyclotron is equipped with SC ECR ion source. The cyclotron was designed to accelerate ions with a fixed energy of 1.2 MeV/nucleon. The range of accelerated ion is from C up to W. The IC-100 is used for polimer film irradiation (200×600 mm) and solid matter investigation. The ^{132}Xe^{23+} beam intensity is, for example, 0.2 pμA at the target. Layout of IC-100 is presented in Fig. 6.

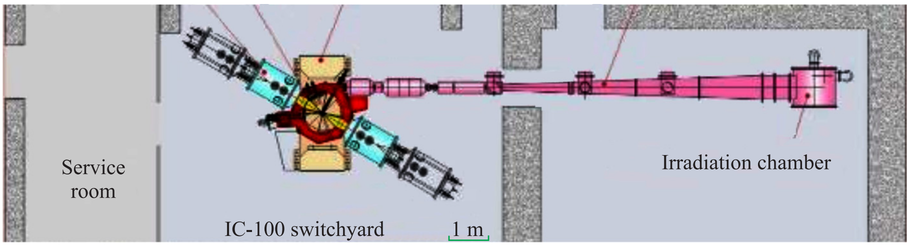

Fig. 6. Plan of a specialized complex for applied research based on the IC-100 cyclic implanter

5. DRIBS PROJECT

The DRIBs (Dubna RIB) project has been running at FLNR since 2002 [3] (Fig. 1). The primary ion beams (^{7}Li or ^{11}B) from U400M are used for production of nuclides such as ^{6}He, ^{8}He at the target (Be or C). The produced radionuclides are transported from hot catcher by diffusion into ECR (2.45 GHz) ion source where they are ionized. Then, the radioactive ions are extracted, separated and transported through 120-m transport line into the U400, where they are accelerated. At the present time ^{6}He^{2+} ions at an energy of 11 MeV/nucleon are available for physical experiments. DRIBs possibilities will be extended after carring out U400 $\rightarrow$ U400R modernization (see Table 2).

6. DUBNA ECR (DECRIS) ION SOURCE AND INJECTION SYSTEMS [4]

For the last 15 years, six room-temperature 14-GHz ECR sources have been developed at FLNR. Two SC ECR (DECRIS-SC) ion sources have been developed too for IC-100 and U400M cyclotrons. Three permanent-magnet 2.45-GHz ECR ion sources have been developed at FLNR for generation of single-charge stable and radioactive ions. For increasing

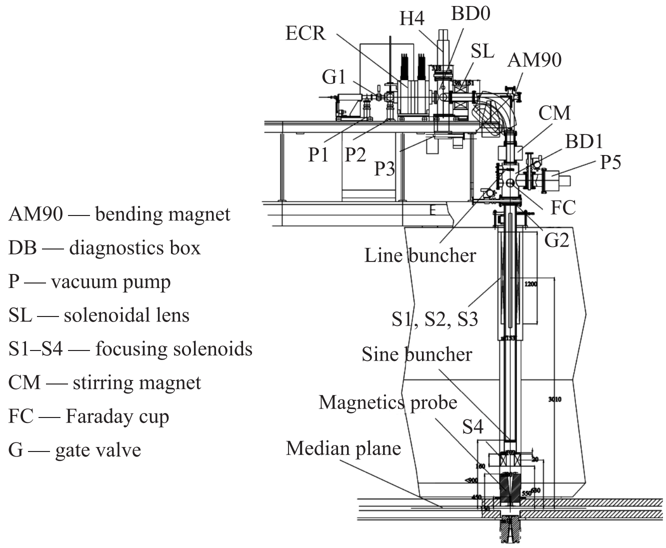

Fig. 7. U400R axial injection system

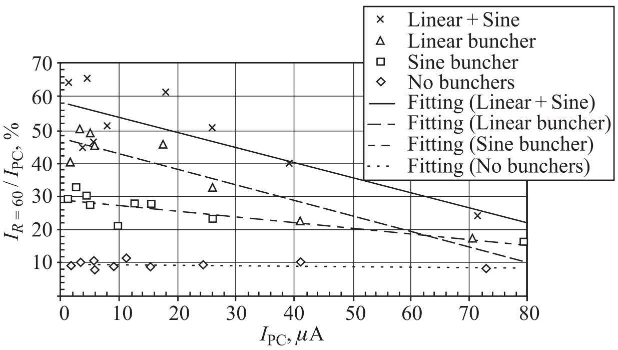

Fig. 8. The efficiency of capture

beam capture efficiency from ECR source by accelerator, axial injection systems have been developed, too. For example, the scheme of U400R axial injection channel is shown in Fig. 7. The results of the capture efficiency for $^{40}Ar^{4+}$ are presented in Fig. 8. The reasons of the efficiency decreasing in the regime with bunchers can be explained by space-charge effects. In the future, we are planning to increase the injection voltage from 13–20 up to 50–100 kV which means shift of the space charge limits by factor 6–20.

7. NEW FLNR ACCELERATOR

In order to improve efficiency of the experiments for the next 7 years, it is necessary to obtain the accelerated ion beams with the following parameters:

- Energy 4–8 MeV/nucleon,

• Masses 10–100,
• Intensity (up to ^{48}Ca) 10 pμA,
• Beam emittance $< 30\ \pi \cdot \text{mm} \cdot \text{mrad}$,
• Efficiency of beam transfer $> 50\%$,
• ECR frequency 18–28 GHz.

Under consideration here are two variants now: SC linac or specialized cyclotron.

Variant 1 — SC LINAC. The proposed superconducting linac structure includes RFQ and 26 QuaterWave Resonators (QWR). The total length is about 46 m, total power consumption 350 kW, average accelerating gradient (along all QWR) about 1.5 MV/m.

Variant 2 — DC200 high-current cyclotron [7]. Main parameters and goals of the DC200 cyclotron are given in Tables 3 and 4. The scheme of DC200 is presented in Fig. 9.

Table 3. **Main parameters and goals of DC200 cyclotron**

DC200 Parameter	Goals
High injecting beam energy (up to 100 kV)	Shift of space charge limits by factor 30
High gap in the center	Space for long spiral inflector
Low magnetic field	High starting radius. High turn separation. Low deflector voltage
High acceleration rate	High turn separation
Flat-top system	High capture. Single turn extraction. Beam quality

Table 4. **Main parameters of the DC200**

Injecting beam potential	Up to 100 kV
A/Z range	4–7
Magnetic field level, T	0.65–1.15
K factor	200
Gap between plugs, mm	250
Valley/hill gap, mm/mm	350/240
Magnet weight, t	470
Magnet power, kW	170
Dee voltage, kV	2×130
RF power consumption, kW	2×30
Flat-top dee voltage, kV	2×14
Beam turn separation, mm	10
Radial beam bunch size, mm	3
Efficiency of beam transferring, %	60
Total accelerating potential, MV	Up to ~ 40

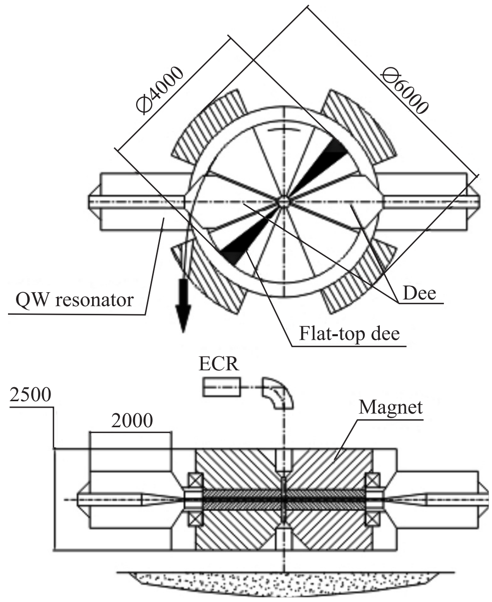

Fig. 9. Scheme of the DC200

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