STATUS OF THE FLEROV LABORATORY OF NUCLEAR REACTIONS JINR HEAVY ION CYCLOTRONS

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Two compact type cyclotrons U400 (1978) and U400M (1991) are at present in operation at the FLNR (Dubna). The first accelerator U400 with K = 600 serves for acceleration of heavy ions with energies in the range of (0.5 ÷ 18) MeV/u. The U400M cyclotron with K = 400 ÷ 550 provides accelerated heavy ion beams with energies of (6 ÷ 100) MeV/u. At present, two cyclotrons are being equipped with ECR ion sources at 14 GHz. In this paper the present status of the cyclotrons and prospects of their development are given.

Introduction

Presently, 4 isochronous four-sector cyclotrons based on compact type magnets [1] (Table 1) operate at the FLNR JINR. Experimental dependencies of average magnetic fields on the excitation of the main coils and the average magnet gap are presented in Figure 1 [2].

Table 1: Technical parameters of the FLNR cyclotrons.

FLNR Cyclotrons	CI 100 *1985*	U 200 *1968*	U 400 *1978*	U 400M *1992*
D [m]	1.05	2.0	4.0	4.0
B [T]	1.94	1.93 ÷ 2.0	1.95 ÷ 2.15	1.5 ÷ 1.95
K	40	145	550 ÷ 625	400 ÷ 550
W [tons]	50	200	2000	2300
d_{valley} / d_{hill} [cm/cm]	11/2	15/7	30/7	50/10
R_{extr}/R_{pole} [m/m]	0.87	0.86	0.86	0.9
$N_{sectors}$/Sect. Angle	4/56°	4/42°	4/42°	4/42°
Spiraling	0	0	0	43°
Trim Coils		10	10	10
Harmonic Coils	1	2	8	8
N_{dee} / Dee Angle	2/34°	2/45°	2/45°	4/45°
V_{dee} [kV]	50	70	100	170
P_{RF} [kW]	2 × 5	2 × 40	2 × 80	4 × 60
f [MHz]	20.5	14 ÷ 22	5.5 ÷ 12	11.5 ÷24
$RF_{harmonics}$	4; 6	2; 3	2; 6	2; 3; 4
Ion Source	PIG	PIG	PIG/ECR	ECR
Z/A	0.185; 0.114	0.18 ÷ 0.36	0.03 ÷ 0.2	0.1 ÷ 0.5
Vacuum [Pa]	$4 . 10^{-4}$	$7 . 10^{-5}$	$3 . 10^{-5}$	$2 . 10^{-5}$
Inflector			spiral	mirror/spiral
Extraction	EM; Z_2 / Z_1	Z_2 / Z_1	Z_2 / Z_1	Z_2 / Z_1 ; M
Ion Energies	1.2; 0.5	3 ÷ 15	0.5 ÷ 20	6 ÷ 100
Emittance [mm.mrad]	40 π	40 π	30 π	15 π
Energy Spread	2 %	1 %	1 %	0.3 %

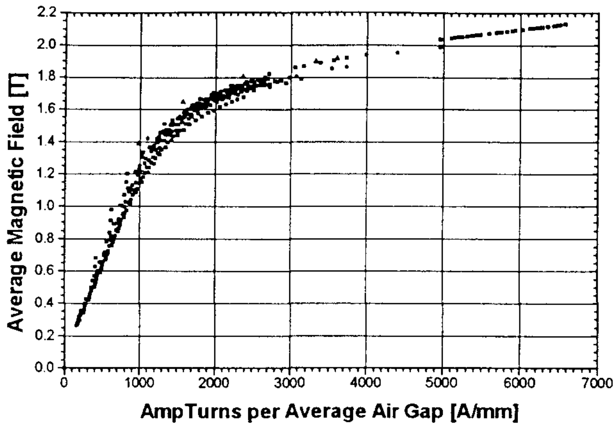

Figure 1: The dependence of <B> on the excitation of the magnet $0.5\times(d_{hill}+d_{valley})$.

Experimental dependencies of the magnetic field azimuthal variation on the average magnetic field and on the gaps ratios are presented in Figure 2.

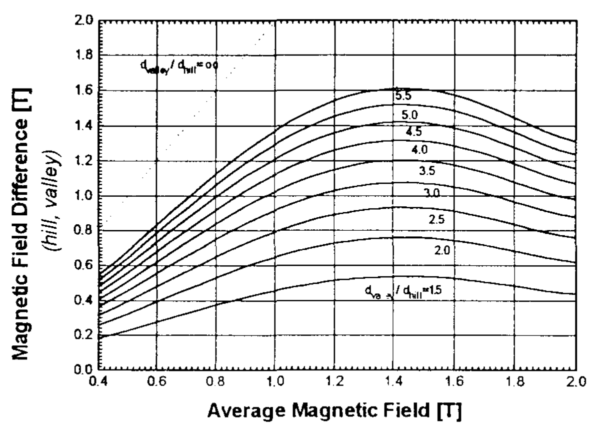

Figure 2: The dependence of $\Delta B=B_{hill}-B_{valley}$ on <B> and d_{hill}/d_{valley}.

● The cyclic implanter CI100 (1985)) (Table 1) [3] is the smallest of the FLNR cyclotrons and is used for 500 hours annually for radiation studies with beams of C, N, O, Ne, Ar, Cl, and Na. The beam intensities are up to 10^{13} pps, ion energies - 1.2 and 0.5 MeV/u.

● The U200 cyclotron (1968) (Table 1) [4] is used annually for 2000 ÷ 2500 hours for the production of isotopes ^{26}Al, ^{237}Pu,...[5] on beams of ^{4}He with an energy of 36 MeV and an intensity up to 10^{15} pps.

● The U400 cyclotron (1978) [6] is intended for the production of intensive beams of heavy ions (up to 10^{14} pps) with energies from 0.5 to 20 MeV/u for nuclear physics and applied research. The annual beam time on the target is 3500 ÷ 4000 hours. The list of beams includes about 70 types of ions from Li to Xe of gaseous, solid, enriched and rare isotopes. Table 2 presents the parameters of several beams of rare isotopes.

Table 2: Parameters of certain beams of rare isotopes for PIG+U400.

Rare *(Enriched)* Isotopes Ion Beams		
Ion	Energy [MeV]	Intensity [pps]
$^{13}C^{2+}$	187	1. 10^{13}
$^{15}N^{2+}$	150	5. 10^{13}
$^{18}O^{3+}$	190	1,5. 10^{13}
$^{22}Ne^{3+}$	180	6. 10^{13}
$^{25,26}Mg^{3+}$	180	8. 10^{12}
$^{34}S^{4+}$	230	1,5. 10^{13}
$^{36}S^{4+}$	230	
$^{42,44,48}Ca^{5+}$	250	2. 10^{12}
$^{49,50}Ti^{5+}$	300	7. 10^{12}
$^{53,54}Cr^{5+}$	300	4. 10^{12}
$^{58}Fe^{6+}$	400	1,2. 10^{13}
$^{64}Ni^{6+}$	380	4. 10^{12}
$^{68}Zn^{8+}$	430	4. 10^{10}

The optimum consumption of gases and solids in the PIG source is 100 and 10 mg/hr respectively, but the ratio of intensities is higher [7]. The high level of matter consumption is one of the main reasons of constructing a system of axial injection in the U400M based on the ECR-4M from GANIL.

Figure 3 and Figure 4 present the expected increase of intensities for energies of 5 and 18 MeV/u correspondingly.

One of the main tasks for the ECR4M+U400 is the acceleration of rare isotopes (^{26}Mg. ^{34}S, ^{36}S, ^{48}Ca, ^{50}Ti, ^{58}Fe, ^{64}Ni and etc.) with beam intensities on the level of 10^{13} pps with the expenditure of matter on the level of 1 mg/hr.

About 500 hours of the beam time is annually used for the production of track membranes. For the purpose $^{84}Kr^{7+}$ beams with an energy of 200 MeV and an intensity of 4×10^{11} pps are used.

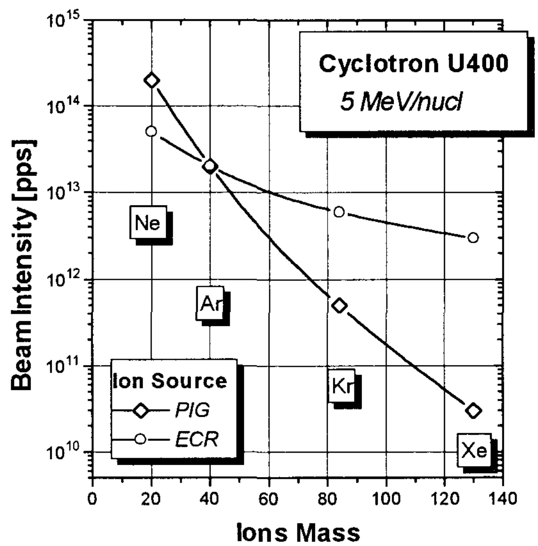

Figure 3: The expected increase of intensity in the complex ECR+U400 for an ion energy of 5 MeV/u.

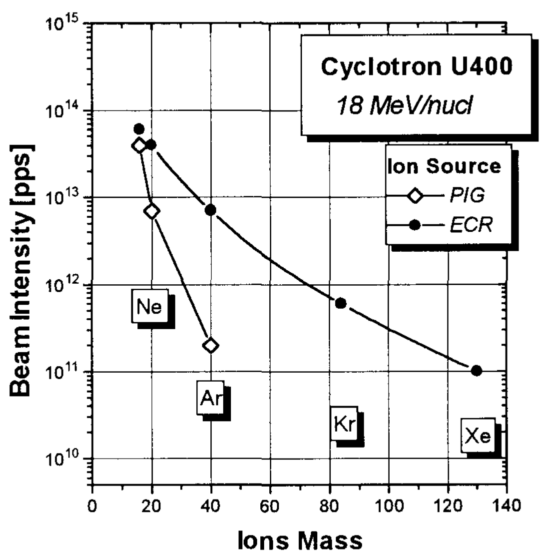

Figure 4: The expected increase of intensity in the ECR+U400 complex for an ion energy of 18 MeV/u.

About 500 hours of the beam time is annually used for the production of track membranes. For the purpose $^{84}Kr^{7+}$ beams with an energy of 200 MeV and an intensity of 4×10^{11} pps are used. For 1996 it is planned to use beams of Xe^{13+} with an energy of 700 MeV and an intensity of 10^{12} pps.

- The cyclotron U400M (1991) is intended for the production of heavy ion beams with energies of 6 ÷ 100 MeV/u. [7]. By 1995 the cyclotron was equipped with an internal PIG source and the parameters of accelerated beams are presented in Table 3.

Table 3: Parameters of the beams of several accelerated ions for PIG+U400M.

Cyclotron U400M + PIG Ion Source		
Ion	Energy [MeV/u]	Intensity [pps]
$^{4}He^{1+}$	30	$1.\ 10^{14}$
$^{14}N^{5+}$	60	$6.\ 10^{11}$
$^{16}O^{5+}$	48	$2.\ 10^{12}$
$^{20}Ne^{6+}$	46	$3.\ 10^{12}$
$^{40}Ar^{4+}$	6	$2.\ 10^{13}$

During 1994 at the FLNR there was created an ECR ion source DECRIS-14 GHz [8]. Simultaneously there was created a system of beam axial injection (Figure 5). [9]

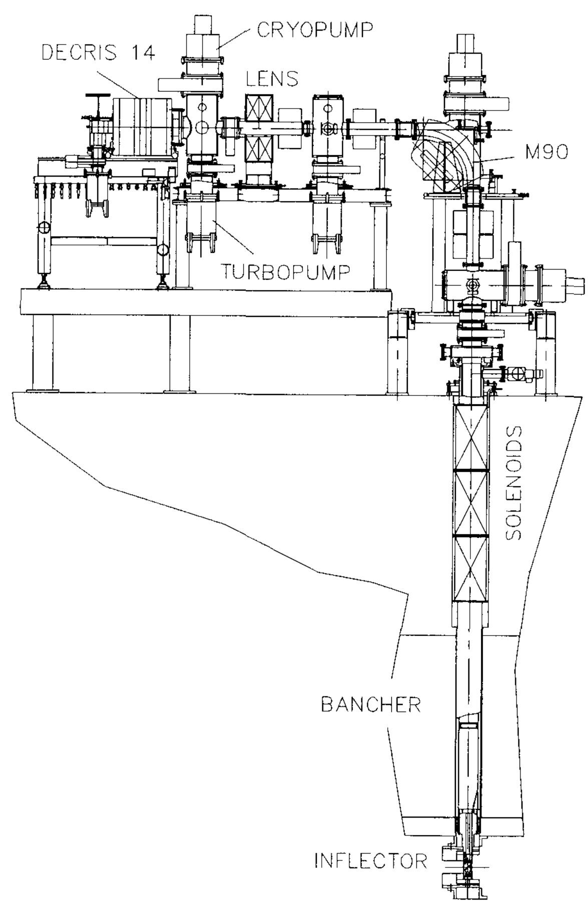

Figure 5: The scheme of the beam axial injection into the U400M.

The beam envelope is presented in Figure 6.

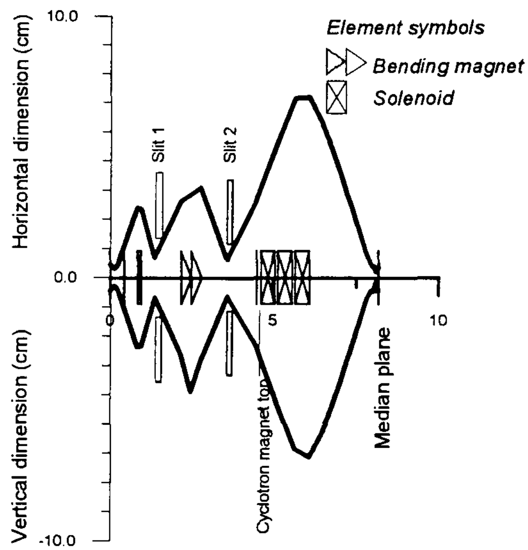

Figure 6: The beam environment in the beam axial injection system of U400M.

The calculated distribution of pressure along the path of the axial injection as well as some experimental points are presented in Figure 7.

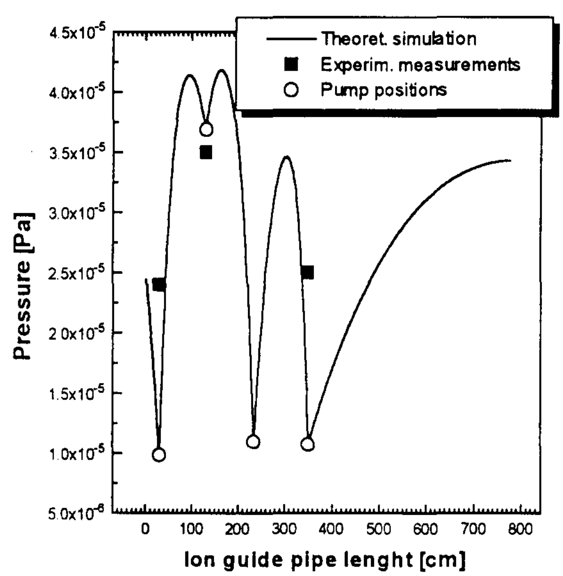

Figure 7: The distribution of pressure in the axial injection system of U400M.

Starting with April 1995 there were carried out several runs of accelerating $^{14}N^{5+}$ and $^{16}O^{5+}$ with energies 45 and 51 MeV/u. It should be noted that the performed increase of the power of 4 HF-generators from 20 too 100 kW made it possible to provide the continuous accerleration mode. The intensities of N^{5+} and O^{5+} beams after separation on the axial injection system are up to 200 μA at a discharge power of up to 200 W. The efficiency of the capture for acceleration without the buncher at a phase angle of 20° is 2÷4 %. The acceleration caused no problems. The beam extraction was carried out by the method of charge exchange on a thin (5 μm) aluminum foil with charge exchange ratios of 1.4 and 1.6 [1]]. An experimental run on the 4π facility FOBOS using a new complex DECRIS-14+U400M took place in June 1995. The optimization of the accelerator systems is the task for the immediate future. The excepted beam parameters of the DECRIS + U400M complex are presented in Table 4

Table 4: The excepted beam parameters of the DECRIS + U400M complex.

Cyclotron U400M + ECR Ion Source		
Ion	Energy [MeV/u]	Intensity [pps]
$^{7}Li^{2+}$	42	6. 10^{12}
$^{16}O^{5+}$	50	1. 10^{13}
$^{20}Ne^{6+}$	45	1. 10^{13}
$^{40}Ar^{14+}$	58	1. 10^{12}
$^{48}Ca^{14+}$	44	1. 10^{12}
$^{129}Xe^{26+}$	22	6. 10^{11}
$^{238}U^{24+}$	6	4. 10^{11}

Conclusion

It is expected that at the end of 1996 the accelerators U400 and U400M will be supplied with ECR-sources and will be capable of generating beams of ions of a wide range of stable isotopes. Any further development (1997-2000) will be connected with the production of RIB.

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