G.G. Gulbekian, <u>I.V. Kalagin,</u> S.N. Dmitriev, Yu.Ts. Oganessian, B.N. Gikal, S.L. Bogomolov, I.A.Ivanenko, N.Yu.Kazarinov, V.A. Semin, G.N. Ivanov, N.F.Osipov

Status of FLNR JINR Cyclotrons

Igor Kalagin

Flerov Laboratory of Nuclear Reactions Joint Institute for Nuclear Research

HIAT 2018



BASIC DIRECTIONS of RESEARCH at FLNR

<u>U-400 & DC-280 cyclotrons (⁴⁸Ca, ⁵⁰Ti 5 ÷ 6 MeV/n)</u>

- Heavy and superheavy nuclei:
- > synthesis and study of properties of super heavy elements;
- > chemistry of new elements;
- Fusion-fission and multi-nucleon transfer reactions;
- > nuclear- , mass- spectrometry of SH nuclei.

<u>U-400M cyclotron (ions 30 ÷ 50 MeV/n)</u>

- Light exotic nuclei:
- > properties and structure of light exotic nuclei;
- reactions with exotic nuclei.

IC-100 (C ÷ Bi 1.2 MeV/n), U-400 (Ar ÷ Bi 2.5 ÷ 3.5 MeV/n)

- Radiation effects and physical groundwork of nanotechnology.

<u>U-400 & U-400M (O ÷ Bi 3 ÷ 5 MeV/n) and</u>

<u>U-400M (O ÷ Bi 15 ÷ 60 MeV/n)</u>

- SEE testing of electronic components

Flerov Laboratory of Nuclear Reactions

Total operation time of	2015	2016	2017
U-400, U-400M, IC-100 AND M1-25 accelerators	14 034	15 724	16 657

OPERATION TIME OF U-400 AND U-400M ACCELERATORS





Parameters	Value/Name
Magnet weight	2100 t
Electrical power of magnet	850 kW
Magnetic field level in center	1.93÷2.1 T
A/Z range	5÷12
RF frequency range	5.42÷12.2 MHz
Sectors angular width	42°
The number of dees	2
Harmonic mode	2
K- factor	625
Vacuum level	2.10 ⁻⁷ Torr

U400 CYCLOTRON (1978)

Ion	Ion energy [MeV/A]	Output intensity
⁶ He ¹⁺	11	3·10 ⁷ pps
¹⁶ O ²⁺	5.7; 7.9	5 pµA
$^{18}O^{3+}$	7.8; 10.5; 15.8	4.4 pµA
$^{40}{\rm Ar}^{4+}$	3.8; 5.1 *	1.7 pµA
⁴⁸ Ca ⁵⁺	3.7; 5.3 *	1.2 рµА
⁴⁸ Ca ⁹⁺	8.9; 11; 17.7 *	1 pµA
⁵⁰ Ti ⁵⁺	3.6; 5.1 *	0.5 pµA
⁵⁸ Fe ⁶⁺	3.8; 5.4 *	0.7 pµA
⁸⁴ Kr ⁸⁺	3.1; 4.4 *	0.3 pµA
¹³⁶ Xe ¹⁴⁺	3.3; 4.6; 6.9 *	0.08 pµA
¹⁶⁰ Gd ¹⁹⁺	5.5	0.01 pµA
²⁰⁹ Bi ¹⁹⁺	3.4	0.01 pµA



- 1. GFRS (Gas-Filled Recoil Separator), channel N1
- 2. Chemical setup, channel N2
- 3. SHELS (separator for Heavy ELement Spectroscopy), channel N3
- 4. Corset (Investigation of the fusion-fission reactions), channel N6
- **5.** SEE testing of electronic components, **channel N8**;
- 6. MAVR (High-resolution magnetic analyser), channel N9
- 7. Channel for applied research, channel N10

Dubna gas-filled recoil separator





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Лантаноиды Lanthanoides

Церий	58 ₄₀₅₀	Празеодим 59	Неодим (50 ₁₁	Прометий 6	1	Самарий	62 ₄₀	Квропий	63 ₁₁	Гадолиний (i4 areat	Тербий	65 _{ar}	Диспрозий 6	6.	Гольмий	67	Эрбий	68 _{4f}	Тулий	69 42	Иттербий	70	Лютеций	71	
Ce	5.5387 6773	Pr 5.47	Nd	5,525 2009	Pm	1.55 726-	Sm	5,5407 7520	Eu	3.6791 5244	Gd	6.159 (50)	Tb	5,8679 \$230	Dy	3.9389 8551	Но	5.02 S 30-25	Er	6,1035 9066	Tm	6.18/31 9321	Yb	6.254-6 6965	Lu	5,42585 984	
140,12 Cerium	799 3424	140,91 or Praseodymium 3510	144,24 Neodymium	1016 5060	[145] Promethium	1042 3000	150,36(2) Samarium	1023 1759	151,96 Europium	\$22 1996	157,25(3) Gadolinium	1314 30%	158,93 Terbium	1489 3221	162,50 Dysprosium	1411 3561	164,93 Holmium	1472 2694	167,26 Erbium	1579 2083	168,93 Thulium	545 1944	173,05 Ytterbium	827 194	174,97 Lutetium	106? 3392	

Актиноиды Actinoides

Водород	1
H	13 99844 306999
1,00794	-259.24
Hydrogen	-252 XX

																						_		-	_	
орий	90 ₅₆₁	Протактиний9	1	Уран	92 _{5.161}	Нептуний	93 _{51'91}	Плутоний 94	51	Америций 9	95 _{ar}	Кюрий	96 _{scor}	Берклий	97 _{s:}	Калифорший9	8.	Эйнштейший 99	Фер	мяй 100	менделевий10	1 _{51'}	Нобелий 102	Лоур	енскії 103	
Гh	6.05 11500	Pa	3.59 15370	U	6.19402 18930	Np	6.2657 20258	Pu	6.05 \$\$10	Am	5,962 13670	Cm	6,82	Bk	6.23 14780	Cf	6.30	Es 5,02	F	n	Md	6.73	No «	Lr		
32,04 borium	1253	231,04 Protactinium	1672	238,03 Uranium	1126	[237] Nentunium	544 2930	[244] Plutonium	140	[243] Americium	1126	[247] Curium	1315	[247] Berkelium	1050	[251] Californium	950	[252] 860 Finsteinium	[251	1	[258] Mendelevium	\$27	[259] sz	[266]	I	162

Н - символ / symbol 1.00794 - атомная масоса / atomic mass 134 - Элистроная конфиграция / electron configuration 135804 - 1-я потенцион наизация, 80 / Lat ionitacion potential, eV 2583.41 - температура палазение, 80 / malting temperature, °C -252.87 - температура клигения, 9C / boiling temperature, °C

Axial injection system of U-400 Cyclotron

ECR4M DB0 H6 Magnetic screen SL CM1 AM90 CM2 DB1 H7 H9 AM90-bending magnet Line buncher **DB-diagnostics box S1-S3** H6-H9-vacuum pumps 4400 SL-solenoidal lens Sine buncher S1-S3-focussing solenoids CM-stirring magnet Magnetic probe Inflector 840 Medial plane

upgraded by FLNR 2013 ⁴⁸Ca⁵⁺ - 100 eμA

made by GANIL 1995,

ECR4M ion source

¹³²Xe¹²⁺ - 50 eμA ²⁰⁹Bi¹⁹⁺ - 20 eμA

Heavy Ion Beam Extraction by Stripping Foil



The method of heavy ion beam extraction from AVF (azimuthally-varying-field) cyclotrons suggested by G.N. Vialov, G.N. Flerov and Yu. Oganesyan



Heavy Ion Beam Extraction by Stripping Foil

1. Charge spread

2. Life time of stripping foil



Dependence of the maximum efficiency of a single charge extraction by stripping versus the ion energy

Dependence of life time of carbon stripping foil versus beam current density at 5 MeV/amu

Efficiency of transporting a ⁴⁸Ca⁵⁺ beam from the ECR source to a physical target

Measuring point	Beam int	Ion	Transmission factor					
ECR source, after separation	1·10 ¹⁴ pps	84 µAe	⁴⁸ Ca ⁵⁺	32%				
Cyclotron centre	3.5·10 ¹³ pps	27 µAe	⁴⁸ Ca ⁵⁺		81%			
Extraction radius	2.8·10 ¹³ pps	22 µAe	⁴⁸ Ca ⁵⁺		0170	40%		
Extracted beam (by charge exchange)	9.7·10 ¹² pps	28 µAe	⁴⁸ Ca ¹⁸⁺				82%	
Target	8.10 ¹² pps	23 µAe	⁴⁸ Ca ¹⁸⁺					8.5%

Ionization efficiency of ⁴⁸Ca (neutral) to ⁴⁸Ca⁵⁺ - about 10%

Efficiency of transporting a ⁴⁸Ca⁵⁺ beam from the ECR source to a physical target

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Extracted beam (by charge exchange)	9.7·10 ¹² pps	28 µAe	⁴⁸ Ca ¹⁸⁺				82%			
Target	8·10 ¹² pps	23 µAe	⁴⁸ Ca ¹⁸⁺	~1	2 p	uA		8.5%		

Ionization efficiency of ⁴⁸Ca (neutral) to ⁴⁸Ca⁵⁺ - about 10%

Development of ⁵⁰Ti beam using MIVOC method

(Collaboration between IPHC (Strasbourg, France) and FLNR JINR.)

Synthesis of compound (two steps)

 50 TiCl₄ + (CH₃)₅C₅Si(CH₃) \rightarrow Cp*TiCl₃ + 3CH₃Li \rightarrow Cp*Ti(CH₃)₃

where $Cp^* - (CH_3)_5C_5$



The spectrum of Ti ions, the source settings are optimized for ${}^{50}\text{Ti}{}^{5+}$ (82 mkA).

Acceleration at the U-400 cyclotron

The intensity of the injected beam of ${}^{50}\text{Ti}{}^{5+} \ge 50 \text{ e}\mu\text{A}$ The intensity on the target ~ 10 e μA (~ 0.5 p μA) The compound consumption rate of 2.4 mg/h (${}^{50}\text{Ti}$ consumption of 0.52 mg/h)

Modernization of the U-400 cyclotron (U-400R project) (2020-2023)

- 1. Beam intensity of masses A \approx 50 and energy 5÷6 MeV/n up to 2.5 $\rho\mu a$.
- 2. Smooth ion energy variation on the target with factor 5.
- **3. Decreasing the cyclotron average magnetic field level from 2.1 to 1.8 T** (Decreasing the total cyclotron power consumption from 1 to 0.25 MW).
- **4. New equipment (**new magnetic system, new RF- resonators; replacement of vacuum pumping system- diffusion pumps to cryopumps and turbopumps; modernization of RF control system- analog to digital LLRF).
- 5. Building of a new experimental hall

Parameters of U400 and U400R typical ions

	U400								
Ion	Ion energy [MeV/u]	Output intensity							
⁴ He ¹⁺	-	-							
⁶ He ¹⁺	11	3.10 ⁷ pps							
⁸ He ¹⁺	7.9	-							
¹⁶ O ²⁺	5.7; 7.9	5 рµА							
¹⁸ O ³⁺	7.8; 10.5; 15.8	4.4 pµA							
⁴⁰ Ar ⁴⁺	3.8; 5.1 *	1.7 рµА							
⁴⁸ Ca ⁵⁺	3.7; 5.3 *	1.2 рµА							
⁴⁸ Ca ⁹⁺	8.9; 11; 17.7 *	1 pµA							
⁵⁰ Ti ⁵⁺	3.6; 5.1 *	0.4 pµA							
⁵⁸ Fe ⁶⁺	3.8; 5.4 *	0.7 pµA							
⁸⁴ Kr ⁸⁺	3.1; 4.4 *	0.3 рµА							
$^{136}Xe^{14+}$	3.3; 4.6; 6.9 *	0.08 pµA							

U400R (expected)							
Ion	Ion energy [MeV/u]	Output intensity					
⁴ He ¹⁺	6.4 ÷ 27	23 рµА					
⁶ He ¹⁺	2.8 ÷ 14.4	10 ⁸ pps					
⁸ He ¹⁺	1.6 ÷ 8	10 ⁵ pps					
¹⁶ O ²⁺	1.6 ÷ 8	19.5 pµA					
¹⁶ O ⁴⁺	6.4 ÷ 27	5.8 pµA					
⁴⁰ Ar ⁴⁺	1 ÷ 5.1	4 pµA					
⁴⁸ Ca ⁶⁺	1.6 ÷ 8	2.5 pµA					
⁴⁸ Ca ⁷⁺	2.1 ÷ 11	2.1 pµA					
⁵⁰ Ti ¹⁰⁺	4.1 ÷ 21	1 pµA					
⁵⁸ Fe ⁷⁺	$1.2 \div 7.5$	1 pµA					
⁸⁴ Kr ⁷⁺	0.8 ÷ 3.5	1.4 pµA					
¹³² Xe ¹¹⁺	0.8 ÷ 3.5	0.9 pµA					

* Fixed ion energy of extracted beam

* Smooth variation ion energy of extracted beam

Reconstruction of the U-400 experimental hall



Reconstruction of the U-400 experimental hall



Reconstruction of the U-400 experimental hall



Experimental area ~1500 m² (2 floors)





U400M CYCLOTRON (1991)



Main tasks:

- Producing of RIBs.
- *Reactions with exotic nuclei;*
- Properties and structure of light exotic nuclei.

U400M E=15 ÷ 60 MeV/A E=4.5 ÷ 9 MeV/A								
Ion	Ion energy [MeV/A]	Output intensity [pps]						
⁷ Li	35	6×10 ¹³						
¹⁸ O	33	1×10 ¹³						
⁴⁰ Ar	40	1×10 ¹²						
⁴⁸ Ca	5	3×10 ¹²						
⁵⁸ Fe	5	1×10 ¹²						
¹²⁴ Sn	5	2×10 ¹¹						
¹³⁶ Xe	5	4×10 ¹¹						
¹³² Xe	25	3×10 ⁵						
²³⁸ Bi	5	3×10 ⁸						
²³⁸ Bi	15	1×10 ⁵						



U-400M. Ion sources and axial injection system



Thickness of stripping foil - 20 -200 μg/cm²









Modernization of the U400-M cyclotron (2019-2020):

- 1. Replacement of the main coils of the cyclotron main magnet; correction of the first harmonic of magnetic field;
- 2. Replacement of vacuum pumping system- diffusion pumps to cryopumps and turbopumps;
- 3. Modernization of RF- resonators; modernization of RF control systemanalog to digital LLRF;
- 4. Increasing intensities and energies of ion beams.

Modernization of the U400-M cyclotron

Prospects of increase in energy and intensity of extracted ions



			Estimation	
Ион	A/Z	Current from DECRIS-2M DECRIS-SC2 μΑ	Extracted current μΑ (10% of injected current)	Extracted current рµА
20 ^{Ne⁹⁺}	2.222	10	1	0.11
₁₆ 0 ⁷⁺	2.2857	20	2	0.28
₂₀ Ne ⁸⁺	2.5	70	7	0.875
16 ⁰⁶⁺	2.667	200	20	3.3
₂₀ Ne ⁷⁺	2.857	100	10	1.43
₃₂ S ¹¹⁺	2.909	12	1.2	0.11
₄₀ Ar ¹¹⁺	3.636	65	6.5	0.59
11 ^{B3+}	3.6667	180	18	6
₈₄ Kr ²⁰⁺	4.2	~ 10	1	0.05
₂₂ Ne ⁵⁺	4.4	~ 200	20	4
₁₃₂ Xe ³⁰⁺	4.4	~ 1	0.1	0.003
₁₃₂ Xe ²⁴⁺	5.5	~ 50	5	0.21
₅₆ Fe ¹⁰⁺	5.6	~ 40	4	0.4
₂₀₉ Bi ³⁷⁺	5.649	~ 4	0.4	0.011
40 Ar 7+	5.7143	~ 150	15	2.14
₁₃₂ Xe ²³⁺	5.7391	~ 50	5	0.22

Extraction by electrostatic deflector

Dependence of energy of extracted ions on A/Z

- **Extraction by charge exchange (existing U-400M)** ٠
- Extraction by electrostatic deflector (R_{out}=1.78 m), after magnetic field correction ٠

Intensities of accelerated ions are determined by cyclotron transmission factor and ion source currents (I^q). As $I^q \propto \omega^2_{ECR}$ (1987 R. Geller), the new ECR ion source with ω_{ECR} =24÷28 GHz could be used for the U-400M.

28 GHZ ECR sources in the world:

SUSI – Michigan State University (MSU), USA; VENUS – Lawrence Berkeley National Laboratory (LBNL), USA; SECRAL – Institute of Modern Physics (IMP), Lanzhou, China; SC-ECRIS– RIKEN, Japan;

Benefits: Higher intensities for high charged ions (factor 10 at least)

> Problems: Technical difficulties, high cost, big risks

Possible decision: Scientific collaboration, involvement of skilled manufacturers

Extraction by electrostatic deflector



Extraction by electrostatic deflector



Deflector parameters: L≈80 см, aperture ∆X=0.8 сm Umax=59 kV (E=74 kV/сm)

Applied research IC-100 cyclotron after reconstruction (2001-2002)



- Production of track membranes
- Testing of reactor components with Kr and Xe ions
- Works on nanotechnology

1	lon source	DECRIS-SC
2	Accelerated ions	²² Ne ⁺⁴ ⁴⁰ Ar ⁺⁷ ⁵⁶ Fe ⁺¹⁰ ⁸⁶ Kr ⁺¹⁵ ¹²⁷ I ⁺²² ¹³² Xe ⁺²³ ¹³² Xe ⁺²⁴ ¹⁸² W ⁺³² ¹⁸⁴ W ⁺³¹ ¹⁸⁴ W ⁺³²
3	Mass-to-charge ratio of ions	A/Z = 5.5 ÷ 5.95
4	lon energy	0.9 ÷ 1.2 MeV/A
5	Average magnetic field	1.78 ÷1.93 T
6	Frequency of the RF system	19.8 ÷ 20.6 MHz
7	Intensity of the accelerated and extracted beam of ⁸⁶ Kr ¹⁵⁺	1.4·10 ¹² pps (<mark>3.5 μA</mark>)
8	Intensity of the accelerated and extracted beam of ¹³² Xe ²³⁺	~ 10 ¹² pps (<mark>3.7 μA</mark>)

<u>U-200 Cyclotron</u>

In 1968 the U-200 was put into operation in the FLNR. In 2013 it was decommissioned, because of being outdated physically and technologically.

Parameters of U-200:

- Diameter of the magnet pole 2 m
- Internal ion source of PIG type
- Accelerated ions He Ar
- The ion energy 3 -18 MeV/nucleon



The project of DC-130 cyclotron

The programme of applied research that is performed at the FLNR cyclotron IC-100, U-400, U-400M takes approximately 6000 hours of accelerator operation.

Main tasks for DC-130:

- research in the field of solid state physics,
- production of track membranes,
- See testing of electronic components,

Technical characteristics of DC-130:

- range of ions from O to Bi,
- external beam injection from ECR ion source,
- ion energies:

2 MeV/nucleon (A/Z=7.818 - 8.25)

4.5 MeV/nucleon (A/Z=5.212 - 5.5).

Physical installations:

- installation for scientific and applied research,
- facility for irradiation of polymer films,
- installation for testing of electronic components.

Semen Mitrofanov: WEOXA01 14:40

<u>U-200 Cyclotron</u>

In 1968 the U-200 was put into operation in the FLNR. In 2013 it was decommissioned, because of being outdated physically and technologically.

Parameters of U-200:

- Diameter of the magnet pole 2 m
- Internal ion source of PIG type
- Accelerated ions He Ar
- The ion energy 3 -18 MeV/nucleon



The project of DC-130 cyclotron

The programme of applied research that is performed at the FLNR cyclotron IC-100, U-400, U-400M takes approximately 6000 hours of accelerator operation.

Main tasks for DC-130:

- research in the field of solid state physics,
- production of track membranes,
- See testing of electronic components,

Technical characteristics of DC-130:

- range of ions from O to Bi,
- external beam injection from ECR ion source,
- ion energies:

2 MeV/nucleon (A/Z=7.818 - 8.25)

4.5 MeV/nucleon (A/Z=5.212 - 5.5).

Physical installations:

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- facility for irradiation of polymer films,
- installation for testing of electronic components.

Semen Mitrofanov: WEOXA01 14:40

Factory of Super Heavy Elements (SHE)



SHE Factory Building

Reports: Igor Kalagin (SHE-Factory): **Tuesday** 9:30 Andrey Efremov (ECR): **Tuesday** 15:10



High-current cyclotron DC-280

New facilities:

- New gas-filled separator (William Beeckman: WEOAA01 9:40)
- Preseparator
- SHELS
- Etc.



Conclusion

- FLNR JINR Accelerator Complex is being developed
- We expect to have essential results of the Accelerator Complex modernization to 2023

THANK YOU FOR YOUR ATTENTION !