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SHE FACTORY: CYCLOTRON FACILITY FOR SUPER HEAVY ELEMENTS RESEARCH

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Abstract

The synthesis of heavy and the heaviest elements and the study of their nuclear and chemical properties are of highest priority in the basic research programme of the Flerov Laboratory of Nuclear Reactions of the Joint Institute for Nuclear Research in Dubna (FLNR JINR). The synthesis of super heavy elements (SHE) with atomic numbers 113-118 has been achieved in the ^{48}Ca-induced reactions. The seventh period of the Periodic Table has been completed. In accordance with the development program, the first in the world SHE Factory was built at the Laboratory on the basis of the new DC280 cyclotron which was commissioned in 2019. DC280 has to provide intensities up to 10 pμA for ions with atomic masses over 50. The main task of the Factory is the synthesis of new chemical elements with atomic numbers 119 and higher, as well as a detailed study of the nuclear and chemical properties of previously discovered super heavy elements. The Factory are being equipped with target materials, new separators and detectors for the study of the nuclear, atomic and chemical properties of the new elements.

INTRODUCTION

Since 1998 priority experiments on synthesis of new superheavy elements (SHE) with atomic numbers of 114-118 in reactions of ^{48}Ca ions with actinide targets (^{242,244}Pu, ^{243}Am, ^{245,248}Cm, ^{249}Bk, ^{249}Cf) have been carried out at the FLNR JINR on the U400 accelerating complex. Over 50 new isotopes of elements 104 to 118 with maximum neutron excess were for the first time produced and their decay properties were determined in these investigations. The International Unions of pure and applied physics (IUPAP) and chemistry (IUPAC) recognized the priority of Dubna in the discovery of elements 114-118. The seventh period of the Periodic Table has been completed. The discovery of the new domain (island) of stability and the very fact of existence of SHE have posed a number of new questions associated with fundamental properties of nuclear matter. Can even heavier nuclei exist? Is the "Island of Stability" of SHE the last one on the Chart of the Nuclides? Can the superheavy nuclei be formed in the process of nucleosynthesis like those stable and long-lived nuclei in the groups of Pt, Pb, and U-Th found in Nature? What is the limit of Mendeleev's Table? How much are the chemical properties of SHE similar to those of their lighter homologues? Direct synthesis of elements with $Z > 118$ in fusion reactions means using projectiles heavier than Ca, since the capability of high-flux reactors to produce target material is limited to Cf isotopes. It is expected that production cross sections of nuclei with $Z = 120$ in the reaction ^{54}Cr+^{248}Cm and nuclei with $Z = 119$ via ^{50}Ti+^{249}Bk will be about ten times lower than those of production of ^{294}Og in experiments with ^{48}Ca. For more detailed studying nuclear - physical and chemical properties of SHE it is necessary significantly increasing efficiency of experiments [1]. For the solution of this task the first in the world Factory of superheavy elements (SHE Factory) was created at the FLNR JINR in 2019.


Figure 1: Building of SHE Factory.

SHE FACTORY

Creation of the SHE Factory was associated with developing the FLNR experimental basis in several directions. These directions are:

- creation of the new powerful accelerator of stable and long-living isotopes with mass range A = 4-238 with intensity up to 10 pμA for A ≤ 50 and energy up to 8 MeV/nucleon;
- construction of a new experimental building and infrastructure for placing the accelerator with five channels for transportation of beams to 3 experimental halls (total area up to 1000 m^2), equipped with systems of shielding and control matching the class two of operations with radioactive materials;
- development of new separating channels, development of new detection modules for the study of nuclear, atomic, and chemical properties of new elements;
- production of new target materials and development of techniques of making targets with high thermal and radiation stability;
- development of a base for research with intense ion beam in related fields of science and technology.

The SHE Factory situated in the stand-alone new building of the FLNR (Fig. 1). The building comprises a hall for accelerator, rooms for auxiliary equipment, offices for service staff and the experimental area which divided into three separated halls. Each experimental hall is radiation shielded. The total experimental area is about 1000 m^2.

Figure 2: DC280 cyclotron, where: 1- main magnet, 2-HV injection system, 3-RF resonator, 4- beam lines.

DC280 Cyclotron

As an accelerator for the SHE Factory the new DC280 cyclotron was created (Fig. 2). The DC280 was designed at the FLNR, the cyclotron intended for carrying out fundamental and applied investigations with ions from He to U, with the range of atomic mass to charge ratio of A/Z = 4 - 7.5, produced by an ECR ion source. Energies of accelerated ions may vary from 4 up to 8 MeV/nucleon. The DC280 has to produce ion beams with intensity up to 10 pμA for ions with A ≤ 50.

Table 1: DC280 Cyclotron - Basic Technical Solutions

Parameter	Goals
High injecting beam energy (up to 80 kV/Z)	Decreasing space charge factor. Decreasing beam emittance. Effective transportation of ions through injection and capture into acceleration.
High gap in the center	Space for a long spiral inflector.
Low magnetic field (up to 1.3 T)	Large starting radius. Good orbit separation. Low deflector voltage.
High accelerating voltage (up to 130 kV)	Higher turns separation. Lower losses of ions on the rest gas in the vacuum chamber.
Beam extraction by the electrostatic deflector with using a flat-top system	Effective ion extraction. Better beam quality.

The DC280 cyclotron was developed as the accelerator with high transmission of ion beams from the ion source to experimental setups (up to 50%) that allows us to carry out experiments with expensive rare isotopes such as ^{48}Ca at low material consumption. Also, maximal ion current from the ion source is limited from above, especially for metallic ions, therefore high transmission efficiency is necessary. The basic technical solutions which have formed the base of the DC280 cyclotron project are shown in the Table 1.

The main design parameters of the cyclotron specified in Table 2. Configuration of the DC280 cyclotron is shown in Fig. 3.

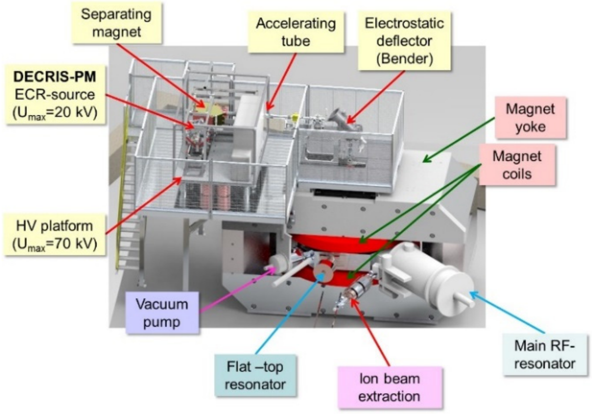

Figure 3: DC280 configuration.

Figure 4: DECRIS-PM source at HV platform, where 1- the source body, 2 – focusing solenoid.

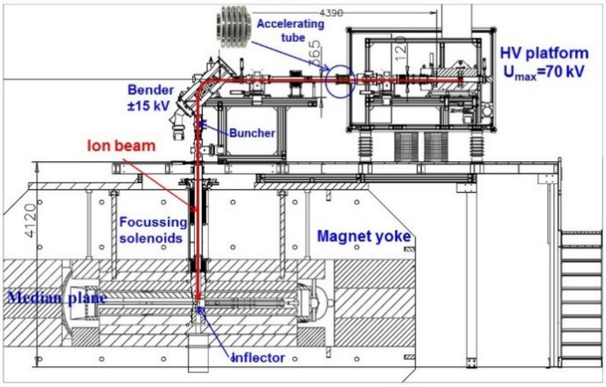

Figure 5: Scheme of the DC280 axial injection.

The DC280 equipped with the high voltage injection system which arranged above the main magnet [2]. The system consists of the high voltage (HV) platform with the DECRIS-PM ECR ion source, the maximal voltage at the platform is 70 kV. The DECRIS-PM is the source with permanent magnet structure created at the FLNR (Fig. 4) [3]. The source extraction voltage is up to 20 kV.

The first focusing solenoid, the 90° analysing magnet, the diagnostic box, the vacuum system and power supplies also installed on the HV platform. After the HV platform, ion beam with energy up to 80 keV/Z is focused by the second solenoid and turned to the DC280 center by spherical electrostatic deflector (bender) (Fig. 5).

The polyharmonic buncher (3 harmonics) [4] and 2 focusing solenoids situated in the vertical part of the injection line. The spiral inflector with quadrupole electrostatic lens at the exit (Fig. 6) is in the cyclotron center to bend the ion beam into the DC280 median plane [5].

For further development of the DC280 creation of a superconducting ECR ion source and the second HV platform which is planned for production of intensive ion beams of elements up to ^{238}U.

Table 2: Main Design Parameters of DC280

Parameter	Value
Injecting beam potential	Up to 80 kV
Pole diameter	4 m
A/Z range of ions	4-7,5
Magnetic field	0,6-1,3 T
K factor	280
Gap between plugs	400 mm
Valley/hill gap	500/208 mm/mm
Magnet weight	1100 t
Magnet power	300 kW max
Dee voltage	2x130 kV
RF power consumption	2x30 kW
Flat-top dee voltage	2x13 kV
Flat-top power consumption	2x2 kW
Beam orbit separation	10-16 mm
Deflector length	1,3 m
Deflector strength	90 kV/cm max
Magnetic channel length	0,9 m
Magnetic channel gradient	4,6-8,4 T/m
Efficiency of beam transfer	>50%

The DC280 is the isochronous cyclotron with four pairs of focusing sectors. The cyclotron has a compact type magnet. The aperture between the sectors is 208 mm that is enough to place Flat-Top dees and 4 pairs of harmonic correcting coils.

Table 3: Designed Beam Parameters of DC280

Ion	Ion energy [MeV/nucleon]	Intensity [pps]
^{7}Li	4	1×10^{14}
^{18}O	8	1×10^{14}
^{40}Ar	5	6×10^{13}
^{48}Ca	5	6×10^{13}
^{54}Cr	5	2×10^{13}
^{58}Fe	5	1×10^{13}
^{84,86}Kr	5	2×10^{12}
^{136}Xe	5	1×10^{14}
^{238}U	7	5×10^{10}

The wide range of the magnetic field levels 0.64-1.32 T allows to make smooth variation of the beam energy in a range 4-8 MeV/nucleon/nucleon. For operative optimization of the magnetic field the 11 radial correcting coils are utilized. The designed beam phase deviation at acceleration is not more than ±2° for ^{48}Ca, and about ±15° for edge operation modes.

Accelerating system of the DC280 consists of two main 45° dees and two flat-top 20° dees combined with RF- resonators (Fig. 7) [6].

The ion beam extraction system of the DC280 equipped with the electrostatic deflector (Fig. 8) and the passive focusing magnetic channel.

The deflector gap is 1 cm and voltage on the potential electrode is up to 90 kV. Designed parameters of extracted ion beams specified in Table 3.

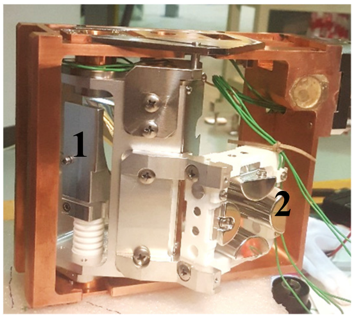

Figure 6: The spiral inflector with quadrupole electrostatic lens, where 1- inflector electrodes, 2 - electrostatic lens electrodes.

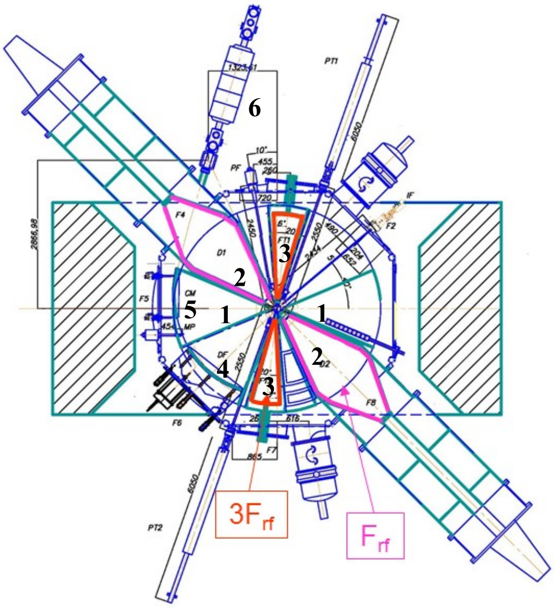

Figure 7: Scheme of the DC280, where: 1-sectors, 2- main dees with resonators, 3- flat- top dees, 4- deflector, 5- passive magnetic channel, 6- beam extraction line, F_{rf} - frequency of RF generators.

After extraction from the cyclotron ion beams are transported inside the extraction beam line to the TM switching magnet. After the TM there are five beam transport lines. Beam lines N3 and N4 are utilized to transport accelerated ion beams to GFS-II and GFS-III gas-filled separators (Fig. 9).

The beam focusing in beam lines is provided by set of quadrupole lenses having magnetic field gradients up to 7.7 T/m.

GFS-II and GFS-III gas-filled separators operate with internal vacuum is about 1 Torr (H_2). Vacuum in beam lines is about $5 \cdot 10^{-7}$ Torr. The differential pumping (DP) system situated between the last beam line quadrupole and the target will be utilized to separate vacuum in separators and beam lines. The ion beam has to be transported through a system of collimators of the DP with minimal losses [7].

The beam diagnostics consists of Faraday caps, slit collimators, sector aperture diaphragms, ionization beam profile monitors and pickups for TOF energy measurement.

The maximal ion beam power in the beam lines can be up to 2.5 kW. Special water cooled aperture diaphragms installed along the beam lines to protect them against damaging by ion beams. Also we can use formation of pulsed beam with 150 Hz repetition rate by using an electrostatic beam chopper in injection line. The chopper control can be operated with adjustable beam duty cycle.

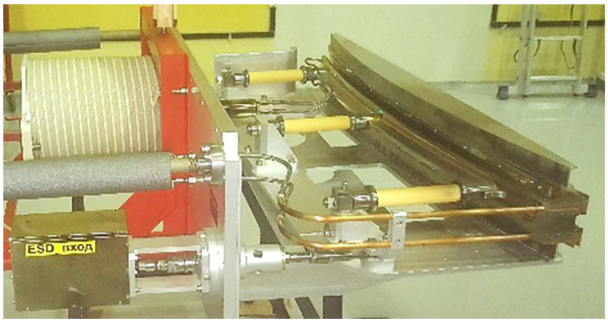

Figure 8: Electrostatic deflector.

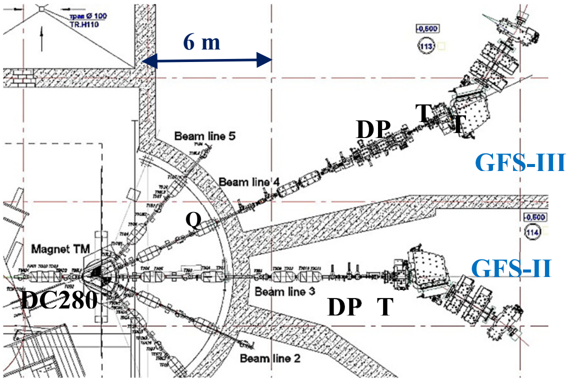

Figure 9: Scheme of beam lines in the SHE Factory building, where Q; quadrupole lens (triplet and doublets), DP; differential vacuum pumping, GFS-II and GFS-III: gas-filled separators at N3 and N4 beam lines, T- targets.

Experimental Results

The DECRIS-PM ECR ion source was tested at the FLNR testing bench. The maximal ion intensities of the source shown in Table 4.

The first beam of $^{84}Kr^{+14}$ ions was accelerated in the DC280 cyclotron on 26.12.2018. The first beam of $^{84}Kr^{+14}$ ions was extracted from the DC280 cyclotron on 17.01.2019. At the DC280 commissioning stage ion beam intensity was not more than 0.2 pμA.

Then, we carried work on test acceleration of $^{84}Kr^{+14}$, $^{12}C^{+2}$ and $^{40}Ar^{+7}$ ions together with improvement of operation of all the cyclotron systems. The DC280 was in testing operation about 3 months. Acceleration time for $^{12}C^{+2}$ ions was only few hours and ion currents were restricted to avoid excess equipment activation by neutrons at tests. Reached currents of accelerated and extracted ions with energy of 5.9 MeV/nucleon are shown in Table 5. Coefficients of ion capture into acceleration with and without the buncher shown in Table 6.

For today, the maximal extracted intensities in CW mode of operation are: 10 pμA for $^{12}C^{+2}$ (beam power is P_{beam}=0,71 kW), 6 pμA for $^{40}Ar^{+7}$ (P_{beam}=1,4 kW) and 1.32 pμA for $^{84}Kr^{+14}$ (P_{beam}=0,67 kW).

Table 4: Ion Intensities From DECRIS-PM

Ion	A/Z	Intensity [pμA]
$^{24}Mg^{+5}$	4,8	90
$^{40}Ar^{+8}$	5	115,8
$^{48}Ca^{+9}$	5,3	24,4
$^{50}Ti^{+9}$	5,6	10
$^{58}Fe^{+9}$	6,2	9,4
$^{84}Kr^{+15}$	5,6	12
$^{136}Xe^{+20}$	6,8	3,9

Table 5: Ion Beam Parameters of DC280 at 5.9 MeV/n

Ion	I_{HVP} [eμA]	I_{INJ} [eμA]	I_{in} [eμA]	I_{out} [eμA]	I_{EXTR} [eμA]
$^{12}C^{+2}$	69,7	59,5	37,8	31,3	20
$^{40}Ar^{+7}$	100,3	91	63	53	42
$^{84}Kr^{+14}$	45,6	40,5	25	21,3	19

I_{HVP}: ion current from ECR after HV platform; I_{INJ} ion current after bender and buncher, R_{in} = 40 cm; I_{in} ion current in the DC280 center, R_{in} = 40 cm; I_{out}: ion current near the DC280 extraction radius, R_{out} = 175 cm; I_{EXTR}: ion current in the extraction beam line.

Table 6: Coefficients of Ion Capture Into Acceleration

Ion	I_{INJ} [eμA]	Without buncher	With buncher
$^{12}C^{+2}$	59,5	11,5%	63,5 %
$^{40}Ar^{+7}$	91	12,2%	69,2 %
$^{84}Kr^{+14}$	40,5	14,1%	61,7 %

Unfortunately, we could not use flat-top resonators at test acceleration due some technical problems, therefore further increasing of ion currents was possible only with using the electrostatic beam chopper to avoid possible damaging of the deflector. When the chopper was operated with beam duty cycle of 25% we observed extracted current of $^{40}Ar^{+7}$ ions which was equivalent to I_{EXTR} = 63 eμA (9 pμA, P_{beam} = 2,1 kW) at I_{INJ} = 150 eμA (21,4 pμA).

The HV platform voltage was U_{HVP} = 47.2 kV for $^{12}C^{+2}$ and $^{84}Kr^{+14}$ ions, for $^{40}Ar^{+7}$ ions it was U_{HVP} = 44.2 kV. The extraction voltage of DECRIS-PM was 15 kV for all the ions. The acceleration frequency was 9 MHz, the optimal RF voltage on the main dees was 115 - 120 kV. The deflector voltage was about -75 kV. Vacuum was: $5\text{-}7\cdot10^{-8}$ Torr in injection, about $8\cdot10^{-8}$ Torr in the cyclotron vacuum chamber and $2\text{-}3\cdot10^{-7}$ Torr in the beam line N3.

Besides that, we carried out brief acceleration of $^{40}Ar^{+6,+7,+8}$ ions at acceleration frequencies of 8.3 MHz and 9.8 MHz, with the aim to check DC280 operation at lower (5 MeV/nucleon) and higher (7 MeV/nucleon) ion energies. Reached intensities of ion beams extracted with the energies were from 3 to 6 pμA depending on cyclotron tuning.

Experimental Setups

As the first experimental set-up for experiments on the synthesis and study of SHE, the GFS-II gas-filled separator has been chosen. The separator comprises the Q1-D1-Q2-Q3-D2 ion optical scheme (Fig. 10). The main magnet D30° with a deflection angle of 30°, rotated rear pole face and a gap of 120 mm separates synthesized heavy nuclei from background particles. The dipole D10° with a deflection angle of 10° reduces the background from light high-energy particles, e.g. protons, alpha-particles.

The separator (Fig. 11) had been manufactured by the SigmaPhi firm (Vannes, France) and installed at the beam line N3 (Fig. 9) of the SHE factory experimental hall designed in compliance with class II radiation safety requirements for work with high radioactive targets made of transuranium isotopes. The GFS-II was commissioned and ready for operation. The first beam of $^{40}Ar^{+6}$ ions was transported to the GFS-II beam stopper on 09.09.2019.

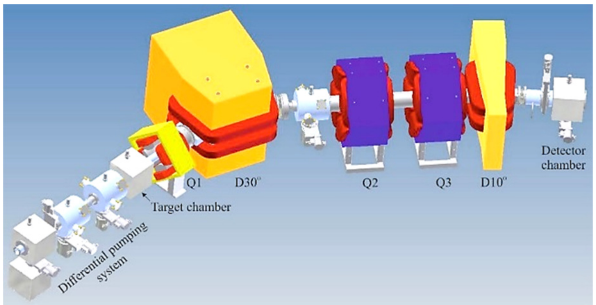

Figure 10: Configuration of GFS-II gas-filled separator, where Q- quadrupole lenses, D- dipole magnets.

Figure 11: GFS-II gas-filled separator.

During the first stage of testing the properties of the separator, the detection and data acquisition systems will be studied using ^{40}Ar+natYb, ^{48}Ca+natYb, ^{48}Ca+^{206}Pb reactions. Tests will be continued using ^{48}Ca+^{242,244}Pu and the ^{48}Ca+^{243}Am reactions. Several hundred decay events of Fl and Mc isotopes are expected to be recorded. After completion of these tests, it is planned to start the synthesis of new superheavy elements in reactions of ^{50}Ti and ^{54}Cr ions with ^{248}Cm, ^{249}Bk and $^{249\text{-}251}$Cf isotopes. The experiments will be conducted in a broad international cooperation.

The second experimental set-up is the GFS-III separator which also was made by the SigmaPhi. The GFS-III has the same ion optical scheme except D2 magnet which has the deflection angle of ±15°. The experimental setup will be installed on the beam line N4. The GFS-III will be utilized for nuclear spectroscopy. The first stage of testing the detection and data acquisition systems will be studying of Mc isotopes- products of the ^{48}Ca+^{243}Am reactions. Also, GFS-III will be used as a pre-separator for chemical experiments with SHE.

CONCLUSION

The SHE Factory was commissioned in 2019. The beam parameters of the DC280 cyclotron are close to required ones for testing of the first experimental setup - GFS-II separator in 2019. The GFS-II is ready for the first experiments on the synthesis and study of SHE.

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