12th Int. Particle Acc. Conf. IPAC2021, Campinas, SP, Brazil JACoW Publishing
ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-THPAB182

DC-280 CYCLOTRON FOR FACTORY OF SUPER HEAVY ELEMENTS, EXPERIMENTAL RESULTS

V. A. Semin†, S. L. Bogomolov, K. Gikal, G. G. Gulbekyan, I. A. Ivanenko, I. V. Kalagin, N. Yu. Kazarinov, V. I. Mironov, L. Pavlov, Joint Institute for Nuclear Research, Dubna, Russia

Abstract

The DC280 is the high current cyclotron with design beam intensities up to 10 pμA for ions with energy from 4 to 8 MeV/nucleon. It was developed and created at the FLNR JINR. The accelerator has worked 9350 hours. Experiments on acceleration of ^{12}C, ^{40}Ar, ^{48}Ca, ^{48}Ti, ^{52}Cr and ^{84}Kr beams production were carried out. The following intensities of accelerated beam have been achieved: 10 pμA for $^{12}C^{+2}$; 10.4 pμA for $^{40}Ar^{+7}$; 7.1 pμA for $^{48}Ca^{+10}$, 1 pμA for $^{48}Ti^{+10}$; 2.4 pμA for $^{52}Cr^{+10}$; 1.43 pμA for $^{84}Kr^{+14}$. The total acceleration efficiency from ion source to transport channel was about 50%.

DC-280 DESCRIPTION

DC-280 is the accelerated ions source for experiments on synthesis of super heavy elements [1]. It is part of Super Heavy Element (SHE) Factory which was created in FLNR in JINR. It is isochronous cyclotron designed for acceleration of ion with mass to charge ratio from 4.5 to 8 to energy from 4 to 8 MeV/n. Main parameters design and achieved present in Table 1.

Table 1: Main Parameters of DC-280 Cyclotron

Parameters	Design	Achieved
Injecting beam energy	Up to 80 keV/Z	38,04 – 72,89 keV/Z
A/Z	4÷7.5	4,4($^{40}Ar^{+7}$) ÷6,9($^{48}Ca^{+7}$)
Energy	4÷8 MeV/n	4,01 – 7 MeV/n
Ion (for DECRIS-PM)	4-136	12 ($^{12}C^{+2}$) – 84 ($^{84}Kr^{+14}$)
Intensity (A~50)	>10 pμA	10,4 pμA ($^{40}Ar^{+7}$);
Magnetic field level	0.6÷1.3 T	0.8÷1.23 T
K factor	280	
Dee voltage	2x130 kV	130 kV
Power of RF generator	2x30 kW	
Accelerator efficiency	>50%	51,9 % ($^{48}Ca^{+10}$ 5 pμA)

Electron Cyclotron Resonance (ECR) source DECRIS-PM is used for production of ions [2, 3]. It has magnetic structure from permanent magnets. It placed on high voltage platform with work voltage up 70 kV for increasing efficiency of initial beam transport and capture to acceleration [4].

For injection to cyclotron, one of two spiral inflectors with magnetic radius R_m= 7.5 (type A) or 9.2 (type B) is used. During experiments both of them were successful tested. There is electrostatic quadrupole lens in central part of cyclotron. Polyharmonic buncher is used for increasing of ions capture to acceleration [4].

Accelerated beam is extracted from cyclotron by electrostatic deflector. It works in conjunction with magnetic channel. Deflector length is 1.3 m. The work electric field strength in gap between electrodes is up 90 kV/cm [1].

† seminva@jinr.ru

Extracted beam is delivered by transport to experimental setups [5]. There are 5 channels connected with 3 isolated halls.

On 26 December 2018, the first accelerated beam was got inside of DC-280 cyclotron [1, 6]. On January 2019, accelerated beam was extracted from cyclotron to transport channel. On September, the new experimental facility Dubna Gas Filled Separator 2 was mounted, and test with accelerator beam was started [7]. On December of 2019, work with beam of ^{48}Ca was initiated. On November 2020, the first experiment on production of ^{115}Mc was started.

The cyclotron has worked 9350 hours during three years. Different mode of work with different ions and energy were explored. The work diagram of DC-280 cyclotron with marks of tested regimes is presented on Fig. 1. The cyclotron has shown reliable and highly effective work. The control and extraction systems were optimized for improving of efficiency and reliable of accelerator.

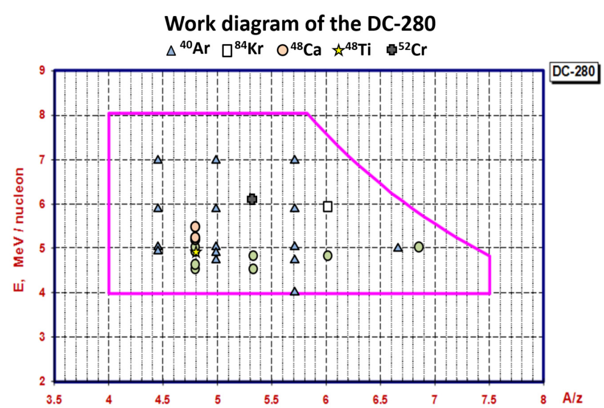

Figure 1: DC-280 work diagram with mark of test modes.

RESULTS

Polyharmonic Buncher Contribution

Polyharmonic buncher is used for increasing of capture to acceleration [1, 4]. It is in vertical part of axial injection system on the distance 3.875 m from median plane of cyclotron. This device converses the continuous beam from ion source to sequence of bunch arrived in cyclotron in phase of capture to acceleration. It consists from one drift tube and two grids Fx2 and Fx3. Their potential varies with frequency by one, two and three times of acceleration frequency, respectively. It allows capture to acceleration 70 % of ions generated in Ion source.

Capture efficiency of ion from axial injection system to acceleration in cyclotron with different buncher mode: buncher Off; work only drift tube (1-st harmonic); work

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-THPAB182

drift tube and two grids (3 harmonic) is presented in Table 2. Capture efficiency increasing is 3.3 times then only drift tube (1-st harmonic) works and 4.5 times then drift tube, both grids work.

Table 2: Efficiency of Capture to Acceleration for Different Mode of Buncher

Ion	I_{ECR} (pμA)	Capture		
		Off	1-t Harmonic	3 Harmonic
^{40}Ar	5.6	15%	40%	66%
^{48}Ca	2.5	15%		67%
^{84}Kr	3.64	12%	43%	57%
Max Design Value of Capture				**70%**

Electrostatic Quadrupole Lens Contribution

The electrostatic quadrupole lens is placed after inflector in central region of cyclotron. It reduces loss during initial turns in cyclotron and decreases beam divergence, which has positive effect on passage inside cyclotron and escape of accelerated ion beam. Every lens electrode has own power supply that allows make additional fine tuning beam direction after inflector.

The impact of quadrupole lens on efficiency of capture to acceleration and efficiency of passing inside cyclotron efficiency is presented in Table 3. Lens's contribution is more relevant with high intensity beams. It gives additional rise of efficiency of capture and acceleration inside cyclotron up to 9%.

Table 3: Contribution of Electrostac Quadrupole Lens to Efficiency of Capture and Acceleration Inside Cyclotron

Quadrupole Lens Mode	Ion	I_{ext} (pμA)	Effectivity		
			Capture	Inside Cyclotron	Difference
Off	^{40}Ar	7	65%	86%	9%
On			74%	88%	
Off	^{48}Ca	5	73%	86%	5%
On			78%	87%	
Off	^{52}Cr	0,5	78%	95%	3%
On			81%	95%	

Achieved Beam Intensity

On the first stage of work, the ions of ^{40}Ar and ^{84} Kr were accelerated. We tested various charges and got different energies. First results were presented earlier [1, 5]. The next step was to obtain of ^{48}Ca beams, which are used for experiments on synthesis of super heavy elements. Moreover, the experiments to study of high intensity beam production and acceleration was carried out.

For further experiments for super heavy elements will be needed beams of accelerated ions of ^{50}Ti and ^{54}Cr. For development of technology, we have accelerated their naturally occurring isotopes ^{48}Ti and ^{52}Cr. We have got intensity 1 pμA for ^{48}Ti and 2.4 pμA for ^{52}Cr. The intensity is limited by ion current from ECR source. The comparison of normalized intensity distribution for ^{52}Cr ion beam in acceleration process is presented on Fig. 2. There are data for different intensities of beam and different ECR source regimes.

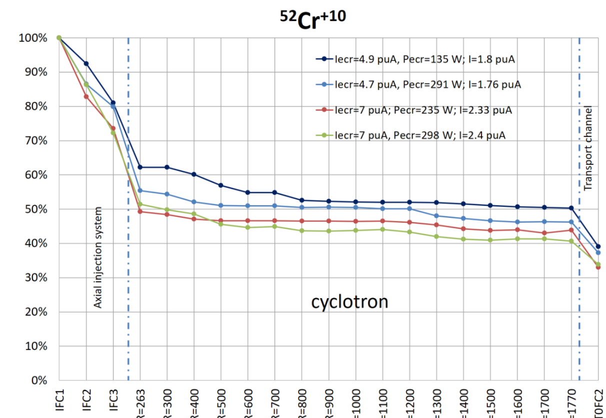

Figure 2: Comparison of normalized ^{52}Cr beam intensity in different points of cyclotron for different beam intensities.

We can see, that efficiency of acceleration worsen then we increase power input to ECR source. We work to improve of the method of ion production and optimize the ECR source work mode.

Table 4: Efficiency in Different Points of Accelerator on Different Stage of Acceleration

Ion	Energy (MeV)	Intensity (pμA)				
		Axial Injection		Cyclotron		Transport Channel
		After Separation	Vertical part	R= 400	R= 1770	
^{40}Ar^{+7}	195	28,7	24,7	17,1	14,2	10,4
^{48}Ca^{+7}	240	10,9	9,8	6,9	6,1	5,2
^{48}Ca^{+10}	240	9	8,1	5,58	5,1	4,7
^{48}Ca^{+10}	240	23	19	12,8	10,6	7,1
^{48}Ti^{+10}	244	2,0	1,9	1,4	1,25	1,0
^{52}Cr^{+10}	320	5,8	5,1	3,3	3,1	2,4
^{84}Kr^{+14}	496	3,1	2,8	1,7	1,6	1,4

We have measured beam current in different places of cyclotron on different stage of acceleration for definition of efficiency and analysis of loss. In axial injection and transport channels we use Faraday's cups. Inside the cyclotron we use inner moving probe.

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-THPAB182

For analysis of phase moving and fine-tuning of the accelerated beam inside cyclotron, the system consisted of 10 coup of Pick-Up electrodes is used. For tuning of beam passing through transport channels and beam space distribution scanning two-dimensional ionization profile monitor were used [8].

The design intensity 10 pμA in transport channel was successfully obtained for ^{12}C and ^{40}Ar ions beam, as well as for ^{48}Ca ions beam inside the cyclotron on extraction radius. Maximum intensity of ^{48}Ca ion beam extracted after acceleration is 7.1 pμA. The full list of obtained results present in Table 4.

Efficiency Analysis

We have analysed the efficiency of work and ions loss on different stage of acceleration. The results is presented in Table 5. Main loss of ions is in axial injection and extraction systems. Capture to acceleration efficiency is about 70%, it is close to possible maximum. Transport efficiency of extracted beam from cyclotron to experimental target is more than 90%. The efficiency is about 50% with beam intensity up to 5 pμA and about 40%, for intensity about 10 pμA.

Table 5: Efficiency of Different Stage of Acceleration

Ion	Energy (MeV)	Efficiency				
		Axial Injection	Capture	Cyclotron	Extraction	Total
$^{40}Ar^{+7}$	195	86%	69%	83%	73%	36%
$^{48}Ca^{+7}$	240	90%	71%	88%	85%	48%
$^{48}Ca^{+10}$	240	90%	69%	91%	91%	51%
$^{48}Ca^{+10}$	240	82%	67%	83%	67%	31%
$^{48}Ti^{+10}$	244	92%	72%	92%	83%	50%
$^{52}Cr^{+10}$	320	89%	64%	93%	78%	41%
$^{84}Kr^{+14}$	496	91%	60%	93%	92%	47%

Efficiency of ^{48}Ca Production

For ^{48}Ca we use method production the working substance by evaporation of compound in crucible [9]. During the work, DECRIS-PM ECR source had high efficiency and small consumption of the material, that very important for experiment with rare isotopes. The consumption of ^{48}Ca compound during the work for different production ion beam present on Fig. 3.

We can see that the ^{48}Ca consumption depends on beam current. But its level is low. For example, during long experiments with intensity about 4 pμA (2 pμA accelerated beam) the consumption was up 0.3 mg/hour.

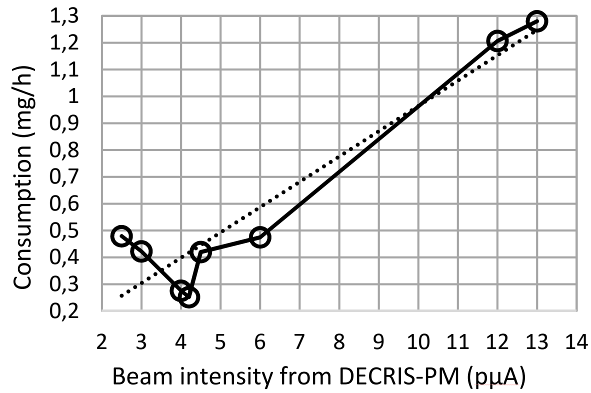

Figure 3: Consumption of 48Ca compound.

CONCLUSION

The cyclotron DC-280 has worked 9350 hour including 1700 hour for experiments. The work and beam current on experimental target was stable during long time experiments. The cyclotron has shown itself like reliable and highly effective machine in terms of energy consumption, as well as in terms of ion beam acceleration and transport. The main part of design parameters has carried out yet. The design intensity 10 pμA in transport channel was successfully obtained for ^{40}Ar ions beam, as well as for ^{48}Ca ions beam inside the cyclotron on extraction radius. Maximum intensity of ^{48}Ca ion beam extracted after acceleration is 7.1 pμA. The efficiency of acceleration is about 50%.

REFERENCES

[1] I. V. Kalagin *et al.*, "SHE factory: cyclotron facility for Super Heavy Elements Research", in *Proc. 22nd Int. Conf. on Cyclotrons and their Applications (Cyclotrons'19)*, Cape Town, South Africa, Sep. 2019, pp. 305-309. doi:10.18429/JACoW-Cyclotrons2019-THC01

[2] V. Mironov *et al.*, "On Optimization of the Metal Ion Production by Electron Cyclotron Resonance Ion Sources", *Physics of Particles and Nuclei Letters*, vol. 18, pp. 370–377, 2021. doi:10.1134/S1547477121030092

[3] S. L. Bogomolov *et al.*, "Production of High-Intensity Ion Beams from the DECRIS-PM-14 ECR Ion Source", *Physics of Particles and Nuclei Letters,* vol. 15, pp. 878–881, 2018. doi:10.1134/S1547477118070191

[4] G. G. Gulbekian *et al.*, "Proposed design of axial injection system for the DC-280 cyclotron", *Physics of Particles and Nuclei Letters,* vol. 11, pp. 763–773, 2014. doi:10.1134/S1547477114060028

[5] I. V. Kalagin *et al.*, "The project of the beam transportation lines for the DC-280 cyclotron at the JINR FLNR", in *Proc. 24th Russian Particle Accelerator Conf. (RuPAC'14),* Obninsk, Russia, Oct. 2014, paper THPSC09, pp. 336-33.

[6] B. N. Gikal *et al.*, "Start-Up of the DC-280 Cyclotron, the Basic Facility of the Factory of Super heavy Elements of the Laboratory of Nuclear Reactions at the Joint Institute for Nuclear Research", *Physics of Particles and Nuclei Letters,* vol. 16, pp. 866-875, 2019. doi:10.1134/S1547477119060177

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-THPAB182

[7] A. G. Popeko, "On-line separators for the Dubna Super heavy Element Factory", *Nuclear Instruments and Methods in Physics Research B*, vol. 376, pp. 144–149, 2016. doi:10.1016/j.nimb.2016.02.025

[8] Yu. G. Teterev, A. T. Isatov, S. V. Mitrofanov, and A. I. Krylov, "Upgrading the Scanning Two-Dimensional Ionization Profile Monitor in Beam Transport Lines", *Instruments and Experimental Techniques*, vol. 63, no. 6, pp. 795–800, 2020. doi:10.1134/S002044122005036X

[9] V. B. Kutner *et al.*, "Production of intense ^{48}Ca ion beam at the U-400 cyclotron", *Review of Scientific Instruments*, vol. 71, pp. 860–862, 2000. doi:10.1063/1.1150313