HEAVY ION BEAM PRODUCTION FROM THE MODERNIZED DECRIS-3 ECR SOURCE AT THE DC-60 CYCLOTRON

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Abstract

The electron cyclotron resonance (ECR) ion source DECRIS-3 of the DC-60 cyclotron is one of the key components of the accelerator complex. It can operate both as an injector of heavy ions into the cyclotron to produce high-energy ion beams and in standalone mode to provide low-energy beams. The ECR source, as part of the DC-60 heavy-ion accelerator, was commissioned in 2006. To ensure the successful implementation of the scientific and technical programs carried out on the accelerator in 2025, the ion source was modernized. The main goal of the upgrade was to increase beam intensity and to improve the operational stability of the DECRIS-3 source.

PREREQUISITES FOR MODERNIZATION

Since its commissioning in 2006, a wide range of works to generate ion beams have been conducted based on the DC-60 heavy-ion accelerator [1], which have been successfully applied to solving both fundamental (nuclear physics and radiation materials science) and applied problems (production of nuclear membranes).

Over the past 19 years of operation, the accelerator has demonstrated high stability across all systems, but these systems must be upgraded in a timely manner to ensure the cyclotron's uninterrupted operation. Most beam users are interested in highly charged ions, which were not included in the design configuration of the ECR source. Currently, the extracted beam currents of krypton $^{84}Kr^{15+}$ and xenon $^{132}Xe^{23+}$ ions in the ECR source are approximately 17 μA and 8 μA, respectively, which is insufficient for most applications. These ion current values are primarily influenced by the ECR source, whose magnetic system has deteriorated over the years.

The core of the accelerator complex is the DC-60 cyclotron, capable of accelerating high-intensity beams of heavy ions from lithium to xenon to energies of 0.35 to 1.75 MeV/nucleon. The accelerator also features a channel for low-energy ion beams ranging from 10 to 25 keV, produced by an external ion source operating on the DECRIS-3 type electron-cyclotron resonance principle [2].

Prior to the upgrade, the DECRIS-3 source had the following specifications:

- Magnetic field at the injection and extraction sides: 1.3 and 1.1 T respectively;
- Hexapole field: 1.0 T;
- Source chamber: length 20 cm, diameter 6.4 cm; insulated up to 25 kV.

Multiply charged ions are formed through stepwise ionization, and the plasma electrons are heated by an electromagnetic wave at the cyclotron resonance frequency of 14.5 GHz. The hexapole is made of NdFeB and consists of four discs with a trapezoidal magnet structure.

Prior to modernization, the hexapole was made of NdFeB and consisted of 4 disks, each 50 mm long. Each disc, in cross-section, consists of 24 trapezoids, which on the inner side are circumscribed around a circle with a diameter of 70 mm, and on the outer side are inscribed in a circle with a 180 mm diameter for the central discs and in a circle with a 160 mm diameter for the outer discs.

The following issues have been observed over the years of operation:

- Sputtering of the coaxial bias electrode due to plasma exposure;
- Localized burnout of the stainless steel protective screen;
- A wide ion beam tail in the vicinity of the plasma electrode, indicating suboptimal beam formation;
- A decrease in the intensity of highly charged ions.

The most probable degradation mechanism was associated with long-term thermal loading of the source components during plasma operation and accidental shutdowns of the water-cooling system, which could affect the permanent magnet system and deteriorate the magnetic field configuration. All of this indicates improper ion beam formation in the ECR source due to the effect of high temperatures on the ion source's magnetic system.

ECR SOURCE MODERNIZATION

To increase beam intensity and improve the operational stability of the DECRIS-3 source, a modernization was carried out that included replacing the hexapole, increasing the diameter of the ionization chamber, modifying its shape, partially reconstructing the magnetic structure, and completely reconstructing the injection section of the housing. The primary design requirement was to preserve the configuration of the source's magnetic yoke, the external dimensions of the hexapole housing and the mounting assembly for the high-voltage extraction insulator.

The new hexapole has a Halbach-type structure and consists of 24 identical trapezoidal sectors made of permanent magnet material (NdFeB) [3]. The use of modern magnetic materials and technologies allows the magnetic field strength to be maintained while increasing the diameter of the inner opening and significantly reducing radial inhomogeneities. To ensure uniform field distribution along the poles, each sector is made from a single piece of magnetic material, which eliminates magnetic field deficiencies near the transitions between permanent magnets. To verify the magnetic characteristics of the renewed hexapole, measurements of the radial and axial magnetic fields were performed using a magnetometer.

The use of specially designed additional iron masses in the injection region increases the peak axial magnetic field on the injection side, which significantly limits ion diffusion into the injection region and, consequently, increases the currents of extracted multiply charged ions [3].

At the Figure 1 shows the radial component of the magnetic field of the hexapole at DECRIS-3 ECR-source.

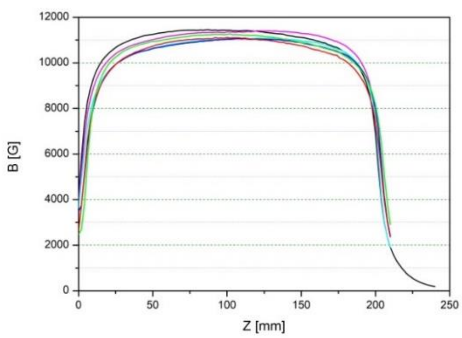

Figure 1: The radial magnetic field distribution of the DECRIS-3 source.

Figure 2 shows the axial magnetic field distribution of the DECRIS-3 source before and after modernization.

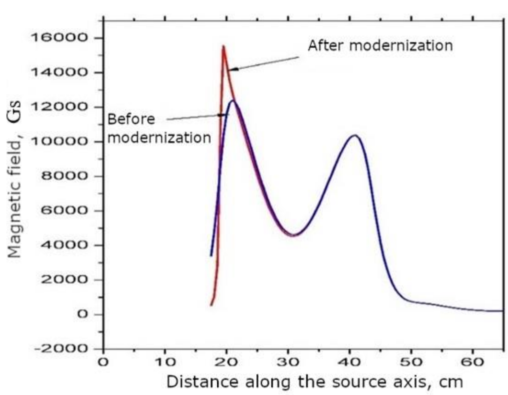

Figure 2: The axial magnetic field distribution of the DECRIS-3 source.

One of the key changes in the source is the increase in the inner diameter of the plasma chamber from 64 mm to 74 mm. Consequently, this should also increase the plasma volume and ion lifetime, enabling the production of ion beams with higher charge states and higher beam intensities. This redesign will require some modifications to the magnetic structure and the introduction of a completely new injection chamber.

The updated double-walled, water-cooled ionization chamber has a constant diameter and is made entirely of stainless steel. Increasing the chamber diameter increases ion retention time in the discharge and, consequently, the maximum charge and intensity of the extracted ion beams.

Figure 3 shows a three-dimensional model of the modernized DECRIS-3 ion source.

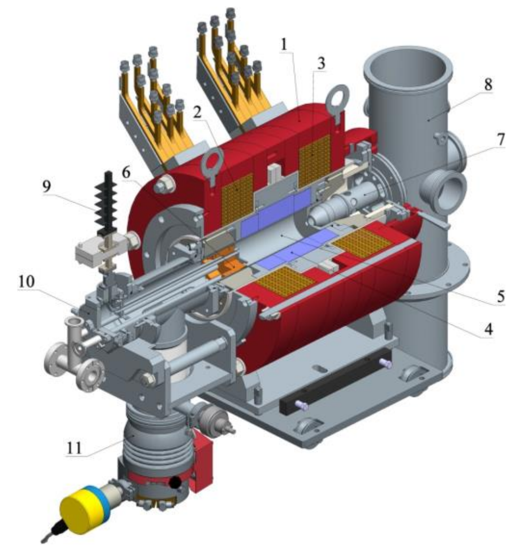

Figure 3: A three-dimensional model of the modernized DECRIS-3 ion source. 1 – magnetic yoke, 2, 3 – current windings, 4 – hexapole, 5 – plasma chamber, 6 – additional ferromagnetic insert, 7 – movable extraction electrode, 8 – extraction unit, 9 – standard waveguide, 10 – UHF and working substance inlet assembly (short circuit), 11 – turbomolecular pump.

Following the completion of the modernization, beams of carbon, nitrogen, oxygen, neon, argon, krypton, and xenon ions were obtained. Table 1 shows the currents achieved after the modernization for these ions. The measurements showed a significant increase in the currents of highly charged ions: the $^{84}Kr^{15+}$ beam current rose to 30 μA, and the $^{132}Xe^{23+}$ beam current to 15 μA, which is corresponds to an almost twofold increase compared with the pre-modernization values. Figures 4–5 show the spectra of krypton and xenon ions.

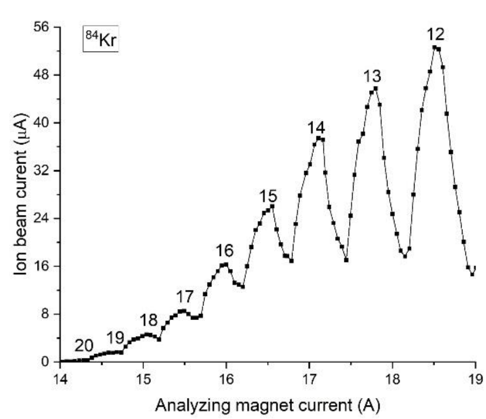

Figure 4: Spectrum of krypton ion beam.

Table 1: Currents of selected ion beams (μA) generated by the ECR source of the DC-60 cyclotron after the modernization under normal operating conditions (Q denotes the ion charge state).

Q	2+	3+	4+	5+	6+	7+	8+	9+	10+	12+	13+	15+	17+	19+	21+	23+
^{12}C	150	97	68													
^{14}N	132	101	55													
^{16}O	201	143	99													
^{20}Ne	173	178	187	194	90	44										
^{40}Ar				59	82	78	94	105	96							
^{84}Kr										52	48	30	8			
^{132}Xe												50	45	35	25	15

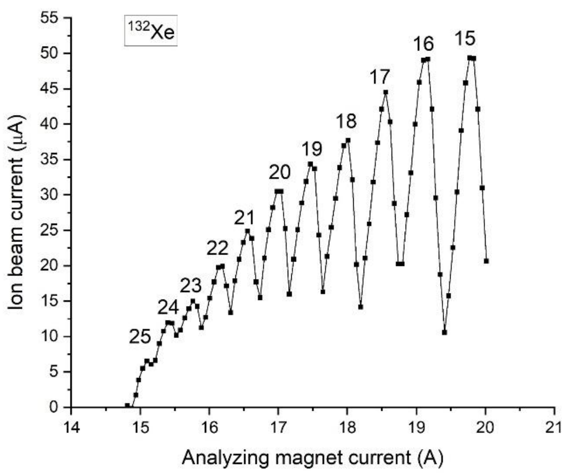

Figure 5: Spectrum of xenon ion beam.

Additionally, the design of the micro-oven insertion assembly was upgraded by increasing its diameter, which makes it possible to use the micro-oven for feeding a larger volume of solid substances. This increases the continuous operating time of the ion source with solid materials and expands the possibilities for using micro-ovens with a higher maximum heating temperature.

For the key highly charged ion beams, the achieved currents increased from 55 to 96 μA for $^{40}Ar^{10+}$, from 17 to 30 μA for $^{84}Kr^{15+}$, and from 8 to 15 μA for $^{132}Xe^{23+}$, corresponding to increase factors of 1.74, 1.76, and 1.87, respectively.

These modifications were selected to address the main degradation factors observed during long-term operation. The replacement of the hexapole restored the required magnetic field configuration, while the use of a Halbach-type structure improved the radial field uniformity. The redesigned injection section and additional ferromagnetic inserts optimized the axial magnetic field distribution and reduced ion losses in the injection region. In addition, the new double-walled water-cooled plasma chamber improved the thermal stability of the source and reduced the influence of local overheating on beam formation.

At present, three methods are employed for ion beam production at the cyclotron ECR source: injection of pure gases, evaporation of organometallic compounds, and heating of the source material using a micro-oven. The pure-gas method is used for the production of ^{4}He, ^{12,13}C, ^{14}N, ^{16,17}O, ^{20,22}Ne, ^{40}Ar, ^{84}Kr, and ^{132}Xe ions. Moreover, the method Metal Ions from Volatile Compound (MIVOC) is used for producing ^{10,11}B, ^{28}Si, ^{48}Ti, ^{52}Cr, ^{56}Fe, ^{58}Ni, ^{59}Co, ^{74}Ge, and ^{180}Hf ions. The micro-oven method is used for the production of ^{6}Li, ^{24}Mg, ^{31}P, and ^{40}Ca ions.

CONCLUSION

The modernization of the DECRIS-3 ECR source at the DC-60 cyclotron has significantly improved its performance. The following key modifications were implemented during the modernization: replacement of the hexapole with a design featuring an increased magnetic field, expansion of the plasma chamber diameter, and reconstruction of the source's injection section. These measures resulted an almost twofold increase in multiply charged ion currents, improved ion beam stability, and extended the service life of the source's critical components. The results of the modernization ensure the reliable operation of the DECRIS-3 source as demands for heavy ion beam intensities continue to grow.

ACKNOWLEDGEMENTS

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REFERENCES

[1] M.V. Zdorovets, I.A. Ivanov, et al. "Accelerator complex based on DC-60 cyclotron", in *Proc. RuPAC'24*, Obninsk, Russia, October, 2014, pp. 287-289. THCA01

[2] B. Gikal et al. "DC-60 heavy ion cyclotron complex: first beams and project parameters", *Physical of particles and nuclei letters*, vol. 5, no. 7, pp. 642-644, 2008. doi:10.1134/S1547477108070248

[3] A. Efremov, S. Bogomolov, V. Bekhterev, A. Dobrosavljević, and N. Nešković. "Upgrading the ECR ion source within

FAMA", *Nuclear Technology & Radiation Protection*, vol. 33, no. 1, pp. 47-52, 2018. doi: 10.2298/NTRP1801047E