UPGRADING THE ECR ION SOURCE WITHIN FAMA

by

Andrey A. EFREMOV [1]***, Sergey L. BOGOMOLOV*** [1]***, Vladimir V. BEKHTEREV*** [1]***,***
Aleksandar S. DOBROSAVLJEVIĆ [2]***, Nebojša B. NEŠKOVIĆ*** [2]***,***
Ivan M. TRAJIĆ [2]***, and Dragana D. ĆIRIĆ*** [2]

[1] Flerov Laboratory of Nuclear Reactions, Joint Institute for Nuclear Research, Dubna, Russia
[2] Laboratory of Physics, Vinča Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia

Scientific paper
http://doi.org/10.2298/NTRP1801047E

Recent upgrading of the Facility for Modification and Analysis of Materials with Ion Beams – FAMA, in the Laboratory of Physics of the Vinča Institute of Nuclear Sciences, included the modernization of its electron cyclotron resonance ion source. Since the old ion source was being extensively used for more than 15 years for production of multiply charged ions from gases and solid substances, its complete reconstruction was needed. The main goal was to reconstruct its plasma and injection chambers and magnetic structure, and thus intensify the production of multiply charged ions. Also, it was decided to refurbish its major subsystems – the vacuum system, the microwave system, the gas inlet system, the solid substance inlet system, and the control system. All these improvements have resulted in a substantial increase of ion beam currents, especially in the case of high charge states, with the operation of the ion source proven to be stable and reproducible.

Key words: ion source, plasma chamber, magnetic structure, ion beam

INTRODUCTION

Research programs dealing with ion implantation and other methods of modification of materials with ion beams were initiated in the Laboratory of Physics of the Vinča Institute of Nuclear Sciences in 1998. That was a result of successful completion of the designing, construction, assembling and commissioning of an electron cyclotron resonance (ECR) ion source – the mVINIS Ion Source. The job was performed by a joint team of the Flerov Laboratory of Nuclear Reactions of the Joint Institute for Nuclear Research, Dubna, Russia, and the Laboratory of Physics. That was a CAPRICE type ECR ion source [1] operating at the microwave frequency of 14.5 GHz with the maximal extraction voltage of 25 kV [2-7]. Different types of multiply charged ion beams produced with that ion source were being used extensively in an experimental channel for surface modification of materials [8-10].

Recently, we have decided to upgrade the ion source and the experimental channel, constituting the Facility for Modification and Analysis of Materials with Ion Beams (FAMA). Since the old ECR ion source was used as „a work-horse" for more than 15 years, all its major subsystems were expended and required modernization or refurbishment. Primarily, it was decided to reconstruct the ion source body, *i. e.*, its plasma and injection chambers and magnetic structure, to enable one to obtain higher currents of high charge state ion beams both from gases and solid substances. The decision was based on the following two facts. The ion energy, which determines the depth of penetration of an ion in an irradiated material, is determined by the chosen charge state and limited by the maximal extraction voltage. On the other hand, the ion current, which determines the time of attaining the required ion fluence, *i. e.*, the time of irradiation of the material, is usually lower for a higher charge state. Hence, the enhanced capabilities of producing higher currents of high charge state ion beams mean that the possibilities of performing irradiation experiments with the ion source have become wider [10].

RECONSTRUCTION OF THE ECR ION SOURCE BODY

During the 15 years of operation, we have noticed some disadvantages in the ECR ion source design, which are listed as folows.

– The use of the microwave coupling system having a standard waveguide connected to a coaxial line

---

* Corresponding author; e-mail: tivan@vin.bg.ac.rs

via a non-standard element (the injection cube) causes big losses of the microwave power. As a result, the injection side of the source body is strongly heated, causing uncontrolled outgassing. A special tuning mechanism for the coupling system is also required.

- The manufacturing of the water-cooled plasma chamber is complicated and expensive (the variable diameter double-wall chamber requires the welding of the parts made of copper and stainless steel).
- There is no room to install additional elements inside the plasma chamber because the injection part of the chamber is used as a coaxial waveguide.
- The only place to introduce a micro-oven to evaporate solid substances is the inner conductor of the coaxial line. It is also used as a bias electrode and has to be insulated from the plasma chamber. As a result, the oven power supply should also be insulated. The size of the oven is strongly restricted by the diameter of the inner conductor of the coaxial line.
- The position of the micro-oven is exactly on the axis of the ion source. The interaction of the oven with plasma causes its additional heating. As a result, the oven temperature depends on the source regime. To minimize this effect, the fine-tuning mechanism is required to define the optimal position of the oven.

It was decided to change the basic construction of the ECR ion source body to eliminate the above-mentioned disadvantages and improve the production of multiply charged ion beams from gases and solid substances. These changes comprised an increase of the volume of the plasma chamber and a change of its shape, a partial reconstruction of the magnetic structure, and a total reconstruction of the injection part of the source body [11].

First, we decided to increase the internal diameter of the plasma chamber from 64 mm to 74 mm to provide enough room for installation of all the required elements. Consequently, this should also increase the plasma volume and ion lifetime, and enable one to obtain higher charge state ion beams and higher beam intensities. Such a reconstruction required some changes in the magnetic structure and introduction of an entirely new injection chamber.

The new water-cooled double-wall plasma chamber has a constant diameter and has been entirely made of stainless steel. We have increased the internal diameter of the injection soft iron plug to 80 mm to allow introduction of the new injection chamber into the source (fig. 1).

To compensate for the magnetic field losses at the injection side of the ion source, it was inserted an additional ferromagnetic plug directly into the plasma chamber. In such a way, it significantly increased the axial magnetic induction at the injection side of the source, reaching 1.8 T for the maximal current of the injection stage coil, being 1300 A. Such a strong axial magnetic field significantly reduced the electron losses through the injection side of the source and provided the increased currents of the extracted ion beams [11]. Comparison of the axial magnetic field distributions for the old and new versions of the axial magnetic system is shown in fig. 2. The small magnetic field drop at the extraction side can be easily compensated by increasing the extraction coil current, Iextr, over 1000 A (the power supply can provide the current up to 1300 A).

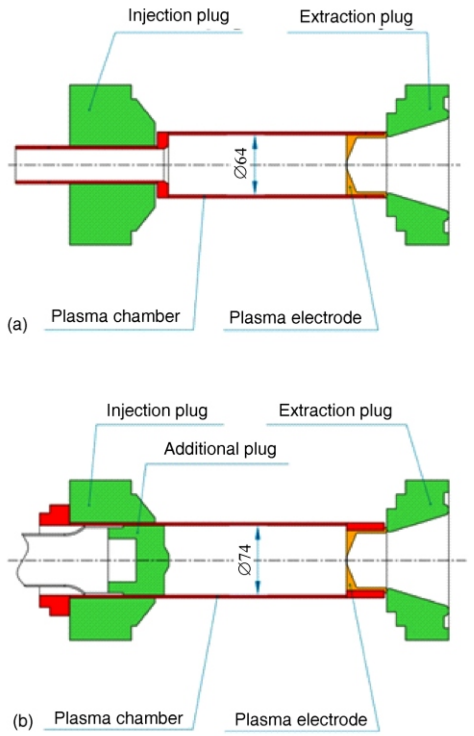

Figure 1. Schematic presentation of (a) the old axial magnetic system and (b) the new axial magnetic system

The old hexapole magnet, ensuring the radial confinement of plasma, was replaced by a new one, allowing

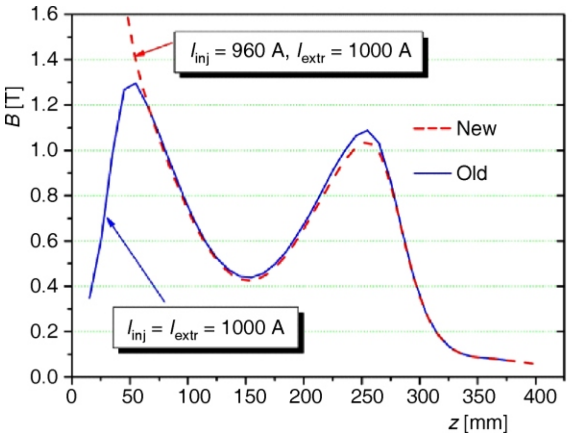

Figure 2. Axial magnetic field distributions for the old and new versions of the magnetic system. Measurements were performed for the currents of the injection stage and extraction stage coils set to nominal values

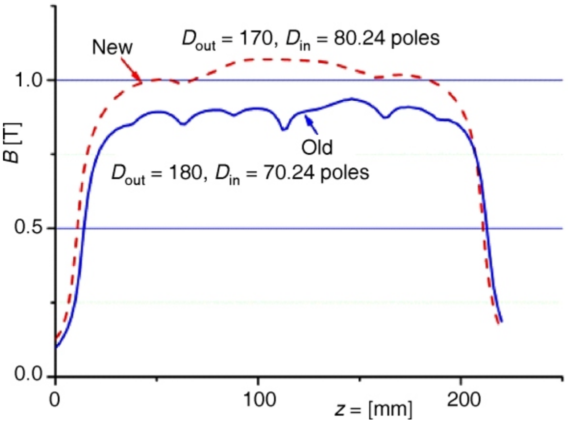

Figure 3. Radial magnetic field distributions for the old and new hexapoles; measurements were performed close to the inner wall of the discharge chamber, at the radius of 37 mm for the new hexapole structure

installation of the new plasma chamber with a bigger external diameter. The new hexapole has a Halbach type structure [12] and consists of 24 identical trapezoidal sectors made of permanent magnet material (NdFeB) with the appropriate easy axis directions. To obtain a smooth magnetic field distribution along the pole, each sector was made from a single piece of magnetic material. This technology eliminated some imperfections in the magnetic field near the permanent magnet junctions. The inner diameter, outer diameter, and length of the hexapole were 80 mm, 170 mm, and 200 mm, respectively. The comparison of the radial magnetic field distributions for the old and new hexapoles is shown in fig. 3. The measurements were performed in the region of the plasma chamber wall in front of the pole. It is evident that the application of the modern magnetic material and new construction technology provided a higher level of the magnetic field, even though the new hexapole inner diameter is bigger and the outer diameter is smaller than the corresponding dimensions of the old hexapole.

The new injection chamber enables the direct introduction of the microwave power into the plasma chamber through a standard waveguide. Two identical stainless-steel tubes placed off the axis of the ion source are used for gas feeding and insertion of a micro-oven for evaporation of solid substances. A biased electrode made of tantalum is mounted on the soft iron plug. The shape and size of the bias electrode are chosen to protect the iron plug from direct interaction with plasma. The disposition of these elements is shown in fig. 4.

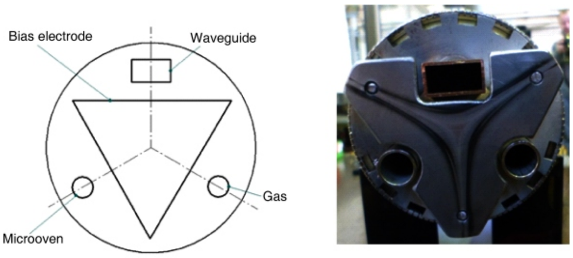

Figure 4. Injection side of the plasma chamber

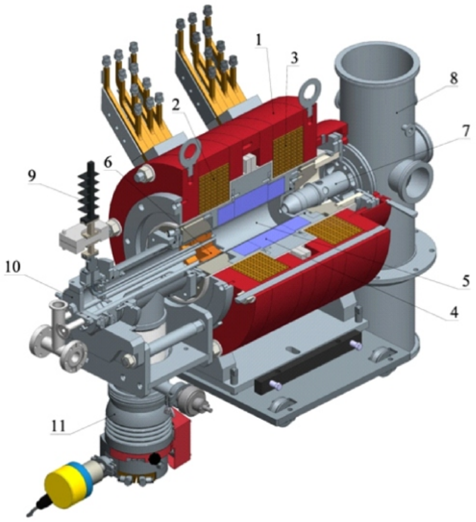

Figure 5. A cross-sectional view of the reconstructed ECR ion source body; *1 – the ferromagnetic yoke, 2 – the injection stage coil, 3 – the extraction stage coil, 4 – the permanent magnet hexapole, 5 – the plasma chamber, 6 – the additional ferromagnetic plug, 7 – the movable extraction electrode, 8 – the extraction chamber, 9 – the standard waveguide, 10 – the injection chamber, and 11 – the turbomolecular pump*

The cross-sectional view of the reconstructed ECR ion source body is presented in fig. 5.

REFURBISHMENT OF THE ECR ION SOURCE SUBSYSTEMS

The upgrading of the ECR ion source included the refurbishment of its major subsystems – the vacuum system, the microwave system, the gas inlet system, the solid substance inlet system, and the control system.

Most of the vacuum system components of the ECR ion source were worn out and required urgent replacement. That comprised three turbomolecular pumps, two cryogenic pumps, several small vacuum valves, the vacuum gauges, and the vacuum seals. The new and bigger injection chamber gave the possibility to install a new turbomolecular pump, having a substantially higher pumping speed than the old one – 260 Ls^{-1} compared to only 53 Ls^{-1}. Thus, it was significantly improved the evacuation efficiency of the plasma chamber. The complete ECR ion source is presented in fig. 6, showing the main new components of the vacuum system.

The old microwave system was replaced by a new one based on a klystron amplifier operating at 14.5 GHz with the maximal output power of 2 kW.

It was also introduced the new gas inlet system with six bottles containing the most commonly used main gases and two bottles of the supporting gases (helium and oxygen). Two fine gas dosing valves were installed for delivery of the main and supporting gases to the plasma chamber. With this system, we solved the

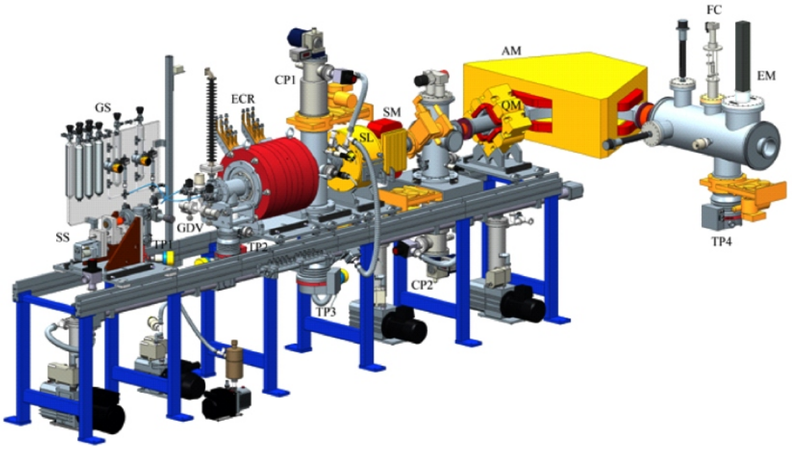

Figure 6. The refurbished subsystems of the ECR ion source; *GS – gas inlet system, SS – solid substance inlet system, GDV – gas dosing valves, TP1, TP2, TP3, TP4 – turbomolecular pumps, CP1, CP2 – cryogenic pumps, ECR – ion source body, SL – solenoid lens, SM – steering magnet, QM – quadrupole magnet, AM – analyzing magnet, FC – Faraday cup, and EM – emittance meter*

problems of atmosphere leaks and contamination of expensive gases and simplified the procedure of switching from one to the other gas (ion type). The system is also presented in fig. 6.

The new solid substance inlet system was adapted to the new injection chamber, allowing insertion of a bigger micro-oven. It would allow us to work at the temperatures up to 1700 ºC, compared to the temperatures up to 900 ºC attainable with the old one. A part of this system can be seen in fig. 6. The high temperature micro-oven has been purchased from Pantechnik [13].

The old control system was replaced by a new one, being a distributed system interlinked with fiber optical lines, which is resistant to the large electromagnetic noise occasionally appearing in the case of plasma brakes in the ion source [14].

RESULTS OF COMMISSIONING OF THE ECR ION SOURCE

The upgraded ECR ion source (M1 machine) was tested via the production of nitrogen, argon, xenon and lead ion beams, and the best obtained results were compared with the corresponding results obtained with the old ion source (mVINIS ion source).

Table 1. Results of commissioning of the refurbished ECR ion source

Ion type	mVINIS ion source	M1 machine
N^{5+}	470 μA	733 μA
N^{6+}	87 μA	205 μA
Ar^{8+}	660 μA	720 μA
Ar^{11+}	130 μA	156 μA
Ar^{12+}	36 μA	68 μA
Xe^{20+}	41 μA	84 μA
Xe^{21+}	37 μA	72 μA
Xe^{22+}	27 μA	64 μA
Xe^{23+}	25 μA	62 μA
Xe^{26+}	–	23 μA
Pb^{20+}	10 μA	40 μA
Pb^{21+}	7 μA	42 μA
Pb^{23+}	2 μA	33 μA
Pb^{26+}	–	9 μA

During these tests, the operation of the source was stable and reproducible. The obtained results have shown a substantial increase of ion beam currents, especially in the case of high charge states. The old results were obtained with the extraction voltages between 15 and 20 kV and the new results with the extraction voltage of 20 kV. This comparison is presented in tab. 1.

Some representative spectra of argon, xenon, and lead ions recorded during the commissioning of the M1 machine are shown in figs. 7-9.

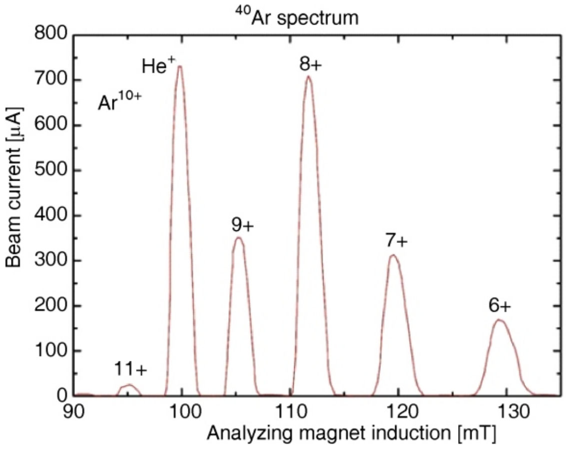

Figure 7. Spectrum of argon ions optimized for maximal production of Ar^{8+} ions

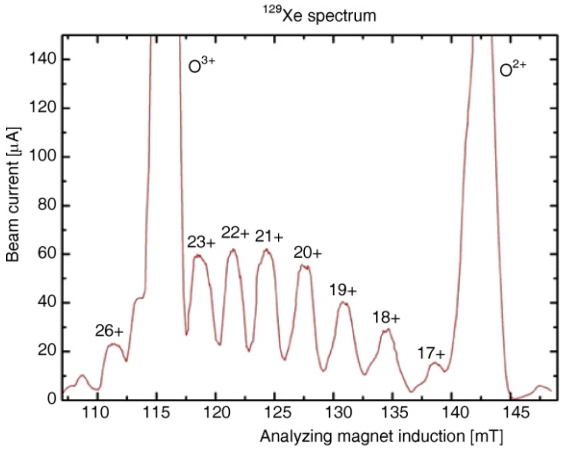

Figure 8. Spectrum of xenon ions optimized for maximal production of Xe^{23+} ions

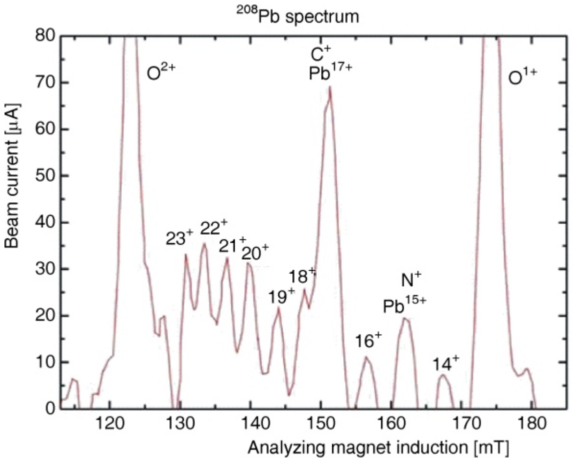

Figure 9. Spectrum of lead ions optimized for maximal production of Pb^{23+} ions

CONCLUSION

The upgraded ECR ion source showed a substantial improvement in operation when compared with the old one. The results obtained during its commissioning demonstrated a significant increase of ion beam currents and the possibility to produce higher charge state ions. The operation of the ion source was stable and reproducible. It will certainly provide wider possibilities for the future operation of the whole FAMA.

ACKNOWLEDGEMENT

A. S. Dobrosavljević, N. B. Nešković, I. M. Trajić, and D. M. Ćirić acknowledge the support to this work provided by the Ministry of Education, Science and Technological Development of Serbia through project Physics and Chemistry with Ion Beams, No. III 45006.

AUTHORS' CONTRIBUTIONS

Reconstruction of the ECR ion source body was carried out by A. A. Efremov and S. L. Bogomolov with V. N. Bekhterev as a project engineer. A. Dobrosavljević was a project leader taking part in the refurbishment of ECR ion source subsystems. Assembling, testing and commissioning of upgraded ion source have been carried out by A. A. Efremov, A. S. Dobrosavljević, I. M. Trajić, and D. D. Ćirić. N. B. Nešković was the project manager.

REFERENCES

[1] Jacquot, B., Pontonnier, M., The New 10 GHz CAPRICE Source – Magnetic Structures and Performances, *Proceedings*, 10th International Workshop on ECR Ion Sources, Oak Ridge, USA, November 1-2, 1990, pp. 133-156

[2] Efremov, A. A., *et al*., Design Aspects and Status of Construction of the mVINIS Ion Source, *Review of Scientific Instruments, 69* (1998), 2, pp. 679-681

[3] Dobrosavljević, A., *et al*., Commissioning of the mVINIS Ion Source, *Proceedings*, 15th International Conference on Cyclotrons and their Applications, Caen, France, June 14-19, 1998, Institute of Physics Publishing, Bristol, UK, 1999, pp. 443-446

[4] Stalevski, T., *et al*., Safety and Control Systems of the mVINIS Ion Source, *Proceedings*, 15th International Conference on Cyclotrons and Their Applications, Caen, France, June 14-19, 1998, Institute of Physics Publishing, Bristol, UK, 1999, pp. 575-578

[5] Dobrosavljević, A., *et al*., First Beams From the mVINIS Ion Souce, Book of Contributed Papers of the 19th Summer School and International Symposium on the Physics of Ionized Gases, Zlatibor, Yugoslavia, August 31-September 4, 1998, Faculty of Physics, Belgrade, 1999, pp. 541-544

[6] Dobrosavljević, A., *et al*., Progress Report on the mVINIS Ion Source, *Review of Scientific Instruments, 71* (2000), 2, pp. 915-917

[7] Dobrosavljević, A., *et al*., Recent Results with the mVINIS Ion Source, *Review of Scientific Instruments, 75* (2004), 5, pp. 1460-1462

[8] Milosavljević, M., *et al*., Channel for Modification of Materials of the TESLA Accelerator Installation, at the Vinča Institute, Book of Invited Lectures, Topical Invited Lectures and Progress Reports of the 19th Summer School and International Symposium on the Physics of Ionized Gases, Zlatibor, Yugoslavia, August 31-September 4, 1998, Faculty of Physics, Belgrade, 1999, pp. 269-281

[9] Dobrosavljević, A., *et al*., L3A Facility at the Vinča Institute – Surface Modification of Materials by Heavy Ion Beams from an Electron Cyclotron Resonance Ion Source, *Review of Scientific Instruments, 71* (2000) 2, pp. 786-788

[10] Dobrosavljević, A., *et al*., Application of ECR Ion Sources for Surface Modification of Materials, *Proceedings*, 16th Conference on Application of Accelerators in Research and Industry, Denton, USA, November 1-5, 2000, American Institute of Physics, New York, 2001, pp. 599-602

[11] Bekhterev, V., *et al*., Modernization of the mVINIS Ion Source, *Proceedings*, 21st International Workshop on ECR Ion Sources, Nizhny Novgorod, Russia, August 24-28, 2014, pp. 68-70

[12] Halbach, K., Design of Permanent Multipole Magnets with Oriented Rare Earth Cobalt Material, *Nucl. Instrum. Methods, 169* (1980), 1, pp. 1-10

[13] ***, PANTECHNIK, PK10-0501-DT04/ Oven Head Technical Datasheet

[14] Trajić, I. M., *et al*., Control System of ECR Ion Source within FAMA, *Serbian Journal of Electrical Engineering, 13* (2016), 3, pp. 423-434

Received on June 6, 2017
Accepted on February 23, 2018

**Андреј А. ЈЕФРЕМОВ, Сергеј Л. БОГОМОЛОВ, Владимир В. БЕХТЕРЕВ,
Александар С. ДОБРОСАВЉЕВИЋ, Небојша Б. НЕШКОВИЋ,
Иван М. ТРАЈИЋ, Драгана Д. ЋИРИЋ**

ПОБОЉШАЊЕ ЈОНСКОГ ЕЦР ИЗВОРА ПОСТРОЈЕЊА ФАМА

Скорашње побољшање постројења за модификацију и анализу материјала јонским сноповима у Лабораторији за физику Института за нуклеарне науке "Винча", укључивало је обнављање и побољшање његовог јонског извора заснованог на електронској циклотронској резонанци. С обзиром да је стари јонски извор обилно коришћен у периоду дужем од 15 година за производњу вишеструко наелектрисаних јона из гасних и чврстих супстанција, било је неопходно његово потпуно обнављање. Главни циљ је обнављање плазмене и инјекционе коморе, магнетне структуре, као и повећање производње вишеструко наелектрисаних јона. Такође, одлучено је да се обнове и побољшају главни припадајући подсистеми – вакуумски систем, микроталасни систем, систем за увођење гасова, систем за увођење чврстих супстанција и управљачки систем. Сва наведена побољшања имала су као резултат суштинско повећање јонских струја, посебно у случају јона са високим степеном јонизације, уз доказани стабилан и поновљив рад јонског извора.

Кључне речи: јонски извор, плазмена комора, магнетна структура, јонски сноп