

## Generation of intense beams of multicharged ions with the use of a high-density electron cyclotron resonant discharge supported by gyrotron radiation

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Advances in nuclear physics research promote ambitious goals for the design of ion sources with previously unattainable characteristics. Existing multicharged ion (MCI) sources are unable to meet all the requirements of flagship projects and provide a sufficiently high current of highly charged ions. One approach to the design of MCI sources with the needed parameters involves the use of a high-current quasi-gasdynamic MCI source. The upgraded SMIS 37/75 setup is used for such studies at the Institute of Applied Physics of the Russian Academy of Sciences. The main results of these studies are reported.

**Keywords:** high-current ion source, electron cyclotron resonance, magnetic plasma confinement, multicharged ions, gyrotron.

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Experimental and theoretical research conducted at the Gaponov-Grekhov Institute of Applied Physics of the Russian Academy of Sciences led to the development of a new type of ion sources with plasma heating under electron cyclotron resonance (ECR) conditions: a gasdynamic ECR source [1,2]. The source implements the quasi-gasdynamic mechanism of confinement in a magnetic trap, which is similar to confinement in thermonuclear mirror traps and differs from the operating principle of traditional Geller ECR sources [3]. This ECR source was examined experimentally at the SMIS 37 facility. Plasma was produced by gyrotron radiation at frequencies of 37.5 and 75 GHz with a power up to 100 kW and a pulse duration of 1 ms. High-frequency microwave radiation allowed us to produce and maintain plasma of a significant density (up to  $8 \cdot 10^{13} \text{ cm}^{-3}$ ) and preserve the main advantages of traditional ECR sources, such as a high degree of ionization and low ion energy. A plasma density this high is achieved though an increase in critical density proportional to the frequency of heating radiation squared. The high microwave power provided an average electron energy of 50–300 eV, which is sufficient for efficient ionization even within the gas pressure range of  $10^{-4}$ – $10^{-3}$  mbar. The gasdynamic ECR source performed fine in experiments on production of high-current (100–300 mA) beams of multicharged ions with a moderate average charge ( $Z = 4$ – $5$  for argon). The results of these studies were analyzed to formulate a new concept for generating high-current beams of multicharged ions (MCIs), which implies the use of a quasi-gasdynamic ion source in combination with a linear preliminary acceleration (to energies on the order of 1 MeV) system and an additional solid-state stripping system (foil stripper). According to

estimates, a beam with a current of 1 mA of heavy ions with a charge of +40 may be obtained via additional stripping of a beam with a charge ranging from +10 to +20 and a current of 10 mA [4].

Note that the initial configuration of the SMIS experimental setup had a low pulse repetition rate (less than 0.1 Hz), which translated into a low efficiency of cleaning of the plasma chamber walls by a discharge and a low efficiency of control over the plasma parameters. A significant flow of impurities from the walls led to a rapid increase in plasma concentration to above-critical values, which resulted in strong reflection of injected radiation and cooling of plasma.

The SMIS 37 installation has recently undergone a significant upgrade, which took its experimental research capabilities to a new level. The main goal was to increase the repetition rate of plasma-producing microwave pulses from 0.1 to 5 Hz. This increase in repetition rate of discharge pulses allows one to largely eliminate various impurities (oxygen, carbon, etc.) that enter plasma uncontrollably from the walls of the discharge chamber and have a significant effect on its main characteristics: the concentration and temperature of electrons.

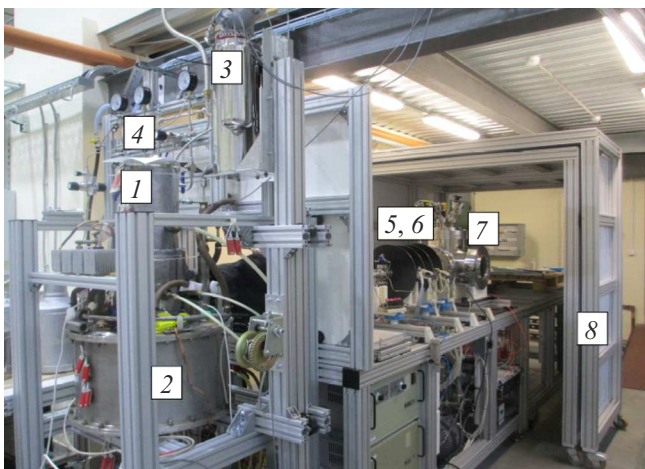
The key units and systems of the SMIS 37/75 experimental stand are as follows:

- 1) high-power microwave radiation source (gyrotron; two gyrotrons with radiation frequencies of 37.5 and 75 GHz may be used in rotation);
- 2) high-voltage gyrotron power supply;
- 3) cryostat with a superconducting solenoid (cryomagnet required for gyrotron operation);
- 4) superconducting solenoid (cryomagnet) power supply;

- 5) liquid helium recovery system;
- 6) quasi-optical system that directs microwave gyrotron radiation and focuses it into a plasma (discharge) chamber located in a pulsed magnetic trap;
- 7) pulsed magnetic trap;
- 8) high-voltage power supply of the magnetic trap;
- 9) plasma (discharge) vacuum chamber with a plasma-forming gas injection system;
- 10) ion beam shaping system (extractor);
- 11) high-voltage extractor power supply;
- 12) diagnostic vacuum chamber;
- 13) system for measuring the parameters of ECR discharge plasma and generated ion beams (diagnostic system);
- 14) vacuum pumping system;
- 15) water cooling system;
- 16) synchronization and control system;
- 17) interlock system and X-ray protection.

The general view of the stand is presented in Fig. 1. Let us take a closer look at the main components of the stand listed above. The gyrotron is the source of high-power microwave radiation that is used to produce ECR discharge plasma.

The research team has two gyrotrons with radiation frequencies of 37.5 GHz (pulse power up to 80 kW) and 75 GHz (pulse power up to 250 kW) at its disposal. The magnetic field required for gyrotron operation (1.34 T at 37.5 GHz and 2.68 T at 75 GHz) is produced by a superconducting solenoid (cryomagnet) located inside the working volume of the cryostat. The superconducting solenoid state is established by filling the cryostat with liquid helium. Approximately 71 of liquid helium „boil away“ from the cryostat in a day of operation of the SMIS 37/75 facility. The liquid helium recovery system (CRYOMECH) was installed in order to minimize the loss of this expensive refrigerant. It consists of a recondenser, which provides a



**Figure 1.** General view of the SMIS 37/75 experimental stand. Structural diagram of the setup. 1 — Gyrotron, 2 — cryostat, 3 — recondenser, 4 — helium line, 5 — solenoids, 6 — plasma chamber in a magnetic trap, 7 — diagnostic vacuum chamber, and 8 — X-ray and microwave protection of the experimental stand.

helium vapor liquefaction temperature (approximately 4 K), and a compressor that are connected by the high-pressure helium line.

One may tune the microwave gyrotron power by adjusting the magnetic field of the superconducting solenoid (i.e., by changing the cryomagnet current). Microwave gyrotron radiation is directed and focused into the plasma (discharge) chamber by the quasi-optical system of two mirrors: a correcting one and a focusing one. The power supply system allows one to vary the microwave pulse duration from 50 to 1000  $\mu\text{s}$ .

The pulsed magnetic trap (Fig. 2) is designed to produce a strong (up to 4 T) magnetic field, which is needed to establish ECR conditions inside the discharge (plasma) vacuum chamber. The trap consists of two series-connected solenoids that form a magnetic field with two maxima (magnetic plugs) on the longitudinal axis. This configuration ensures that plasma is contained between the specified maxima. The solenoids are wound with copper tubing, enclosed in a frame, and water-cooled.

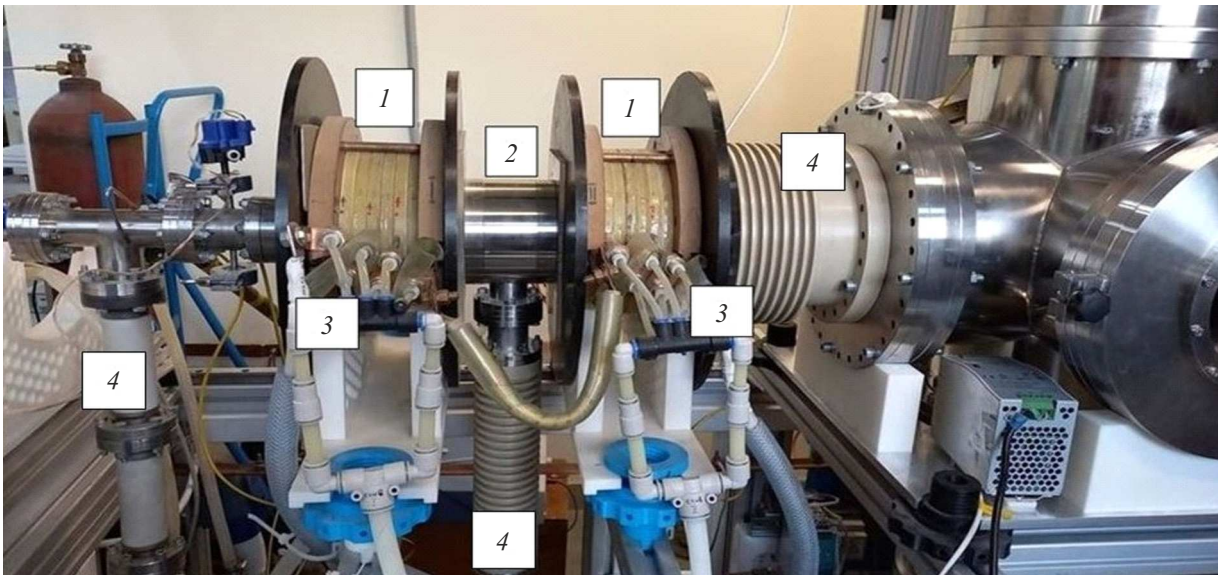
When SMIS 37 was upgraded, the power supplies of the gyrotron and the magnetic trap were replaced, the coil cooling system was improved, and cooling of the plasma chamber and the microwave input window was arranged.

Under ECR conditions, gyrotron microwave radiation produces and heats plasma in the plasma (discharge) vacuum chamber, which is positioned in the magnetic trap, with a valve for plasma-forming gas supply. Multicharged ions are produced in this plasma. When an ion beam is shaped, a high (up to 70 kV) positive potential is applied to the chamber; therefore, it is isolated from the ground and the solenoids of the magnetic trap by high-voltage insulators.

The ion beam shaping system (extractor), which features two electrodes of a certain (adjustable) geometry with holes for ion extraction, is located at the exit of the plasma chamber (outside the magnetic trap). One electrode (plasma) is in contact with the plasma (discharge) chamber and is under high (up to 70 kV) positive potential; the other electrode (puller) is neutral.

An ion beam shaped by the extractor is directed into the diagnostic vacuum chamber. The chamber has standard CF flanges with an inside diameter of 250 mm. Diagnostic elements found inside the chamber (Faraday cups with different entrance apertures, a scintillator, a pepper-pot plate) allow one to determine such characteristics of the ion beam as its total current, transverse structure, and emittance. In addition, a magnetostatic ion analyzer attached to the diagnostic chamber provides an opportunity to measure the mass and ion composition of the beam with a resolution in parameter „ionization multiplicity/specific ion mass“ of approximately 20.

To produce ECR discharge plasma and form ion beams from it with subsequent diagnostics of their parameters, one needs to maintain the pressure in the vacuum chambers of the experimental setup within the range from  $10^{-3}$  to  $5 \cdot 10^{-7}$  Torr.



**Figure 2.** Pulsed magnetic trap. 1 — solenoids, 2 – plasma chamber in the magnetic trap, 3 — water cooling tubes, and 4 — high-voltage insulators.

The control and synchronization system is based on a personal computer and modern programmable microcontrollers. The developed control program is used not only to adjust and monitor the main operating parameters of the setup, but also to set the necessary time delays between synchronization pulses that trigger the actuation mechanisms and ensure timely operation of the corresponding equipment of the experimental complex (valve for pulsed supply of working gas, magnetic trap, gyrotron, extractor, etc.).

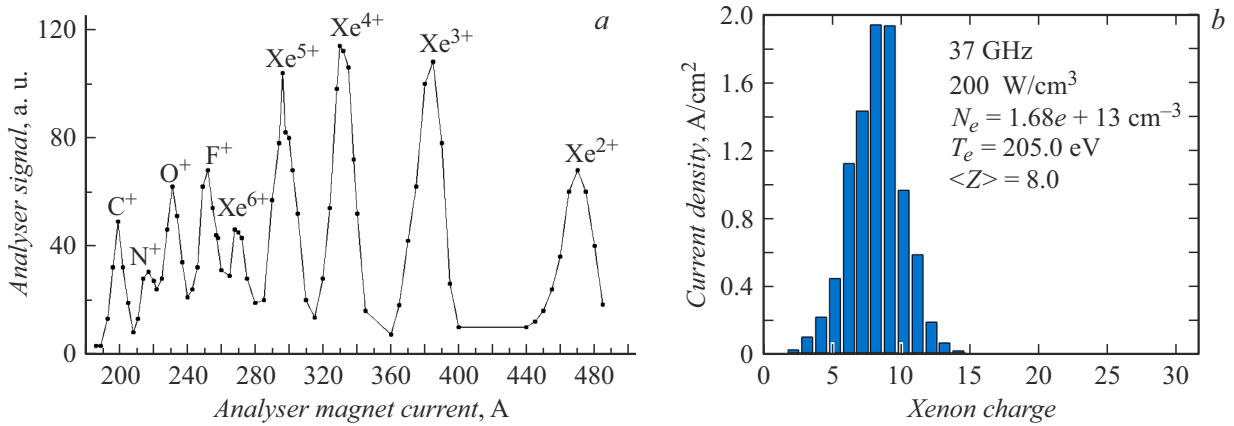
Thus, the upgrade of the SMIS 37/75 experimental setup made it possible to increase the discharge pulse repetition rate from 0.1 to 5 Hz, which is a crucial step toward reducing radically the amount of impurities that enter plasma uncontrollably from the inner walls of the plasma chamber and affect the key characteristics of discharge plasma (electron concentration and temperature). The operating modes of the gyrotron with a frequency of 37 GHz were also optimized, which allowed us to increase its maximum power (as a first step, to 130 kW). In the future, this parameter is expected to be raised to 250 kW through the use of an additional solenoid in the cathode region of the gyrotron and optimization of the pitch angle of the electron beam of the vacuum tube.

Research work aimed at determining the limiting parameters of MCI beams attainable with the use of a high-current ECR source with quasi-gasdynamic confinement pumped by 37 GHz radiation was performed. Xenon was chosen as a chemical element with a high atomic number that remains in gaseous form under normal conditions. Figure 3, *a* shows the distribution by ionization multiplicity in xenon at the SMIS 37 stand before its upgrade. It is evident that the amount of impurities in plasma is very significant, which results in a moderate level of average charge. Experimental studies have demonstrated that a high pulse repetition rate

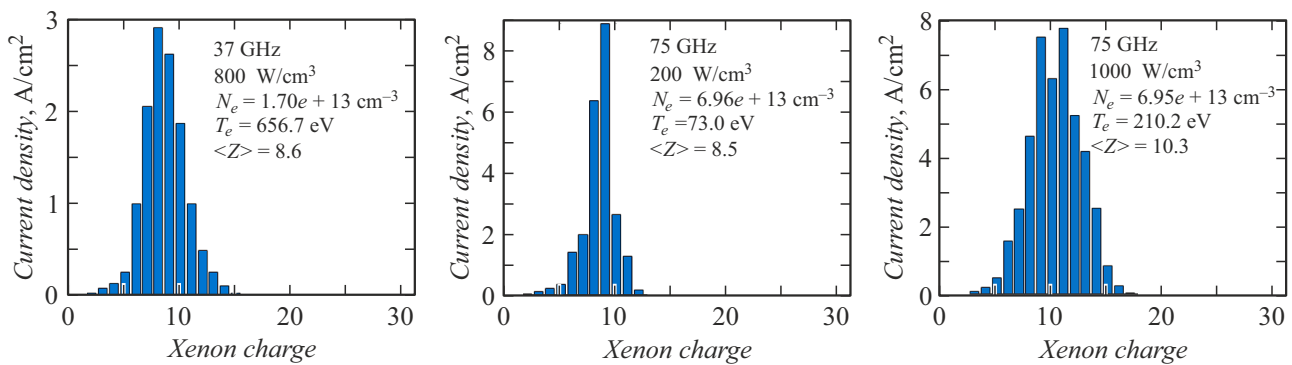
alters the level of impurity ions radically (reduces it by more than an order of magnitude). It then becomes possible to obtain the distribution shown in Fig. 3, *b*.

The average ion charge is expected to be at the level of +8 with a current density in the trap plug of several amperes per square centimeter. The presented distribution was obtained by numerical modeling with the software code [5] developed by the authors that was verified against a large set of experimental data from several facilities located in Russia and abroad. The first experiments at the upgraded setup have demonstrated that impurities, such as carbon, fluorine, and nitrogen, had vanished from the ion beam and the amount of hydrogen and oxygen (components of water) had decreased significantly.

Studies aimed at obtaining the dependence of the characteristics of MCI beams generated by the high-current ECR source with quasi-gasdynamic confinement on radiation power were also performed. In experiments, the specific energy input into plasma will be increased in two ways: by increasing the gyrotron radiation power and by changing the volume of heated plasma through the use of different magnetic systems. The longitudinal dimensions of plasma are set by the distance between the magnetic plugs (i.e., the trap length), while its transverse size may be set by additional metal limiters (e.g., the diameter of the plasma chamber itself). It was demonstrated via numerical modeling that the use of both approaches simultaneously allows one to raise the specific energy input into plasma to 1 kW per cubic centimeter. If radiation with a frequency of 75 GHz is used for plasma heating, the density may reach  $7 \cdot 10^{13} \text{ cm}^{-3}$  in this case at an electron temperature up to 210 eV. A significant increase in ionization efficiency will be observed. Figure 4 presents the limiting characteristics of xenon ion flows from the trap. Losses due to plasma



**Figure 3.** *a* — distribution of ions by ionization multiplicity in a xenon discharge before the SMIS 37 stand upgrade; heating by 37.5 GHz radiation with a power of 80 kW. *b* — distribution of xenon ions by ionization multiplicity in a discharge without impurities; heating by 37.5 GHz radiation with a power of 100 kW.



**Figure 4.** Distributions of xenon ions by ionization multiplicity at different values of specific energy input into plasma and its density.

radiation in the vacuum ultraviolet range are likely to have a significant impact in experiments at this average charge level, and the end result is expected to be slightly worse.

The data presented in Fig. 4 illustrate the possibility of production of high-current beams of ions of heavy elements with a charge at the +10 level. Notably, the central panel of Fig. 4 makes it evident that temperature optimization at high density provides an opportunity to obtain a narrower charge distribution, which is convenient in terms of beam shaping and separation of a specific ion. This effect of distribution narrowing is attributable to a sharp increase in ionization potential observed when one moves from one electron shell to another (deeper) shell.

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## Conflict of interest

The authors declare that they have no conflict of interest.

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