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FIRST OPERATION OF THE ECR ION SOURCE DECRIS

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Recent results of extracted beams from the ECR (Electron Cyclotron Resonance) ion source DECRIS (Dubna Electron Cyclotron Resonance Ion Source) for argon, oxygen and nitrogen are given, after describing source assembly. The main features of the source vacuum system are also presented.

I. INTRODUCTION

For almost 20 years by some laboratories [1-3] the ECR ion sources (ECRIS) of multiply charged ions has developed, both for small and large scale experiments. At the Flerov Laboratory of Nuclear Reactions in Dubna the ECRIS DECRIS is also being built [4]. It will be devoted to all fields of science using heavy multiply charge ions [5]. Its performance keeps regularly accepted world standard. Multicharged ions are produced in plasma with hot electrons and cold ions via electron impact.

The present paper does not give a full scope of the possibilities of the DECRIS, only few of them will be shown. We rather analyse the present state of the DECRIS and giving the main features of the ion source vacuum system.

II. GENERAL CONSIDERATIONS

About 40 ECR ion sources have been built in different countries. Their performances have been steadily improved over the last decade.

In the ECR systems [6-7], an ECR surface exists in a vacuum containing microwaves and magnetics fields. On this surface the microwave frequency ω must match the cyclotron frequency $\omega_c = e|B|/m$ (e is the electron charge, B is the resonance magnetic field and m is the electron mass) of electrons in order to arise the ECR. The electrons that pass through the ECR surface can gain or loss energy, according to their phases. Their energy change also depends on the magnitude

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of the electric field, perpendicular to the magnetic field, and upon the magnetic gradient. Globally they are heated up a certain limit, and this heating is called the ECR stochastic heating. Experimentaly it was found [8] that the electron increases quasi linearly with the microwave power. Besides the ECR one can also introduce another resonances. One of them is an upper hybrid resonance ω_H which is determinated by the formula $\omega_H^2 = \omega_c^2 + \omega_p^2$ (ω_p is the plasma frequency defined by the relation $\omega_p^2 = n_e e^2/\varepsilon_0 m$, where n_e is the electron density of the plasma, ε_0 is the vacuum permitivity [9]. If then, an electron temperature T_e is about few keV and the confinement time τ of the electrons is sufficiently high (α 10^{-2}s) we can produce the high charge state of ions, up to 18^+ for argon [1]. Ions are generaly not affected by the new resonances.

By the way the ion charge q extracted from the plasma of the ion source strongly depends on the particle life-time, which depends on the magnetics confinement system. In order to determine the ion charge q that can be achieved a product of $n_e v_e \tau$ (v_e is the velocity of electrons and τ is the plasma confinement time) is introduced. At the same time, v_e should exceed 10^9 cm s^{-1} in order to reach the ionization potential of the inner shell electrons, i.e. several keV. Then, if one takes a modern ECRIS where $n_e v_e \tau$ exceeds 10^{19} cm^{-2} ($n_e \tau$ equals 10^{10} cm^{-3}s), and n_e is of the order 10^{12} cm^{-3} it needs to get $\tau \simeq 10^{-2}$ s; in an ordinary plasma mirror device one achieves only 10 - 100 μs.

Nevertheless, in order to obtain the required plasma confining time of 10^{-2} s one has to use special magnetic confinement systems. In the real ECR ion sources the magnetic confinement systems are obviously created by two axisymmetric coils with a multipole between them. Therefore, inside the vacuum chamber of the ion sources the plasma with the hot electrons and the cold ions is formed.

Originally, only ions of the gas elements can be produced by ECR sources. However lately a variety of metallic ion beams was also extracted and accelerated. For the metal ion production one uses direct evaporation of a sample by direct plasma impact or an oven for the sublimation of higher vapour pressure metals [1, 10].

III. DESCRIPTION OF THE ION SOURCE

The scheme of the DECRIS ion source is shown in Fig.1 and the axial magnetic field distribution is given in Fig.2. The source, like classical MINIMAFIOS [6], has two stages. In the first one a cold plasma is ignited and then diffuses towards the second stage with the "minimum B" configuration. The axial magnetic field is produced by the water cooled solenoidal coils which consume a power of 130 kW. The radial magnetic field is produced by a NdFeB hexapole with a magnetic field on the ionization chamber surface about 0.8 T. The hexapole has flux concentration geometry and consists of six poles and six supporting bars.

The ion source uses a 2 kW 14 - 1.5 GHz klystron. At 14 GHz the ECR resonance occurs at 0.5 T. The resonance zone has a symmetrical form and does not cross any wall of the chamber. The single UHF feed for both stages is located between the first and second stages near the axial field maximum in order to reduce UHF transmission problems which can take place in the plasma between the location of the UHF power input and the ECR zone, respectively.

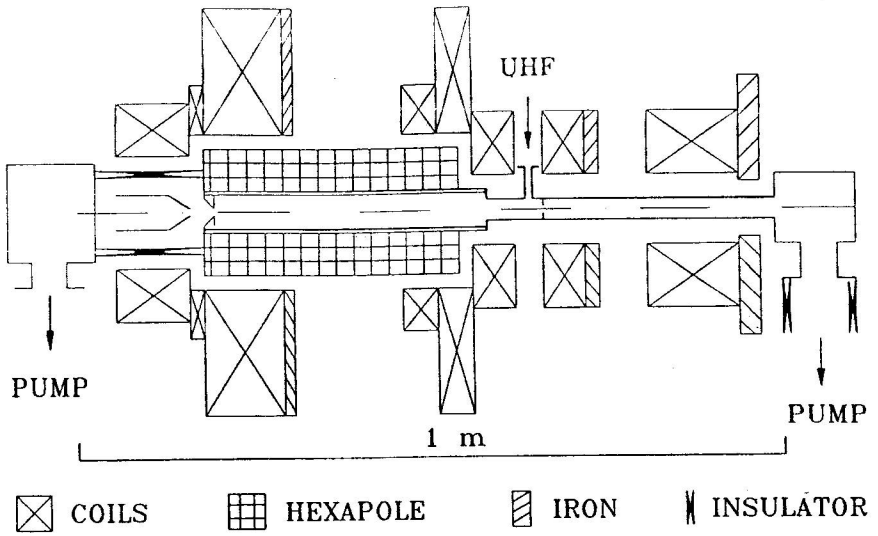

Fig. 1. Layout of the DECRIS ion source.

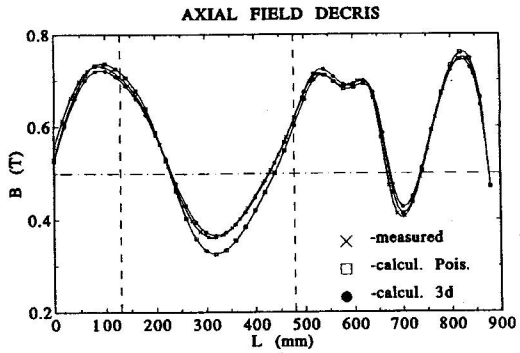

Fig. 2. Axial magnetic field distribution inside the first and second stages of the DECRIS.

The only adjustable parameters are the gas flow handled by two piezoelectric valves, microwave power (continuos), axial magnetic field and extraction voltage. The dosing gas valves are located near the first stage of the DECRIS. In our configuration, every adjustable parameter is manually operated from the operating room which is about 40 m far from the DECRIS. The ion extraction electrode is near the peak of the axial field. Its optimum position is now experimentaly determined. The first and second stages of the DECRIS are isolated up to 30 kV and connected to a high voltage power supply, except of the solenoids and the main and auxiliary vacuum systems and diagnostic line which are grounded.

A photograph of the DECRIS together with the beam analyzing line and the

main and auxiliary vacuum systems is shown in Fig. 3. The method of recording ion yields is the same as it is described in the paper [6]. The extracted ions were collected after the analyzing magnet by a Faraday cup placed in a cube C3 (see Fig. 5).

IV. HEXAPOLE CONFIGURATION

A "minimum B" 3 dimensional magnetic trap has to be created inside the ion source. Such magnetic field configuration one can make by superposition of mirror axial magnetic field and hexapole field. In order to produce closed resonance surface for the electron heating the magnetic field on the hexapole surface must be at least more than the resonance field B determined by the given microwave frequency ω ($|B| = m\omega/e$).

The hexapole field for the ECRIS operated at room temperature is obviously made by a hexapole constructed with rare earth permanent magnets based on the compound SmCo or NdFeB. The materials have both high remanence B_r and intrinsic coercivity H_c.

In Fig. 4 there is shown the cross section geometry of the hexapole [11] which was chosen for the DECRIS ion source. One ring of the hexapole includes 12 identical NdFeB trapezoidal bars with corresponding easy axis directions. The ring internal diameter is 7 cm. It is defined by dimension of discharge chamber.

A hexapole thickness is determined not only with respect of providing the needed magnetic field inside the ion source but also in order to minimize the weight and corresponding cost. An increase of hexapole external diameter also significantly raises a power supply for the solenoidal coils of the ECRIS. Therefore to choose the hexapole thickness the magnetic field calculations for the hexapole with different external diameters were done [11]. According to these calculations 6 cm thickness was used.

Whole hexapole is 35 cm long. It consists of 7 rings. The maximum size of the permanent magnet ring is 5 cm. The NdFeB with the remanence $B_r = 1.05$ T and the coercivity $_JH_c = 1400$ kA m^{-1} was used in order to make 12 corresponding bars for each ring. First, the corresponding 12 bars were connected to each other by a special compound in order to produce 7 rings and further all rings were coupled by the same technology in order to complete the hexapole.

Because of the extreme sensitivity of the NdFeB material to corrosion, the open hexapole was also surrounded by thin stainless steel screen and all spaces were filled up by the compound used at coupling of bars in order not to interact with air or cooling water.

V. VACUUM SYSTEM

One main and two auxiliary pumping units are used providing clean, safe pumping with pressure monitoring the ion source. This is designed in order to produce an average dynamic pressure of 10^{-4} Pa. Basically, it consists of 7 cm dia stainless steel, 4 cm dia copper, 10 cm dia steel and 4 cm dia duralumin beam tubes pumped by a combination of the 500 l s^{-1} turbomolecular pumps (VMN -

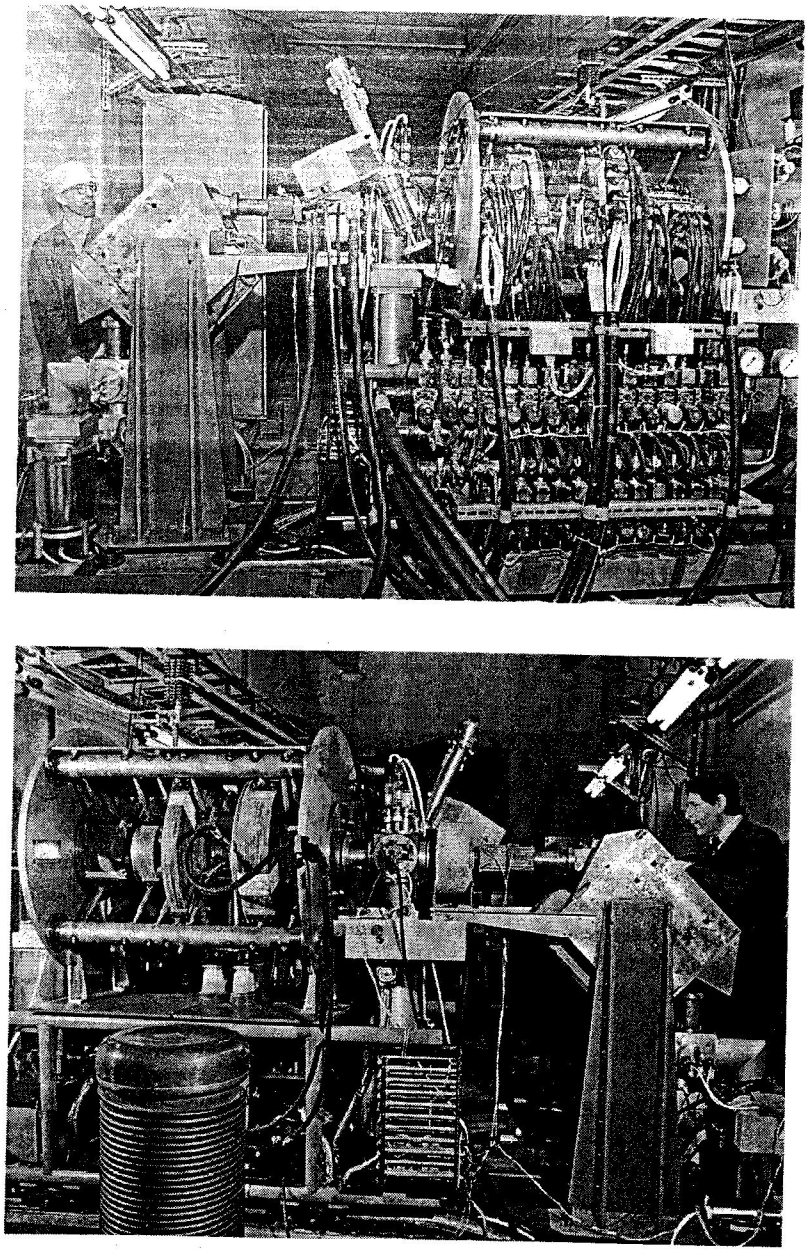

Fig. 3. DECRIS ion source on its test stand with analyzing magnet and collector box.

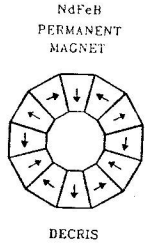

Fig. 4. Cross section geometry of the DECRIS hexapole.

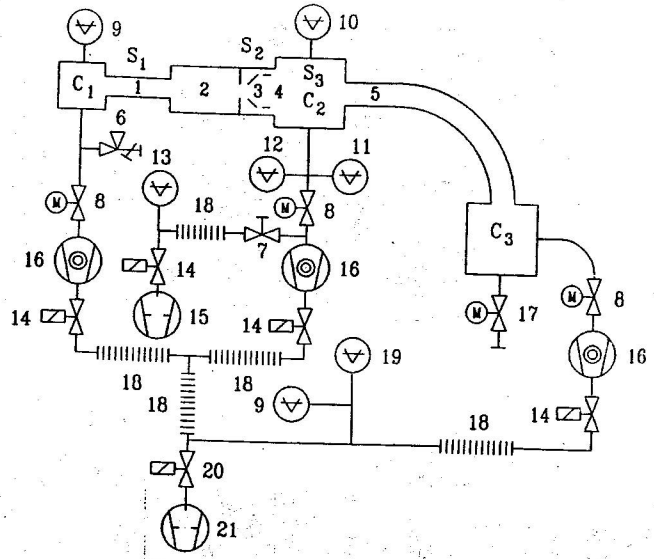

Fig. 5. Scheme of the main and auxiliary vacuum units. 1, 2 first and second stages of the ion source, 3 extraction electrode, 4 focusing electrode, 5 beam tube, 6 dosing valve, 7 manual drive, 8 electric motor drive, 9 thermocouple gauge, 10, 11 ionization gauges, 12 Penning gauge, 13 Pirani gauge, 14 solenoid valve, 15 rotary pump, 16 turbomolecular pump, 17 electric motor drive, 18 flexible tubing, 19 Pirani gauge, 20 solenoid valve and 21 rotary pump.

500) and the rotary pump (BL - 90) [12]. The pumping units are spaced at about 1.5 m intervals and contain besides the pumps, high vacuum gauges, electrodes and various beam diagnostic elements. The total length of the high vacuum beam tubes is about 3 m.

The size of the forepump is determined by the desired maximum time constant "t" for evacuating the system and the length and the diameter of the vacuum line to the remote forepump [$t = 2.3(V/S)\log(p_0)$, where V is the evacuating volume, S is the pumping speed at the atmospheric pressure p_0 and p is the pressure in time

t]. The desired roughing time is 10 min. The foreline is about 5 cm dia and about 6 m length with five 90° bends. The foreline pressure is to be reduced by about 4 orders from atmospheric pressure before the high vacuum pump is started. This requires about 10 time constants. At its lowest operating pressure (1 Pa), the time is in the high transition flow regime, and at that point has a conductance of about 5 l s^{-1}. The forepump should have a speed no greater than the line conductance for economic reasons. In our case, the pump of 25 l s^{-1} is used. The time constant for this combination is about 0.1 min. Thus the roughing cycle takes about 1 min.

To achieve a good vacuum one should maintain a clean surface for a few minutes, e.g. if one uses a stainless steel then the partial pressure of active gases would be below 10^{-5} Pa. At room temperature, the time for a monolayer of gas being produced at a surface and remained there, if the sticking probability is the unity, is given by equation [13]

$$t = \frac{3.3 \times 10^{-4}}{p(\mathrm{Pa})}\ \mathrm{s}\ . \qquad (1)$$

The high vacuum pumps are selected so that their pumping speed is high at 10^{-4} Pa. It must also effectively pump all the active gases. The required pumping speed is determined by that required to maintain the pressure at 10^{-5} Pa. The sources of gas are devided equally between the beam line walls account for about 2×10^4 cm^2. The outgassing rate from moderately clean stainless steel is about 10^{-8} Pa l s^{-1} cm^{-2} [13]. If the gas load is 4×10^{-3} Pa l s^{-1} thus a pump of about 4000 l s^{-1} pumping speed is required to maintain a 10^{-5} Pa pressure. Turbomolecular pumps of 500 l s^{-1} pumping speed were selected to maintain the vacuum system at low pressure.

The scheme of the vacuum system is shown in Fig.5. It is designed to pump the ion source area, the beam line and beam diagnostic cubes C_1, C_2 and C_3, respectively. The entire system including the electrodes is constructed of stainless steel combined with copper, steel and duralumin materials, respectively. The turbomolecular pumps are powered by an electronic frequency converter which provides a controlled three - phase drive of variable frequency and voltage to the pump. The suitable 400 Hz converters with very little risk of failure or damage are used. The bearings of the pumps are lubricated and the pumps are also cooled by water.

Two rotary pumps are operated in order to produce the forevacuum (BL - 90 and NVR - 5 with the pumping speed of 90 m^3 h^{-1} and 5 m^3 h^{-1} at 0.1 MPa, respectively). The BL - 90 is the main forepump which is continuously pumped the whole system. The NVR - 5 forepump is used for slow - acting evacuation of the ion source before connecting of the turbomolecular pumps.

Proceeding from the dimensions of the vacuum system effective pumping speeds S^i_{eff} of the vacuum units are calculated in the cross - sections S_1, S_2, and S_3. It holds that: $S^1_{\mathrm{eff}} = 30$ l s^{-1}, $S^2_{\mathrm{eff}} = 70$ l s^{-1} and $S^3_{\mathrm{eff}} = 200$ l s^{-1} for air at 1.2×10^{-5} Pa, respectively. The reduction pumping speed of the turbomolecular pumps is mainly due to the small diameter of the vacuum beam lines.

A protecting system which provides the reliable running of the vacuum system is described in the paper [10].

After 20 h of pumping the leak rate of the vacuum system is below 5×10^{-3}

Pa l s^{-1}. The standard leak test where helium is applied for about 1 min at slight overpressure does not show any leaks (detection limit is 2×10^{-3} Pa l s^{-1}).

Access parts of the vacuum system endure the bakeouts to about 60° C without any damage. Leak detection after 24 h shows neither leak nor diffusion even after this test.

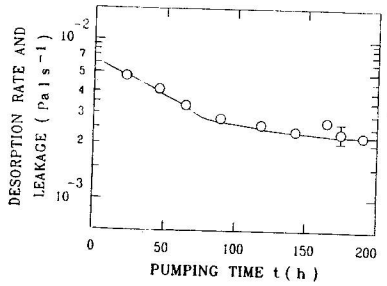

Fig. 6. Measured desorption rate and leakage "q^d" of the vacuum system volume vs pumping time "t". The lowest value of "q^d is obtained after about 200 h pumping of the ion source volume ($q^d_{min} = 2 \times 10^{-3}$ Pa l s^{-1}).

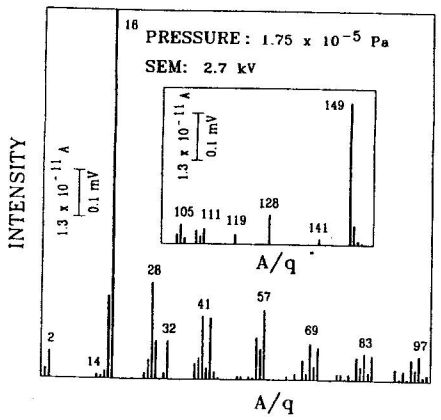

Fig. 7. Spectrum of the residual gases from the vacuum system of the DECRIS ion source pumped by the turbomolecular pumps VMN - 500 and the rotary pump BL - 90 (A is the mass number and q is the ion charge state; $q \geq 1$).

Results of the outgassing rate and leakage measurements are shown in Fig. 6. The best vacuum condition are obtained after 200 h pumping. After this time and after three mild 5 h bakeouts the outgassing rate and leakage of 2×10^{-3} Pa l s^{-1} are reached.

The vacuum system is mainly designed by elastomer seals as the pressure requirement is moderate. Residual vapours from these seals and also the oils vapours from the rotary pumps contaminate the vacuum system. The residual gas analysis is very clearly confirmed by the presence of these vapours in the spectrum.

In Fig. 7 a spectrum of the residual gases measured by a mass spectrometer MX 7304 [14] is shown. The spectrometer gauge is placed directly on the cube 2 of the beam line (Fig. 5). The spectrum is taken at the pressure of 1.75×10^{-5} Pa. By spectra analysis one can see the subsequent contamination by hydrocarbons and other organics. In the paper [15] the peak sets of 27,29; 39,41,43; 55,57,59; 69; 79; 89; 109; 119; 139; 149; 159; 199; 209 from the rotary pump oil are shown. However, many of these hydrocarbons are also observed in the spectrum of elastomer seals such as Silicone "O" rings etc [15-16]. Nevertheless, the spectrum illustrates the expressive water vapour contamination. All these effects could be, however, smaller by using two or more sorption pumps in sequential operation, or adsorption traps above the rotary pumps.

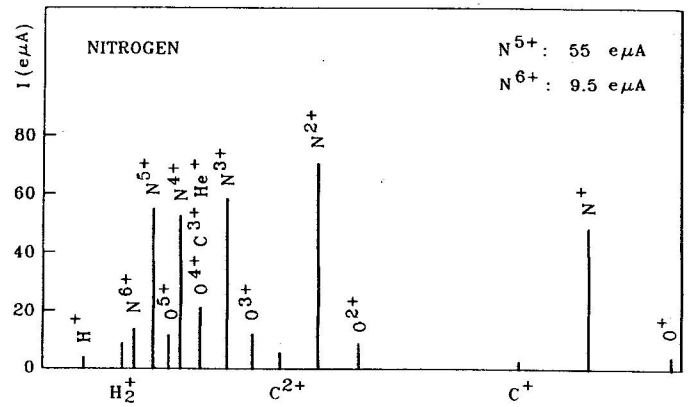

Fig. 8. DECRIS nitrogen charge state distribution optimized for N^{5+}. The spectrum was measured at: P_{UHF} = 590 W, V_{ext} =11 kV/0.8 mA and p=(1 - 3)×10^{-4} Pa.

VI. RECENT EXPERIMENTS WITH DECRIS

In Fig.8, Fig.9 there are shown preliminary results obtained from the DECRIS during some weeks of functioning. The production of typical ECRIS spectra of multicharged ions shows that the DECRIS is a reliable ion source able to run in continuous mode of operation at different UHF powers (P_{UHF}). The typical UHF power consumption is 200 - 700 W.

A power of 580 - 640 W, for example is enough for producing charge states like N^{5+} (55 eμA), N^{6+} (9.5 eμA), or O^{5+} (57 eμA), O^{6+} (52 eμA), O^{7+} (10 eμA), respectively. The ions were extracted at the extraction voltage (V_{ext}) (10 - 11) kV, the vacuum (p) (1 - 3)×10^{-4} Pa and the solenoid current of two power supplies: $I_1 \geq 1000$ A (U_1 = 83 V) and I_2 = 840 A (U_2 = 55 V).

It is also shown that the helium and oxygen injection into the DECRIS, where argon multiply charged ions are expected, improves the yields of extracted ions.

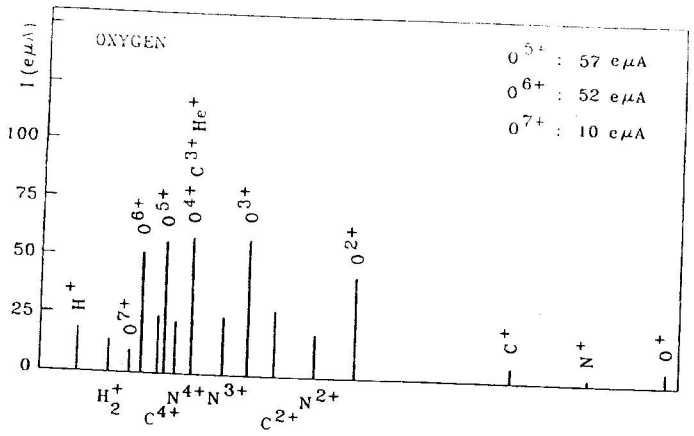

Fig. 9. DECRIS oxygen charge state distribution optimized for O^{+5}. The spectrum was measured at: P_{UHF} = 580 W, V_{ext} = 10 kV/1.0 mA and p=(1 - 3)×10^{-4} Pa.

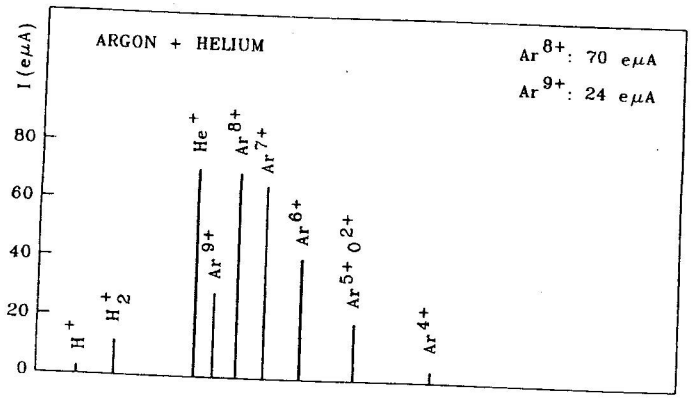

Fig. 10. DECRIS argon charge state distribution optimized for Ar^{8+} with helium support gas. The spectrum was measured at: P_{UHF} = 680 W, V_{ext} = 10kV/1.4 mA and p = (1-3)×10^{-4} Pa.

In Fig.10, Fig.11 there are shown spectra obtained with the adding of helium and oxygen to argon. At a microwave power of 600 W it has been produced the charge states like Ar^{11+} (15 eμA), Ar^{9+} (34 eμA) or Ar^{8+} (84 eμA) when O_2 is used as a support gas. It is seen that by adding of oxygen to an argon plasma, we are obtaining the best results for argon (see Fig.11). The ions were produced at the extraction voltage (V_{ext}) 10 kV, the vacuum (p) (1 - 3)×10^{-4} Pa, and the solenoid currents of two power supplies: $I_1 \geq 1000$ A, I_2 = 900 A. The most suitable data shown in Fig.8 - 11 are also summarized in Tab.1.

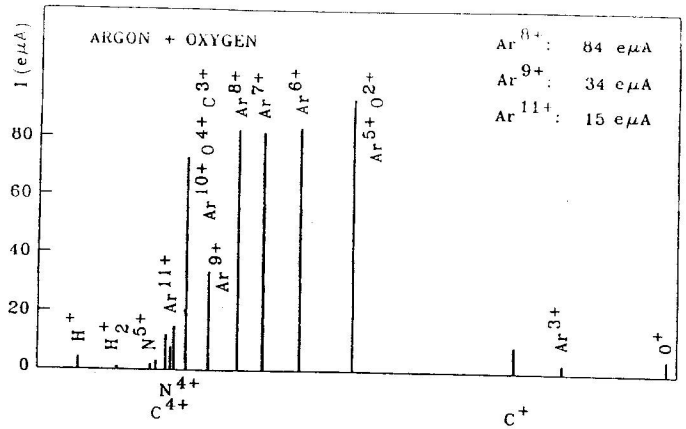

Fig. 11. DECRIS argon charge state distribution optimized for Ar^{9+} with oxygen support gas. The spectrum was measured at: P_{UHF} = 600 W, V_{ext} = 10 kV/1.6 mA and p=(1 - 3)×10^{-4} Pa.

Table 1.

Charge state distribution and corresponding currents for some ion beams obtained from the last DECRIS experiments. Currents are given in (eμA).

Ion/Charge	5^+	6^+	7^+	8^+	9^+	11^+	Support gas
N	55	9.5					
O	57	52	10				
Ar				70	24		helium
				84	34	15	oxygen

In order to compare different ECRIS it is convenient to show absolute extracted currents measured in the diagnostic chambers placed behind the analysing magnets of the ion source bench - marks.

In Fig.12 the argon extracted ion currents of different ECRIS in continuous mode of operation at different frequencies (curve: a - 18 GHz, b - 14 GHz, d - 14.4 GHz), and the recent results of the DECRIS are shown. The data "a, b" are taken from the paper [3], the data "c" are obtained from the last DECRIS experiments, and the data "d" are taken from the paper [17]. The same behaviours are observed not only for argon but also for other elements, as for example uranium, tantalum, calcium etc [3, 8, 18-19]. If one compares further the data "a" and "b", with respect of scaling $I_q^{max} \alpha\ \omega^2$ or $\alpha\ B^2$ [3] there can be observed that the predicted scaling does not hold. The scaling law for the compared ECRIS performance is not yet known.

As folows from the last results a present configuration of the DECRIS has to be slightly explored yet in order to reach both higher multiply charged ion beams and

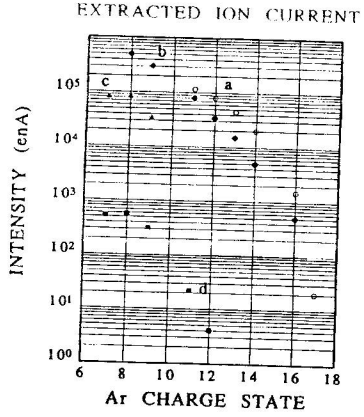

Fig. 12. Argon extracted ion currents (eμA) of different ECRIS at defferent microwave frequencies (curve: a - 18 GHz, b - 14.5 GHz, c - 14 GHz, d - 14.4 GHz) in continuous mode of operation and recent results of the DECRIS. The data "a", "b" are taken from the paper [3], the data "c" are obtained from the last DECRIS experiments and the data "d" are taken from the paper [17].

intensity. Although no evident breakthrough may be foreseen, but the following trend of efforts are considering: i) changes in the magnetic field configuration, ii) fine regulation of the gaseous supply, iii) increase of the effective pumping speed in the extraction region of the DECRIS and iv) decrease of the outgassing from the beam tube and materials closed inside the ion source.

VII. CONCLUSION

Legendary reliability and stability of such type of the ion source allows to neglet all difficulties of the PIG (Phillips Ionization Gauge) ion source. Such a source gives access to a variety of heavy ion beams of better stability and higher intensity and energy which presently is available at every accelerator. Such ion source is competitive with whatever other source. It is able to provide a broad spectrum of interest not only in nuclear physics, but also in atomic and solid state physics, chemistry and biology.

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