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ABSTRACT

Minimono is a new 2.45 GHz Electron Cyclotron Resonance (ECR) ion source for singly charged ions which uses only permanent magnets. Measurements of ionization efficiencies, maximum currents extracted and emittances for H^+ , $^3,^4He^+$, N^+ , Ne^+ , Ar^+ , Kr^+ , S^+ and Si^+ were carried out. In the case of buckminster fullerenes, C_{60}^+ , C_{60}^{2+} and C_{60}^{3+} ions were extracted. The results obtained, the general mechanical simplicity of this ion source and its low cost make this source attractive for the production of stable and radioactive ions.

INTRODUCTION

The production of radioactive ions from atoms ever further from the valley of stability^{1,2} is strongly dependent on the efficiency of the production system, target and ion source, while there is a constant demand for the latter to be more and more reliable, simpler and cheaper. The ion source series for singly charged ions, such as Mono1000³ or Mono 300⁴ have been developed at GANIL with this aim in mind.

To minimize the effusion time and the losses caused by sticking, the radioactive elements must be produced as close as possible to the ionization area. For noble gases, an ECRIS (ECR Ion Source) seems suitable compared to other ion sources⁵. But for short-lived isotopes, we have to consider the time needed to transport and transform atoms into ions, i.e. effusion and ionization times. To minimize the effusion time we need to reduce the “dead” volume of the source chamber through which the atoms effuse before reaching the plasma. We decided to design a small source, which could still meet all the previous criteria. We show here a complete description of this new ion source called MINIMONO. After a brief description of the experimental setup, results are given for stable elements. Finally, we suggest some future developments and the setup we have designed to test the on-line production of short half-life isotopes.

I. DESCRIPTION

A. Magnetic structure

Minimono works at the ECR frequency of 2.45 GHz. The magnetic structure presents a resonance surface at $B_{\text{res}} = 875$ Gauss. We chose to use a magnetic structure which presents several closed magnetic layers, as described in a CEA-CNRS6 patent proposed by GANIL in 1996⁷. The Minimono magnetic structure is obtained with rings of permanent magnets (NdFeB). Those magnets are mass-produced and this reduces the cost of the ion source considerably. The magnetic field was calculated with the QuickfieldTM⁸ program, which validated the use of such magnets and permitted us to adjust the mechanical parameters. Finally we mapped equipotential surfaces of B (Fig.1).

One can observe that the magnetic field decreases progressively from 0.2 T down to zero. If we define the mirror ratio as the value of the magnetic field at the last closed equipotential line divided by the resonant field, it is equal to 2.

The axial field is shown Fig. 2 where the measurements are compared to the calculated values.

B. Design

Fig. 3 shows the scheme of the source. The plasma chamber consists of a simple stainless steel tube. Injection and extraction flanges as well as the plasma electrode are made from aluminum. The main characteristics of the ion source are shown in Table 1.

C. High frequency

The source is supplied with a generator through a coaxial cable and a N-type connector ending in a copper antenna. The source is able to work with radial as well as axial RF injection. The nominal working power is of the order of 30 watts with most gases. To produce helium or neon ions, a support gas with a lower first ionization potential is needed to ignite the plasma. If we need to use more RF power, it would be necessary to cool the plasma chamber.

II. EXPERIMENTAL SETUP

A. Test bench

All tests were done on the test bench at GANIL (Fig.4). The maximum magnetic rigidity of the bending magnet is about 0.108 Tm. The high voltage can be adjusted from 0 to 20 kV. The vacuum in the extraction chamber was in the range of 10^{-4} to 5×10^{-4} Pa while the ion source was working. The pressure in the diagnostic chamber was about 5×10^{-5} Pa.

B. Measurements

1. Transport efficiency of the beam

The transport efficiency ϵ_t was determined from the sum of currents for each ion divided by the total current delivered by the high-voltage power supply. In all cases this efficiency was better than 50% during the tests except for SF_6 (30%) and C_{60} (from 0,2 to 2%). For those ions the maximum magnetic rigidity of the dipole magnet limits the extraction voltage to lower values.

2. Ionization efficiency

The gas of interest was injected through a compressed-powder reference leak or through a dosing valve. In this second case, this valve was calibrated by a comparison with the reference leak, supplied with different upstream pressures. For another gas, the flux was deduced from the square root of the masses.

Calibrated fluxes for different gases used for the tests are shown in Table 2. The calibrated flux was injected alone or with a continuous background. The superposition of the calibrated flux with the continuous background allows us to check the ionization efficiency of the source for higher fluxes by measuring the increase of the current with and without the calibrated flux. The ionization efficiency ϵ_i was calculated with the relation below,

$$\epsilon_i = \frac{1}{\epsilon_t} \times \frac{\sum \frac{\Delta I_{q+}}{q}}{\phi_{\text{Calibrated flux}}}$$

where $\phi_{\text{calibrated flux}}$ is the flux of injected particles in particle $\mu\text{Amperes}$, and ΔI_{q+} is the difference between the currents for the ion of interest with and without the calibrated flux.

3. Emittance meter

The test bench allows the measurement of the emittance when removing the Faraday cup. The beam slit is displaced behind the horizontal profiler and a suitable program calculates the result on a computer. If we assume that this ion source is totally symmetric in term of magnetic field in the extraction area, the emittance pattern is nearly the same in both x- and y- direction.

III. RESULTS

A. Recapitulation

The results are summarized in Table 3 except for C_{60} (see below).

S^+ and Si^+ ions are obtained from SF_6 and SiH_4 compounds, respectively. We note that for argon and krypton the ionization efficiency was almost 100%. He^+ and Ne^+ were more difficult to produce with a good efficiency because of their higher first ionization potential. The ionization efficiency for N^+ ions was equal to 11% and nevertheless, the total efficiency for nitrogen was close to 100%.

H^+ ions were obtained from the decomposition of H_2 .

working stability, low power (electrical and high-frequency) consumption and the general simplicity of this source make it attractive for other applications using singly-charged ions.

V. Outlook

A. On-line production yield measurements

The results obtained for stable gases in terms of ionization efficiency allow us to test this ion source for on-line production of radioactive ions. The target/ion-source system will be tested on the SIRa test bench⁹ at GANIL.

For this experiment, we have chosen to adapt to the ion source the current SPIRAL target designed for radioactive noble gas ion beam production¹⁰; the primary beam will go through the plasma between the source magnets and, in order to maximize the conductance for radio-isotopes diffusing from the target, it was necessary to move aside the two rings of permanent magnets and to reinforce them. Figure 10 shows the new magnetic map that we obtained.

A new mechanical system was designed and built with a cooled aluminum plasma chamber. The final scheme of this assembly is given Fig. 11.

B. Inductive-coil ion source development

Radioactive ion production by the ISOL (Isotopic Separation On-Line) method involves an intense flux of neutrons which can damage ion sources fitted with permanent magnets. We are therefore making calculations with inductive coils to reproduce the magnetic configuration of this kind of ion source.

Concerning argon, we can note in Fig. 5 that the Ar^{2+} ion proportion was never more than 5% of the extracted particles.

B. Molecular ion beams and condensable elements

The total efficiency of decomposition of the SF_6 gas was nearly 100% as shown Fig. 6. The efficiency for SiH_4 was never more than 3%. If we assume that the SF_6 molecule is successively decomposed into SF_x gaseous molecular compounds which are not lost on the walls by sticking, so it remains possible for the S atoms to be ionized by the plasma. In the case of Si coming from SiH_4 , the decomposition of the molecule leads to the production of condensable molecular compounds which are lost on the walls.

C_{60} molecules were obtained from the sublimation of powder in a micro-oven. The oven was placed on the axis of the ion source. We began to observe ions for a temperature of the oven of about 450°C . The extraction voltage applied was 0.7 kV (C_{60}^{1+}) and 1.65 kV (C_{60}^{2+} and C_{60}^{3+}) and that corresponds to a transport efficiency of 0.2 and 1.5%, respectively. The spectrum with the number of particles per second observed and corrected for that efficiency is shown in Fig. 7.

C. Emittance pattern

Emittances were measured with an extraction voltage of 14 kV, except for hydrogen (13 kV), and for extracted currents from 15 e μ A (Si) to 120 e μ A (H). The plasma electrode had a 4 mm diameter hole.

Fig. 8 shows the emittance of the Ar^+ ion beam observed at 14 kV with a total current of about 80 e μ A.

Emittances measured with the other elements (see Table 3) are never greater than 60 π x mm x mrad.

D. Stability

The ion source was tuned by adjusting the RF power and the gas flow. Fig. 9 shows the observed current of a H^+ ion beam during one hour without any adjustment. The source was tuned to deliver about 160 e μ A and is nevertheless stable (the spark at 12 min became from desorption of the plasma chamber). We observed the same behavior with each element tested.

IV. Conclusion

Minimono is an ultra-compact ion source for singly-charged ions. Results with stable gas are acceptable in terms of efficiency, simplicity and cost of radioactive ion production from gases. On the other hand, the

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Table 1: Main characteristics of the Minimono ion source

Dimensions	105 x 130 mm
Total volume total (chamber)	106 cm ³
Total weight	2.7 kg
Internal chamber diameter	39 mm
Plasma electrode aperture	4 mm
Volume of the plasma	30 cm ³
Surface of resonance	60 cm ²
Magnetic field at walls	2000 Gauss
Magnetic field in the extraction area	1800 Gauss

Table 2: Calibrated flux used for efficiency measurements ($4,3 \text{ p}\mu\text{A} = 10^{-6} \text{ mbar l s}^{-1}$)

Gas	Calibrated fluxes p μ A	Determined by means of
He	116	Calibrated leak
Ne	47	Calibrated leak
Ar	37	Calibrated leak
Kr	15	Calibrated leak
SF ₆	85	Calibrated valve
SiH ₄	180	Calibrated valve

Table 3: Minimono's results with gas. Maximum currents I_{FC} measured in the Faraday cup, ionization efficiency for calibrated flux injected and emittances are listed.

Elements	Ion	I_{FC} max e μ A	$\epsilon_{ionization}$ ($\pm$ 5%)	Total efficiency %	Emittance RMS π mm mrad	
						I_{total} e μ A
H ₂	H ⁺	207	-	-	60	120
	H ₂ ⁺	896	-	-	-	-
	H ₃ ⁺	140	-	-	-	-
³ He (99,95%)	³ He ⁺	810	-	-	-	-
He	⁴ He ⁺	764	21	22	57	110
	⁴ He ²⁺	3	1			
N ₂	N ⁺	31	11	95	55	13
	N ²⁺	0,1	<1			
	N ₂ ⁺	251	84			
Ne	Ne ⁺	304	13.5	14	51	110
Ar	Ar ⁺	252	90	95	40	80
Kr	Kr ⁺	40	90	95	-	-
SF ₆	S ⁺	8	32	95	36	30
	S ²⁺	1,2	5			
	SF ₅ ⁺	0,4	1,5			
SiH ₄	Si ⁺	25	1,5	<5	56	15
	Si ₂ ⁺	0,9	-			

FIGURE CAPTIONS

Fig. 1: Closed equipotential lines in the magnetic field map for Minimono. The potential is plotted every 0,01 T.

Fig. 2: Axial field $B_z = f(z)$ for Minimono. Comparison between calculated and measured field.

Fig. 3: Mechanical design of the Minimono ion source.

Fig. 4: Schematic view of the experimental setup.

Fig. 5: Hydrogen spectrum.

Fig. 6: Argon spectrum.

Fig. 7: SF_6 spectrum.

Fig. 8: C_{60} spectrum.

Fig. 9: Ar^+ emittance pattern. $40 \pi \text{ mm mrad}$ for $80 \text{ e}\mu\text{A}$ at 14 kV .

Fig. 10: Stability graph with H^+ $160 \text{ e}\mu\text{A}$ $U_{\text{HV}}=15\text{kV}$ $P_{\text{HF}}=30\text{W}$.

Fig. 11: Magnetic map for Minimono in SIRa.

Fig. 12: The on-line production setup.

Fig. 1.

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11