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V.B. Kutner, S.L. Bogomolov, A.A. Efremov,
A.S. Pasyuk, Yu.P. Tretyakov

THE EFFICIENCY OF CONSUMING RARE
ISOTOPES IN A PIG ION SOURCE

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The accelerated beams of rare and radioactive isotopes are of great interest for heavy ion physics lately ^{1,2/}.

However the production of these ion beams requires the use of high-efficiency ion sources. This requirement becomes very important when rare and expensive isotopes, as ^{40}Ca , or radioactive ones, such as ^{14}C , are used. In the case of using, e.g. Be, it is possible to run with a low concentration of working substance if the ion source has a high efficiency.

In the present paper the efficiency of consuming the working substance in the cyclotron arc ion source during operation at the JINR LNR cyclotrons is analyzed in comparison with the results obtained for the ECR ion sources of GANIL and of the Berkeley cyclotron.

At present the PIG ion sources are used at the cyclotrons of the Laboratory of Nuclear Reactions JINR. The successful development of this type of ion source has made it possible to obtain at the cyclotron U-400 intense ion beams ($10^{12} - 10^{14}$ pps) in the range from N^{2+} to Kr^{9+} . Such a source provides beams of multiply-charged gas ions, for example, Ar^{8+} , Kr^{11+} and Xe^{15+} , with intensities of 1.5×10^{13} , 8×10^{11} and 4×10^{11} pps respectively.

In table 1 there are presented the ions produced from solids in the PIG source with cathode sputtering. Most of the ions of the elements of the Mendeleev Periodic Table were accelerated at the LNR cyclotrons.

The main studies with ion sources at the U-400 cyclotron dealt with the production and acceleration of ion beams of enriched isotopes ranging from ^{26}Mg to ^{76}Ge to energies above 6 MeV/n (table 2).

Recently studies aimed at the production and acceleration of the ions of the radioactive isotope ^{14}C have been carried out.

The acceleration of ^{14}C ions is a very difficult technical problem. However, these beams were needed for generation of the heavy isotopes of light nuclei, for example, ^6H , ^7H , ^9He , ^{10}He and other nuclides. Also they are required for the synthesis and study of transfermium elements.

To solve this and other problems of heavy ion physics $^{14}\text{C}^{2+}$ and $^{14}\text{C}^{3+}$ ion beams were produced using a PIG ion source with $^{14}\text{CO}_2$ as a working gas.

Table 1
Solid states ion yield from the PIG source at test operation

Element	Discharge sputtering				Ion yield, mA/peak												Total current, mA	Conditions of current sample			
	U ₁ , V	I _d , A	U ₂ , V	I _d , A	1+	2+	3+	4+	5+	6+	7+	8+	9+	10+	11+	12+					
12 Mg	860	7.5	520	1.9	Ar	18	85	32	3.0	0.4	0.06	0.006					146	77	3.6	18	
13 Al	300	8.2	980	1.9	Ar	22	59	20	3.4	0.5	0.04						100	95	3.6	18	
14 Si	620	11	1900	2.3	Ar	12	46	35	13	1.6	0.18	0.018					104	80	3.6	24	
15 P	1000	3.3	1000	1.0	Ar	3	6.3	5.5	1.2	0.26	0.03						16	18	3.6	17	
20 Ca	900	9.5	540	1.6	Ar	3	23	22	14	4.5	1.0	0.18	0.038				66	60	3.6	17	
21 Sc	500	9	1700	0.94	Ar	1.3	18	19	4.8	0.8	0.03	0.01					48	74	3.6	17	
22 Ti	750	16	1250	2.4	Ar	2.1	9.5	14	24	6.8	1.1	0.28	0.036				43	43	4.4	22	
23 V	900	15	1400	1.6	Ar	8.3	19	12	14	6.4	1.1	0.18	0.09				53	74	4.4	21	
24 Cr	1200	15	850	1.0	Ar	3.7	11	5.2	10	8.8	3.3	0.85	0.08	0.002			48	61	4.4	21	
25 Mn	650	8.5	800	0.7	Ar	3	16	14	11.3	6.1	1.6	0.39	0.09	0.026	0.001		36	83	4.4	20	
26 Fe	480	13	600	1.6	Ar	3	13	14	8.4	1.7	0.33	0.12	0.04	0.004			36	78	5.3	23	
27 Co	300	13	790	1.3	Ar	13	19	15	10	2.5	0.83	0.06	0.01	0.003			59	70	3.6	17	
28 Ni	800	8	1000	1.0	Ar	-	23	24	16	6.7	1.5	0.44	0.08	0.02			75	60	3.6	17	
29 Cu	540	10	400	2.3	Ar	-	30	32	38	26	6.6	1.9					150	70	3.6	17	
30 Zn	400	7.5	580	1.6	Ar	-	70	56	29	2.3	3.96	0.76	0.2	0.024			170	83	3.6	18	
32 Ge	900	5.5	2000	0.3	Ar	6.4	17	9.5	11	6.4	1.36	0.48	0.09				64	77	3.6	20	
34 Se	930	10	500	0.63	Ar	-	3.9	9.5	7.6	5.8	1.35	0.36	0.18	0.01			19	32	5.3	22	
40 Zr	1100	9	1100	0.8	Ar	-	6.9	4.1	3.9	3.72	1.41	1.0	0.47	0.15	0.04		24	34	3.6	16	
41 Rb	700	20	850	1.6	Ar	-	0.7	4.8	3.8	11	17.3	3.8	2.1	0.33	0.044	0.004	19	45	4.4	24	
42 Mo	380	9.5	940	1.8	Ar	-	24	25	25	16.8	9.4	2.0	0.4				100	90	3.6	16	
46 Cd	900	10	200	1.0	Ar	-	14	18	28	37	22	11.9	3	0.74	0.11	0.025	146	90	4.4	20,5	
49 In	540	11	1250	0.65	Ar	-	1.7	2.9	6.4	7.4	4.4	3.2	1.2	0.33	0.018		29	65	5.3	22	
50 Sn	840	11	550	0.75	Ar	-	1.6	2.6	3.2	2.9	3.0	3.7	1.3	0.13			18	40	4.5	22	
57 La	760	11	830	1.1	Ar	-	-	8.3	7.7	7.9	3.5	5.0	3.3	1.0	0.9	0.042	37	37	4.4	20	
72 W	650	7	750	1.0	Ar	3.9	4.1	3.6	4.5	4.71	2.33	0.6	0.21	0.06	0.01		34	72	5.3	18	
73 Ta	470	9.8	970	1.3	Ar	-	-	11.4	18.9	12.5	8.4	3.0					54	65	3.6	16	
74 W	350	9	980	1.4	Ar	-	-	20	17.1	13.1	8.8	3.3	0.7	0.12			61	65	3.6	15	
75 Re	380	20	540	2.8	Ar	-	13	14	12.4	14.3	8.6	5	0.9	0.6			96	68	5.7	18	
82 Pb	950	10	300	0.85	Ar	-	-	1.3	4.9	5.5	8.9	3.8	7	3.9	2.1		42	46	3.3	22	
83 Bi	860	8.5	480	0.8	Ar	-	-	2.4	2.8	5.6	6.3	4.2	2.0	1.2	0.91	0.22	0.03	30	35	3.6	17
90 Th	1200	10	750	0.9	Ar	-	-	1.6	4.3	6.6	6.8	15	18	18	12	4.8	89	53	5.3	17	

Table 2
Ions of the enriched isotopes accelerated at the U-400 cyclotron

Accelerated ion	Working substance	Content of the isotope in a sputtering electrode, atoms/%	Substance after regeneration	The intensity of internal beam, pps
26 Mg ³⁺	MgO	37	MgO	4.0x10 ¹³
48 Ca ⁵⁺	CaO	20	CaO	5.0x10 ¹²
49 Ti ⁵⁺	TiO ₂	11	TiO ₂	1.0x10 ¹³
50 Ti ⁵⁺	TiO ₂	10	TiO ₂	9.6x10 ¹²
53 Cr ⁵⁺	Cr ₂ O ₃	17	-	6.0x10 ¹²
54 Cr ⁶⁺	Cr	36	Cr	6.3x10 ¹²
58 Fe ⁶⁺	Fe	91	Fe	1.0x10 ¹³
64 Ni ⁶⁺	Ni	78	-	3.5x10 ¹²
70 Zn ⁸⁺	Zn	45	-	4.0x10 ¹¹
76 Ge ⁸⁺	Ge	74	-	1.0x10 ¹²

Since $^{14}\text{CO}_2$ is a radioactive gas, a hermetically-sealed feed and recover gas system has been designed to avoid the leakage of the radioactive gas.

Special investigations have been done to determine the optional working gas consumption. The consumption was decreased to about 0.03 cm^3 per minute for Ar as a supporting gas.

Bearing in mind that the main experiments to produce and accelerate rare and radioactive ion beams in the world's cyclotron laboratories were performed with FIG and ECR ion sources, the efficiencies of consuming some working substances in such ion sources is compared in Fig. 1 and in table 3 ^{/1-9/}.

The efficiencies of consuming a working substance in the cyclotron multiply charged ion source and during acceleration in cyclotrons is made using Green's method ^{/10/}, used for singly charged ions.

In our case for multiply-charged ion beams

$$E_{is}^i = \frac{N_i}{N_0},$$

where E_{is}^i is the efficiency of consuming a working substance in the production of ions in the i -th charged state from the ion source; N_0 is the number of the atoms of the working substance, fed into the discharge per unit time; N_i is the number of ions with the charge i in the beam.

It is clear that E_{is}^i characterizes the ion source type and also the sort and the charge of the ions produced. But of practical importance for a physical experiment is also the total efficiency of consuming a working substance ($E_t^i = E_{ac}^i \frac{N_i}{N_0}$) where E_{ac}^i is the efficiency of ion acceleration and beam transport.

Conclusion

The investigations and the experience of using FIG and ECR ion sources at cyclotrons show that the problems of the effective production and acceleration of ion beams in a wide mass range can be successfully solved.

At the present time the efficiency of consuming a solid working substance is somewhat higher in FIG ion source than in an ECR ion source. It depends mainly on the technology of working substance feeding into the discharge chamber. But the ECR discharge has a higher efficiency of consuming gases for the production of highly charged ions.

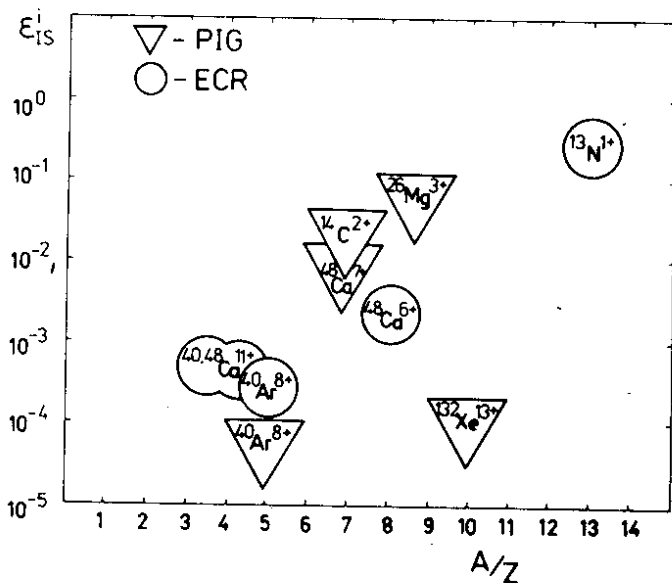


Fig. 1. Comparison of the efficiencies of consuming some working substances in PIG and ECR ion sources.

Table 3
Comparison of the efficiencies of consuming some working substances in PIG and ECR ion sources

Ion source	Ion	$\frac{m}{t}, \text{mg} \times \text{h}^{-1}$	$Q, \text{cm}^3 \times \text{min}^{-1}$	E_{is}	E_t
PIG	$^{14}\text{C}^{2+}$	-	0.03	1.5×10^{-2}	1.5×10^{-4}
	$^{26}\text{Mg}^{3+}$	4.4	-	5×10^{-2}	1.2×10^{-3}
	$^{40}\text{Ar}^{8+}$	-	0.6	5.5×10^{-5}	3.3×10^{-7}
	$^{48}\text{Ca}^{7+}$	4.0	-	1×10^{-2}	1.2×10^{-4}
	$^{132}\text{Xe}^{13+}$	-	0.4	1×10^{-4}	-
ECR	$^{13}\text{N}^{1+}$	-	-	2.5×10^{-1}	-
	$^{40}\text{Ar}^{8+}$	-	0.6	3×10^{-4}	-
	$^{40}\text{Ca}^{11+}$	2.1	-	6×10^{-4}	-
	$^{48}\text{Ca}^{11+}$	0.15	-	6×10^{-4}	2.5×10^{-5}
	$^{48}\text{Ca}^{6+}$	1.8	-	1.6×10^{-3}	1.3×10^{-5}

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Кутнер В.Б. и др.

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Эффективность использования редких изотопов
в дуговом ионном источнике

Проводится анализ эффективности использования рабочего вещества при получении и ускорении пучков ионов из дугового источника ионов на циклотронах ЛЯР ОИЯИ в сравнении с результатами для источника ионов с электронно-циклотронным резонансом (ЭЦР) ГАНИЛ (циклотронный комплекс тяжелых ионов в Кане, Франция) и циклотрона в Беркли (США). Представлены экспериментальные результаты, полученные при ускорении на циклотронах У-400 и У-300 пучков ионов редких изотопов (Mg-Ge). Описаны особенности подачи в циклотронный источник твердого рабочего вещества. Обсуждаются оптимальные условия для эффективного использования рабочих веществ в дуговом разряде. Приведены результаты исследований, получения и ускорения пучков ионов редких изотопов газов, в том числе радиоактивного изотопа углерода-14. Обсуждаются возможности и перспективы развития эффективных источников ионов ЛЯР ОИЯИ для циклотронного комплекса циклотронов У-400 и У-400М.

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The Efficiency of Consuming Rare Isotopes
in a Pig Ion Source

The efficiency of consuming a working substance in the cyclotron arc ion source during operation at the LNR JINR cyclotrons is analyzed in comparison with the results obtained for the ECR ion source of GANIL and the Berkeley cyclotron. The experimental results are described, which have been obtained during the acceleration of rare isotopes ion beams (Mg-Ge) at the U-400 and U-300 cyclotrons. Some features of solid working substances fed into the cyclotron ion source are described. The optimal conditions for the efficient use of working substances in the arc discharge are discussed. The results of producing and accelerating rare gas isotopes ion beams, including the radioactive isotope carbon-14, are presented. Prospects for the future development of efficient ion sources for the LNR cyclotron complex, consisting of the U-400 and the U-400M are discussed.

The investigation has been performed at the Laboratory of Nuclear Reactions, JINR.

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