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METHODS FOR PRODUCTION OF INTENSE METAL ION BEAMS AT THE DC-60 CYCLOTRON

V.N. Loginov, A.E. Bondarchenko, K.I. Kuzmenkov†, S.L. Bogomolov, V.E. Mironov,
FLNR, JINR, Dubna, Moscow Region, Russia
I.A. Ivanov, M.V. Zdorovets, E.K. Sambayev, V.V. Alexandrenko, A.E. Kurakhmedov, S.G. Kozin,
M.V. Koloberdin, D.A. Mustafin, Astana Branch of Institute of Nuclear Physics, Astana,
Kazakhstan

Abstract

The paper is devoted to the description of research conducted in 2017-2018 at the accelerator complex DC-60 of the Astana branch of INP, on production and acceleration of intense ion beams of solids.

The main purpose of this work was to develop techniques for obtaining accelerated ions using evaporation method and the volatile compounds (MIVOC) method. The development of these techniques will significantly expand the range of accelerated ions, which gives particular relevance to the purpose of the study. With the increase in the spectrum of accelerated elements, the possibilities of posing, searching for and solving new problems and experiments in the field of experimental nuclear physics, solid-state radiation physics, and various applied problems will increase.

INTRODUCTION

The DC-60 cyclotron [1] is designed for acceleration of ions from Li to Xe with A/Z in the range from 6 to 12. The accelerator is equipped with the normally-conducting 14-GHz DECRIS-3 ion source [2]. The main parameters of the source are: magnetic fields at the injection and extraction sides of the source are 1.3 and 1.1 T respectively, the hexapole field at the wall is 1.0 T, the source chamber length is 20 cm, and the chamber diameter is 6.4 cm. Microwaves are injected into the source through the coaxial waveguide along the source axis. The extraction voltage of the source is up to 25 kV.

We use three different methods for metal ion production: evaporation of material from large volume crucible heated by microwaves in the source chamber, evaporation from a filament-heated oven, and injection into the source of volatile compounds that contain the desired atoms.

When producing ions of the solid elements, thin cylindrical tantalum sheet is inserted into the source chamber to facilitate atom recycling from the walls [3]. As a support gas, we always use helium, which was found to be the best choice for production of moderately charged ions requested by the DC-60 cyclotron.

MIVOC PRODUCTION OF IONS OF SOLID ELEMENTS

MIVOC (Metal Ions from Volatile Compounds) method is based on use of metal compounds that have a high vapor pressure at room temperature [4]. Ferrocene Fe $(C_5H_5)_2$ has a vapor pressure of 2.6×10^{-3} Torr at 20 °C, and dicarba-*closo*-dodecaborane compound $C_2B_{10}H_{12}$ has a vapor pressure of about 1-2 Torr. Using these compounds, intense beams of B and Fe ions were obtained for the first time at the DC-60 cyclotron of Astana Branch of INP.

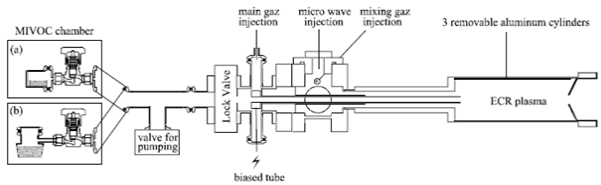

Figure 1: Schematic view of MIVOC chamber connection to ECR ion source.

Compound is placed into a glass container connected to the gas transport line at the injection side of the source. No extra heating of the container is needed, and the gas flow into the source is regulated by a needle valve. (Fig.1)

Up to 25 μA of $^{56}Fe^{10+}$ ions were extracted at the optimized conditions (Fig.2) with Fe consumption of 0.8 mg/h.

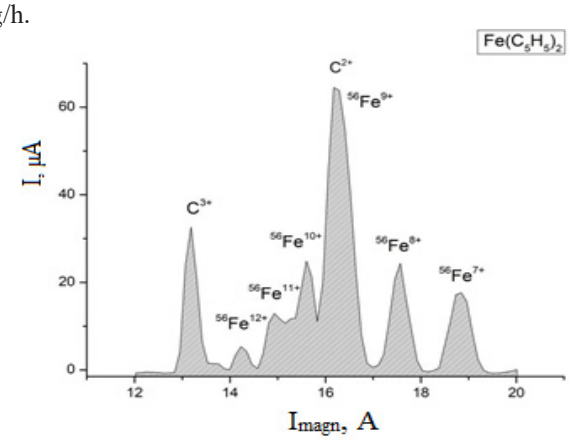

Figure 2: Charge state distribution of the extracted Fe ions.

The maximum current of $^{11}B^{2+}$ is up to 60 μA. Spectrum of the extracted boron ions is shown in Fig. 3. Consumption of the compound is about of 1.2-1.4 mg/h.

† e-mail: k.i.kuzmenkov@gmail.com

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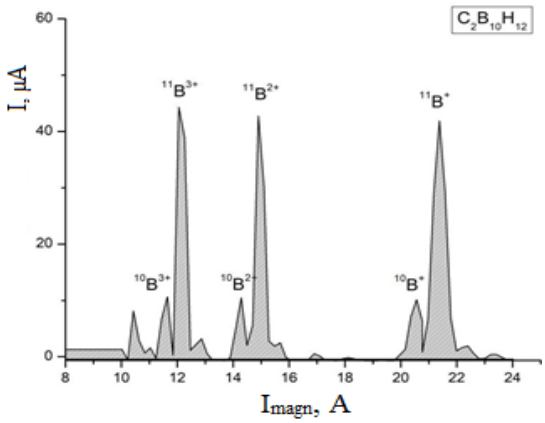

Figure 3: Charge state distribution of the extracted B ions.

EVAPORATION FROM OVEN

The upper temperature limit for our oven is 900 °C, which defines the range of working materials. The heating power is 25 W, the 0.1-mm diameter nichrome wire is used to heat the tantalum (standard) crucible (SC), with length of 28 mm, inner diameter 2 mm, outer diameter 2.8 mm. The oven is mounted on a movable holder inside the waveguide such that the orifice position can be regulated in the range (-15÷15) mm in respect to the edge of biased electrode.

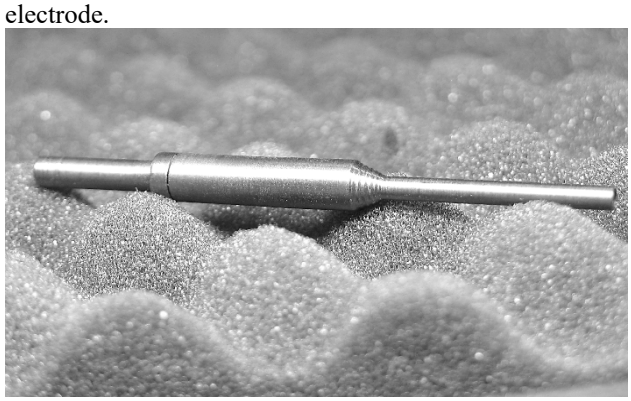

Figure 4: The large volume crucible.

To increase the oven's operational time, we use enlarged crucible (EC) for some materials. This crucible is presented in Fig.4. The central cylinder contains the working material; inner diameter of the container is 6 mm, outer diameter is 7 mm, the container length is 20 mm. On one side, the container is connected to the solid rod heated by the filament; the rod has the same sizes as the standard crucible. Vapors leave the container through the 10-mm-long nozzle with the inner diameter of 1 mm. Twisted tantalum wire is pressurized inside the nozzle to shield the working material from the plasma and to prevent spilling of the melted material into the source chamber.

The nozzle and container are mainly heated by microwaves with some extra-heating by plasma. The crucible temperature is controlled by moving the holder in and out of the source chamber and by changing the filament current. Heating of the container from backside by filament is optional feature that gives additional control for adjusting the material evaporation rate.

Charge state distributions of the extracted Li ions are shown in Figs.5 and 6 for enlarged crucible (Fig.4) and for the standard crucible. Operational temperatures of the crucibles are 200 °C, and metal consumptions are 0.7 and 1.1 mg/h for EC and SC respectively, with the extracted Li^{1+} currents of 200 and 500 μA.

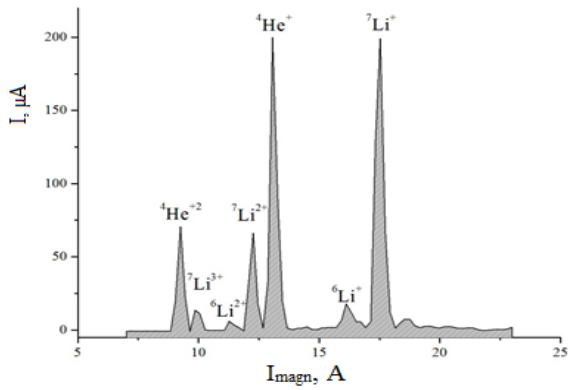

Figure 5: Charge state distribution of the extracted Li ions with the enlarged crucible (EC).

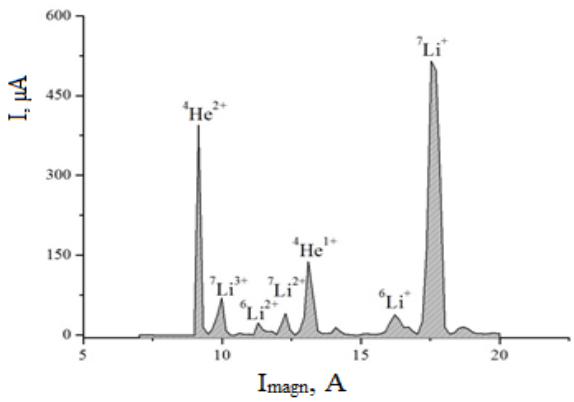

Figure 6: Charge state distribution of the extracted Li ions with the standard crucible (SC).

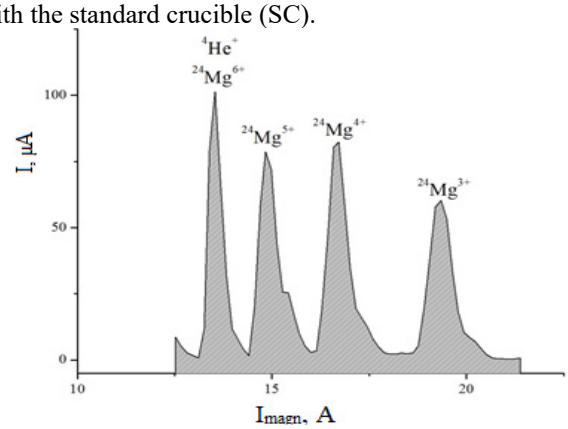

Figure 7: Charge state distribution of the extracted Mg ions (EC).

Current of Mg^{4+} ions (EC) reaches the level of 80 μA at the metal consumption of 2.1 mg/h. The extracted magnesium ion distribution is shown in Fig.7.

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For calcium ion production, the oven (SC) is heated up to 720 °C. Metal consumption is 0.7 mg/h when tuning the source to extract 140 μA of $^{40}Ca^{5+}$ and 75 μA of $^{40}Ca^{7+}$ ion currents. The charge state distribution distribution is shown in Fig.8.

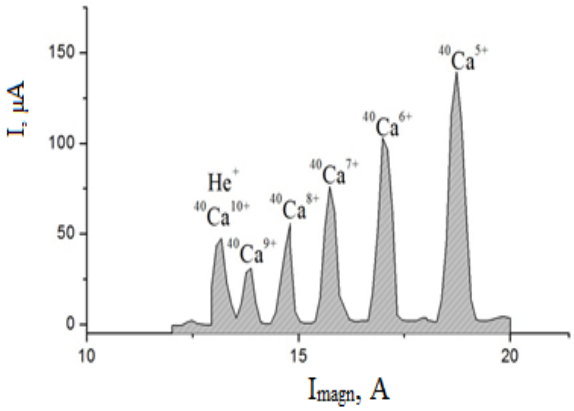

Figure 8: Charge state distribution of the extracted Ca ions (SC).

The phosphorus ions were produced at the oven temperature of 100 °C. Consumption of phosphorus equals to 1.7 mg/h, and we reached the level of 60 μA for $^{31}P^{5+}$ ion current (Fig.9). As a working substance red phosphorus was used.

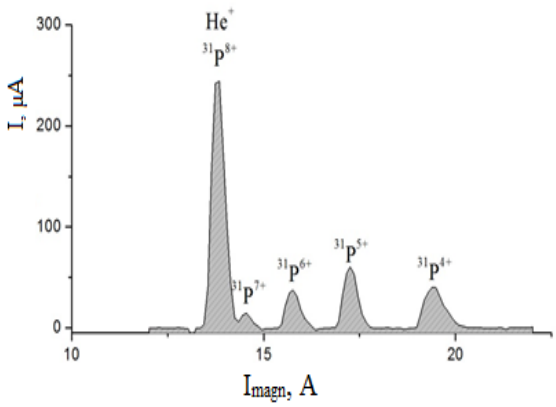

Figure 9: Charge state distribution of the extracted P ions (SC).

The extracted ions of Fe, B, Li, Ca, P, Mg were injected into the DC-60 cyclotron and accelerated up to the energies shown in Table 1. Quality of the beams was good enough to obtain the transmission coefficients from extraction to the target at the level of a few percent.

Table 1: Accelerated Beams

Ion	E, MeV/u	I_{extr}, μA	I_{target}, μA	Tr.ratio %
$^{40}Ca^{7+}$	1.75	50	1.35	2.75
$^{31}P^{5+}$	1.75	20	0.58	3.00
$^{24}Mg^{4+}$	1.75	46	1.14	2.48
$^{7}Li^{+}$	1.32	100	1.5	1.5
$^{56}Fe^{10+}$	1.75	15.6	0.22	1.4
$^{11}B^{2+}$	1.5	24.2	0.7	2.85

CONCLUSIONS

The main purpose of this work was to develop techniques for obtaining accelerated ions using evaporation method and the volatile compounds (MIVOC) method. The development of these techniques will significantly expand the range of accelerated ions, which gives particular relevance to the purpose of the study. With the increase in the spectrum of accelerated elements, the possibilities of posing, searching for and solving new problems and experiments in the field of experimental nuclear physics, solid-state radiation physics, and various applied problems will increase. As a result of the performed work, the accelerated beams of lithium $^{7}Li+$, magnesium $^{24}Mg^{4+}$, calcium $^{40}Ca^{7+}$, phosphorus $^{31}P^{5+}$, iron $^{56}Fe^{10+}$ and boron $^{11}B^{2+}$ were produced at the DC-60 cyclotron for the first time.

ACKNOWLEDGEMENTS

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