

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

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## Abstract

In 2017-2018, research program of the DC-60 cyclotron (Astana Branch of the Institute of Nuclear Physics, Kazakhstan) requests acceleration of intense ion beams of solid elements. Beams of B and Fe ions are produced in ECR ion source by using the volatile compounds, while ions of Li, Mg, P and Ca are produced by evaporation from an oven. Beams of  $^{56}\text{Fe}^{10+}$ ,  $^7\text{Li}^{1+}$ ,  $^{24}\text{Mg}^{4+}$ ,  $^{31}\text{P}^{5+}$ ,  $^{40}\text{Ca}^{7+}$ , and  $^{11}\text{B}^{2+}$  ions were accelerated up to energies of 1.32-1.75 MeV/u.

## 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 container 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.

## 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.

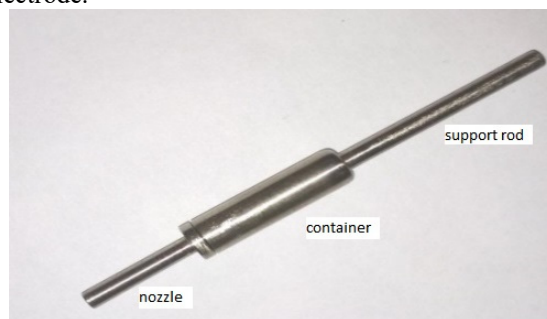


Figure 1: The large volume crucible.

To increase the oven's operational time, we use enlarged crucible (EC) for some materials. This crucible is presented in Fig. 1. 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. 2 and 3 for enlarged crucible (Fig. 2) 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  $\text{Li}^{1+}$  currents of 200 and 500  $\mu\text{A}$ .

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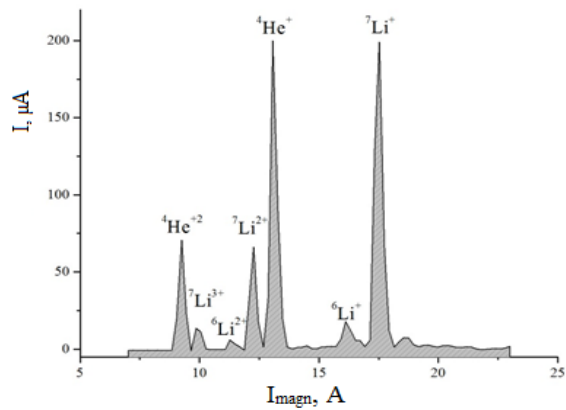


Figure 2: Charge state distribution of the extracted Li ions with the enlarged crucible (EC).

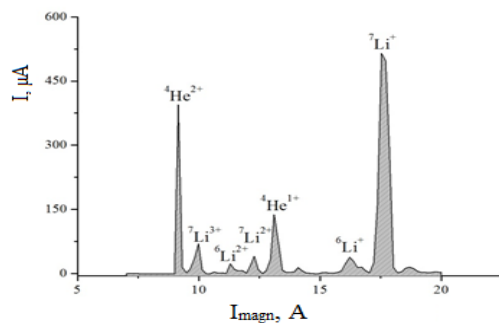


Figure 3: Charge state distribution of the extracted Li ions with the standard crucible (SC).

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

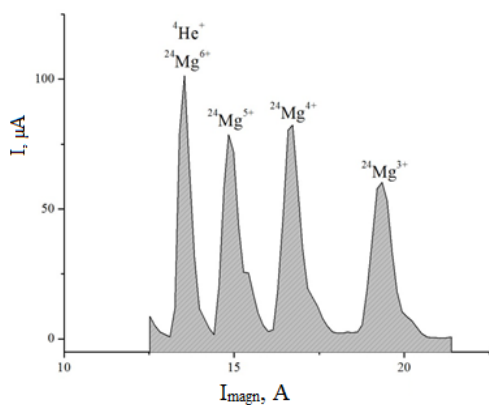


Figure 4: Charge state distribution of the extracted Mg ions (EC).

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  $\mu A$  of  $^{40}Ca^{5+}$  and 75  $\mu A$  of  $^{40}Ca^{7+}$  ion currents. The current distribution is shown in Fig. 5.

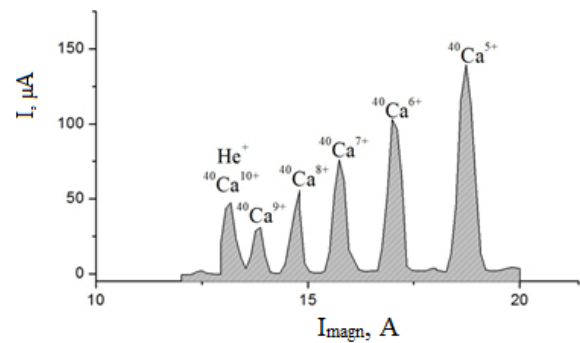


Figure 5: Charge state distribution of the extracted Ca ions (SC).

Oven temperature for production of P ions is 100 °C. Consumption of phosphorus is 1.7 mg/h, and we reach the level of 60  $\mu A$  for  $^{31}P^{5+}$  ion current (Fig. 6). As a working substance we used red phosphorus.

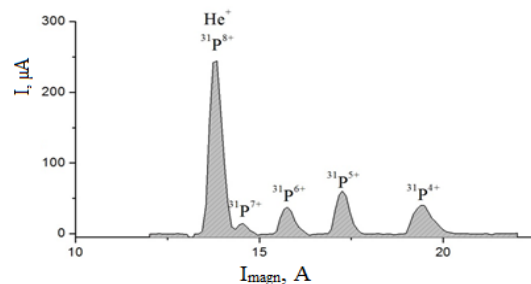


Figure 6: Charge state distribution of the extracted P ions (SC).

## MIVOC PRODUCTION OF IONS OF SOLID ELEMENTS

MIVOC (Metal Ions from Volatile Compounds) method is based on use of metal compounds (metallocenes) that have a high vapor pressure at room temperature [4]. Ferrocene  $Fe(C_5H_5)_2$  has a vapor pressure of  $2.6 \times 10^{-3}$  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.

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.

Up to 25  $\mu A$  of  $^{56}Fe^{10+}$  ions is extracted in the optimized conditions (Fig. 7) with Fe consumption of 0.8 mg/h.

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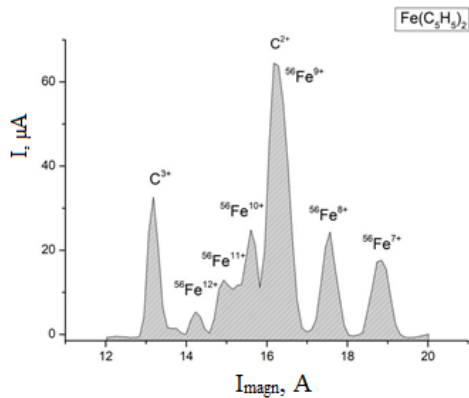


Figure 7: Charge state distribution of the extracted Fe ions.

The maximum current of  $^{11}\text{B}^{2+}$  is up to 60  $\mu\text{A}$ . Spectrum of the extracted boron ions is shown in Fig. 8. Consumption of the compound is about of 1.2-1.4 mg/h.

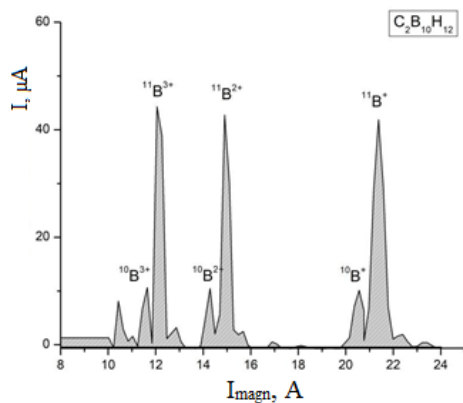


Figure 8: Charge state distribution of the extracted B ions.

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	$I_{\text{extr}}, \mu\text{A}$	$I_{\text{target}}, \mu\text{A}$
$^{40}\text{Ca}^{7+}$	1.75	50	1.35
$^{31}\text{P}^{5+}$	1.75	20	0.58
$^{24}\text{Mg}^{4+}$	1.75	46	1.14
$^7\text{Li}^+$	1.32	100	1.5
$^{56}\text{Fe}^{10+}$	1.75	15.6	0.22
$^{11}\text{B}^{2+}$	1.5	24.2	0.7

## CONCLUSIONS

Techniques for production of intense beams of solid materials are successfully tested at DC-60 cyclotron. The accelerated beams will be used for experiments in the fields of nuclear physics, solid-state radiation physics, and various applied researches.

## ACKNOWLEDGEMENTS

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