# PRODUCTION OF METAL ION BEAMS FROM ECR ION SOURCES BY MIVOC METHOD*

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*Abstract*

The production of metal ion beams with ECR ion sources using MIVOC method is described. The method is based on the use of metal compounds having a high vapor pressure at room temperature: for example, $C_2B_{10}H_{12}$, $Fe(C_5H_5)_2$ and several others. Intense ion beams of B and Fe were produced at the FLNR JINR cyclotrons using this method. The main efforts were went into production and acceleration of $^{50}$Ti ion beam at the U-400 cyclotron.

The experiments on production of $^{50}$Ti ion beam were performed at the test bench with the natural and enriched compounds of titanium $(CH_3)_5C_5Ti(CH_3)_3$. In the experiments at the test bench the beam currents of $^{50}Ti^{5+}$ - 80 mkA and $^{48}Ti^{11+}$ - 70 mkA were achieved at different settings of the source. After successful tests two 3 weeks runs with Ti-50 beam were performed at the U-400 cyclotron for the experiments on spectroscopy of super heavy elements. The intensity of the injected beam of $^{50}Ti^{5+}$ was about of 50-60 μA, during experiment the source have shown stable operation. The compound consumption rate was determined to be about of 2.4 mg/h, corresponding to $^{50}$Ti consumption of 0.52 mg/h.

## INTRODUCTION

The most heavy target, with which it is possible to carry out experiments on the synthesis of super heavy elements in heavy-ion reactions is $^{249}$Cf, and the further progress in the area of the elements with Z > 118 requires the production of intense beams of accelerated neutron-enriched isotopes such as $^{50}$Ti, $^{58}$Fe, $^{64}$Ni and others. The use of each new isotope for production of the accelerated beam requires investigations directed on optimization of the ECR source operation mode and development of technique for material feed into the source.

The method of solid materials feed into an ECR ion sources strongly depends on the specific properties of materials.

Several methods for production of ions of solids from ECR sources have been developed. Solid material can be evaporated by resistor or inductive oven, which is inserted into the source chamber [1]. Refractory metals can be sputtered by plasma ions [2] or inserted into the plasma and heated by energetic plasma electrons ("insertion technique") [3].

The other possibility for production of ions of solids is the feeding of the plasma with an organometallic compound through the Metal Ions from VOlatile Compounds (MIVOC) method [4].

*Work supported by Russion Foundation for Basic Research under grant number 13-02-12011

## PRODUCTION OF IONS OF METALS BY MIVOC METHOD

MIVOC method is based on the use of organometallic compounds having a high vapor pressure at room temperature: for example, $C_2B_{10}H_{12}$, $Fe(C_5H_5)_2$ and several others.

First time in FLNR the MIVOC method was used for production of intense beam of $^{11}B^{3+}$ required for generation of secondary beams of $^{6}$He and $^{8}$He at the U400M cyclotron [5]. The compound $C_2B_{10}H_{12}$ which has the vapor pressure of about 1÷2 Torr at the room temperature has been used. The ion source operated stable without addition of support gas.

The maximal current of $^{11}B^{3+}$ up to 200 eμA was produced from DECRIS-2 [6] ion source. The material consumption measured at 100 eμA current of $^{11}B^{3+}$ constitutes 2,2 – 2,8 mg/h.

Later this method was successfully applied for production of iron, cobalt and chromium ion beams using the ferrocene, cobaltocene and chromocene as a working substances. The results, obtained at the test bench are presented in the Table 1.

Table 1: Intensity (eμA) of Metal Ion Beams Produced by MIVOC Methods at the Test Bench (* - intensity optimisation)

| | Fe | Co | Cr |
|---|---|---|---|
| 6+ | 43 | 57 | 70* |
| 7+ | 93 | 80 | 60 |
| 8+ | 125 | 86 | 37 |
| 9+ | 172 | 80* | 17 |
| 10+ | 145* | | 7 |
| 11+ | 114 | 82* | |
| 12+ | 73 | 25 | |
| 13+ | 45 | | |

At the U-400 cyclotron the beam of $^{58}$Fe was accelerated using the same technique. The intensity of injected $^{58}Fe^{7+}$ beam was 40÷50 eμA (6 ÷ 7 pμA), and the $^{58}Fe^{23+}$ beam intensity at the target constitutes 15 ÷ 17 eμA (~ 0.7 pμA). The consumption of $^{58}$Fe constitutes about of 1,5 mg/h.

## PRODUCTION OF TITANIUM ION BEAM

The experiments on production of Ti ion beams were carried out at many laboratories with the use of different methods.

The production of Ti ion beams by evaporation from the resistor oven was studied at GSI [7]. The evaporation



ISBN 978-3-95450-170-0

of pure titanium requires the temperature between 1750 °C and 1800 °C. During the experiments more than 50 eμA of $^{50}Ti^{8+}$ were produced with high level of beam stability. The oven life time of 6 days was obtained.

The experiments on production of Ti ion beams by evaporation from the induction oven were carried out at ANL [8]. The beam of $^{50}Ti^{12+}$ with the intensity of 5.5 eμA was produced during seven days.

The MIVOC method was first adopted for production of Ti ion beam by JYFL group [9]. Commercially available $(CH_3)_5C_5Ti(CH_3)_3$ compound was used as a working substance. In the case of $^{48}Ti^{11+}$ion beam the intensity of 45 eμA was produced.

The consumption of the compound was measured to be 47 mg giving the value of 0.22 mg/h for the consumption of titanium. The ion beam was very stable during the period of 282 h.

So, from the point of view beam intensity, stability, reliability and material consumption the MIVOC method seems very promising for providing $^{50}Ti$ ion beam for long term experiments on synthesis of super heavy elements. But, the compound is sensitive to air, moisture, temperature and light that needs cautious handling when loading the material for use. The synthesis of this compound is rather complicated especially with the use of enriched titanium which is available in a small, about several grams, quantity.

### *Test Experiments*

First time the $^{50}Ti$ ion beam was accelerated at the U-400 cyclotron in 2005. The task was to provide about of 30 enA of $^{50}Ti$ beam at the target for experiments on the fission physics. The natural $TiCl_4$ (5.2 % of $^{50}Ti$) was used as a working substance. The intensity of $^{50}Ti$ ion beam, extracted from the cyclotron constitutes about of 200 enA, the source was running stable during two weeks.

But the use of $TiCl_4$ do not provide the intensity required for the experiments on the synthesis of super heavy elements.

Taking into account the problems with synthesis and handling of $(CH_3)_5C_5Ti(CH_3)_3$ we decided to try to find the other compounds, suitable for MIVOC method. The titanium isopropoxide ($Ti\{OCH(CH_3)_2\}_4$) and cyclopentadienyl cycloheptatrienyl titanium ($C_5H_5TiC_7H_7$) were tested, but no noticeable titanium current were observed, just a few microamperes of $Ti^{5+}$. The ($C_5H_5TiC_7H_7$) compound was later used at IMP [10] with LAPECR2 source for production of titanium ions by oven method. During the test, 24 eμA of $Ti^{11+}$ has been achieved with 250 W 14.5 GHz microwave power.

The commercially available compound was tested with DECRIS-4 [11] and DECRIS-2 sources. The sources were optimized for production of $Ti^{5+}$, similar results were produced with both sources – about of 50÷60 μA. In the experiments with the modified ECR4M [12] source at the test bench about of 80 μA of $Ti^{5+}$ were produced. In all experiments no support gas and no control of MIVOC chamber temperature were used. The operation of the sources was stable and reproducible.

### *Production of Titanium-50 Ion Beams*

The development of titanium-50 beam production was performed in the frame of collaboration between IPHC (Strasbourg, France) and JINR.

After several years of chemistry developments at IPHC the $C_5(CH_3)_5Ti(CH_3)_3$ compound was synthesized using 92.57 % enriched $^{50}Ti$. A two step chemistry was done starting from $TiCl_4$ going to $C_5(CH_3)_5Ti(CH_3)_3$ through an intermediate $C_5(CH_3)_5TiCl_3$ organic compound with quite high efficiency.

First isotopicaly enriched beam of $^{50}Ti$ by MIVOC method was produced in 2011 at the University of Jyväskylä. After optimization, up to 19.4 eμA of $^{50}Ti^{11+}$ was extracted from the JYFL 14 GHz ECRIS2 ion source [13, 14].

The compound from natural titanium, synthesized at IPHC, was also tested at GANIL [15]. An intensity of 20 eμA for $^{48}Ti^{10+}$ was maintained for 4 days, with regulation the temperature of the MIVOC chamber. The consumption of 1.5 mg/h for the MIVOC compound has been deduced, i.e. 0.23 mg/h for $^{48}Ti$.

First natural material synthesized at FLNR by IPHC group was tested in October 2013 with ECR4M ion source at the test bench. After optimization, very stable $^{48}Ti$ beams were produced with intensities up to 70 eμA for the $11^+$ charge state (6.2 pμA) and 75 eμA for the $5^+$ charge state (15.0 pμA). Figure 1 shows the charge state distribution of $^{48}Ti$ ion beam with the source settings for optimum production of $^{48}Ti^{11+}$.

Following these very promising results, a 92.57 % enriched compound was synthesized and tested with ECR4M at test bench. Under similar conditions up to 80 eμA of $^{50}Ti^{5+}$ beam was extracted, corresponding to 16.0 pμA. Figure 2 shows the charge state distribution of $^{50}Ti$ ion beam with the source settings for optimum production of $^{50}Ti^{5+}$.

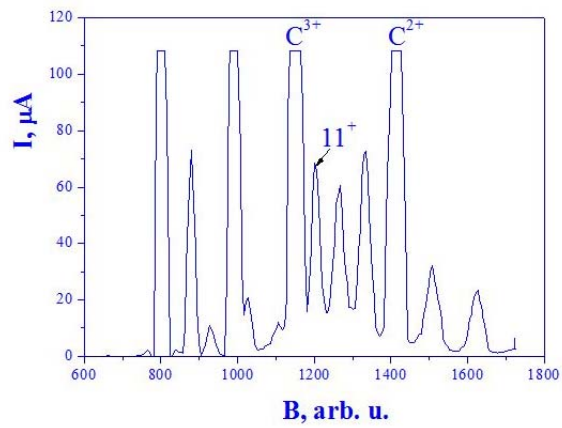


Figure 1: Ti ion spectrum, produced by MIVOC method from the ECR4M source at microwave power of 300 W.

ISBN 978-3-95450-170-0

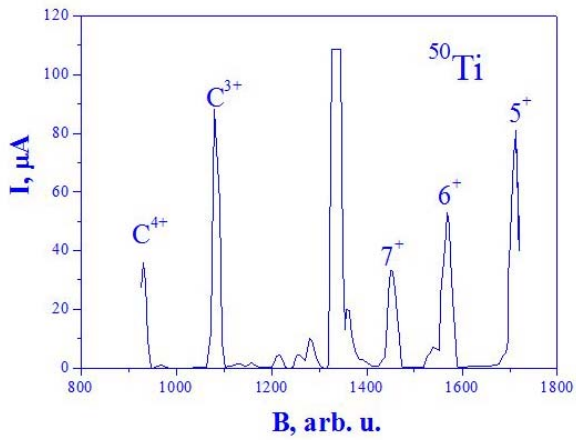


Figure 2 : $^{50}$Ti ion spectrum, produced by MIVOC method from the ECR4M source at microwave power of 30 W.

This beam was then produced with the DECRIS-2m [16] source and accelerated at the U400 cyclotron. A very stable $^{50}Ti^{5+}$ beam with the intensity of 55 eμA (11.0 pμA) was injected in the cyclotron. Extracted titanium-50 ion beam with the intensity of 0,49 pμA was used on target for several weeks in October-November 2013. This beam was very stable with wery low, about of 0.6 mg/h titanium consumption.

Next run with titanium-50 ion beam was performed at the U-400 cyclotron during April-May 2014. By then the DECRIS-2m source at the U-400 cyclotron was replaced by ECR4M source. During three weeks the intensity of $^{50}Ti^{5+}$ beam was maintained at the level of 55÷62 eμA. The material consumption was similar to the previous run with DECRIS-2m ion source.

Table 2 summarise the results of titanium ion beam production at different Laboratories by MIVOC (JYFL, GANIL, FLNR) and oven (GSI, ANL, IMP) methods.

Table 2: Intensity (eμA) of Titanium Ion Beams Produced at Different Laboratories by MIVOC and Oven Methods

| | JYFL | GANIL | FLNR | GSI | ANL | IMP |
|---|---|---|---|---|---|---|
| $^{48}Ti^{5+}$ | | | 79 | | | |
| $^{48}Ti^{10+}$ | | 20 | | | | |
| $^{48}Ti^{11+}$ | 45 | | 68 | | | 24 |
| $^{50}Ti^{5+}$ | | | 82 | | | |
| $^{50}Ti^{8+}$ | | | | 50 | | |
| $^{50}Ti^{11+}$ | 20 | | | | | |
| $^{50}Ti^{12+}$ | | | | | 5.5 | |

## CONCLUSION

During last years significant progress was achieved in production of intense multiply charged ion beams of metals from ECR ion sources by MIVOC method.

The MIVOC method was successfully used for production and acceleration of titanium-50 and iron-58 ion beams at the U-400 cyclotron.

This method provides intense ion beams with long term stability, and is quite promising for experiments on synthesis of super heavy elements.

## ACKNOWLEDGMENT

This work was supported by Russian Foundation for Basic Research under Grant number 13-02-12011.

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ISBN 978-3-95450-170-0