RECENT DEVELOPMENT IN METALLIC BEAM PRODUCTION WITH AN ECR ION SOURCES AT FLNR (JINR)*

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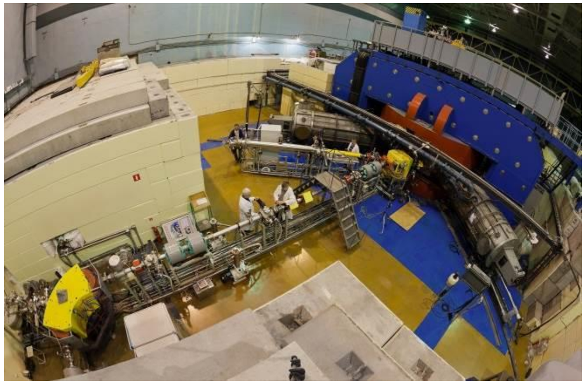
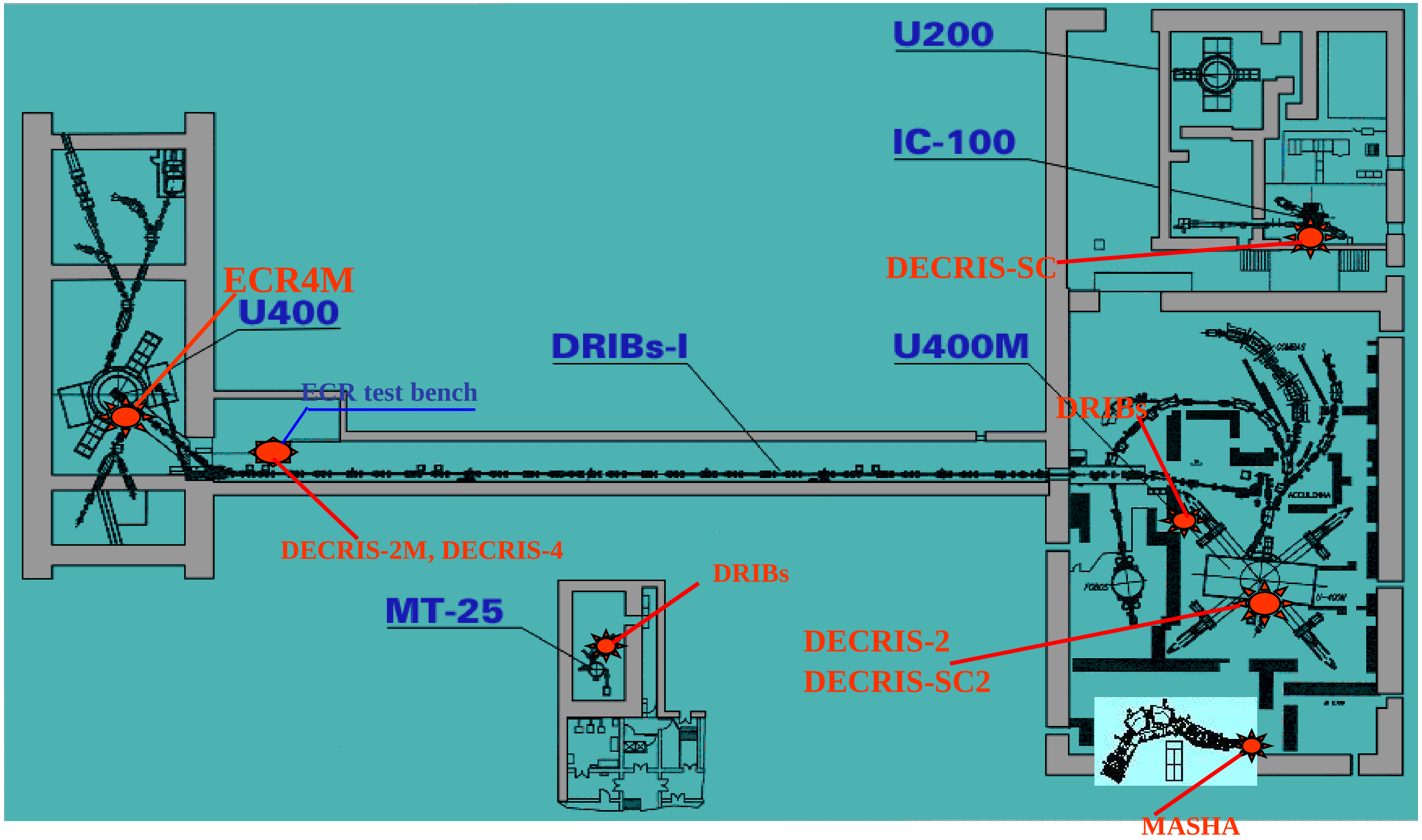
OVERVIEW OF THE FLNR (JINR) CYCLOTRONS WITH ECR ION SOURCES

U400 + ECR4M

U400M + DECRIS-2/DECRIS-SC2



CI-100 + DECRIS-SC



FLNR’s BASIC DIRECTIONS of RESEARCH

1. Heavy and superheavy nuclei:

- **synthesis and study of properties of superheavy elements;**
- **chemistry of new elements;**
- **fusion-fission and multi-nucleon transfer reactions;**
- **nuclear- , mass-, & laser-spectrometry of SH nuclei.**

2. Light exotic nuclei:

- **properties and structure of light exotic nuclei;**
- **reactions with exotic nuclei.**

3. Radiation effects and physical groundwork of nanotechnology.

Many of the elements required for acceleration at the FLNR cyclotrons are available in the solid state form only.

<u>Production of neutron reach light nuclei (^{6}He, ^{8}He,…)</u>

Required beams -Li, B..

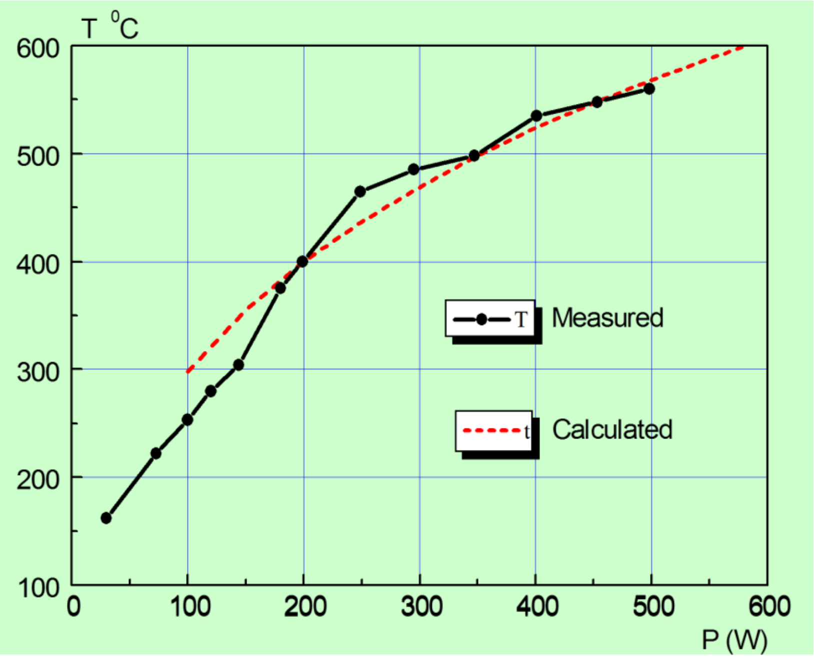
<u>Synthesis of new super heavy nuclei</u>

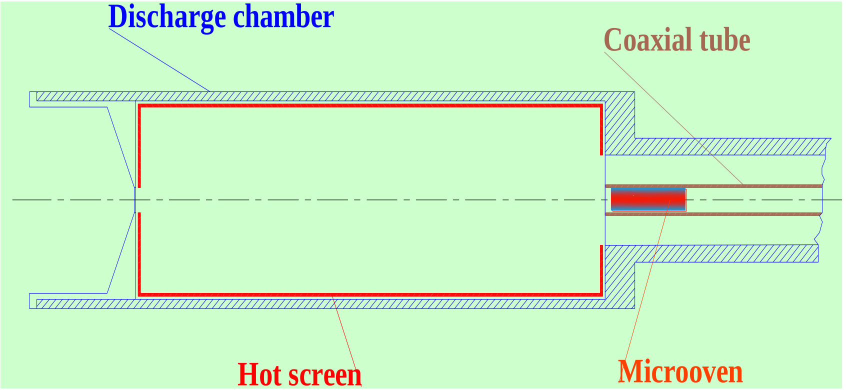
Required beams: ^{48}Ca-(0,19 %); ^{50}Ti - (5,2 %); ^{58}Fe–(0,3 %) ...

For the production of intense beams an expensive enriched isotopes are used

Efficiency of material consumption !!!

Production of the Li ion beam with hot screen

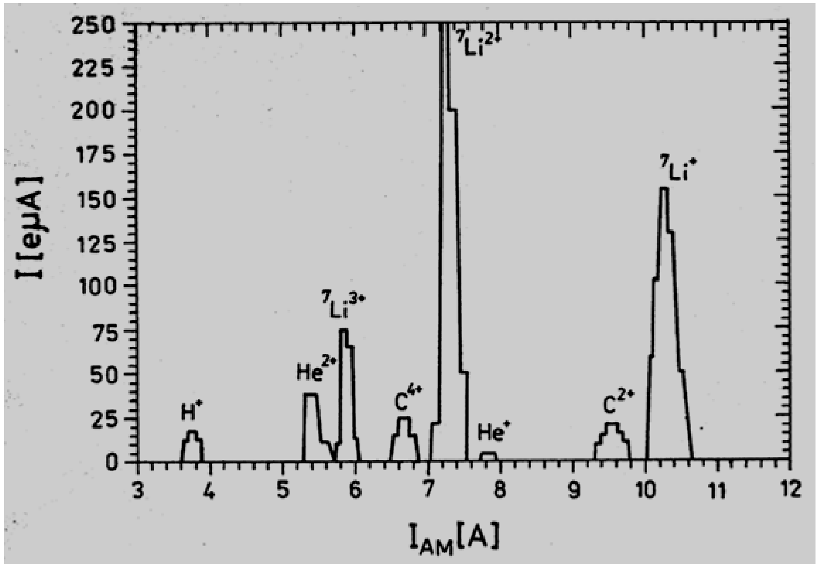




The screen is heated by microwaves and plasma electrons.

Yields ($e\mu$A) for Li from the DECRIS-2 with UHF power in the range 300–400 W.

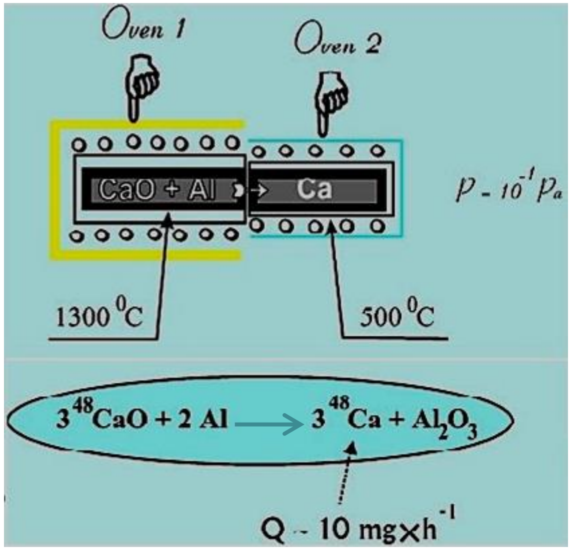
Q	1+	2+	3+	
7Li	15	50	25	No screen
7Li	180	290	50	With hot screen



Li spectrum with hot screen

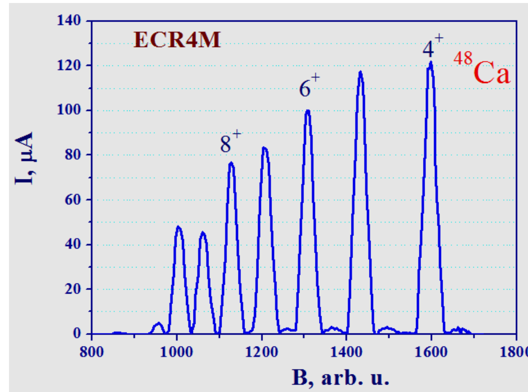
The same technique was used for production of ^{26}Mg, ^{48}Ca, Bi

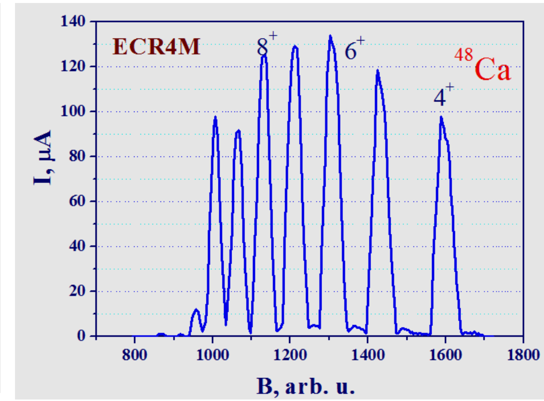
Production of ^{48}Ca beam with ECR4M source



Reduction of calcium from calcium oxide

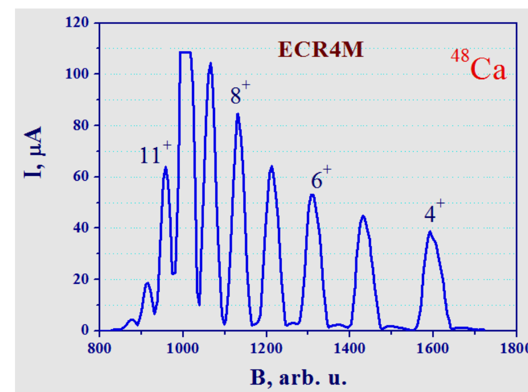
Since 1997 about 70% of the total beam time were used for acceleration of $^{48}Ca^{5+}$ ions for synthesis of new superheavy elements.





Spectra of Ca ions at different source settings

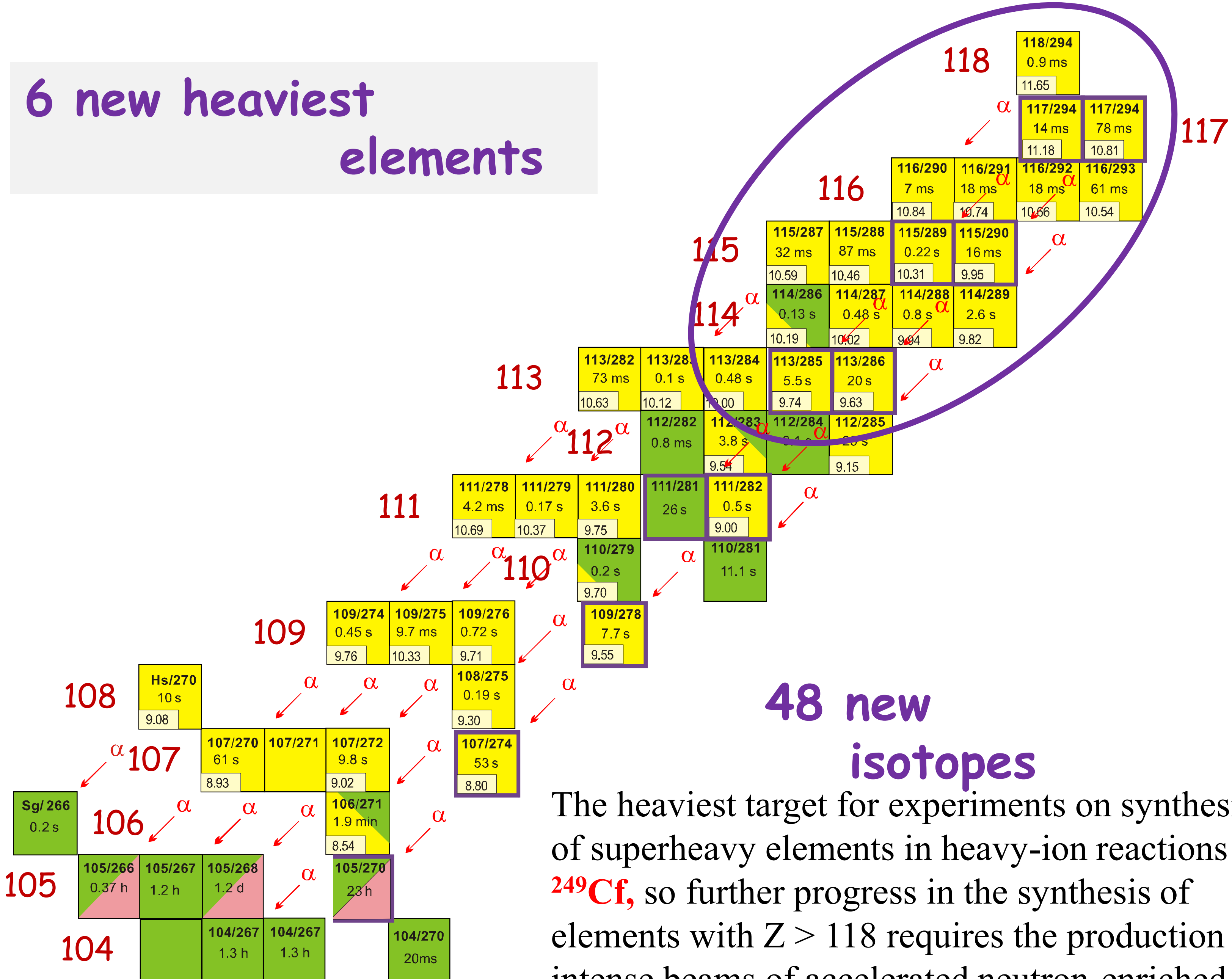
Measuring point	Beam intensity		Ion	Transmission factor				
ECR source, after separation	$1\cdot10^{14}$ pps	84 µAe	$^{48}Ca^{5+}$	32%				8.5%
Cyclotron centre	$3.5\cdot10^{13}$ pps	27 µAe	$^{48}Ca^{5+}$		81%			
Extraction radius	$2.8\cdot10^{13}$ pps	22 µAe	$^{48}Ca^{5+}$			40%		
Extracted beam (by charge exchange)	$9.7\cdot10^{12}$ pps	28 µAe	$^{48}Ca^{18+}$				82%	
Target	$8\cdot10^{12}$ pps	23 µAe	$^{48}Ca^{18+}$					



^{48}Ca consumption ~ 0.8 ÷ 1 mg/h

905 samples of metallic ^{48}Ca were used since November 1997 till the end of June 2015

6 new heaviest elements



48 new isotopes

The heaviest target for experiments on synthesis of superheavy elements in heavy-ion reactions is **^{249}Cf**, so further progress in the synthesis of elements with Z > 118 requires the production of intense beams of accelerated neutron-enriched isotopes, such as **^{50}Ti**, ^{58}Fe, ^{64}Ni, etc.

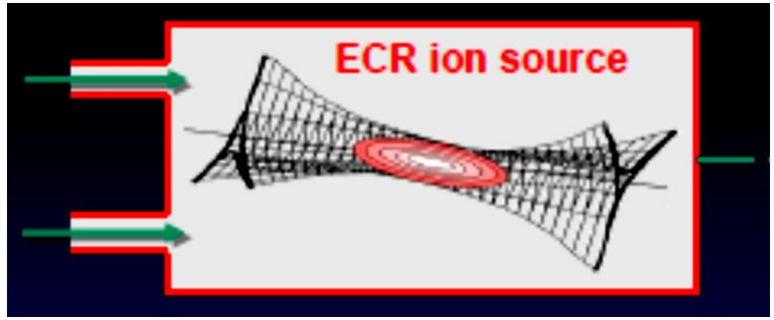
Production of ions of solids

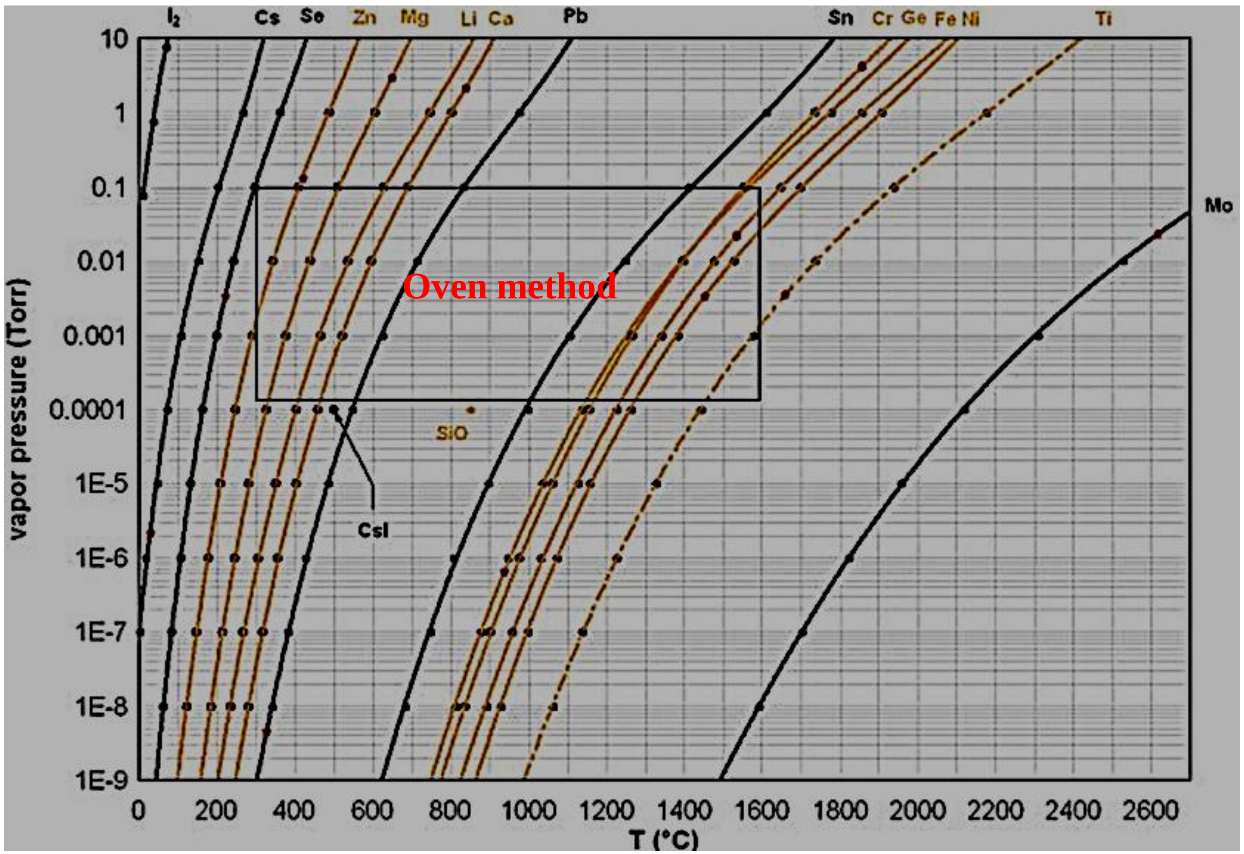
Vapor of metals (oven method)

or

Volatile compounds

(MIVOC method)





MIVOC-method (Metal Ions from VOlatile Compounds)

Requirements:

1) Chemical compound containing required element has to be found

2) The saturated vapour pressure (at room temperature) of the compound has to be high enough ($\geq 10^{-3}$ mbar)

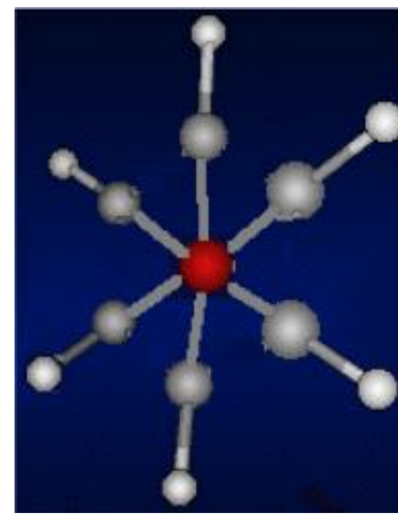
- minimum usable vapour pressure of the compound is determined by the material consumption rate of the ion source and by the conductance between the MIVOC chamber and the ion source

$C_2B_{10}H_{12}$ - carboran

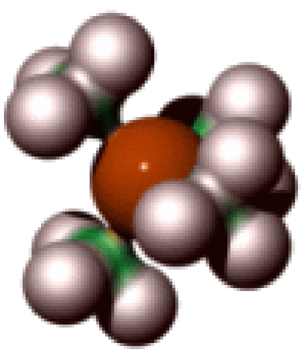
$(C_5H_5)_2Me$ – metallocene molecule (Fe, Ni,Cr..)

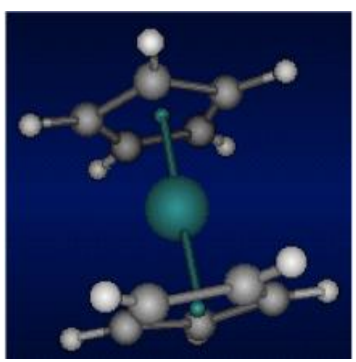
$(CH_3)_4Me$ – tetrameethyl molecule (Sn, Ge)

$(CO)_6Me$ – hexacarbonyl molecule (Cr, W)



W$(CO)_6$

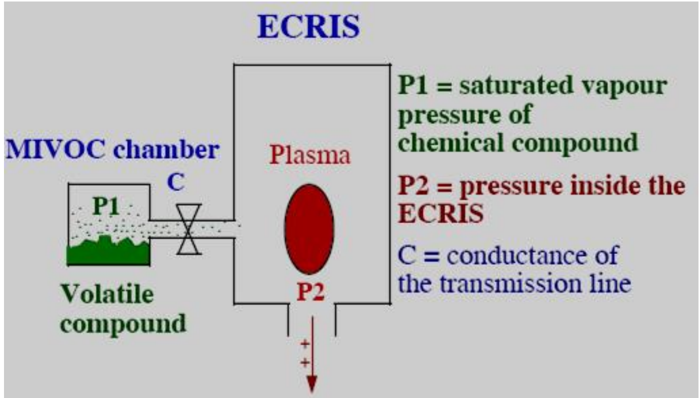


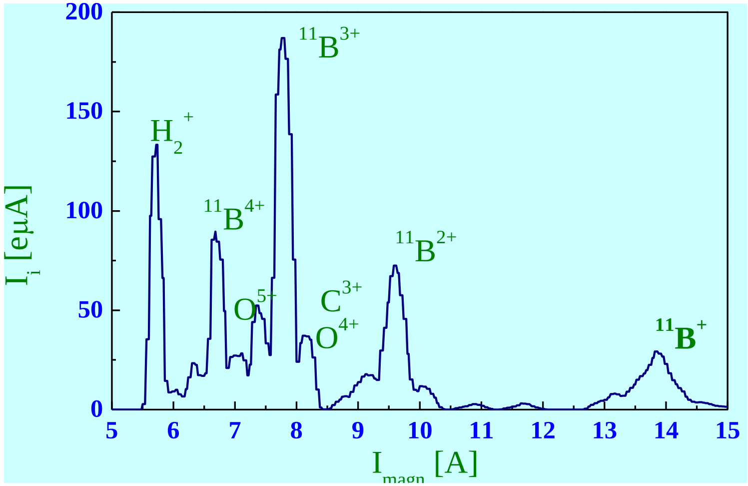


Fe$(C_5H_5)_2$

First MIVOC beams at FLNR

U-400M - 1998





The spectrum of boron ions

Working substance - $C_2 B_{10} H_{12}$

Material consumption 2,2÷2,8 mg/h.

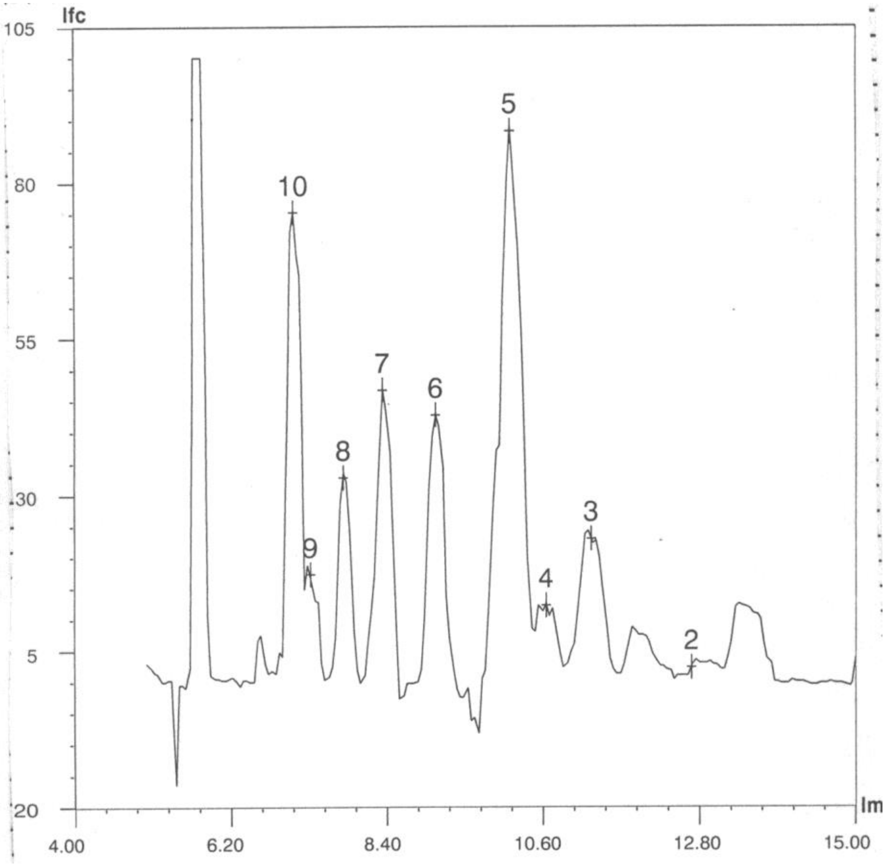
Target current > 5 pμA

U-400 - 2005

Acceleration of ^{58}**Fe** at the U-400 cyclotron

$^{58}Fe(C_5H_5)_2$

Injected ^{58}**Fe**$^{7+}$ beam 40÷50 eμA (6 ÷ 7 pμA)
^{58}**Fe**$^{23+}$ at the target 15 ÷ 17 eμA (~ 0.7 pμA).
The consumption of ^{58}**Fe** 1,5 mg/h.



PRODUCTION OF TITANIUM ION BEAM

GSI — a resistor oven (temperature 1750 °C ÷ 1800 °C)
$^{50}Ti^{8+} \geq 50$ eμA. The oven lifetime ÷ 6 days.

ANL — induction oven (temperature 1600 °C)
$^{50}Ti^{12+}$ — 5.5 eμA (7 days) 0.7 mg/h

JYFL — MIVOC method
commercially available $(CH_3)_5C_5Ti(CH_3)_3$ compound was used as a working substance.
$^{48}Ti^{11+}$ion — 45 eμA. 0.22 mg/h. The ion beam was stable during a 282 hour period.

$(CH_3)_5C_5Ti(CH_3)_3$ - sensitive to air, moisture, temperature and light

Synthesis of compound

$$TiO_2 + CCl_4 \longrightarrow TiCl_4 + (CH_3)_5C_5Si(CH_3)_3 \longrightarrow Cp^*TiCl_3 + 3CH_3Li \longrightarrow Cp^*Ti(CH_3)_3$$

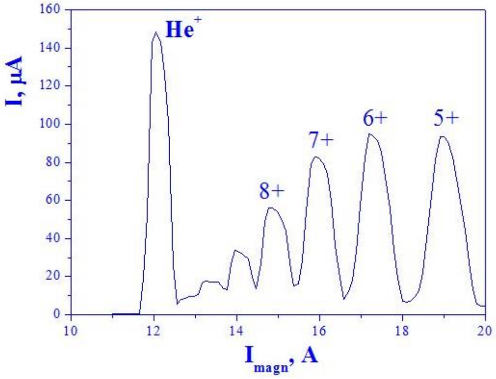
where Cp^* - $(CH_3)_5C_5$

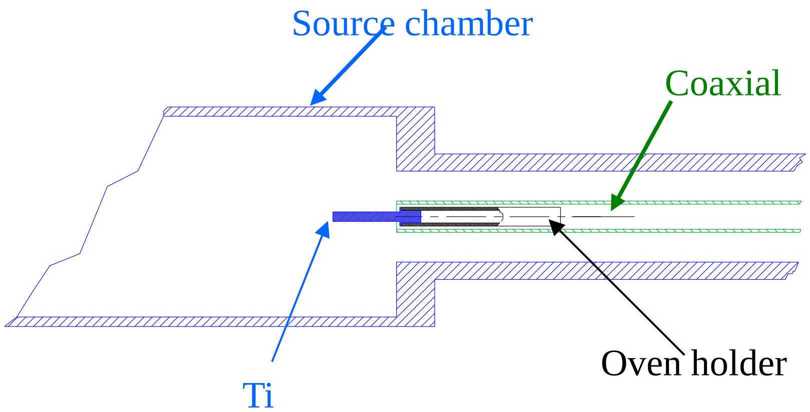
- All reactions should be performed under inert atmosphere or air-free conditions due to the reactivity of the transition metal species and other reagents.
- Extra care must be taken when handling CH_3Li due to the large quantities required and extreme reactivity of this compound.

PRODUCTION OF TITANIUM ION BEAM

INSERTION METHOD

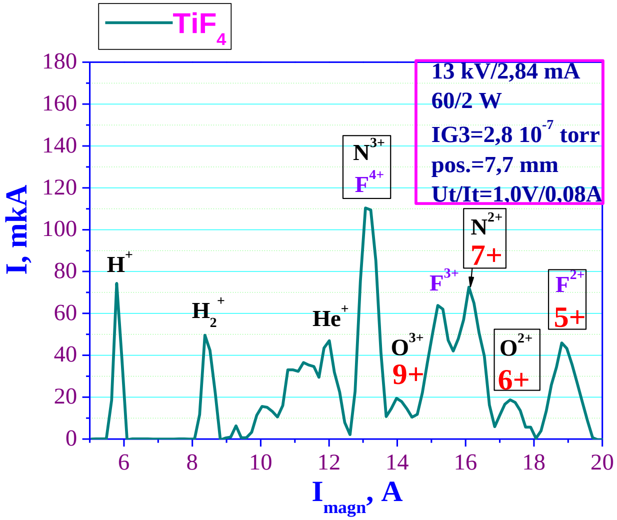
Ti rod 3 mm in diameter was inserted axially into the DECRIS-2 source chamber

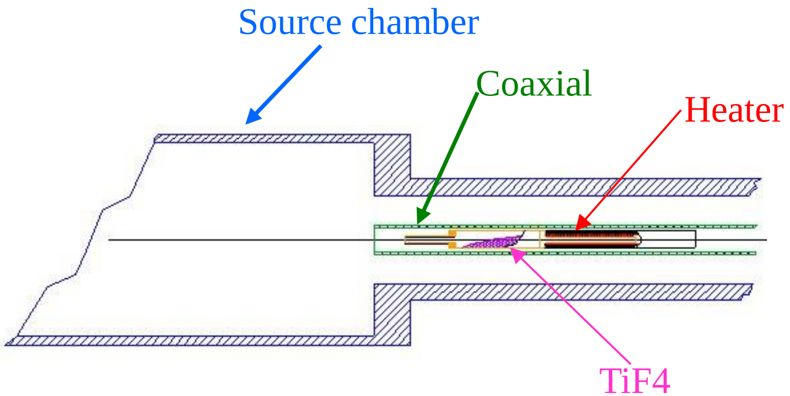




no long term stability

OVEN METHOD





TiF_4 was used as a working substance

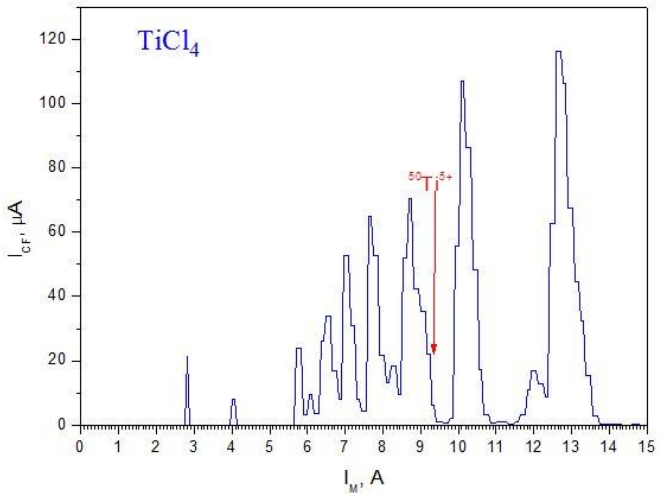
about 10÷20 eμA of $^{48}Ti^{6+}$ was produced

Unstable mode of operation

PRODUCTION OF TITANIUM ION BEAM

MIVOC

^{50}Ti ion beam was accelerated at the U-400 cyclotron in 2005



$TiCl_4$ (5.2% of ^{50}Ti)

The intensity of the ^{50}Ti ion beam extracted from the cyclotron was about 200 enA.

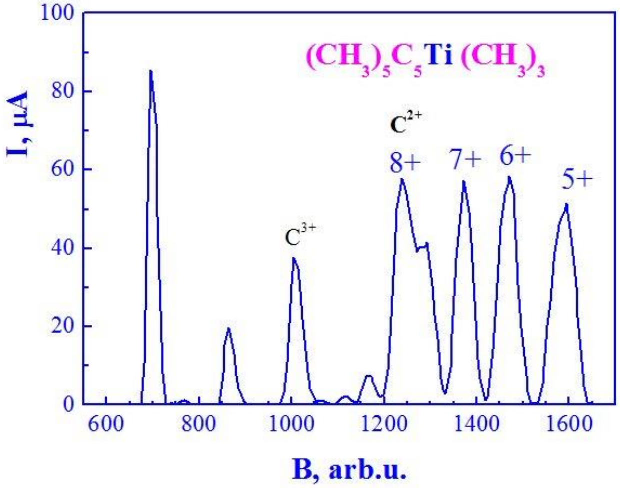
Titanium isopropoxide ($Ti\{OCH(CH_3)_2\}_4$)

Cyclopentadienyl cycloheptatrienyl titanium ($C_5H_5TiC_7H_7$)

Pure beam intensity - few microamperes of Ti^{5+}

Commercial compound $(CH_3)_5C_5Ti(CH_3)_3$
Sigma-Aldrich (Germany)
DALCHEM (Russia)

ECR sources:
DECRIS-2, DECRIS-4, ECR4M



Ti ion spectrum produced from DECRIS-4.
The source settings are optimized for $^{48}Ti^{5+}$

Development of ^{50}Ti beam using MIVOC method

Collaboration between IPHC (Strasbourg, France) and FLNR JINR.

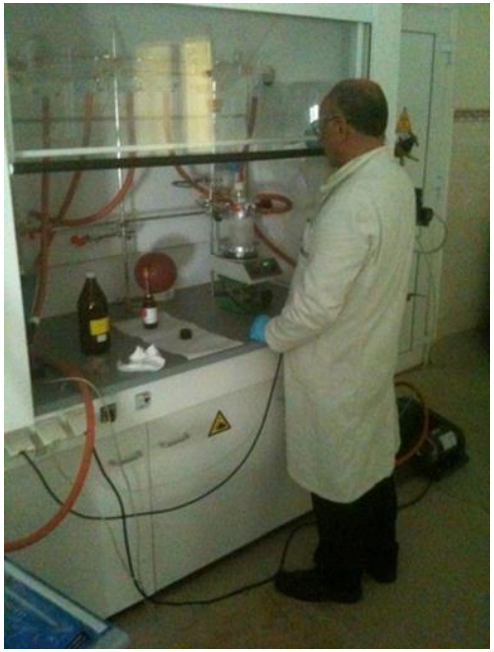
Synthesis of compound (two steps)

$TiCl_4 + (CH_3)_5C_5Si(CH_3)_3 \rightarrow Cp^*TiCl_3 + 3CH_3Li \rightarrow Cp^*Ti(CH_3)_3$

where Cp^* - $(CH_3)_5C_5$

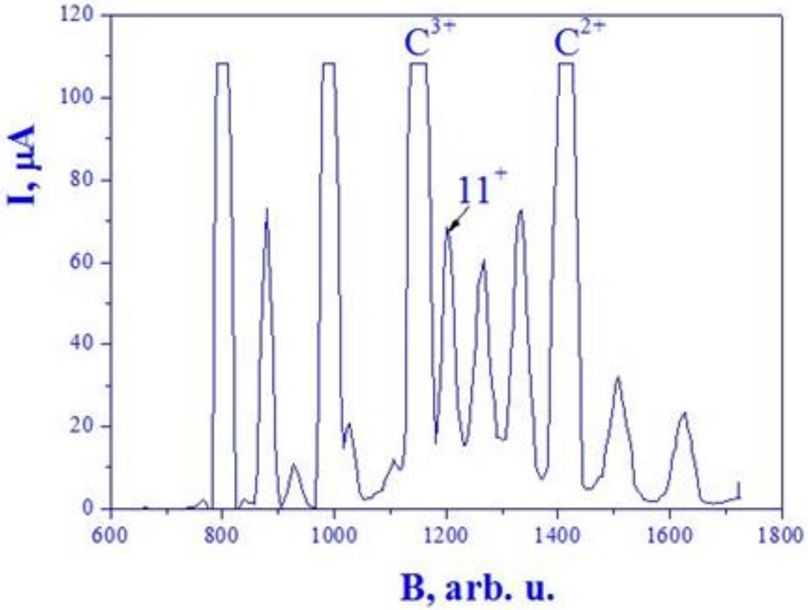
Starting material: $^{50}TiCl_4$ enrichment > 90% - available from Trace Sciences International Inc.

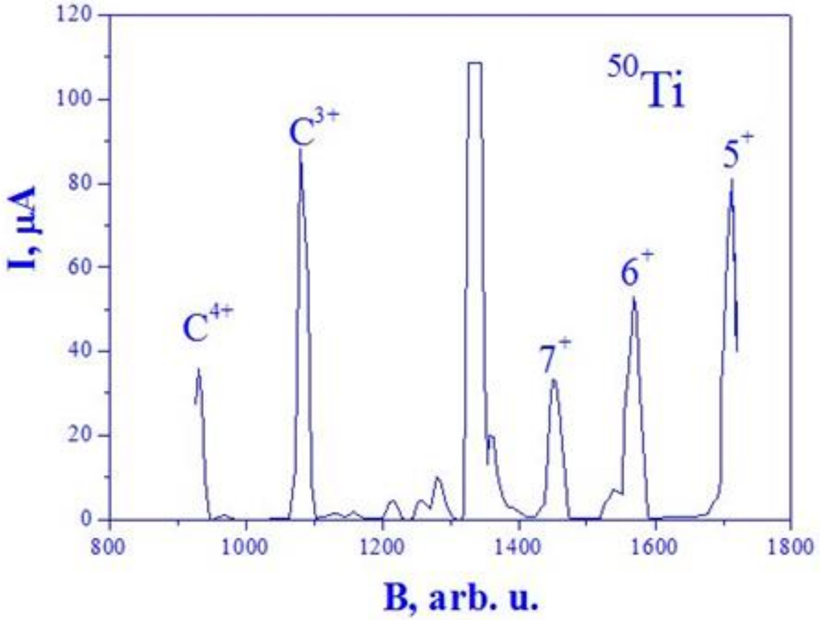
The first step of synthesis was performed at IPHC, the final step at FLNR.
The efficiency of synthesis is more than 90%.



Chemistry laboratory

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





Following these extremely promising results, a 92.57 % enriched compound was synthesized and tested at the ECR4M test bench. Under similar conditions, up to 80 eμA of the $^{50}Ti^{5+}$ beam was extracted.

Acceleration at the U-400 cyclotron

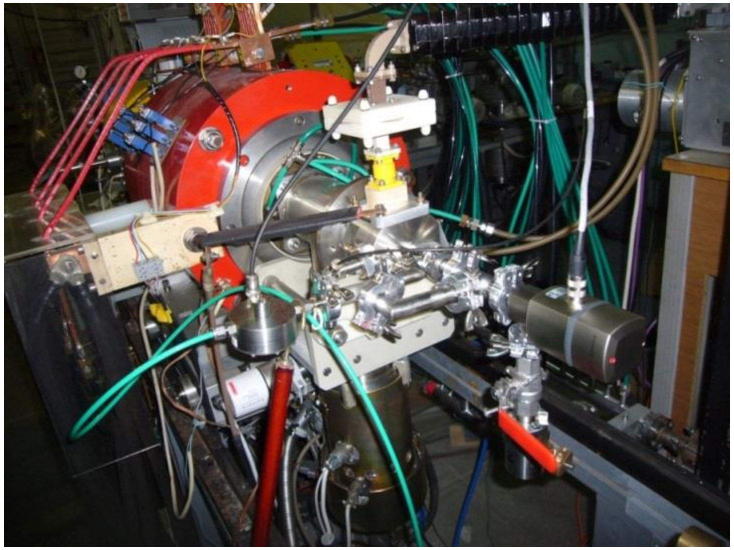
After successful tests at the test bench the accelerated beam of $^{50}Ti^{5+}$ was produced at the U-400 cyclotron for the experiment on spectroscopy of super heavy elements.

The intensity of the injected beam of $^{50}Ti^{5+} \geq 50$ eμA

The intensity at the target ~ 10 eμA (~ 0.5 pμA)

The compound consumption rate of 2.4 mg/h (^{50}Ti consumption of 0.52 mg/h)

During the experiment (two three week runs) the source have shown stable operation.

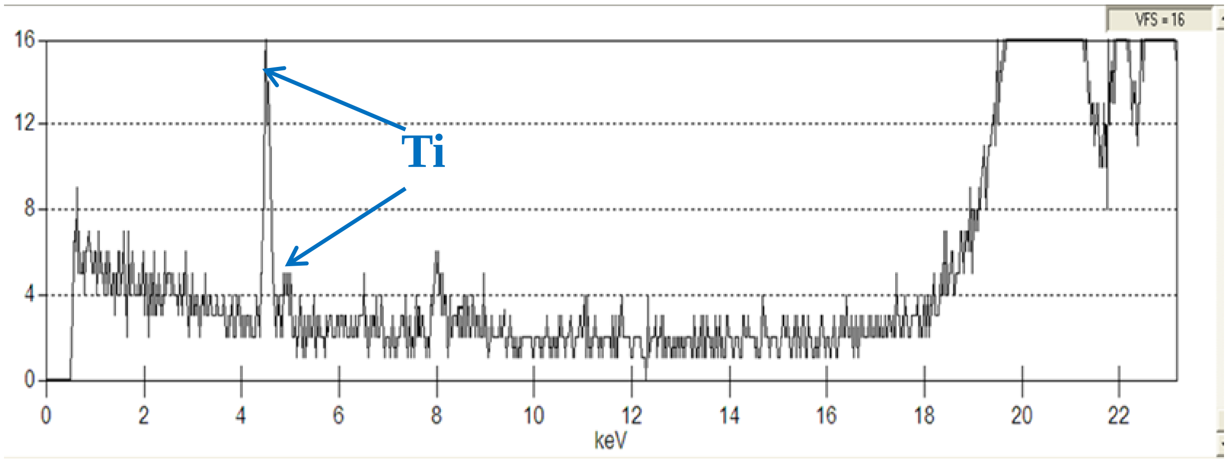


ECR4M source

MIVOC chamber with EVR116 regulating valve

Recovery of used material

$$cp^*Ti\,(CH_3)_3 + nHCl + (4\text{-}n)H_2O \rightarrow cp^*H + 3CH_4 + Ti(OH)_{(4\text{-}n)}Cl_n$$



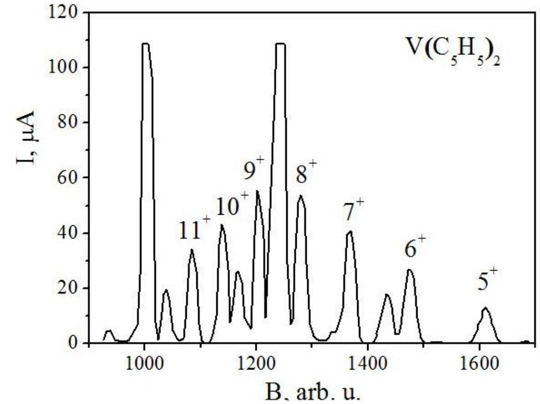
X-ray fluorescence spectrum of dried sediment

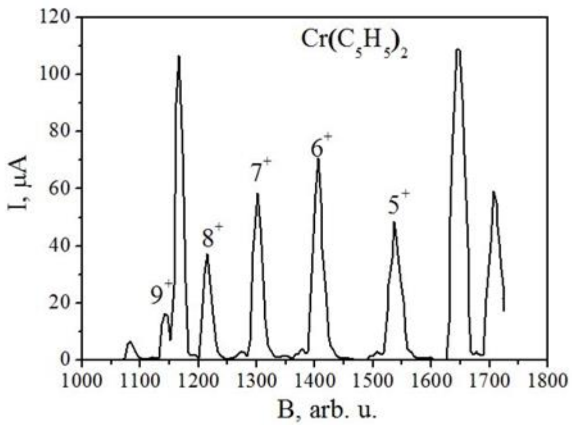
Operation time ÷ 370 hours
^{50}Ti consumption ~ 190 mg
Collected ~ 22 mg (~ 11%)

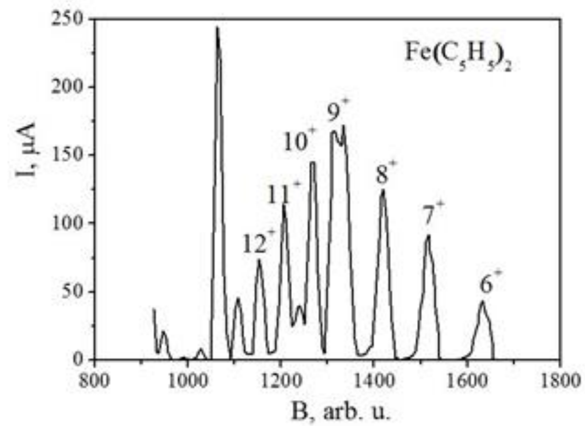
Intensity (eμA) of Titanium Ion Beams Produced at Different Laboratories by MIVOC (a) and Oven (b) Methods

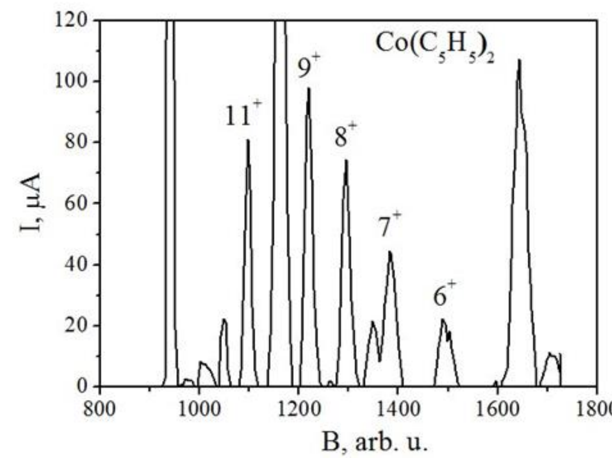
	JYFL[a]	GANIL[a]	FLNR[a]	GSI[b]	ANL[b]	IMP[b]
$^{48}Ti^{5+}$			79			
$^{48}Ti^{10+}$		20				
$^{48}Ti^{11+}$	45		70			24
$^{50}Ti^{5+}$			82			
$^{50}Ti^{8+}$				50		
$^{50}Ti^{11+}$	20					
$^{50}Ti^{12+}$					5.5	

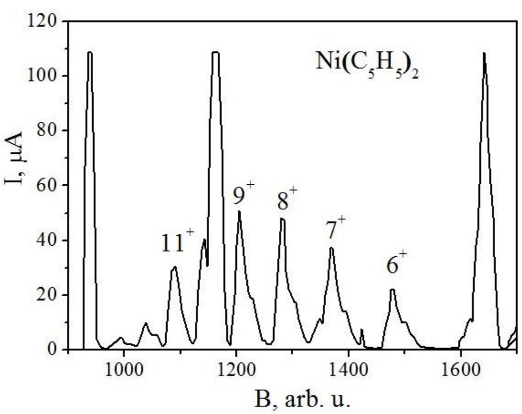
Set of experiments on production of metal ion beams by MIVOC method was performed at the ECR test bench

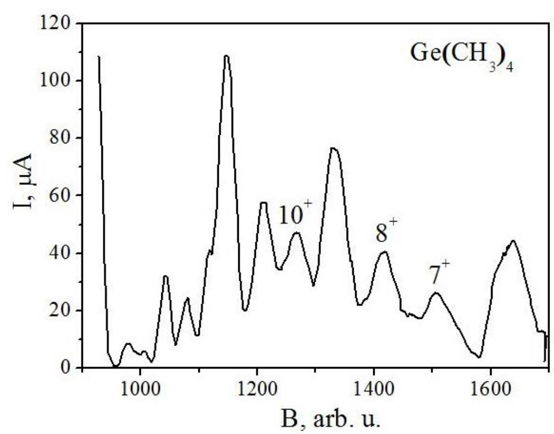


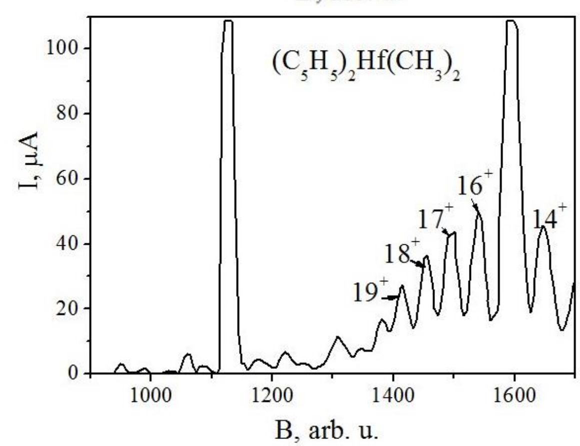












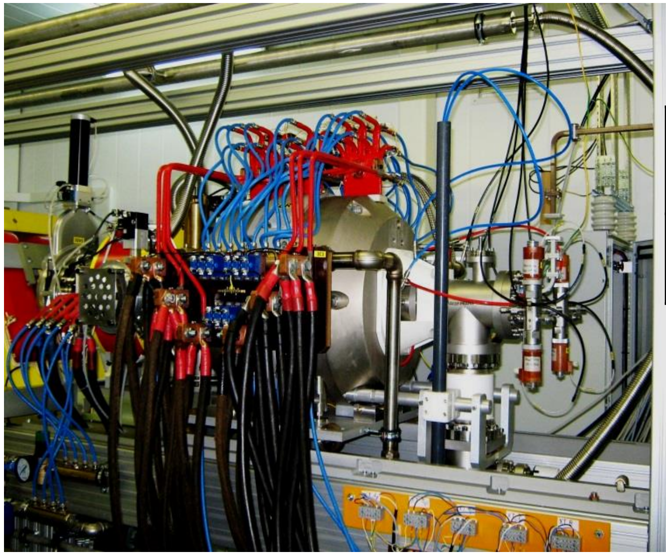
The intensity (eμA) of metal ion beams produced at the ECR test bench using the MIVOC method

Q	5+	6+	7+	8+	9+	10+	11+	12+	13+
V	75*	54	41	54	55.5*	43	34	19.5	
Cr	50	70*	60	37	17	7			
Fe		43	93	125	172	145*	114	73	45
Co		57	80	86	98		82*	25	
Ni		45*	43	48	53*		30	10	
Ge			43*	54		47*			
Q	**13+**	**14+**	**16+**	**17+**	**18+**	**19+**	**20+**		
Hf	31	45	50*	45*	36	27	17		

(* - intensity optimisation)

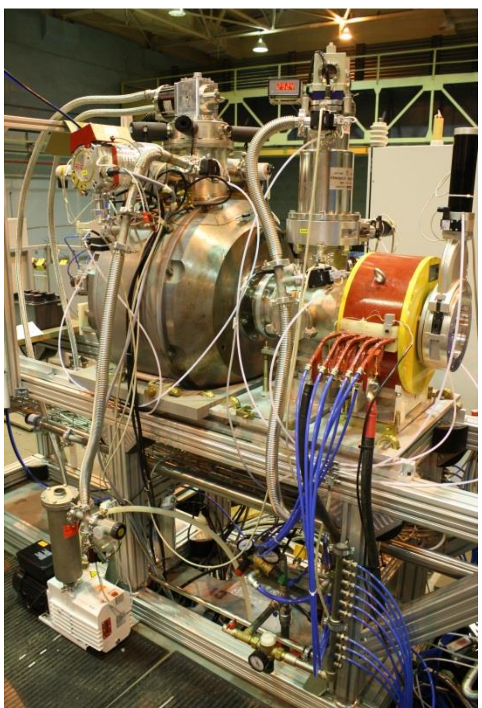
CONCLUSION

The MIVOC method was successfully used for producing and accelerating titanium-50 ion beam at the U-400 cyclotron. This method helps produce intense ion beams, provides long-term stability and is promising for experiments on synthesis of superheavy elements.



DECRIS-5
Room temperature source, 18 GHz

Ion	Ar^{8+}	Ar^{9+}	Ar^{11+}	Kr^{15+}	Kr^{17+}	Kr^{18+}	Kr^{19+}	Kr^{20+}	Xe^{20+}
I, (eμA)	1200	750	300	325	230	182	120	70	220



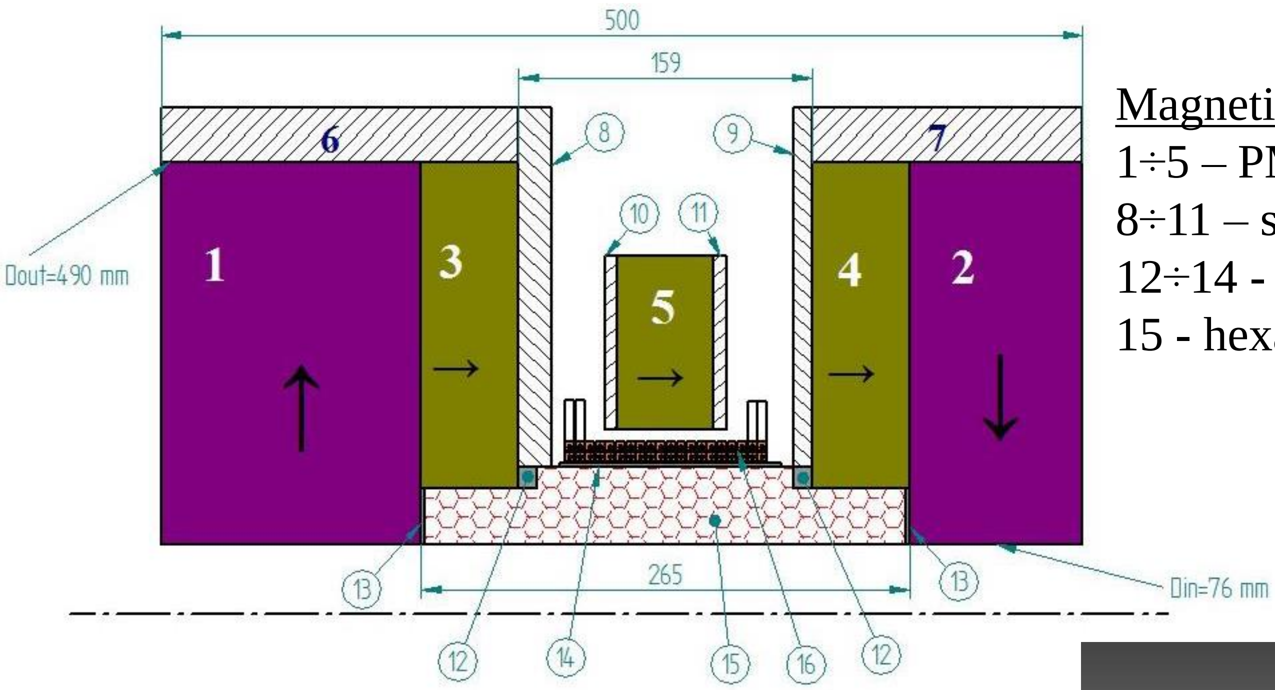
DECRIS-SC2
Hybrid type source, 14 GHz

Ion	O^{5+}	O^{6+}	S^{9+}	S^{11+}	Ar^{8+}	Ar^{9+}	Ar^{11+}	Ar^{12+}	Kr^{15+}	Kr^{17+}	Xe^{30+}
I, (eμA	920	820	265	90	880	680	250	120	250	150	~ 1

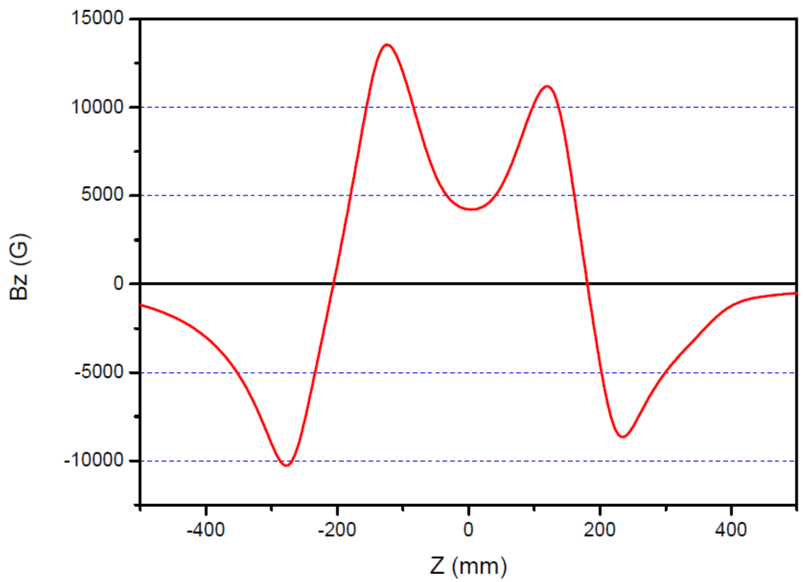
DC-280 Cyclotron

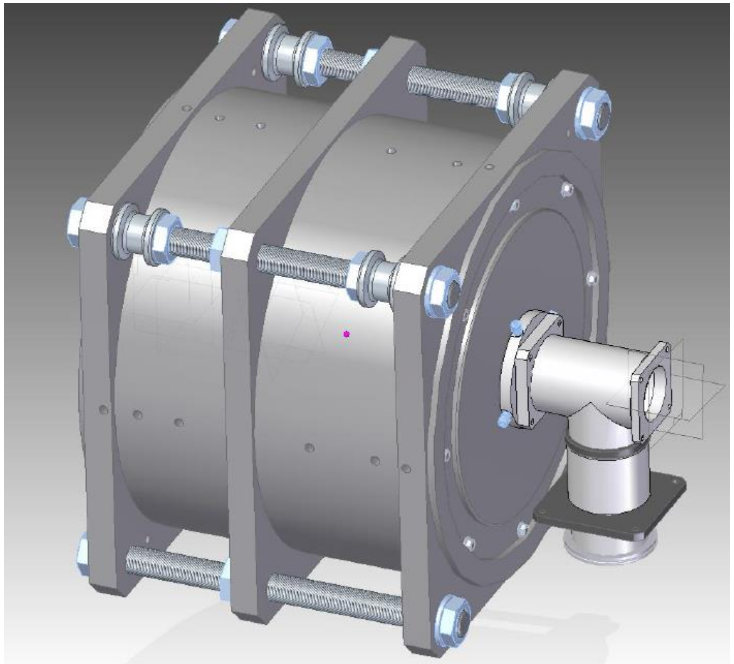
Parameters of DECRIS-PM.

Frequency	14 GHz
B_{inj}	$\geq$ 1.3 T
B_{min}	0.4 T
B_{extr}	1.0 ÷1.1 T
B_r	1.05÷1.15 T
Plasma chamber internal diameter	70 mm

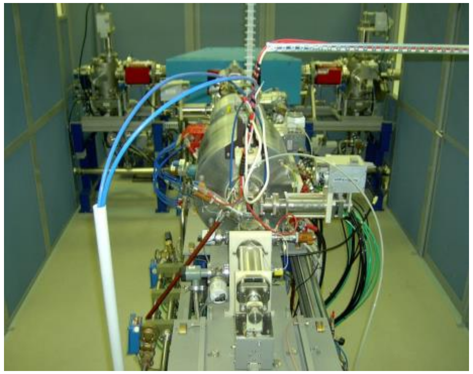


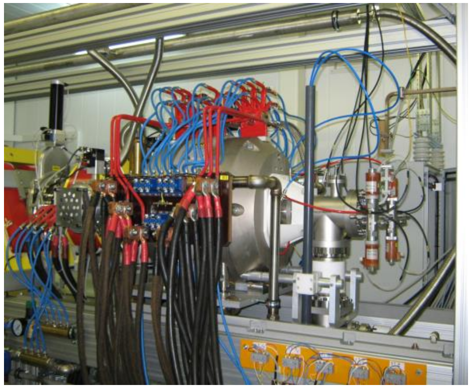
<u>Magnetic structure of DERIS-PM</u>.
1÷5 – PM rings; 6, 7 – soft iron rings;
8÷11 – soft iron plates,
12÷14 - auxiliary elements,
15 - hexapole, 16 – coil.

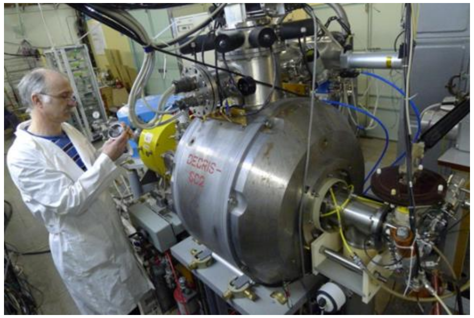


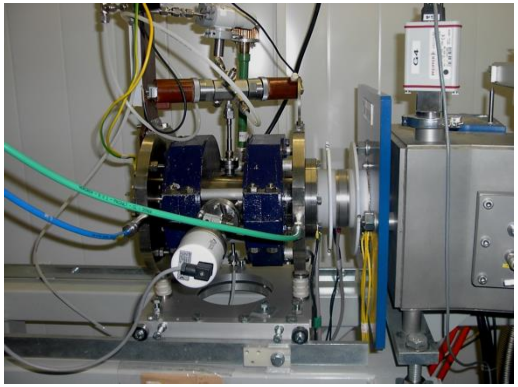


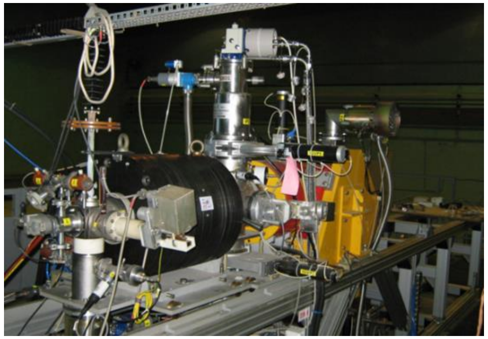
DECRIS ion sources











THANK YOU!!