Current Status of the 18 GHz ECR Ion Source DECRIS-5M at JINR FLNR

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The purpose of the work

Production and use of high-intensity, highly charged ion beams. Heavy-ion beams of high energy for basic, applied, and cross-disciplinary scientific research at the DC-140 Cyclotron complex.

Scientific motivations:

Material Sciences

Implantation, crystalline structure modification, track membranes, testing of electronic components….

Beam energy:

$$\frac{E_k}{A} = K\left(\frac{Q}{A}\right)^2$$

K – cyclotron K-value

A – atomic mass

Q – charge state of accelerated ion

→ **Multicharged ions**

↓

Electron Cyclotron Resonance (ECR) ion source

E ~ q for linear accelerators

E ~ q^2 for ring accelerators

The purpose of the work

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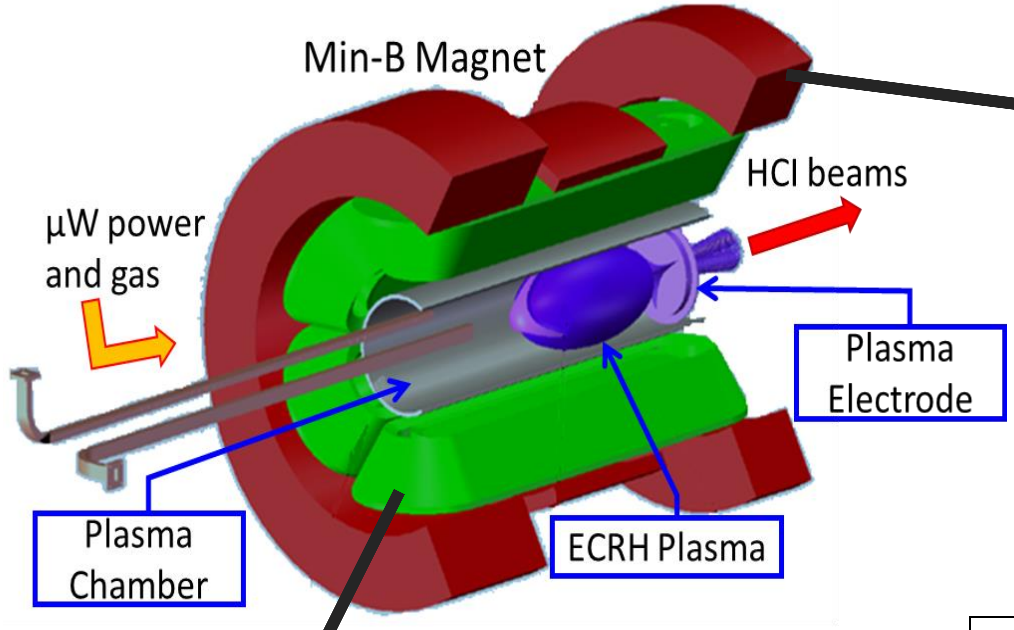
Technical requirements:

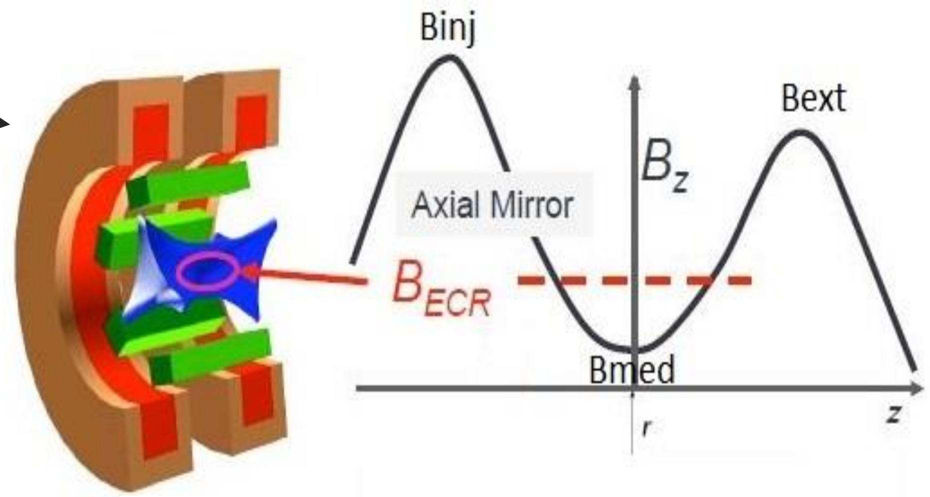
Ion	Ne^{4+}	Ar^{8+}	Kr^{16+}	Xe^{26+}	Bi^{37+}
I nA	~2.5	~5	~10	~15	~20

Studying of methods for obtaining ***Ti*** ion beams.

Bases of ECR Ion Sources



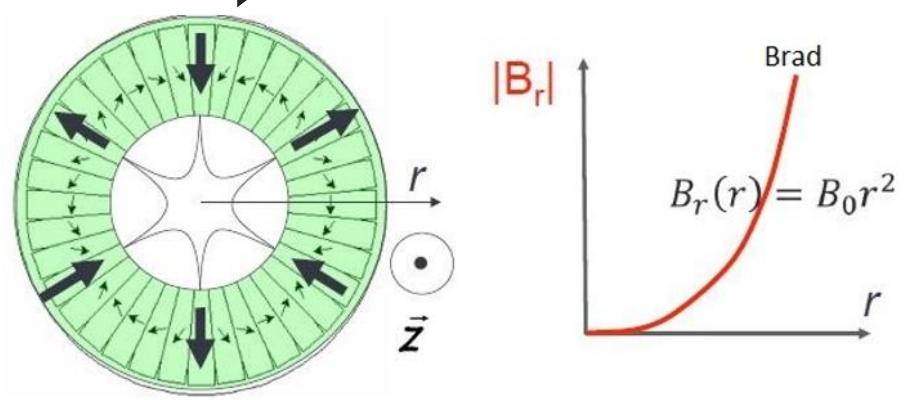
ECR Ion Source



Magnets for axial field

$$f_{HF} = 2 \cdot \pi \cdot f_{ce} = \frac{eB_{ECR}}{m}$$

f[GHz]	B[kG]	n_{ec} [cm^{-3}]
2.45	0.0875	7.44×10^{10}
6.4	0.23	5.08×10^{11}
10	0.36	1.24×10^{12}
14	0.5	2.43×10^{12}
16	0.57	3.2×10^{12}
18	0.64	4×10^{12}
28	1	10^{13}



Permanent magnet hexapole

$$B_{rad} = 2 \div 2.2 B_{ECR}$$

$$B_{injection} = 3 \div 4 B_{ECR}$$

$$B_{extr} \geq B_{radial}$$

$$B_{min} = 0.3 \div 0.45 B_{radial}$$

DECRIS-5M design parameters

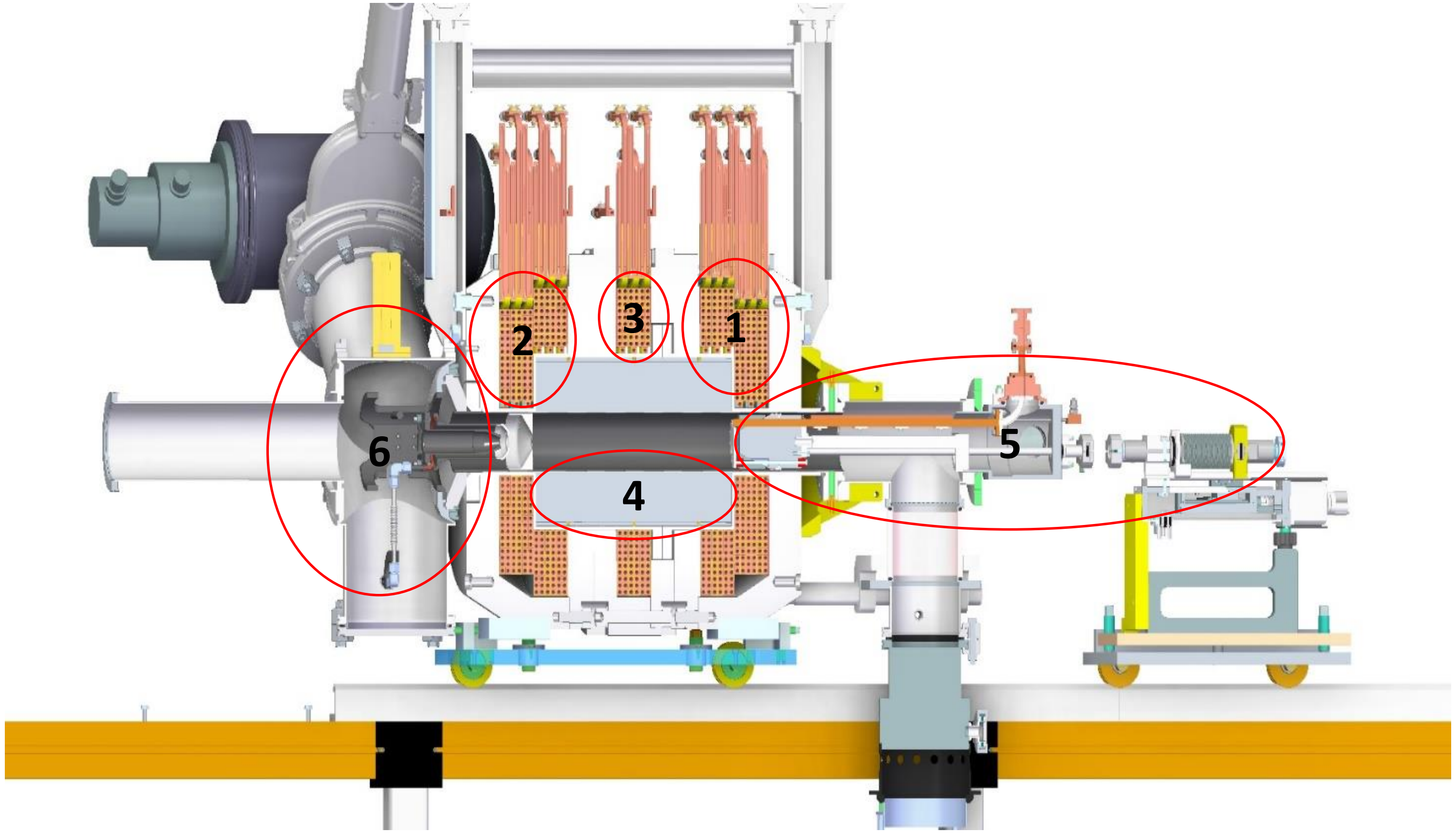
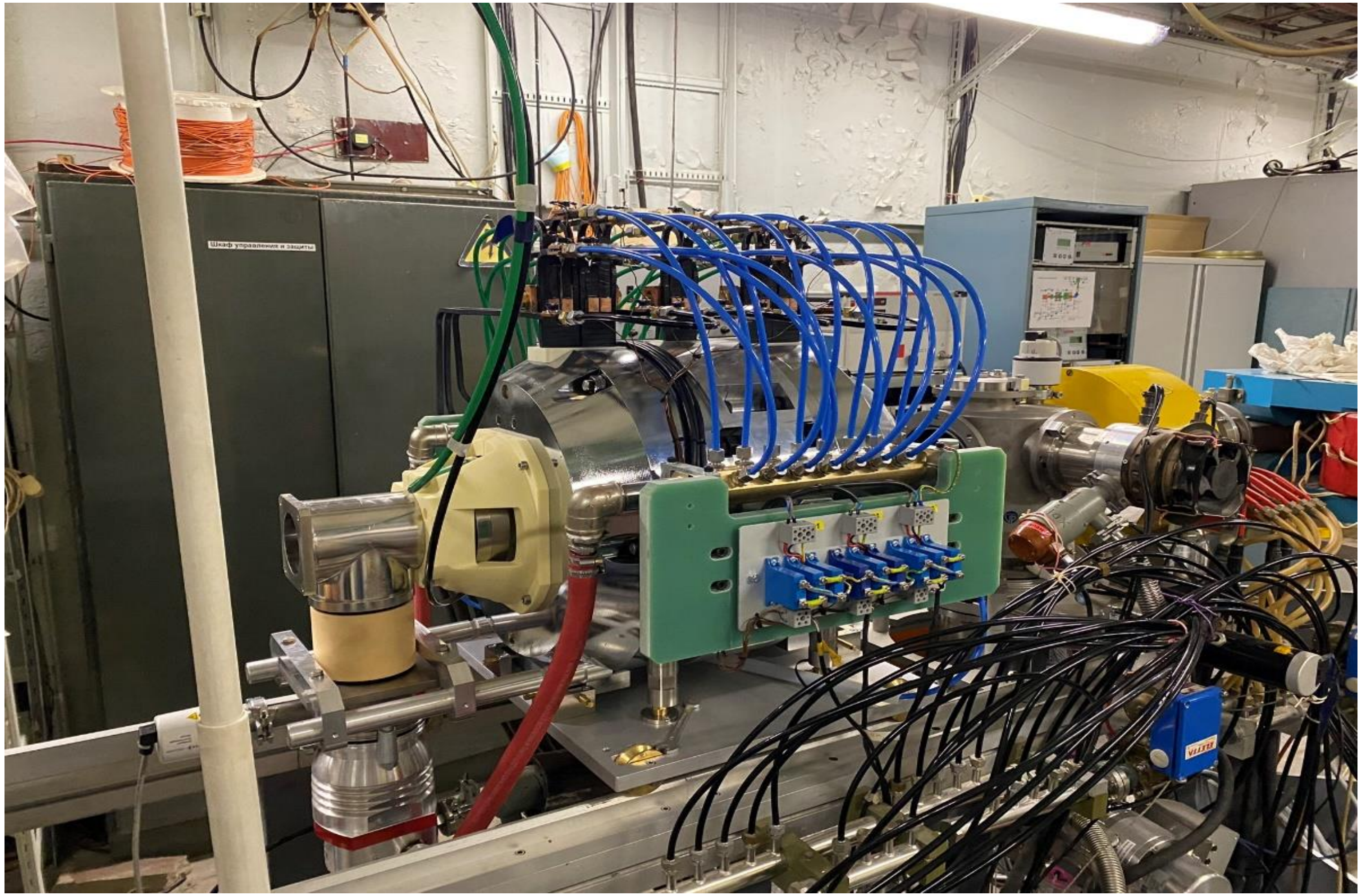


Table 1: Design parameters of DECRIS-5M

UHF	18 GHz
Mirror field on axis: Extraction side Injection side	 1.4 T 2.5 T
Radial field at the wall	1.3 T
Plasma chamber internal diameter	74 mm
Number of coils	5
Max. coil current 1,2,4,5	1250 A
Max. coil current 4	800 A
Max. power assume	160 kW

Cross section of the DECRIS-5M ECR Ion source:
1 – injection coils, 2 – extraction coils, 3 – central coil, 4 – hexapole magnet, 5 – injection system (waveguide, substance input system, magnetic plug, bias electrode), 6 – extraction system.

DECRIS-5M design parameters



DECRIS-5M ECR Ion source

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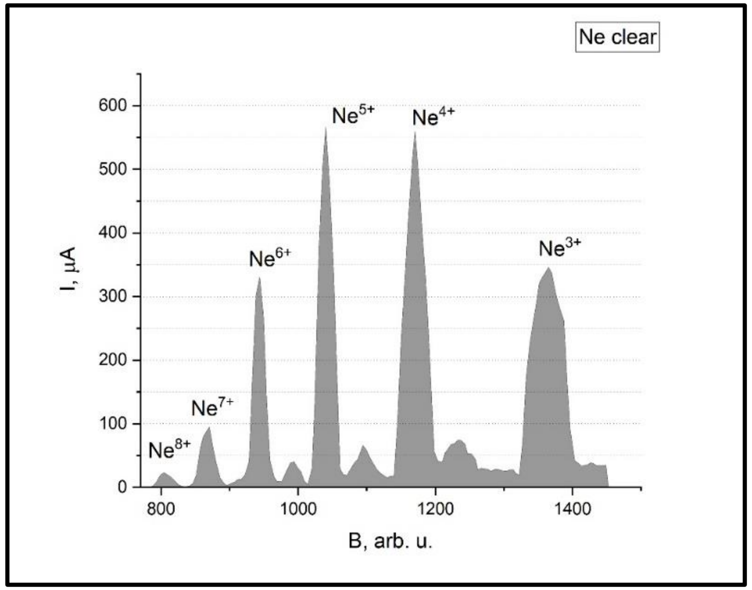
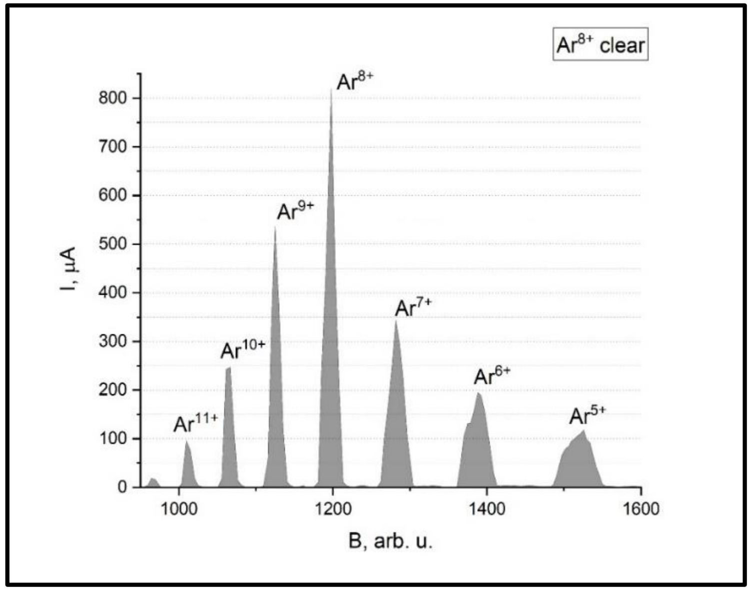
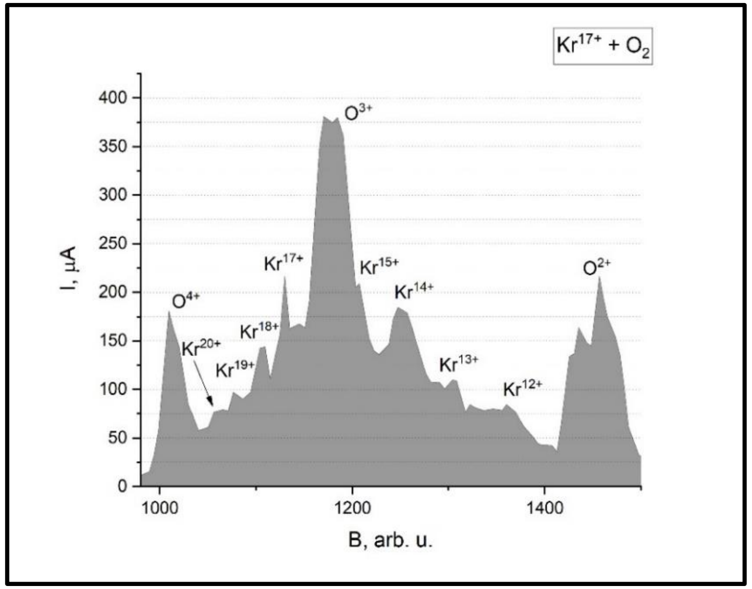
DECRIS-5M: Experimental results



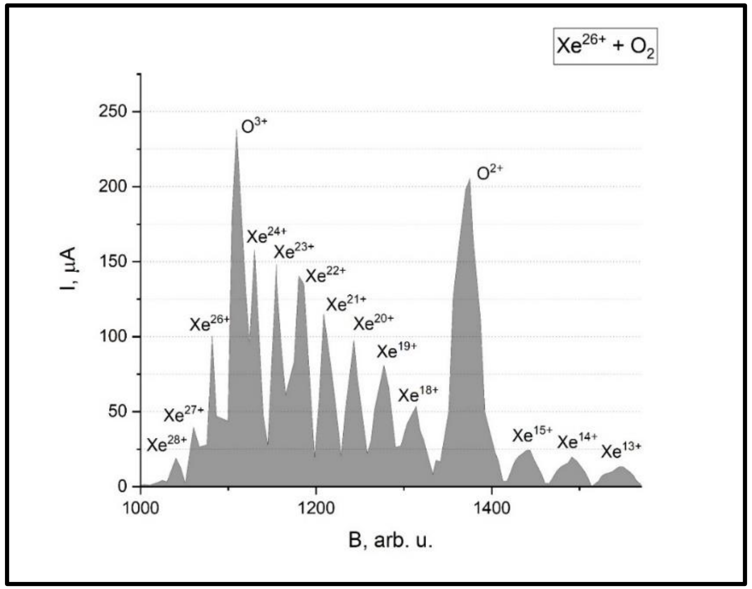
Neon ion spectra



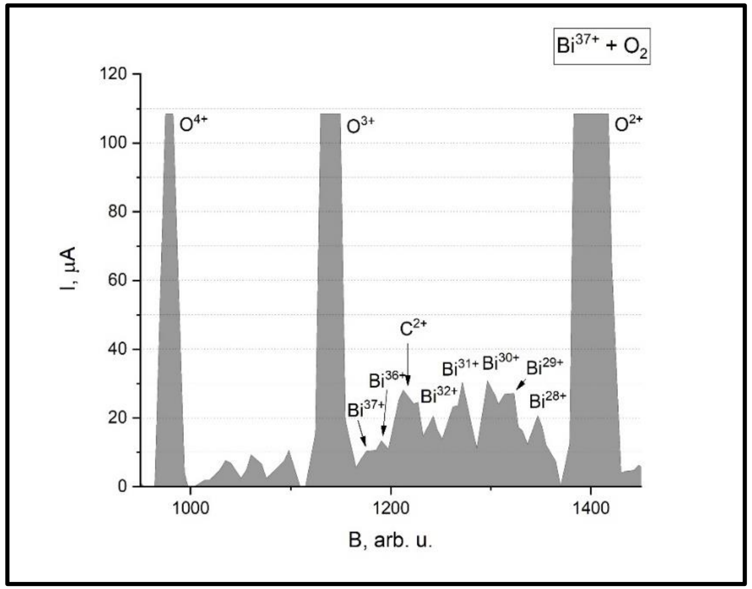
Argon ion spectra



Krypton ion spectra



Xenon ion spectra



Bismuth ion spectra

Table 2: Technical requirement results

Ion	***I, μA***	***U_{inj}, kV***	***P_{UHF}, W***
Ne^{4+}	560	20.4	317
Ar^{8+}	818	21.4	418
Kr^{17+}	216	19.5	938
Xe^{26+}	100	17.4	913
Bi^{37+}	10	18.2	553

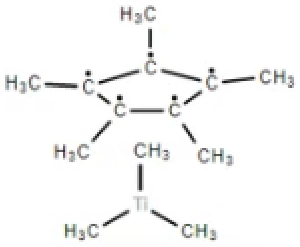
Metal ions production

Method	*Bases*	*Advantages*	*Disadvantages*
Evaporation by heating	The substance evaporates from the crucible using an external heater	Materials with low and high evaporation temperature are available Simple operation Stability	Slow response to control evaporation High temperature heaters require the use of additional shielding to protect themselves temperature gradient
MIVOC (Metal Ions from VOlatile Compounds)	Organic compound evaporates at room temperature	High intensity No support gas	Big amounts of carbon, hydrogen and other impurities High sensitivity of samples to external factors
Direct injection Into plasma	The sample is heated by direct contact with the plasma	High melting point materials are available The technique is simple and can be easily used for any ECR source	Hard to control heating Difficult to implement for materials with low melting point
Ion sputtering	The sample is under negative potential, sputtered by plasma ions	High melting point materials are available Relative stability	Low intensity Support gas must be used during operation

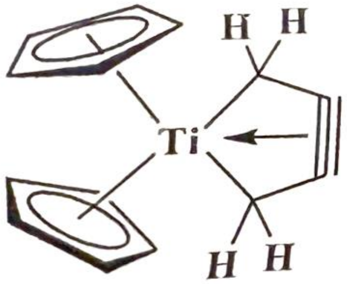
DECRIS-5M: Titanium Ion beams (MIVOC)

Trimethyl(pentamethylcyclopentadiene)titanium

$(CH_3)_5C_5Ti(CH_3)_3$

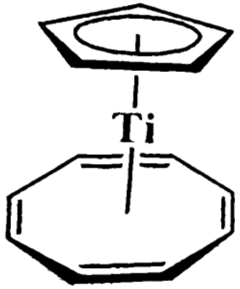


$C_{14}H_{14}Ti$



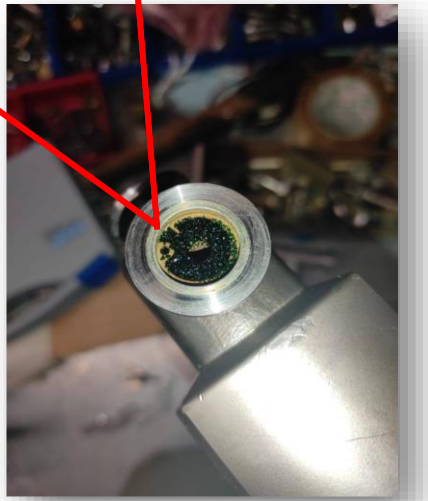
Titanacyclopentine complex of titanocene

$C_{13}H_{13}Ti$



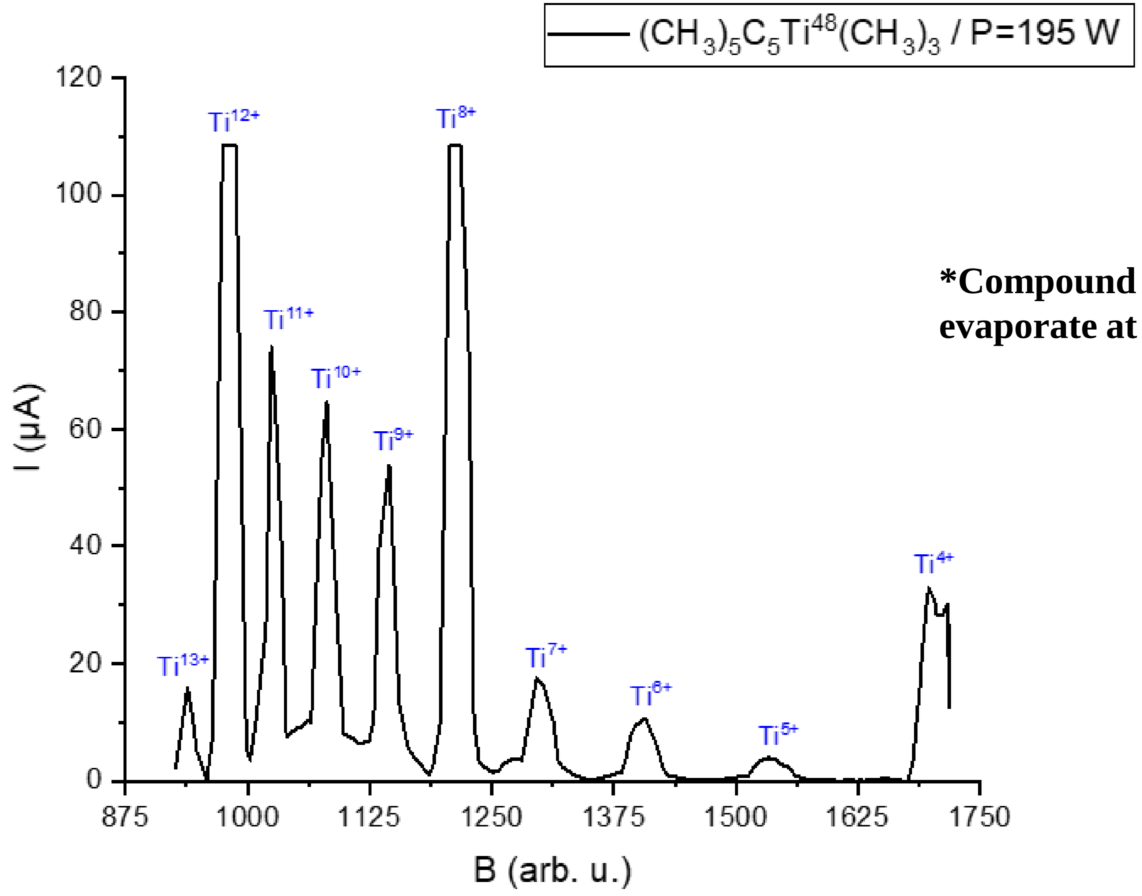
Cyclooctatetraene Cyclopentadiene titanium

Compound / *Properties*	$(CH_3)_5C_5Ti(CH_3)$	$C_{14}H_{14}Ti$	$C_{13}H_{13}Ti$
Molar mass, $g \cdot mole^{-1}$	228.3	230.13	217.11
Form	yellow crystals	green crystals	green crystals
Density, $\frac{g}{cm^3}$	1.1	-	-
Sublimation temperature, C	>0	~100	~100-130
Sensitivity	Air, light, humidity, high temperature	Air, light, humidity	Air, light, humidity



DECRIS-5M: Experimental results of "room temperature" MIVOC $(CH_3)_5C_5Ti(CH_3)^*$

Container for compound

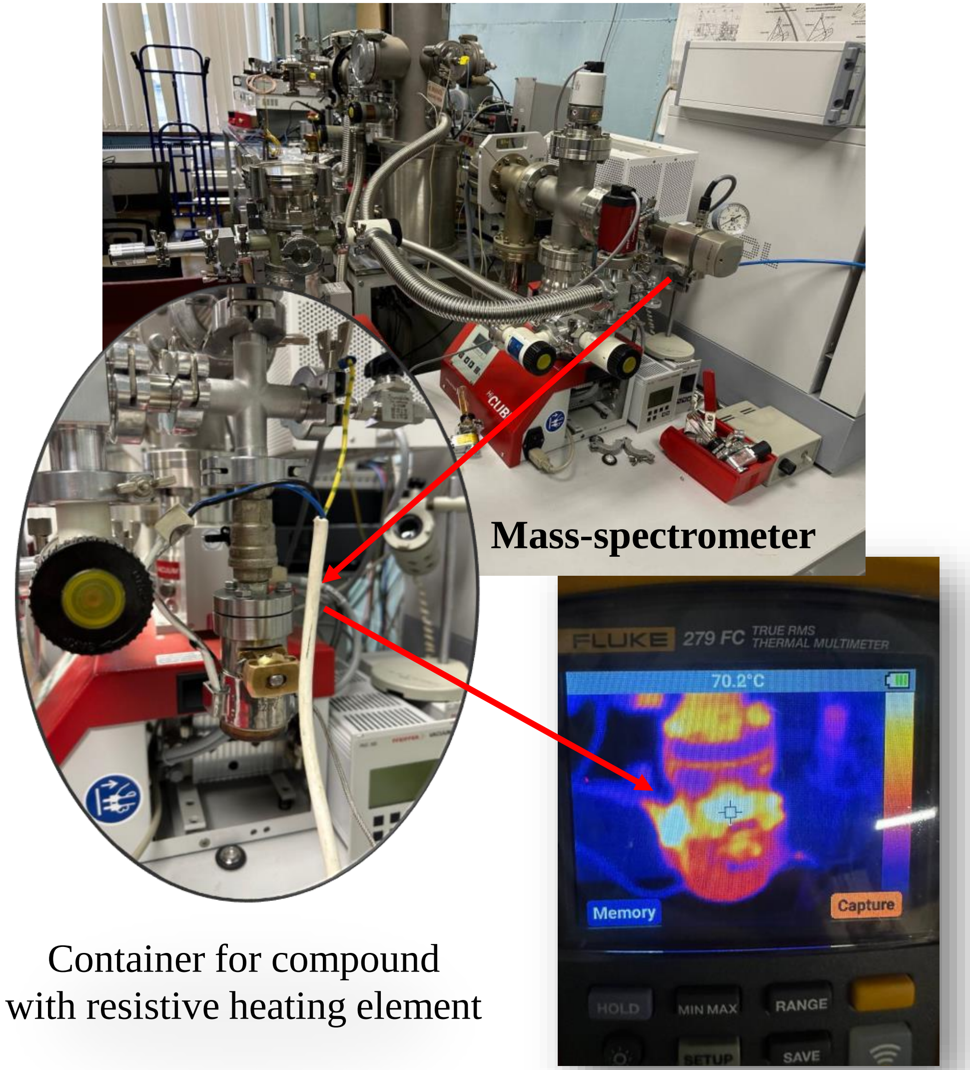


Titanium ion spectra

***Compound $(CH_3)_5C_5Ti(CH_3)$ starts to evaporate at room temperature**

Ion	***I, μA***	U_{inj}***, kV***	P_{UHF}***, W***
Ti^{10+}	64	18.3	195

DECRIS-5M: Experimental results of "high temperature" MIVOC $C_{14}H_{14}Ti^{*}$ and $C_{13}H_{13}Ti^{**}$ on mass-spectrometer

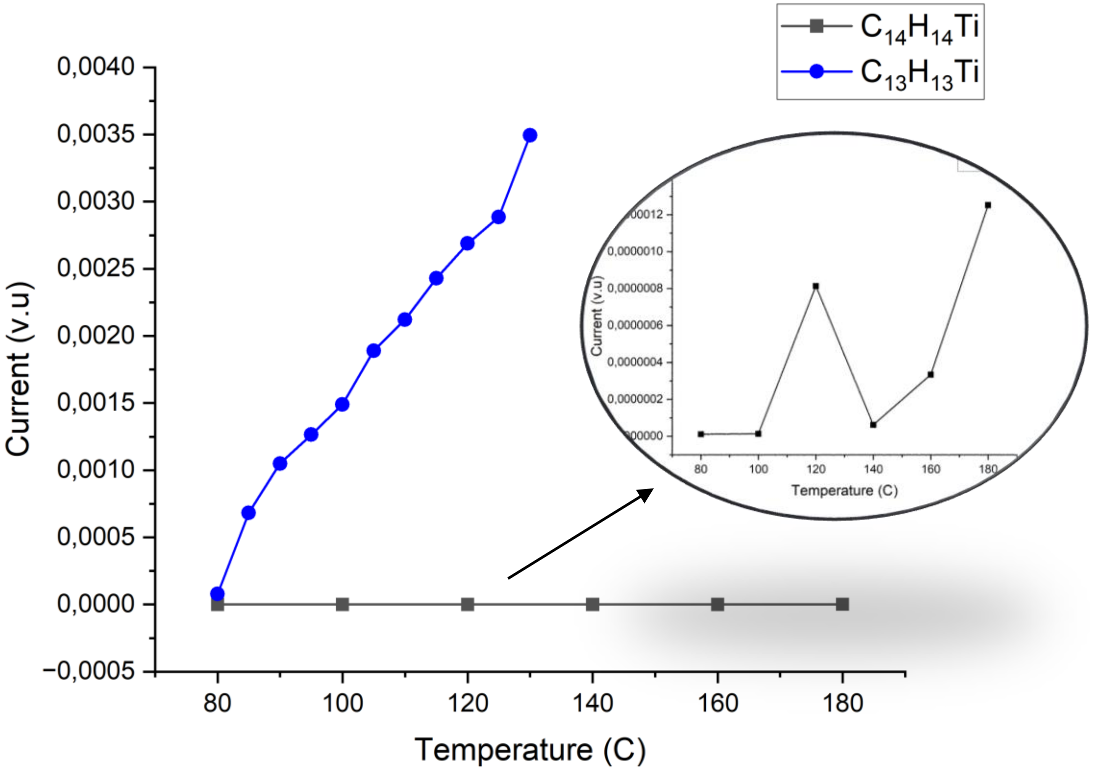


Container for compound
with resistive heating element

Compound heating

***Compound $C_{14}H_{14}Ti$ starts to evaporate at ~100 C**

****Compound $C_{13}H_{13}Ti$ starts to evaporate at ~100-130 C**



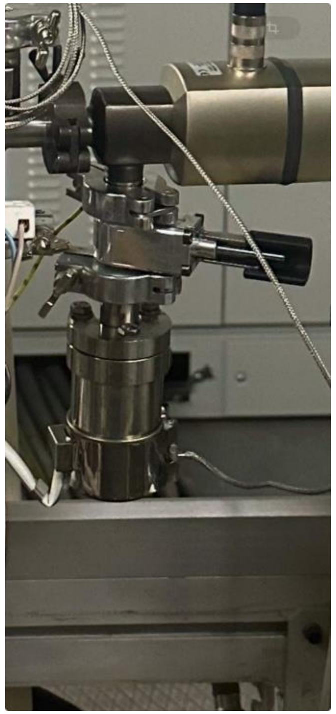
Presence of titanium in the spectrum vs temperature of compound $C_{14}H_{14}T$ and $C_{13}H_{13}Ti$ (mass-spectrometer)

DECRIS-5M: Experimental results of "high temperature" MIVOC $C_{14}H_{14}Ti^{*}$ and $C_{13}H_{13}Ti^{**}$ with particular heating

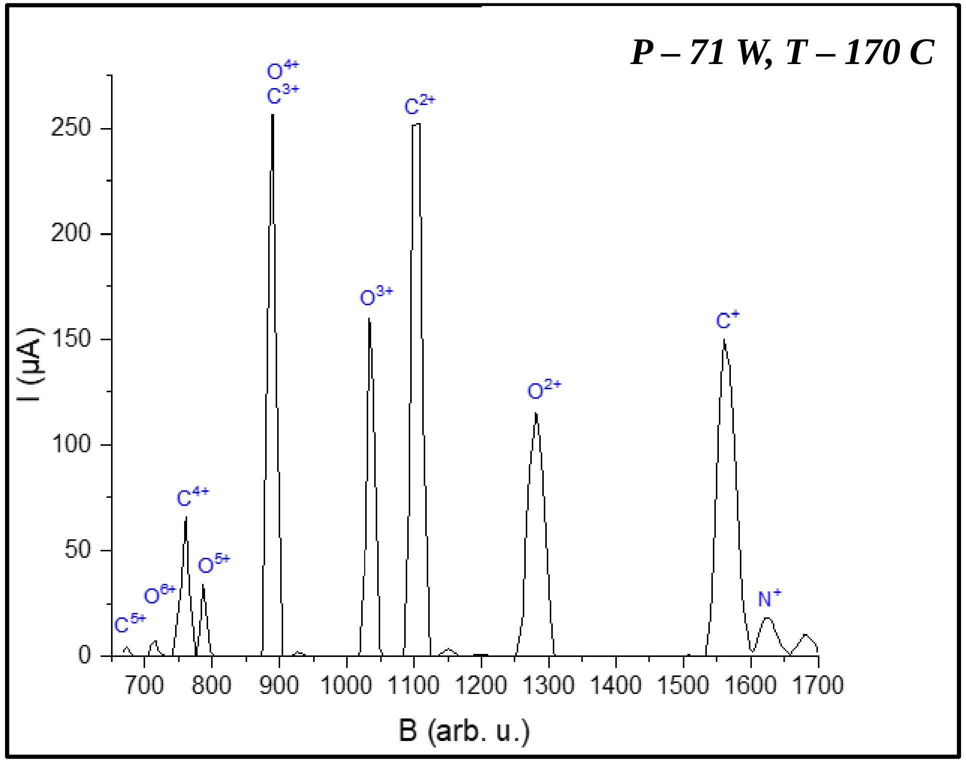
***Compound $C_{14}H_{14}Ti$ starts to evaporate at ~100 C**

****Compound $C_{13}H_{13}Ti$ starts to evaporate at ~100-130 C**

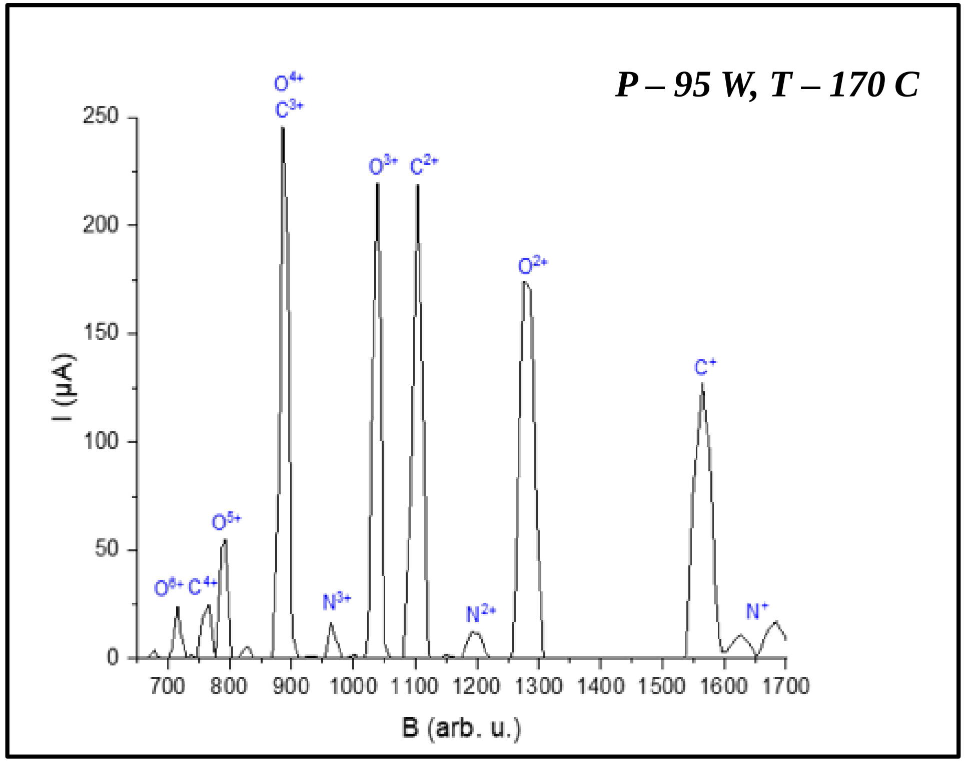
During the experiment, heating was carried out only in the area of the container with the compound, the gas injection line was not heated. The substance supply was regulated using an EVR valve.



Compound heating system



Titanium ion spectra for $C_{14}H_{14}Ti$

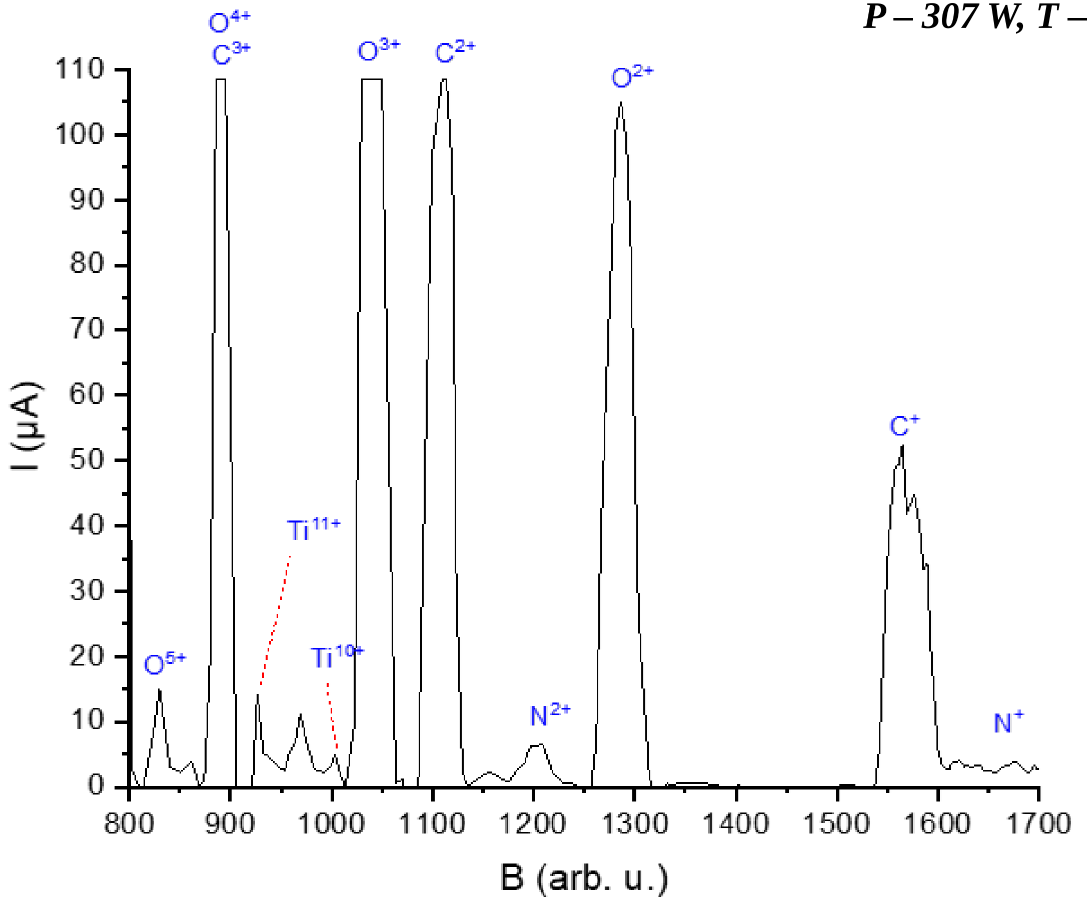


Titanium ion spectra for $C_{13}H_{13}Ti$

DECRIS-5M: Experimental results of "high temperature" MIVOC and $C_{13}H_{13}Ti^{*}$

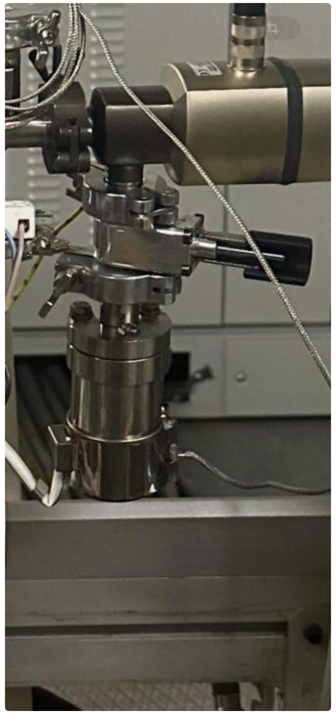
During the experiment, heating was carried out in the area of the container with the compound and partially in the gas injection line. The substance supply was regulated using an EVR valve without a filter.

P – 307 W, T – 170 C



Titanium ion spectra for $C_{13}H_{13}Ti$

***Compound $C_{13}H_{13}Ti$ starts to evaporate at ~100-130 C**

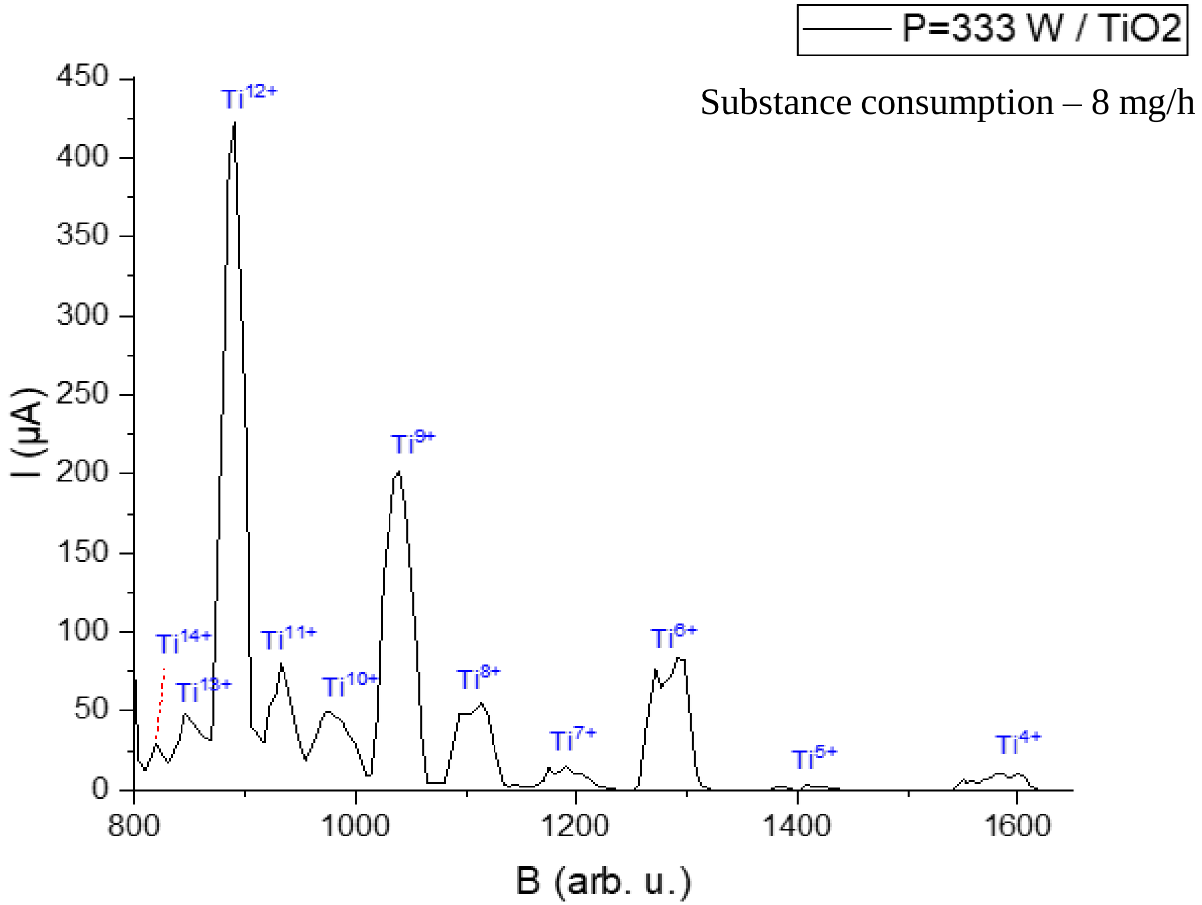


Container heating system

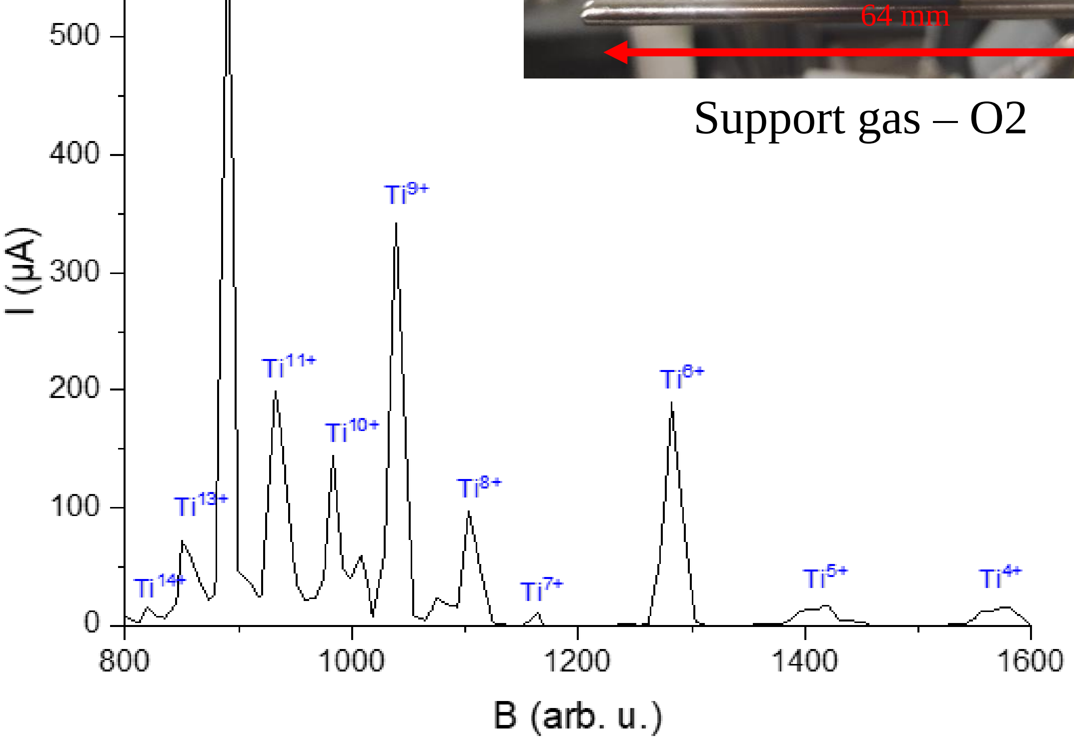
Gas injection line heating system

Ion	***I, μA***	***U_{inj}, kV***	***P_{UHF}, W***
Ti^{11+}	14	15.2	307

DECRIS-5M: Experimental results of direct injection of TiO_2 and Ti into plasma

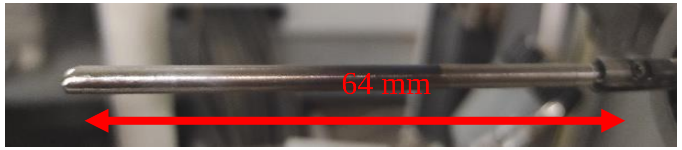


Titanium ion spectra for TiO_2



Titanium ion spectra for Ti

P – 286 W / Titanium rod



Support gas – O2

Before

TiO_2

After

Ion	***I, μA***	***U_{inj}, kV***	***P_{UHF}, W***
(TiO_2) / Ti^{11+}	80	15.2	333
(Ti) / Ti^{11+}	200	15.2	286

DECRIS-5M: Results and technical requirements

Results

Q+	**4+**	**5+**	**8 +**	**10+**	**11+**	**17 +**	**20+**	**26+**	**29+**	**37+**
Ne	**560**	-	**60**	-	-	-	-	-	-	-
Ar	-	**110**	**818**	**250**	**100**	-	-	-	-	-
Kr	-	-	-	-	-	**216**	-	-	-	-
Xe	-	-	-	-	-	-	**150**	**100**	-	-
Ti / MIVOC - $(CH_3)_5C_5Ti(CH_3)_3$	-	-	-	**64**	-	-	-	-	-	-
Ti / $C_{13}H_{13}Ti$ + compound heating + gas injection line heating	-	**5**	-	-	**14**	-	-	-	-	-
TiO_2 / direct injection	-	-	-	**50**	**80**	-	-	-	-	-
Ti / direct injection	-	-	-	**144**	**200**	-	-	-	-	-
Bi	-	-	-	-	-	-	-	-	**68**	**10**

Technical requirements:

Ion	Ne^{4+}	Ar^{8+}	Kr^{16+}	Xe^{26+}	Bi^{37+}
I nA	~2.5	~5	~10	~15	~20

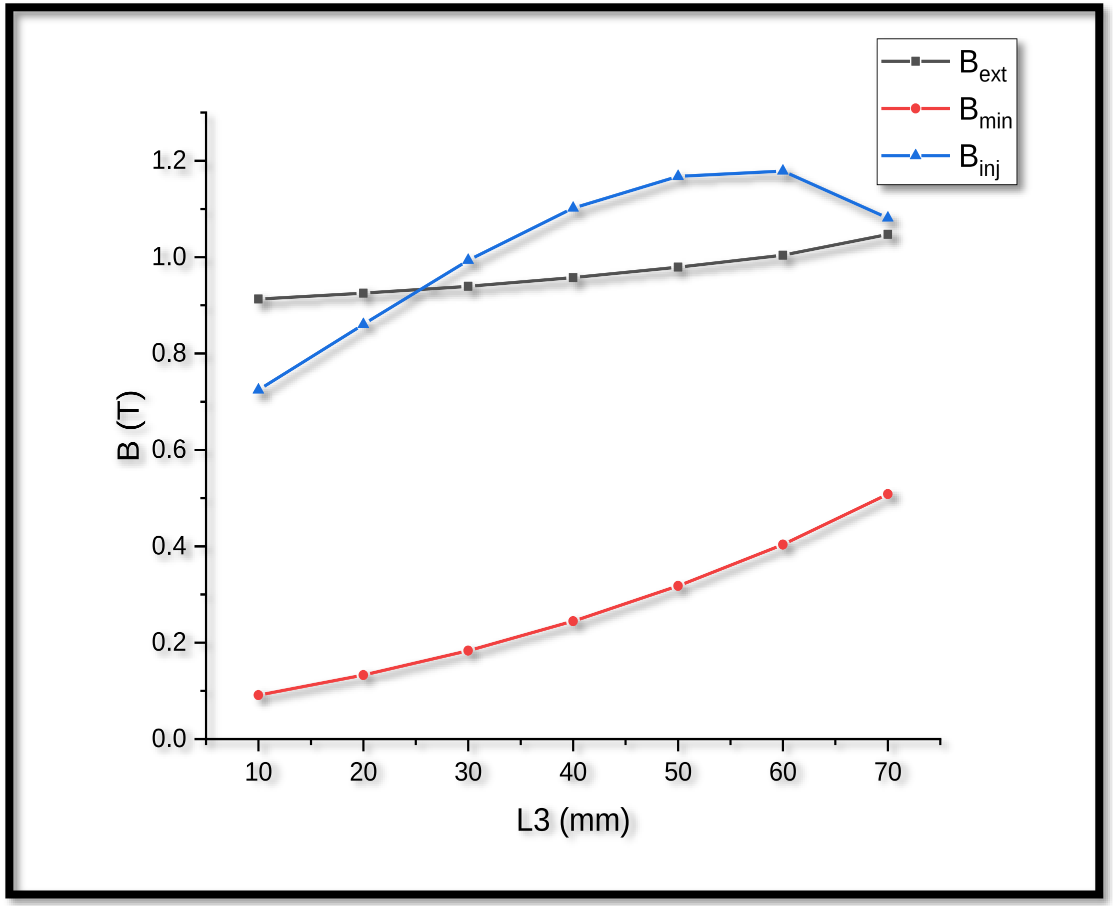
Conclusion

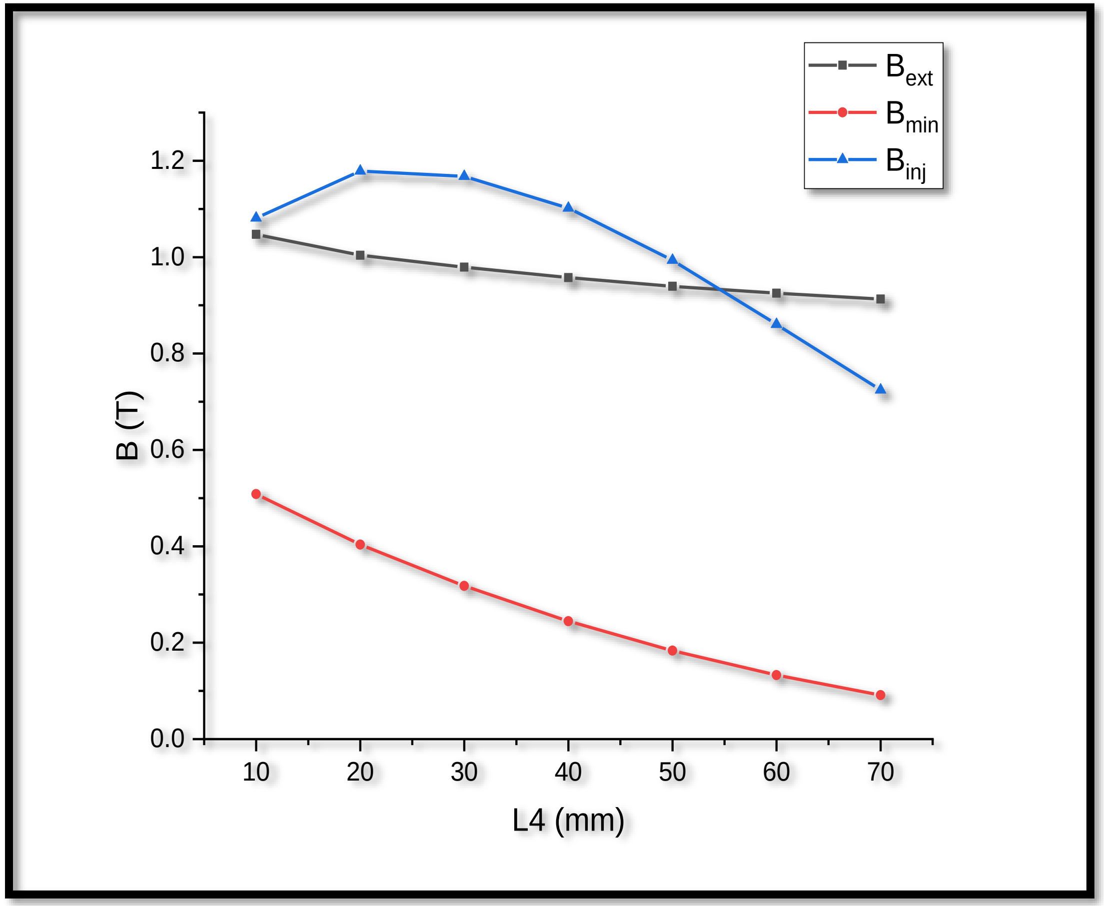
Highly charged gas and metal ion beams were obtained using different methods (Gas / MIVOC / Resistive heating / Direct injection into plasma):

1. The obtained ion beams meet the technical requirements for operation on the DC-140 cyclotron complex.
2. Ti (MIVOC) – compound $(CH_3)_5C_5Ti(CH_3)$ best results among compounds (64 μA). However, beam production from the "high-temperature" MIVOC compound $C_{13}H_{13}Ti$ showed that partial heating of the feed line significantly increased the beam intensity compared to the result obtained without heating (from 0 to 14 μA). This suggests that further research is needed to generate ion beams using this method, ensuring full heating of the feed line.
3. Ti (Direct Injection) – Results for producing titanium beams using the direct injection method showed the best results among those available, but further experiments are required to determine the optimal operating parameters.

Thanks for your attention!

Magnetic System Parameters





Magnetic Plasma-Retention System Parameters B_{inj}, B_{ext} and B_{min} as a function of parameters (a) L_3 and (b) L_4