Cyclotron DC-280
of Super Heavy Elements factory

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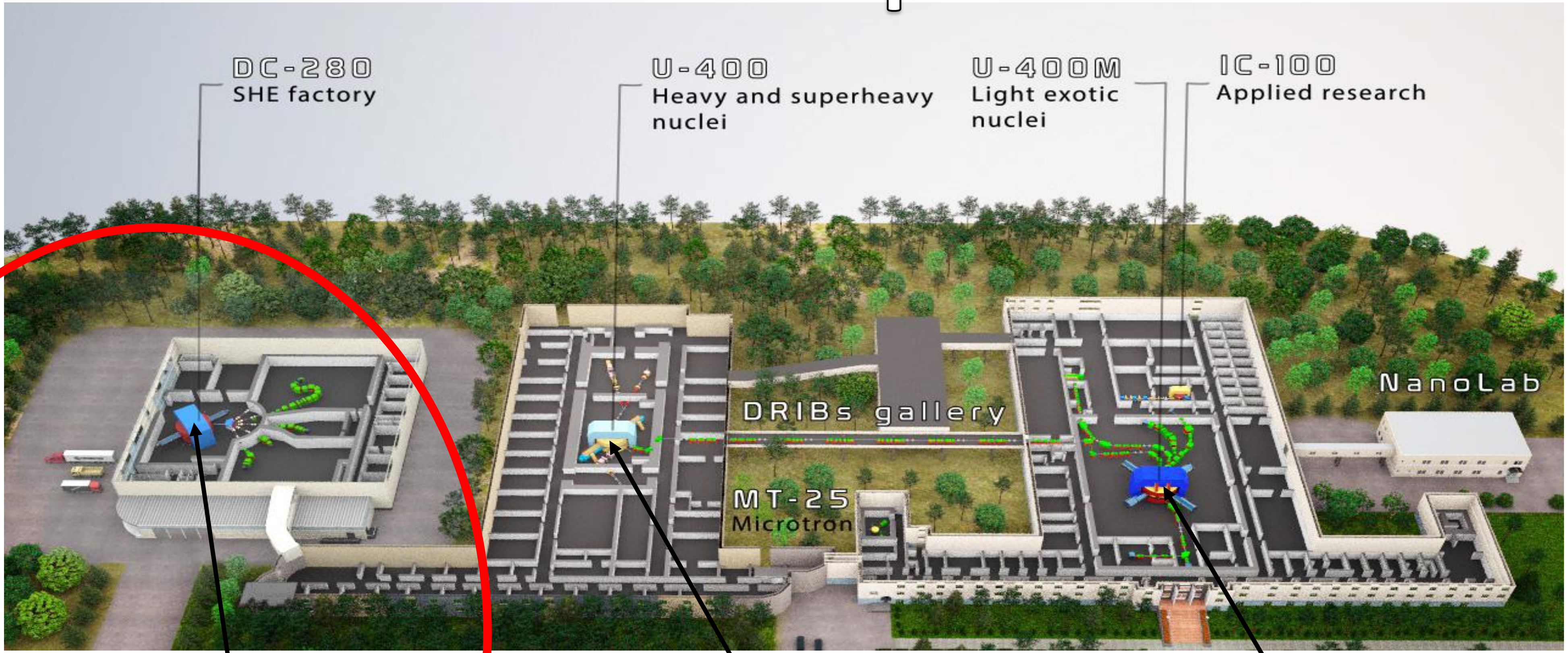
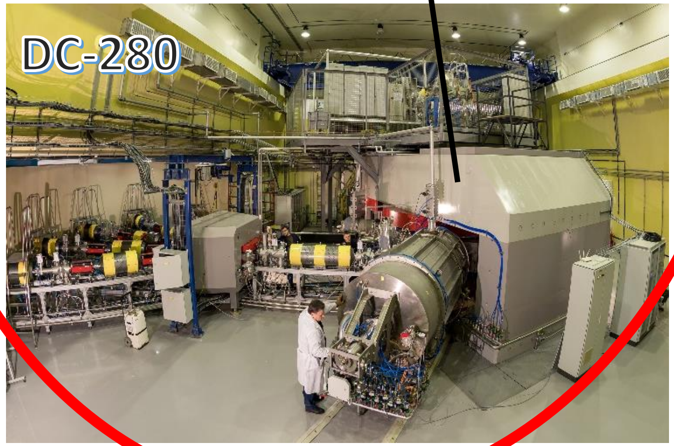
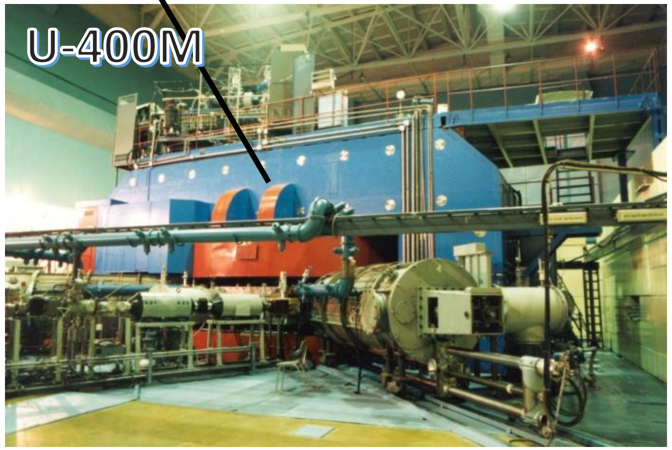
Accelerated complex FLNR

Technical parameters	DC-280	U-400	U-400M	IC-100
magnetic poles diameter [m]	4.0	4.0	4.0	1.05
Magnetic induction [T]	0.6÷1.3 T	1.95÷ 2.15	1.5 ÷1.95	1.78 -1.93
Weight of magnet [т]	1100	2000	2300	50
Injection potential [kV]	Up 90	Up 25	Up 25	Up 25
N sectors/ angle	4/ 28 → 42°	4/42°	4/42°; Spiral 43°	4/56°
N dee	2	2	4	2
Dee voltage [kV]	Up 110	Up 100	Up 170	Up 55
Frequency [MHz]	7.3÷ 10.4	5.5÷ 12	11.5÷ 24	19.8 - 20.6
Harmonic	3	2	2; 4	4
A/Z	4 ÷ 7.5	5 ÷ 12	7-10; 2,5-6	5.5 - 5.95
Extraction type	Electrostatic Deflector	Recharge foil, Two direction	Recharge foil, Two direction	Electrostatic Deflector
Ion energy MeV/nucleon	4÷8	0.5 ÷20	4-11; 15-60	1.05-1.2

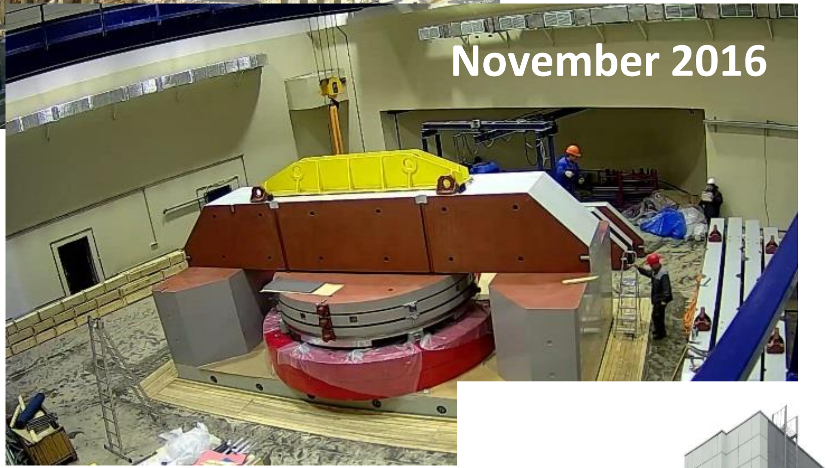
Accelerated complex FLNR



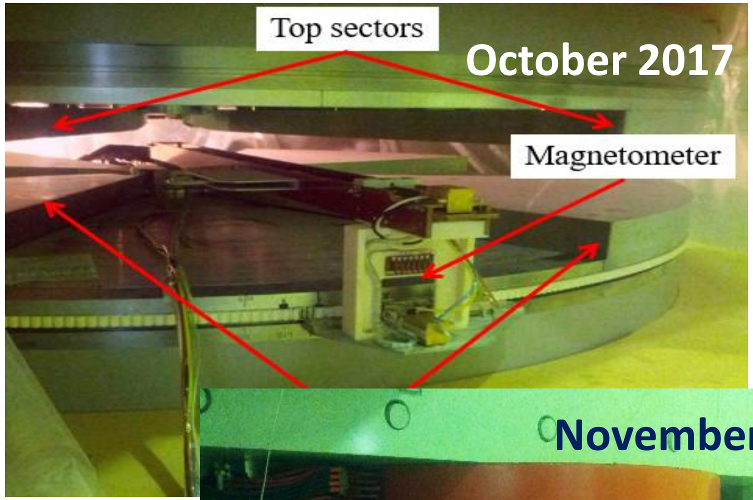





March 2012


November 2016


August 2017
SHE-Factory


Top sectors
October 2017
Magnetometer


November 2017


First extracted beam **17.01.2019**

obtained

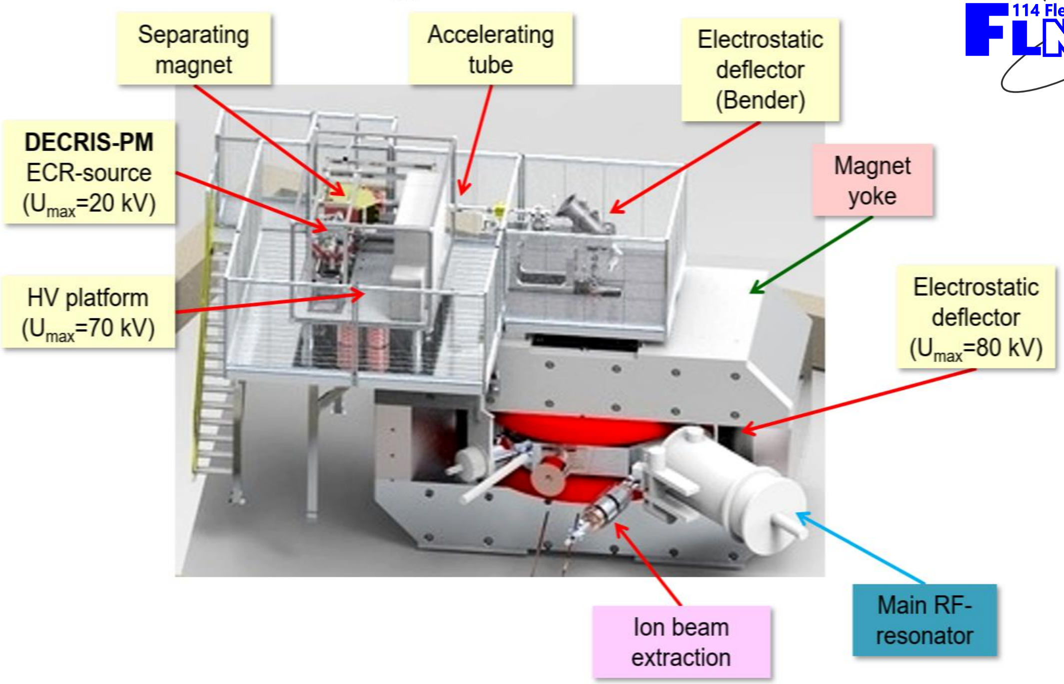
Cyclotron DC-280

Year	Total work time	Ions
2018	First Beam	^{84}Kr
2019	3377	^{12}C, ^{40}Ar, ^{48} Ca, ^{84}Kr
2020	3705	^{40}Ar, ^{48} Ca, ^{48}Ti
2021	5357	^{48} Ca, ^{48}Ti , ^{52}Cr
2022	6037	^{40}Ar, ^{48}Ca, ^{48}Ti , ^{52}Cr

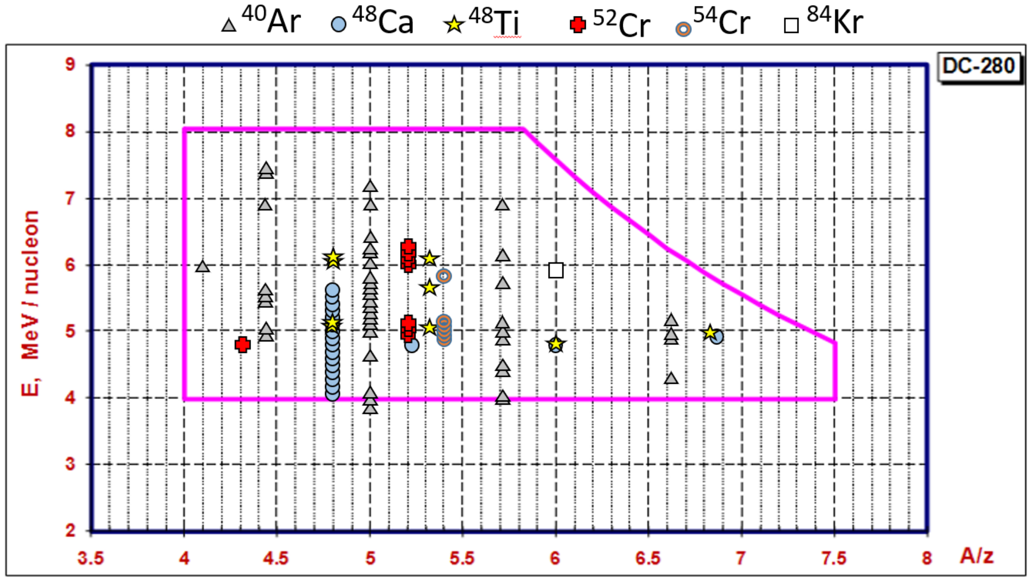
Main parameters of the DC-280

parameters	design	realized
Ion source	DECRIS-PM - 14 GHz on the HV platform (U_{max}=60kV)	
Injecting beam potential	Up to 80 keV/Z	38,04 – 72,89 keV/Z
A/Z	4÷7.5	4,44 ($^{40}Ar^{+7}$) – 6,86 ($^{48}Ca^{+7}$)
Energy	4÷8 MeV/n	4,01 – 7 MeV/n
Ion (for DECRIS-PM)	4-136	12 ($^{12}C^{+2}$) – 84 ($^{84}Kr^{+14}$)
Intensity (A~50)	>10 pμA	10,43 pμA ($^{40}Ar^{+7}$), 7,7 pμA ($^{48}Ca^{+10}$)
Magnetic field level	0.6÷1.3 T	0.8÷1.23 T
K factor	280	
Dee voltage	2x130 kV	130 kV
Power of RF generator	2x30 kW	
Flat-top dee voltage	2x13 kV	13 kV
Power of Flat-top generator	2x2 kW	
Emittance	less than 30 π mm·mrad	
Accelerator effectivity	>50%	51,9 % ($^{48}Ca^{+10}$ 5 MeV/n 5 pmkA)

Configuration of the DC-280

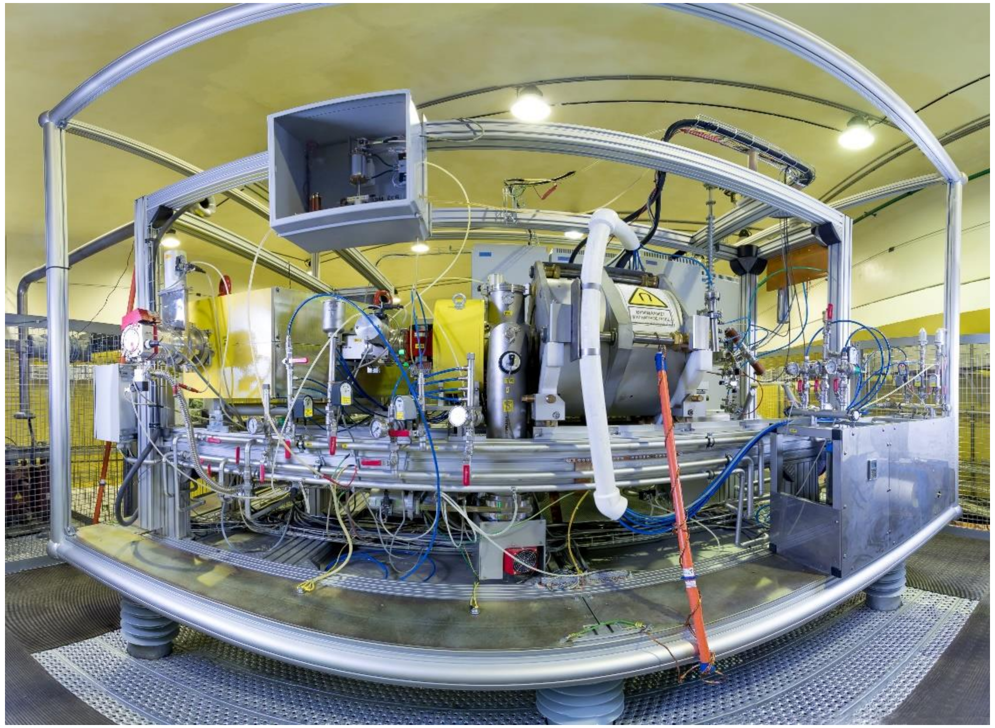


Working diagram of the DC-280

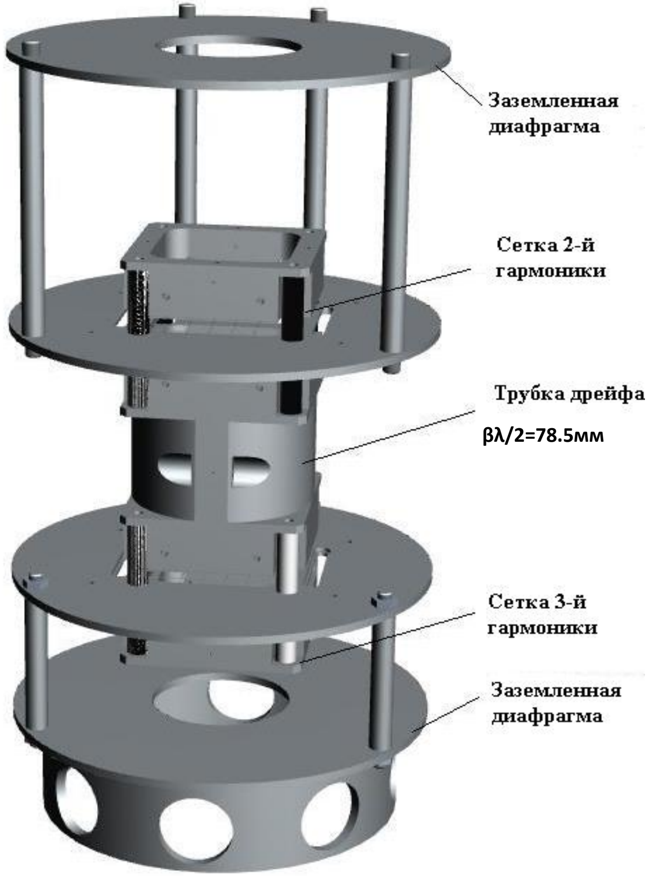


HV platform:

Work potential up 70 kV
Power of equipment 75 kW



The calculated efficiency of bunching the beam into the phase region of the accelerating field ± 20º was 80%, the losses on the grids were 8 ÷ 10%, they reduce the overall efficiency to ~ **70%**



Design and general view of polyharmonic buncher

The center of the Buncher drift tube is located at a distance of 387.5 cm from the median plane of the cyclotron.

Work frequencies of harmonics:
1-st: 7.32 ÷ 10.38 MHz
2-nd: 14.64 ÷ 20.76 MHz
3-td: 21.96 ÷ 31.14 MHz

Typical work amplitude of voltage for harmonics:
1-st: 850 V
2-nd: 600V
3-rd: 380 V

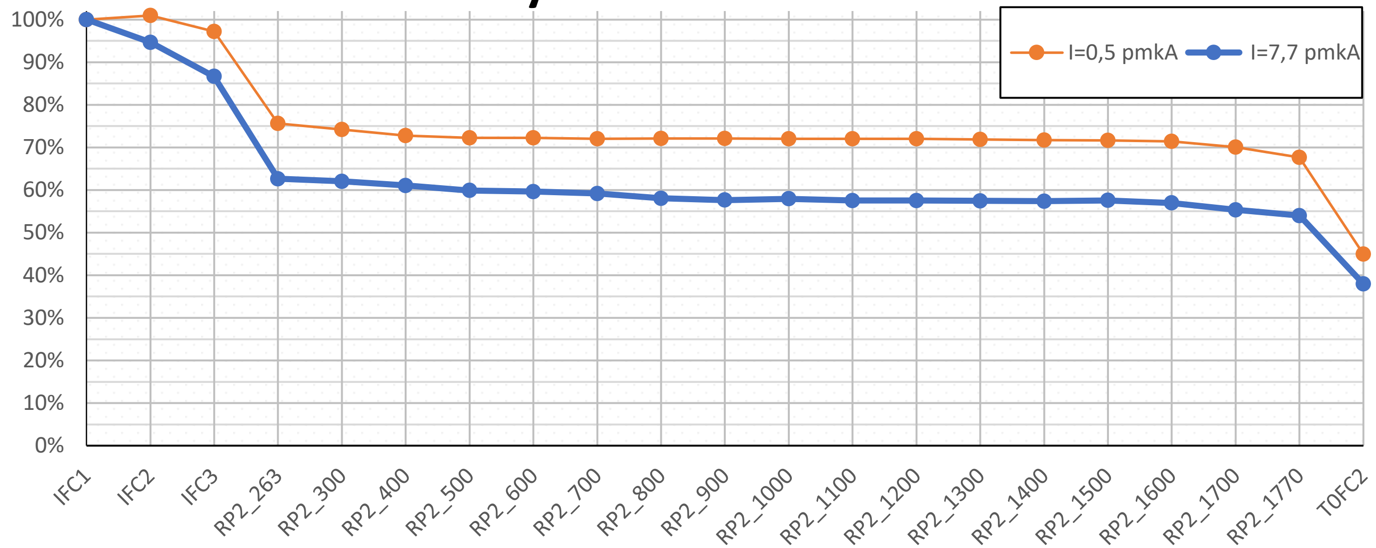
Ion	I_{ECR} (pμA)	Capture to acceleration		
		Off	1 harmonic	3 harmonic
^{40}Ar	5.6	15%	40%	66%
^{48}Ca	2.5	15%		67%
^{84}Kr	3.64	12%	43%	57%
Max design value of capture				70%

Cyclotron
DC-280

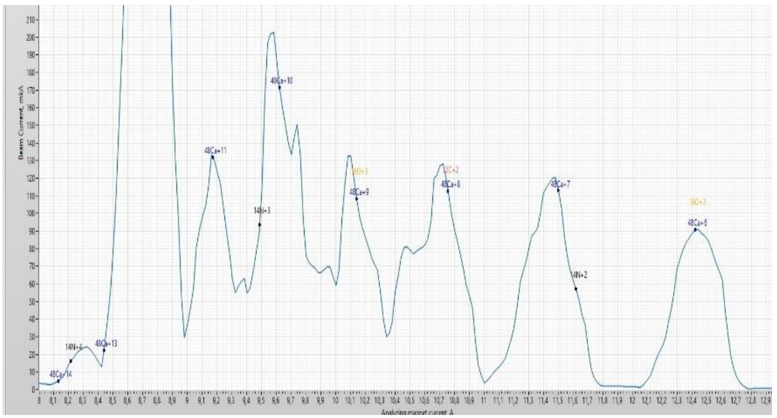
High intensive ^{48}Ca beam

$^{48}Ca^{10+}$	7.73 pμA

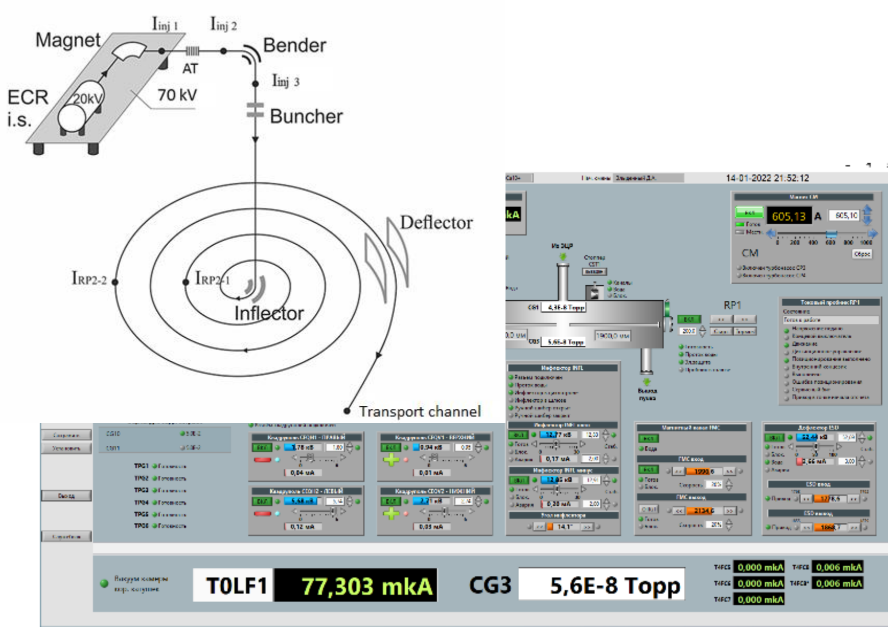
Efficiency of acceleration $^{48}Ca^{10+}$



Comparison of $^{48}Ca^{10+}$ acceleration efficiency for different intensity



Spectrum from DECRIS-PM in regime optimized to $^{48}Ca^{10+}$ production



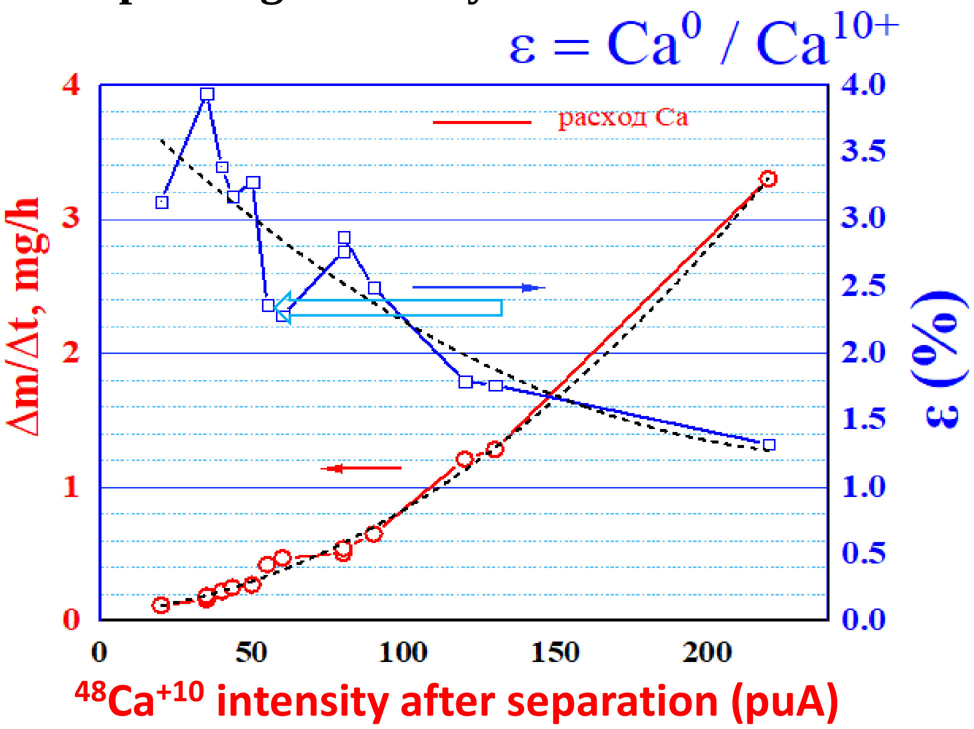
Efficiency $^{48}Ca^{10+}$ beam acceleration in different phase

Axial injection system		Cyclotron		Transport channel
After separation (IFC2), pμA	Before injection (IFC3), pμA	R=400 mm, pμA	R=1770 mm, pμA	(TOFC2), pμA
19,3	17,6	12,4	11,0	7,7
91,5%				
	70,5%			
		88,4%		
			70,3%	
40,1%				

obtained

Efficiency

Spending efficiency of ^{48}*Ca* material



$\mathcal{E}_{tot}$ = ^{48}Ca accelerated beam

$\mathcal{E}_{tot}$ (I= 7 *pμA*) = 0.4%

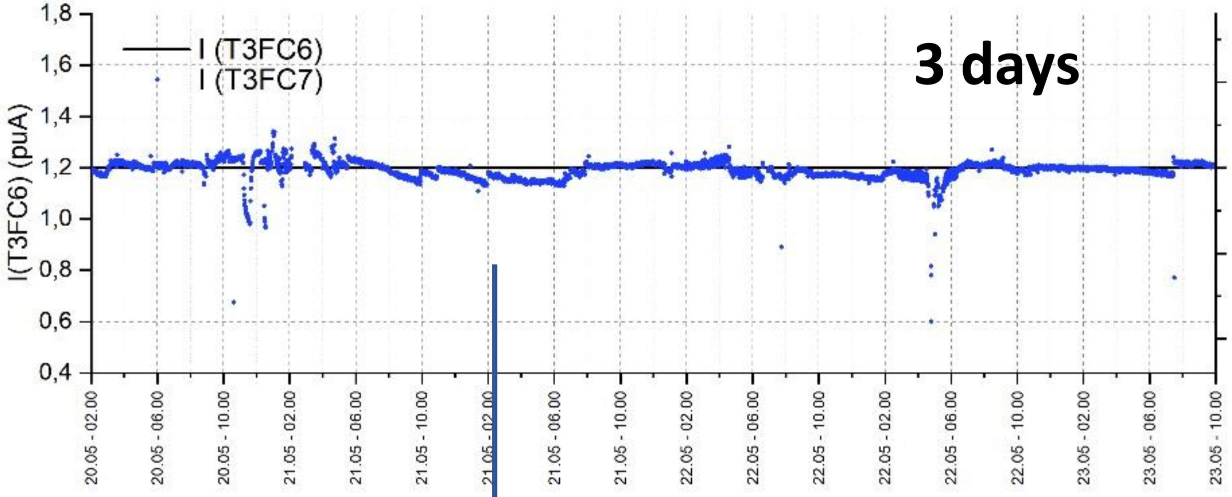
$\mathcal{E}_{tot}$ (I= 0.5 *pμA*) = 1.32%

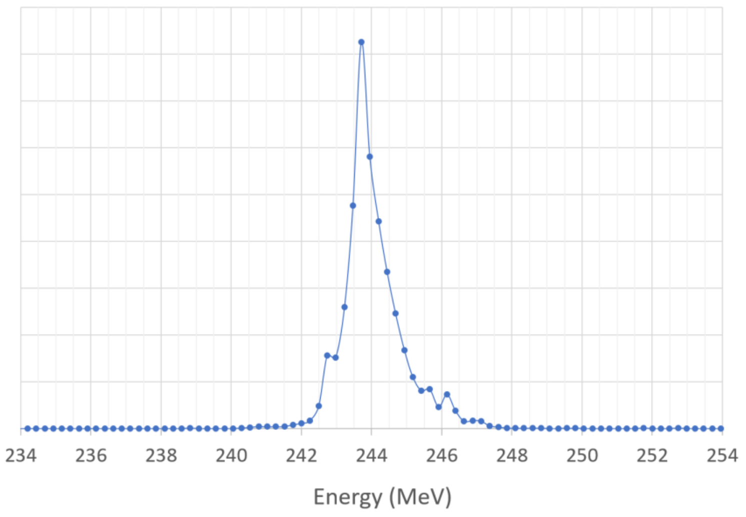
U-400: $\mathcal{E}_{tot}$ (I= 0.5 pμA) = 0.17%

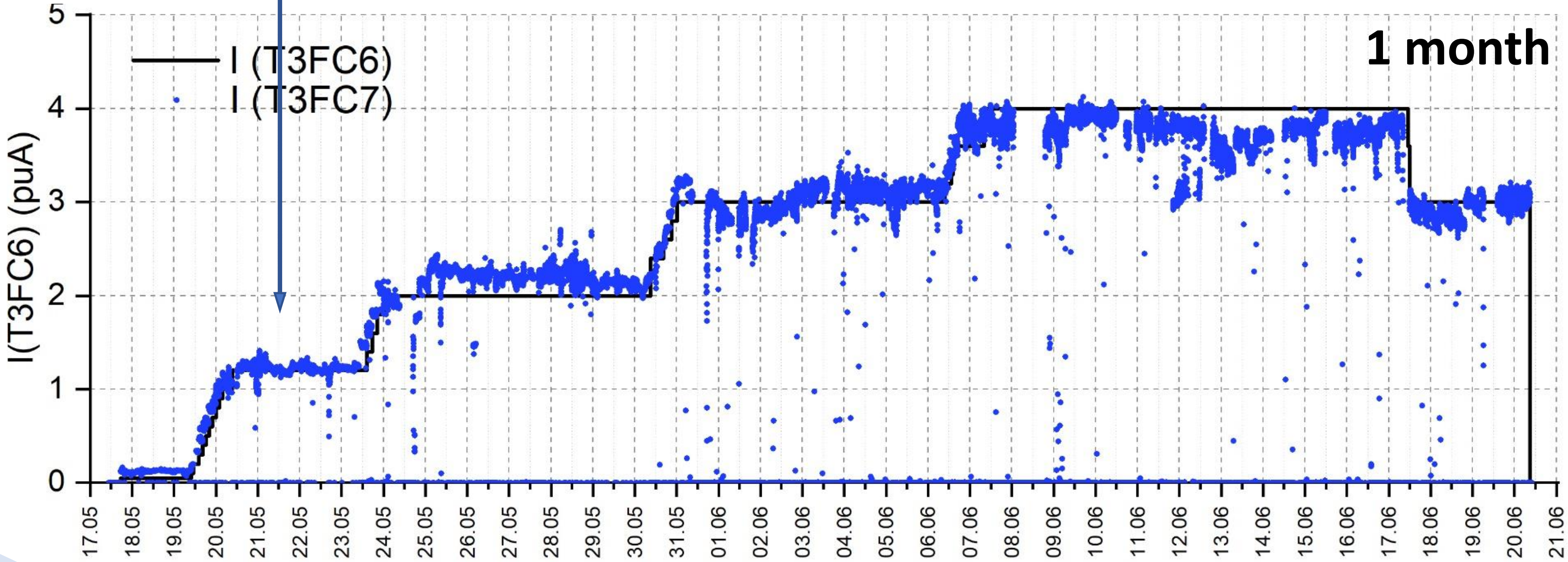
Intensity (puA)	Efficiency of acceleration of ^{48}Ca beam				
	Axial injection system	Capture	Acceleration	Extraction	Total
2.1	85%	78%	97%	86%	55%
3.3	91%	68%	94%	79%	46%
3.3	91%	73%	88%	75%	44%
4.7	90%	69%	91%	91%	50%
4.8	93%	73%	92%	77%	48%
5.3	97%	74%	93%	71%	47%
6	89%	72%	91%	73%	42%
7.7	91%	71%	88%	70%	40%

obtained

Stability of beam 48Ca during month of work





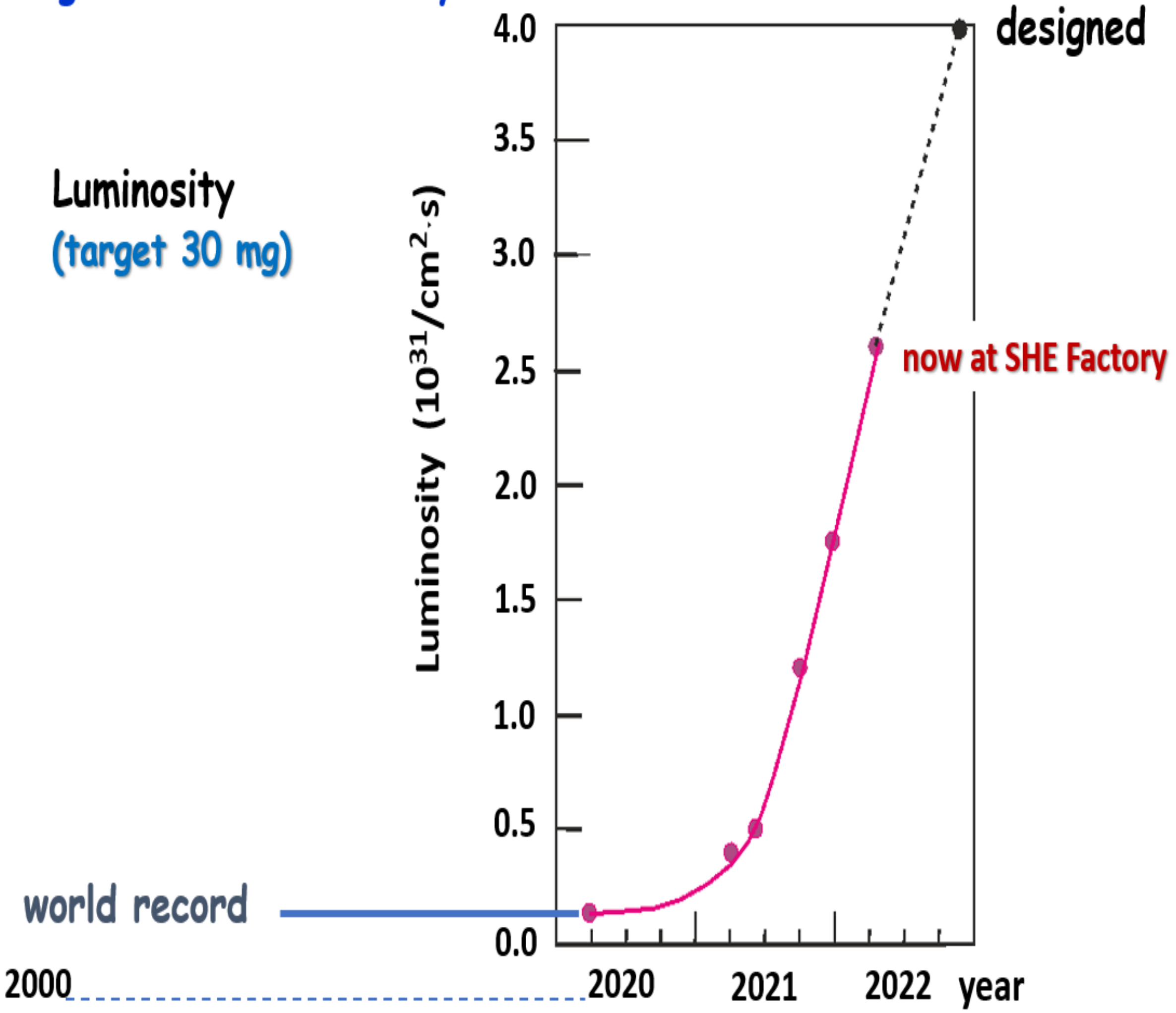


Current of ^{48}Ca beam on target during experiment

obtained

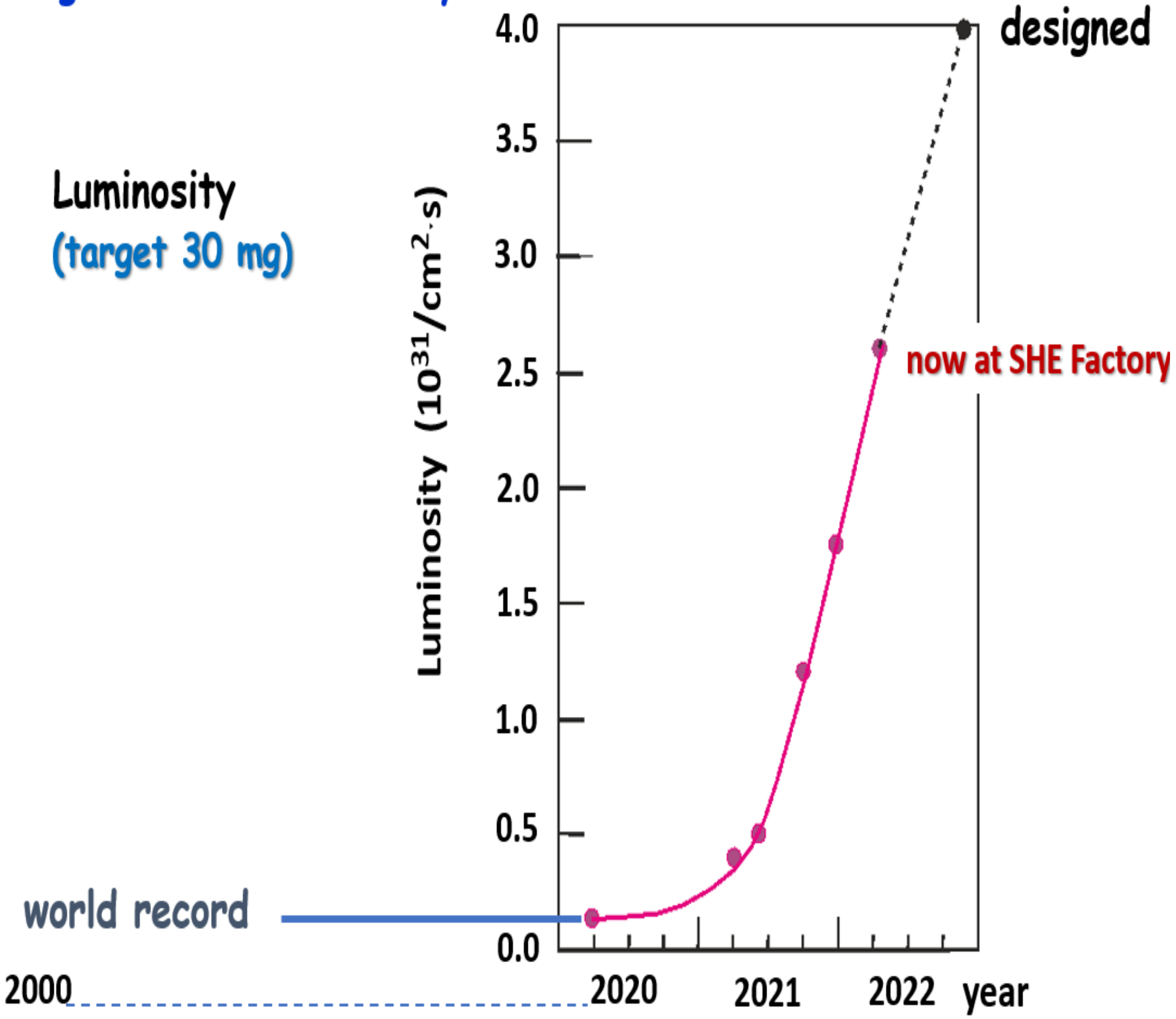
Progress at SHE-Factory

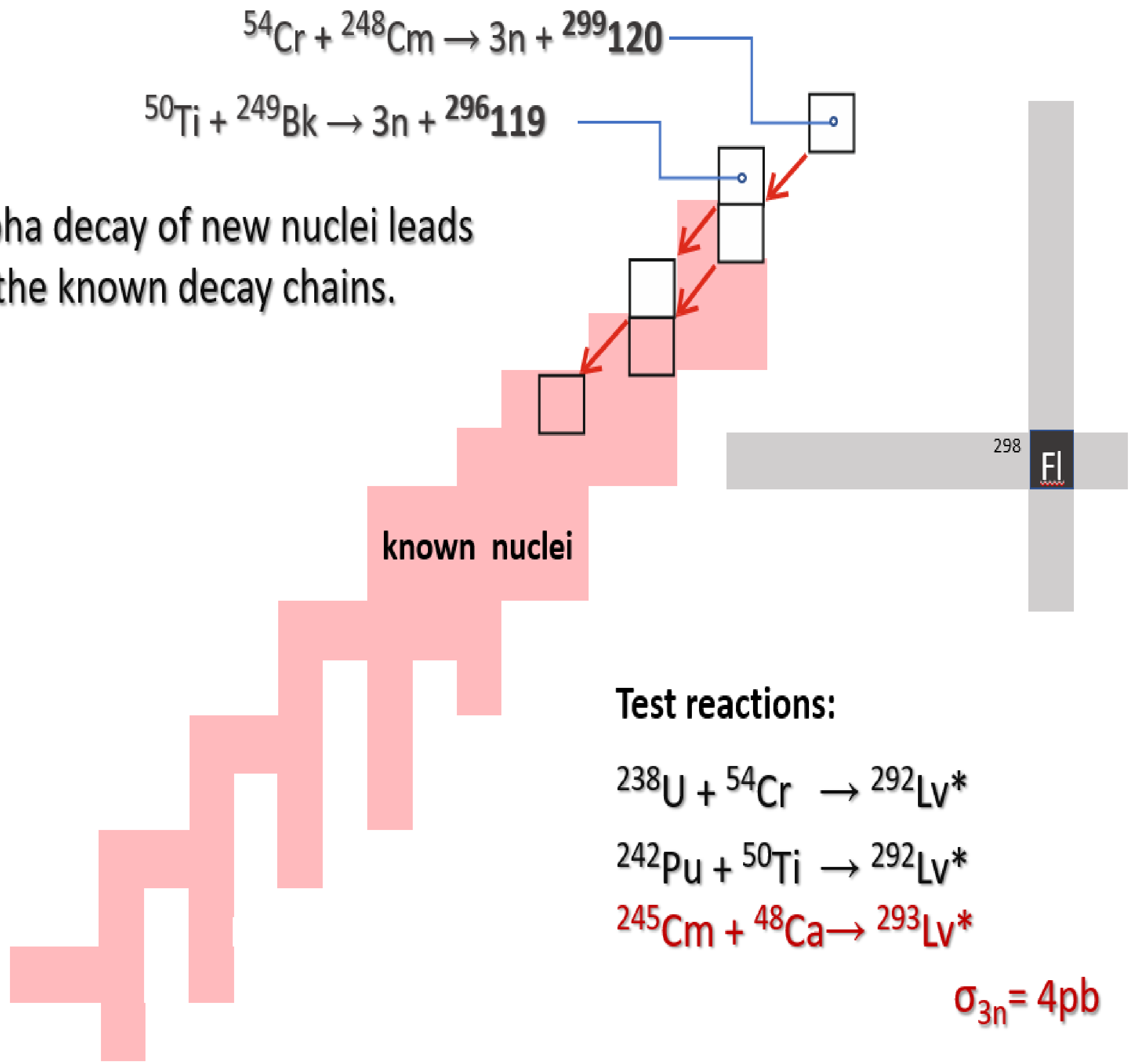
Luminosity
(target 30 mg)



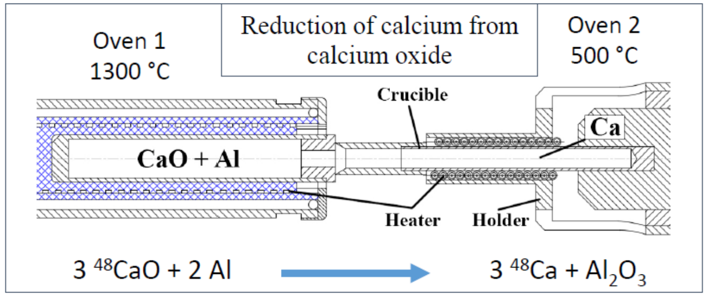
Synthesis of new elements at SHE Factory

Progress at SHE-Factory

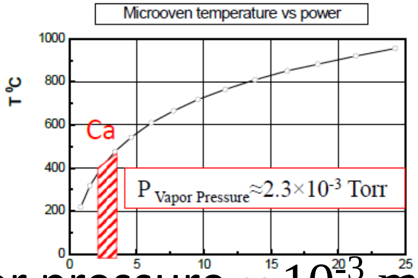




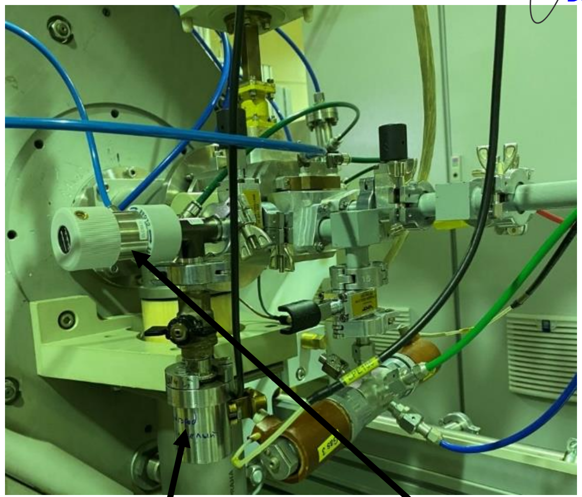
Production of ions Ca, Ti and Cr



$3\,{}^{48}CaO + 2\,Al \rightarrow 3\,{}^{48}Ca + Al_2O_3$



vapor pressure ~ 10^{-3} mbar

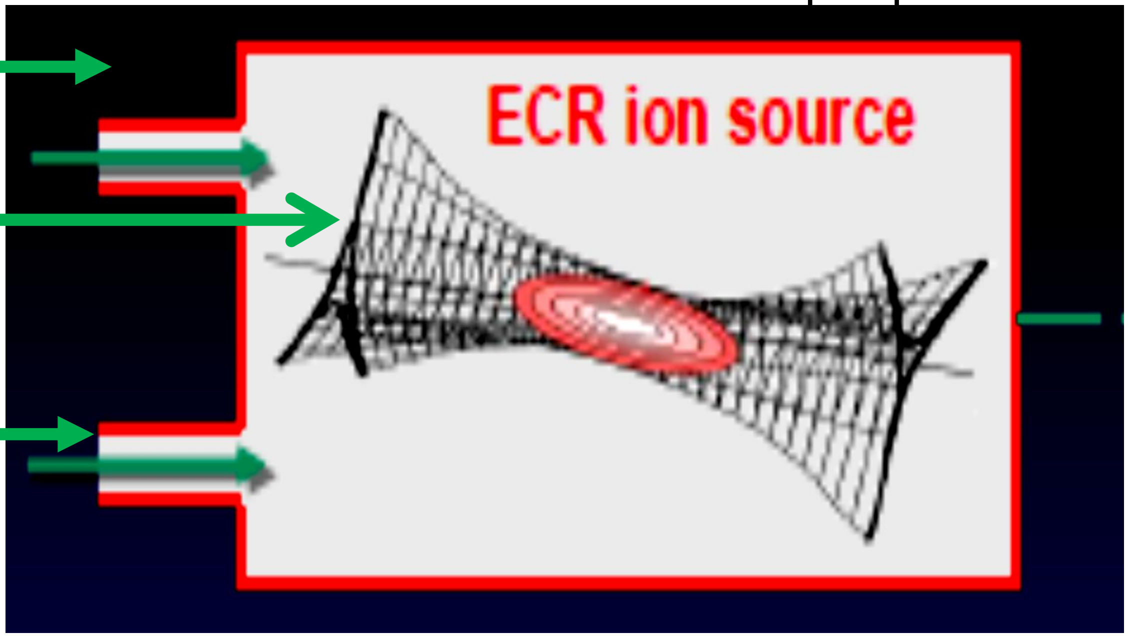


Substance container

Substance supply regulator

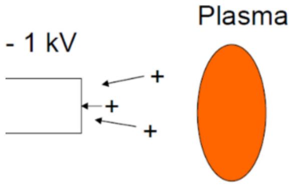
Vapor of metals (oven method)

Li, Mg, Ca….Pb, Bi



Sputtered atoms

Ta, W….



Volatile compounds (MIVOC method)

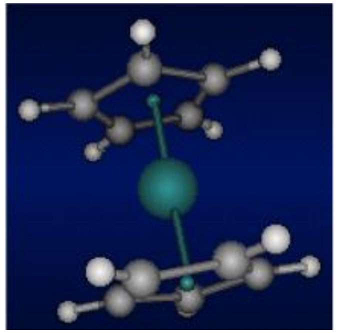
***MIVOC** - Metal Ions from VOlatile Compounds*

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

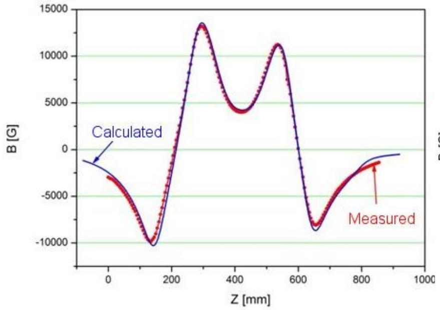
$(C_5H_5)_2Me$ – metallocene molecule (Fe, Ni,Cr..)

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

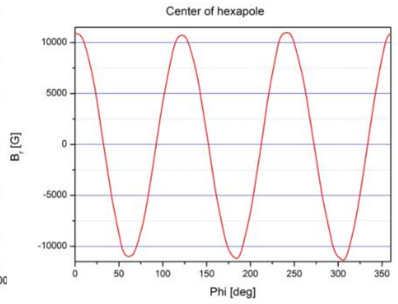
$(CH_3)_5C_5Ti(CH_3)_3$



$Cr(C_5H_5)_2$



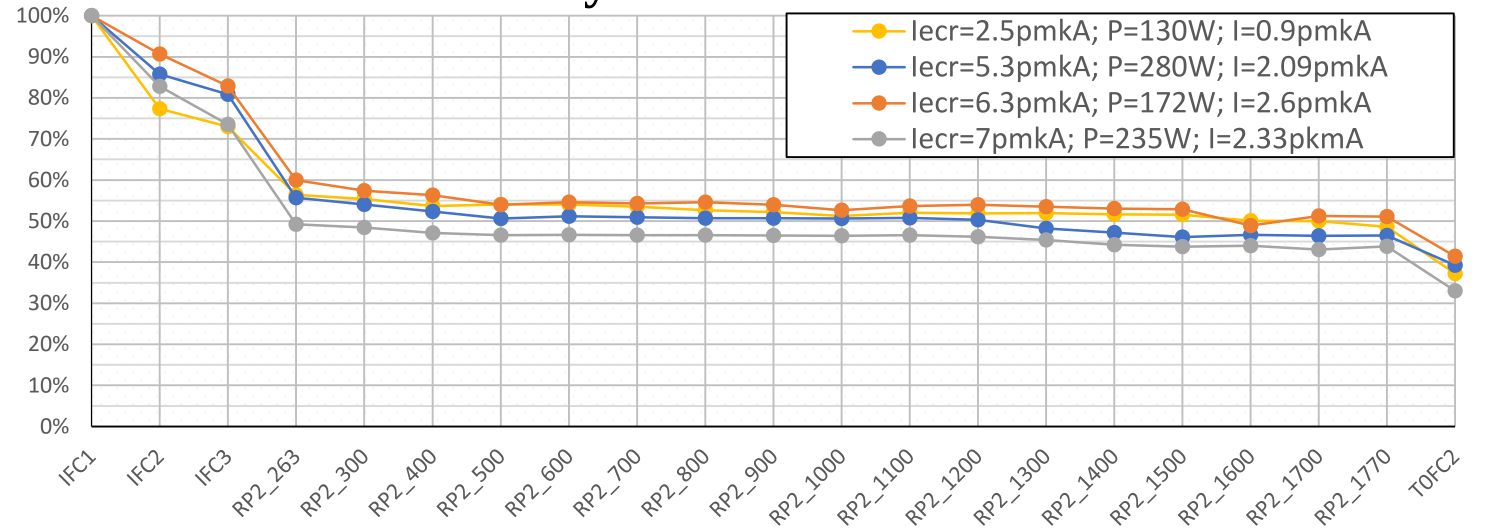
Axial magnetic field



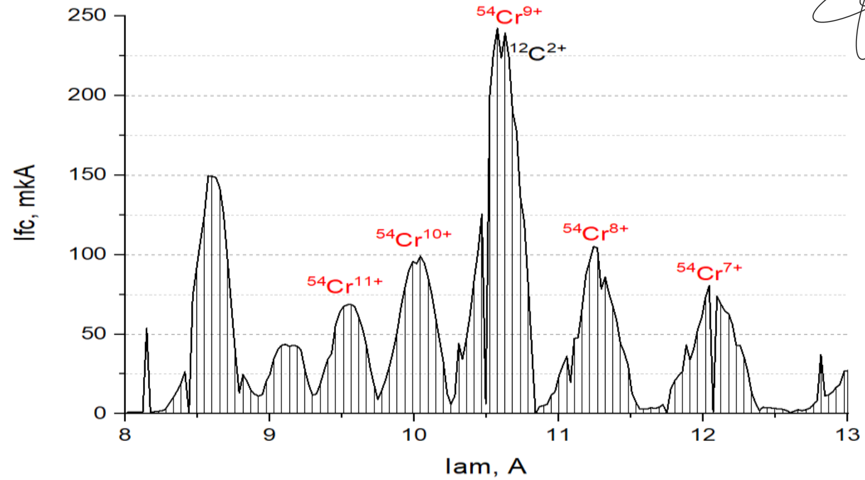
Radial magnetic field

Production of Cr beams

Efficiency of acceleration $^{52}Cr^{10+}$



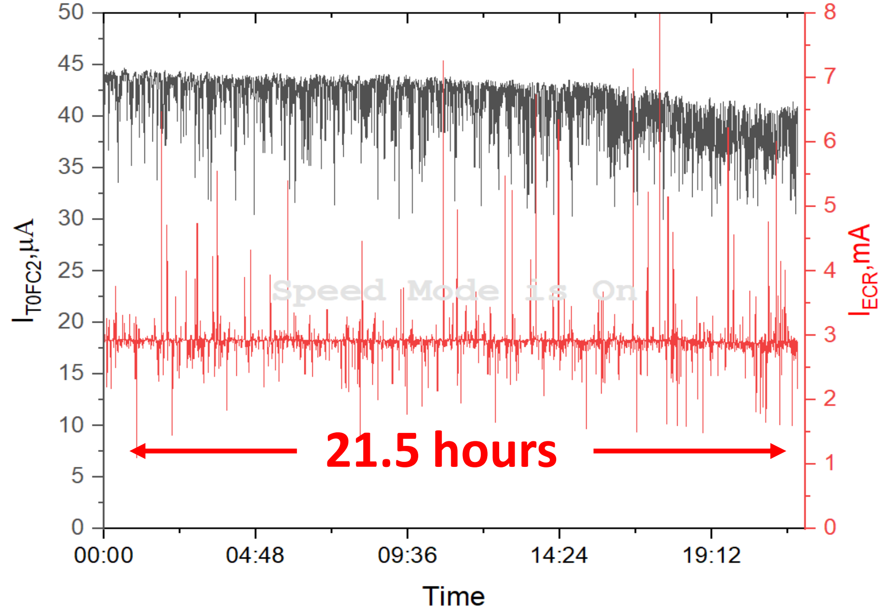
Comparison of $^{52}Cr^{10+}$ acceleration efficiency in different mode of ECR source work



Spectrum from DECRIS-PM in regime optimized to $^{52}Cr^{10+}$ production $Cr(C_5H_5)_2$

Efficiency $^{54}Cr^{10+}$ beam acceleration in different phase

Axial injection system		Cyclotron		**Transport channel** (T0FC2), pμA
After separation (IFC2), pμA	Before injection (IFC3), pμA	R=400 mm, pμA	R=1770 mm, pμA	
9.5	8.2	5.8	5.4	4.3
86.3%				
	70.7%			
		93.1%		
			79.6%	
45.3%				



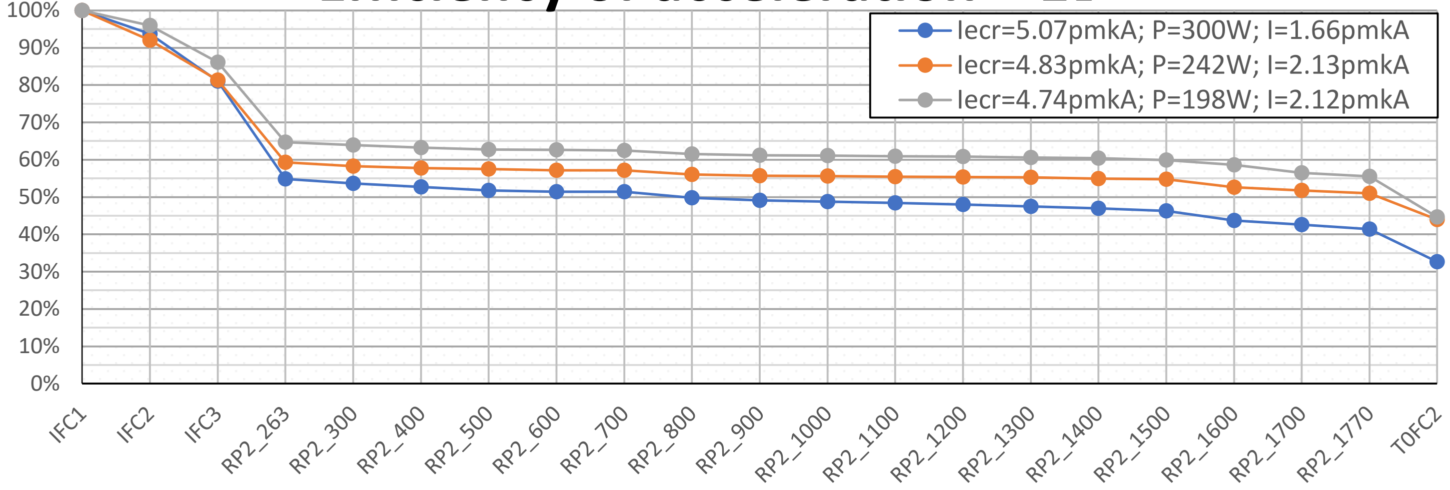
Accelerated beam stability $^{54}Cr^{10+}$

obtained

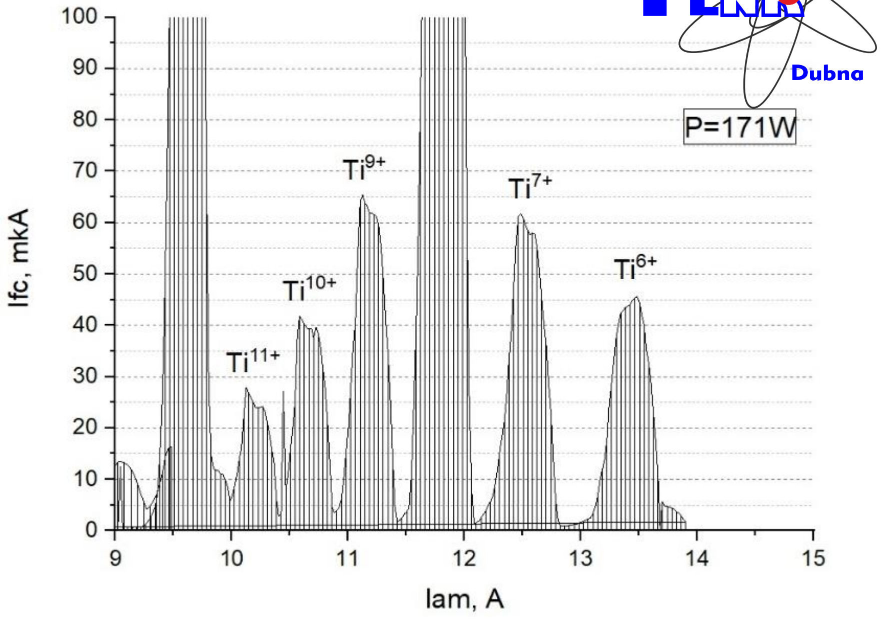
Cyclotron
DC-280

Production of $^{48}Ti^{9+}$ beams

Efficiency of acceleration $^{48}Ti^{9+}$

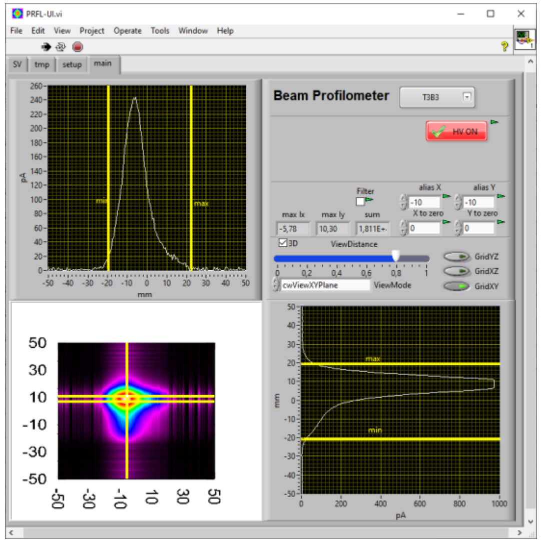


Comparison of $^{48}Ti^{9+}$ acceleration efficiency in different mode of ECR source work



Spectrum from DECRIS-PM in regime optimized to $^{48}Ti^{9+}$ production $(CH_3)_5C_5Ti(CH_3)_3$

Profile of $^{48}Ti^{9+}$ beam in transport channel



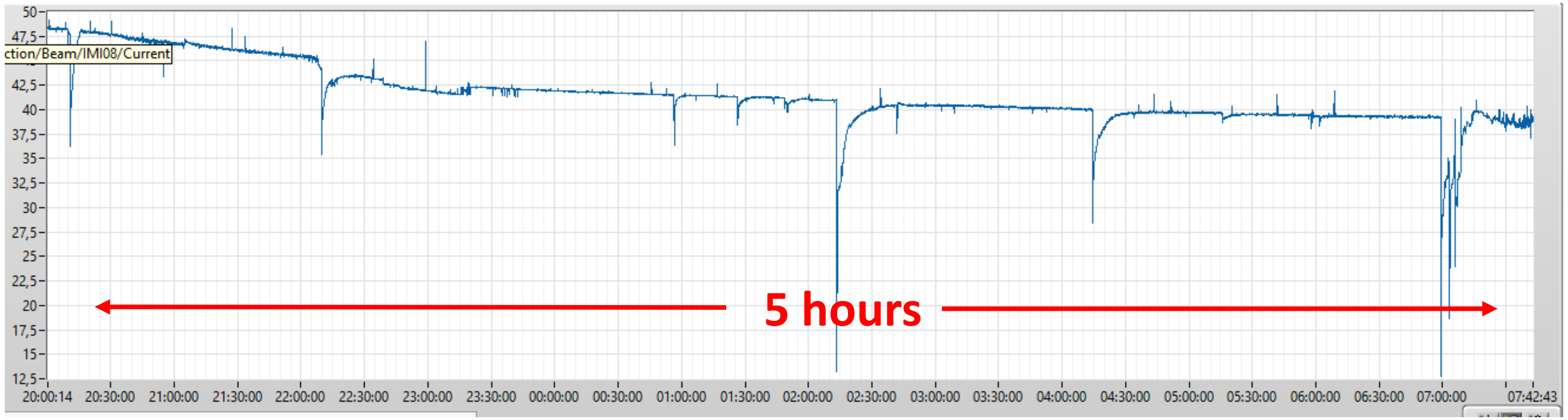
Axial injection system		Cyclotron		**Transport channel**
After separation (IFC2), pµA	Before injection (IFC3), pµA	R=400 mm, pµA	R=1770 mm, pµA	(T0FC2), pµA
4,4	4,1	3,0	2,7	2,1
92,5%				
	73,0%			
		88,9%		
			79,2%	
47,5%				

obtained

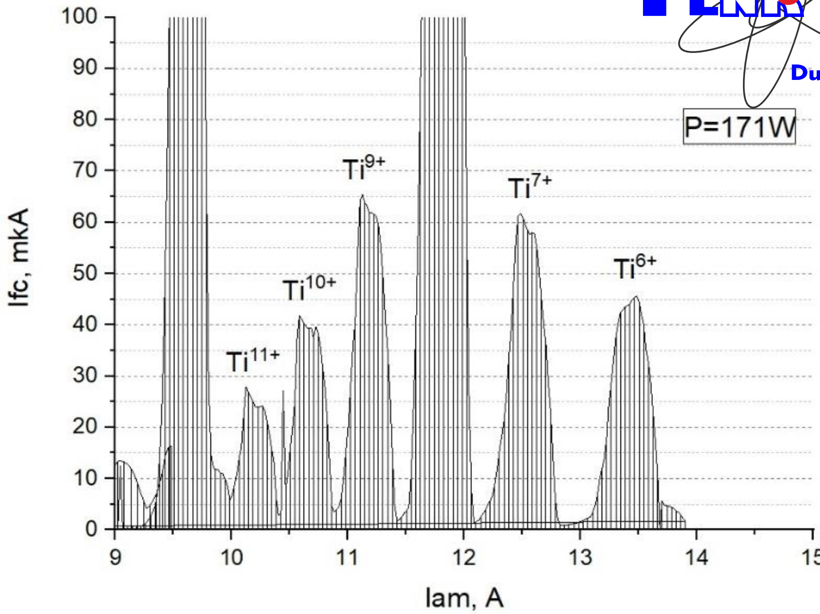
Cyclotron

DC-280

Production of $^{48}Ti^{9+}$ beams



Stability of $^{48}Ti^{9+}$ beam with intensity 4.4 puA from DECRIS-PM



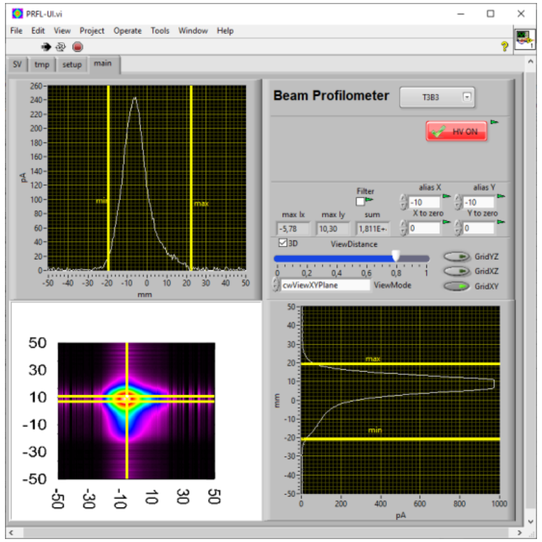
Spectrum from DECRIS-PM in regime optimized to $^{48}Ti^{9+}$ production $(CH_3)_5C_5Ti(CH_3)_3$

Ion source → Axial injection system → Transport channel

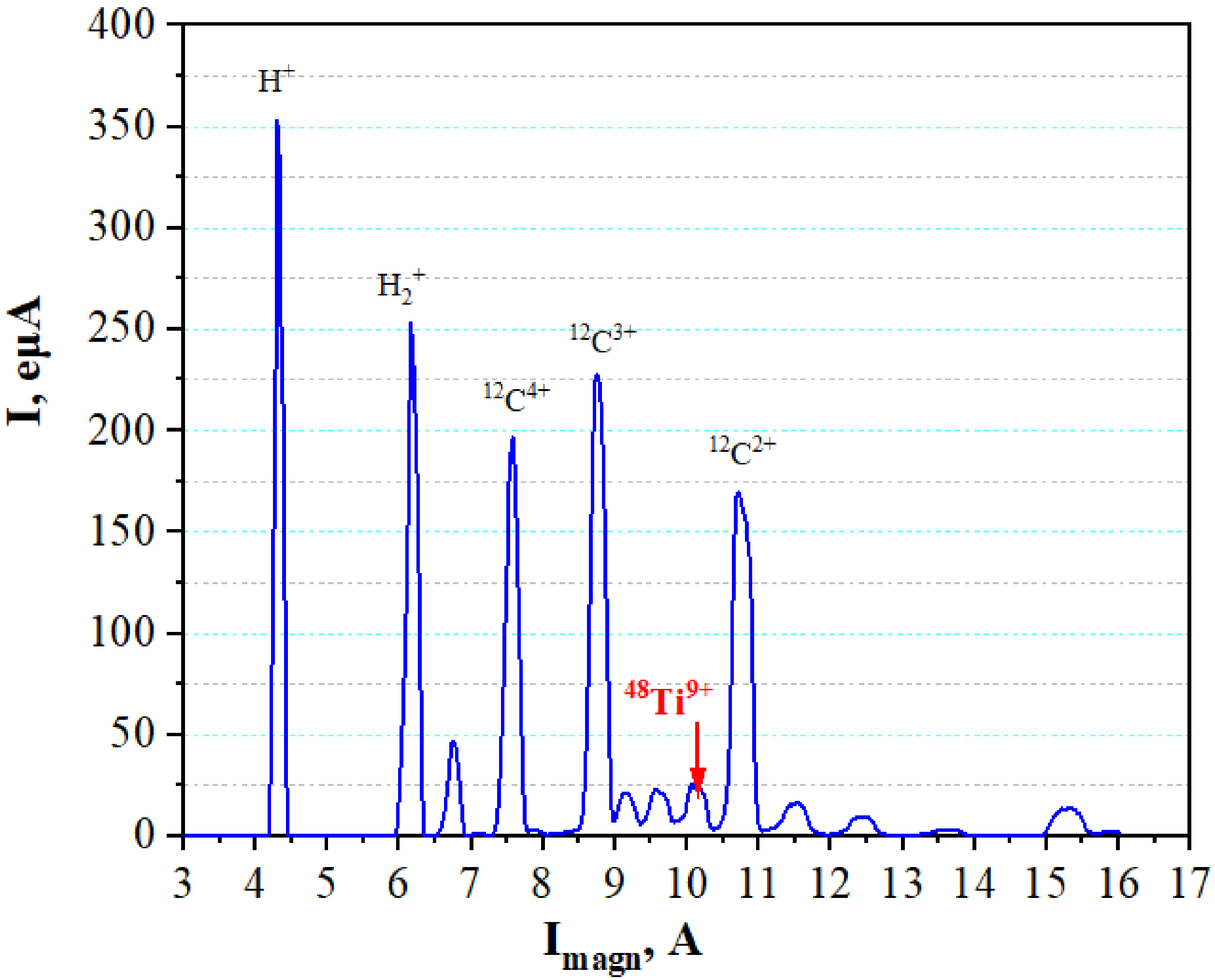
Axial injection system		Cyclotron		Transport channel
After separation (IFC2), pμA	Before injection (IFC3), pμA	R=400 mm, pμA	R=1770 mm, pμA	(T0FC2), pμA
4,4	4,1	3,0	2,7	2,1
92,5%				
	73,0%			
		88,9%		
			79,2%	
47,5%				

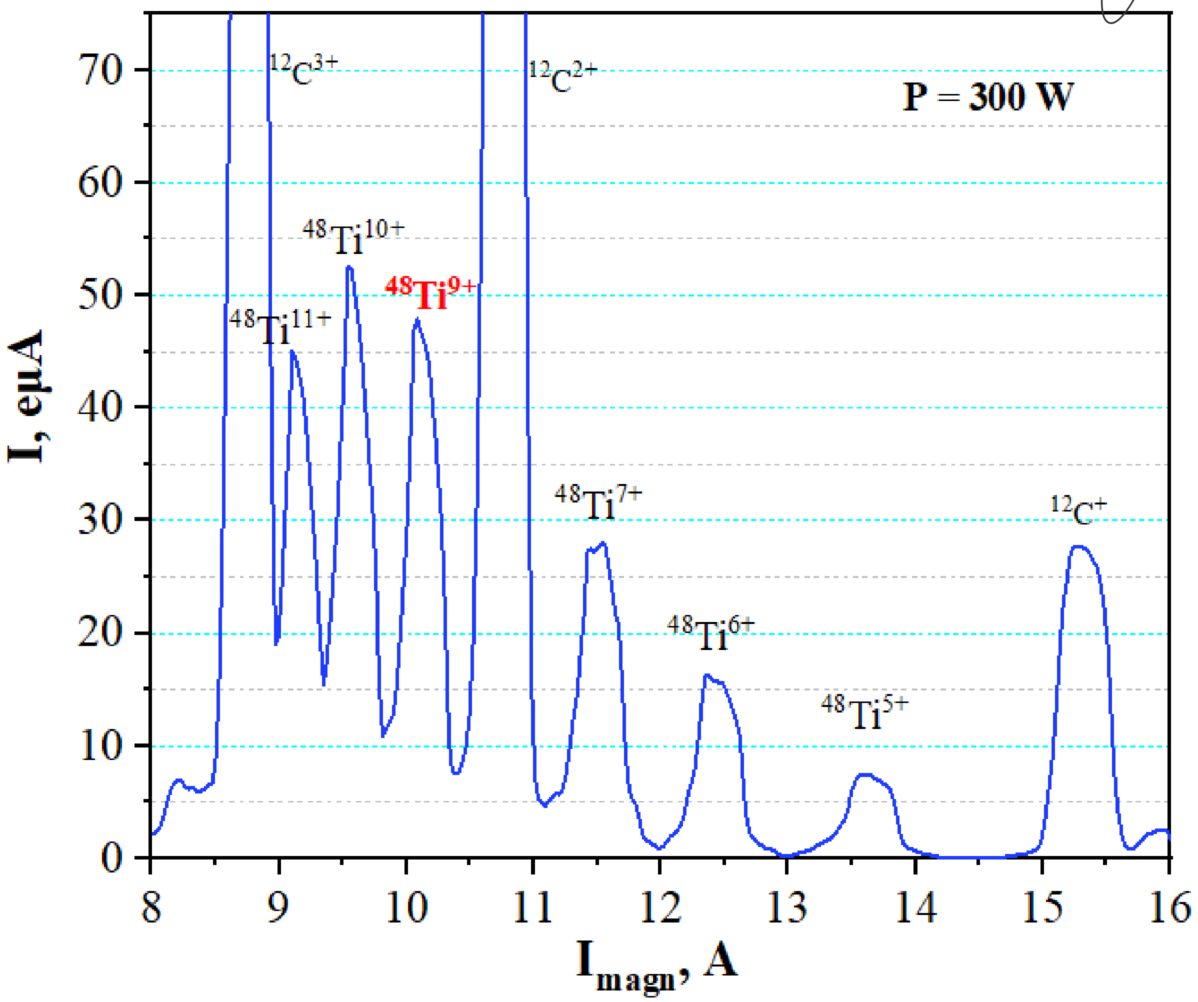
obtained

Profile of $^{48}Ti^{9+}$ beam in transport channel



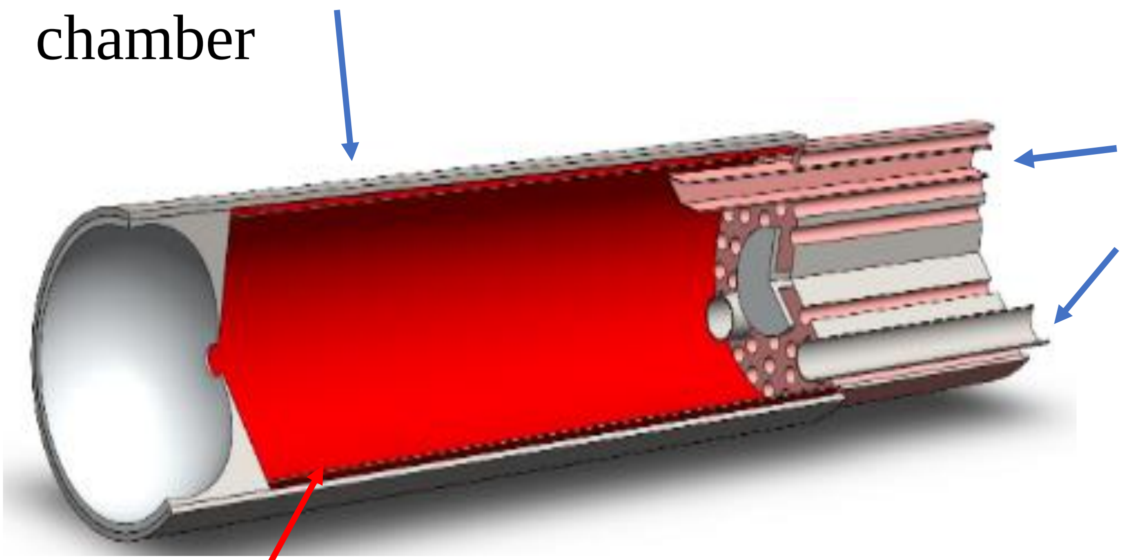
Ion DECRIS-PM spectrum produced from $(CH_3)_5C_5Ti(CH_3)_3$

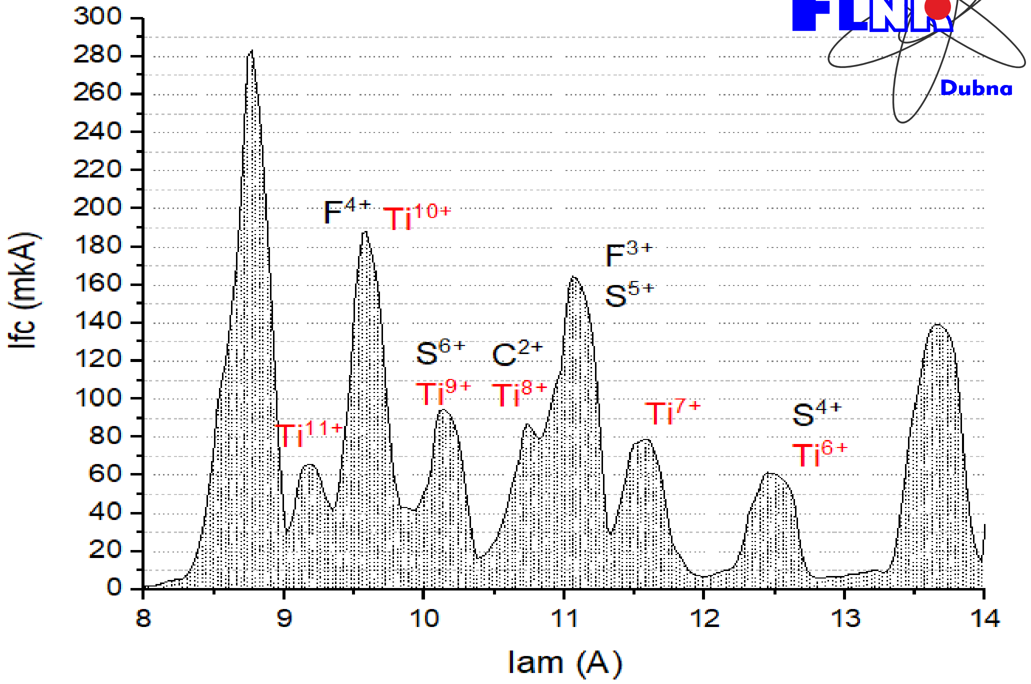




Hydrogen ions flow ~ 6×10^{15} pps; Carbon ions flow ~ 1.5×10^{15} pps
Helium ions flow (work with Ca) ~ $1.5 \div 3\times10^{15}$ pps

Ti ion production using SF_6 plasma*





The ^{48}Ti ion spectrum, optimized for $^{48}Ti^{10+}$

Screen with Ti foil after operation with SF_6 plasma

***Production of multiply charged metallic ions by compact electron cyclotron resonance ion source with SF_6 plasma** Y. Saitoh et al.
REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 69, NUMBER 2 FEBRUARY 1998

***Recycling effect of germanium on ECR ion source** P. Leherissier et al.
Nuclear Instruments and Methods in Physics Research B 211 (2003) 274–280

in progress

Development of ion production methods

Production of high-intensity ion beams $^{48}Ti^{+10}$ at the DC-280 cyclotron

<table>
<tr><th colspan="2">Axial injection system</th><th colspan="2">Cyclotron</th><th rowspan="2">Transport channel (T0FC2), pμA</th></tr>
<tr><th>After separation (IFC2), pμA</th><th>Before injection (IFC3), pμA</th><th>R=400 mm, pμA</th><th>R=1770 mm, pμA</th></tr>
<tr><td>13,2</td><td>10,6</td><td>4,6</td><td>4,1</td><td>3,26</td></tr>
<tr><td colspan="2">80,0%</td><td></td><td></td><td></td></tr>
<tr><td></td><td colspan="2">43,5%</td><td></td><td></td></tr>
<tr><td></td><td></td><td colspan="2">88,4%</td><td></td></tr>
<tr><td></td><td></td><td></td><td colspan="2">79,7%</td></tr>
<tr><td colspan="5">24,5%</td></tr>
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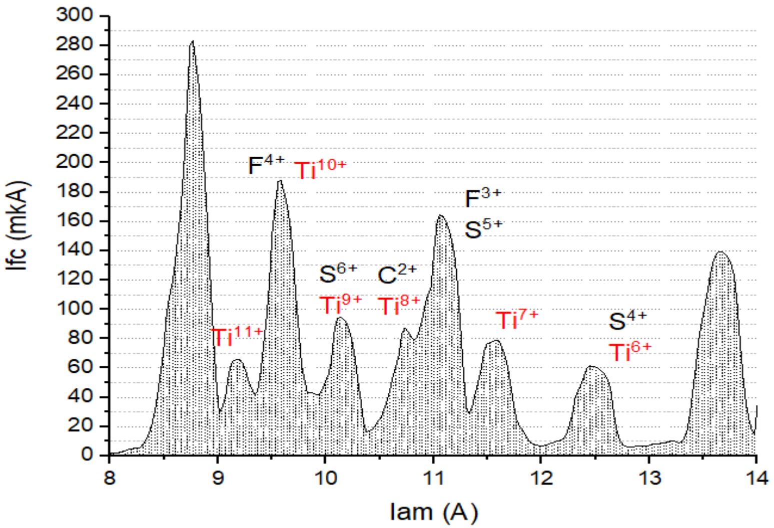
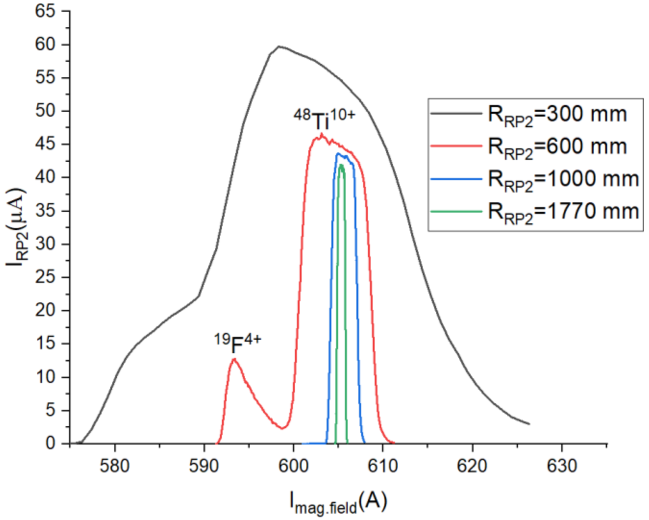
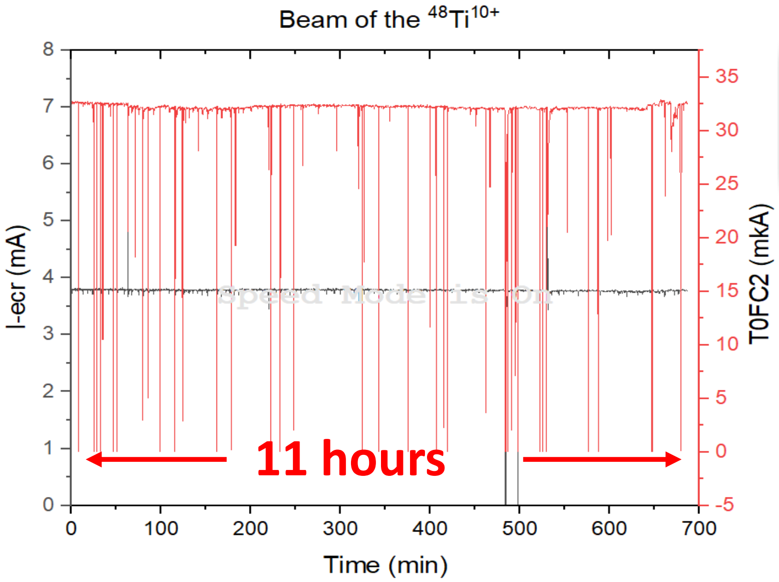


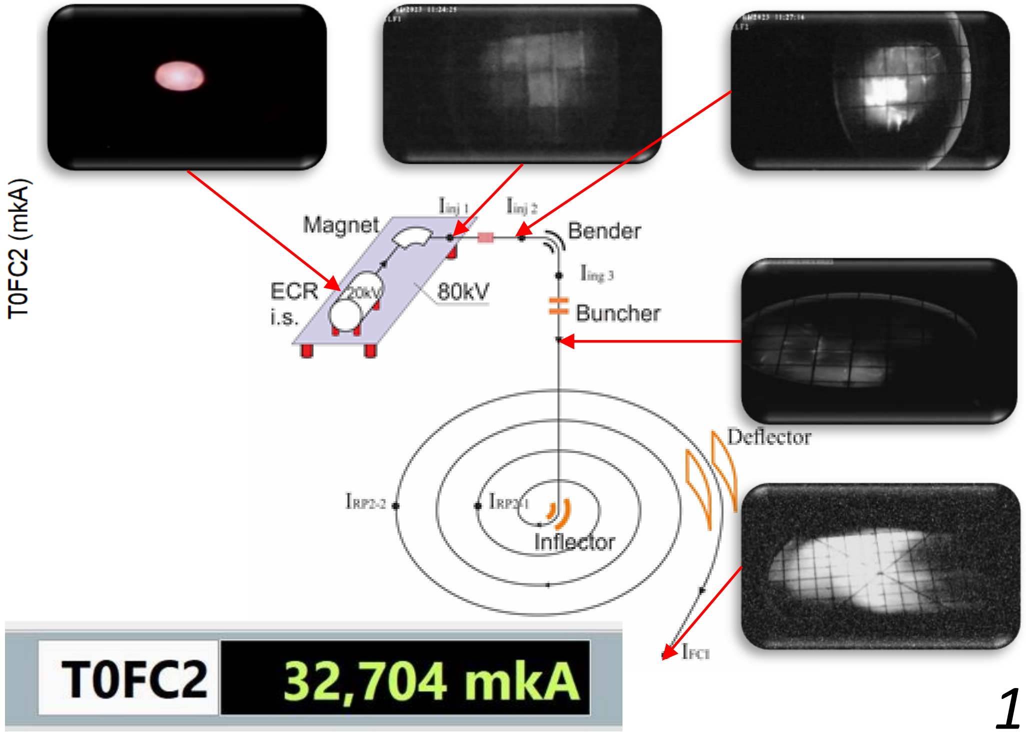
The ^{48}Ti ion spectrum, optimized for $^{48}Ti^{10+}$



Separation of $^{19}F^{4+}$ and $^{48}Ti^{10+}$ ions inside the DC-280 cyclotron

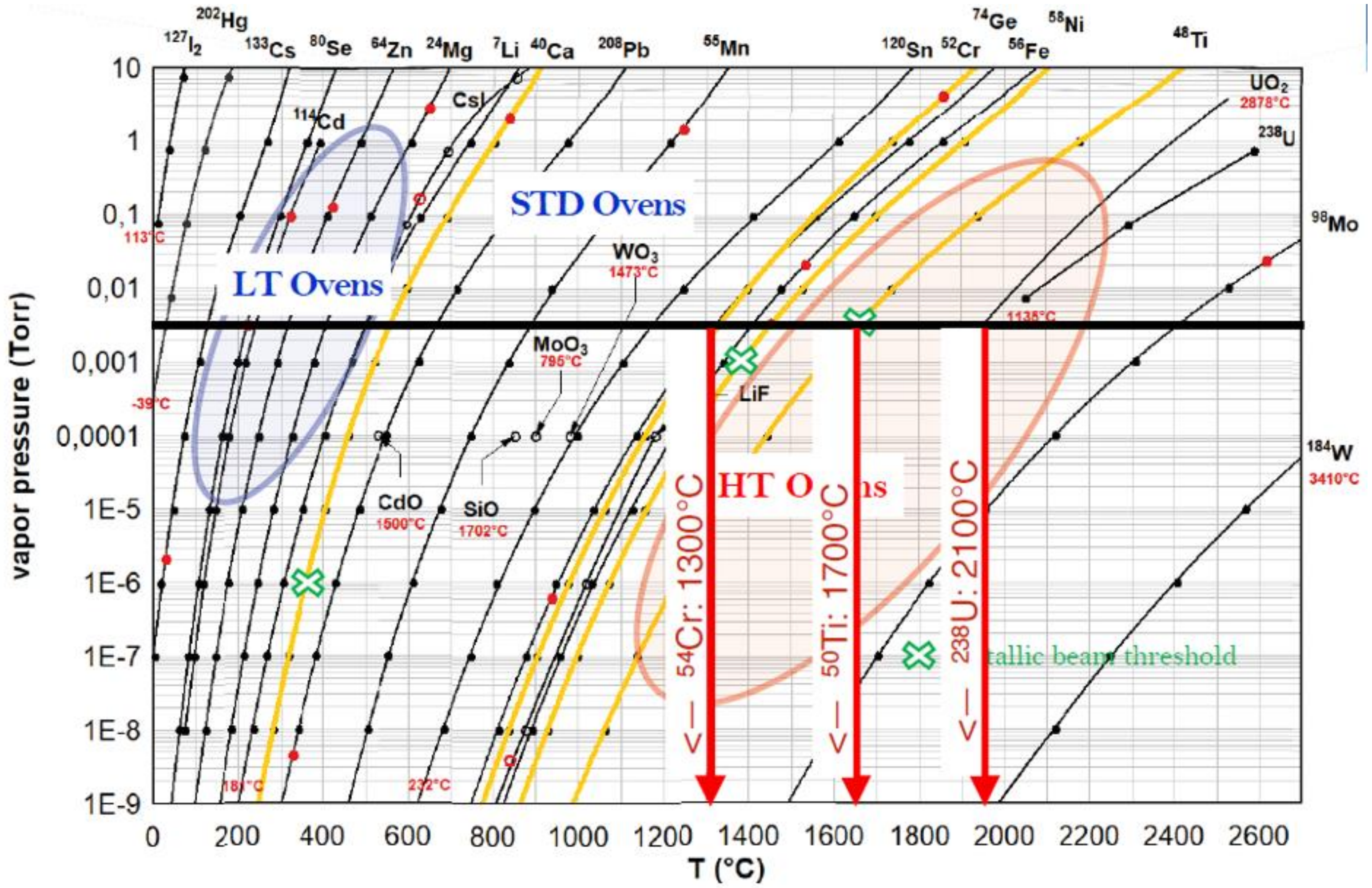


Accelerated beam stability $^{48}Ti^{+10}$



obtained

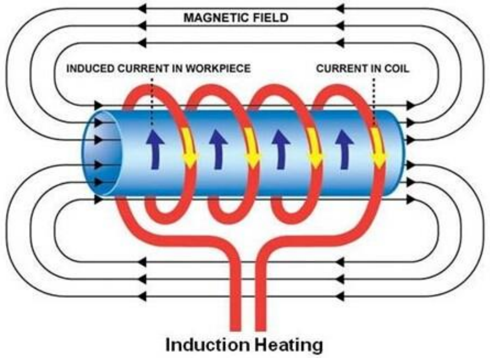
High temperature evaporator

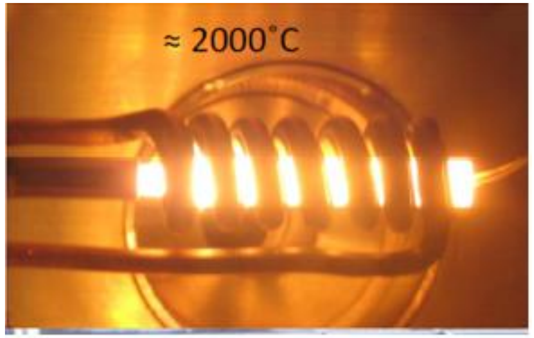


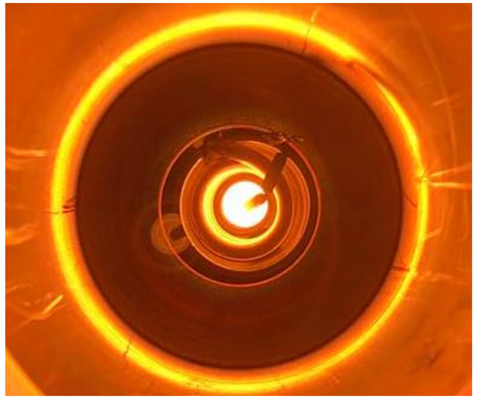
For refractory metals, the typical temperature to produce enough vapor (0.001-0.1 torr) in ECR ions source is 1600~2000º C.

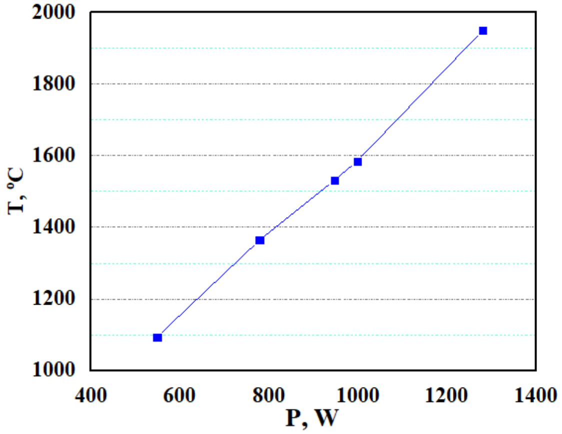
INDUCTIVE OVEN

Collaboration FLNR – IPHC (Strasburg)

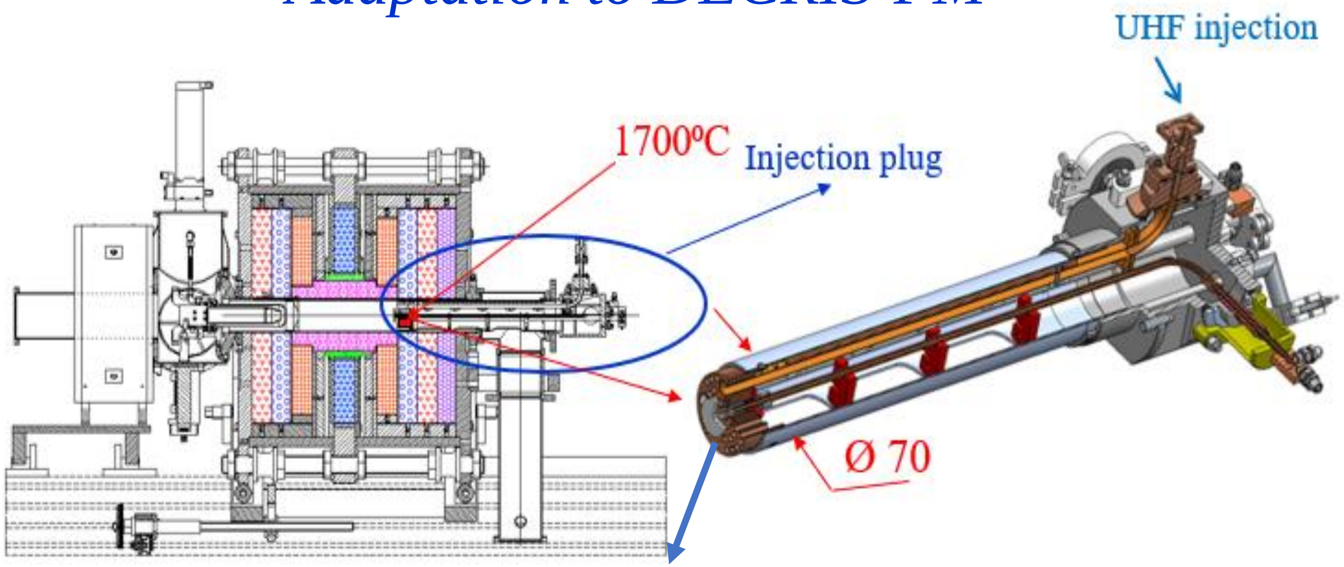


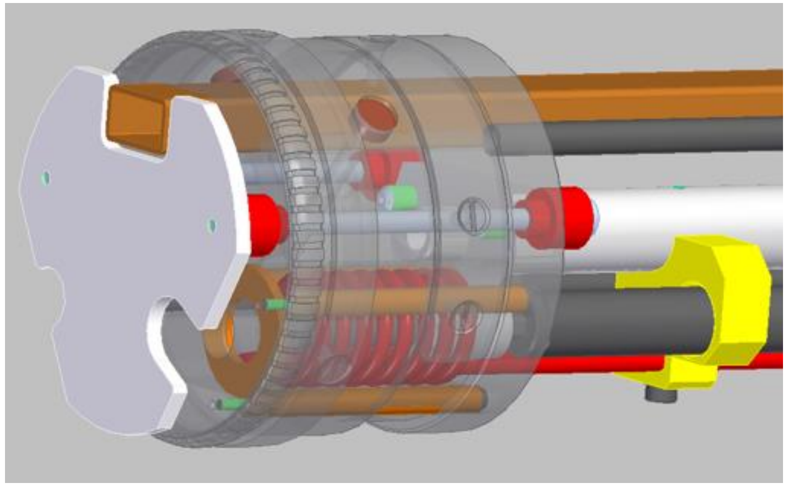




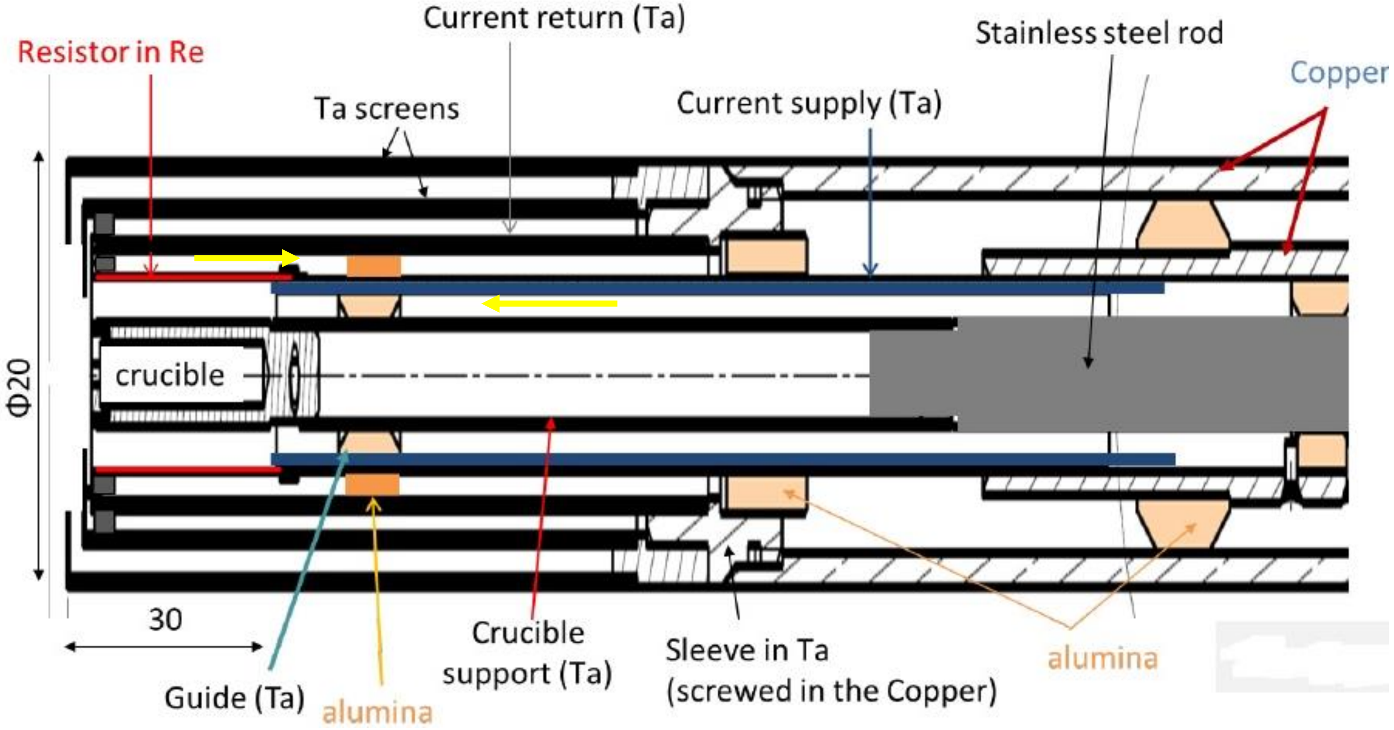


Adaptation to DECRIS-PM

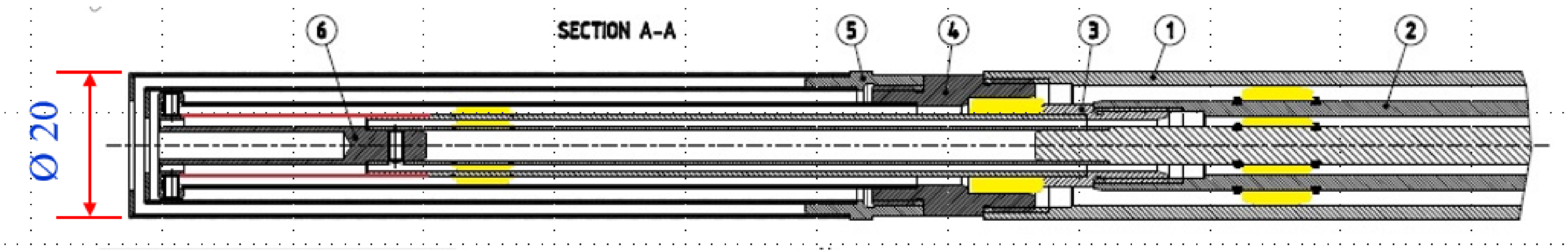




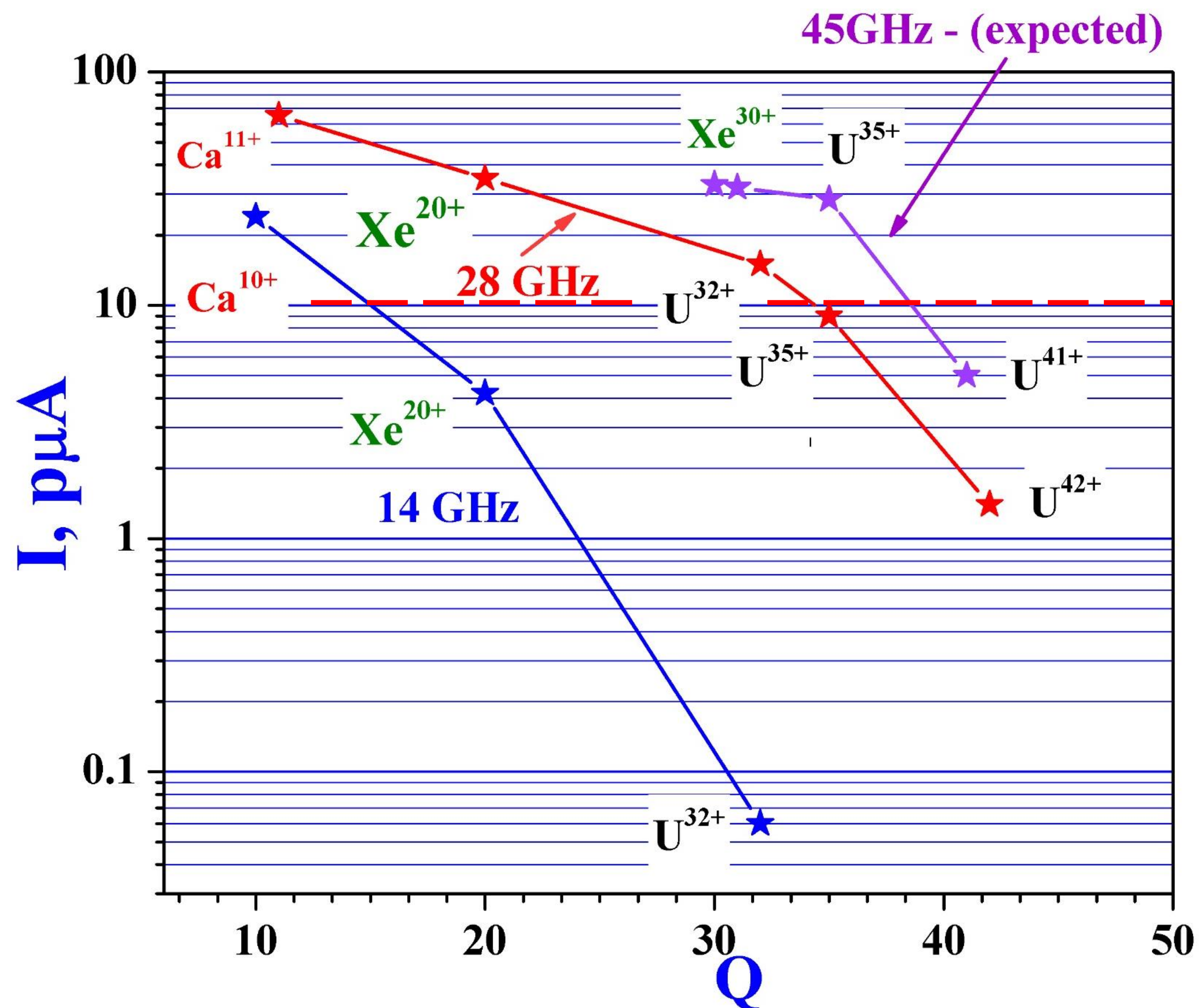
"FOIL" OVEN (GANIL type)



Technical drawings are developed in collaboration with VINCA (Belgrade)



Beam intensities of 14 GHz, 28 GHz and 45 GHz ECR ion sources



Development of heavy ion injector with 28 GHz ECR ion source

NIIEFA ROSATOM

JINR 114 Flerovium FLNR Dubna

Injector characteristics:

- Injection energy – up to 100 кV × charge
- Beam intensity of $^{40}Ar^{12+}$ - $1.2 \cdot 10^{14}$ pps
- Beam intensity of $^{132}Xe^{30+}$ - $1.2 \cdot 10^{13}$ pps
- Beam intensity of $^{48}Ca^{11+}$ - $8 \cdot 10^{13}$ pps

ИПФ РАН

IAP RAS

UHF system:

- UHF system type – gyrotron
- UHF frequency – 28 GHz
- UHF power – up to 10 kW

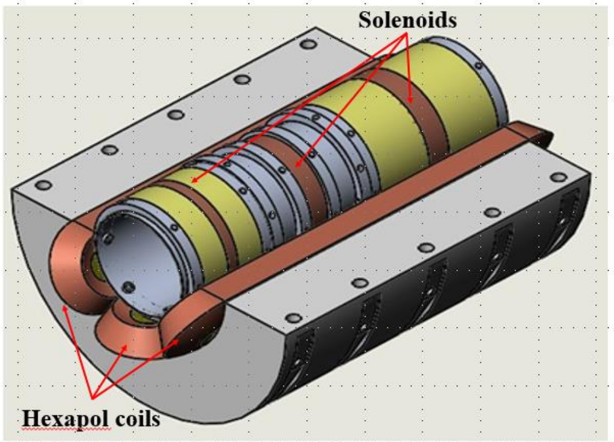
Superconducting magnet system:

NIIEFA ROSATOM

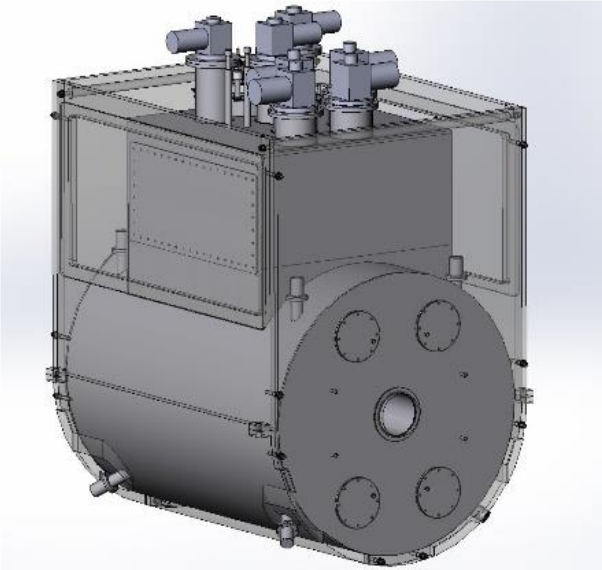
- “Warm” bore diameter = **Ø 142 mm**.
- Plasma chamber internal diameter = **Ø 124 mm**.
- Field peak-to-peak axial distance (B_{inj} and B_{extr}) $\boldsymbol{L}$ **= 420 mm,**
- B_{inj} on axis $\boldsymbol{B_{inj}}$ **= 4 Тл,**
- B_{extr} on axis $\boldsymbol{B_{extr}}$ **= 2 ÷ 2,5 Тл,**
- Minimal axial field $\boldsymbol{B_{min}}$ **= 0,5 ÷ 0,8 Тл,**
- Field module |**B**| at diameter = Ø 124 mm **2,02 Тл**,

New superconductor ***ECR source*** SC-ECRIS (28 GHz)

Structure



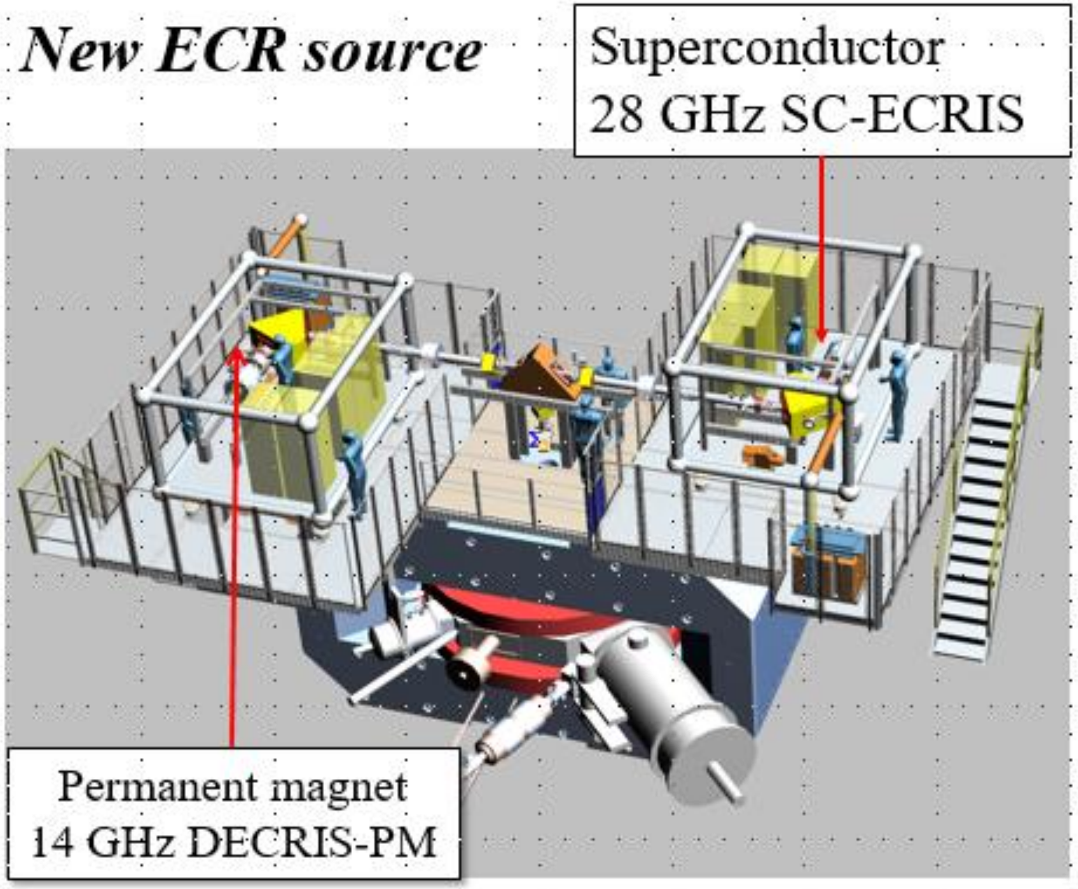
Gyrotron 28 GHz / 10 kW during bench test

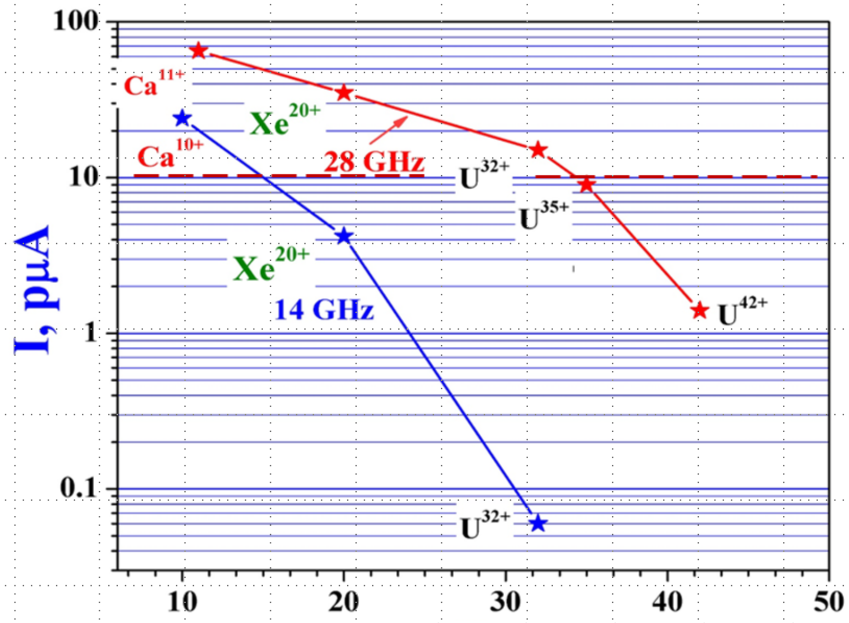


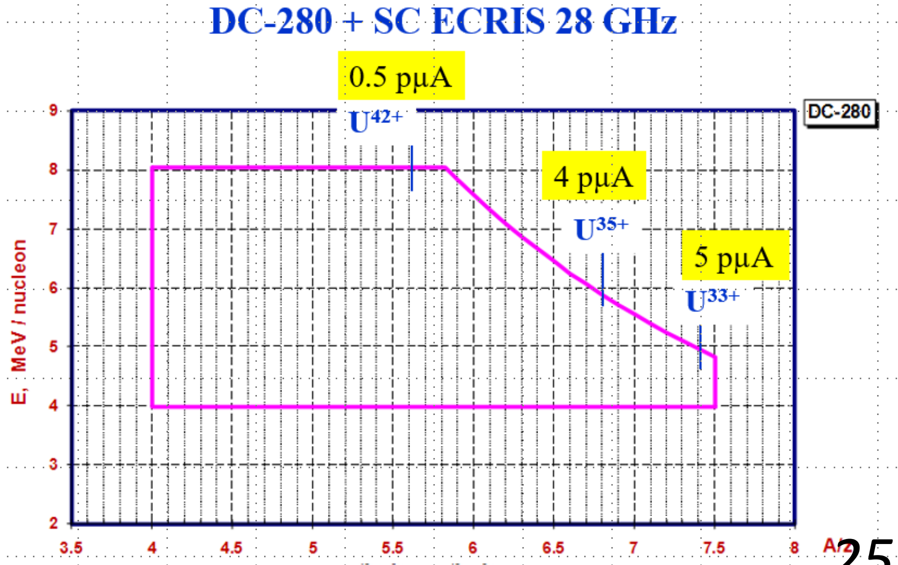
Cryostat common view

in progress

New superconductor *ECR source* SC-ECRIS (28 GHz)







in progress

Accelerated ^{48}Ca beam intensity

DC-280 beam intensity and efficiency of acceleration

Ion	Energy (MeV)	Intensity (pμA)				Transport Channel	Efficiency (%)				
		Axial injection		Cyclotron							
		after separation	before injection	R=400 mm	R= 1770 mm		Axial injection	Capture	Cyclotron	Extraction	Total
$^{48}Ca^{+10}$	240	1,2	1,15	0,86	0,80	0,5	96%	75%	93%	67%	45%
$^{48}Ca^{+10+}$	240	9	8,1	5,6	5,1	4,7	90%	69%	91%	91%	50%
$^{48}Ca^{+10}$	240	20	17,6	12,4	11	7,7	87%	70%	88%	71%	38%
$^{48}Ti^{+9}$	265	4,8	3,9	2,8	2,5	2,1	81%	71%	88%	86%	44%
$^{48}Ti^{+10}$	244	13,2	10,6	4,6	4,1	3,2	80%	43%	88%	80%	25%
$^{52}Cr^{+10}$	250	6,3	5,2	3,6	3,2	2,6	83%	69%	91%	81%	42%
$^{54}Cr^{+10}$	270	9,8	8,2	5,8	5,4	4,3	86%	71%	93%	80%	44%