

S.N. Dmitriev, Yu.Ts. Oganessian, G.G. Gulbekyan, I.V. Kalagin, B.N. Gikal,
S.L. Bogomolov, I.A. Ivanenko, N.Yu. Kazarinov, G.N. Ivanov, N.F. Osipov,
S.V. Pashchenko, M.V. Khabarov, V.A. Semin, A.V. Yeremin, V.K. Utyonkov

SHE-Factory:
**cyclotron facility for super heavy
element research**

Igor Kalagin

*FLEROV LABORATORY of NUCLEAR REACTIONS
JOINT INSTITUTE for NUCLEAR RESEARCH*

CYCLOTRONS 2019

DC-280
SHE factory

U-400
Heavy and superheavy
nuclei

U-400M
Light exotic
nuclei

IC-100
Applied research

NanoLab

DRIBs gallery

MT-25
Microtron



Cyclotron U400

Efficiency of transporting a $^{48}\text{Ca}^{5+}$ beam from the ECR source to a physical target

Measuring point	Beam intensity		Ion	Transmission factor				
ECR source, after separation	$1 \cdot 10^{14}$ pps	84 μAe	$^{48}\text{Ca}^{5+}$	32%				8.5%
Cyclotron center	$3.5 \cdot 10^{13}$ pps	27 μAe	$^{48}\text{Ca}^{5+}$		81%			
Extraction radius	$2.8 \cdot 10^{13}$ pps	22 μAe	$^{48}\text{Ca}^{5+}$		40%			
Extracted beam (by charge exchange)	$9.7 \cdot 10^{12}$ pps	28 μAe	$^{48}\text{Ca}^{18+}$				82%	
Target	$8 \cdot 10^{12}$ pps	23 μAe	$^{48}\text{Ca}^{18+}$					

DUBNA Gas Filled Recoil Separator

Target



Beam

Isotopes

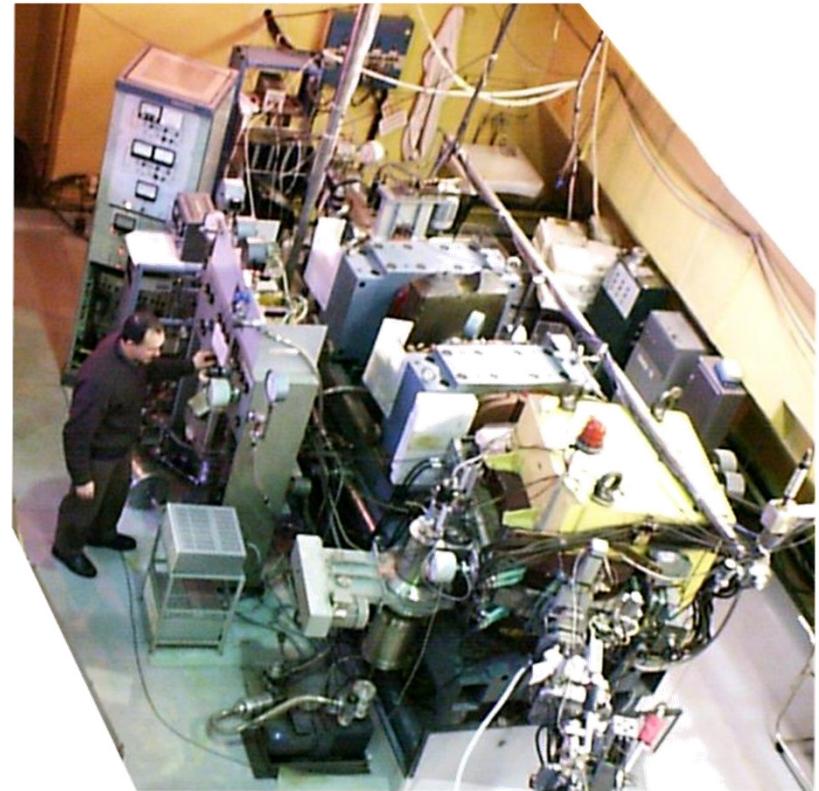
U-400 cyclotron, ^{48}Ca beams:

Ion beam energy: 5.00 – 5.75 MeV/A

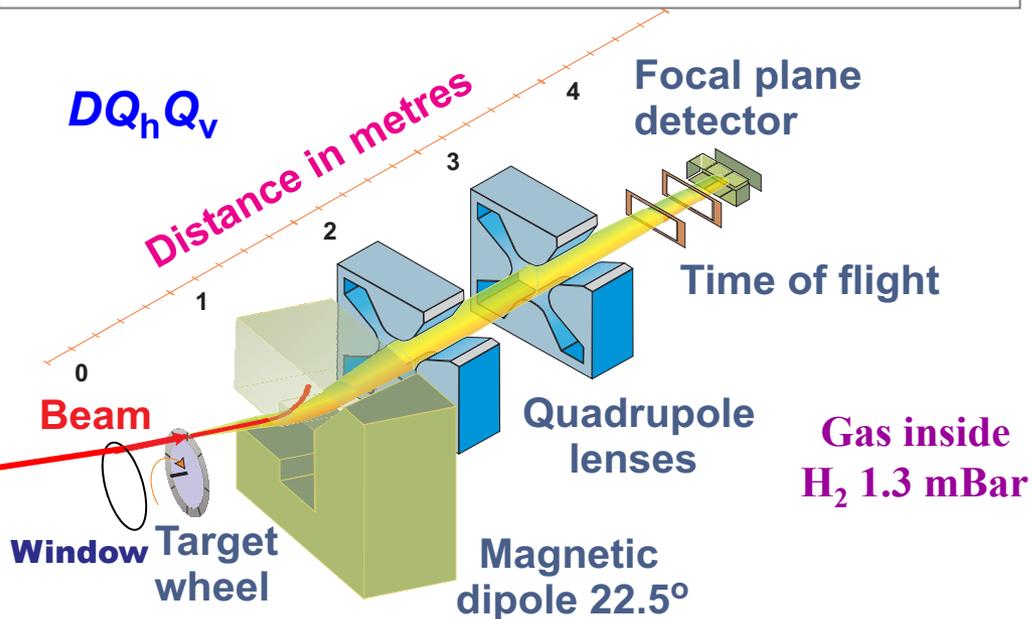
Beam intensity: 6 - 8 · 10¹² pps (up to 1.2 μA)

Consumption of ^{48}Ca = 0.5-0.8 mg/h

Beam time: 2000 – 4000 hours per year



In operation since 1989



DUBNA Gas Filled Recoil Separator

Target



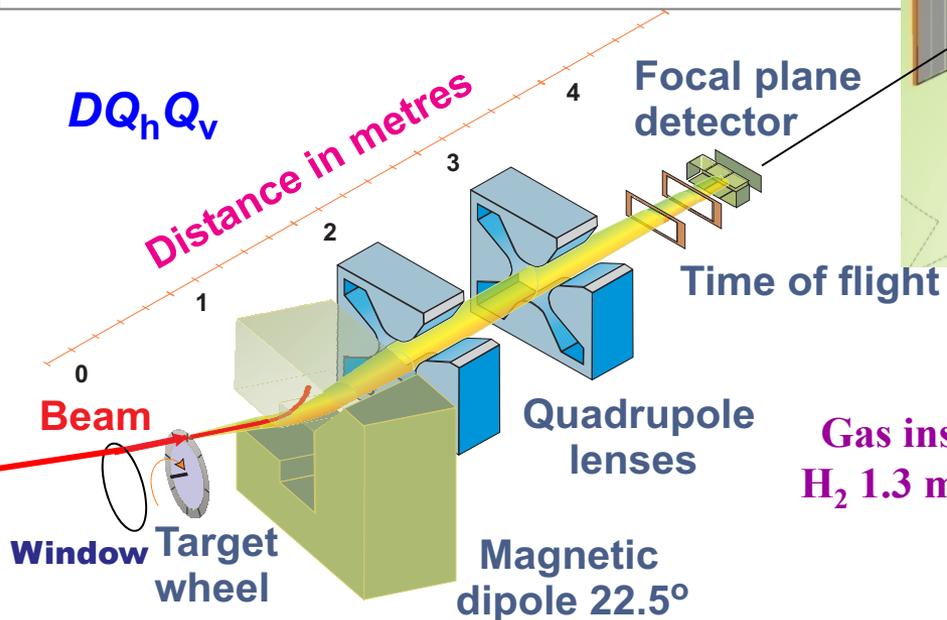
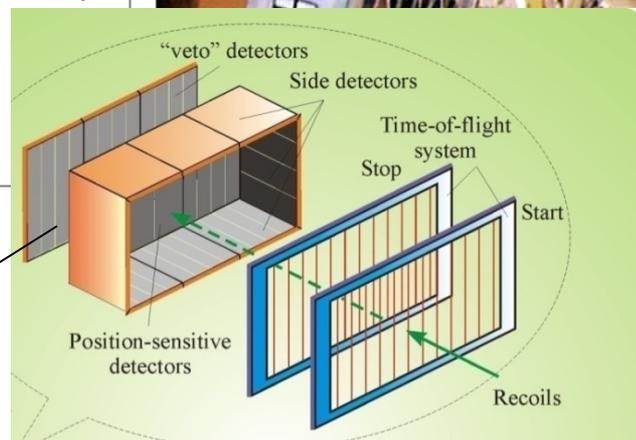
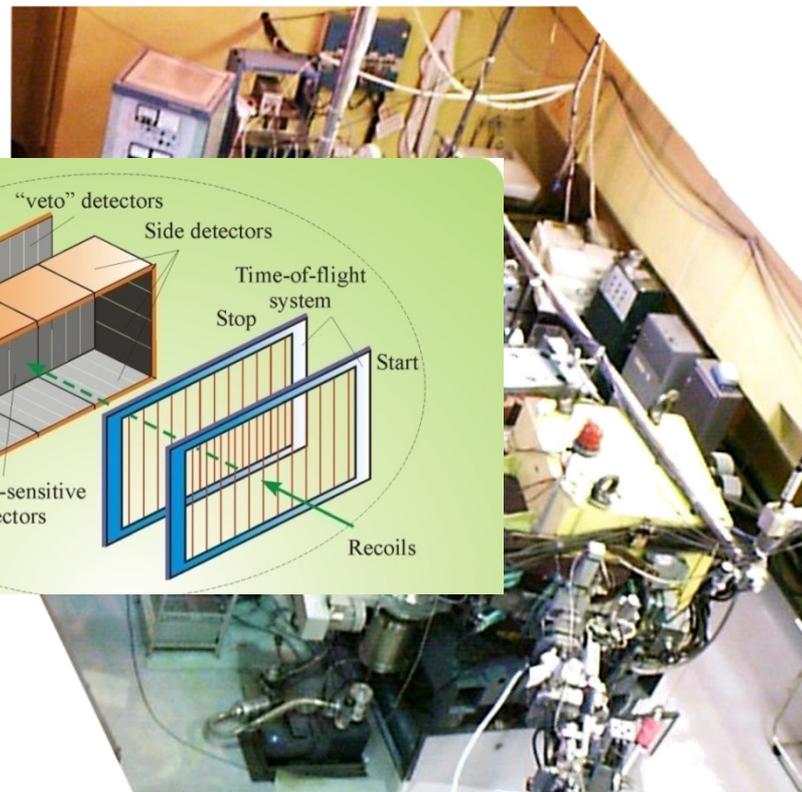
U-400 cyclotron, ^{48}Ca beams:

Ion beam energy: 5.00 – 5.75 MeV/A

Beam intensity: 6 - 8 · 10¹² pps (up to 1.2 μA)

Consumption of ^{48}Ca = 0.5-0.8 mg/h

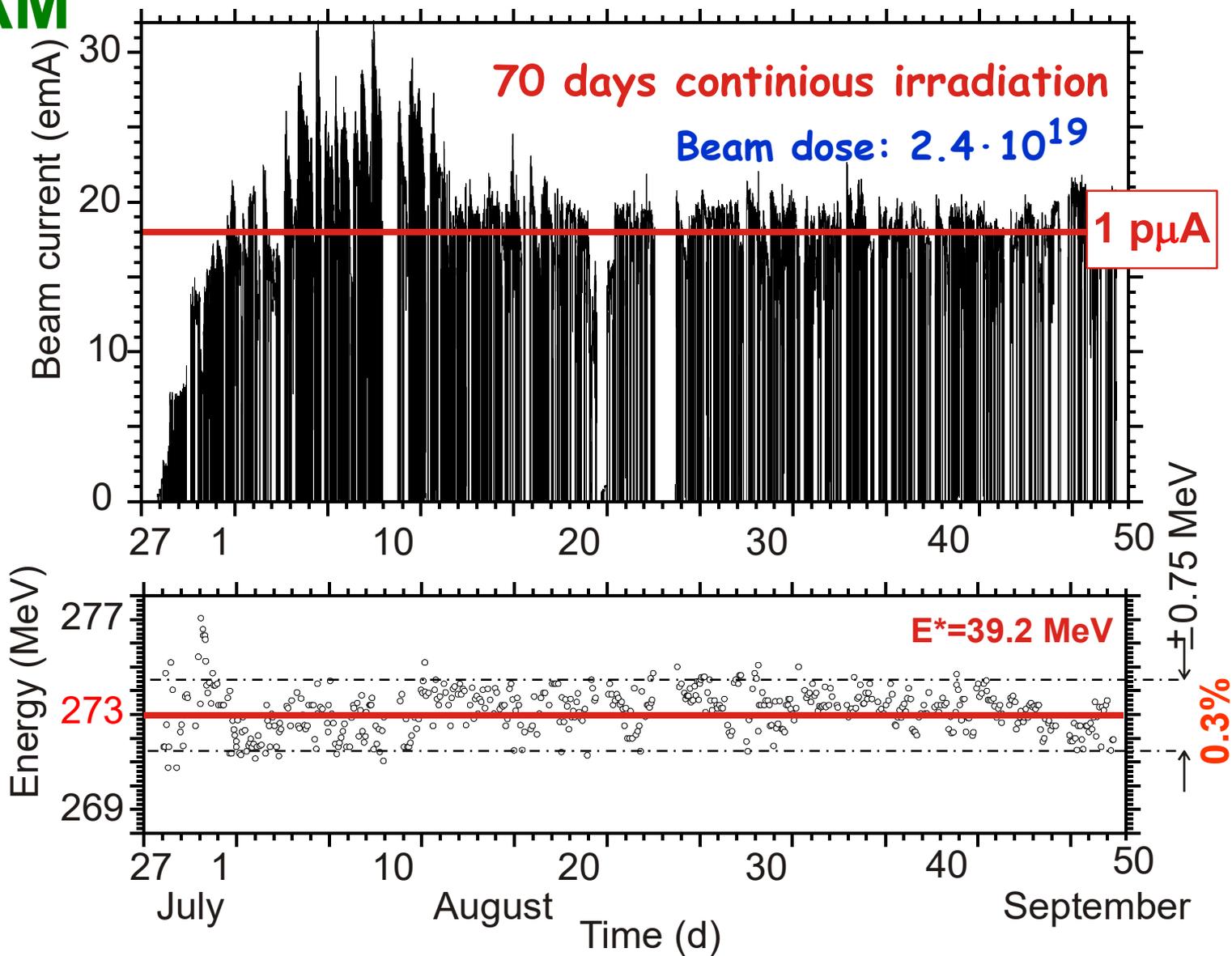
Beam time: 2000 – 4000 hours per year



Gas inside H_2 1.3 mBar

In operation since 1989

BEAM





ЛАБОРАТОРИЯ ЯДЕРНЫХ РЕАКЦИЙ



Периодическая таблица элементов Д.И. Менделеева

D.I. Mendeleev's Periodic Table of Elements

1																	18
Водород 1 H 1.008 Hydrogen	2															Гелий 2 He 4.0026 Helium	
Литий 3 Li 6.94 Lithium	Бериллий 4 Be 9.0122 Beryllium															Неон 10 Ne 19.9984 Neon	
Натрий 11 Na 22.99 Sodium	Магний 12 Mg 24.305 Magnesium	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Калий 19 K 39.098 Potassium	Кальций 20 Ca 40.078(4) Calcium	Скандий 21 Sc 44.956 Scandium	Титан 22 Ti 47.867 Titanium	Ванадий 23 V 50.942 Vanadium	Хром 24 Cr 51.996 Chromium	Марганец 25 Mn 54.938 Manganese	Железо 26 Fe 55.845(2) Iron	Кобальт 27 Co 58.933 Cobalt	Никель 28 Ni 58.693 Nickel	Медь 29 Cu 63.546(3) Copper	Цинк 30 Zn 65.38(2) Zinc	Галлий 31 Ga 69.723 Gallium	Германий 32 Ge 72.630(8) Germanium	Фосфор 15 P 30.974 Phosphorus	Сера 16 S 32.06 Sulfur	Хлор 17 Cl 35.45 Chlorine	Аргон 18 Ar 39.948 Argon
Рубидий 37 Rb 85.468 Rubidium	Стронций 38 Sr 87.62 Strontium	Иттрий 39 Y 88.906 Yttrium	Цирконий 40 Zr 91.224(2) Zirconium	Ниобий 41 Nb 92.906 Niobium	Молибден 42 Mo 95.94 Molybdenum	Технеций 43 Tc [98] Technetium	Рутений 44 Ru 101.07(2) Ruthenium	Родий 45 Rh 102.51 Rhodium	Палладий 46 Pd 106.42 Palladium	Серебро 47 Ag 107.87 Silver	Кадмий 48 Cd 112.41 Cadmium	Индий 49 In 114.82 Indium	Олово 50 Sn 118.71 Tin	Сурьма 51 Sb 121.76 Antimony	Селен 34 Se 78.971(8) Selenium	Бром 35 Br 79.904 Bromine	Криpton 36 Kr 83.798 Krypton
Цезий 55 Cs 132.91 Cesium	Барий 56 Ba 137.33 Barium	Лантан 57 La 138.91 Lanthanum	Гафний 72 Hf 178.49(2) Hafnium	Тантал 73 Ta 180.95 Tantalum	Вольфрам 74 W 183.84 Tungsten	Рений 75 Re 186.21 Rhenium	Осмий 76 Os 190.23(3) Osmium	Иридий 77 Ir 192.22 Iridium	Платина 78 Pt 195.08 Platinum	Золото 79 Au 196.97 Gold	Ртуть 80 Hg 200.59 Mercury	Таллий 81 Tl 204.38 Thallium	Свинец 82 Pb 207.2 Lead	Висмут 83 Bi 208.98 Bismuth	Полоний 84 Po [209] Polonium	Астат 85 At [210] Astatine	Радон 86 Rn [222] Radon
Франций 87 Fr [223] Francium	Радий 88 Ra [226] Radium	Актиний 89 Ac [227] Actinium	Резерфордий 104 Rf [261] Rutherfordium	Дубний 105 Db [268] Dubnium	Сибиргий 106 Sg [271] Seaborgium	Борий 107 Bh [270] Bohrium	Хассий 108 Hs [278] Hassium	Мейтнерий 109 Mt [278] Meitnerium	Дармштадтий 110 Ds [281] Darmstadtium	Рентгений 111 Rg [281] Roentgenium	Коперниций 112 Cn [285] Copernicium	Нихоний 113 Nh [286] Nihonium	Флеровий 114 Fl [289] Flerovium	Московий 115 Mc [290] Moscovium	Ливерморий 116 Lv [293] Livermorium	Теннесси 117 Ts [294] Tennessine	Оганesson 118 Og [294] Oganesson

Лантаноиды Lanthanoides

Перий 58 Ce 140.12 Cerium	Прасеодимий 59 Pr 140.91 Praseodymium	Неодим 60 Nd 144.24 Neodymium	Прометий 61 Pm [145] Promethium	Самарий 62 Sm 150.36(2) Samarium	Европий 63 Eu 151.96 Europium	Гадолиний 64 Gd 157.25(3) Gadolinium	Тербий 65 Tb 158.93 Terbium	Диспрозий 66 Dy 162.50 Dysprosium	Гольмий 67 Ho 164.93 Holmium	Эрбий 68 Er 167.26 Erbium	Тулий 69 Tm 168.93 Thulium	Иттербий 70 Yb 173.05 Ytterbium	Лютеций 71 Lu 174.967 Lutetium
------------------------------------	--	--	--	---	--	---	--------------------------------------	--	---------------------------------------	------------------------------------	-------------------------------------	--	---

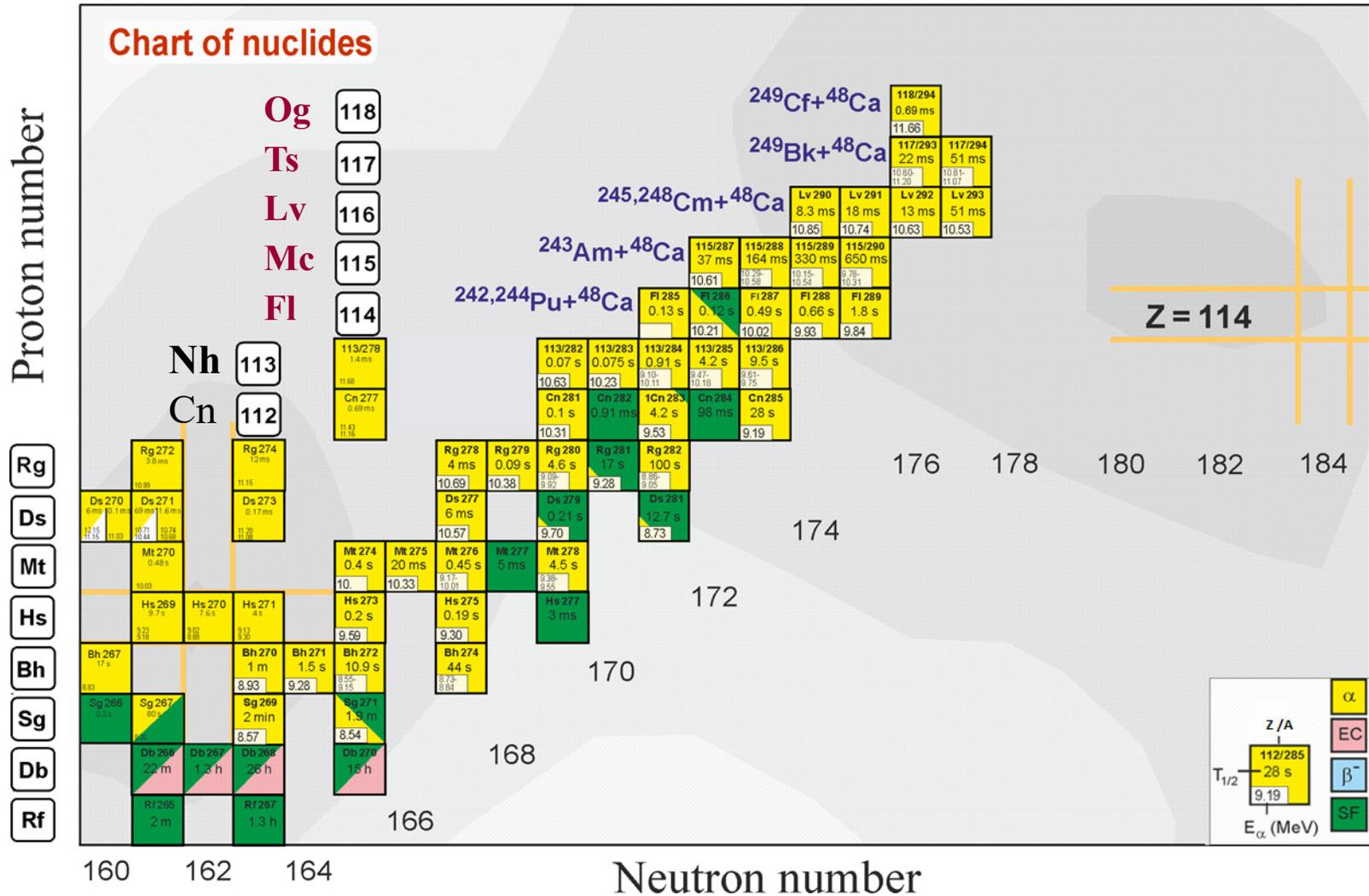
Водород 1 H 1.00794 Hydrogen

Актиноиды Actinoides

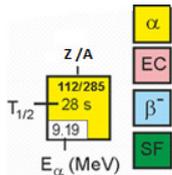
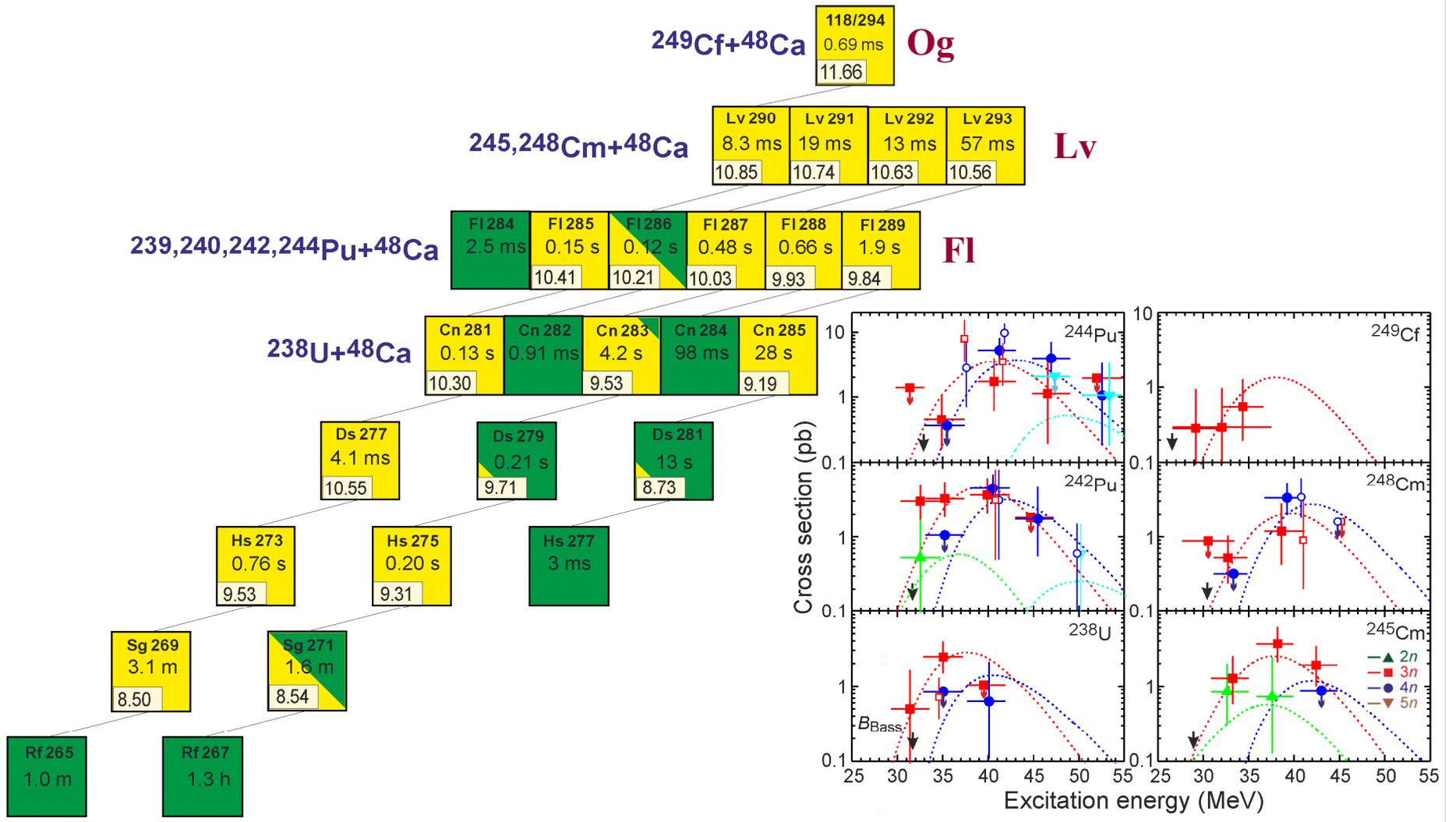
Торий 90 Th 232.04 Thorium	Протактиний 91 Pa 231.04 Protactinium	Уран 92 U 238.03 Uranium	Нептуний 93 Np [237] Neptunium	Плутоний 94 Pu [244] Plutonium	Америций 95 Am [243] Americium	Кюрий 96 Cm [247] Curium	Берклий 97 Bk [247] Berkelium	Калифорний 98 Cf [251] Californium	Эйнштейний 99 Es [252] Einsteinium	Фермий 100 Fm [257] Fermium	Менделеевий 101 Md [258] Mendelevium	Нобелий 102 No [259] Nobelium	Лавренсий 103 Lr [260] Lawrencium
-------------------------------------	--	-----------------------------------	---	---	---	-----------------------------------	--	---	---	--------------------------------------	---	--	--

H - символ / symbol
1.00794 - атомная масса / atomic mass
[237] - электронная конфигурация / electron configuration
15.259844 - 1-я потенциал ионизации, эВ / 1st ionization potential, eV
-259.34 - температура плавления, °C / melting temperature, °C
-252.87 - температура кипения, °C / boiling temperature, °C

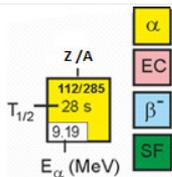
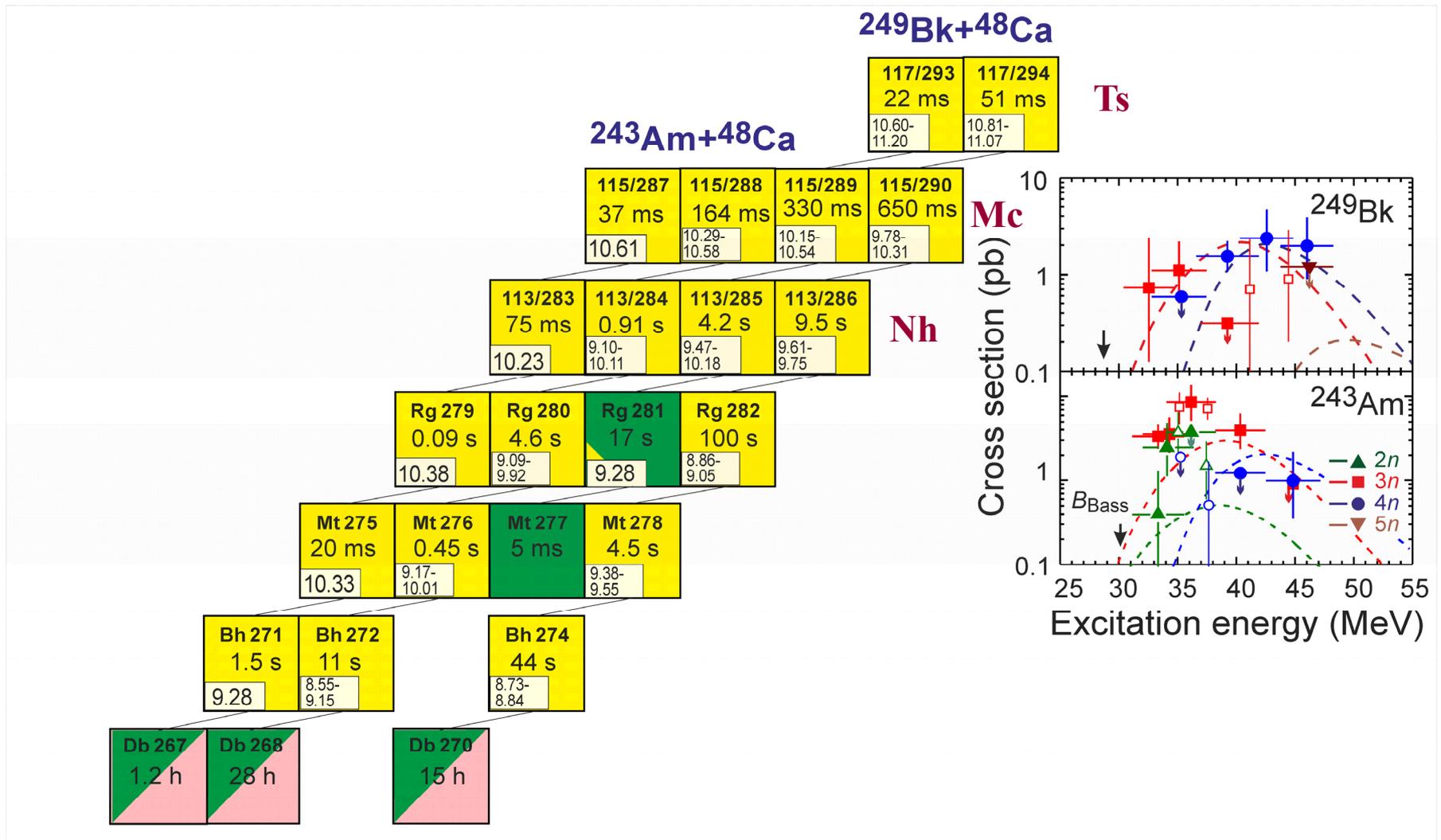
Region of superheavy nuclei



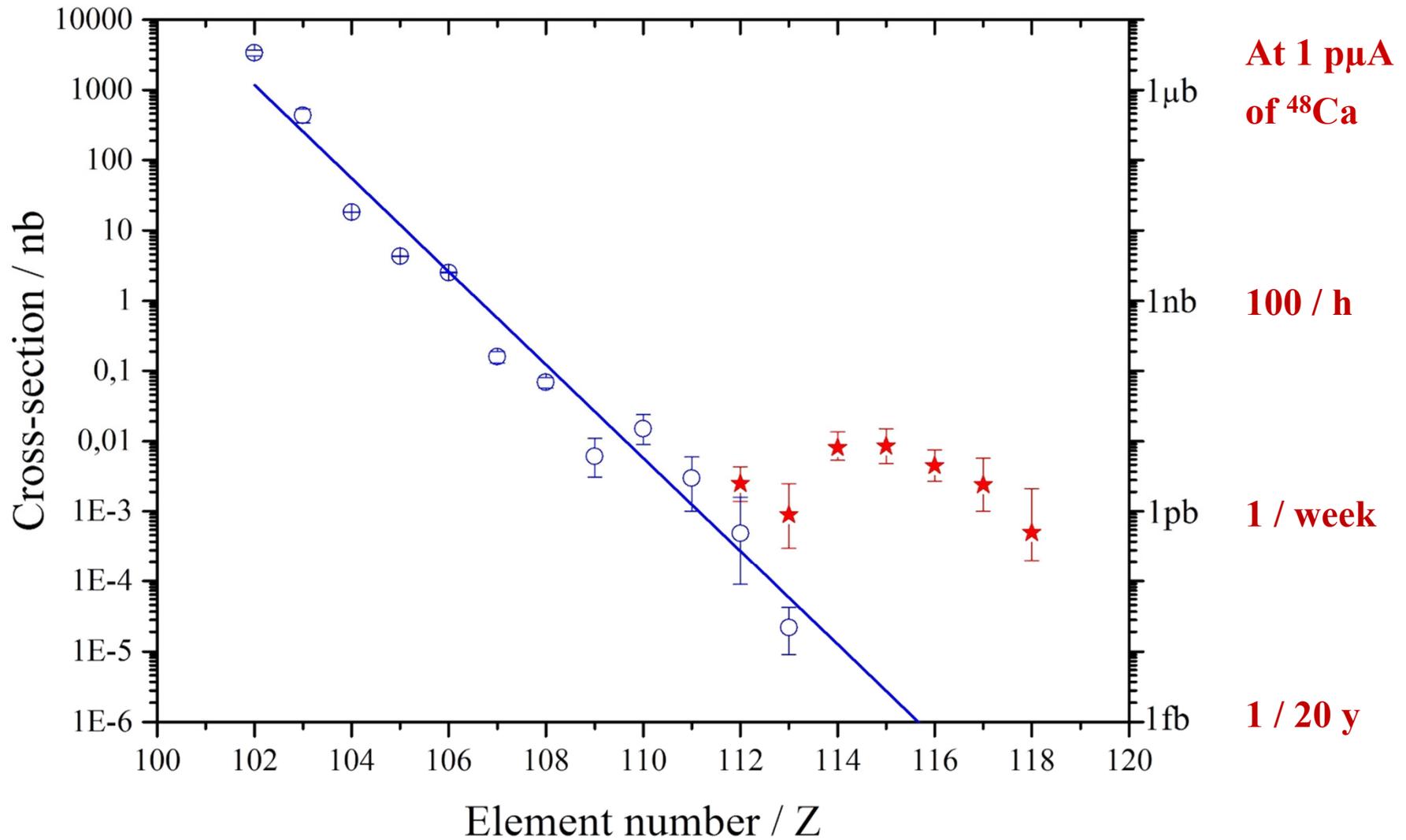
114, 116 and 118 elements



115 and 117 elements



Production cross-sections of heavy and super-heavy



What is beyond 118 element?

Heaviest target: $^{251}\text{Cf} + Z_{\text{max}} = 118 \dots$



➤ Heavier projectiles (^{50}Ti , ^{54}Cr , ^{58}Fe , ^{64}Ni)

Sufficient increasing of overall experiment efficiency is needed!

Superheavy Elements (SHE) Factory



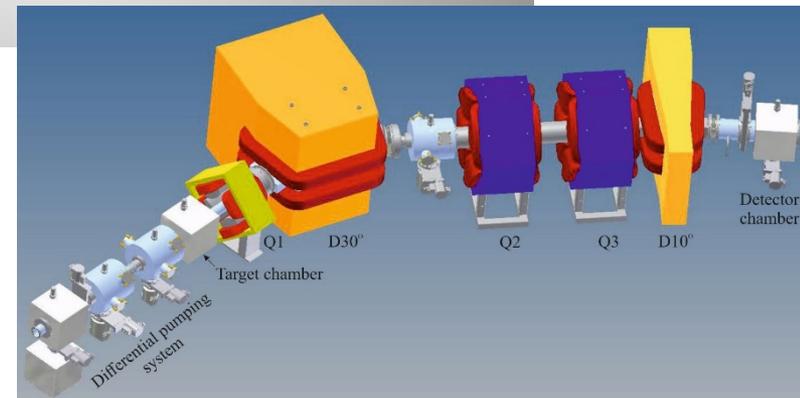
SHE Factory Building

High-current cyclotron DC-280



New facilities:

- New gas-filled separator
- Preseparator
- SHELS
- Etc.



SHE Factory – the Goals

- **Experiments at the extremely low ($\sigma < 100$ fb) cross sections:**
 - **Synthesis of new SHE in reactions with ^{50}Ti , ^{54}Cr ...;**
 - **Synthesis of new isotopes of SHE;**
 - **Study of decay properties of SHE;**

- **Experiments requiring high statistics:**
 - **Nuclear spectroscopy of SHE;**
 - **Study of chemical properties of SHE.**

DC-280 CYCLOTRON- THE NEW FLNR ACCELERATOR

To satisfy the **Goals**, the DC-280 has to provide the following parameters of ion beams:

Ion energy	4÷8 MeV/n
Ion masses	10÷238
Intensities (A~50)	>10 pμA
Beam emittance	less than 30 π mm·mrad
Efficiency of beam transfer	>50%

Allows to carry out experiments with expensive rare isotopes such as ⁴⁸Ca at low material consumption

Stand-alone SHE factory with DC-280 cyclotron



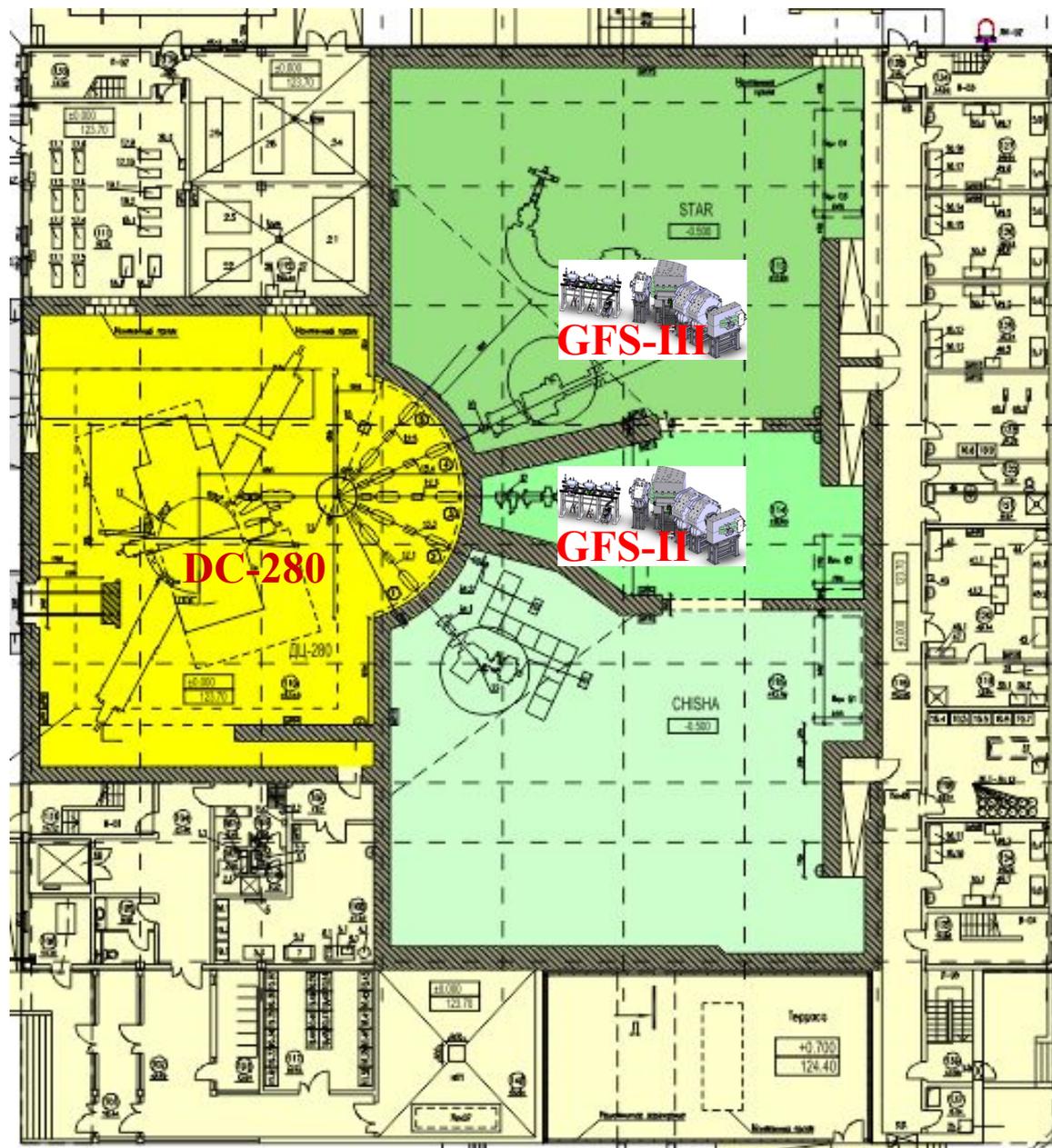
SHE factory building 2019



DC280 cyclotron 2019

DC280 E=4÷8 MeV/A		
Ion	Ion energy [MeV/A]	Expected output intensity
${}^7\text{Li}$	4	1×10^{14}
${}^{18}\text{O}$	8	1×10^{14}
${}^{40}\text{Ar}$	5	6×10^{13}
${}^{48}\text{Ca}$	5	$6,2 \times 10^{13}$
${}^{54}\text{Cr}$	5	2×10^{13}
${}^{58}\text{Fe}$	5	1×10^{13}
${}^{124}\text{Sn}$	5	2×10^{12}
${}^{136}\text{Xe}$	5	1×10^{14}
${}^{238}\text{U}$	7	5×10^{10}

Plan of the 1-st floor of the SHE Factory



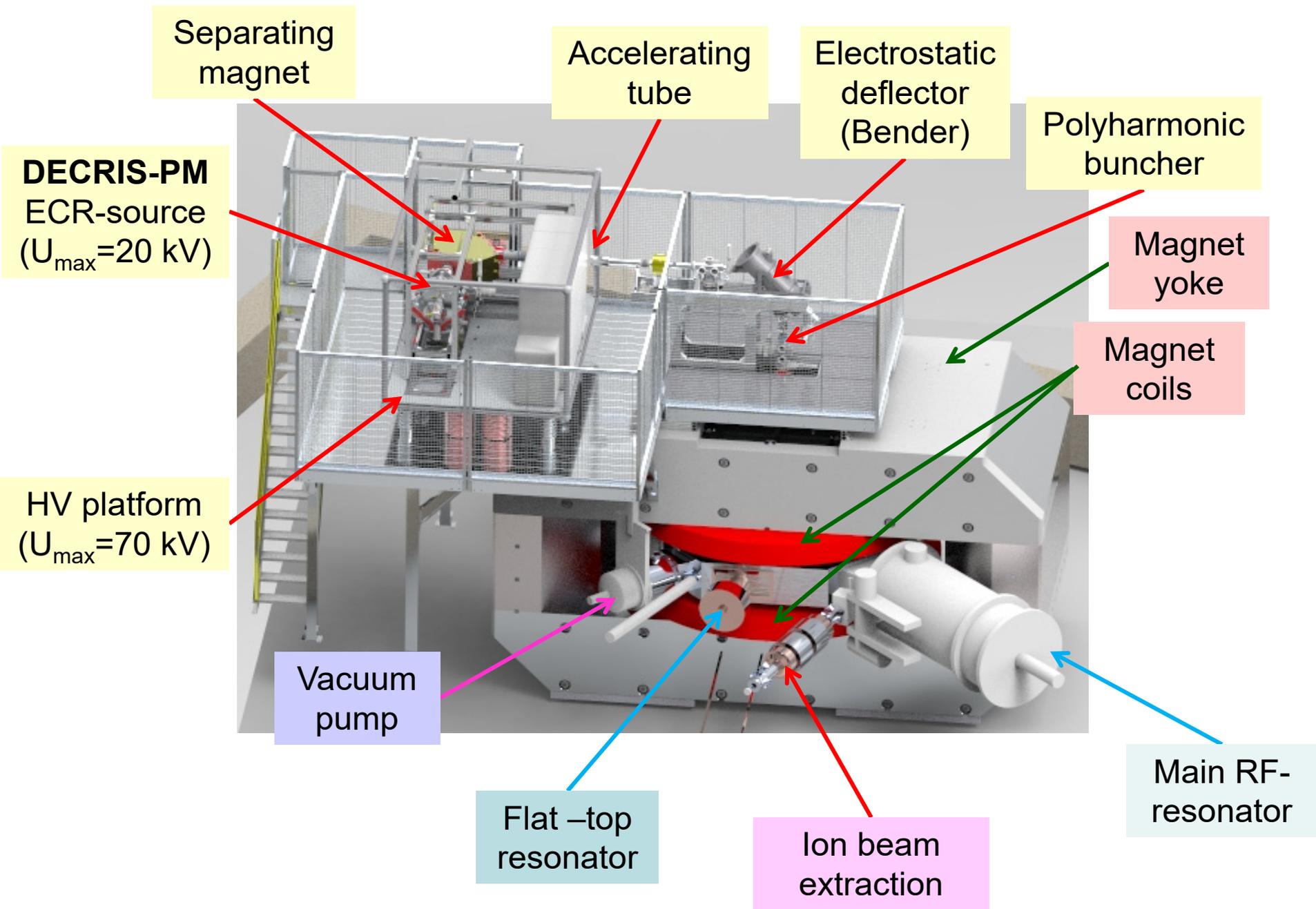
Experimental area ~1000 m² (3 halls)

DC-280

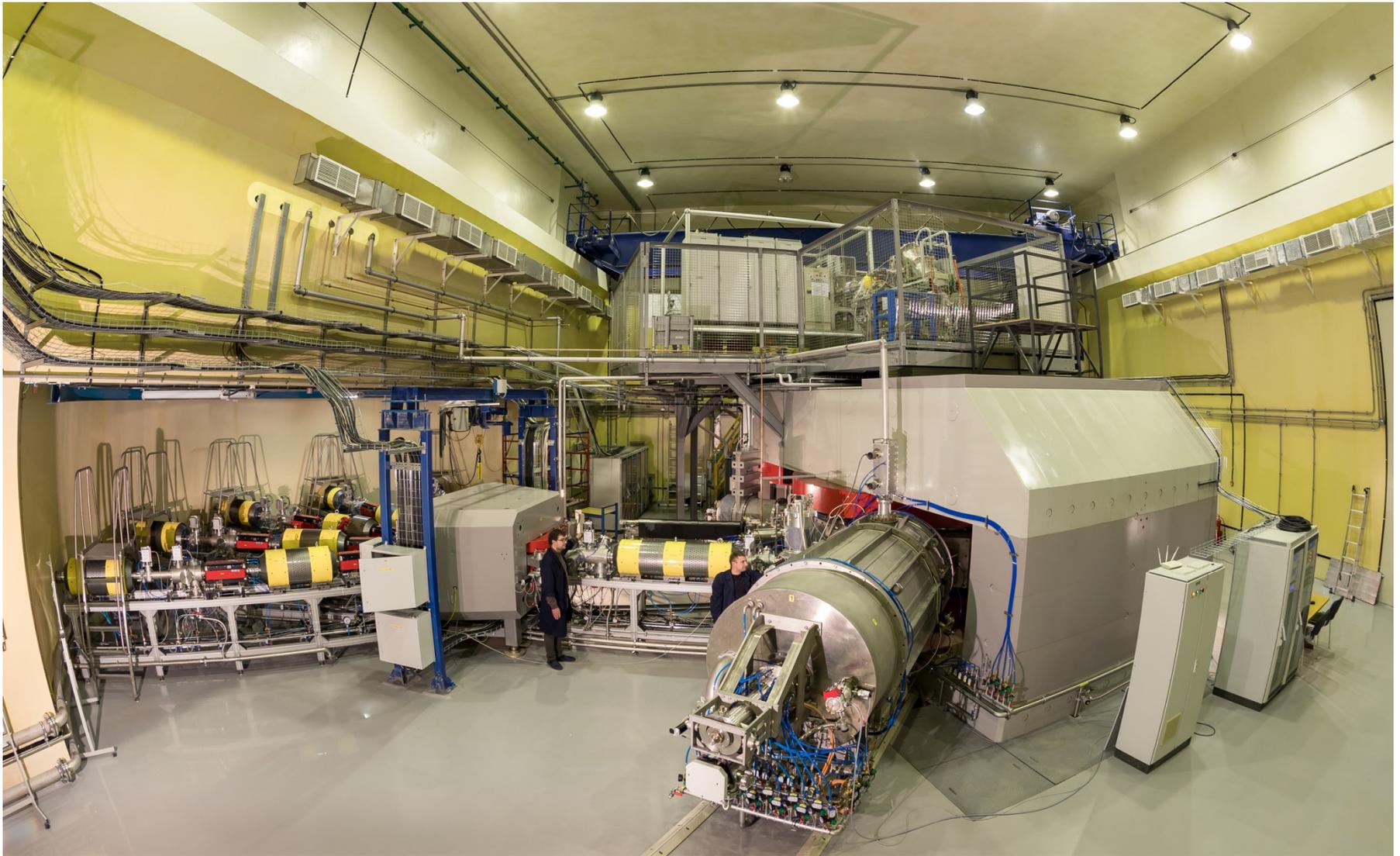
Main Parameters

Ion sources	DECRIS-PM - 14 GHz Superconducting ECR (developing stage)
Injection energy	Up to 80 keV/Z
A/Z range	4÷7.5
Ion energy	4÷8 MeV/n
Magnetic field level	0.6÷1.3 T
K factor	280
Dee voltage	2x130 kV
RF power consumption	2x30 kW
Flat-top dee voltage	2x14 kV
Deflector voltage	Up to 90 kV

Configuration of the DC-280



DC-280

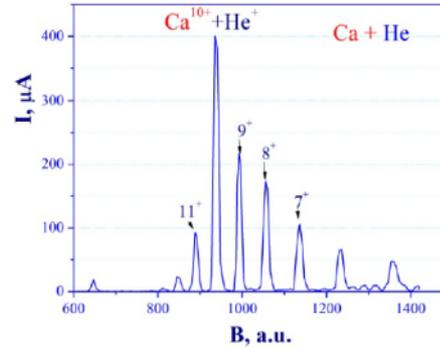


2019

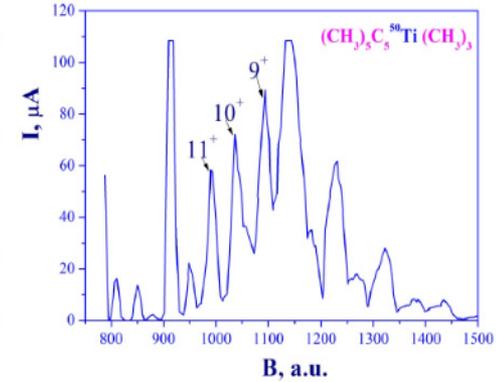
DECRIS-PM ion source



$\text{Ca}^{9+} = 210 \mu\text{A}$



$^{50}\text{Ti}^{10+} = 72 \mu\text{A}$



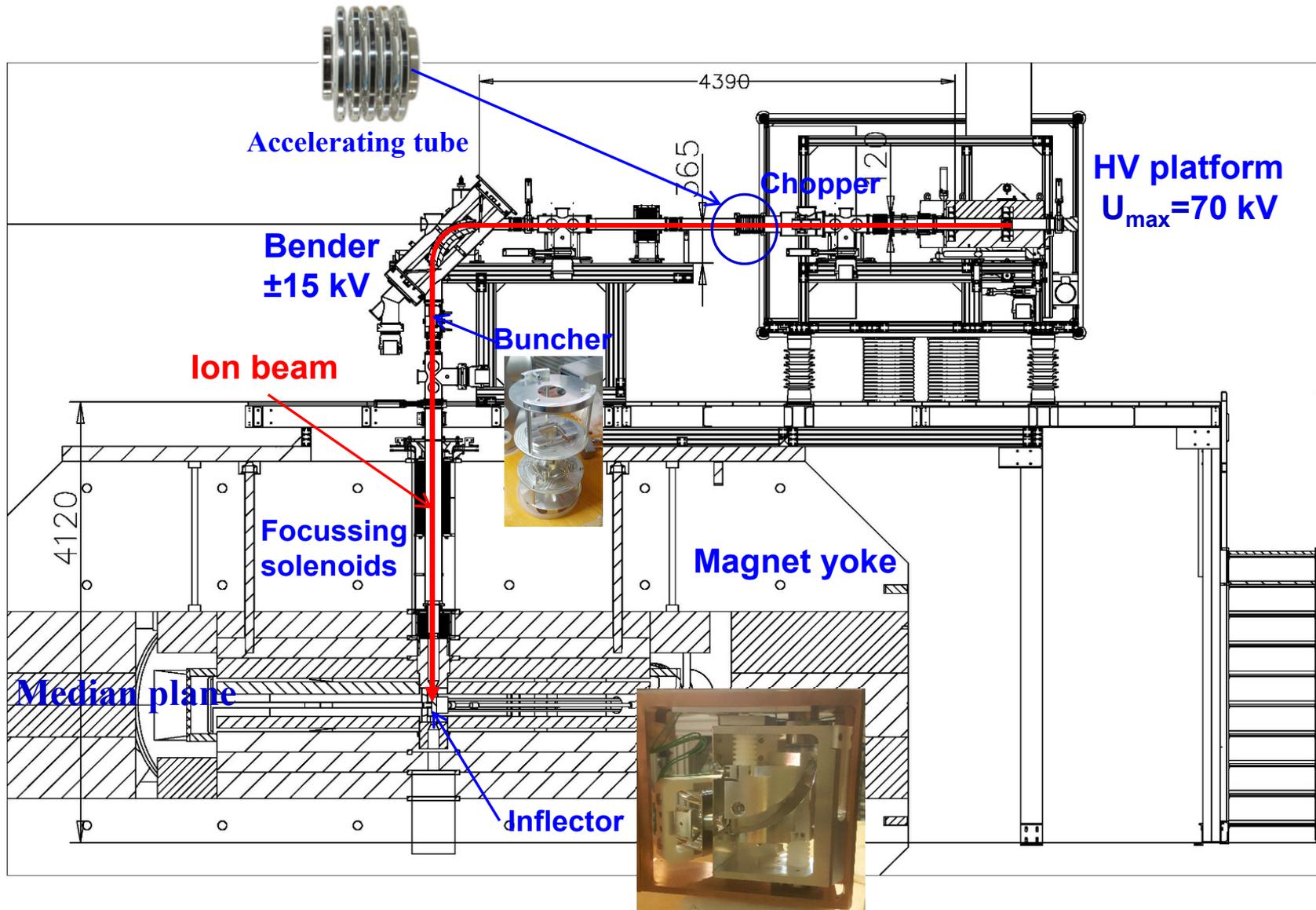
Results of bench test of DECRIS-PM

Frequency	Power consumption
14 GHz	5 kW

Magnetic fields	Value
Binj	$\geq 1.3 \text{ T}$
Bmin	0.4 T
Bextr	1.0 ÷ 1.1 T
Br	1.05 ÷ 1.15 T

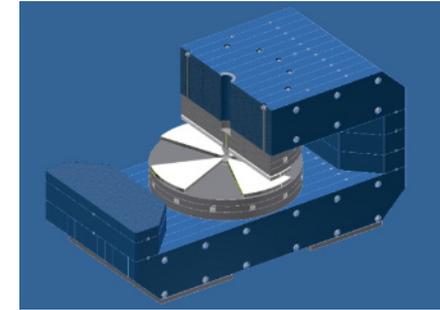
Ion currents, μA													
Q+	5+	7+	8+	9+	10+	11+	12+	15+	17+	19+	20+	23+	26+
Ar			116	56		19	13						
Kr							13	12	7,3	2,6			
Xe											3,9	3	2
²⁴ Mg	90	20	5	1,7									
⁴⁰ Ca		16	22	24		14	4,8						
⁵⁰ Ti				10	7,2	5,5	1,9						
⁵⁶ Fe				9,4	8	5							

Beam injection system



Magnetic system of ДЦ-280

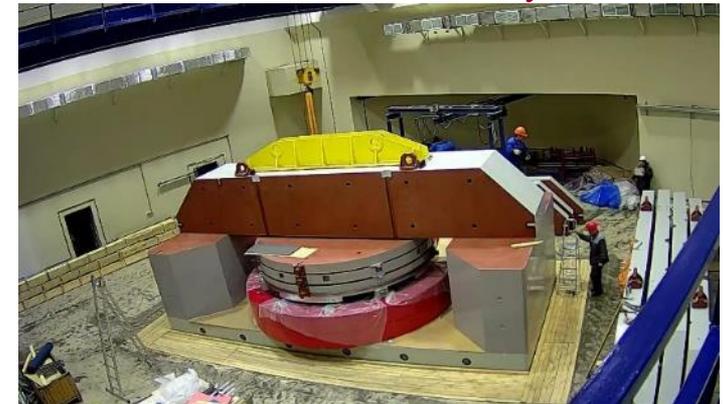
Size of magnet yoke LxWxH	8.76x4.08x4.84 m ³
Pole diameter	4 m
Gap between central plugs	400 mm
Valley/hill gap	500/208 mm/mm
Magnet weight	1000 t
Magnet power	300 kW
Maximal current	1000 A
Magnetic field level	0.6÷1.3 T



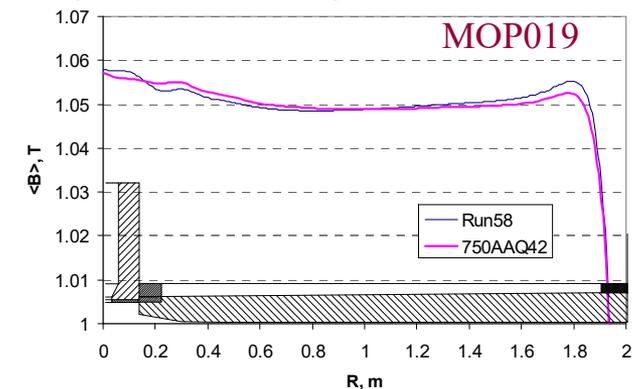
DC-280- isochronous cyclotron



Magnet assembling: September-November 2016
Magnetic field measurements: June-September 2017



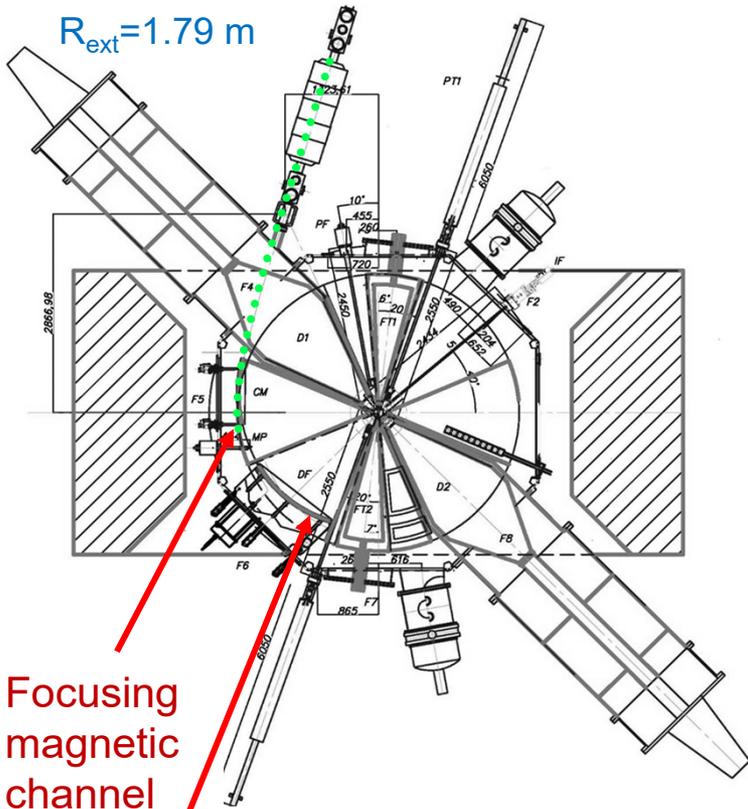
Magnet assembling (November 2016)



Comparative radial distributions of calculated and measured average magnetic field at the main coil current of 750A

Beam extraction system

Extraction radius of
 $R_{\text{ext}}=1.79\text{ m}$



Focusing
magnetic
channel

Electrostatic
deflector



Magnetic channel

$L=0.9\text{ m}$, $G=4.6\div 8.4\text{ T/m}$



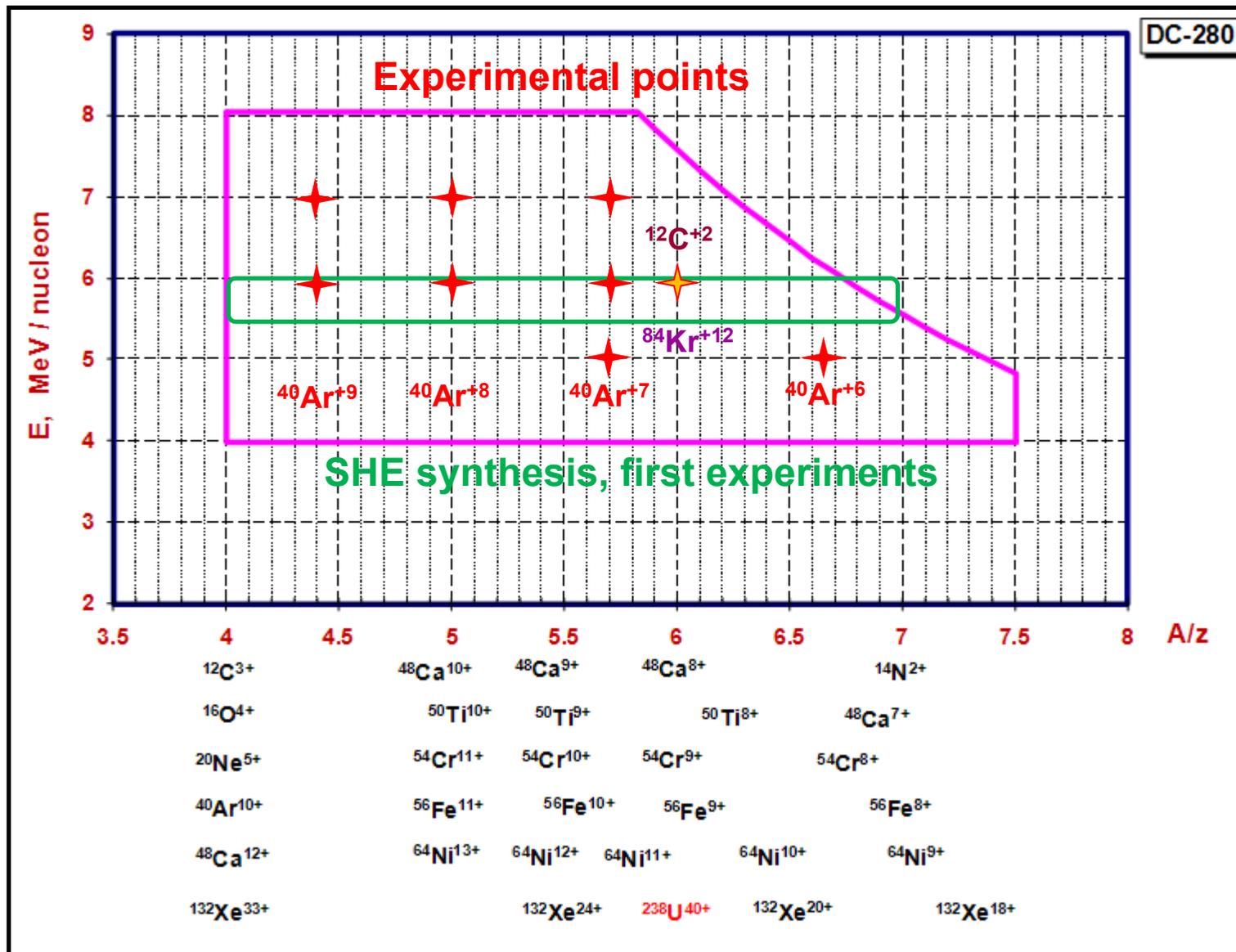
Assembling of the deflector

$L=1.3\text{ m}$, $E_{\text{max}}=90\text{ kB/cm}$, gap $D=1\text{ cm}$

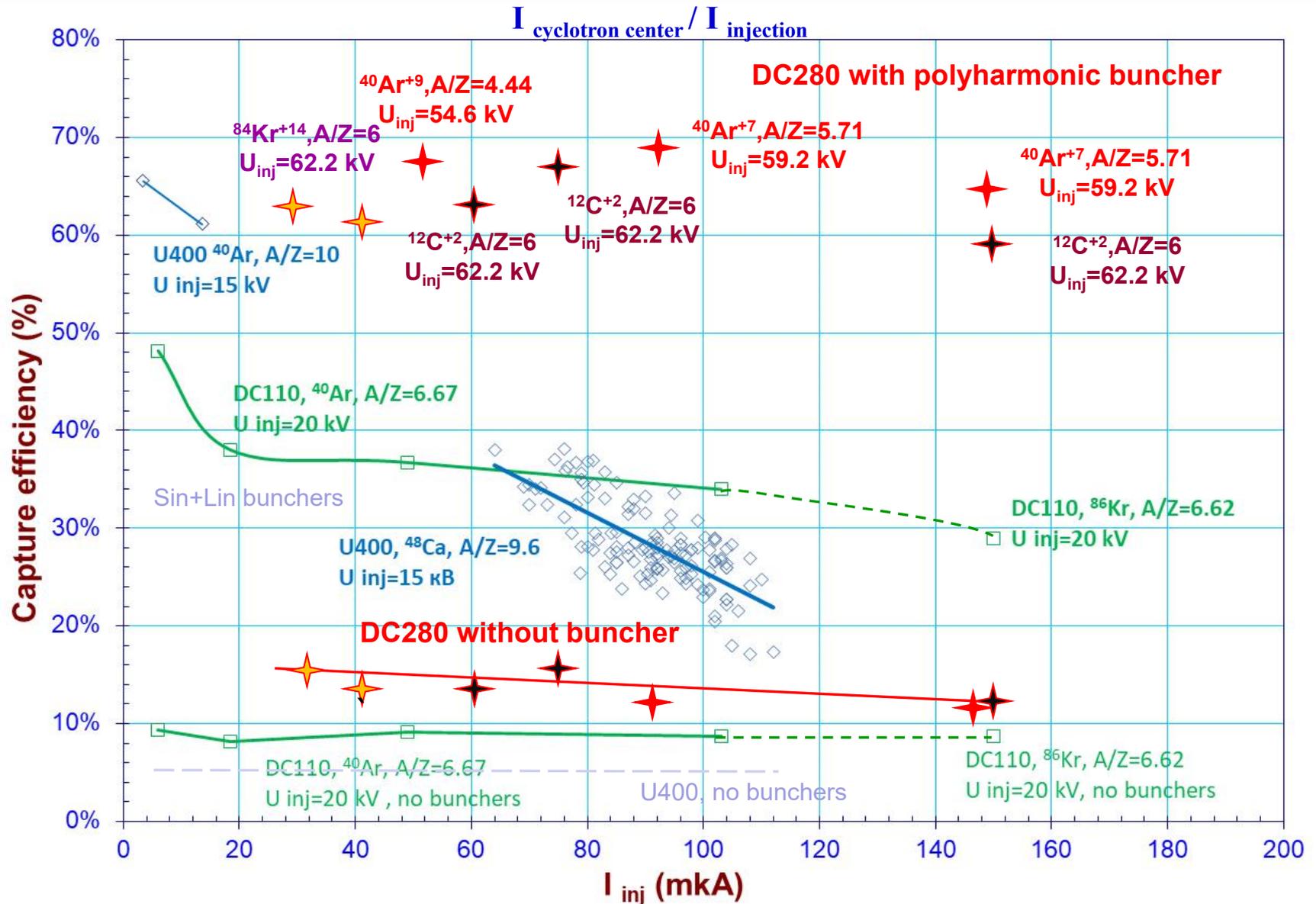


Electrostatic deflector in vacuum chamber

Working diagram of the DC-280

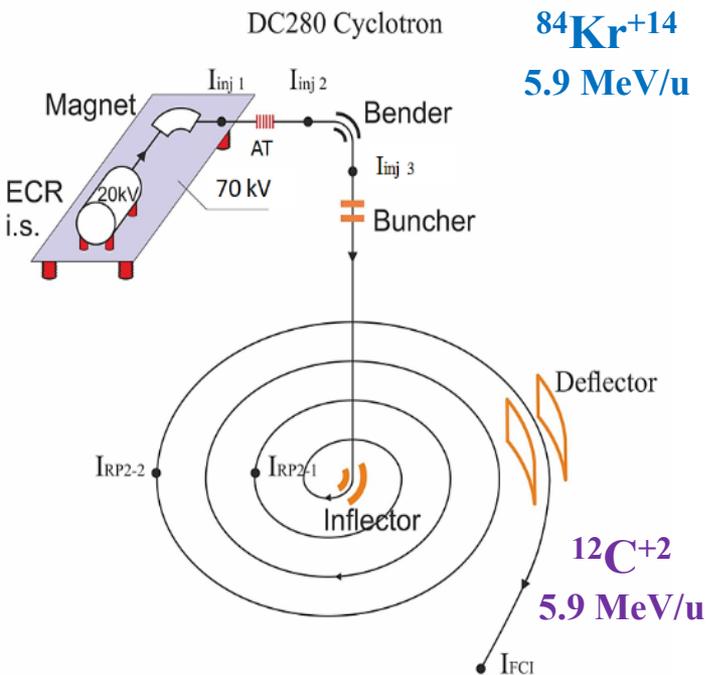


Comparative capture efficiencies of U400, DC110 and DC280



Experimental results

with polyharmonic buncher
without flat-top resonators



$^{84}\text{Kr}^{+14}$
5.9 MeV/u

$^{12}\text{C}^{+2}$
5.9 MeV/u

Injection			Acceleration		Beam transport
Ion current from ECR (I_{inj1}) eμA	Ion current after HV platform (I_{inj2}) eμA	Ion current in vertical channel (I_{inj3}) eμA	Ion current at R=40 cm (I_{RP2-1}) eμA	Ion current at R=175 cm (I_{RP2-2}) eμA	Ion current of extracted beam in transport channel (I_{FC1}) eμA
~56 (spectrum)	45,6	40,5	25	21,3	19 (1,36 μA)
88,8%					
			61,7%		
			85,2%		
					89,2%
41,7%					

69,7	69,7	59,5	37,8	31,3	20 (10 μA)
100%					
		85,4%			
		63,5%			
				82,8%	
				63,9%	
28,7% (extraction was not optimised)					

At $I_{inj3}=150 \text{ e}\mu\text{A}$ (21.4 μA) with 25% chopper the equivalent current of $^{40}\text{Ar}^{+7}$ ions was about $I_{FC1}=63 \text{ e}\mu\text{A}$ (9 μA)

$^{40}\text{Ar}^{+7}$
5.9 MeV/u

101	100,3	91	63	53	42 (6 μA)
99,3%					
		90,7%			
		69,2%			
				84,1%	
				79,2%	
41,6%					

Vacuum:

Injection: $5 \div 7 \cdot 10^{-8}$ Torr

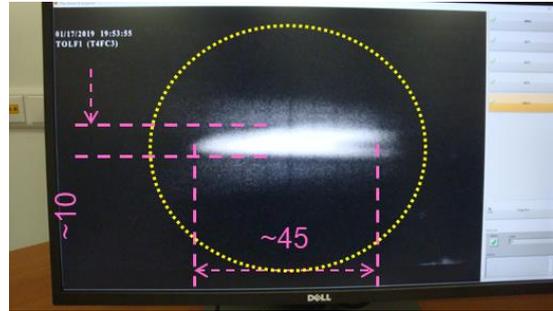
Cyclotron: $8 \div 9 \cdot 10^{-8}$ Torr

Beam line N3: $2 \div 3 \cdot 10^{-7}$ Torr

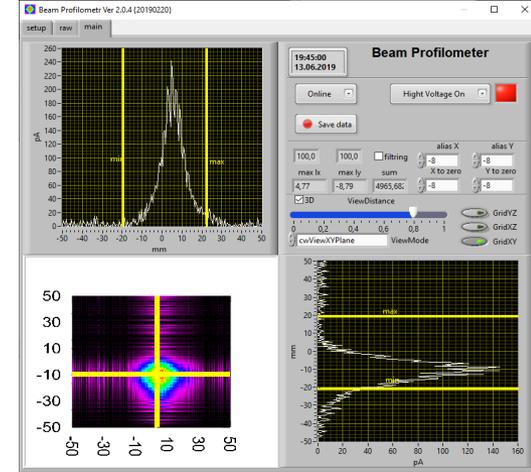
First beams of DC-280



The first accelerated beam of $^{84}\text{Kr}^{+14}$
26.12.2018



The first extracted beam of $^{84}\text{Kr}^{+14}$
17.01.2019



$^{40}\text{Ar}^{+7}$ beam profiles in N3 channel
June 2019



$$U_{\text{DECRISS-PM}} = 15 \text{ kV}$$

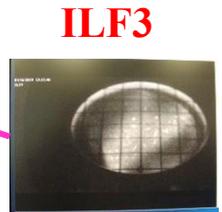
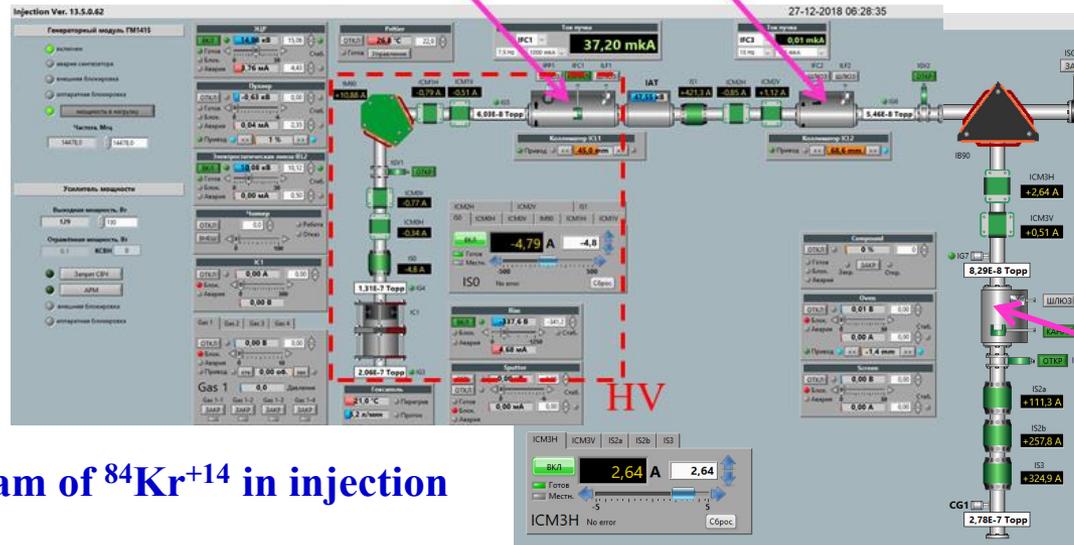
$$U_{\text{HV platform}} = 47.5 \text{ kV}$$

$$F_{\text{rf}} = 9 \text{ MHz}$$

$$I_{\text{M}} = 853 \text{ A}$$

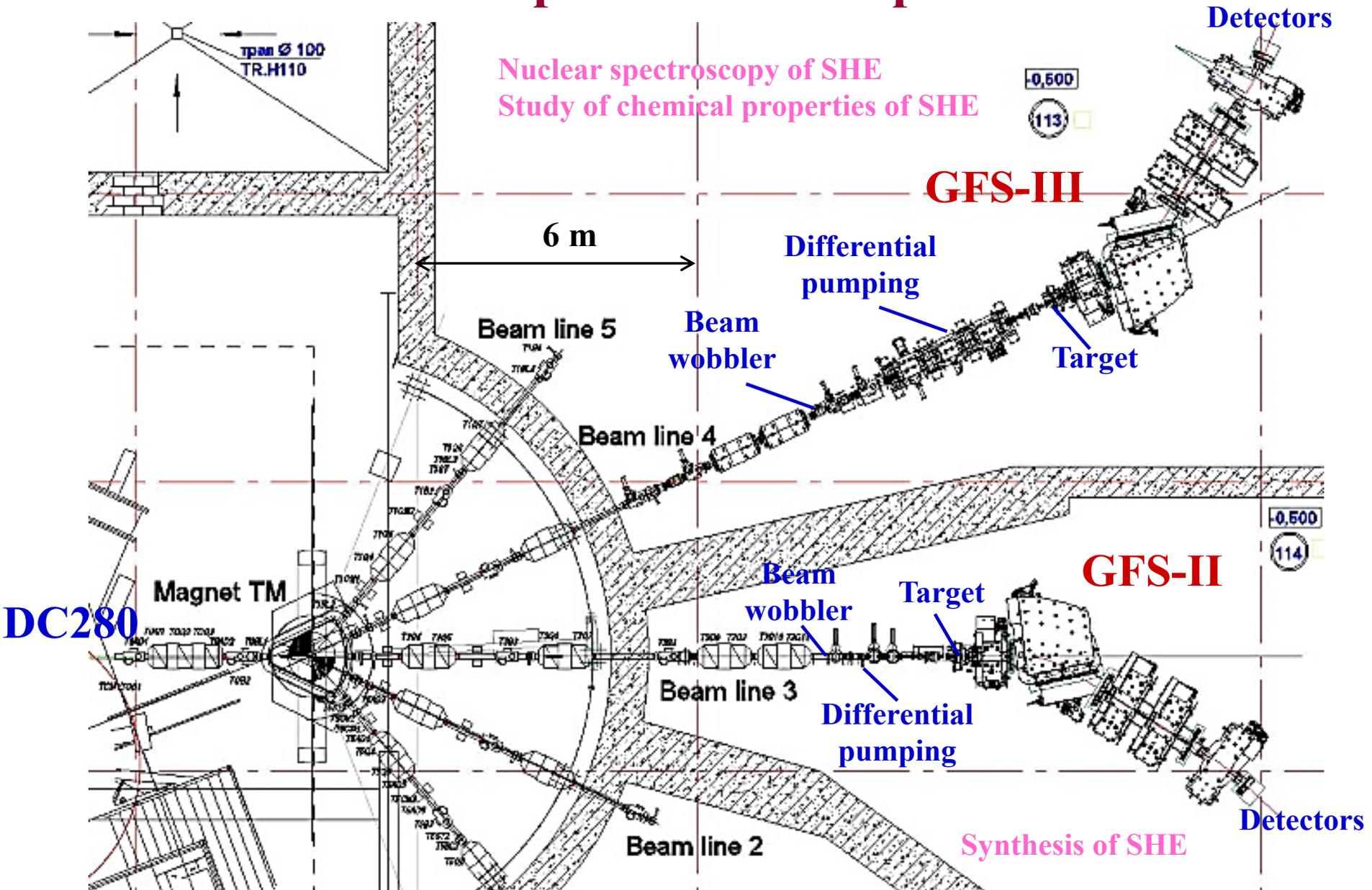
$$U_{\text{defl}} = -75 \text{ kV}$$

The first beam of $^{84}\text{Kr}^{+14}$ in injection



Cyclotron center

Experimental setups



First-day experiments at SHE Factory

Aims of the experiments:

1. Test of functionalities of all the systems of new accelerator and new gas-filled recoil separator. Test reactions are: $^{40}\text{Ar} + ^{\text{nat}}\text{Yb} \rightarrow \text{Ra}$, $^{48}\text{Ca} + ^{\text{nat}}\text{Yb} \rightarrow \text{Th}$ and $^{48}\text{Ca} + ^{206,208}\text{Pb} \rightarrow \text{No}$
2. Accumulate additional statistics for the chosen reactions

Chosen reactions:

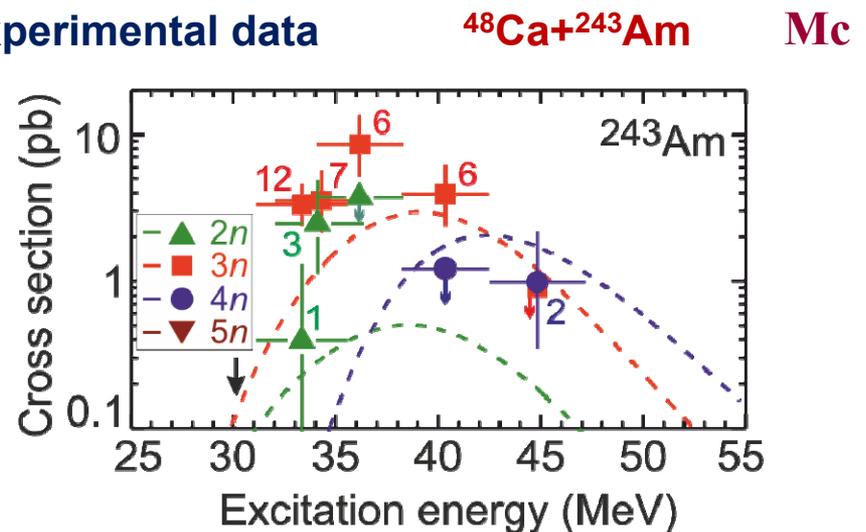
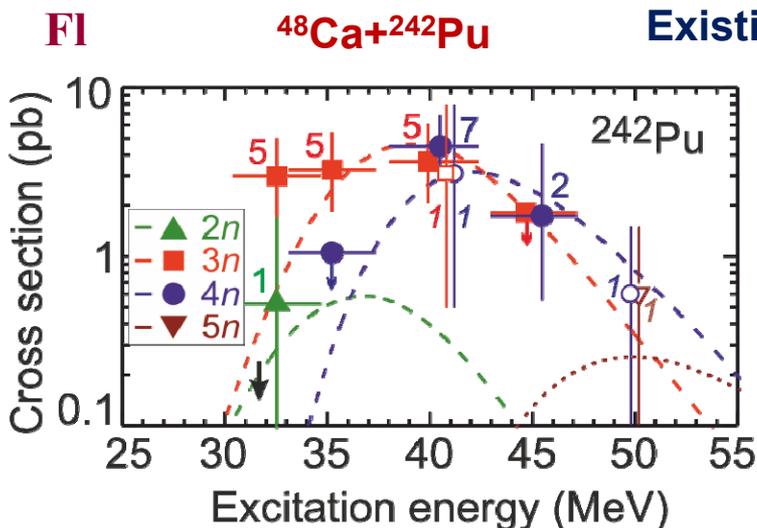
$^{48}\text{Ca} + ^{243}\text{Am} \rightarrow \text{Mc}$ (50 days experiment)

and

$^{48}\text{Ca} + ^{242}\text{Pu} \rightarrow \text{Fl}$ (50 days experiment)

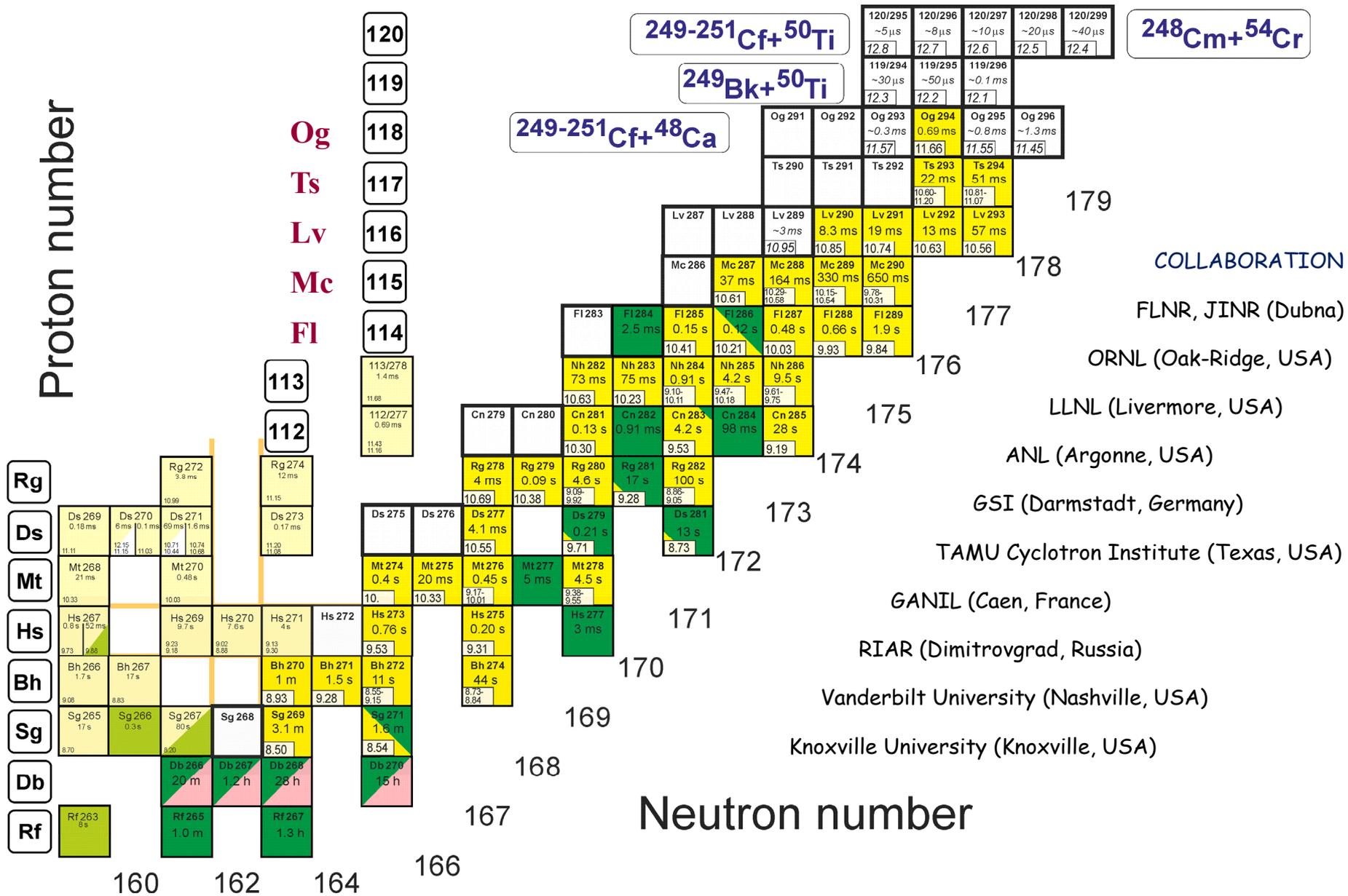
Beam intensity at first up to 5 μA then more

1. Enough material to prepare “big” targets (60 mg)
2. Relatively large cross sections (~ 8 pb)
3. Well-studied in previous experiments. Good for testing of the accelerator complex



First experiments at SHE Factory

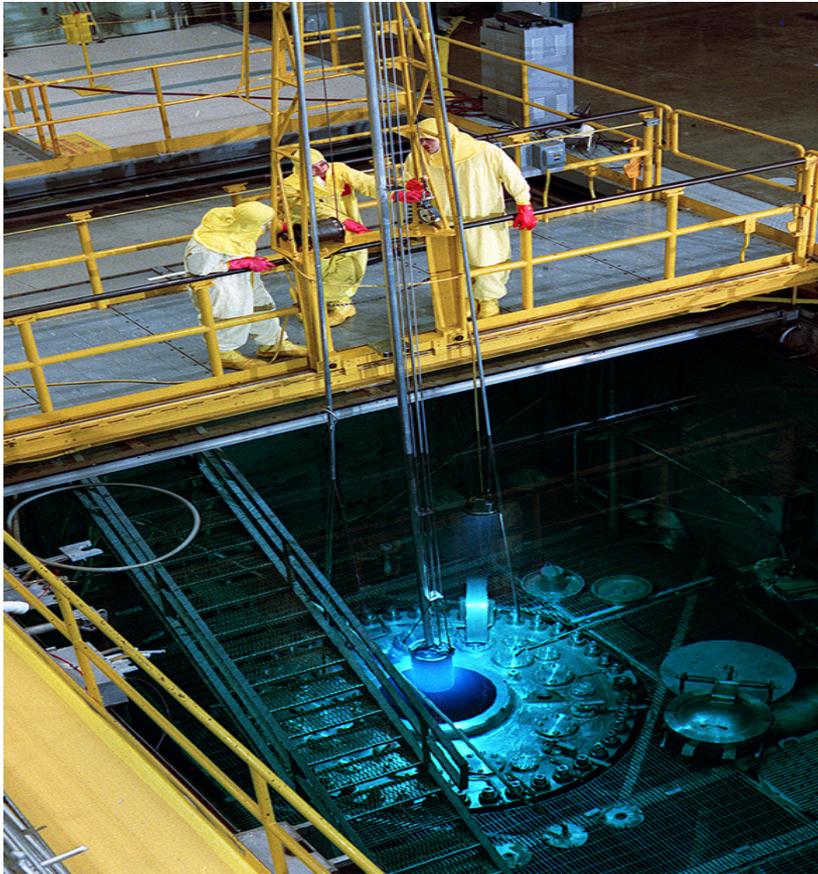
Synthesis of new elements 119 and 120



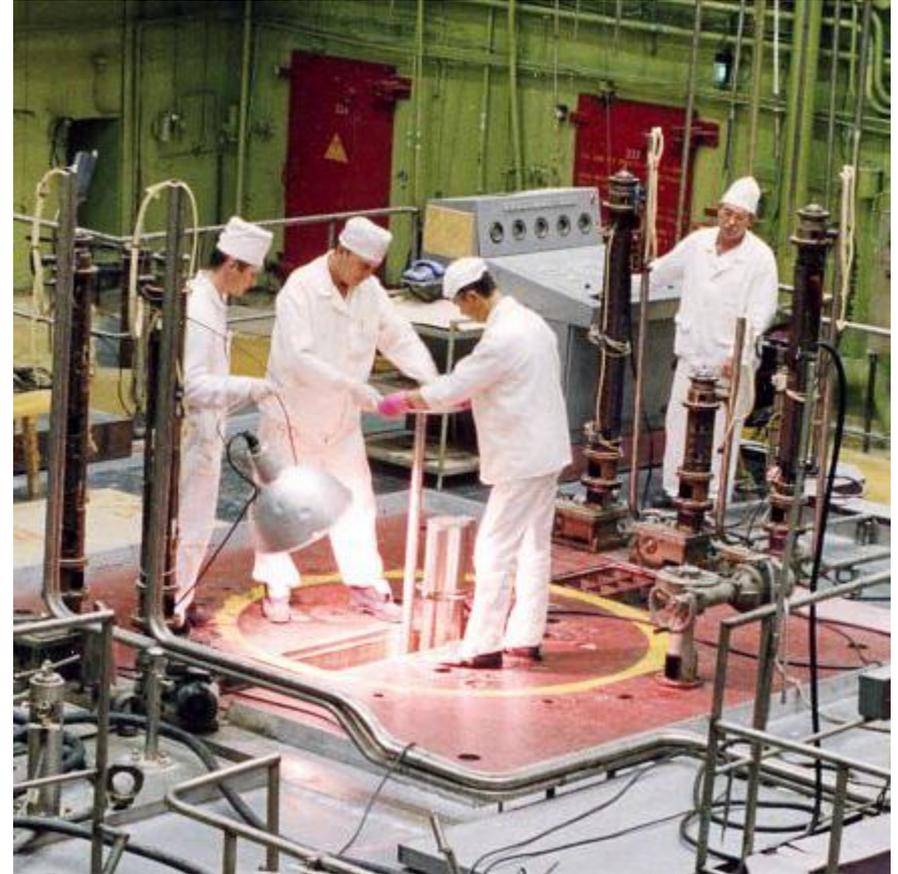
Target materials	Producer	Isotope enrichment (%)
^{237}Np	IAR	99.3
^{239}Pu	RFNC	---
^{240}Pu	IAR/ORNL	99.98
^{242}Pu	RFNC/ORNL	99.98
^{244}Pu	ORNL	98.6
^{243}Am	IAR / ORNL	99.9
^{245}Cm	IAR	98.7
^{248}Cm	IAR /ORNL	97.4
^{249}Bk	ORNL	≥ 95
^{249}Cf	IAR/ORNL	97.3
$^{249,250,251}\text{Cf}$	ORNL	(50+14+36)%
0,35-0,40 mg /cm² - \approx 12 mg		

Isotope reactors irradiation of targets at HFIR

HFIR, ORNL, Oak Ridge, USA



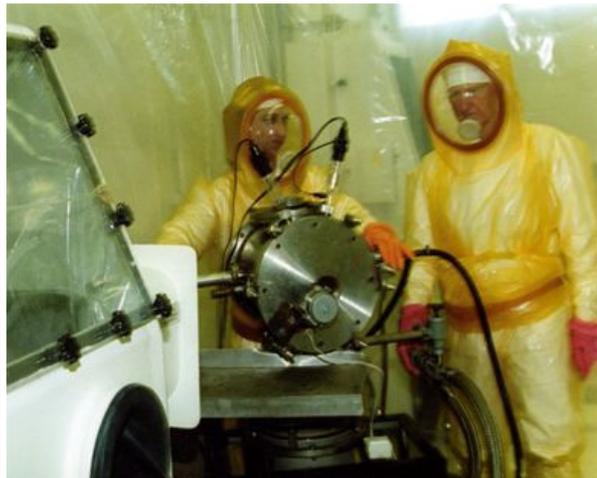
CM-3, IAR, Dimitrovgrad, RF



22 mg of ^{249}Bk
have been produced in 250 days
irradiation
at HFIR (ORNL)

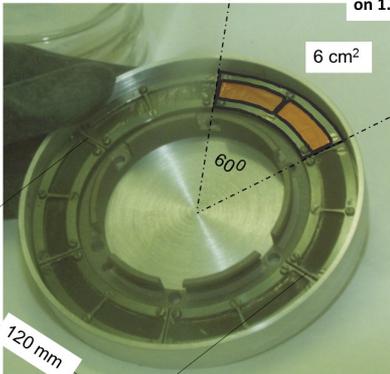
Target block design

Old target



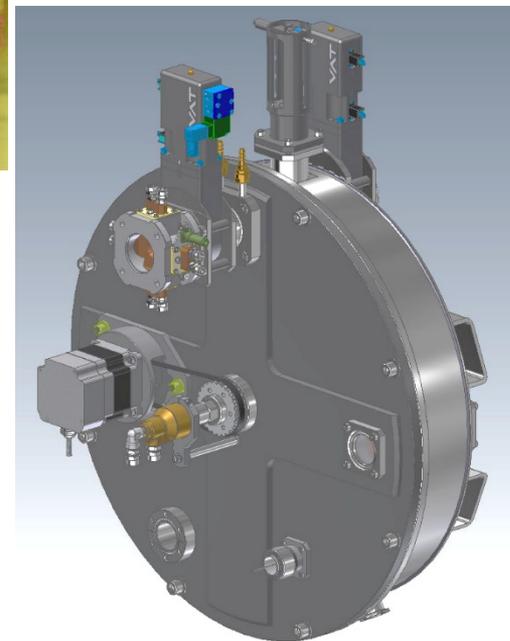
Target

310 $\mu\text{g}/\text{cm}^2$ BkO_2
on 1.5 μm -Ti foil



^{249}Cf @ DGFRS
radiation safety

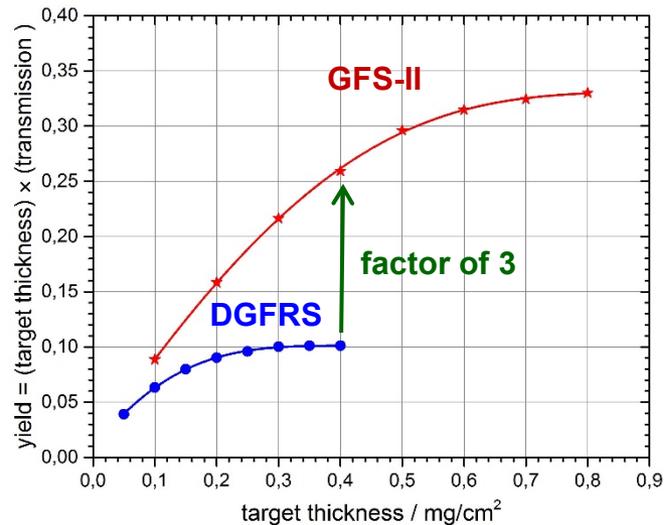
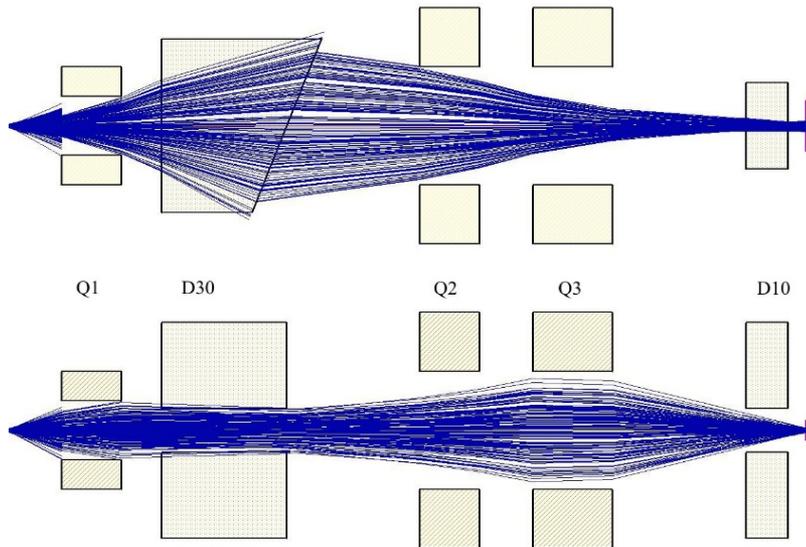
New target



- $\text{Ø} = 120$ mm, 1500 r.p.m. synchronous
- Beam wobbler
- Segmented beam diafragm
- Is in use at DGFRS, SHELS, MASHA

- At first, $\text{Ø} = 150$ mm, 1500 r.p.m.
- Then $\text{Ø} = 240$ mm, 1500 r.p.m.
- water cooling

New FLNR gas-filled separator (contracted)

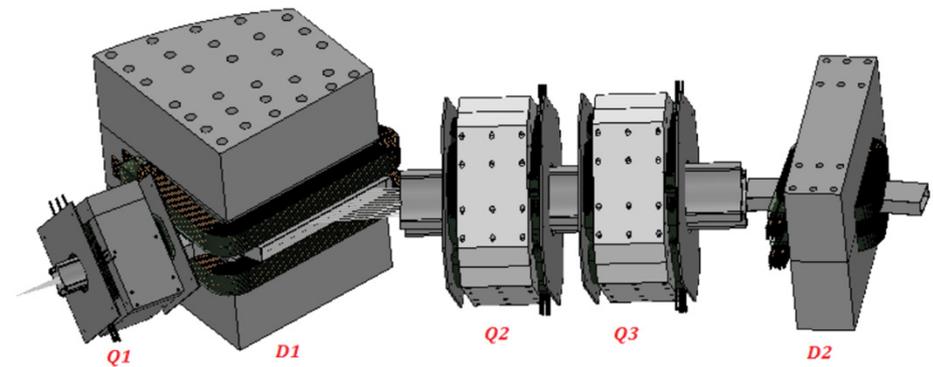


Simulated yields of FI isotopes (A.G. Popeko)

$DQ_h Q_v$ set-up $Q_v D Q_h Q_v D$ set-up



Technical Design
Report No 412923



Reaction	Transmission
$^{244}\text{Pu}(^{48}\text{Ca}, 3n)^{289}\text{Fl}$	60 %
$^{244}\text{Pu}(^{58}\text{Fe}, 4n)^{298}120$	75 %

GFS-II at the beam line No3



Installation of magnets: 2018

William Beeckman: MOB03

**First $^{40}\text{Ar}^{+6}$ beam on the GFS-II beam stopper:
09.09.2019**



Preparation to first experiments Sep. 2019

Conclusion

- The **SHE Factory** was commissioned in **2019**.
- The beam parameters of the **DC280** cyclotron are close to required ones for testing of the first experimental setup - **GFS-II** separator in **2019**.
- The **GFS-II** was assembled and ready for the first experiments on the synthesis and study of **SHE**.
- First experiments on the **SHE Factory**: **2019 - 2020**

THANKS FOR YOUR ATTENTION!



Inauguration of the SHE Factory 25.03.2019