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Helmholtzzentrum für Schwerionenforschung,
Darmstadt Germany

Perspectives of SHE research at Dubna

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Joint Institute for Nuclear Research**

OUTLINES

What do we know about SHE?

Targets and projectiles.

SHE – factory.

High-current cyclotron DC-280.

New facilities.

Conclusions.

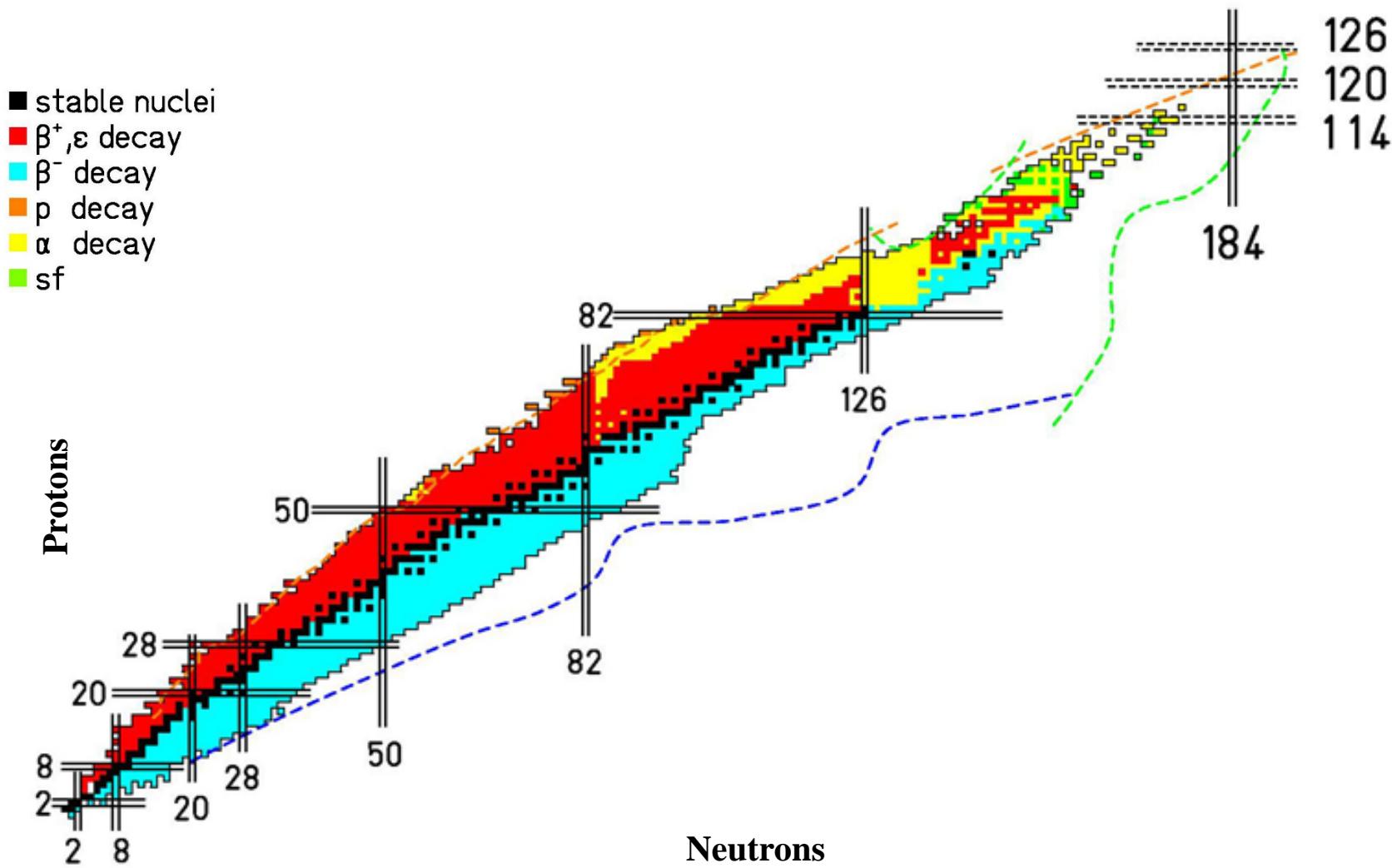
History

- 1966: A. Sobiczewski, F.A. Gareev, B.N. Kalinkin: next “magic numbers” are Z=114, N=184;
- 1966: W.D. Myers, W.J. Swiatecki: next “magic numbers” are Z=126, N=184
- 1966: V.M. Strutinsky; “shell correction” method

Accuracy of predictions:

- Spontaneous fission half-life: $T_{1/2} * 10^{\pm 10}$!!
- α -decay: $T_{1/2} * 10^{\pm 10}$!!

Chart of the Nuclides (decay modes)



Synthesis of SHE at accelerators

- 1968: Berkeley, USA; $^{248}\text{Cm} + ^{40}\text{Ar} \rightarrow ^{284}\text{114} + 4\text{n};$
- 1969: Dubna, SU; $^{208}\text{Pb} + ^{70}\text{Zn} \rightarrow ^{276}\text{112} + 2\text{n};$
(1996, GSI, Germany);
- 1970: Orsay, France; $^{232}\text{Th} + ^{82}\text{Kr} \rightarrow ^{310}\text{126} + 4\text{n};$
- 1971-1975: Dubna, SU; deep inelastic or fission reactions
of ^{76}Ge , $^{136}\text{Xe} + ^{238}\text{U};$
- 1975: Dubna, SU; $^{48}\text{Ca} + \text{actinides};$
- 1985: Berkeley, USA; $^{254}\text{Es}(0.6 \mu\text{g}) + ^{48}\text{Ca} \rightarrow ^{298}\text{119} + 4\text{n};$

Reactions of Synthesis

Act. + ^{48}Ca

Projectiles ^{48}Ca produced by Heavy Ion Accelerator U400;

Energy: 235-250 MeV
($v \approx 0.1 c$);

Intensity: 1.0-1.5 pμA
($n \times 10^{12} \div 10^{13} \text{ 1/s}$);

Consumption: 0.5-0.8 mg/h

Beam dose: $(0.3-3.0) \cdot 10^{19}$

Prices per 1 mg

$^{197}\text{Au} \approx 0.045 \text{ US\$}$

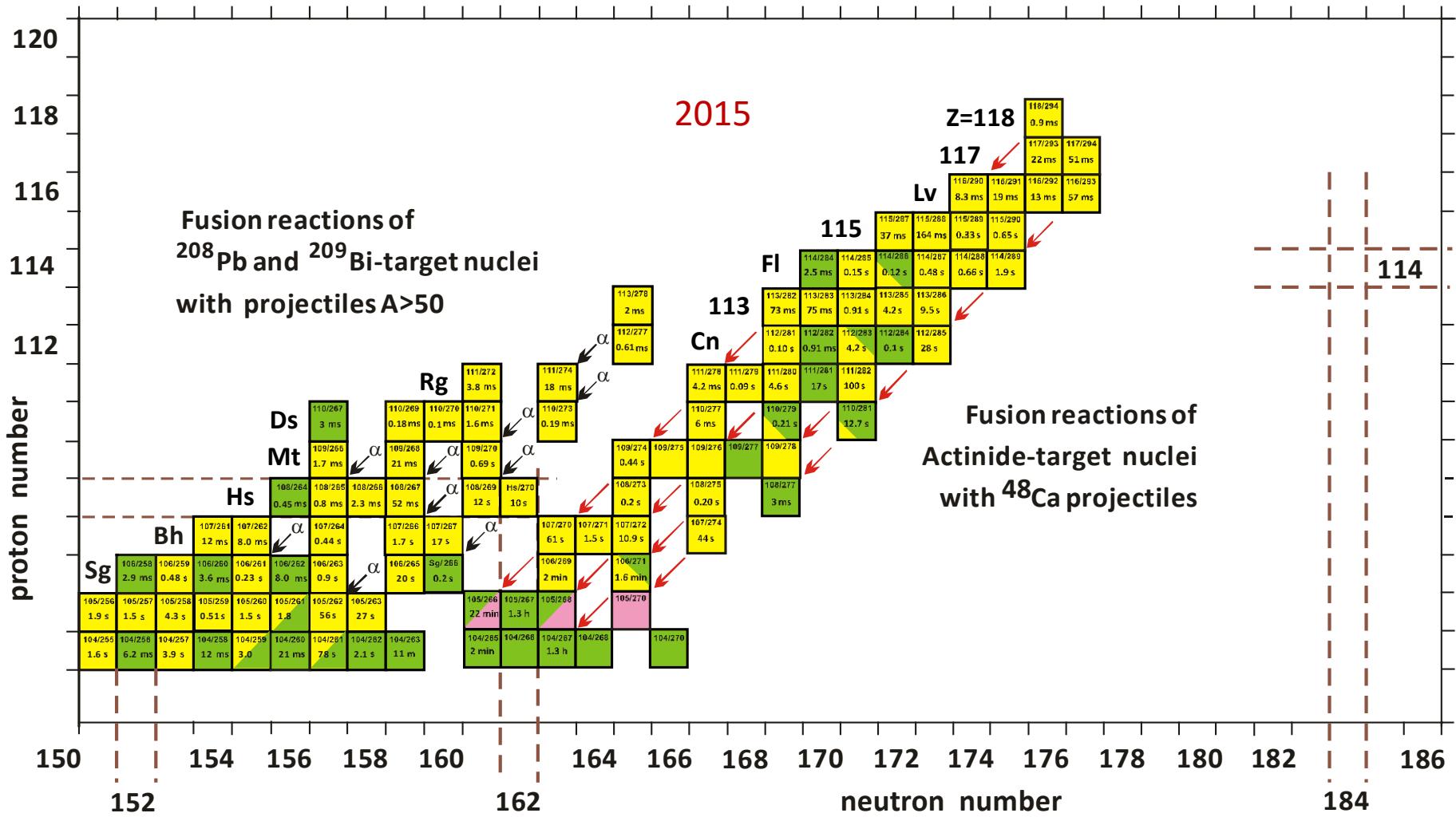
$^{\text{nat}}\text{U}_3\text{O}_8 \approx 0.03 \text{ US\$}$

$^{239}\text{Pu} \approx 4 \text{ US\$}$

$^{48}\text{Ca} \approx 80 \text{ US\$}$

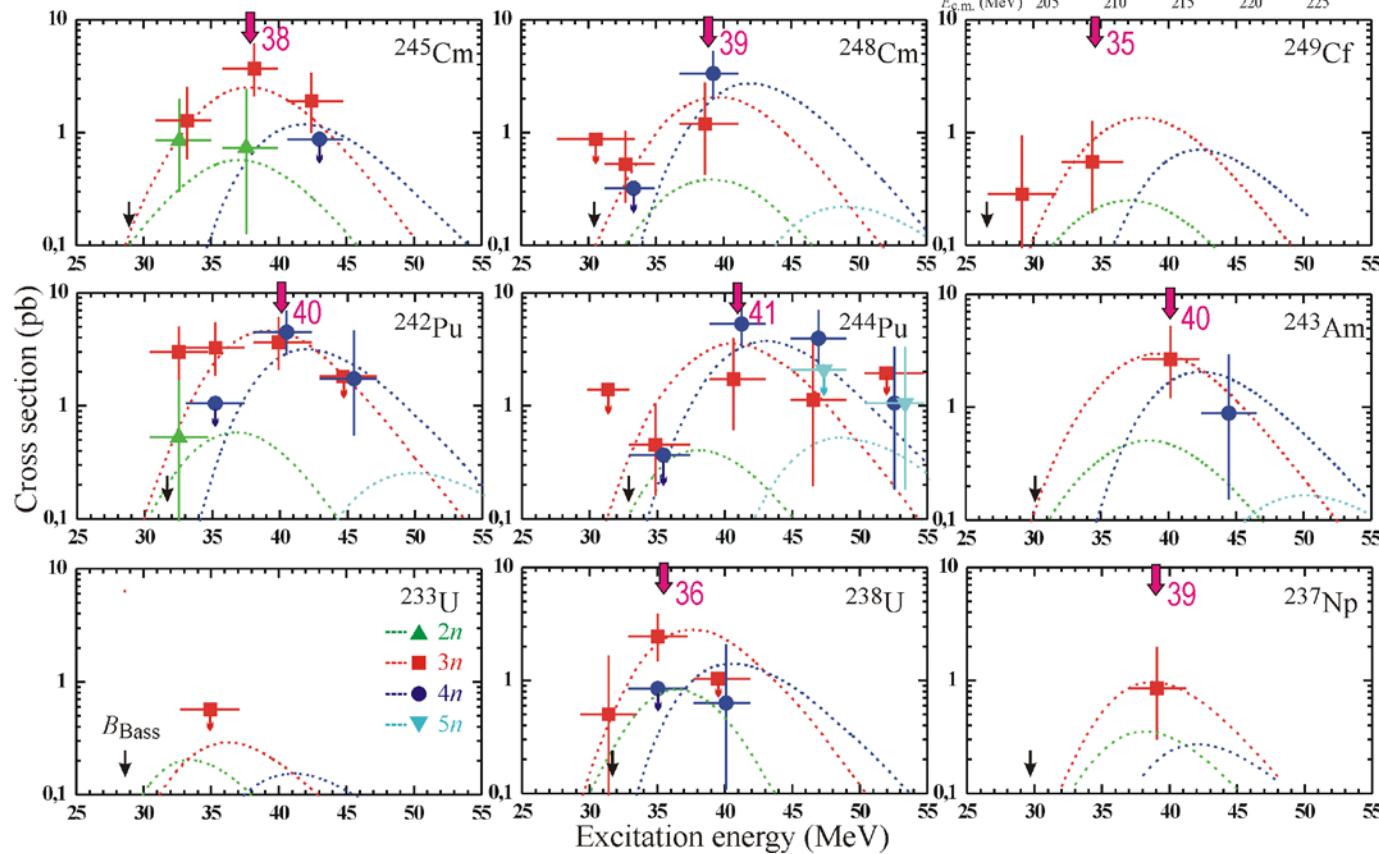
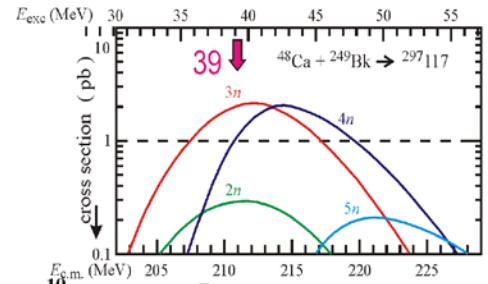
$^{249}\text{Cf} \approx 60,000 \text{ US\$}$

Target materials	Producer	Isotope enrichment (%)
^{232}Th	----	100
^{233}U	RFNC	---
^{238}U	----	99.3
^{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)%

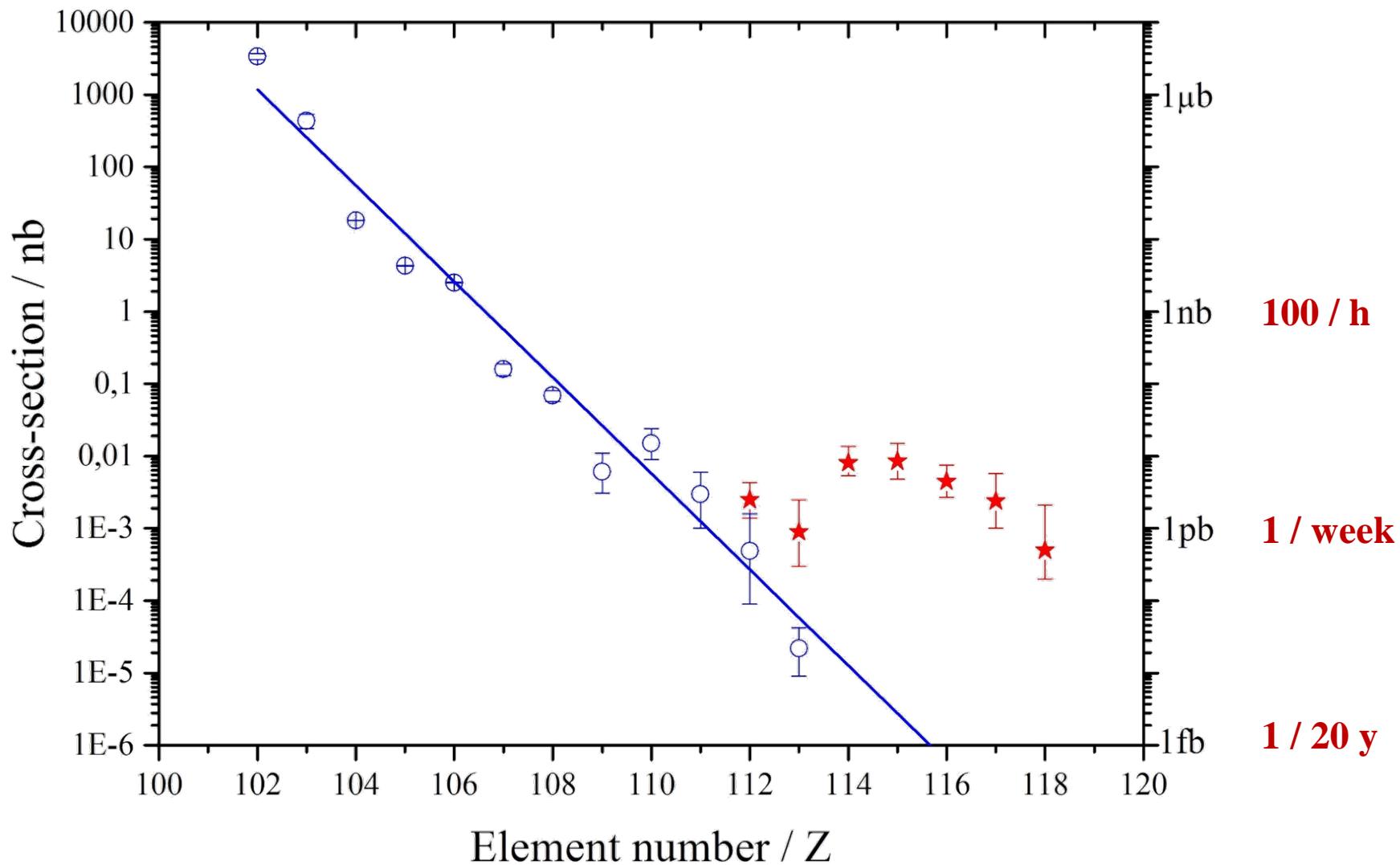


Excitation functions of SHE

$$\text{FWHM} \approx 10 \text{ MeV} \rightarrow \sigma = (\text{FWHM})/(2*(2\ln 2)^{1/2}) = (\text{FWHM})/2.355 = 4.25 \text{ MeV} \rightarrow \sigma \approx 0.58 \text{ mg/cm}^2$$

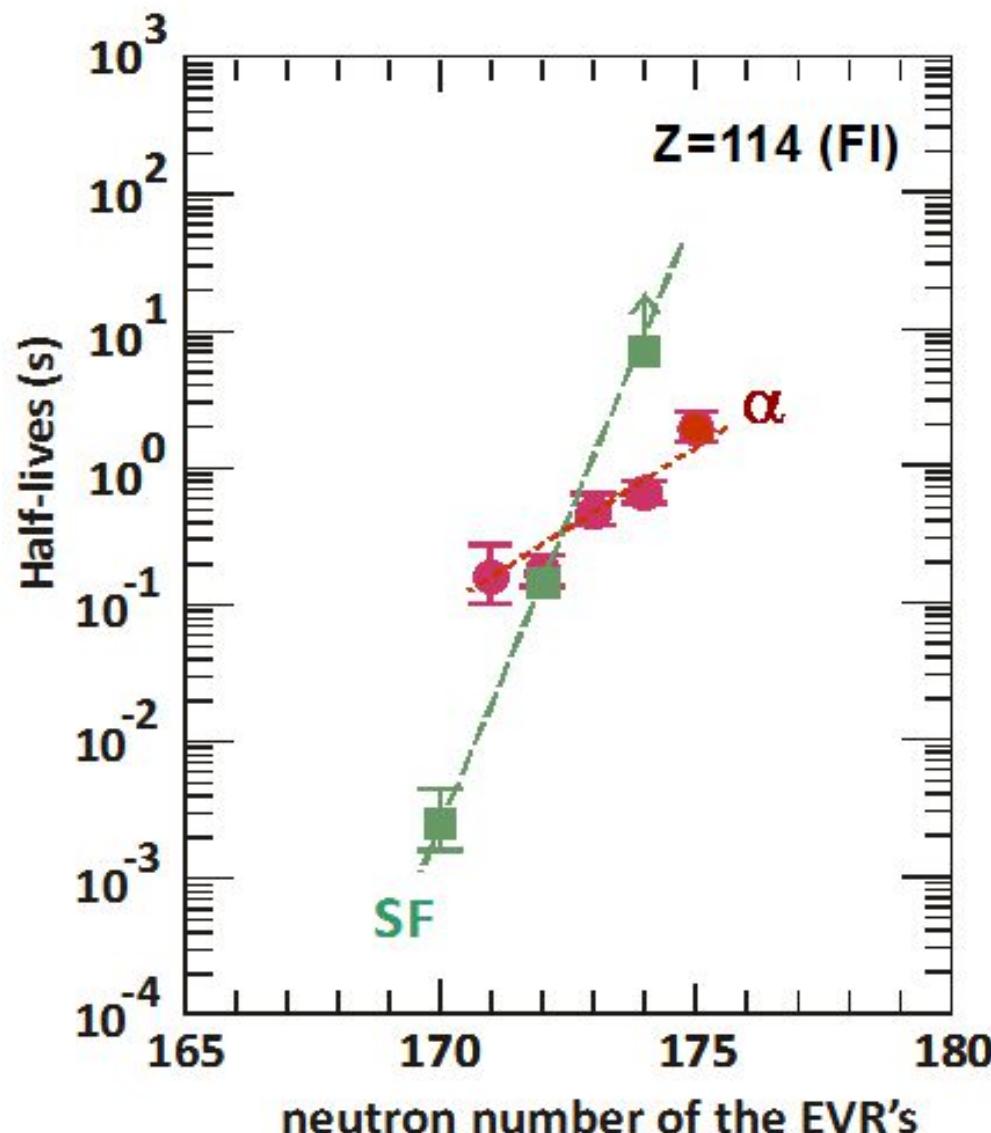


Production cross-sections of heavy and super-heavy



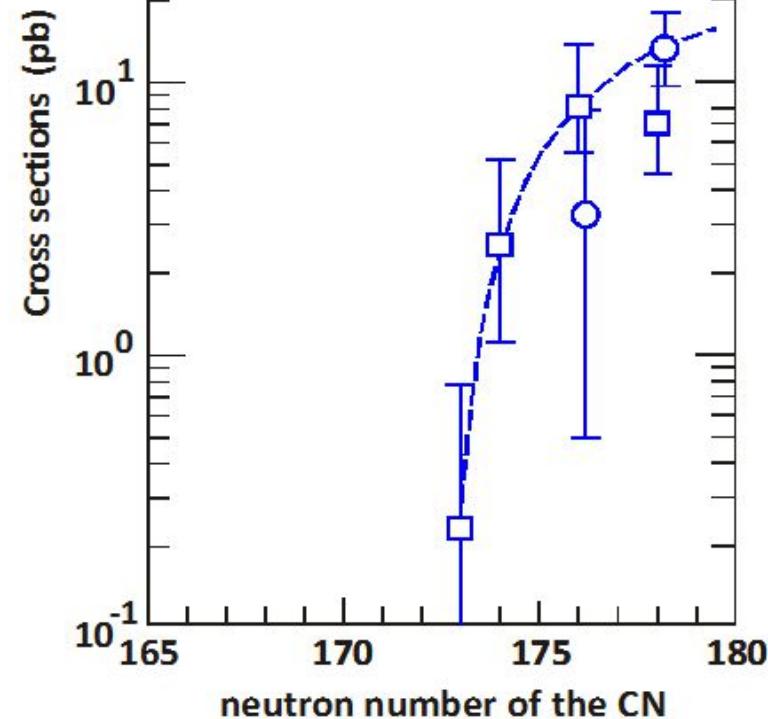
α -decay and S.F. of Fl isotopes from reactions

$^{239,240,242,244}\text{Pu} + ^{48}\text{Ca}$

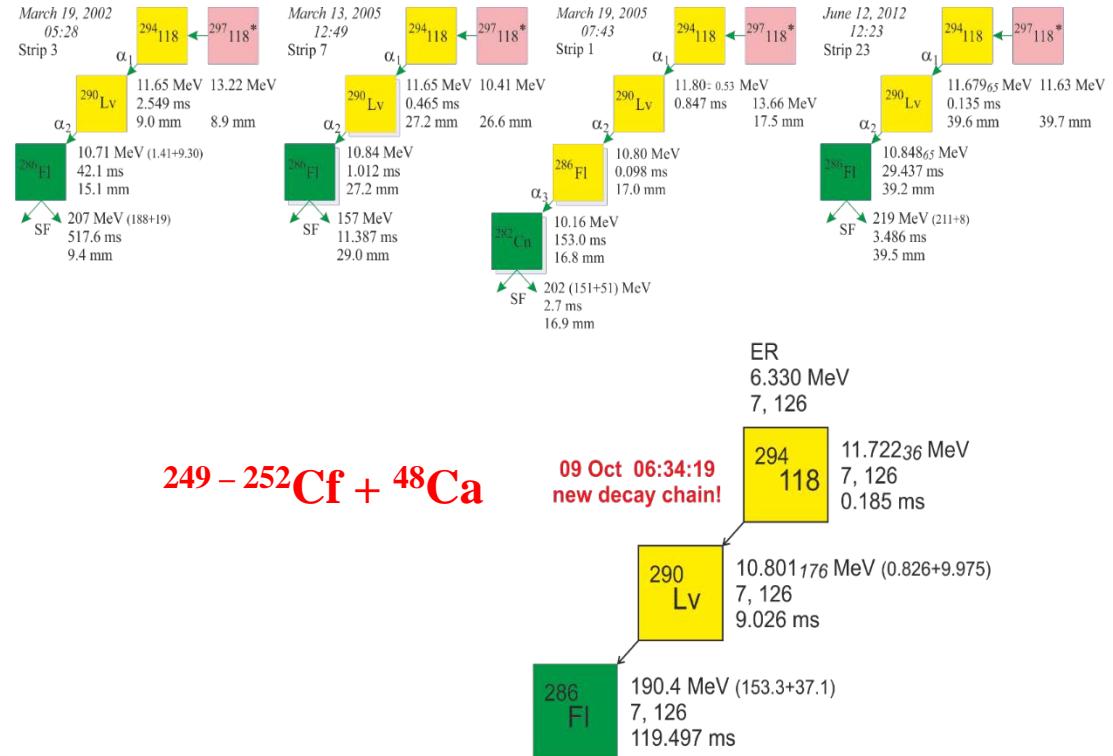


The borders of the SHE-island

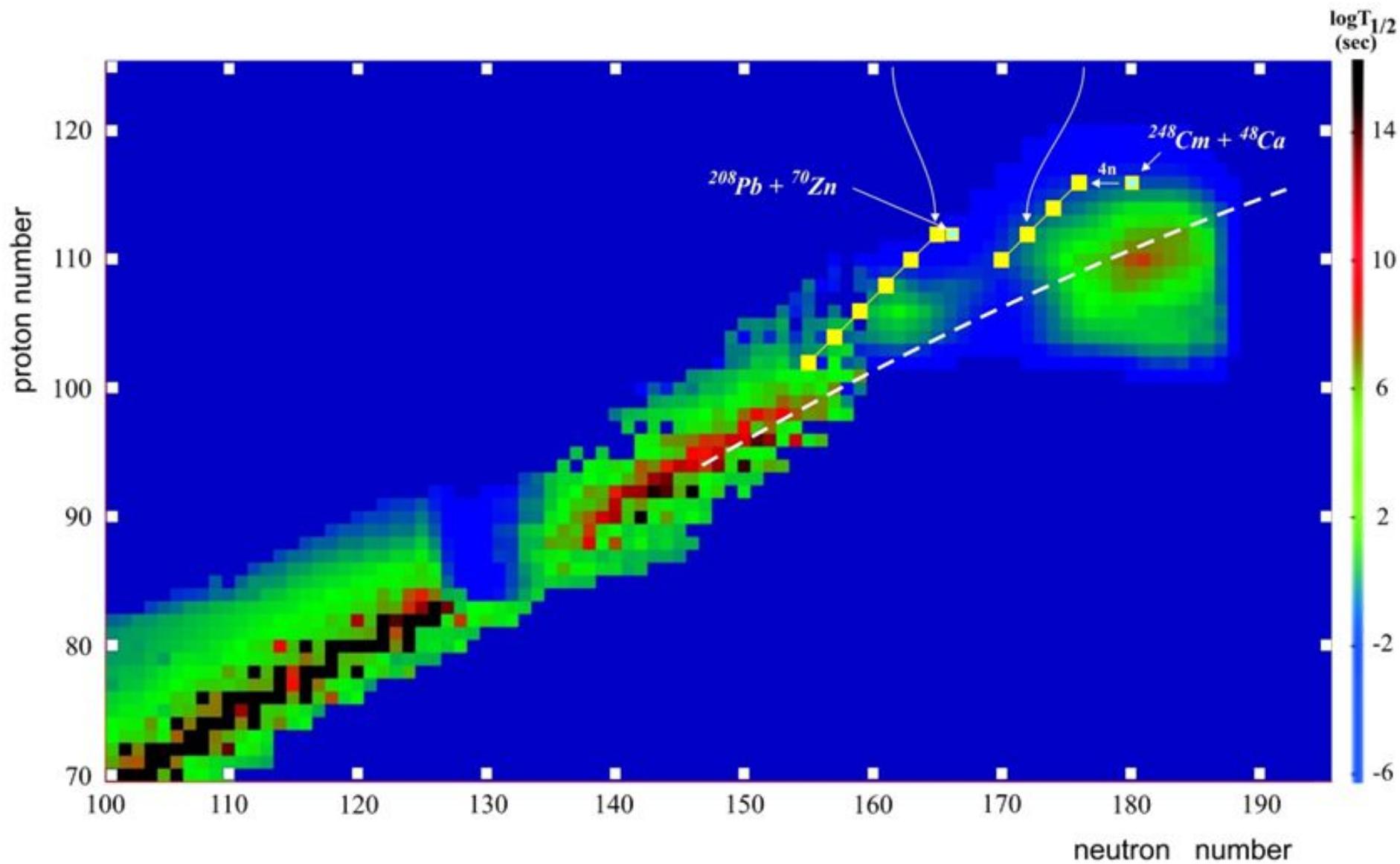
$^{239,240,242,244}\text{Pu} + ^{48}\text{Ca}$



$^{249}\text{Cf} + ^{48}\text{Ca}$



We are still far from the center of the SHE-island



D.I. Mendeleev's Periodic Table of the Elements (2015)

1																																			
IA																																			
Водород 1 H 1,00794 Hydrogen	2	Бериллий 4 Be 9,01218 Beryllium	IIA	3	Титан 11 Ti 4,941 Titanium	4	Бор 5 B 10,811 Boron	5	Марганец 25 Mn 54,93805 Manganese	6	Хром 24 Cr 50,9415 Chromium	7	Железо 26 Fe 55,847 Iron	8	Кобальт 27 Co 58,9320 Cobalt	9	Никель 28 Ni 58,6934 Nickel	10	Медь 29 Cu 63,546 Copper	11	Цинк 30 Zn 65,39 Zinc	12	Галлий 31 Ga 69,723 Gallium	13	Алюминий 13 Al 26,98139 Aluminum	14	Кремний 14 Si 28,0855 Silicon	15	Фосфор 15 P 30,97376 Phosphorus	16	Сера 16 S 32,0566 Sulfur	17	Хлор 17 Cl 35,45527 Chlorine	18	Аргон 18 Ar 39,948 Argon
Натрий 11 Na 22,989768 Sodium	12	Магний 12 Mg 24,3050 Magnesium	IIIIB	3	Скандиний 21 Sc 44,95591 Scandium	4	Титан 22 Ti 47,88 Titanium	5	Ванадий 23 V 50,9415 Vanadium	6	Хром 24 Cr 50,9415 Chromium	7	Марганец 25 Mn 54,93805 Manganese	8	Железо 26 Fe 55,847 Iron	9	Кобальт 27 Co 58,9320 Cobalt	10	Никель 28 Ni 58,6934 Nickel	11	Медь 29 Cu 63,546 Copper	12	Цинк 30 Zn 65,39 Zinc	13	Галлий 31 Ga 69,723 Gallium	14	Алюминий 13 Al 26,98139 Aluminum	15	Кремний 14 Si 28,0855 Silicon	16	Фосфор 15 P 30,97376 Phosphorus	17	Сера 16 S 32,0566 Sulfur	18	Хлор 17 Cl 35,45527 Chlorine
Калий 19 K 39,9893 Potassium	20	Кальций 20 Ca 40,078 Calcium	Scandий 21 Sc 44,95591 Scandium	Титан 22 Ti 47,88 Titanium	Ванадий 23 V 50,9415 Vanadium	Хром 24 Cr 50,9415 Chromium	Марганец 25 Mn 54,93805 Manganese	Железо 26 Fe 55,847 Iron	Кобальт 27 Co 58,9320 Cobalt	Никель 28 Ni 58,6934 Nickel	Медь 29 Cu 63,546 Copper	Цинк 30 Zn 65,39 Zinc	Галлий 31 Ga 69,723 Gallium	Алюминий 13 Al 26,98139 Aluminum	Кремний 14 Si 28,0855 Silicon	Фосфор 15 P 30,97376 Phosphorus	Сера 16 S 32,0566 Sulfur	Хлор 17 Cl 35,45527 Chlorine	Аргон 18 Ar 39,948 Argon																
Рубидий 37 Rb 85,4678 Rubidium	38	Стронций 38 Sr 87,62 Strontium	Иттрий 39 Y 88,90585 Yttrium	Цирконий 40 Zr 91,224 Zirconium	Ниобий 41 Nb 92,90638 Niobium	Молибден 42 Mo 95,94 Molybdenum	Технеций 43 Tc 98 Technetium	Рутений 44 Ru 101,07 Ruthenium	Родий 45 Rh 102,90550 Rhodium	Платиний 46 Pt 106,42 Platinum	Серебро 47 Ag 107,86682 Silver	Кадмий 48 Cd 112,411 Cadmium	Иодий 49 I 114,818 Iodine	Олово 50 In 115,710 Tin	Сурьма 51 Sn 121,757 Antimony	Темпур 52 Te 127,60 Tellurium	Иод 53 I 128,90447 Iodine	Ксенон 54 Xe 131,29 Xenon																	
Цезий 55 Cs 132,90543 Cesium	56	Барий 56 Ba 137,327 Barium	Лантан 57 La 138,9055 Lanthanum	Гадолин 72 Hf 178,49 Hafnium	Танген 73 Ta 180,9479 Tantalum	Вольфрам 74 W 183,84 Tungsten	Рений 75 Re 190,23 Rhenium	Осмий 76 Os 192,22 Osmium	Иридий 77 Ir 195,08 Iridium	Платина 78 Pt 196,96654 Platinum	Золото 79 Au 196,96654 Gold	Ртуть 80 Hg 200,59 Mercury	Таллий 81 Tl 204,93533 Thallium	Санеци 82 Bi 207,2 Bismuth	Висмут 83 Po 209 Polonium	Астат 84 At 210 Astatine	Радон 86 Rn 222 Radon																		
Франций 87 Fr 223	Радий 88 Ra 226,025 Radium	Актиний 89 Ac 227 Actinium	Резерфордий 104 Rf 261 Rutherfordium	Дубий 105 Db 262 Dubnium	Себорий 106 Sg 266 Seaborgium	Барий 107 Bh 268 Berkelium	Хасций 108 Hs 269 Hassium	Менгерий 109 Mt 268 Meitnerium	Дормштадий 110 Ds 268 Darmstadtium	Рентгений 111 Rg 272 Rutherfordium	Копперий 112 Cn 277 Copernicium	Флеровий 114 Fl 287 Flerovium	Лимнерий 116 Lv 291 Livermorium																						
Лантаноиды Lanthanides																																			
Серий Ce 140,115 Септи	58	Праводиоид 59 Pr 140,90765 Praseodymium	Неодим 60 Nd 144,24 Neodymium	Прометий 61 Pm 145 Promethium	Самарий 62 Sm 150,36 Samarium	Европий 63 Eu 151,965 Europium	Гадолин 64 Gd 157,25 Gadolinium	Тербий 65 Tb 158,92534 Terbium	Диспрозий 66 Dy 162,50 Dysprosium	Голдеми 67 Ho 164,93032 Holmium	Эрбий 68 Er 167,26 Erbium	Тундем 69 Tm 169,93421 Thulium	Иттербий 70 Yb 173,04 Ytterbium	Лютений 71 Lu 174,967 Lutetium	Водород 1 H 1,00794 Hydrogen																				
Актиноиды Actinides																																			
Горий 90 Th 232,0381 Thorium	91	Протактиний 91 Pa 231,03568 Protactinium	Уран 92 U 238,0269 Uranium	Нептуний 93 Np 237 Neptunium	Плутоний 94 Pu 239 Plutonium	Америций 95 Am 243 Americium	Кордиций 96 Cm 247 Curium	Берклий 97 Bk 248 Berkelium	Калифорний 98 Cf 251 Californium	Экзакий 99 Es 252 Einsteinium	Фермий 100 Fm 257 Fermium	Менделеевий 101 Md 258 Mendelevium	Нобелий 102 No 259 Nobelium	Лоренций 103 Lr 262 Lawrencium	Водород 1 H 1,00794 Hydrogen																				

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Горий 90 Th 232,0381 Thorium	91	Протактиний 91 Pa 231,03568 Protactinium	Уран 92 U 238,0269 Uranium	Нептуний 93 Np 237 Neptunium	Плутоний 94 Pu 239 Plutonium	Америций 95 Am 243 Americium	Кордиций 96 Cm 247 Curium	Берклий 97 Bk 248 Berkelium	Калифорний 98 Cf 251 Californium	Экзакий 99 Es 252 Einsteinium	Фермий 100 Fm 257 Fermium	Менделеевий 101 Md 258 Mendelevium	Нобелий 102 No 259 Nobelium	Лоренций 103 Lr 262 Lawrencium	Водород 1 H 1,00794 Hydrogen									

С-элементы	d-элементы	f-элементы

What to do further? Complete fusion reactions:

- Higher beam current;
- More target material: 15 mg → 150 mg;

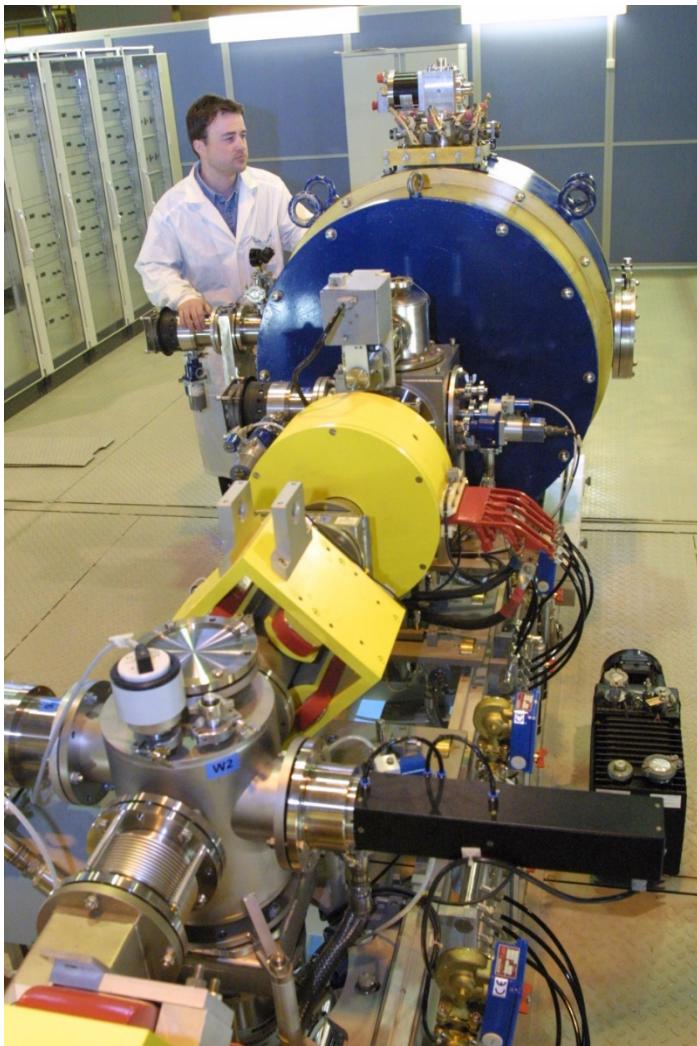
Heaviest target: $^{249}\text{Cf} \rightarrow Z_{\max} = 118$



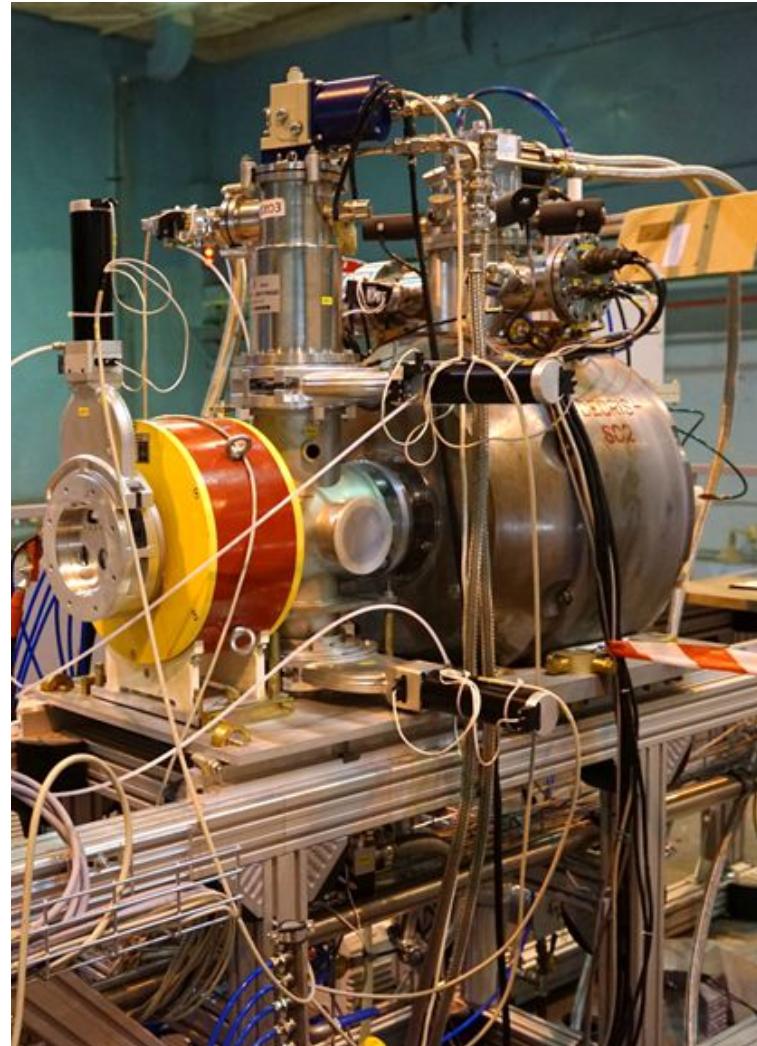
- Heavier projectiles (^{50}Ti , ^{54}Cr , ^{58}Fe , ^{64}Ni ...)
- Heavier targets: ^{250}Cm , ^{251}Cf ;
- Exotic targets: ^{254}Es , ^{257}Fm -???
- Symmetric reactions:
 $^{136}\text{Xe} + ^{136}\text{Xe}$, $^{136}\text{Xe} + ^{150}\text{Nd}$, $^{150}\text{Nd} + ^{150}\text{Nd}$;
- Reactions with RI.

Superconducting 18 GHz ECR ion sources

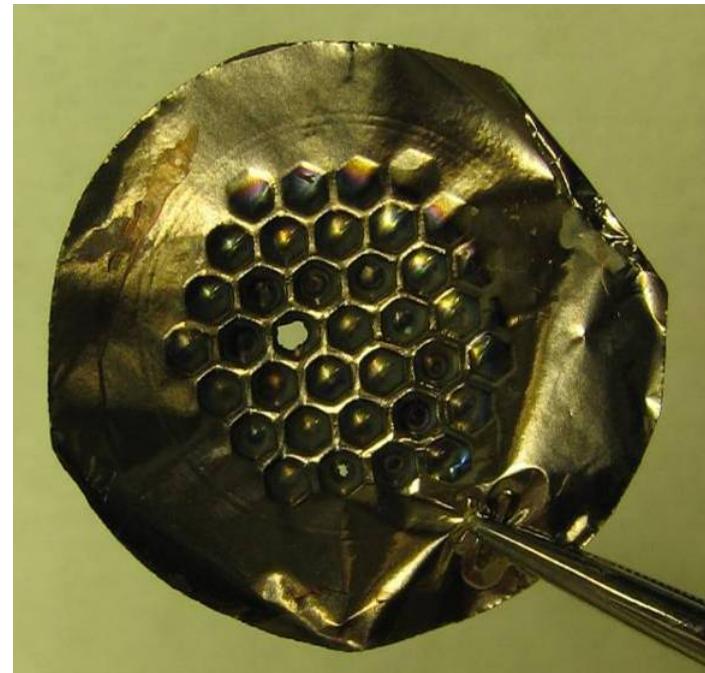
DECRIS-SC1



DECRIS-SC2



Targets I – destruction



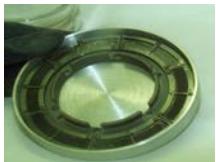
- Heating and melting;
- sputtering;
- radiation damage.

Targets II – reduction of heating

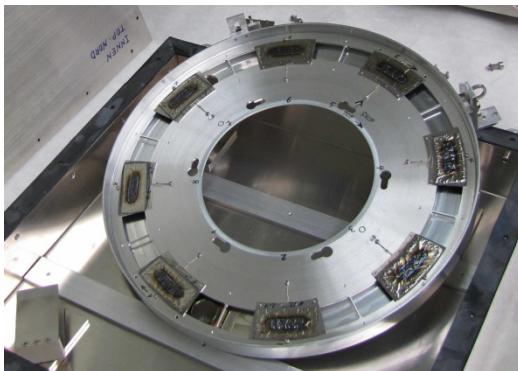
$\phi 5\text{ cm}$



$\phi 10\text{ cm}$



$\phi 30\text{ cm}$

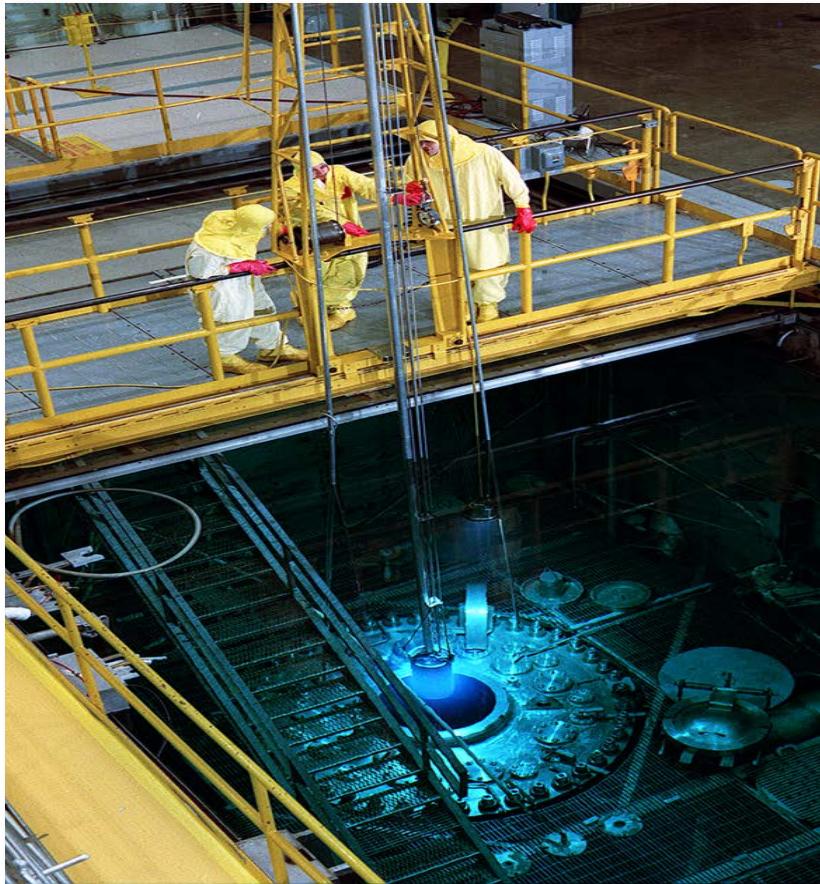


$\phi 60\text{ cm} \rightarrow$

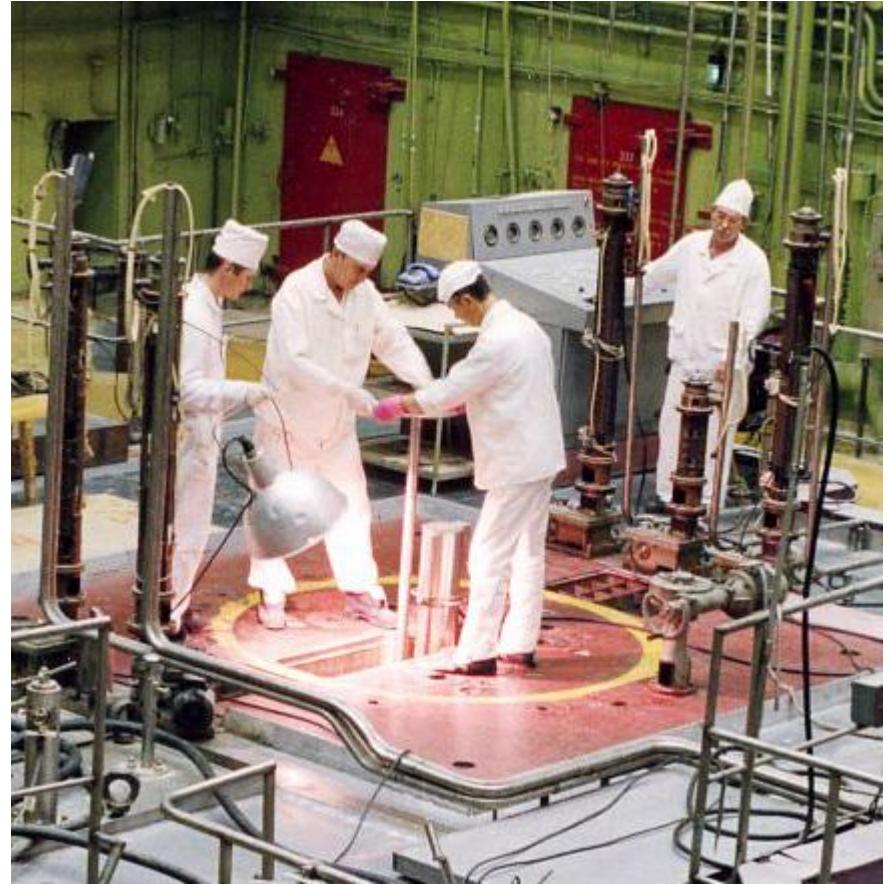


Isotope reactors

HFIR, ORNL, Oak Ridge, USA, 85 MW



CM-3, IAR, Dimitrovgrad, RF, 100 MW



Isotope separator is necessary !

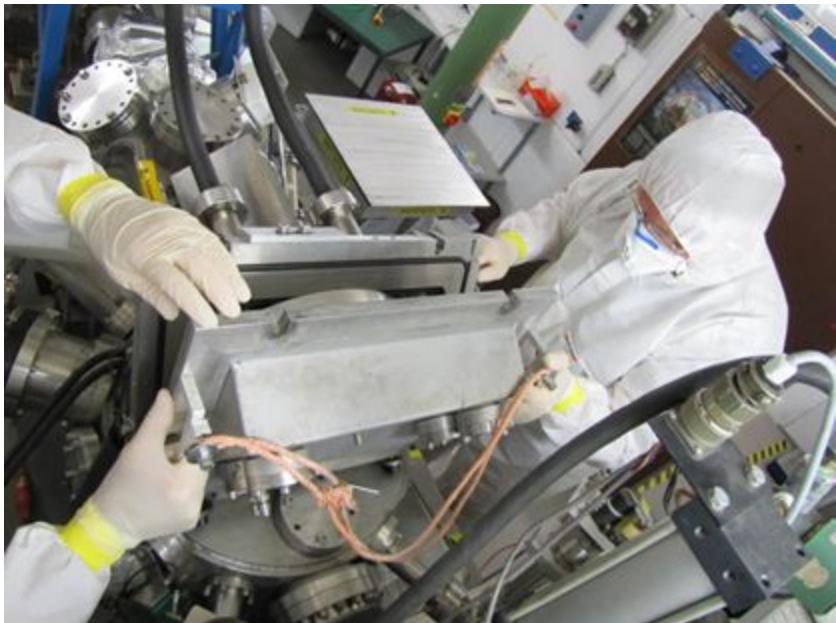
Targets III – material availability

22 mg of ^{249}Bk , $\approx 1 \text{ M\$}$, 1 year at HIFR ORNL



$\text{Bk}(\text{NO}_3)_3$ Product

Targets IV – radiation safety



^{248}Cm @ SHIP

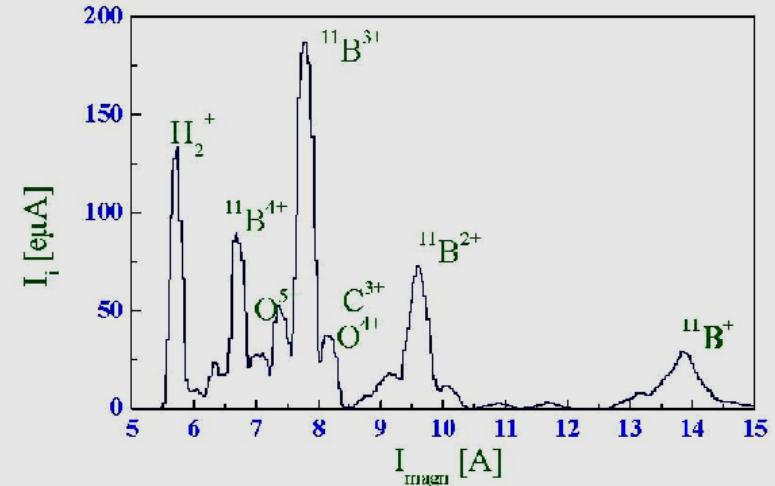
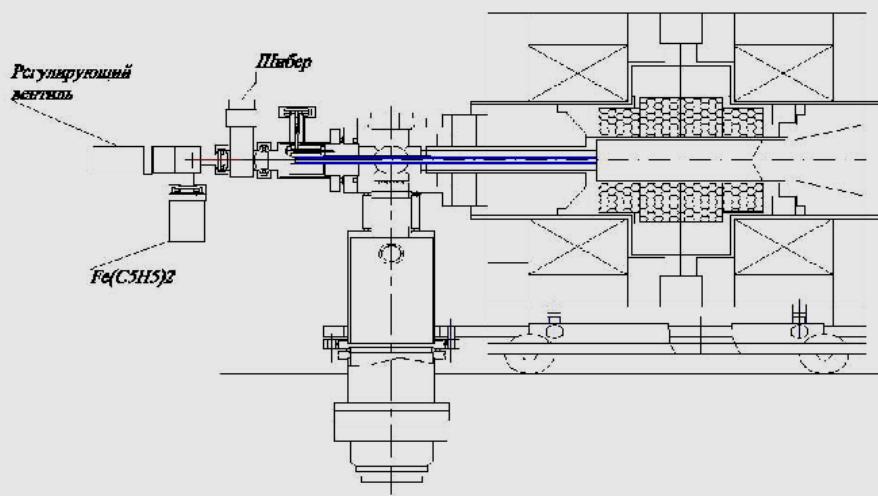


^{249}Cf @ DGFRS

MIVOC-method (Metal Ions from Volatile Compounds)

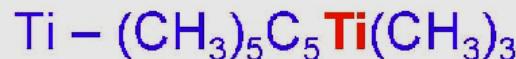
The vapour pressure of a compound should be about 10^{-3} torr

Evaporation of a compound and its diffusion into the source take place without dissociation.



The spectrum of boron ions

Working substance - $\text{C}_2\text{B}_{10}\text{H}_{12}$

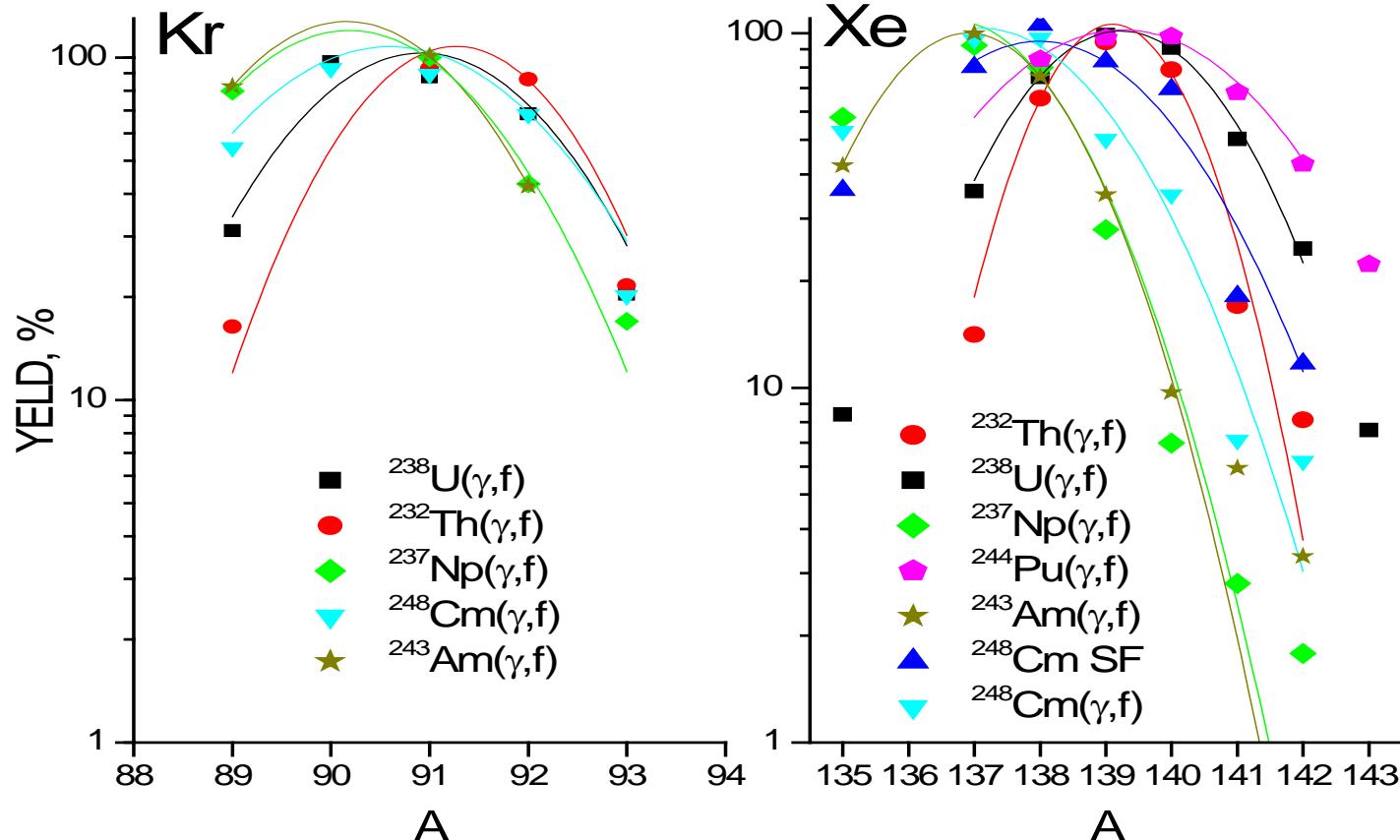


U-400 – $^{58}\text{Fe}^{7+}$ - $40 \div 50 \mu\text{A}$

**Material consumption $\sim 3 \text{ mg/h}$
($\sim 1.5 \text{ mg/h}$ for ^{58}Fe)**

More projectile material: 5 g/y → XX g/y !

The use of RI-beams

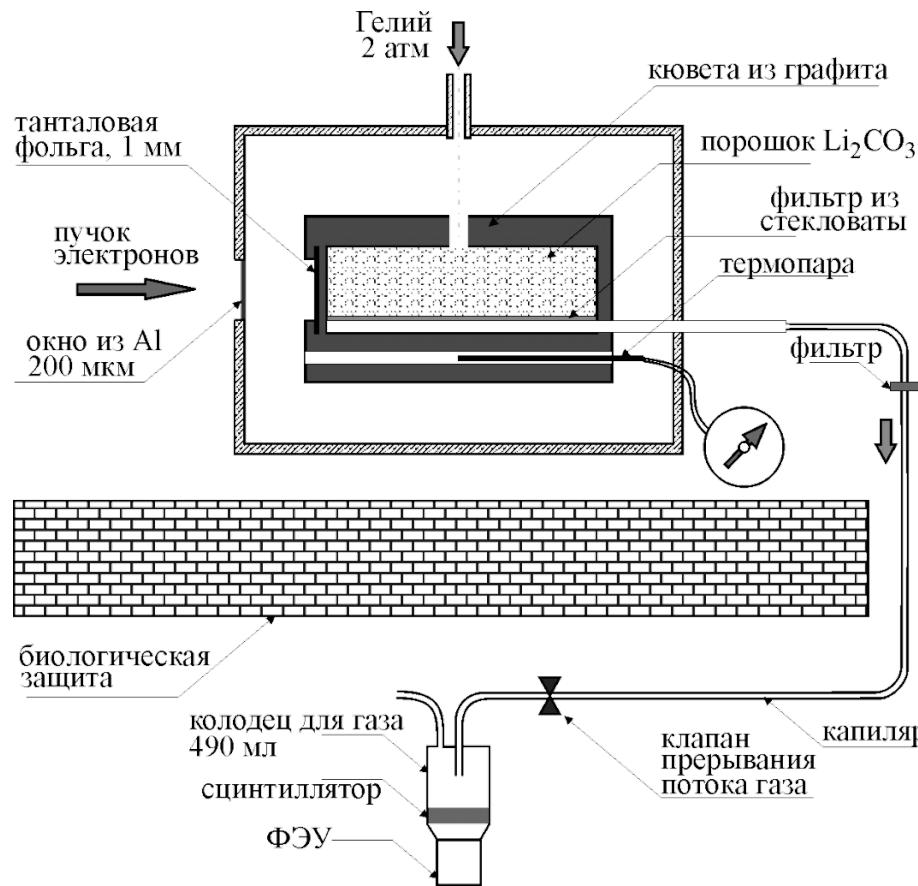


**Yields of Kr and Xe isotopes in photofission of actinides at γ -energy of 25 MeV
Due to hard radiation conditions the project was stopped (not cancelled!)**

The use of RI-beams



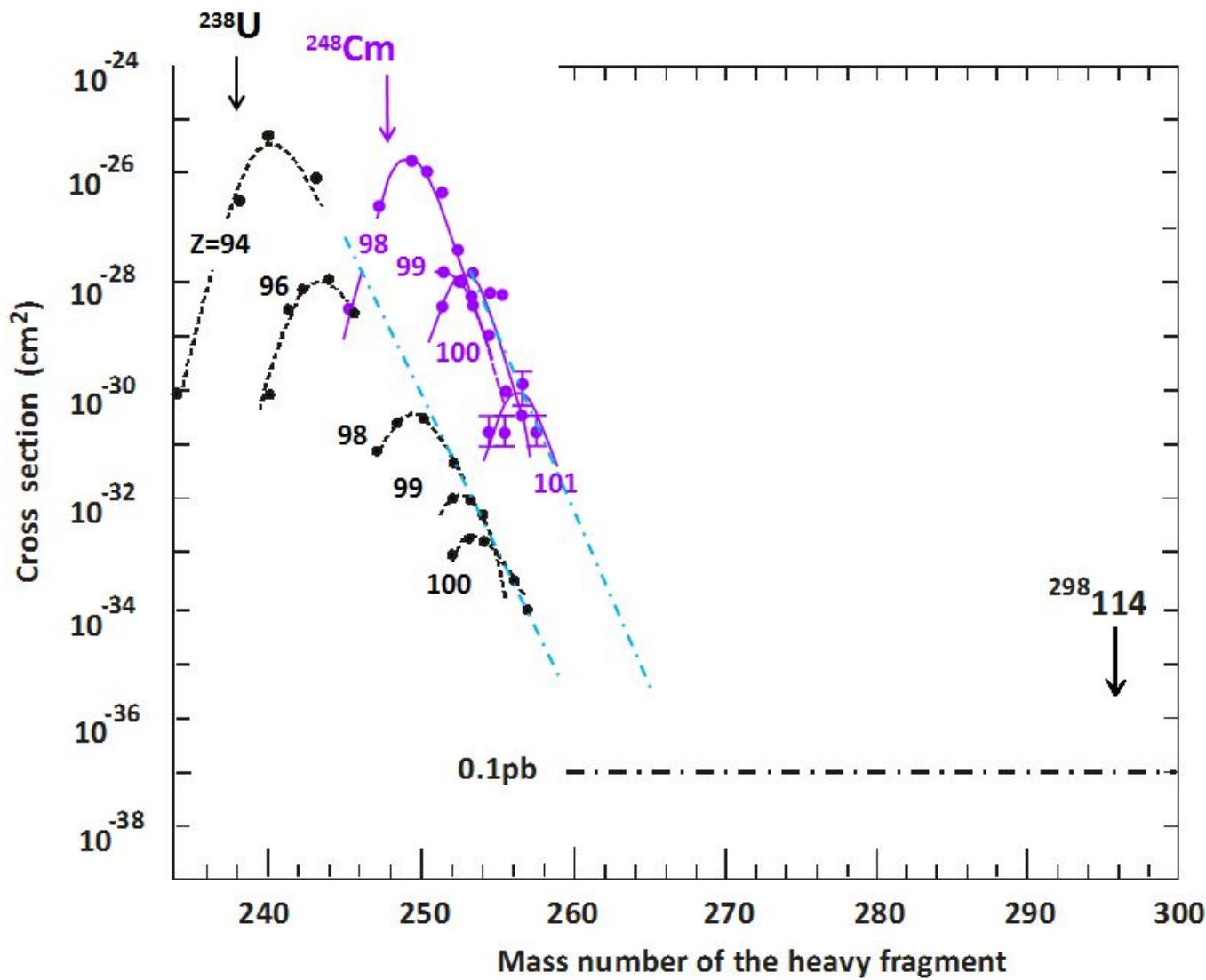
Production of ^{46}Ar in $^{48}\text{Ca}(\gamma, 2\text{p})$ reaction, $\sigma = 1 - 10 \text{ mb}$



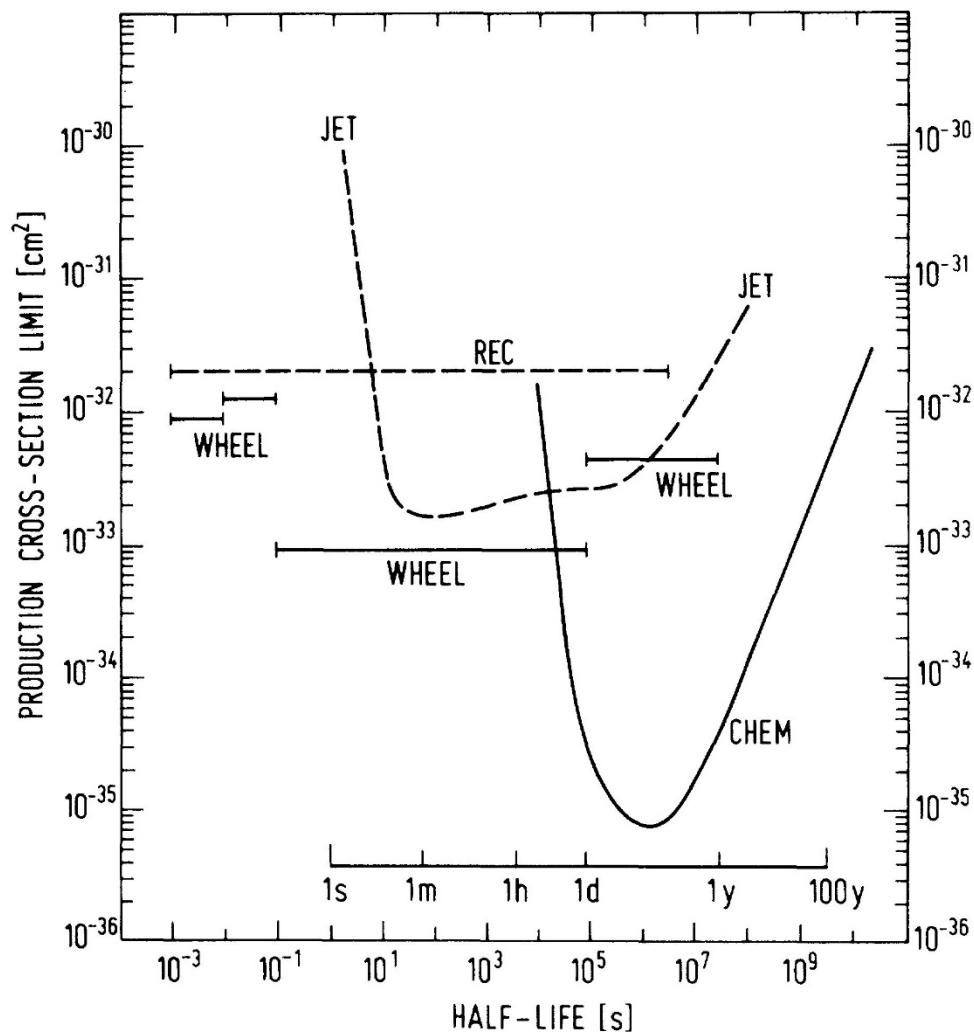
Incomplete fusion & transfer reactions:

- Nucleon transfer reactions ($^{136}\text{Xe}+^{208}\text{Pb}$, $^{238}\text{U}+^{248}\text{Cm}$).

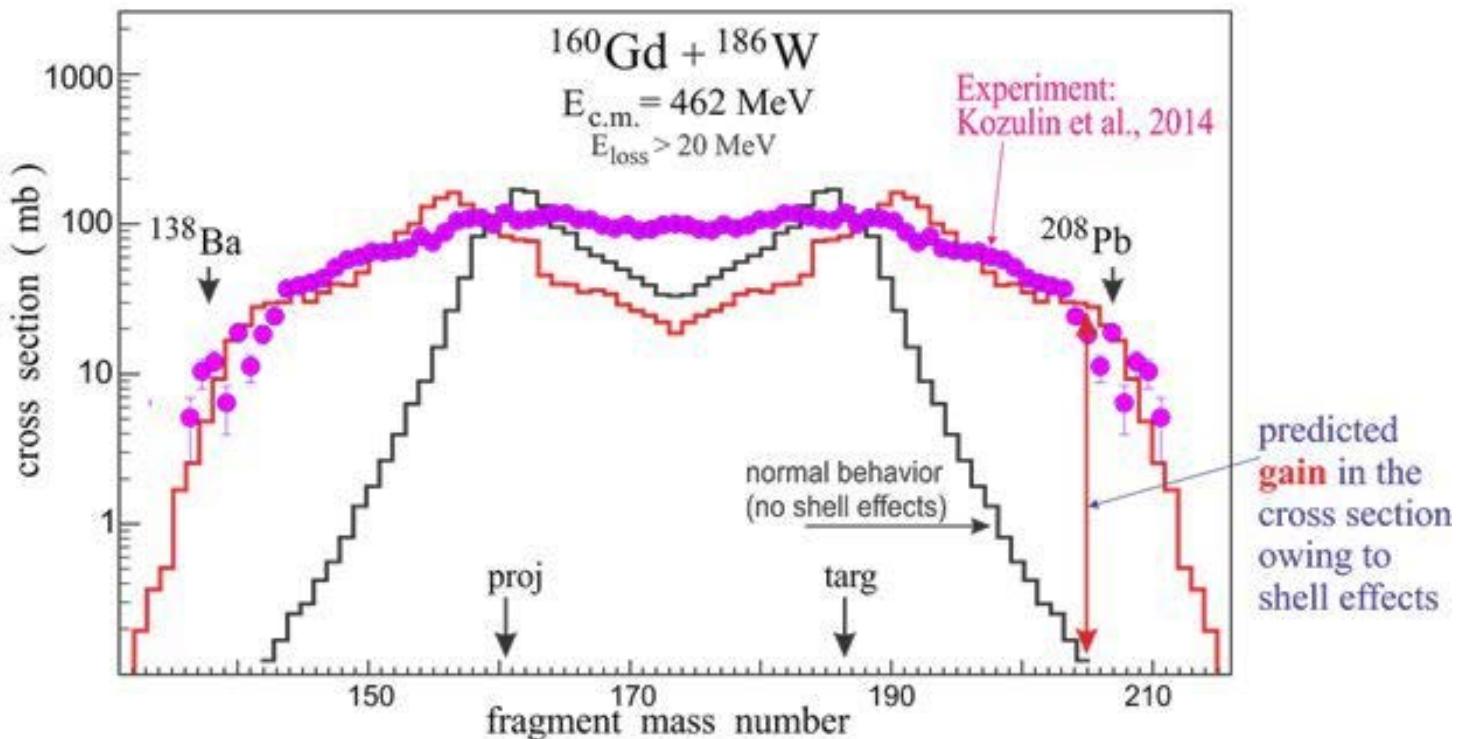
$^{238}\text{U} + ^{238}\text{U}$, $^{238}\text{U} + ^{248}\text{Cm}$,
GSI, 1977 - 1981



Upper limits for the production cross sections of SHE in the $^{238}\text{U}+^{238}\text{U}$ reaction



Test reaction $^{160}\text{Gd} + ^{186}\text{W}$





Nucl.	E(MeV)	B ρ (vac. T·m)	B ρ (He. T·m)	B ρ (H ₂ . T·m)	V (cm/ns)	E/q _{vac} (MV)
²³⁸ U	1586	1.31	1.94	1.94	3.6	23.5
²⁴⁸ Cm	1585	1.30	1.96	1.96	3.51	22.9
²⁹⁸ 114	19.6	0.83	2.04	2.52	0.36	1.49
¹⁷⁸ Yb	1532	1.30	1.77	1.77	3.97	25.8
²⁹⁸ 114	1538	1.30	2.13	2.13	3.15	20.4
¹⁷⁸ Yb	← 20.1	0.68	1.75	1.93	← 0.45	1.55
⁴ He	103		1.46		5.7	
¹ H ₂	26			0.74	6.0	

That we have learnt:

- SHE can be synthesized;
- Chemistry of SHE can be studied;
- We have only 12,000 hours beam time / year;
- We need new facilities;
- We have not enough experimental space;
- We can not accelerate ions heavier than Xe;
- Radiation safety requirements are strong;

SHE – factory !

DC280-cyclotron – stand-alone SHE-factory



DC280 (expected)
 $E=4\div8 \text{ MeV/A}$

Ion	Ion energy [MeV/A]	Output intensity
^7Li	4	1×10^{14}
^{18}O	8	1×10^{14}
^{40}Ar	5	6×10^{13}
^{48}Ca	5	$0,6\text{-}1,2\times10^{14}$
^{54}Cr	5	2×10^{13}
^{58}Fe	5	1×10^{13}
^{124}Sn	5	2×10^{12}
^{136}Xe	5	1×10^{14}
^{238}U	7	5×10^{10}

- Synthesis and study of properties of superheavy elements.
- Search for new reactions for SHE-synthesis.
- Chemistry of new elements.

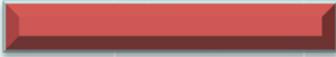
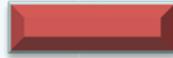
Specialized high-current cyclotron DC280



SHE-factory



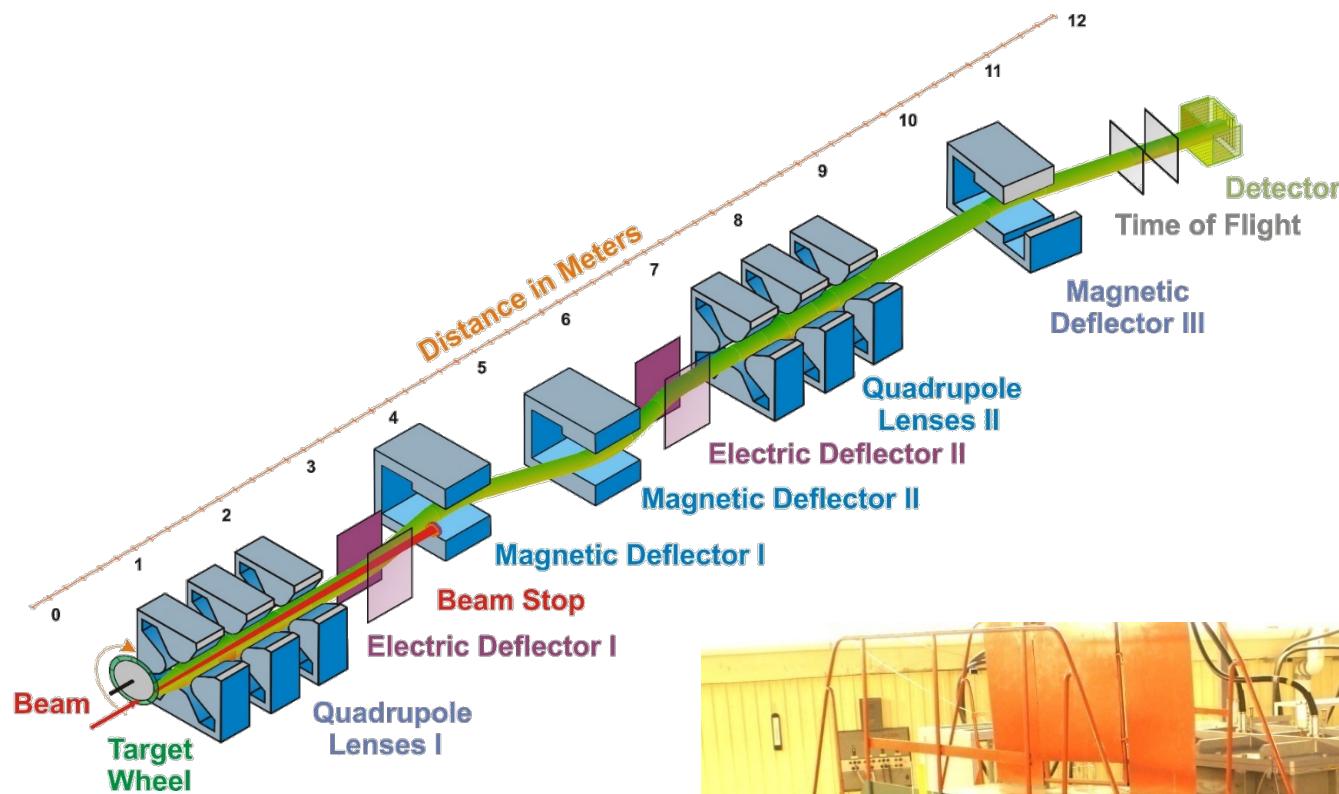
DC280 Construction Timetable

		2011	2012	2013	2014	2015	2016	2017
1	Building design							
2	Building construction							
3	DC280 design and manufacturing							
4	DC280 installation and adjustments							
5	First beam @ target							

New set-ups

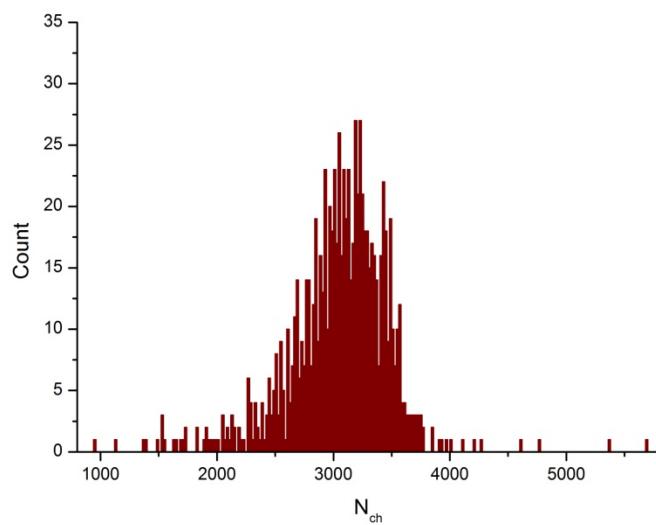
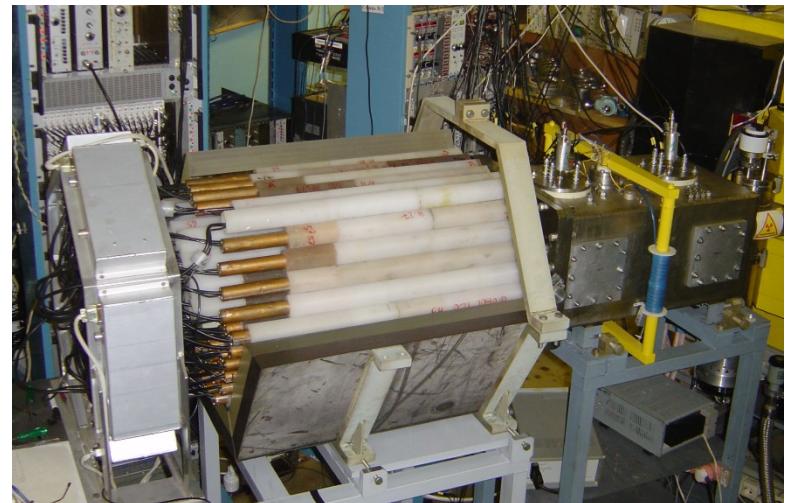
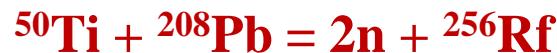
- New separators-spectrometers,
- New gas filled separator,
- Preseparator,
- Gas catcher,
- Fast radiochemical methods,
- Something for transfer reactions products,
- Laser ionization,
- ...

Separator for Heavy Element Spectroscopy (SHELS)



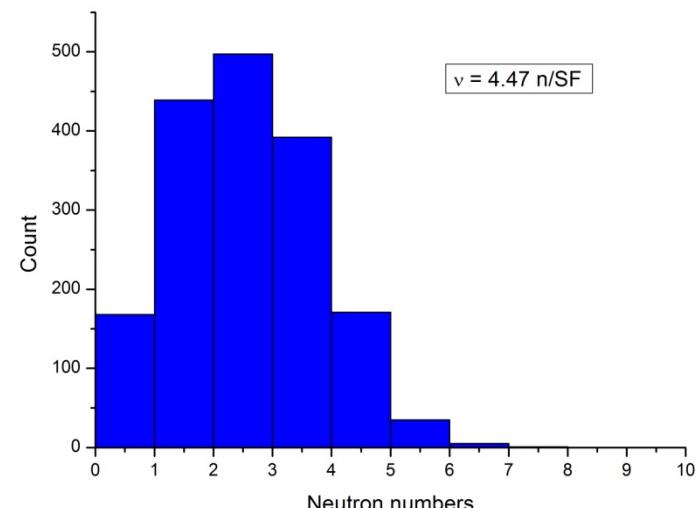
First research experiment with accelerated ^{50}Ti beam at FLNR U400 cyclotron FLNR, CSNSM, IReS (France)

^{50}Ti beam intensity – 3×10^{12} pps.



TKE spectra for S.F. of ^{256}Rf isotope

^3He – neutron detector system at the focal plane of SHELS, $\epsilon(^{252}\text{Cf}) = 40\%$



Neutron multiplicity measured for spontaneous fission of ^{256}Rf

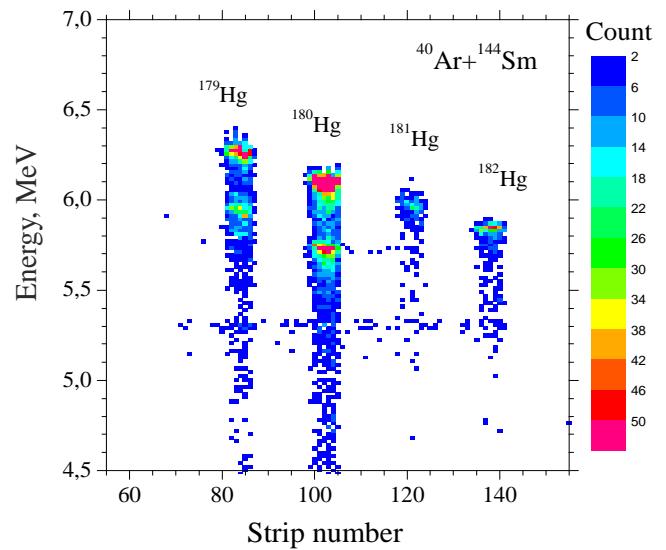
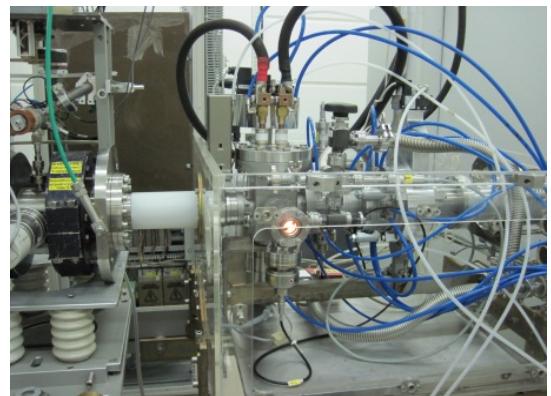
New focal plane detector GABRIELA



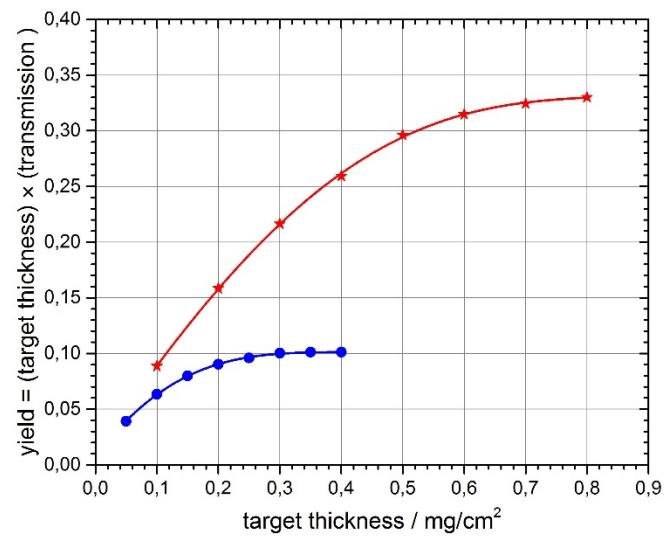
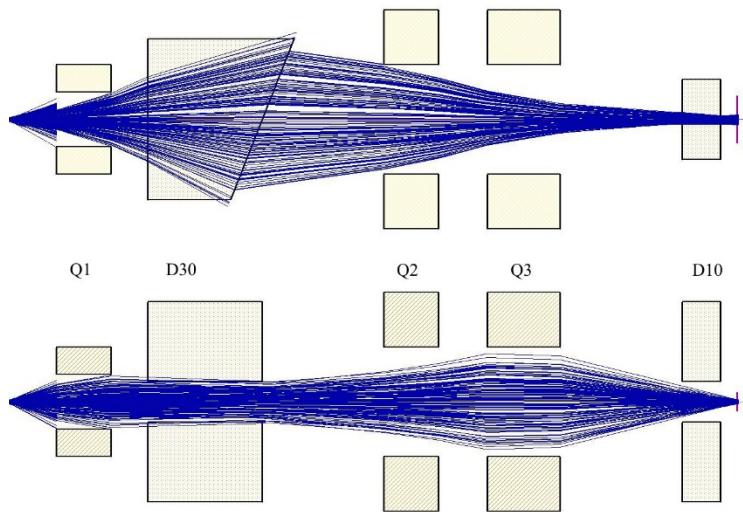
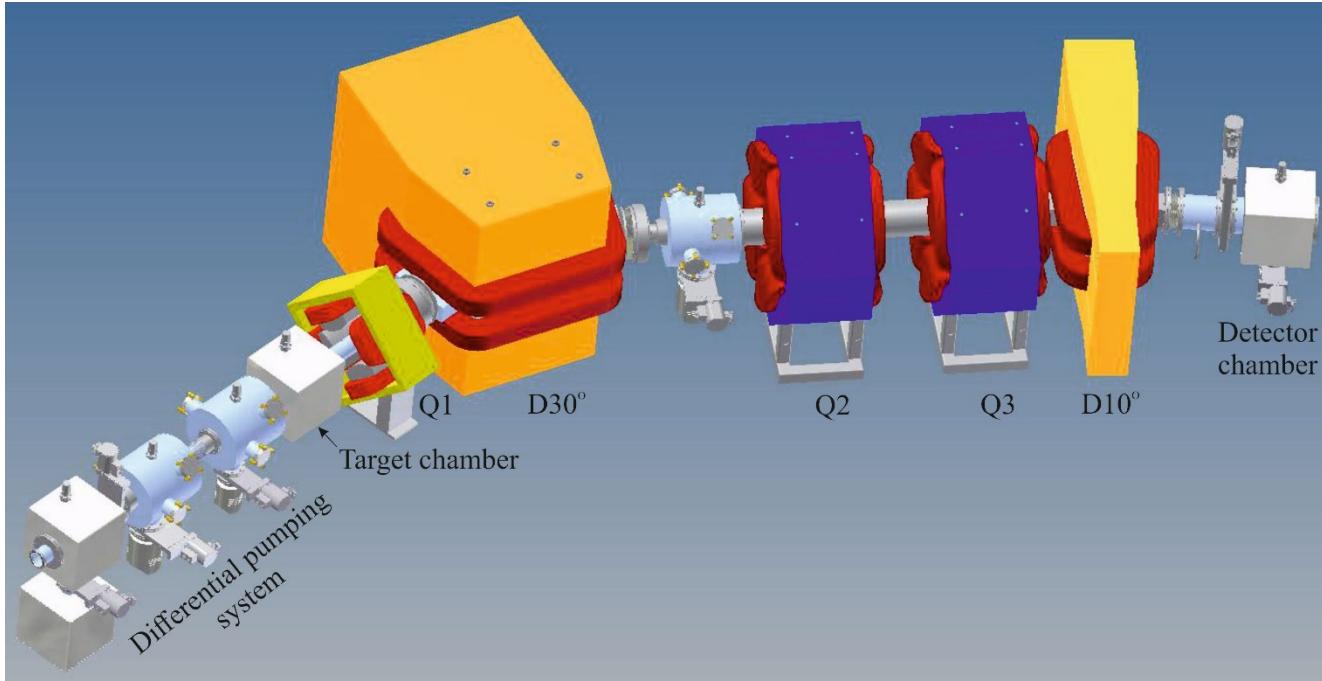
GABRIELA - Gamma Alpha Beta Recoil Investigation with the Electromagnetic Analyser

MAss-Separator of Heavy Atoms - “MASHA” @ U400M

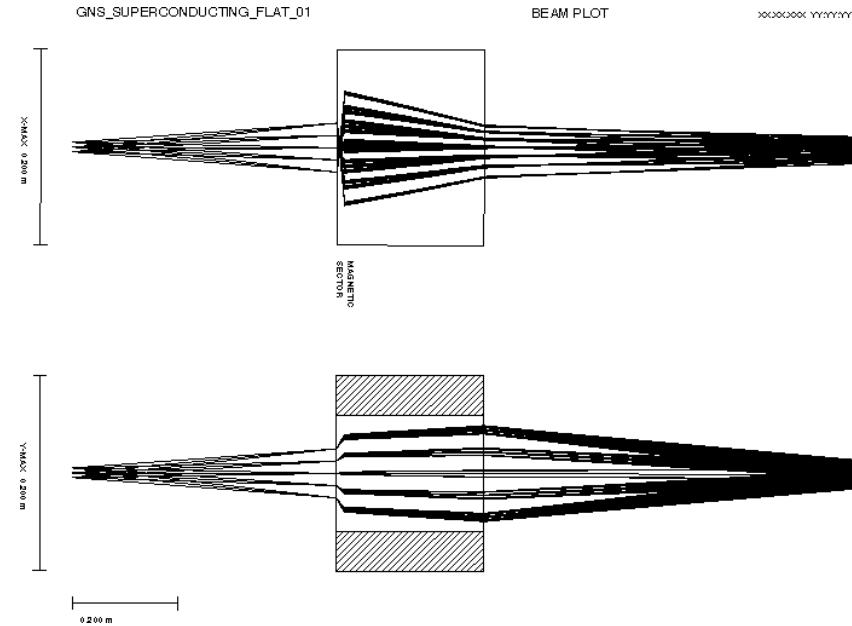
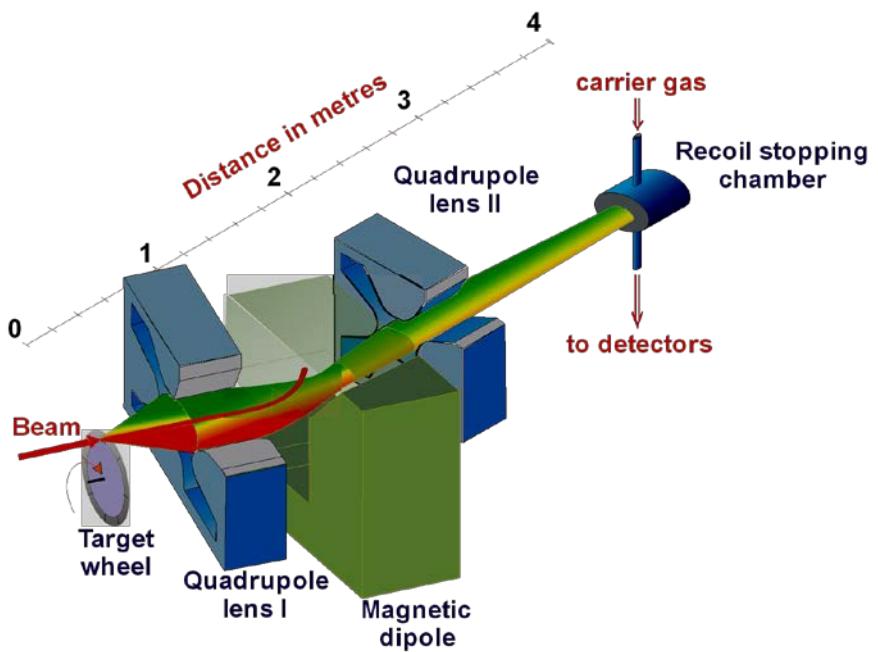
Hot catcher



New gas-filled separator DGFRS-II



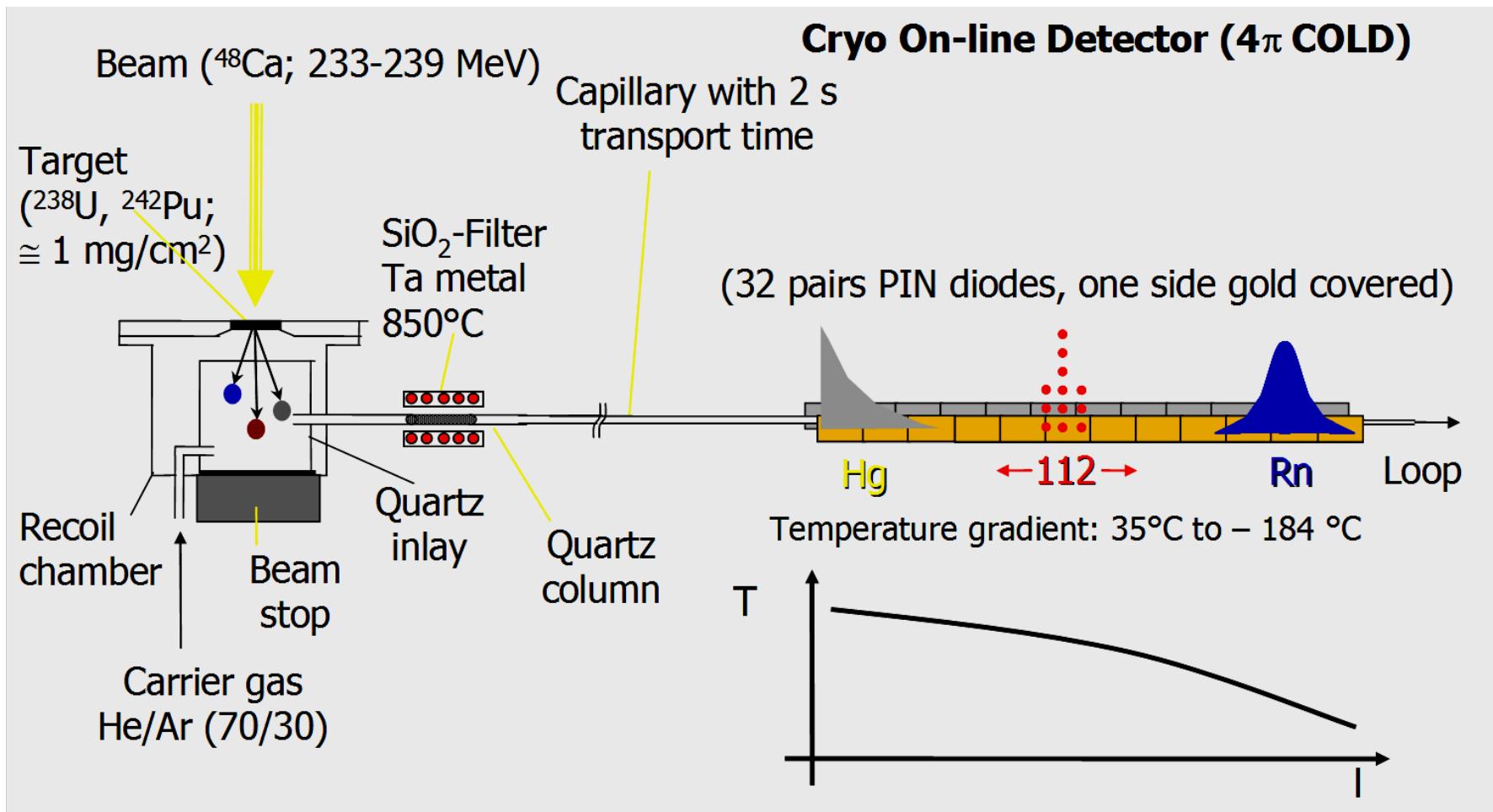
Gas-filled pre-separators



$Q_v D Q_h$

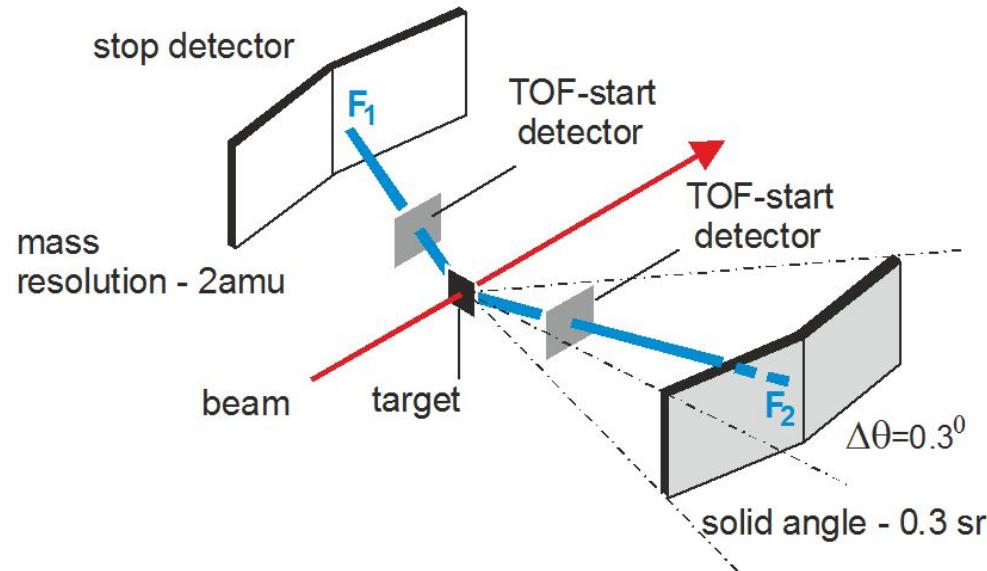
Superconducting

Gas Phase chemistry (IVO Technique)

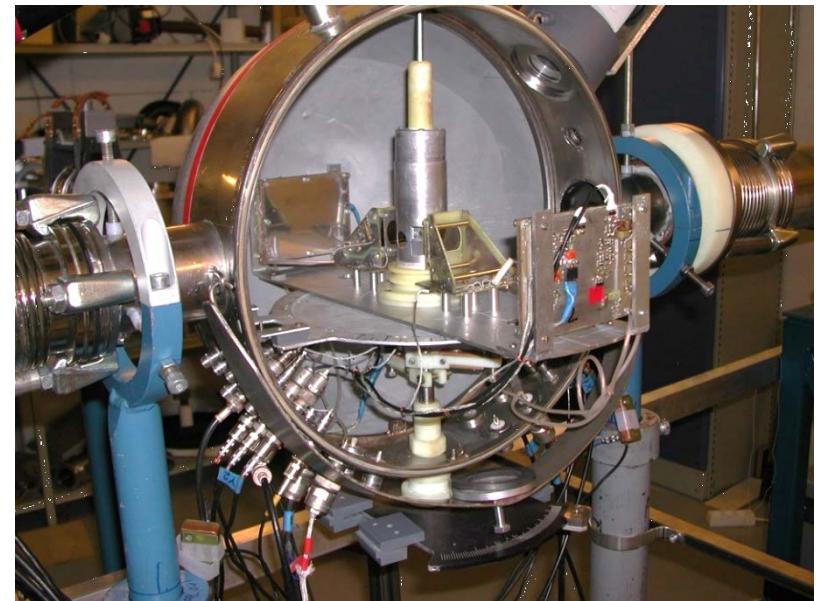
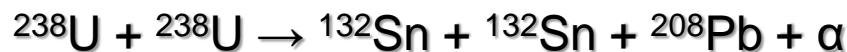
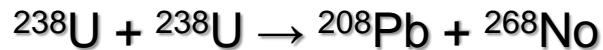
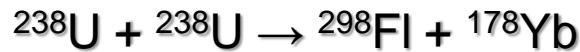


Also in combination with a preseparator

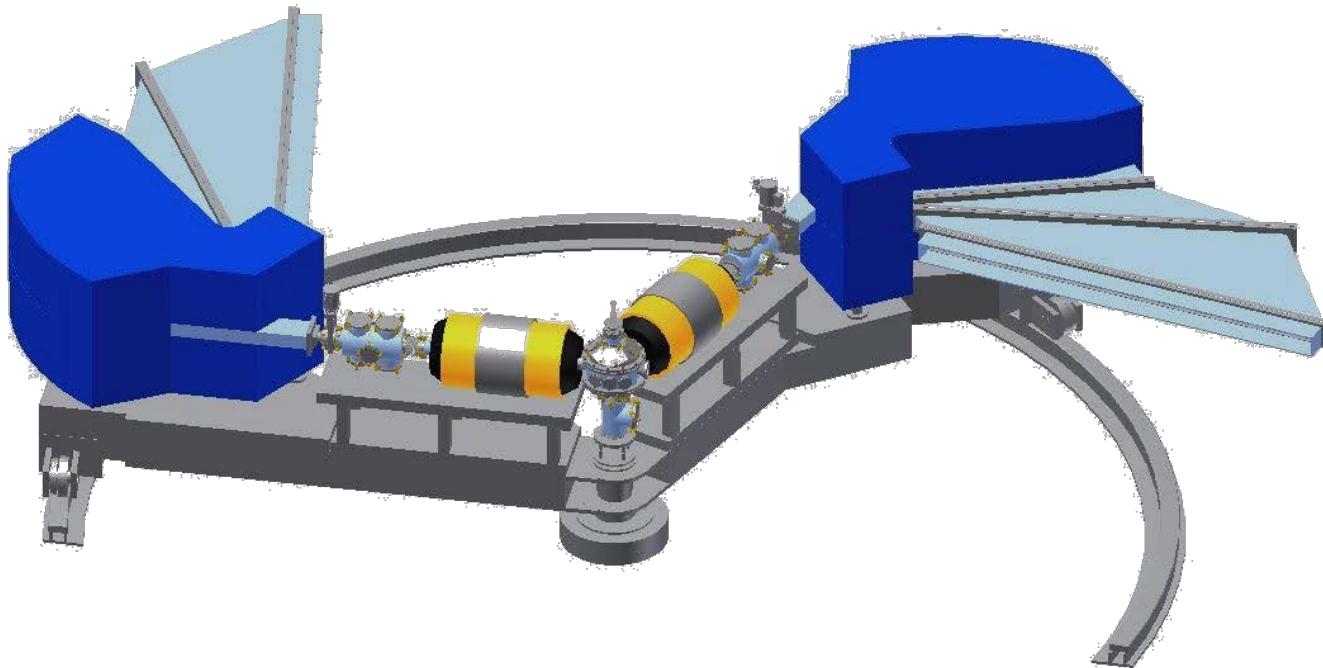
Time-of-Flight spectrometer CORSET



Search for processes like:

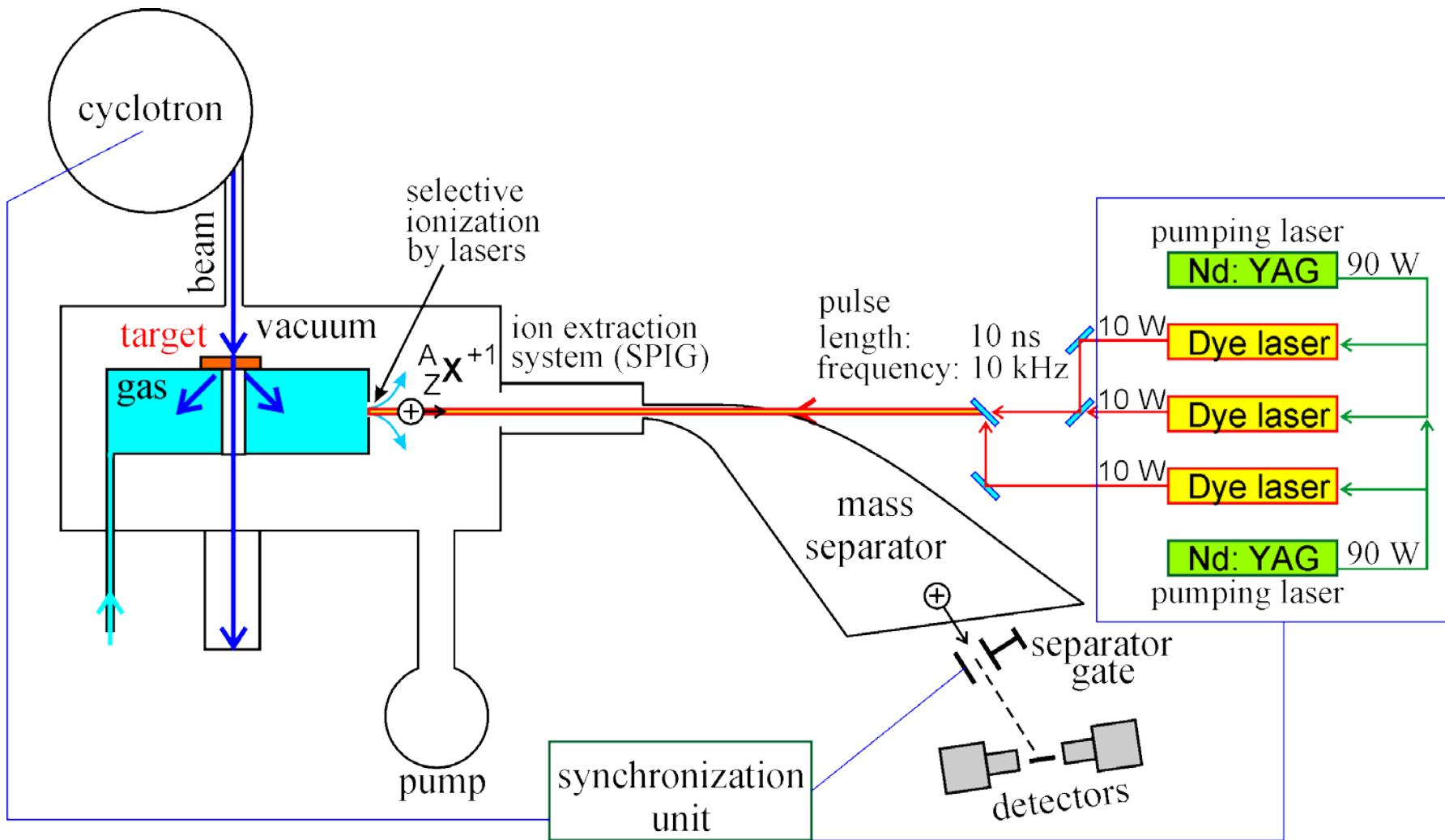


High resolution magnetic double arm spectrometer “MAVR”



Reaction study with primary and secondary beams

New setup for selective laser ionization of multi-nucleon transfer reaction products stopped in gas



New setup for selective laser ionization. Laser room

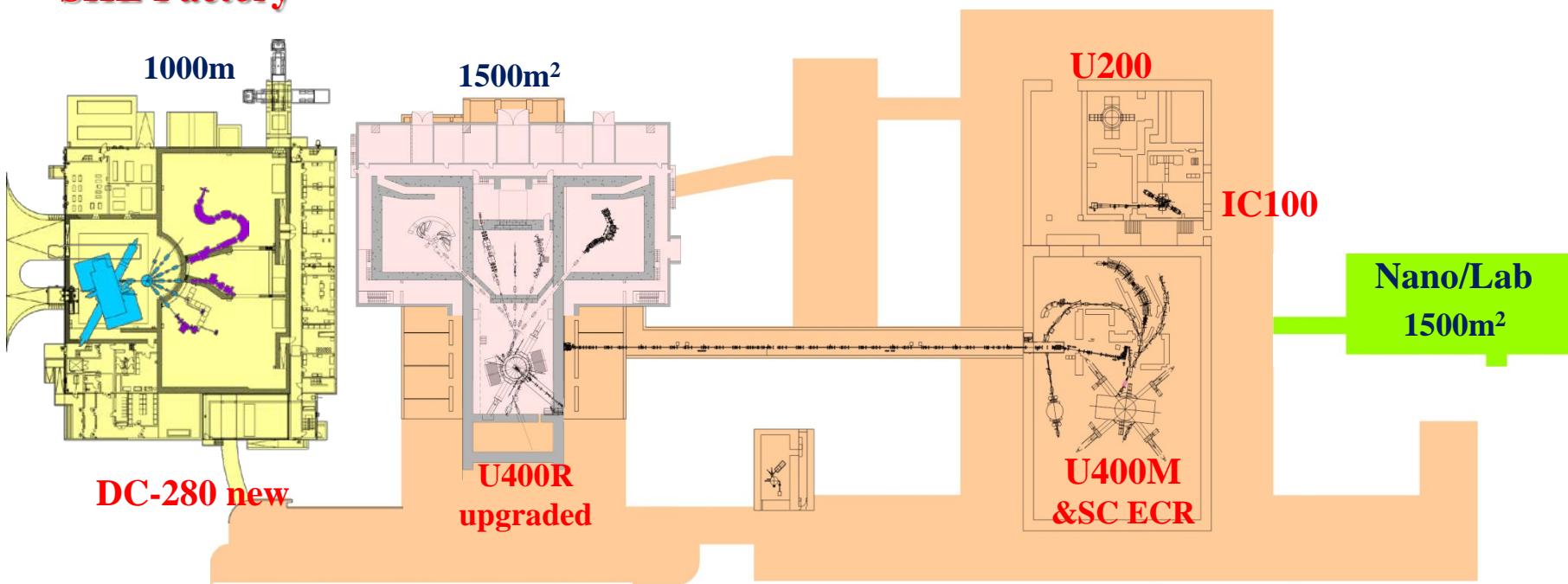


Conclusion

- The SHE – factory is a part of the project DРИBs-III → modernization of basic facilities of FLNR,
- The realization of the DРИBs-III project will provide the quantitative increase of the efficiency of experiments as a whole by at least one order of magnitude.

Full-scale realization off the DRIBs-III -project

SHE Factory



**Heavy &
Super heavy**

**Nuclear
spectroscopy**

**Light exotic nuclei &
Applied research**

**THANK YOU
FOR YOUR
ATTENTION !**



Flerov Laboratory of Nuclear Reactions (JINR)