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Helmholtzzentrum für Schwerionenforschung,
Darmstadt Germany

Perspectives of SHE research at Dubna

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OUTLINES

What do we know about SHE?
Targets and projectiles.
SHE – factory.
High-current cyclotron DC-280.
New facilities.
Conclusions.

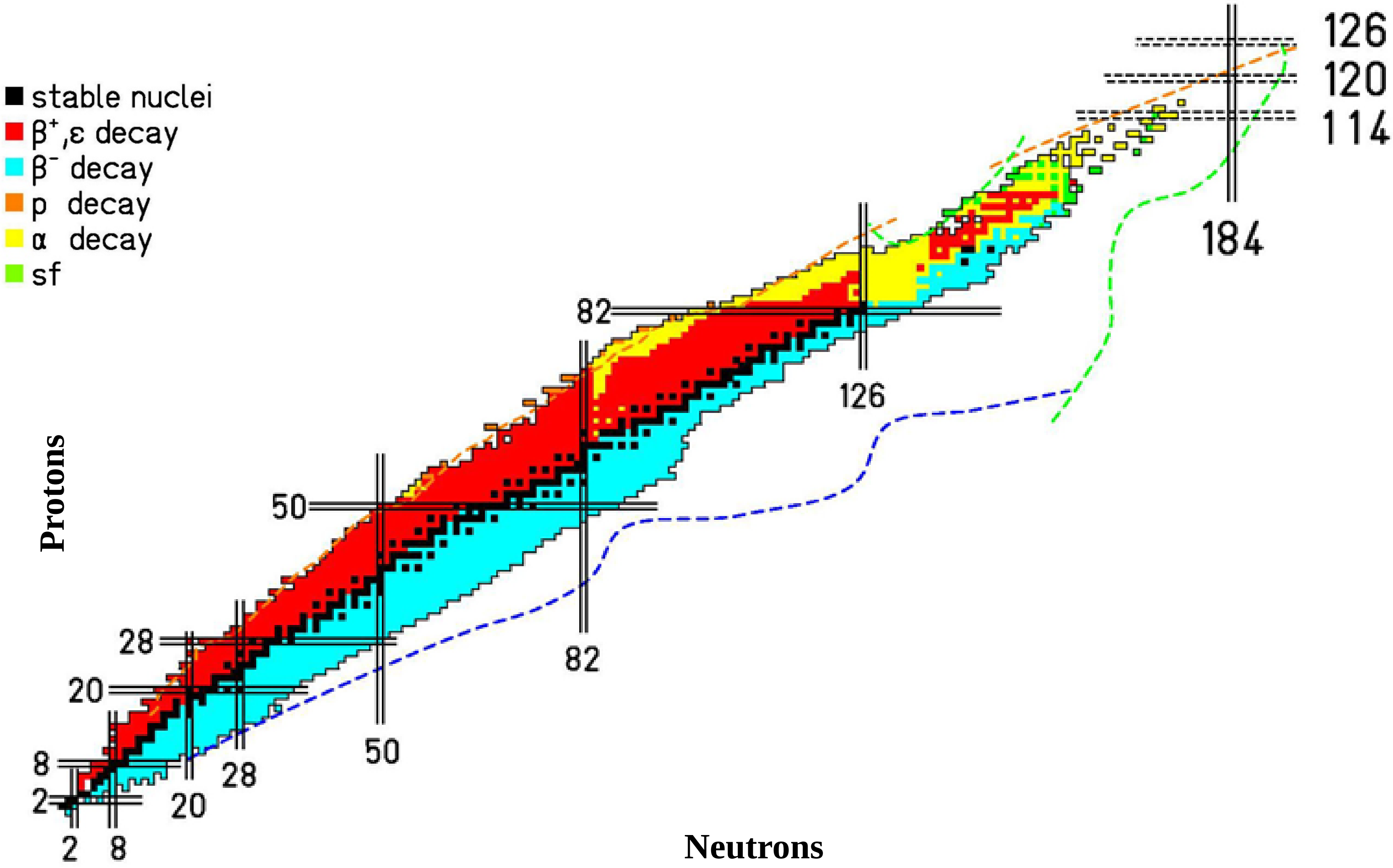
History

- **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: $T_{1/2} \ast 10^{\pm 10}$!!**
- **α-decay: $T_{1/2} \ast 10^{\pm 10}$!!**

Chart of the Nuclides (decay modes)



Synthesis of SHE at accelerators

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

Reactions of Synthesis

Act. + ^{48}Ca

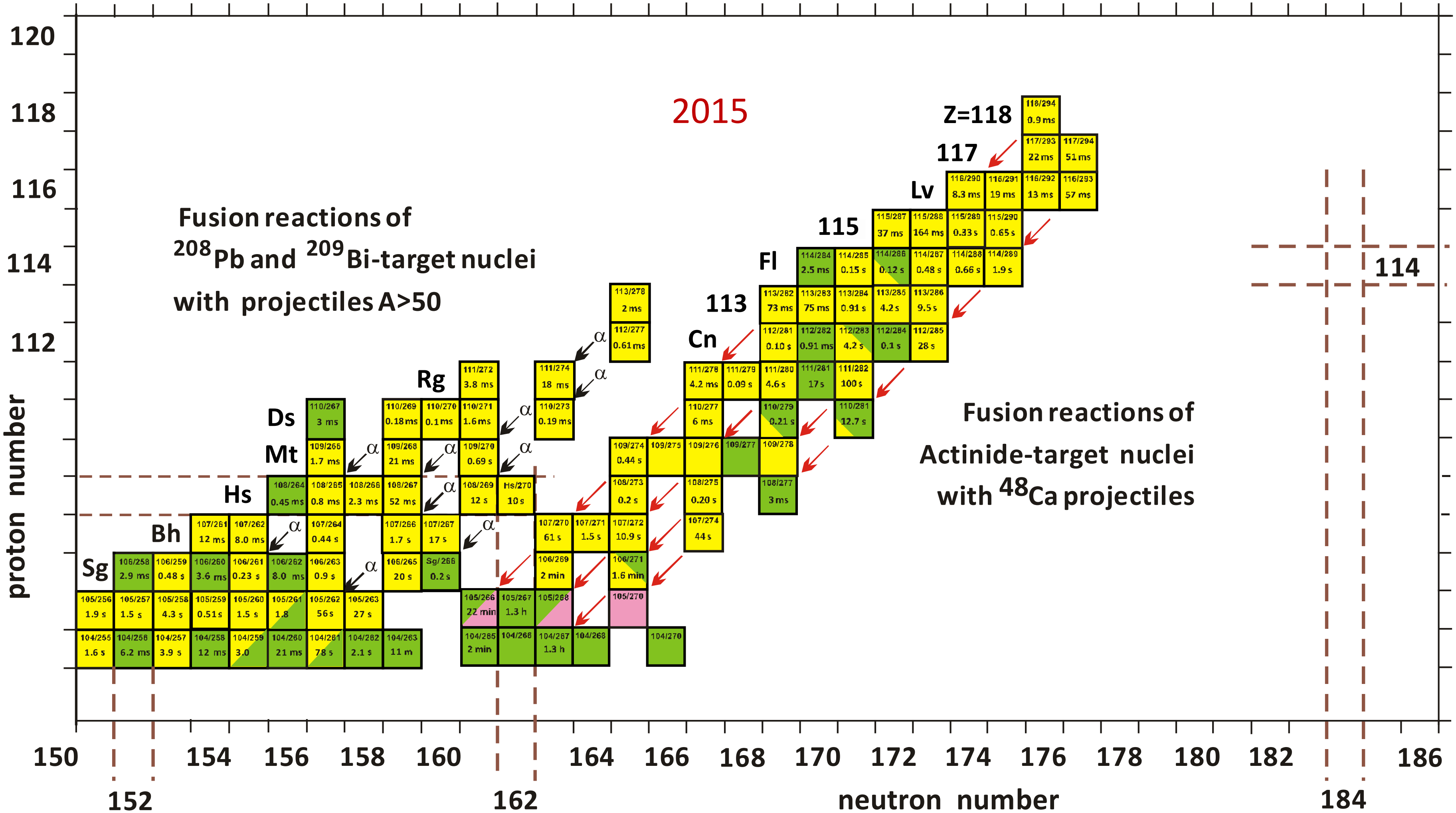
Projectiles ^{48}Ca produced by Heavy Ion Accelerator U400;

Energy: 235-250 MeV
($v \approx 0.1$ c);
Intensity: 1.0-1.5 pμA
($n \times 10^{12} \div 10^{13}$ 1/s);
Consumption: 0.5-0.8 mg/h
Beam dose: $(0.3\text{-}3.0) \cdot 10^{19}$

Prices per 1 mg

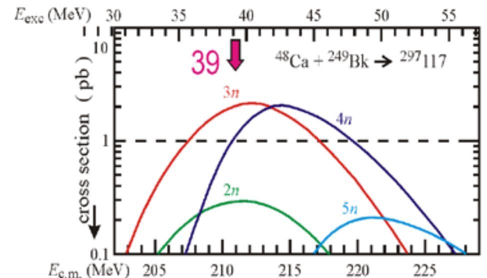
^{197}Au ≈ 0.045 US$
$^{nat}U_3O_8$ ≈ 0.03 US$
^{239}Pu ≈ 4 US$
^{48}Ca ≈ 80 US$
^{249}Cf ≈ 60,000 US$

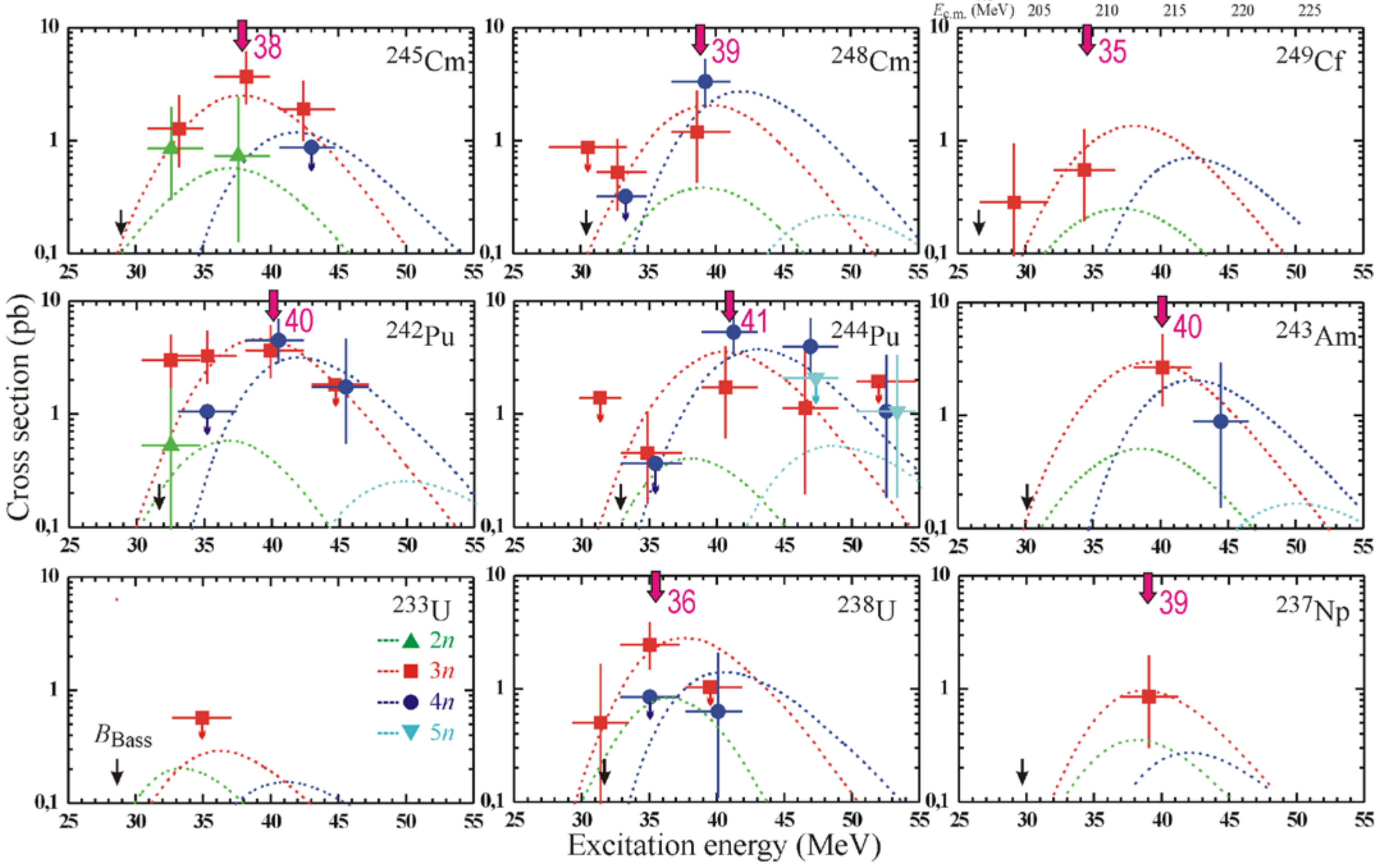
Target materials	Producer	Isotope enrichment (%)
^{232}Th	----	100
^{233}U	RFNC	---
^{238}U	----	99.3
^{237}Np	IAR	99.3
^{239}Pu	RFNC	---
^{240}Pu	IAR/ORNL	99.98
^{242}Pu	RFNC/ORNL	99.98
^{244}Pu	ORNL	98.6
^{243}Am	IAR / ORNL	99.9
^{245}Cm	IAR	98.7
^{248}Cm	IAR /ORNL	97.4
^{249}Bk	ORNL	≥ 95
^{249}Cf	IAR/ORNL	97.3
^{249,250,251}Cf	ORNL	(50+14+36)%


2015
Fusion reactions of
^{208}Pb and ^{209}Bi-target nuclei
with projectiles A>50
Fusion reactions of
Actinide-target nuclei
with ^{48}Ca projectiles
Z=118
117
Lv
115
Fl
113
Cn
Rg
Ds
Mt
Hs
Bh
Sg
proton number
neutron number
120
118
116
114
112
150
152
154
156
158
160
162
164
166
168
170
172
174
176
178
180
182
184
186

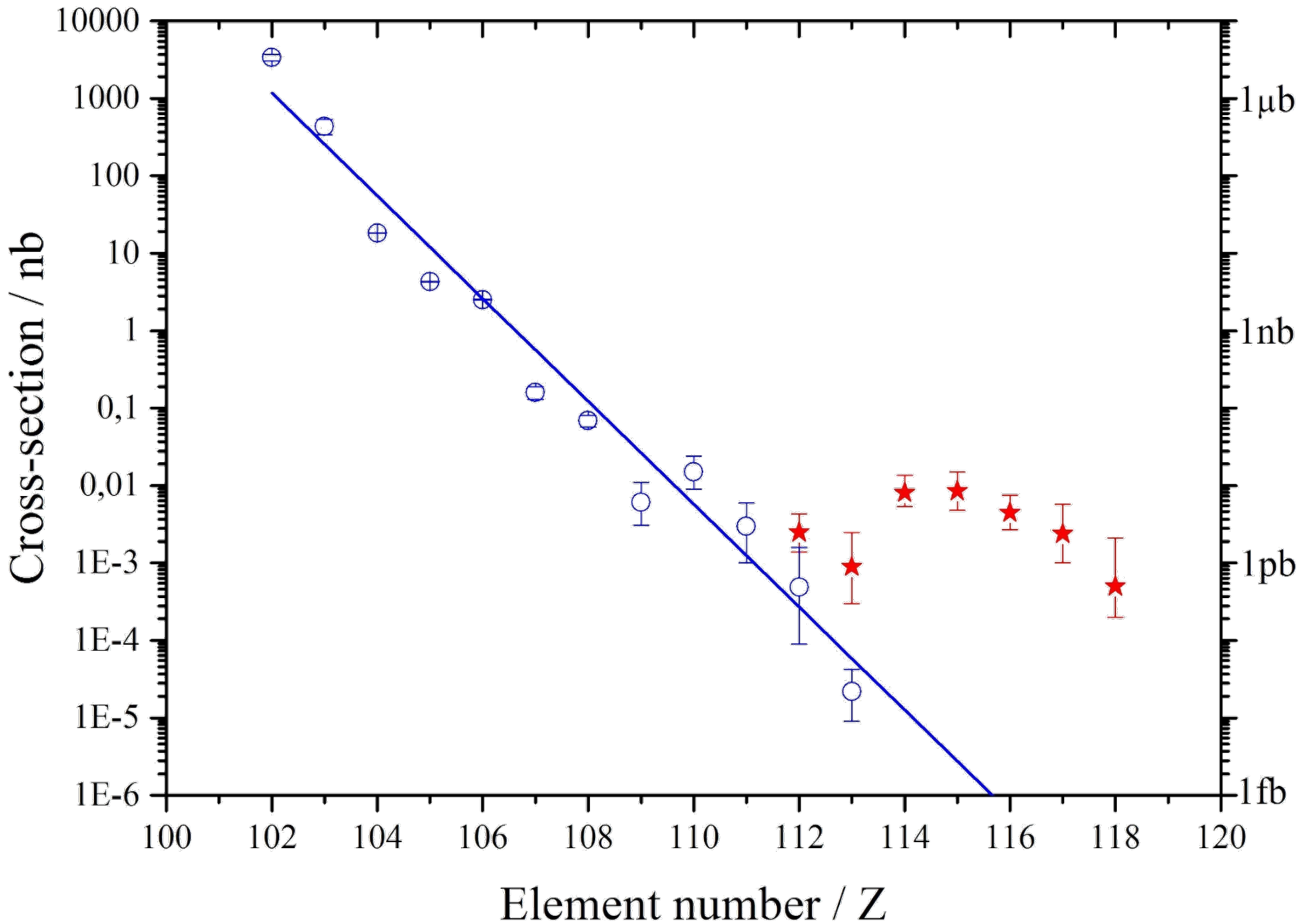
Excitation functions of SHE

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





Production cross-sections of heavy and super-heavy

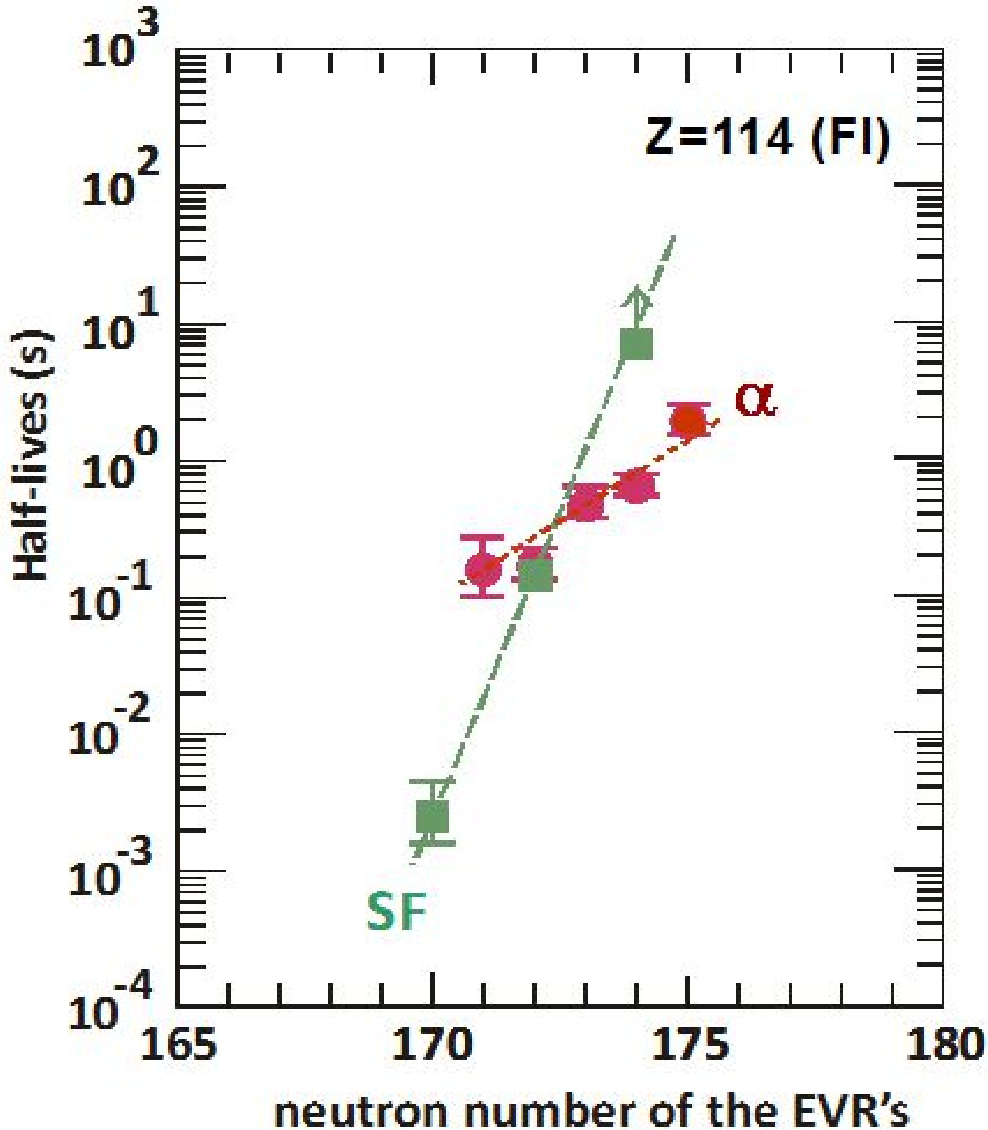


100 / h

1 / week

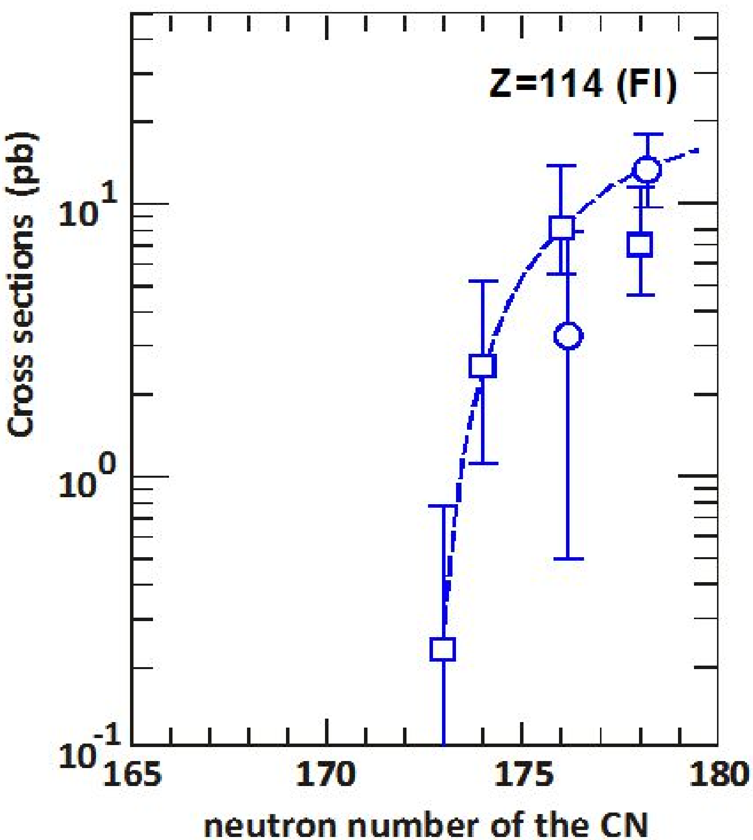
1 / 20 y

α-decay and S.F. of Fl isotopes from reactions $^{239,240,242,244}Pu + ^{48}Ca$

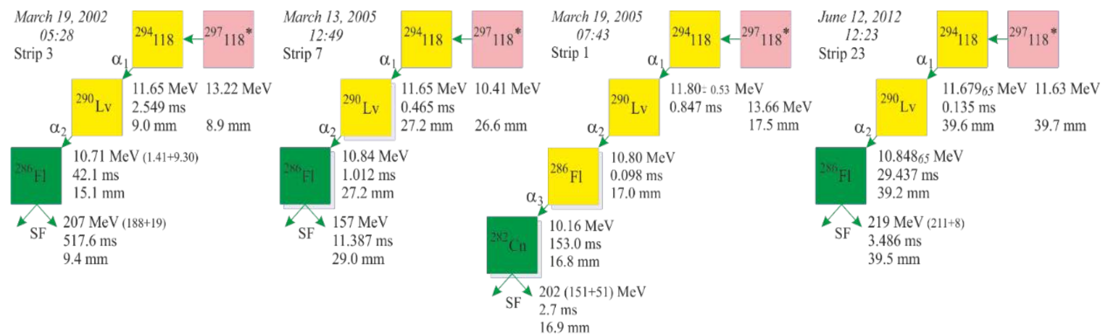


The borders of the SHE-island

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

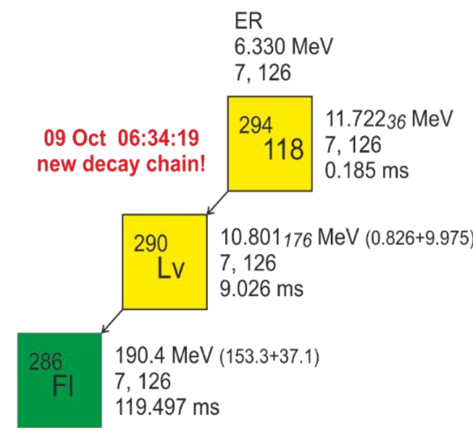


^{249}Cf + ^{48}Ca

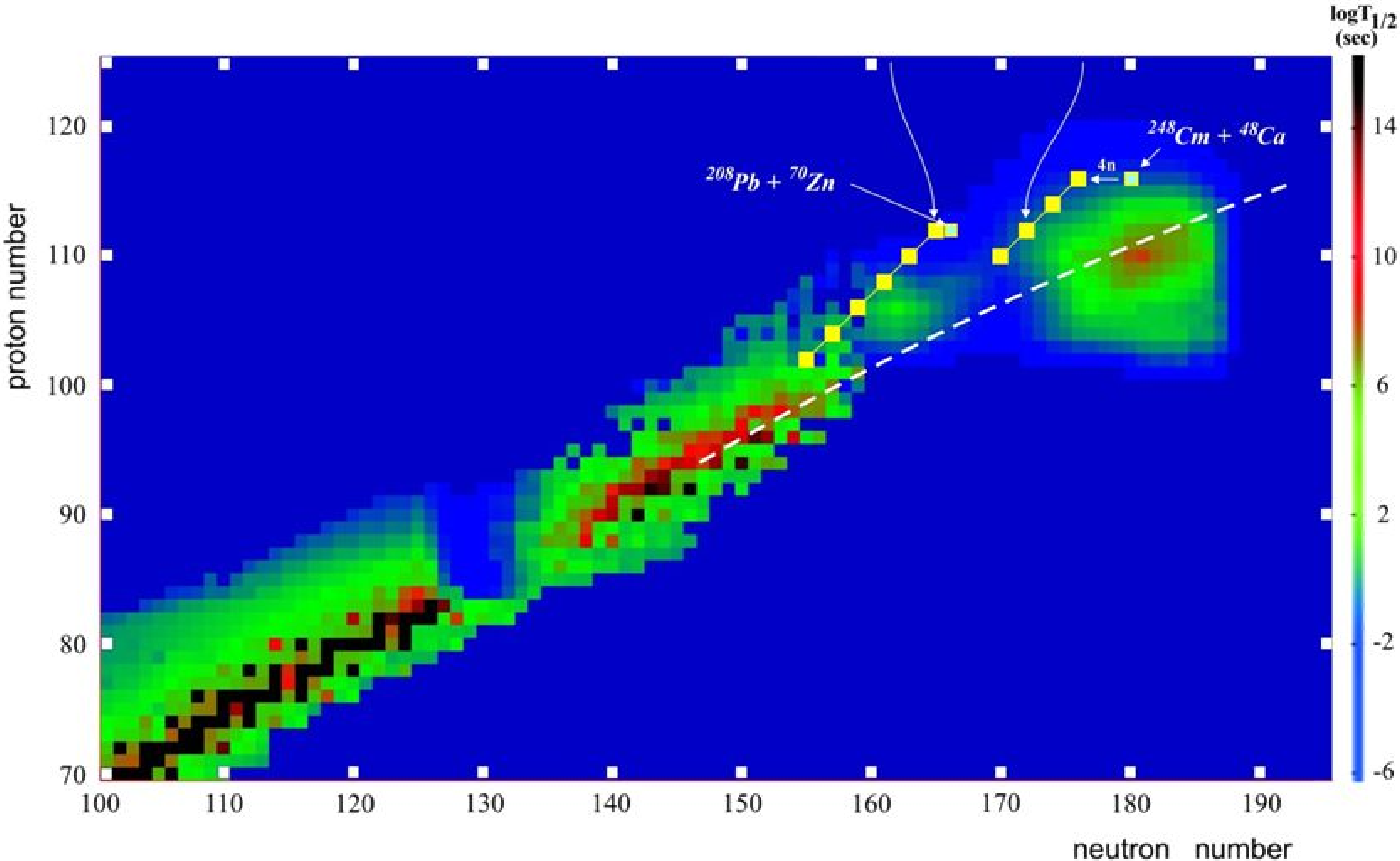


$^{249-252}$Cf + ^{48}Ca

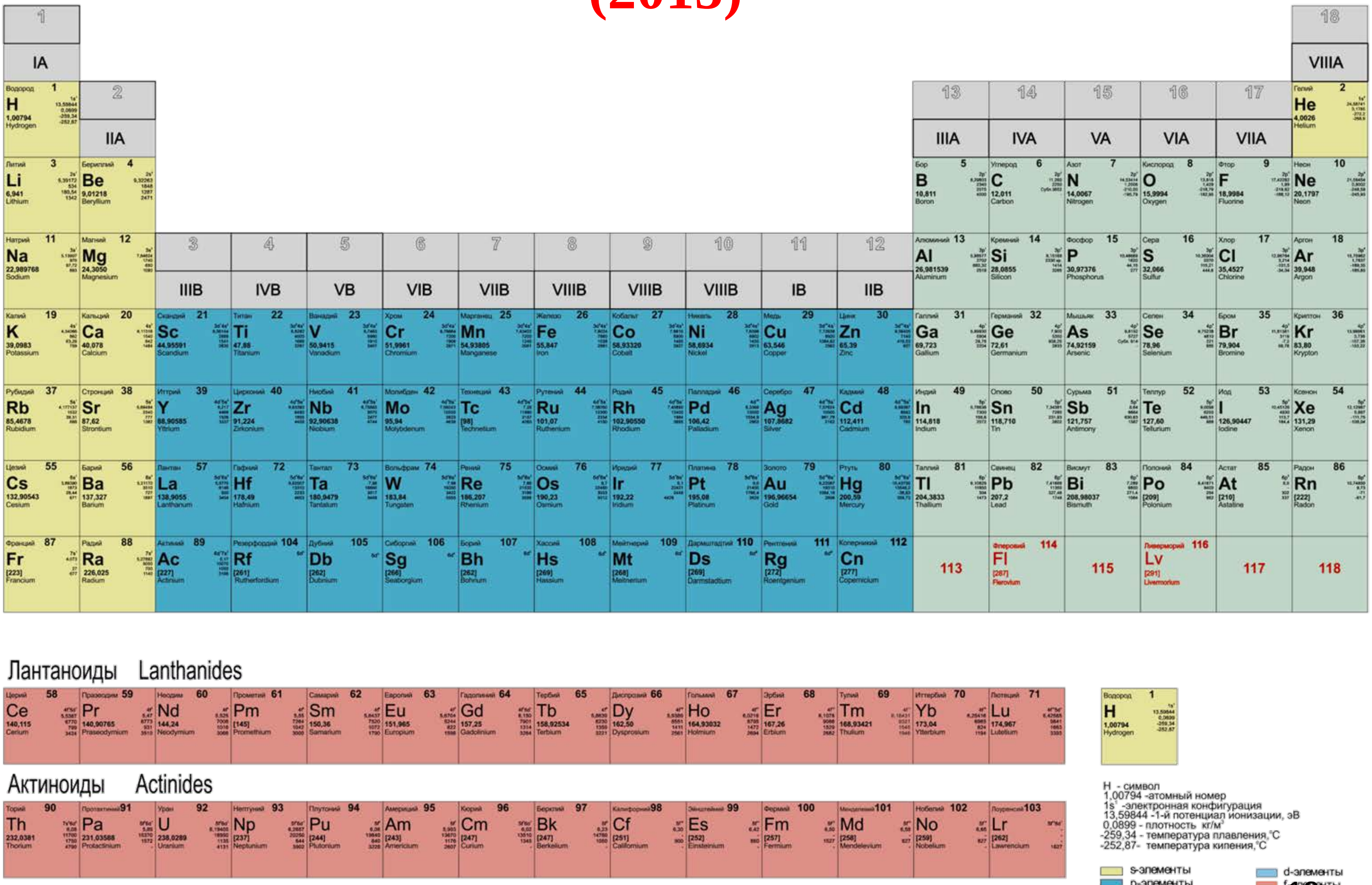
09 Oct 06:34:19
new decay chain!



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



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



What to do further?
Complete fusion reactions:

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

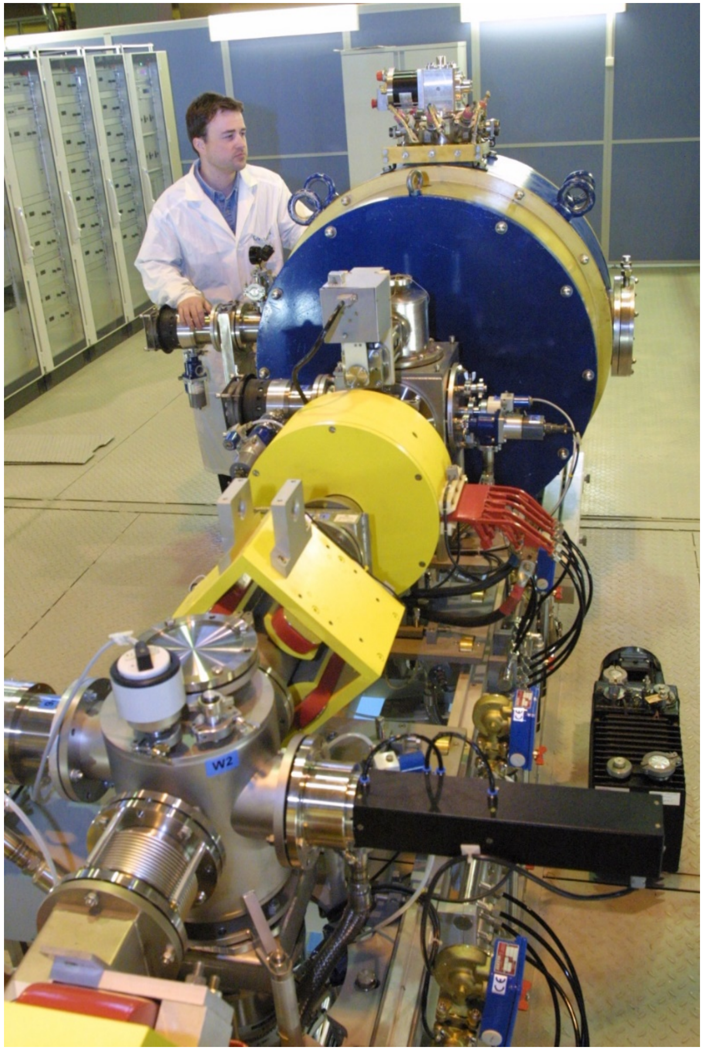
Heaviest target: $^{249}Cf \rightarrow Z_{max} = 118$

↓

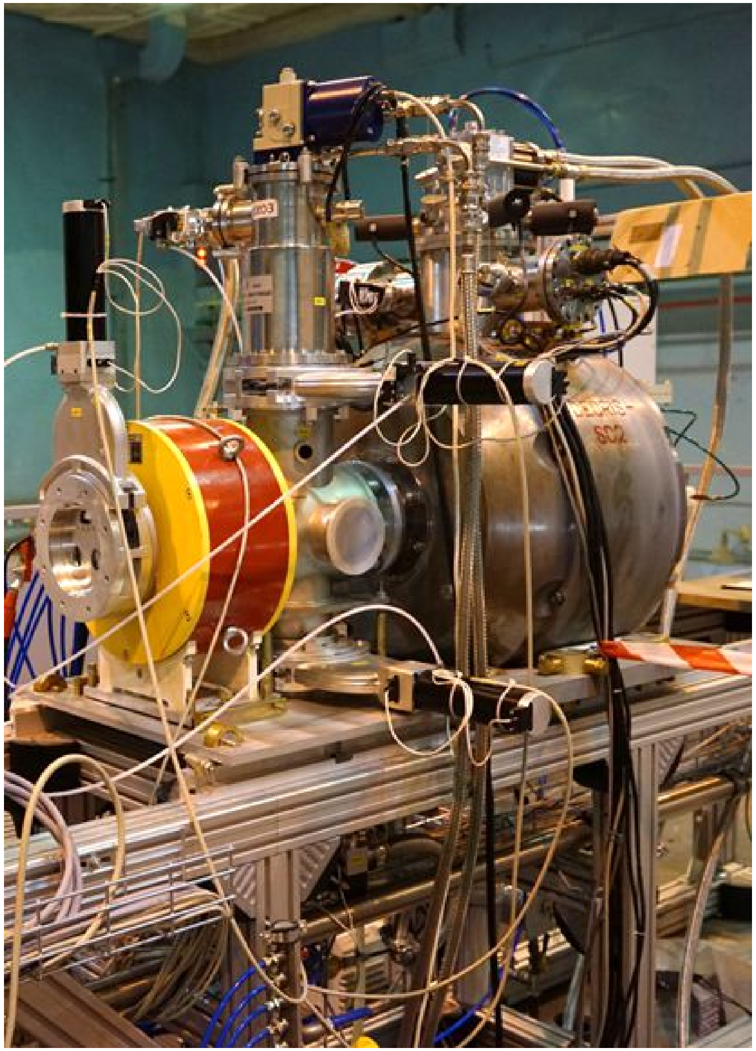
- Heavier projectiles (^{50}Ti, ^{54}Cr, ^{58}Fe, ^{64}Ni …)
- Heavier targets: ^{250}Cm, ^{251}Cf;
- Exotic targets: ^{254}Es, ^{257}Fm -???;
- Symmetric reactions:
  $^{136}Xe+^{136}Xe$, $^{136}Xe+^{150}Nd$, $^{150}Nd+^{150}Nd$;
- Reactions with RI.

Superconducting 18 GHz ECR ion sources

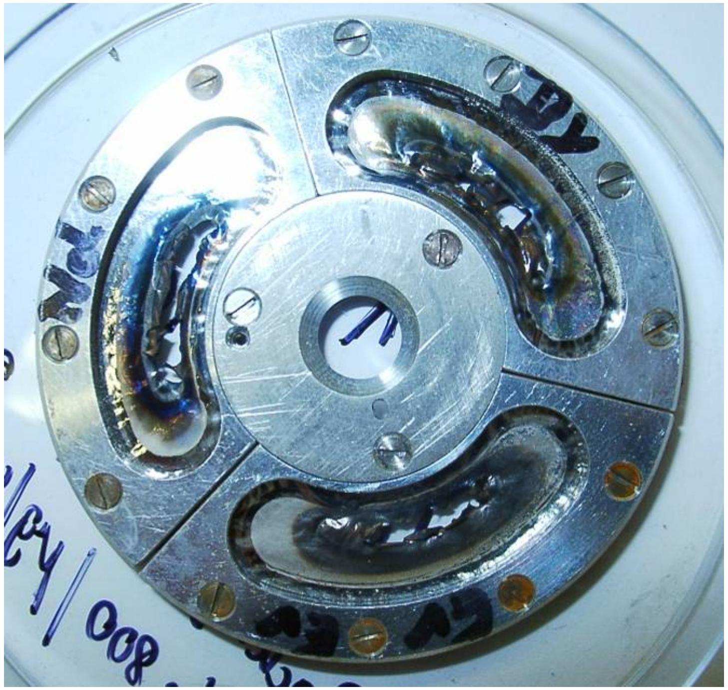
DECRIS-SC1

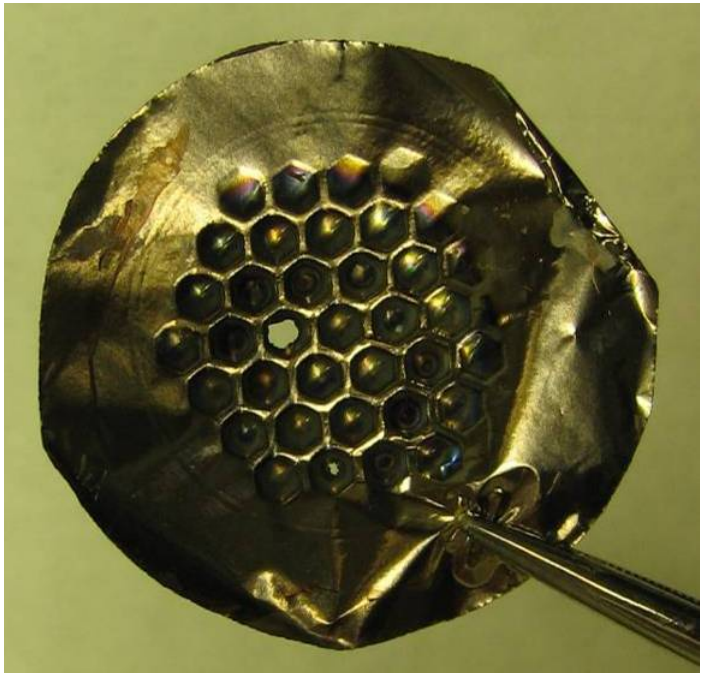


DECRIS-SC2



Targets I – destruction



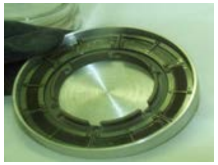


- Heating and melting;
- sputtering;
- radiation damage.

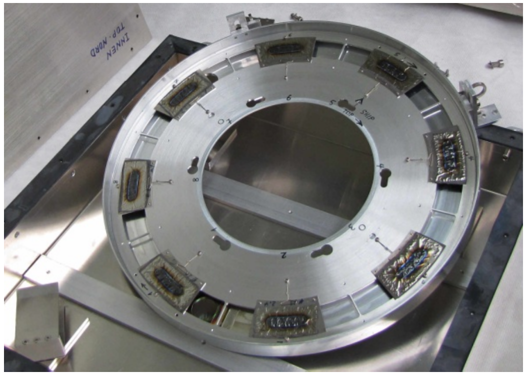
Targets II – reduction of heating

ø5 cm

ø10 cm



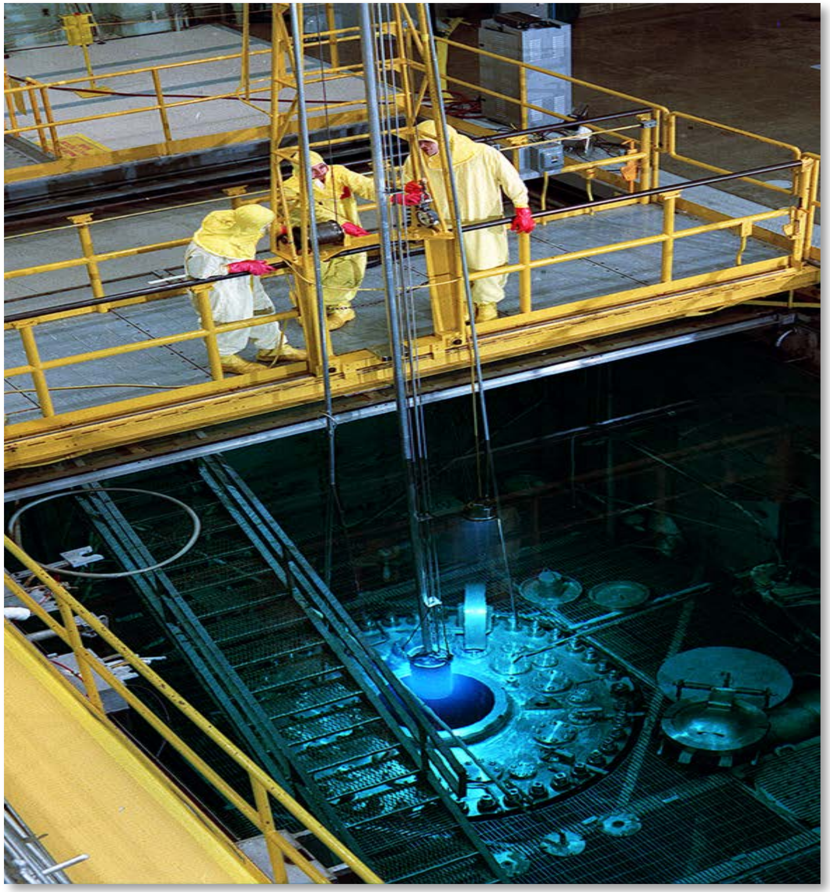
ø30 cm



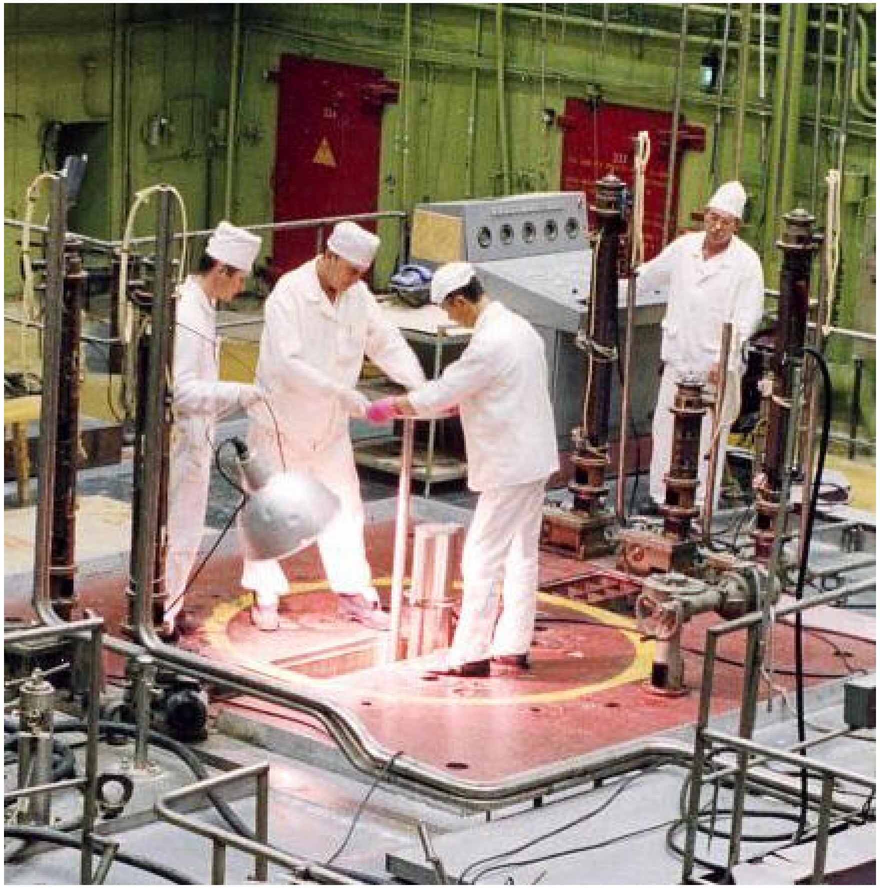
ø60 cm →

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, ≈ 1 M$, 1 year at HIFR ORNL

$Bk(NO_3)_3$Product

Targets IV – radiation safety

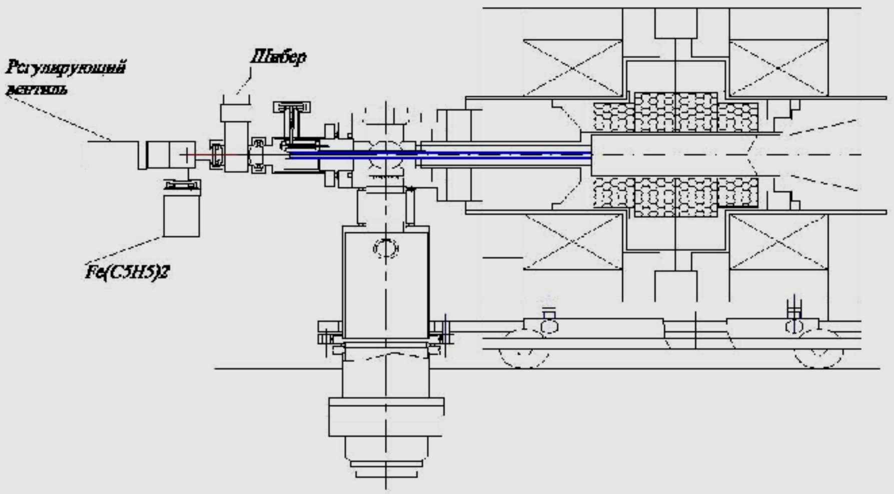
^{248}Cm @ SHIP

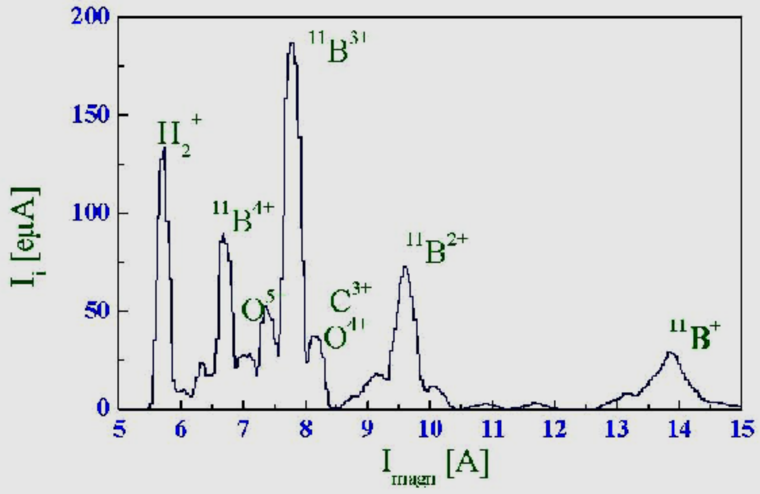
^{249}Cf @ DGFRS

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 - $C_2B_{10}H_{12}$

Ti – $(CH_3)_5C_5\mathbf{Ti}(CH_3)_3$

Fe – $\mathbf{Fe}(C_5H_5)_2$; Ni – $\mathbf{Ni}(C_5H_5)_2$

Cr – $Cr(CO)_6$; W – $W(CO)_6$

U-400 – $^{58}Fe^{7+}$ - 40÷50 μA

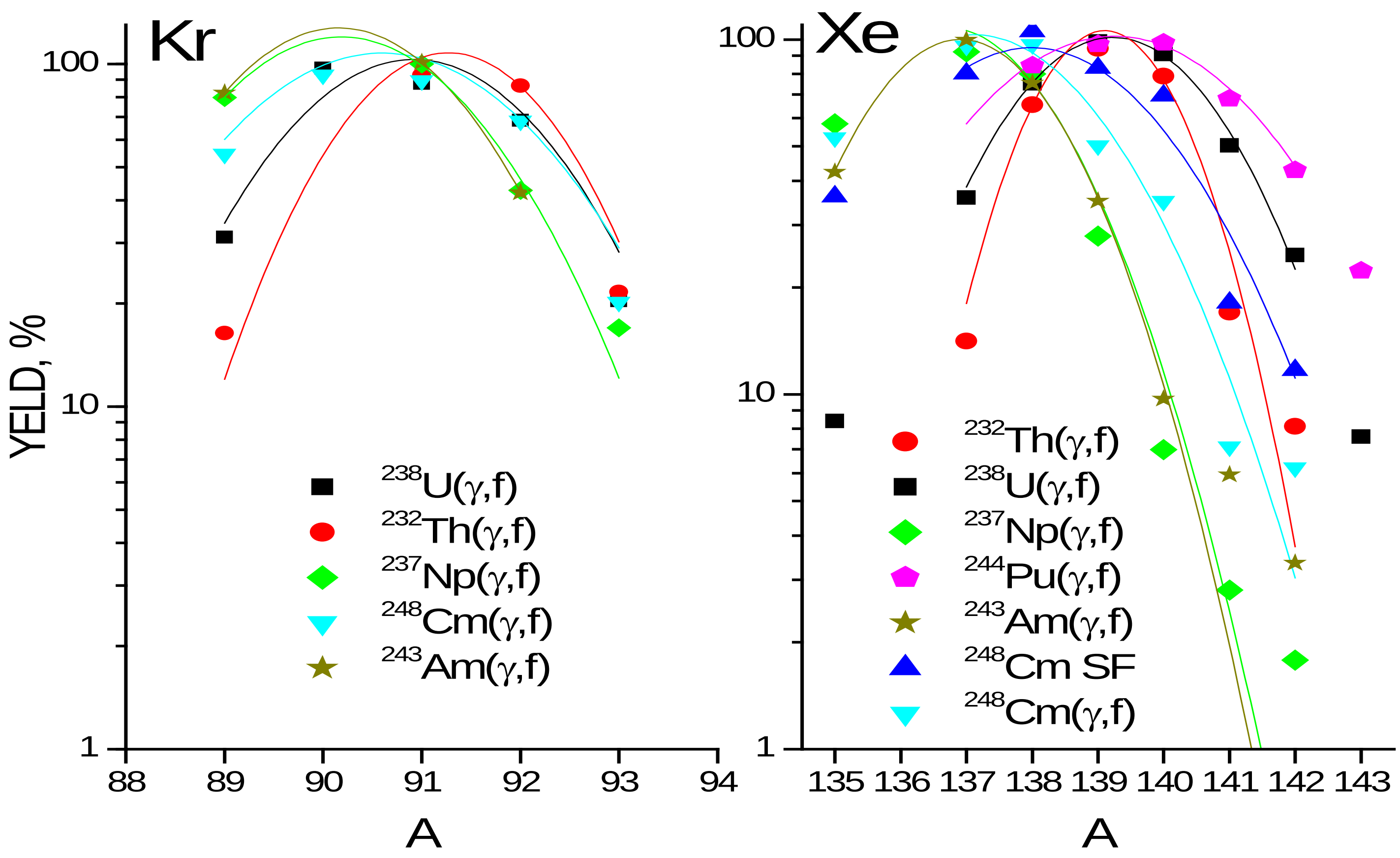
Material consumption ~ 3 mg/h

(~ 1.5 mg/h for ^{58}Fe)

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

The use of RI-beams

^{93}Kr + ^{226}Ra $\longrightarrow$ ^{319}124*, N = 195

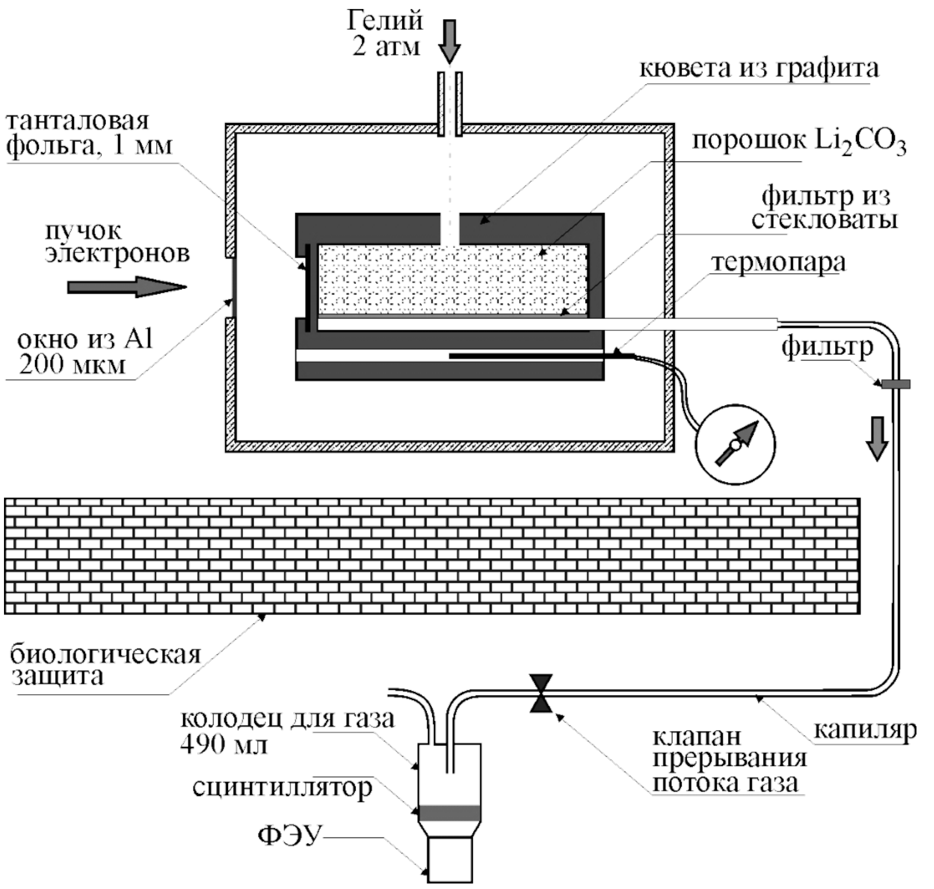


Yields of Kr and Xe isotopes in photofission of actinides at γ-energy of 25 MeV
Due to hard radiation conditions the project was stopped (not cancelled!)

The use of RI-beams

^{46}Ar + ^{250}Cm ⟶ ^{296}Fl*, N = 182

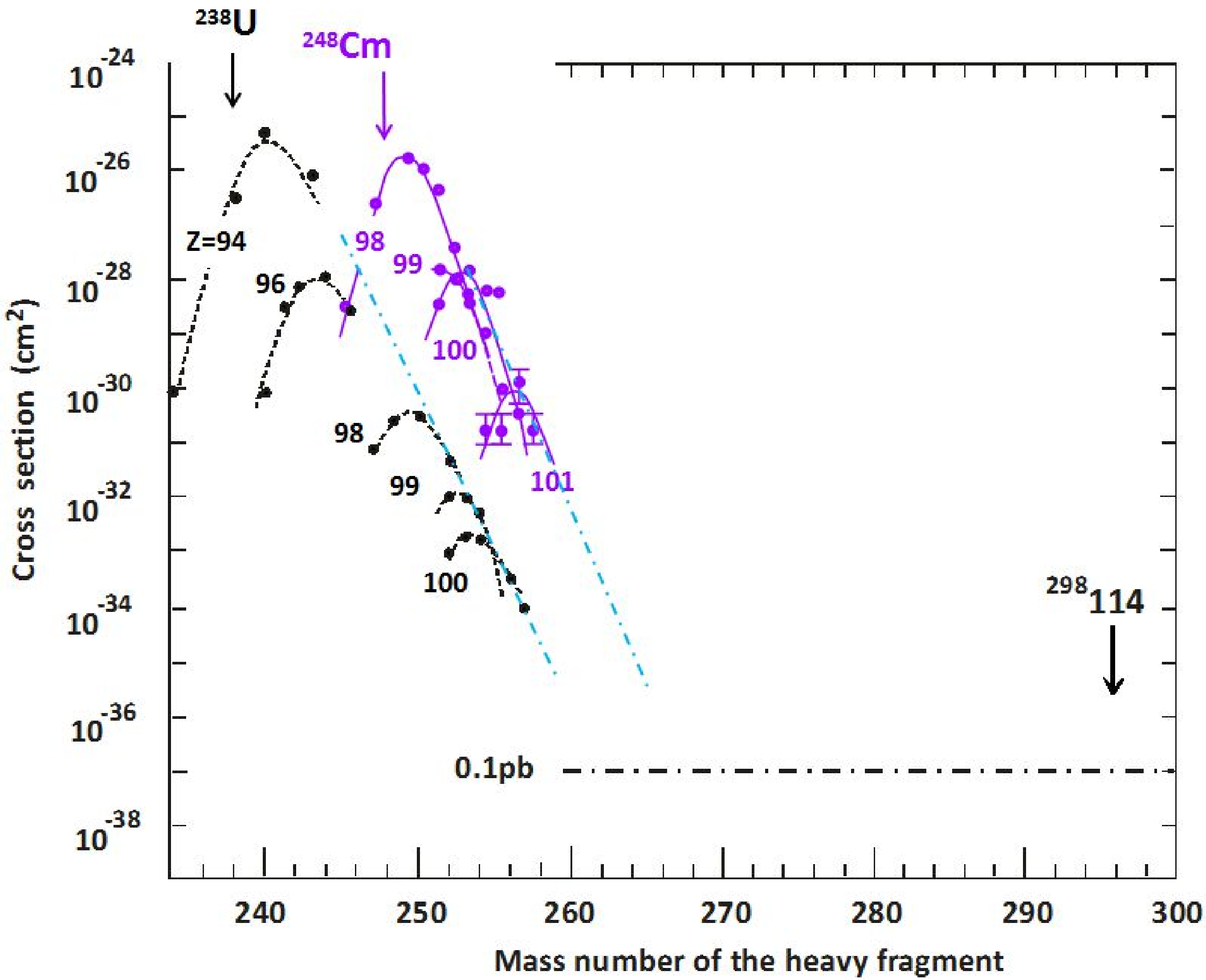
Production of ^{46}Ar in ^{48}Ca(γ,2p) reaction, σ = 1 – 10 mb



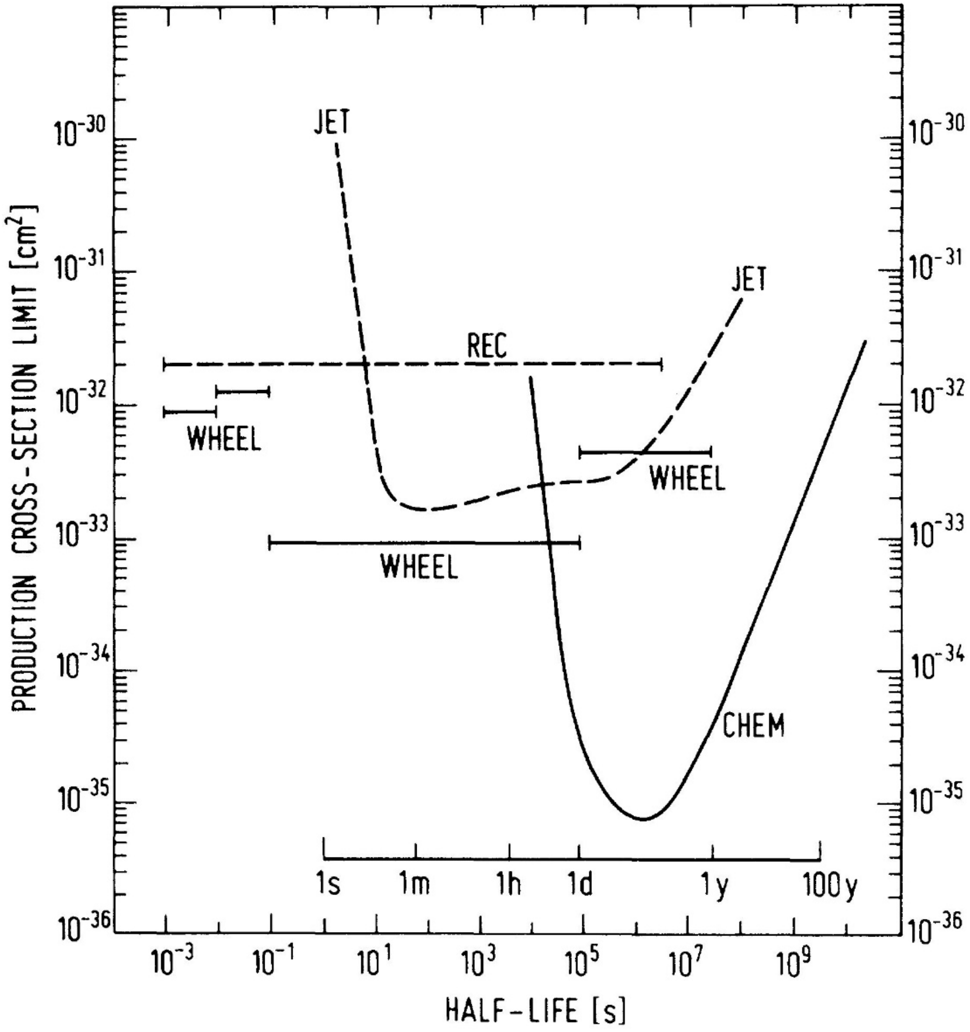
Incomplete fusion & transfer reactions:

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

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

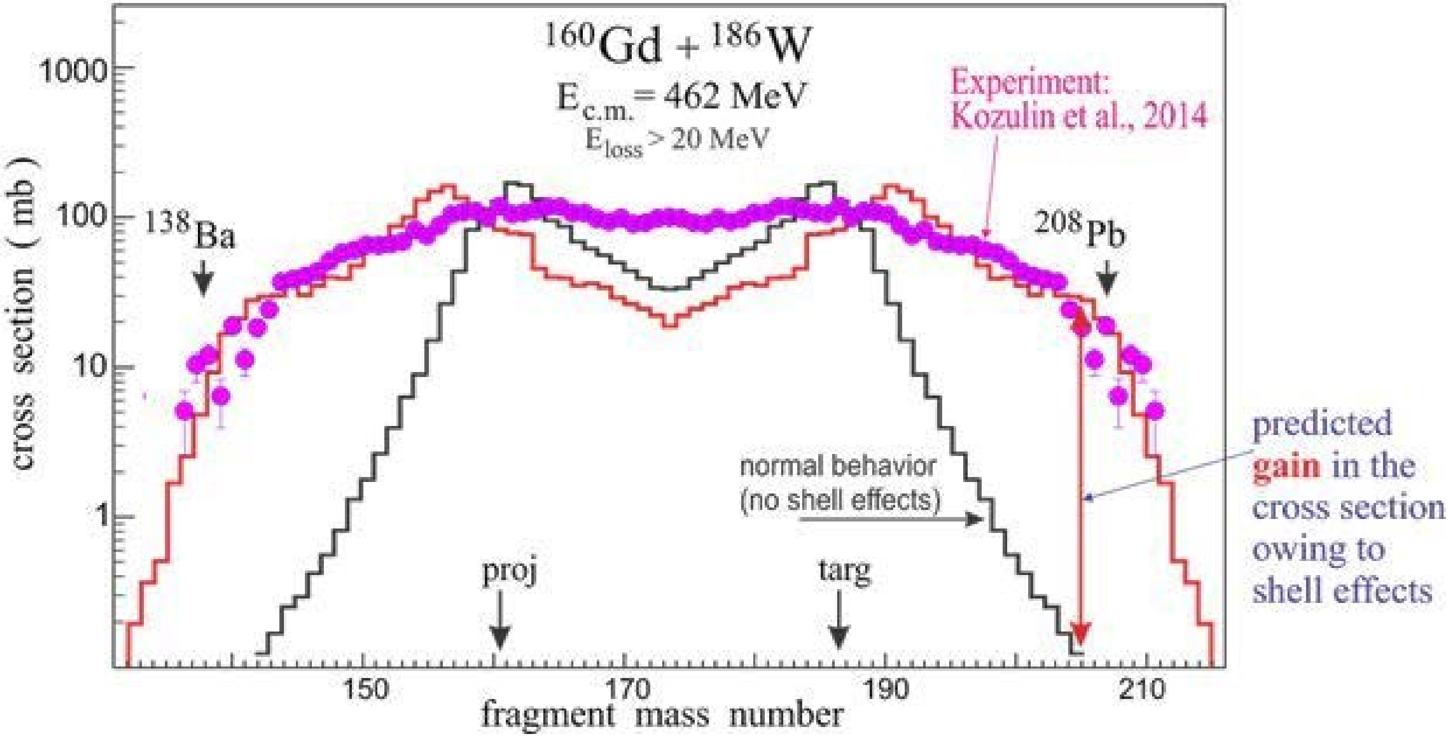


Upper limits for the production cross sections of SHE in the $^{238}U+^{238}U$ reaction



Phys. Rev. Lett. 45 (1980) 1824

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



$$^{238}U + {}^{248}Cm \longrightarrow \approx {}^{298}114 + \approx {}^{178}Yb$$

Nucl.	E(MeV)	Bρ (vac. T·m)	Bρ (He. T·m)	Bρ (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;

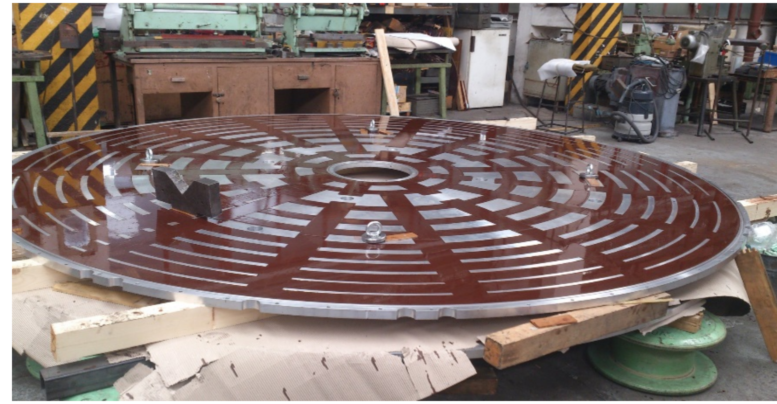
SHE – factory !

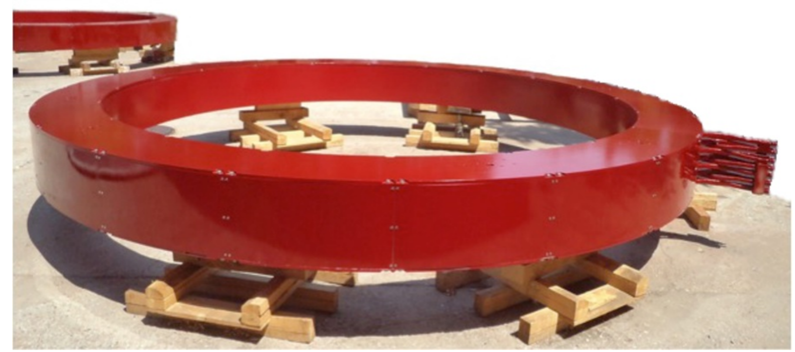
DC280-cyclotron – stand-alone SHE-factory

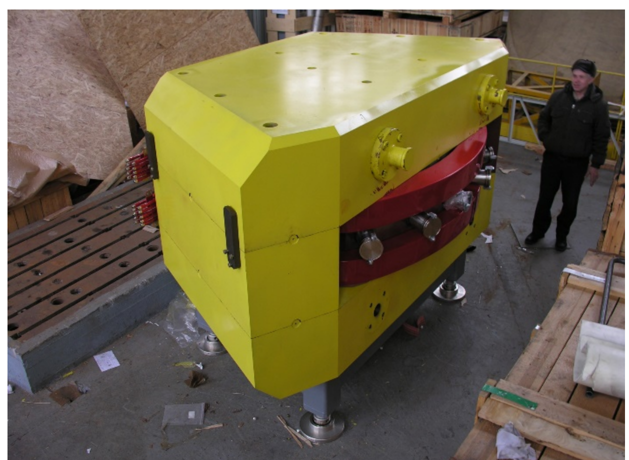
- Synthesis and study of properties of superheavy elements.
- Search for new reactions for SHE-synthesis.
- Chemistry of new elements.

DC280 (expected) E=4÷8 MeV/A		
Ion	Ion energy [MeV/A]	Output intensity
^{7}Li	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}

Specialized high-current cyclotron DC280



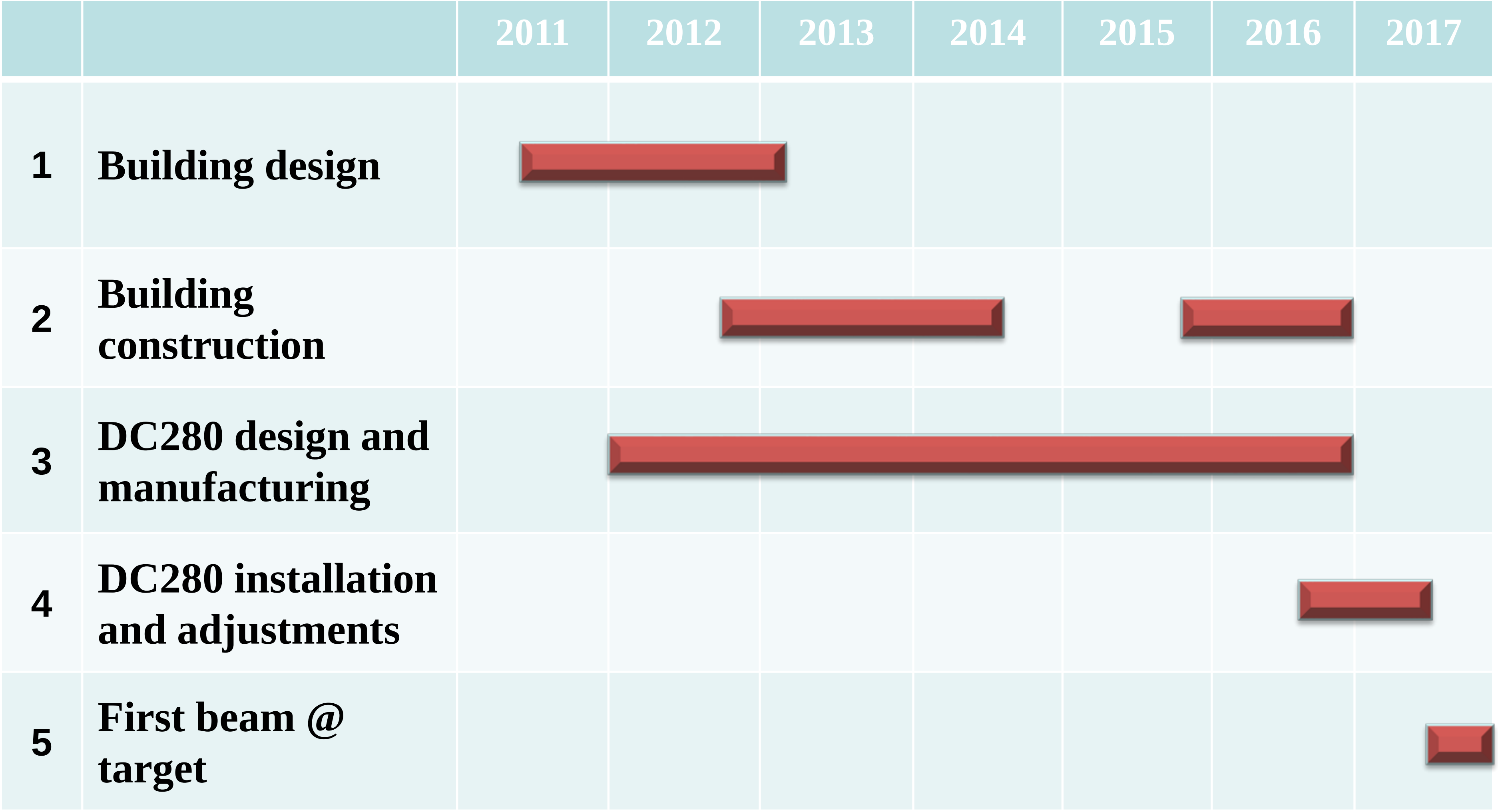




SHE-factory

http://inflnr.jinr.ru/dc280.html

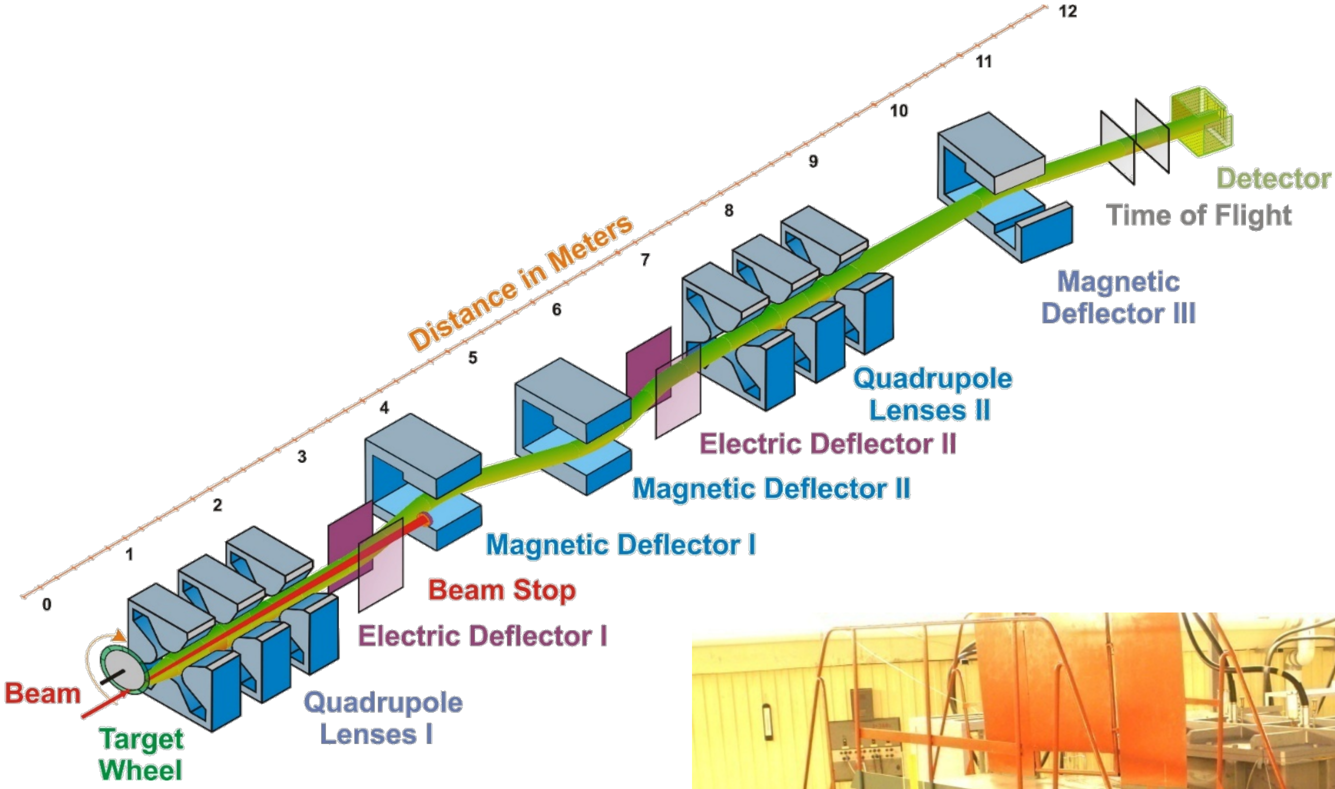
DC280 Construction Timetable

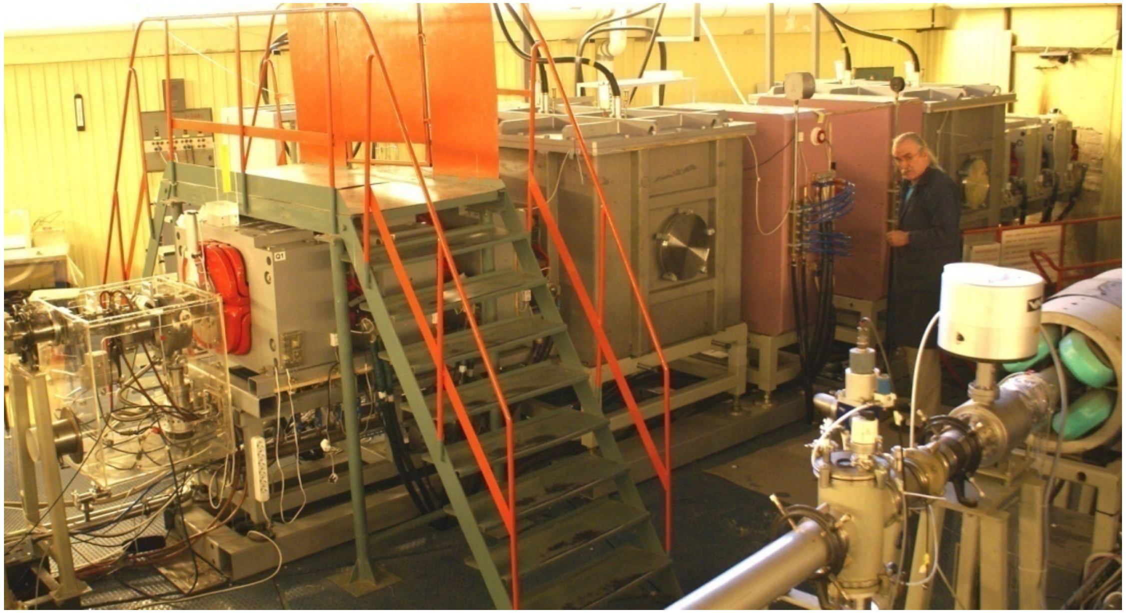


New set-ups

- **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)



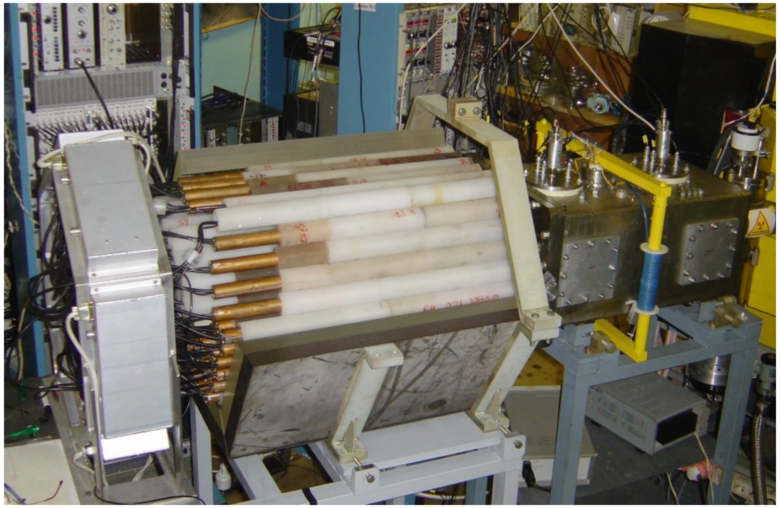


First research experiment with accelerated ^{50}Ti beam at FLNR U400 cyclotron

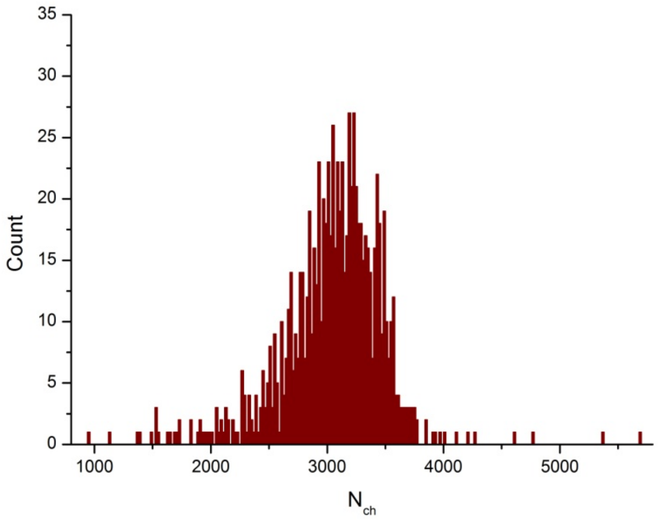
FLNR, CSNSM, IReS (France)

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

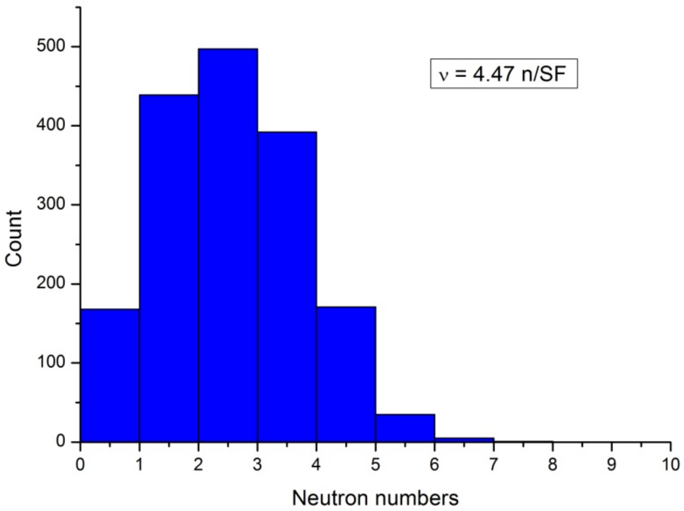
$^{50}Ti + ^{208}Pb = 2n + ^{256}Rf$



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



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



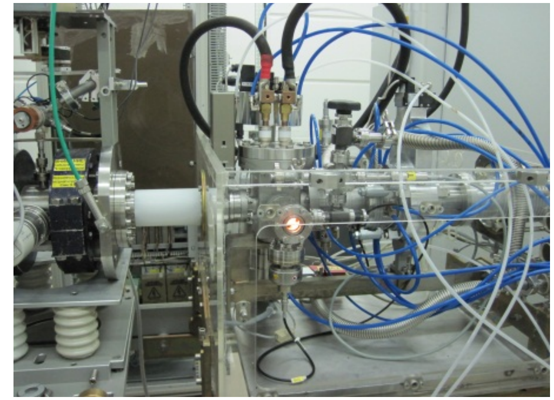
Neutron multiplicity measured for spontaneous fission of ^{256}Rf

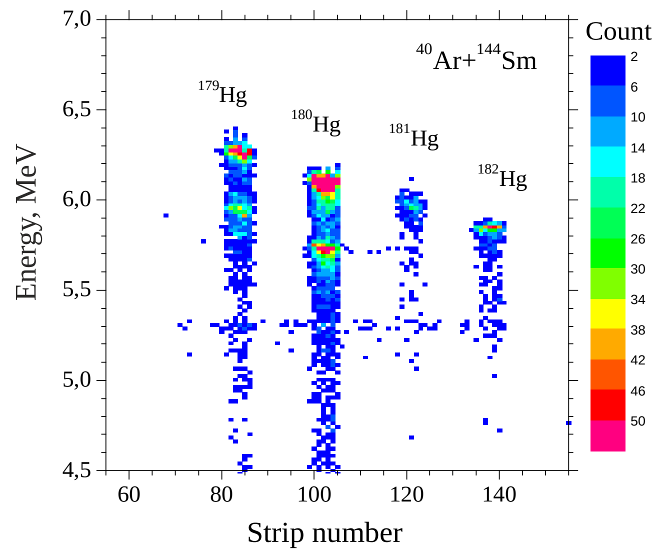
New focal plane detector GABRIELA

GABRIELA - Gamma Alpha Beta Recoil Investigation with the Electromagnetic Analyser

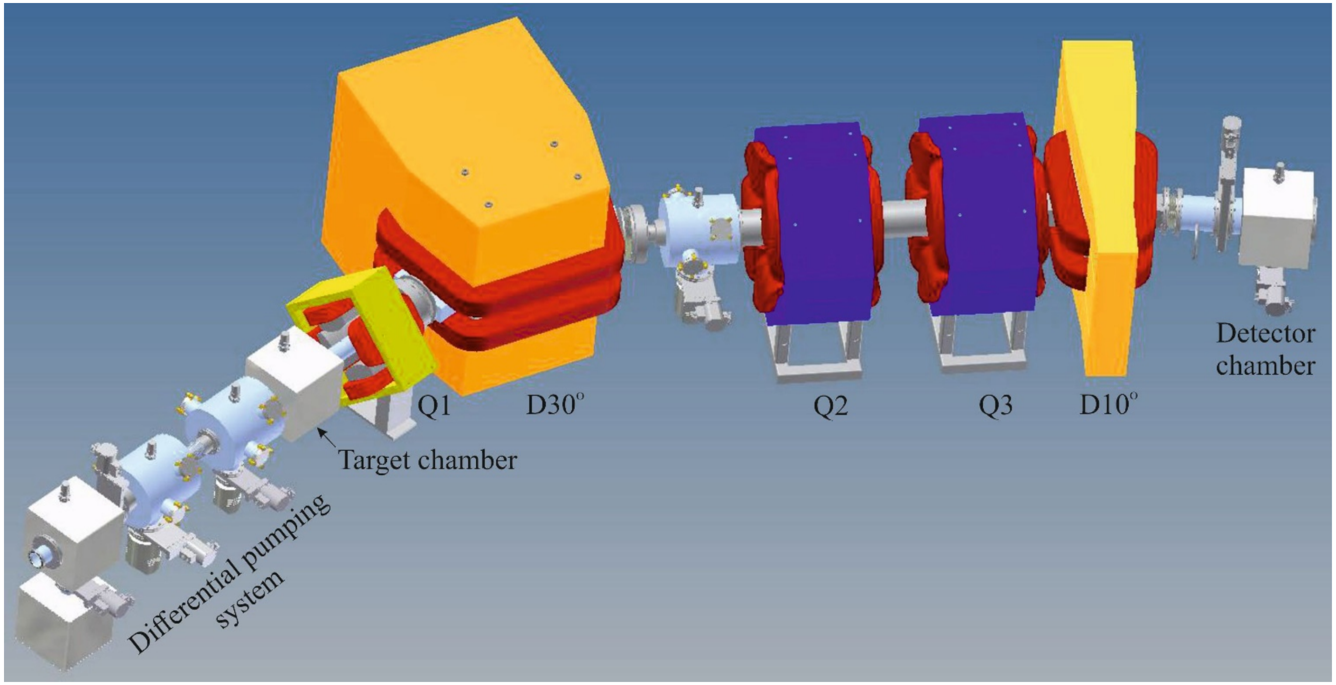
MAss-Separator of Heavy Atoms - “MASHA” @ U400M

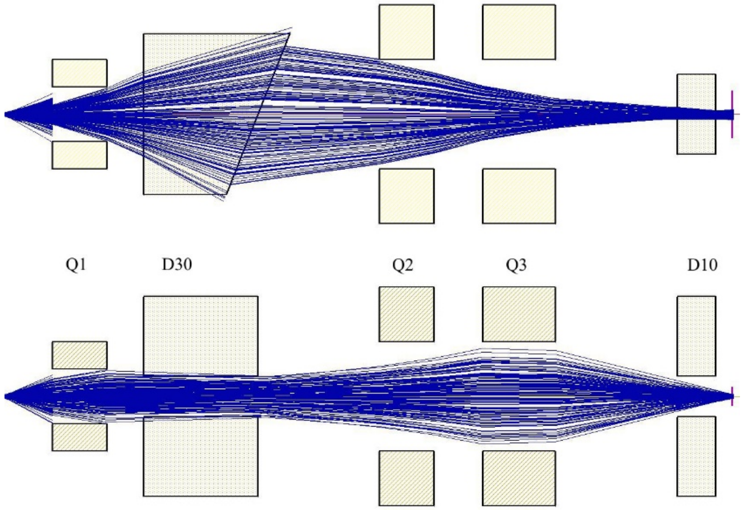
Hot catcher

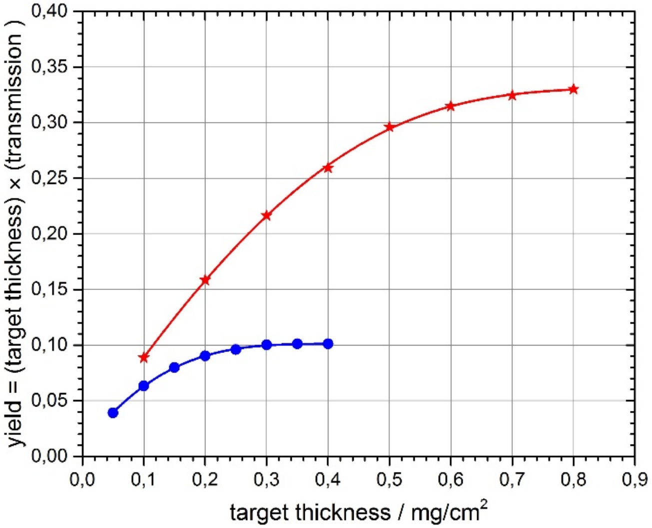




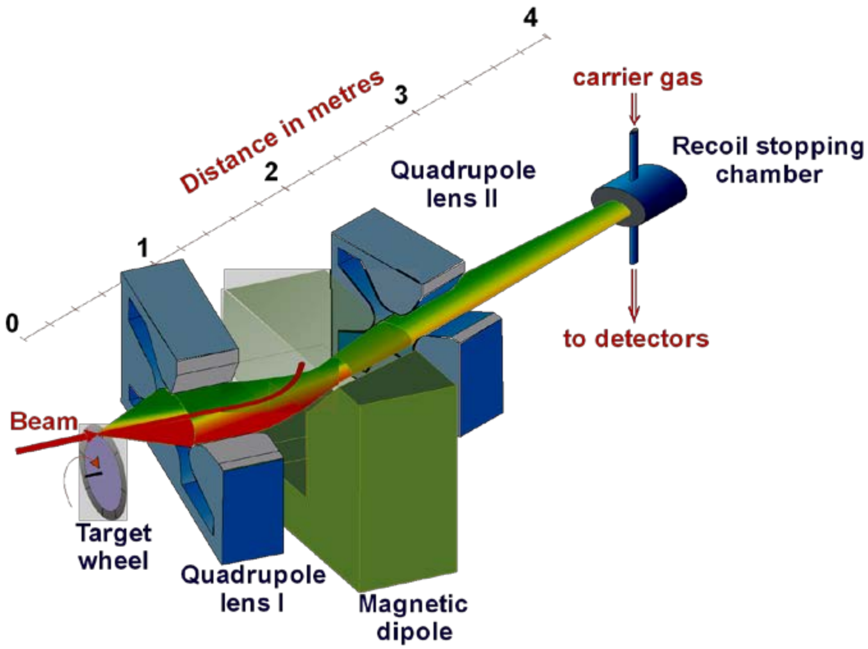
New gas-filled separator DGFRS-II



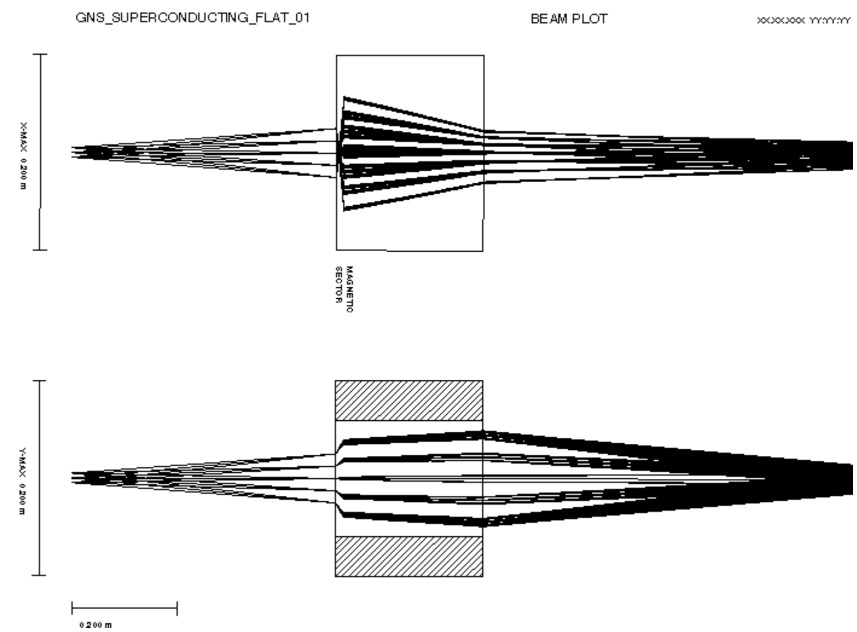




Gas-filled pre-separators

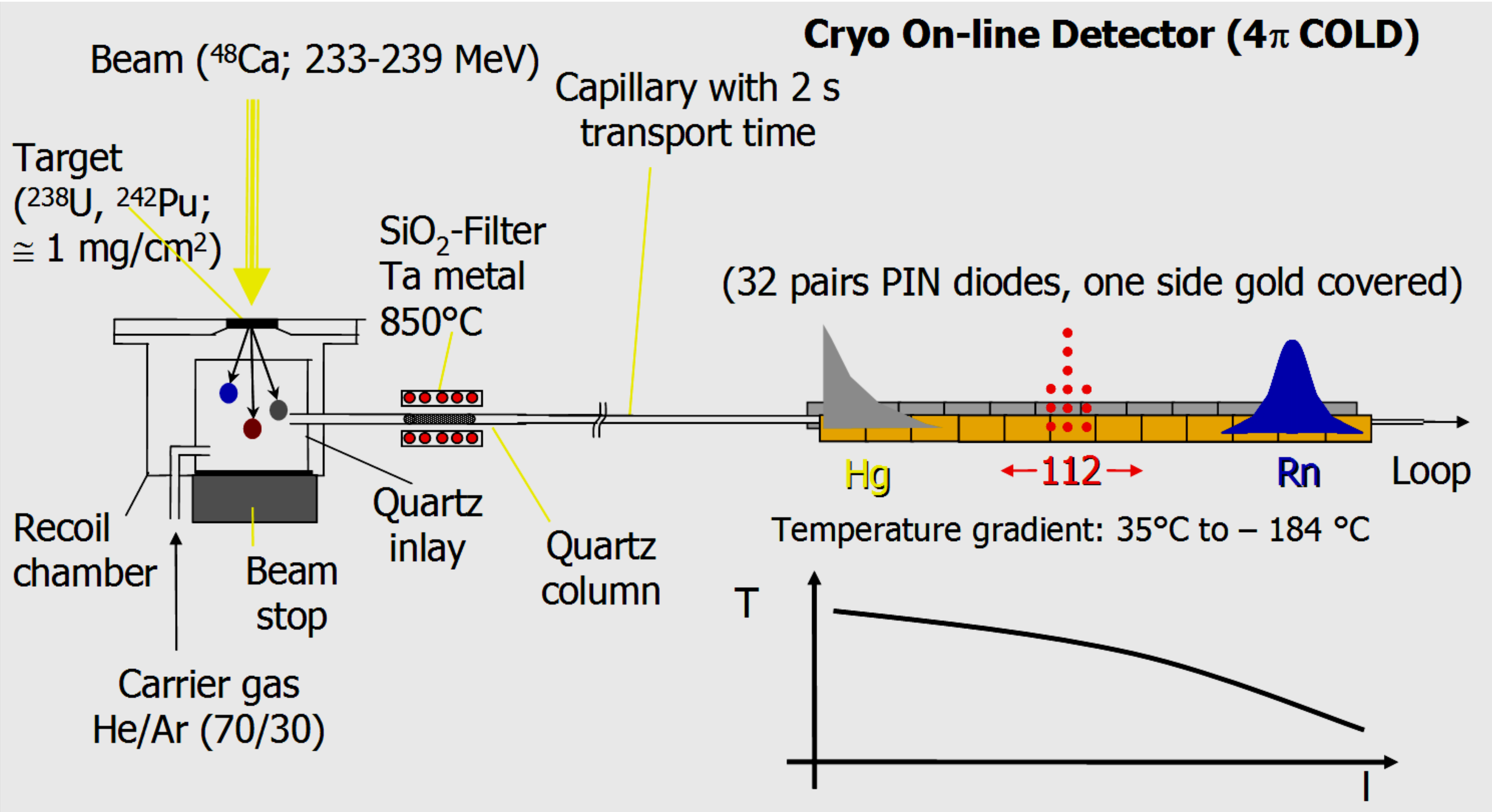


Q_vDQ_h



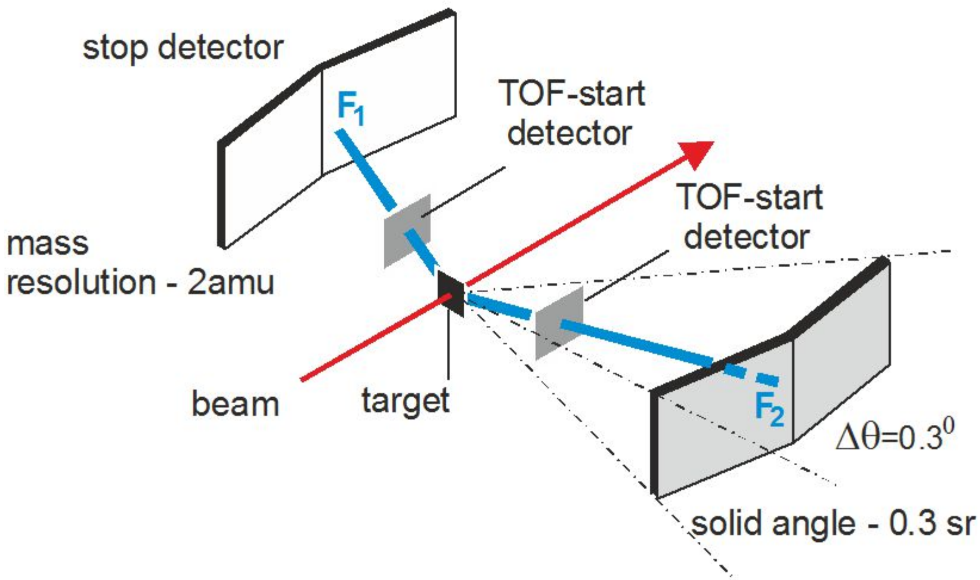
Superconducting

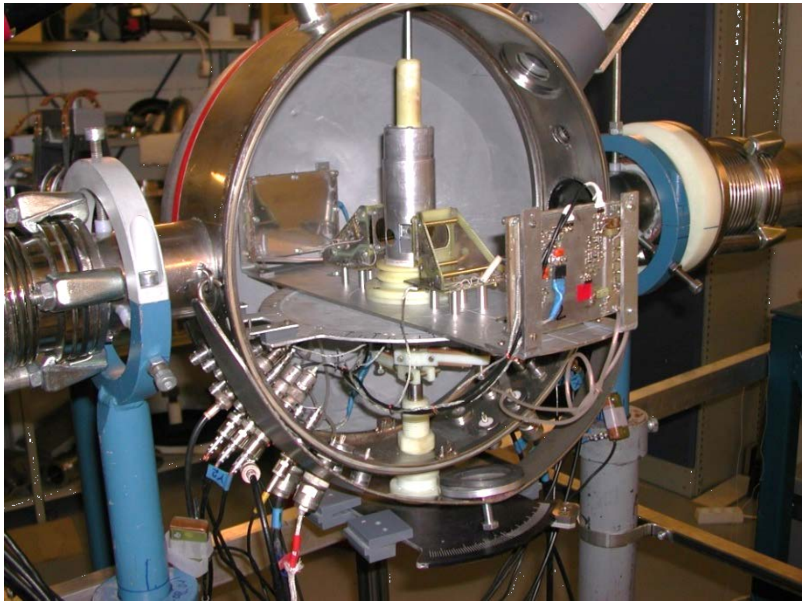
Gas Phase chemistry (IVO Technique)



Also in combination with a preseparator

Time-of-Flight spectrometer CORSET





Search for processes like:

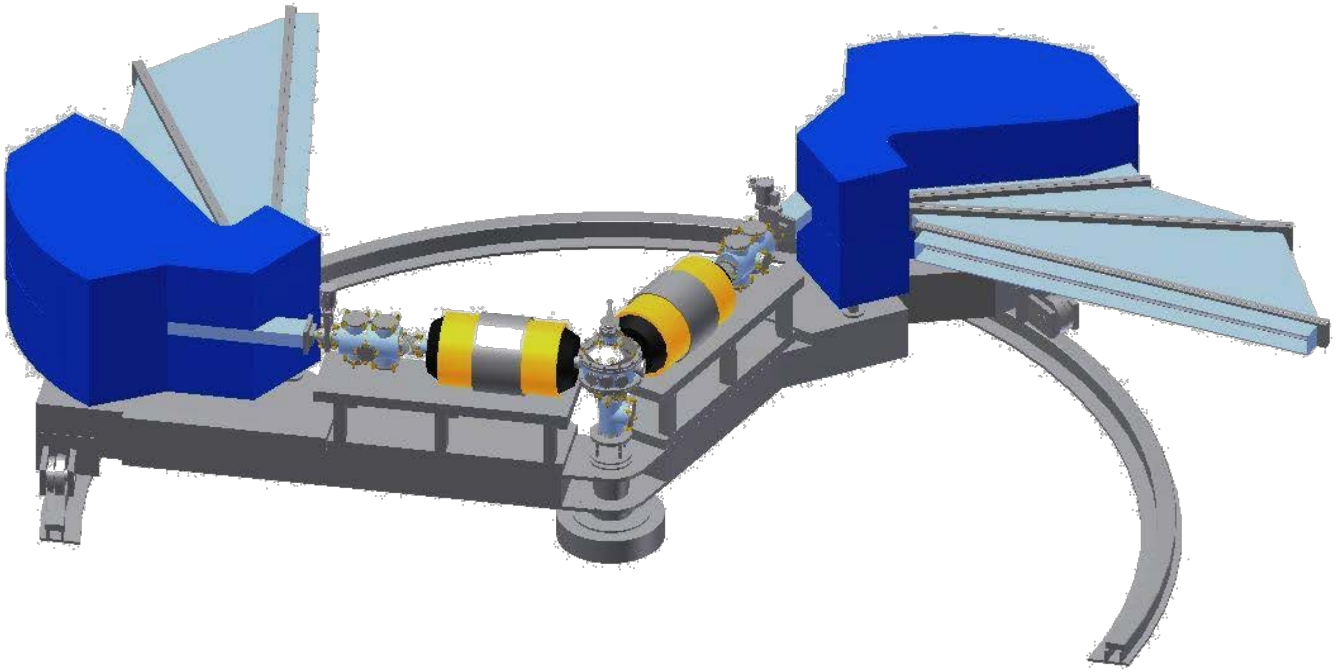
$^{238}U + ^{238}U \rightarrow ^{298}Fl + ^{178}Yb$

$^{238}U + ^{238}U \rightarrow ^{208}Pb + ^{268}No$

$^{238}U + ^{238}U \rightarrow ^{208}Pb + ^{208}Pb + ^{60}Ca$

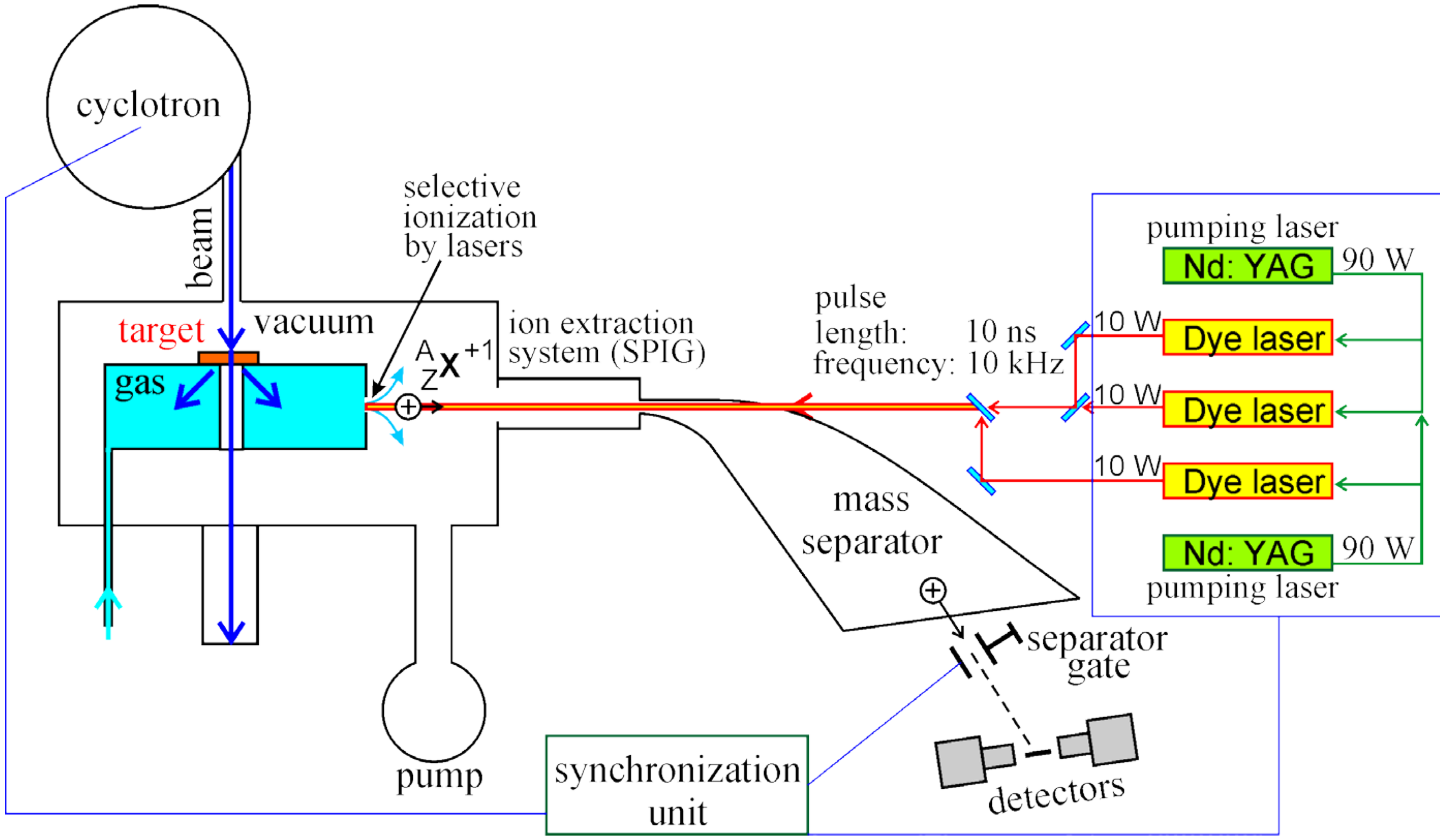
$^{238}U + ^{238}U \rightarrow ^{132}Sn + ^{132}Sn + ^{208}Pb + \alpha$

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

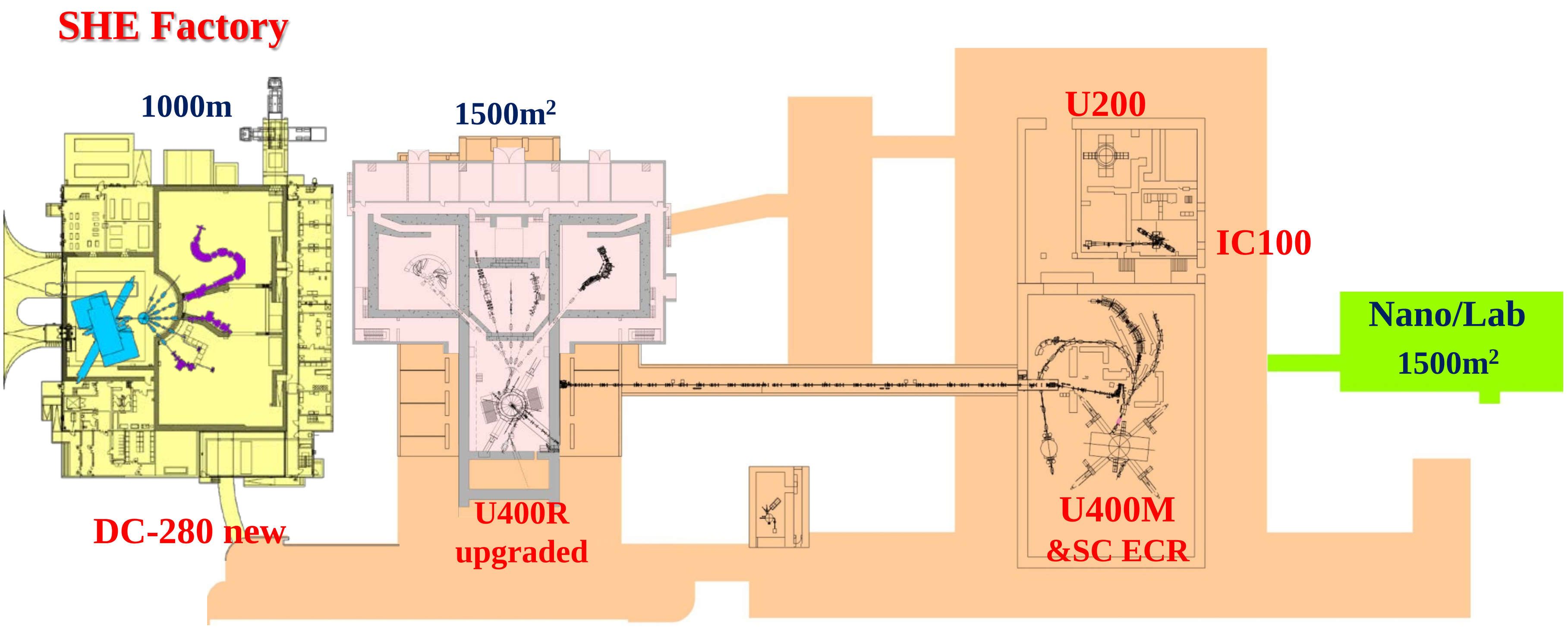


New setup for selective laser ionization. Laser room

Conclusion

- **The SHE – factory is a part of the project DRIBs-III → modernization of basic facilities of FLNR,**
- **The realization of the DRIBs-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



Heavy &
Super heavy

Nuclear
spectroscopy

Light exotic nuclei &
Applied research


THANK YOU
FOR YOUR
ATTENTION !
Flerov Laboratory of Nuclear Reactions (JINR)