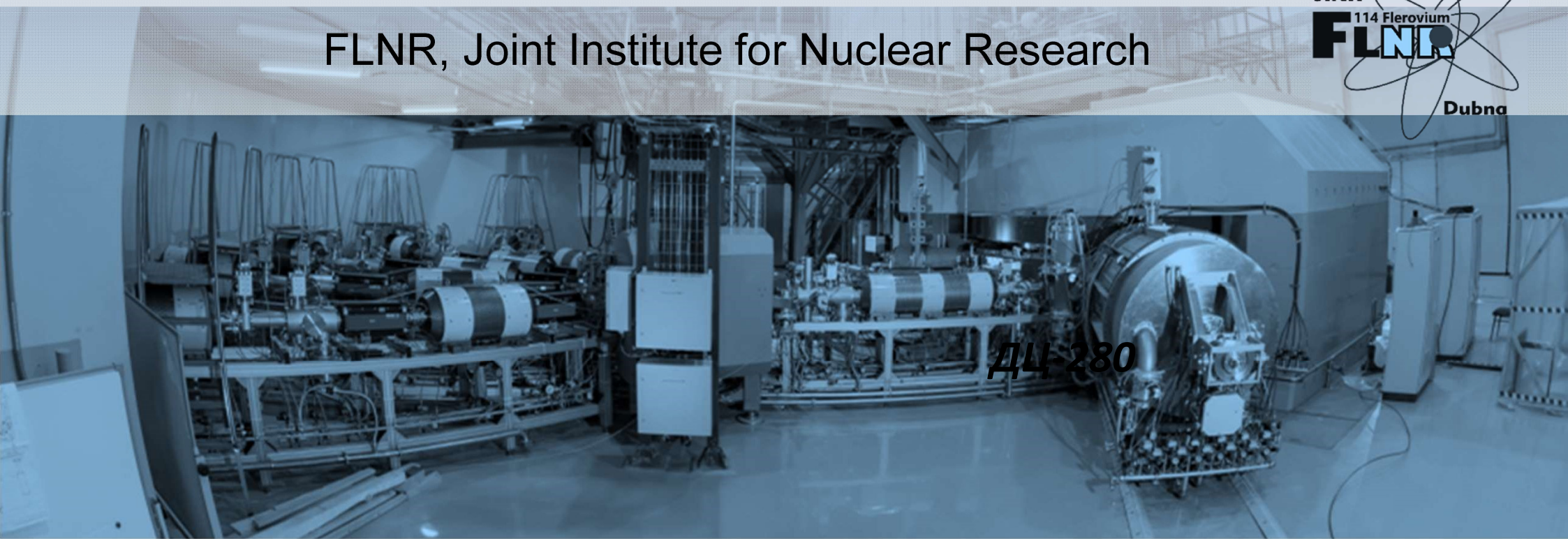
Nuclear physics: superheavies and others

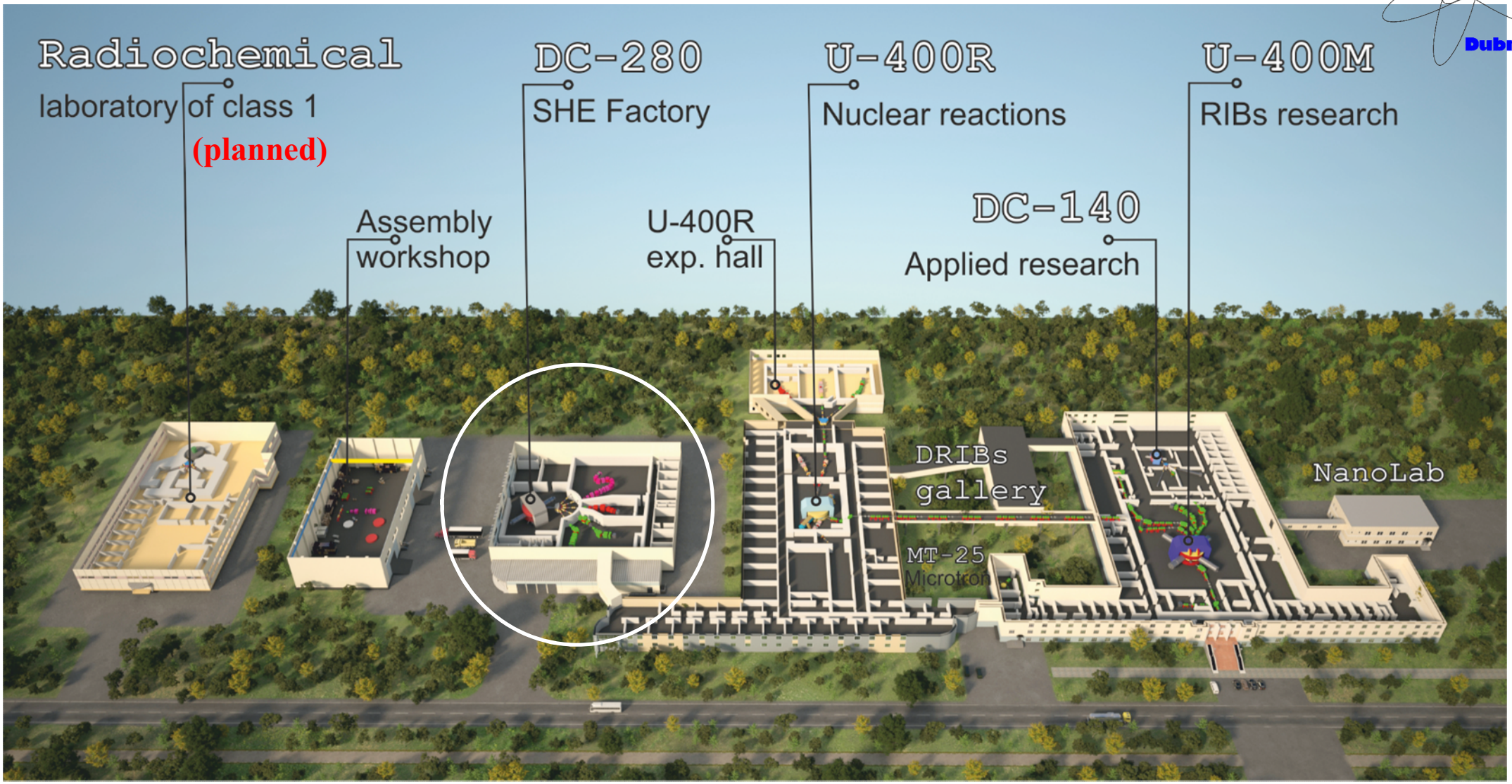
Alexander Karpov (*karpov@jinr.ru*)

FLNR, Joint Institute for Nuclear Research



Superheavy elements: synthesis and properties

FLNR ACCELERATOR COMPLEX



Periodic Table today (since November, 28, 2016)

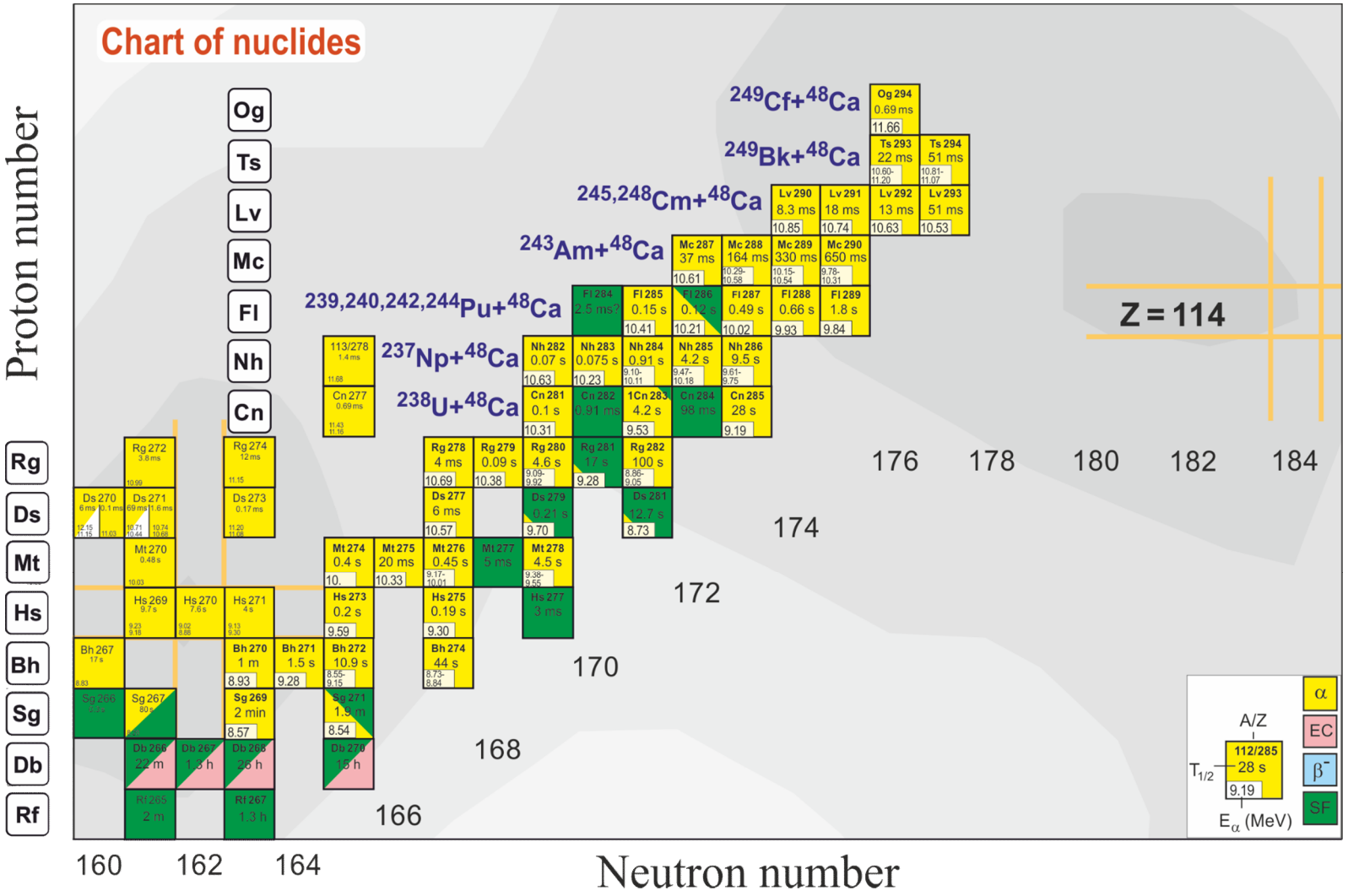
1	2											13	14	15	16	17	18
1 **H** hydrogen 1.0080 ± 0.0002																	2 **He** helium 4.0026 ± 0.0001
3 **Li** lithium 6.94 ± 0.06	4 **Be** beryllium 9.0122 ± 0.0001											5 **B** boron 10.81 ± 0.02	6 **C** carbon 12.011 ± 0.002	7 **N** nitrogen 14.007 ± 0.001	8 **O** oxygen 15.999 ± 0.001	9 **F** fluorine 18.998 ± 0.001	10 **Ne** neon 20.180 ± 0.001
11 **Na** sodium 22.990 ± 0.001	12 **Mg** magnesium 24.305 ± 0.002	3	4	5	6	7	8	9	10	11	12	13 **Al** aluminium 26.982 ± 0.001	14 **Si** silicon 28.085 ± 0.001	15 **P** phosphorus 30.974 ± 0.001	16 **S** sulfur 32.06 ± 0.02	17 **Cl** chlorine 35.45 ± 0.01	18 **Ar** argon 39.95 ± 0.16
19 **K** potassium 39.098 ± 0.001	20 **Ca** calcium 40.078 ± 0.004	21 **Sc** scandium 44.956 ± 0.001	22 **Ti** titanium 47.867 ± 0.001	23 **V** vanadium 50.942 ± 0.001	24 **Cr** chromium 51.996 ± 0.001	25 **Mn** manganese 54.938 ± 0.001	26 **Fe** iron 55.845 ± 0.002	27 **Co** cobalt 58.933 ± 0.001	28 **Ni** nickel 58.693 ± 0.001	29 **Cu** copper 63.546 ± 0.003	30 **Zn** zinc 65.38 ± 0.02	31 **Ga** gallium 69.723 ± 0.001	32 **Ge** germanium 72.630 ± 0.008	33 **As** arsenic 74.922 ± 0.001	34 **Se** selenium 78.971 ± 0.008	35 **Br** bromine 79.904 ± 0.003	36 **Kr** krypton 83.798 ± 0.002
37 **Rb** rubidium 85.468 ± 0.001	38 **Sr** strontium 87.62 ± 0.01	39 **Y** yttrium 88.906 ± 0.001	40 **Zr** zirconium 91.224 ± 0.002	41 **Nb** niobium 92.906 ± 0.001	42 **Mo** molybdenum 95.95 ± 0.01	43 **Tc** technetium [97]	44 **Ru** ruthenium 101.07 ± 0.02	45 **Rh** rhodium 102.91 ± 0.01	46 **Pd** palladium 106.42 ± 0.01	47 **Ag** silver 107.87 ± 0.01	48 **Cd** cadmium 112.41 ± 0.01	49 **In** indium 114.82 ± 0.01	50 **Sn** tin 118.71 ± 0.01	51 **Sb** antimony 121.76 ± 0.01	52 **Te** tellurium 127.60 ± 0.03	53 **I** iodine 126.90 ± 0.01	54 **Xe** xenon 131.29 ± 0.01
55 **Cs** caesium 132.91 ± 0.01	56 **Ba** barium 137.33 ± 0.01	57-71 lanthanoids	72 **Hf** hafnium 178.49 ± 0.01	73 **Ta** tantalum 180.95 ± 0.01	74 **W** tungsten 183.84 ± 0.01	75 **Re** rhenium 186.21 ± 0.01	76 **Os** osmium 190.23 ± 0.03	77 **Ir** iridium 192.22 ± 0.01	78 **Pt** platinum 195.08 ± 0.02	79 **Au** gold 196.97 ± 0.01	80 **Hg** mercury 200.59 ± 0.01	81 **Tl** thallium 204.38 ± 0.01	82 **Pb** lead 207.2 ± 1.1	83 **Bi** bismuth 208.98 ± 0.01	84 **Po** polonium [209]	85 **At** astatine [210]	86 **Rn** radon [222]
87 **Fr** francium [223]	88 **Ra** radium [226]	89-103 actinoids	104 **Rf** rutherfordium [267]	105 **Db** dubnium [268]	106 **Sg** seaborgium [269]	107 **Bh** bohrium [270]	108 **Hs** hassium [269]	109 **Mt** meitnerium [277]	110 **Ds** darmstadtium [281]	111 **Rg** roentgenium [282]	112 **Cn** copernicium [285]	113 **Nh** nihonium [286]	114 **Fl** flerovium [290]	115 **Mc** moscovium [290]	116 **Lv** livermorium [293]	117 **Ts** tennessine [294]	118 **Og** oganesson [294]

Key: atomic number **Symbol** name abridged standard atomic weight

57 **La** lanthanum 138.91 ± 0.01	58 **Ce** cerium 140.12 ± 0.01	59 **Pr** praseodymium 140.91 ± 0.01	60 **Nd** neodymium 144.24 ± 0.01	61 **Pm** promethium [145]	62 **Sm** samarium 150.36 ± 0.02	63 **Eu** europium 151.96 ± 0.01	64 **Gd** gadolinium 157.25 ± 0.03	65 **Tb** terbium 158.93 ± 0.01	66 **Dy** dysprosium 162.50 ± 0.01	67 **Ho** holmium 164.93 ± 0.01	68 **Er** erbium 167.26 ± 0.01	69 **Tm** thulium 168.93 ± 0.01	70 **Yb** ytterbium 173.05 ± 0.02	71 **Lu** lutetium 174.97 ± 0.01
89 **Ac** actinium [227]	90 **Th** thorium 232.04 ± 0.01	91 **Pa** protactinium 231.04 ± 0.01	92 **U** uranium 238.03 ± 0.01	93 **Np** neptunium [237]	94 **Pu** plutonium [244]	95 **Am** americium [243]	96 **Cm** curium [247]	97 **Bk** berkelium [247]	98 **Cf** californium [251]	99 **Es** einsteinium [252]	100 **Fm** fermium [257]	101 **Md** mendelevium [258]	102 **No** nobelium [259]	103 **Lr** lawrencium [262]

INTERNATIONAL UNION OF PURE AND APPLIED CHEMISTRY

Synthesis of Superheavy Nuclei (*1999-2019*)



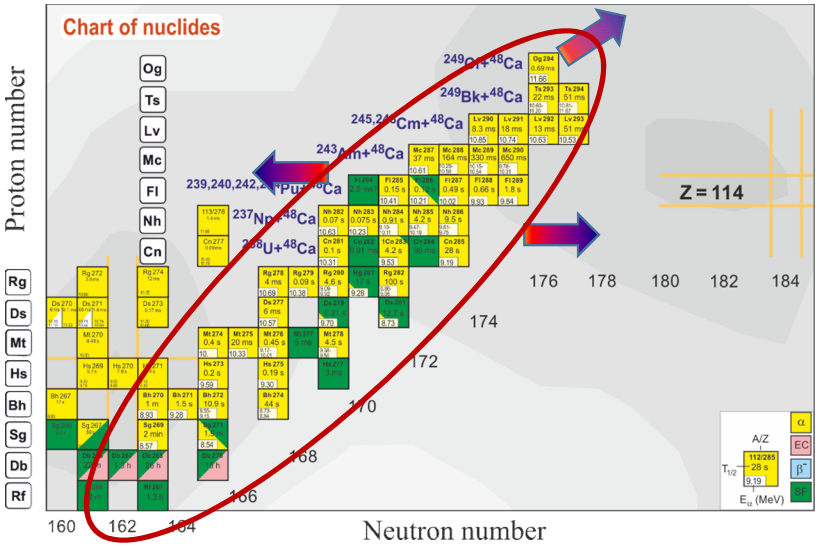
SHE research: Main tasks

Experiments at the extremely low (σ<100 fb) cross sections:

- Synthesis of new SHE with Z = 119 and 120 in reactions with ^{50}Ti, ^{54}Cr ...;
- Synthesis of new isotopes of SHE;
- Study of decay properties of SHE;
- Exploring limits the Island of Stability;
- Study of excitation functions.

Experiments requiring high statistics:

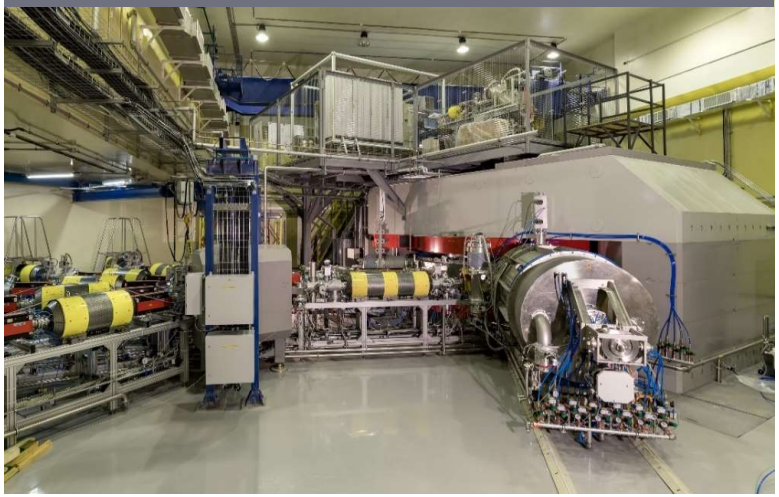
- Nuclear spectroscopy of SHE;
- Precise mass measurements;
- Study of chemical properties of SHE.





Beam of ^{48}Ca @ DC-280:

- *Intensity: >8 pμA*
- *Energy: 5 - 8 A·MeV*
- *Efficiency: ~50%*



SHE research program with existing separators @ SHE Factory



- Spectroscopy of SHE;
- Chemical studies for SH nuclei with half-lives **longer than 1 sec** (114 and lighter);
- Precise mass measurements (new developments are due);



- Synthesis of new SHE;
- Synthesis of new neutron-deficient isotopes of SHE: “shaping” of island of stability;
- Search for rear decay channels in ^{48}Ca-induced reactions (EC, pxn, 1-2n): towards island of stability;
- Decay modes, excitation functions, etc.

Summary of experiments @ Superheavy Element Factory in 2020-2025

Experiments:

110: ^{232}**Th + ^{48}Ca → ^{280}Ds*,**
^{238}**U + ^{40}Ar → ^{278}Ds***

112: ^{238}U + ^{48}Ca → ^{286}Cn*

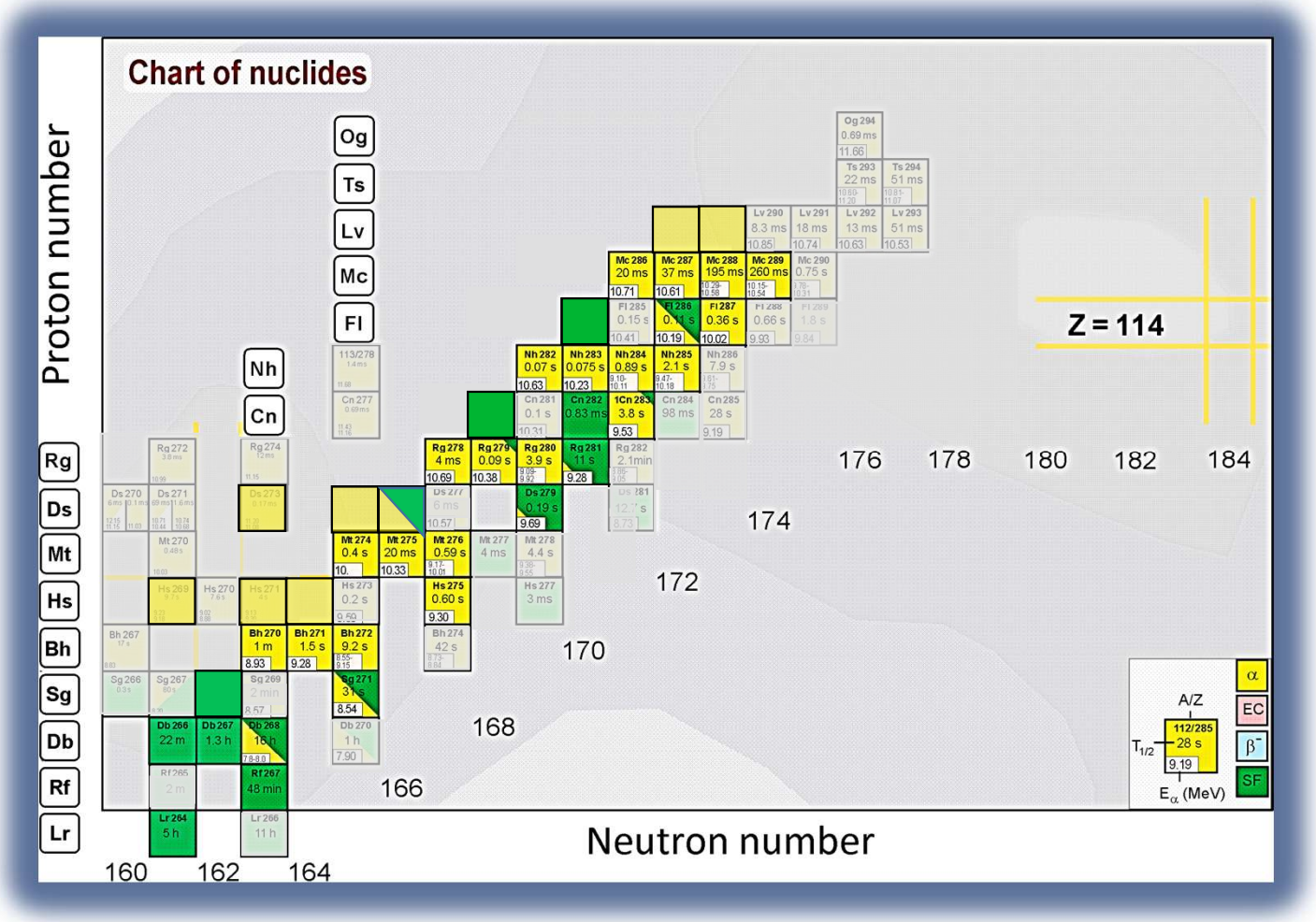
113: ^{237}Np + ^{48}Ca → ^{285}Nh*

114: ^{242}Pu + ^{48}Ca → ^{290}Fl*

115: ^{243}Am + ^{48}Ca → ^{291}Mc*

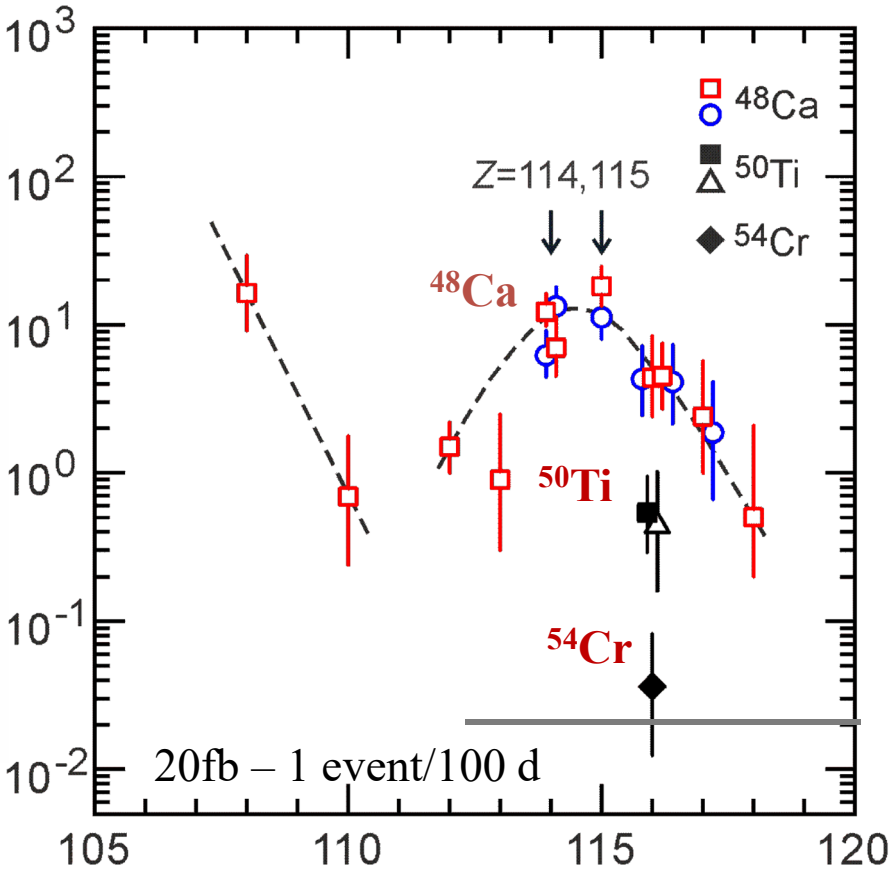
116: ^{238}**U + ^{54}Cr → ^{292}Lv***
^{242}**Pu + ^{50}Ti → ^{292}Lv***

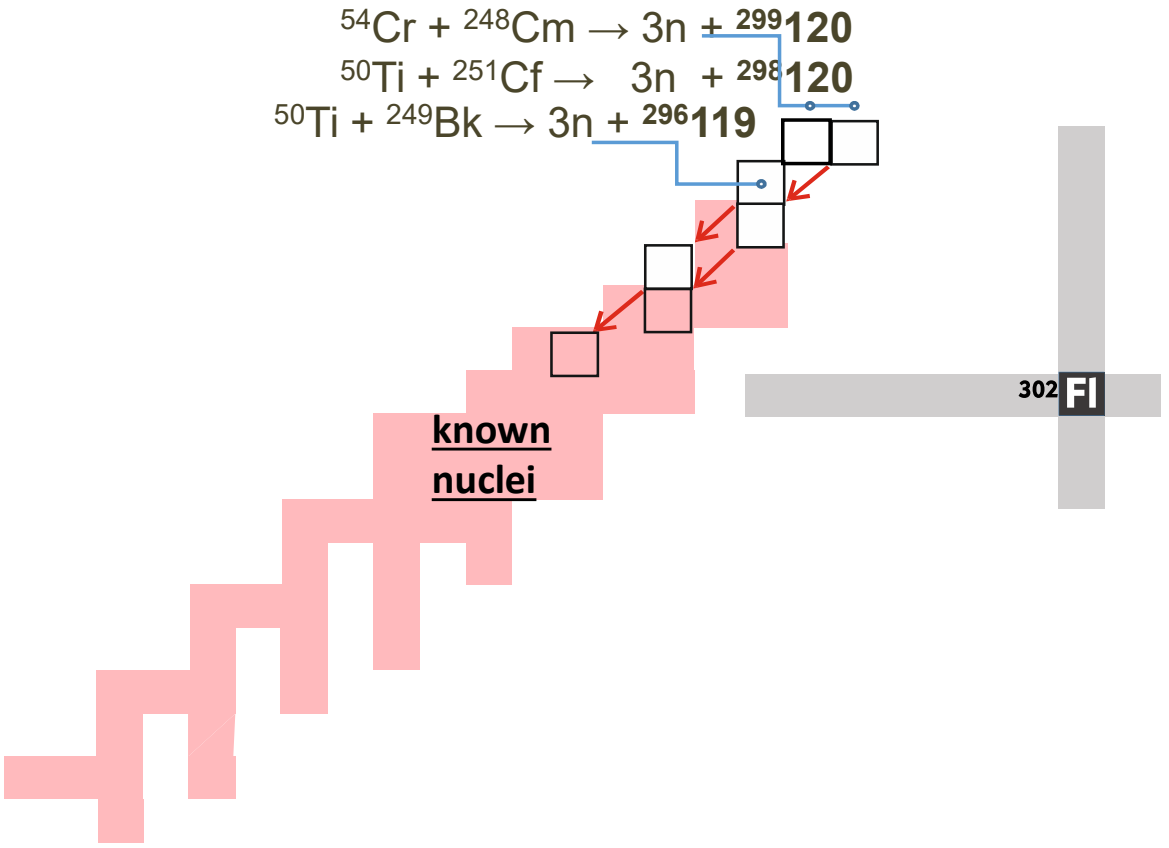
- ~250 new events of synthesis of superheavy nuclides;
- Decay properties 45 isotopes;
- New isotopes: ^{288,289}Lv, ^{286}Mc, ^{280}Cn, ^{275,276}Ds, ^{272}Hs , ^{268}Sg, ^{264}Lr;
- New decay modes;
- Indication of the 1st excited state in ^{282}Cn;
- Test of target stability up to 6.5 pμA of ^{48}Ca;



Perspectives

Towards 119 and 120





cross section decreases by ~10 times (^{50}Ti) and ~150 times (^{54}Cr) compared to the ^{48}Ca case

△ *J.M. Gates et al., PRL 133 (2024) 172502*

▲ ■ *Yu. Ts. Oganessian, V. K. Utyonkov, et. al, PRC **112** (2025) 014603*

Synthesis of SH nuclei in fusion reactions *pxn* evaporation channels

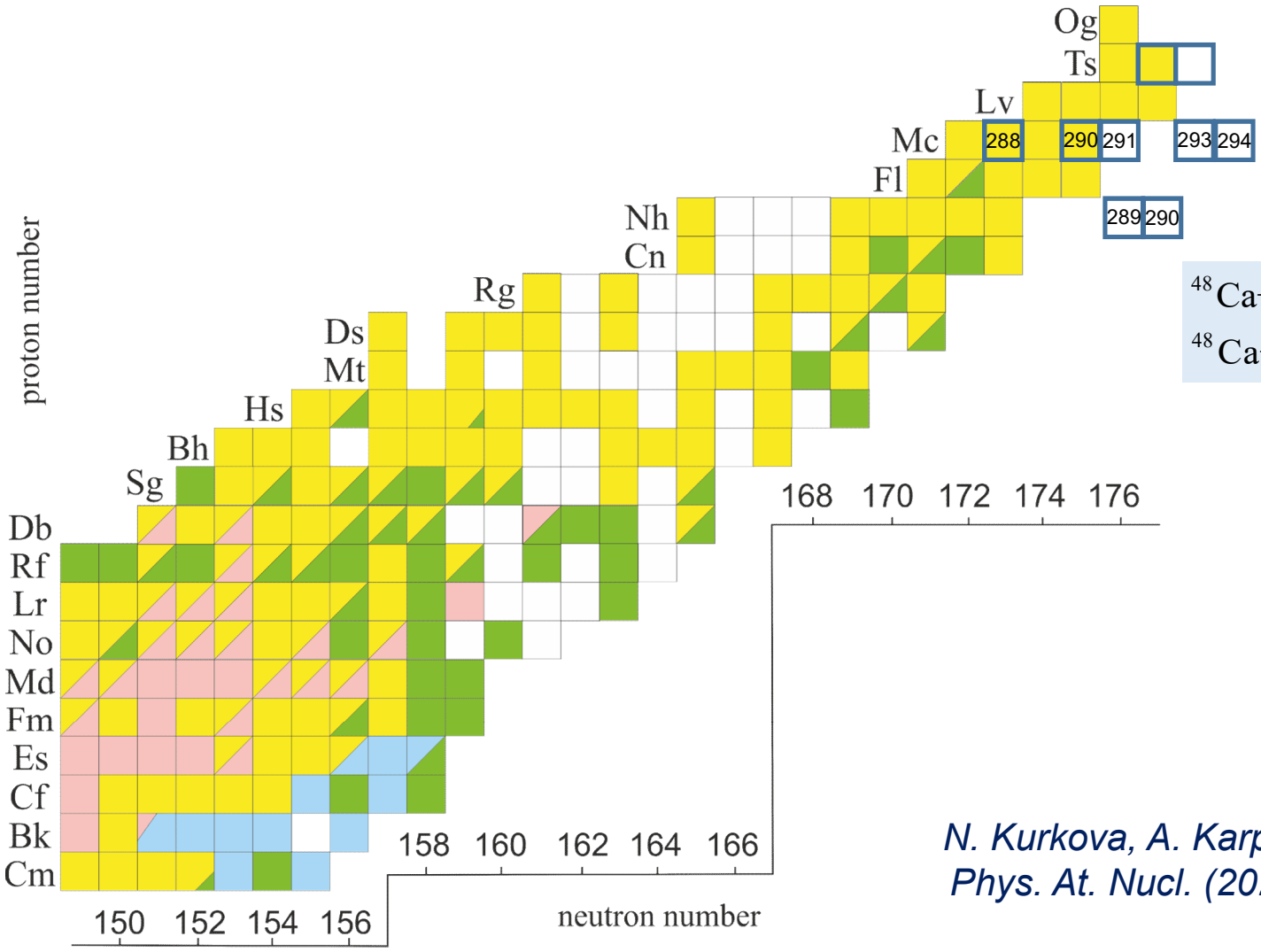
$^{48}Ca+^{249}Bk \rightarrow ^{297}Ts^{*} \rightarrow ^{284}Ts+2n$ (~0.3 pb)

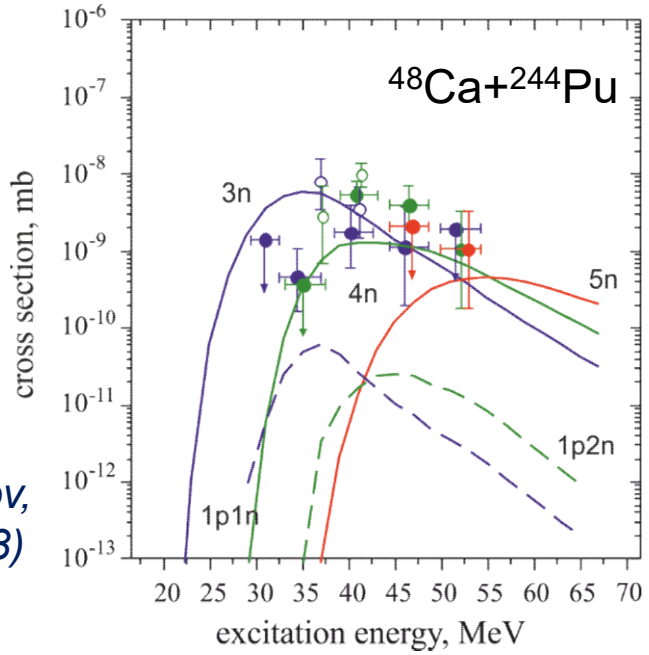
$^{48}Ca+^{249}Bk \rightarrow ^{297}Ts^{*} \rightarrow ^{284}Ts+3n$ (~2 pb)

$^{48}Ca+^{243}Am \rightarrow ^{291}Mc^{*} \rightarrow ^{288}Mc+3n$ (~3 pb)

$^{48}Ca+^{248}Cm \rightarrow ^{296}Lv^{*} \rightarrow ^{293\text{-}294}Mc+1p+(1\text{-}2)n$ (?)

$^{48}Ca+^{244}Pu \rightarrow ^{292}Fl^{*} \rightarrow ^{289\text{-}290}Nh+1p+(1\text{-}2)n$ (?)





N. Kurkova, A. Karpov, Phys. At. Nucl. (2023)

Spectroscopy of SH isotopes @ SHE Factory



GRAND (DGFRS-3) separator



GABRIELA set-up

planned experiments:

$^{48}Ca + {}^{242}Pu \rightarrow {}^{287}Fl + 3n$

$^{48}Ca + {}^{243}Am \rightarrow {}^{288}Mc + 3n$

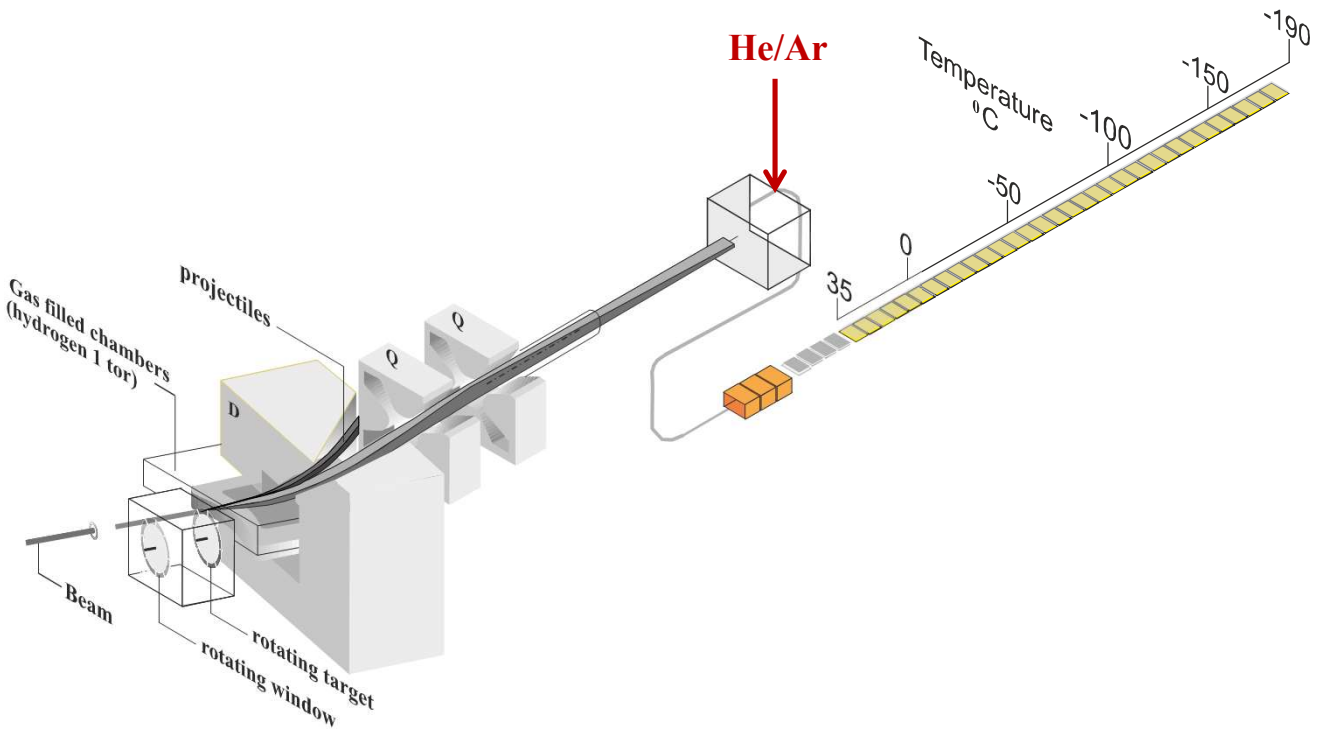


480 mm target unit

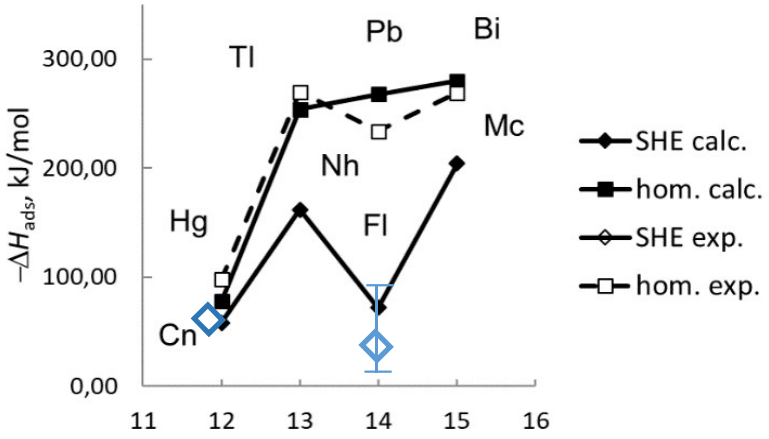
Cross section ~ 10 pb;
Target thickness ~ 1.5×10^{18} at/cm^2;
Beam intensity of ^{48}Ca ~ 3.3×10^{13} pps (5 pμA);
$\varepsilon_{transmission}$ ~ 50 %;

100 days → 250 gamma quanta can be detected.

CHEMISTRY OF SHE

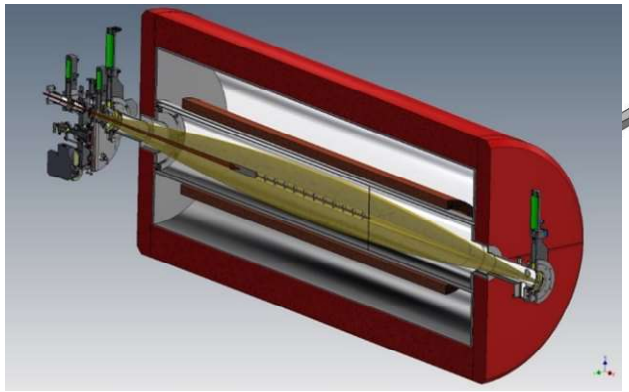


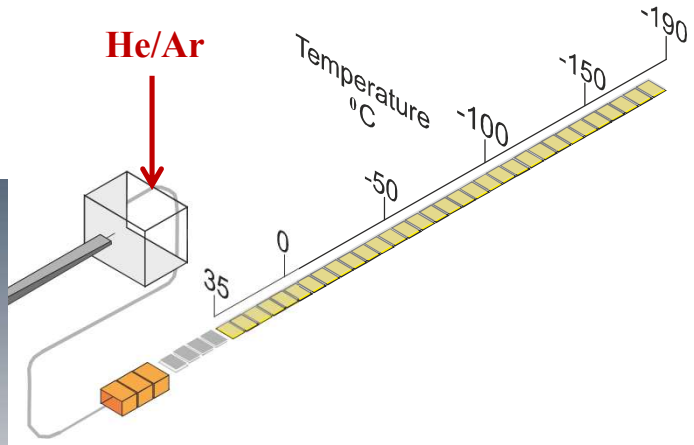
Z	Isotope	Half-life
112	^{283}Cn	3.6 s
113	^{284}Nh	0.9 s
114	^{287}Fl	0.3 s
115	^{288}Mc	0,16 s
116	^{293}Lv	57 ms
117	^{294}Ts	51 ms
118	^{294}Og	0.6 ms



Shortcoming: a relatively large volume of the stopping cell

CHEMISTRY OF SHE





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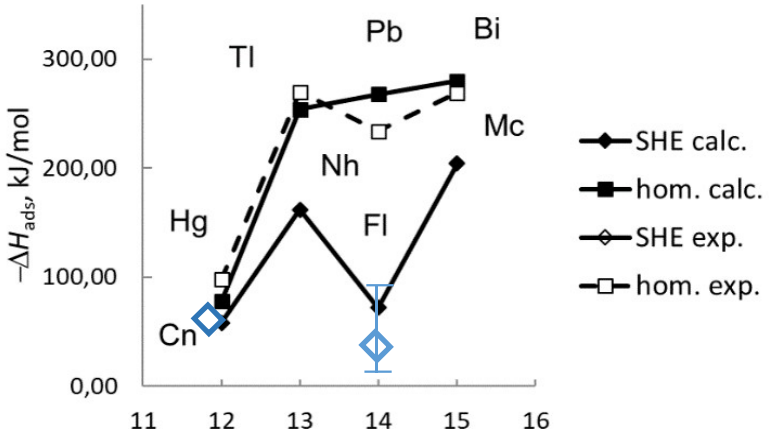
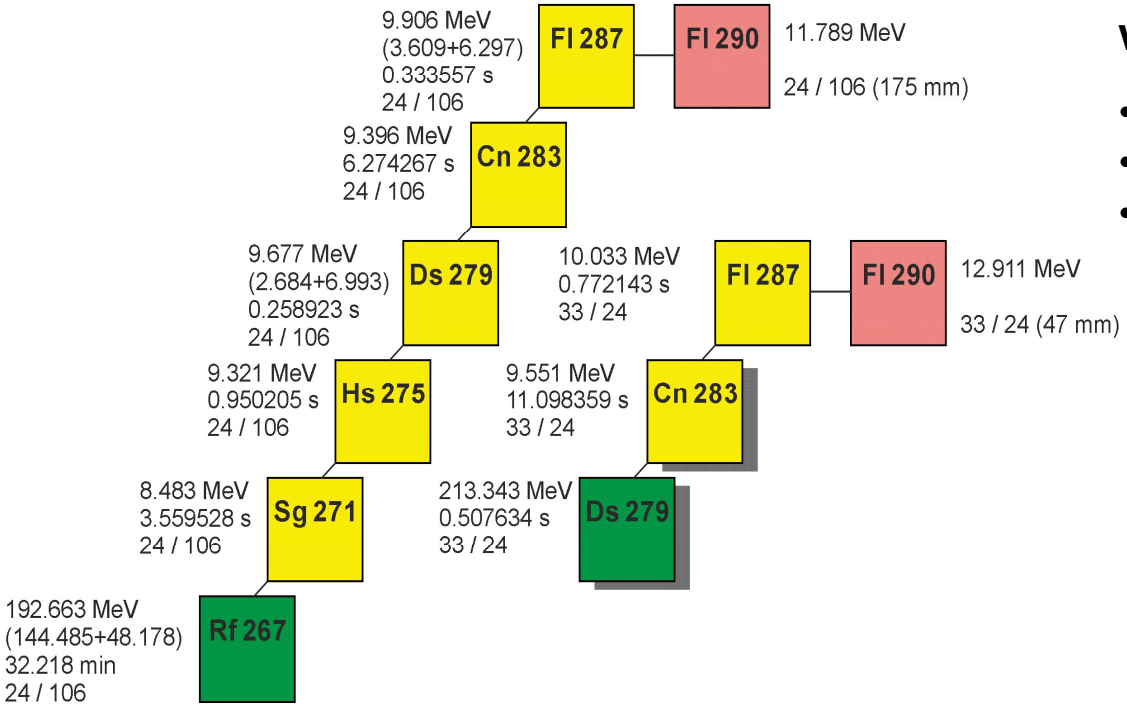
116	^{293}Lv	57 ms
117	^{294}Ts	51 ms
118	^{294}Og	0.6 ms

GASSOL – Solenoid-based separator

- *Stopping SH atoms in a small volume of 1-2 cm^3*
- *Chemistry of short-lived SHE $T_{1/2}$ ≥ 30 ms (up to elements 116-117)*

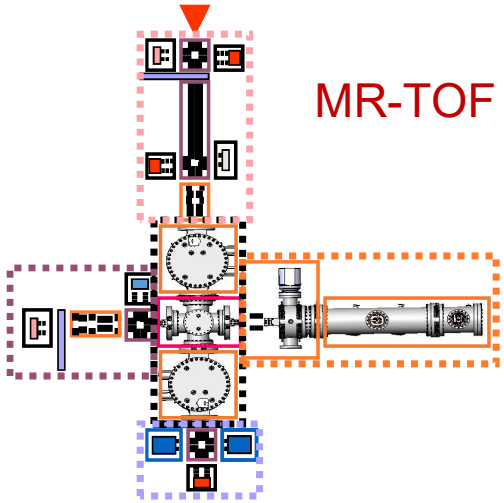


Precise mass measurements of SH nuclei @ SHE Factory



Measuring masses of SH isotopes with accuracy 10^{-7} (30 кeV)

- $T_{1/2}$ > 100 ms
- Production rate ~ 1 event/day
- Background rate ≥ 1 event/s

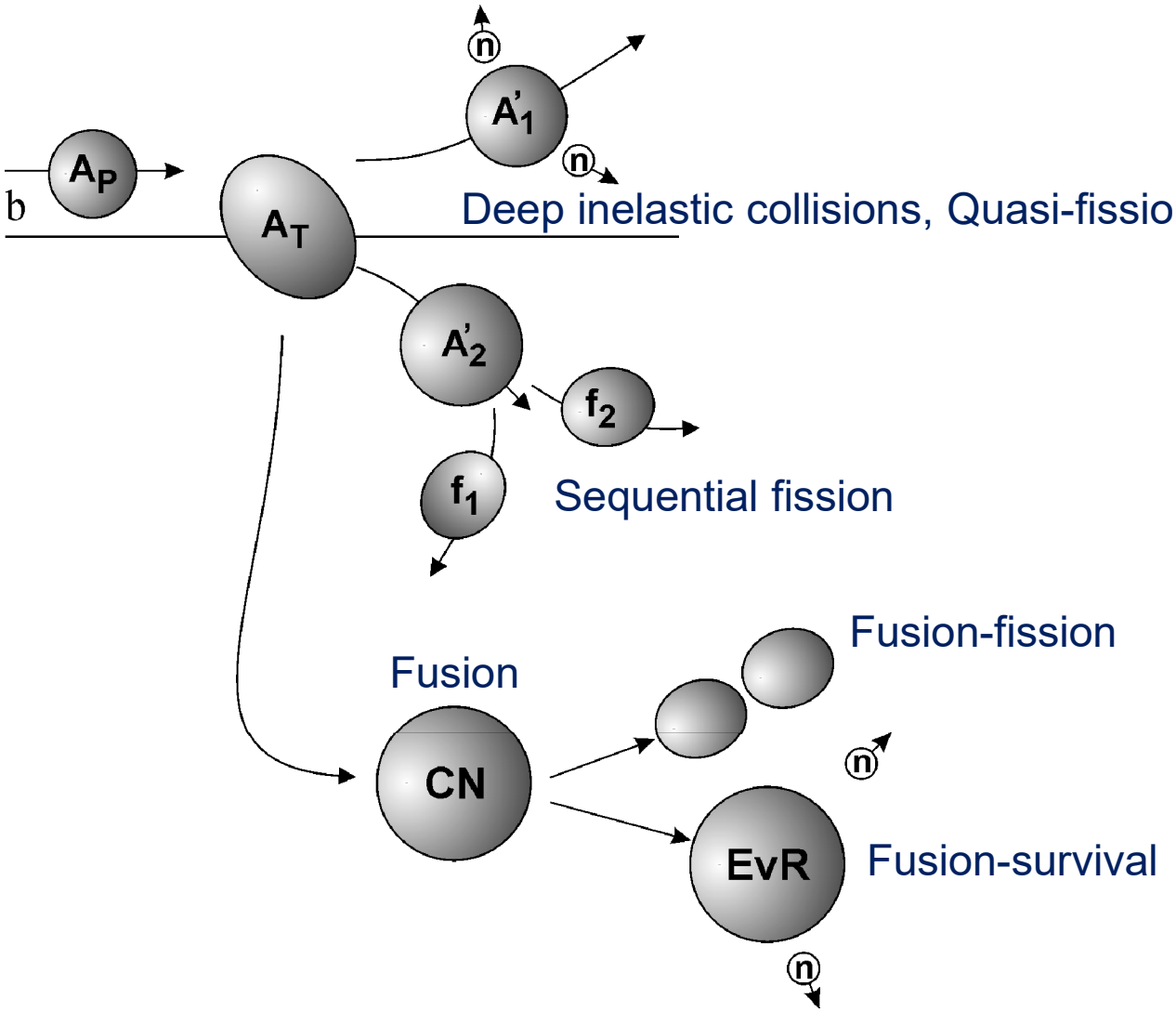


MR-TOF Mass-Analyzer

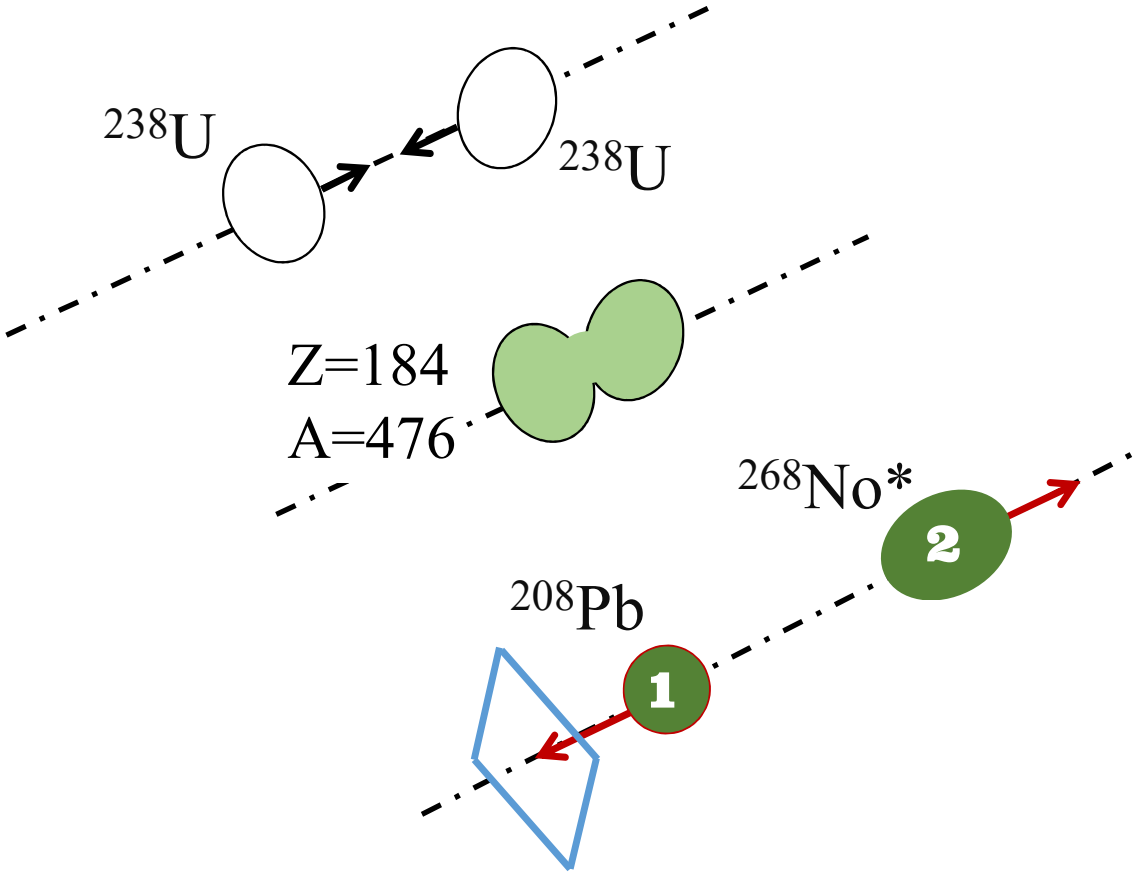
M.I. Yavor, Journal of Instrumentation, ***17*** *(2022) 11033*

Nuclear reactions

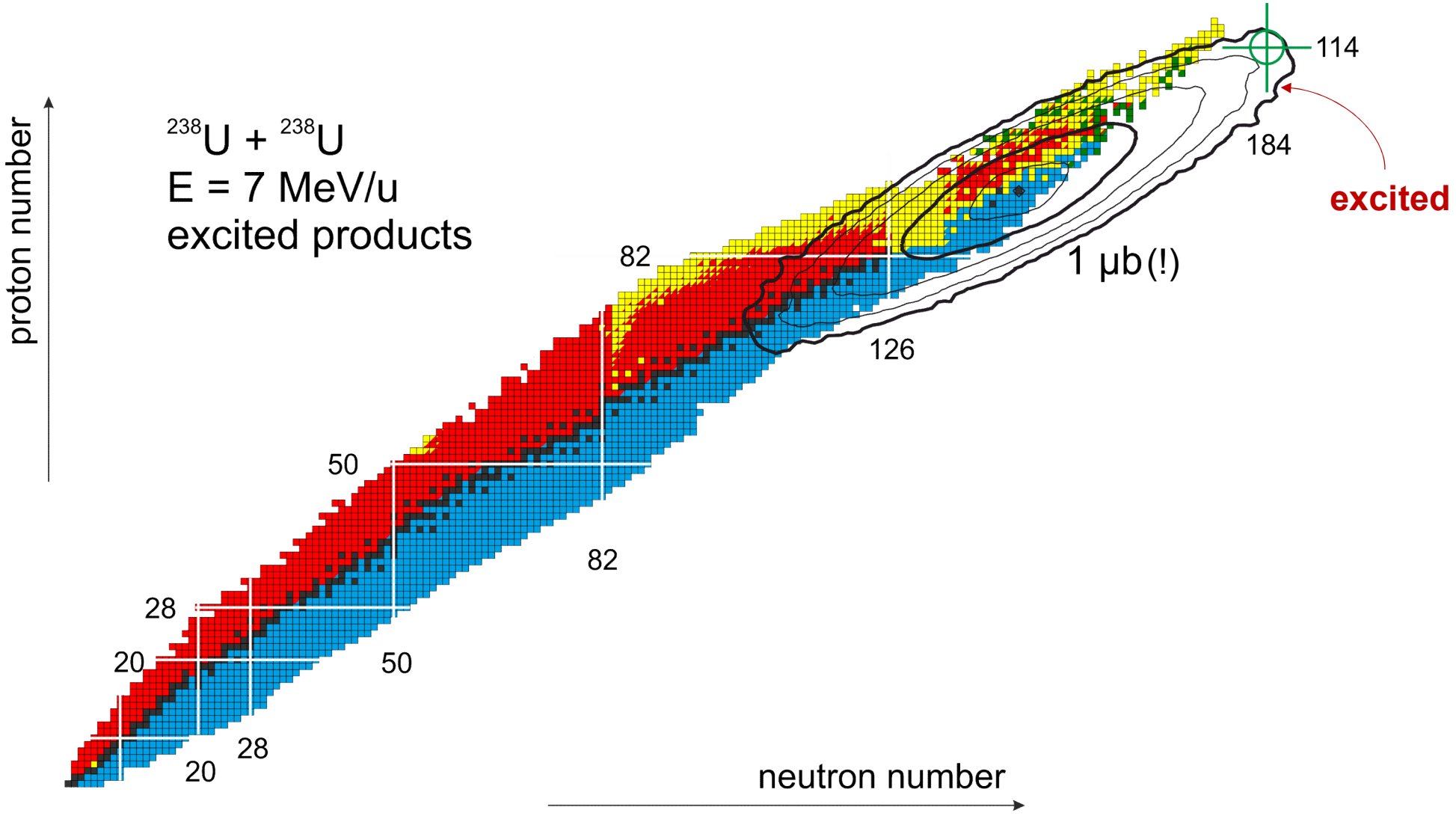
Mechanisms of reactions induced by heavy ions at near barrier energies



Studying the $^{238}U + ^{238}U$ reaction



Multinucleon transfer processes in U + U reaction



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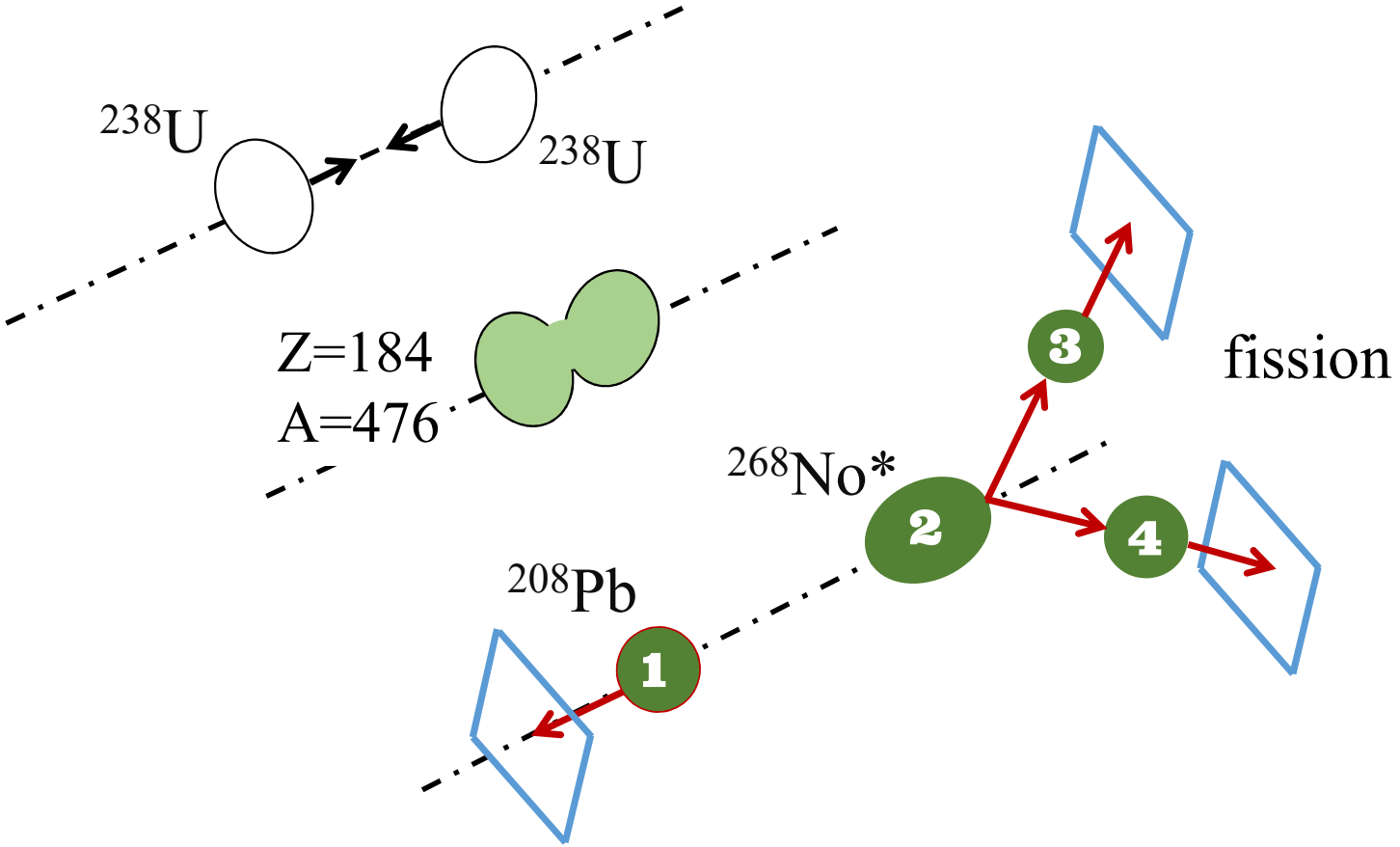

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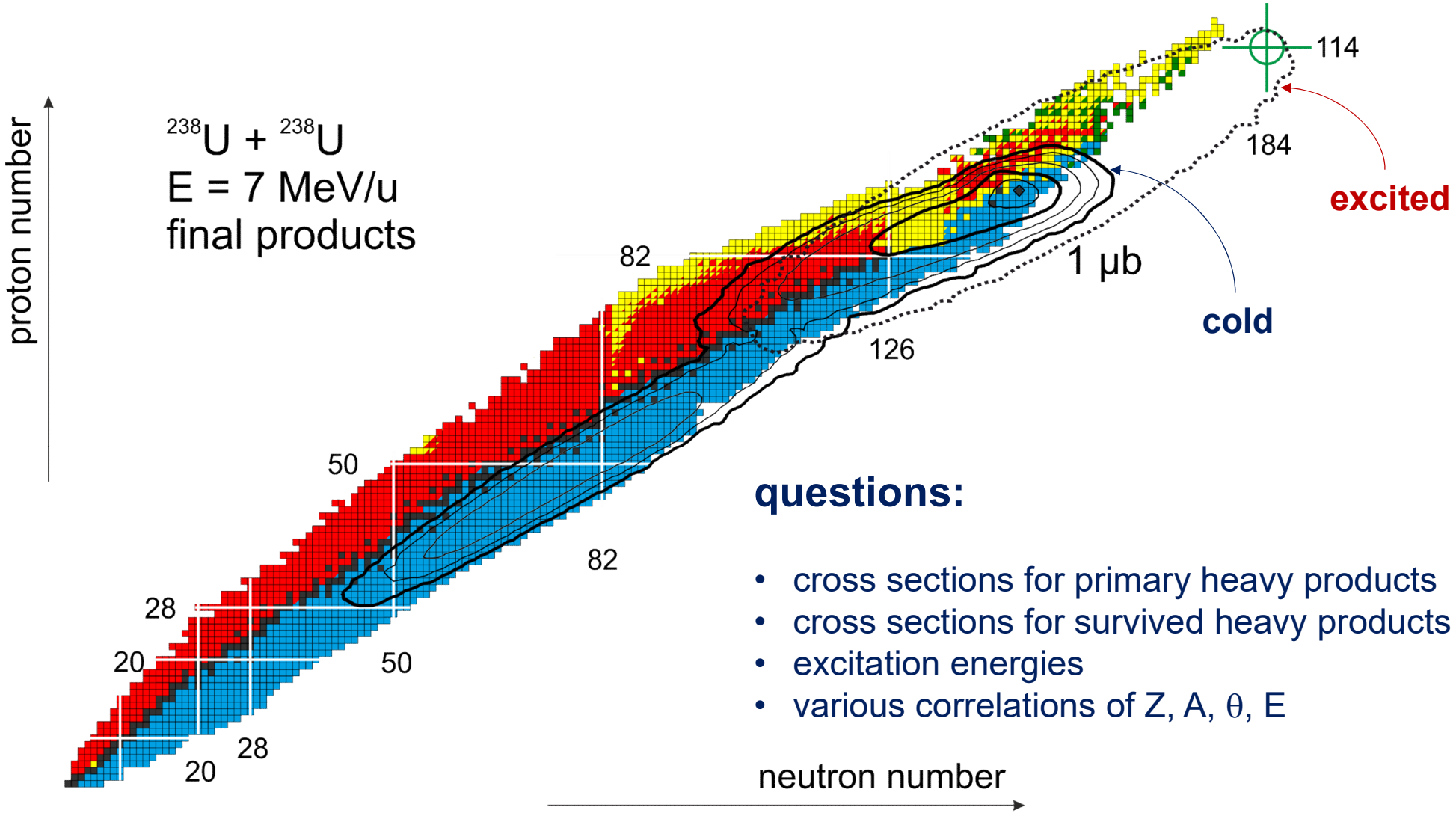

questions:

- cross sections for primary heavy products
- cross sections for survived heavy products
- excitation energies
- various correlations of Z, A, θ, E

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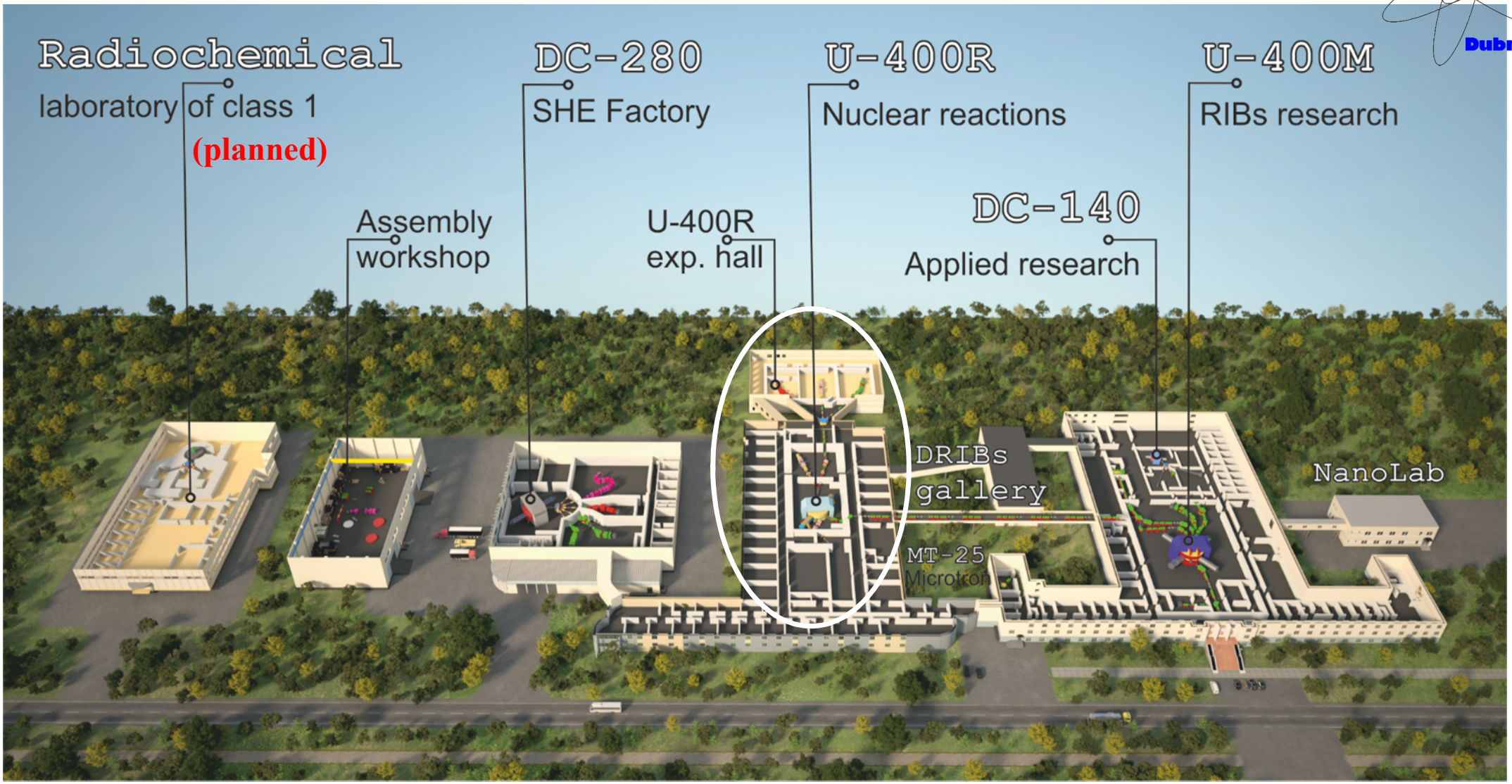
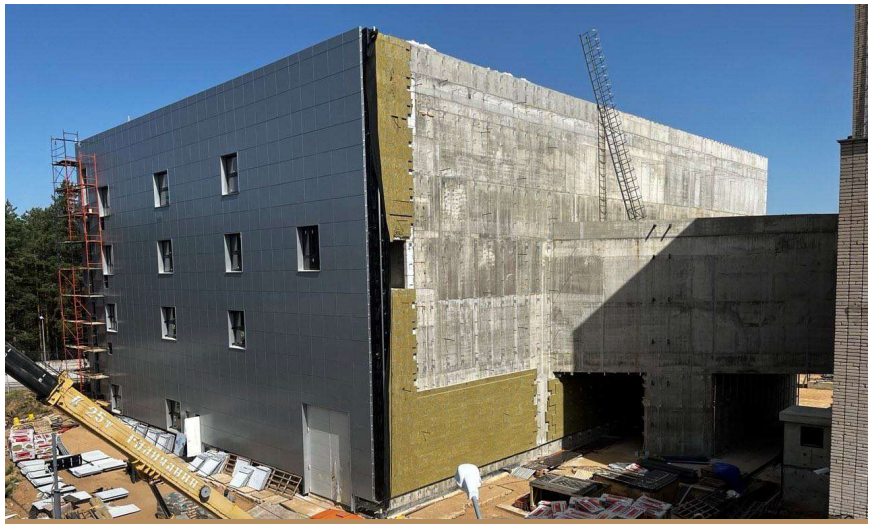


New experimental hall and upgrade of U-400R

U400R (expected)		
Ion	Ion energy [MeV/u]	Output intensity
^{4} He $^{1+}$	6.4 ÷ 25	23 pμA **
^{6} He $^{1+}$	2.8 ÷ 14.4	$(1\text{-}5)10^{9}$ pps
^{8} He $^{1\text{-}2+}$	1.6 ÷ 25	$10^{5\text{-}6}$ pps
^{16} O $^{2\text{-}4+}$	1.6 ÷ 25	5.8 pμA
$^{18}O^{3+}$	1.2 ÷ 18	4.4 pμA
^{40} Ar $^{4\text{-}6+}$	1.1 ÷ 18	5 pμA
^{48} Ca $^{5\text{-}10+}$	1.6 ÷ 18	2.0 pμA
^{50} Ti $^{5\text{-}10+}$	1.0 ÷ 21	1 pμA
^{58} Fe $^{7\text{-}12+}$	1.0 ÷ 17:	1 pμA
^{84} Kr $^{7+}$	0.8 ÷ 3.5	1.4 pμA
^{132} Xe$^{11\text{-}22}$	0.8 ÷ 15	1-0.3 pμA
^{238} U $^{27\text{-}44+}$	1.5 ÷ 15	1- 0.1 pμA



Completion of the pile field 08.12.23



21.08.25

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	1666	1.33	1.63	1.63	**3.67**	24.4
^{268}No	1596	1.32	1.67	1.67	**3.39**	22.3

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

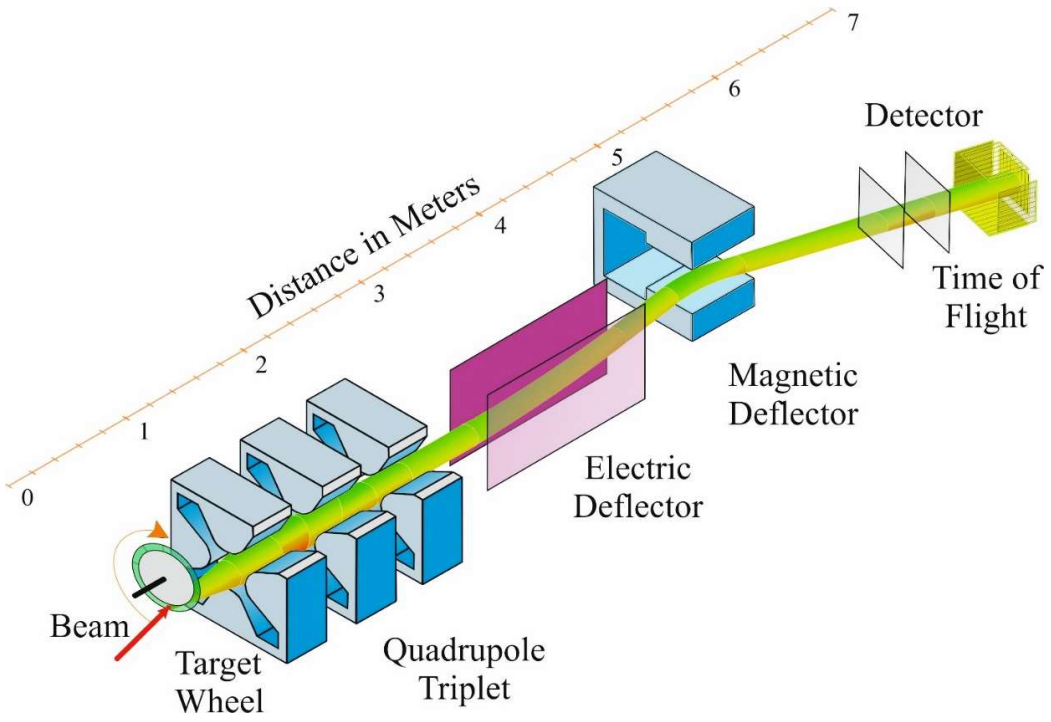
What do we need

Bρ (T×m)	E/q (MV)	
1.5	**25**	**rotatable**

What do we have

Separator	Institute	Bρ(max) T×m	E/q (max) MV
SHIP	GSI	1.2	20 (?)
SHELS	JINR	1.0	10
FMA	ANL	1.0	18
MARA	JYFL	1.0	14
S3	GANIL	1.8	12

STAR
(Separator for TransActinide Research)

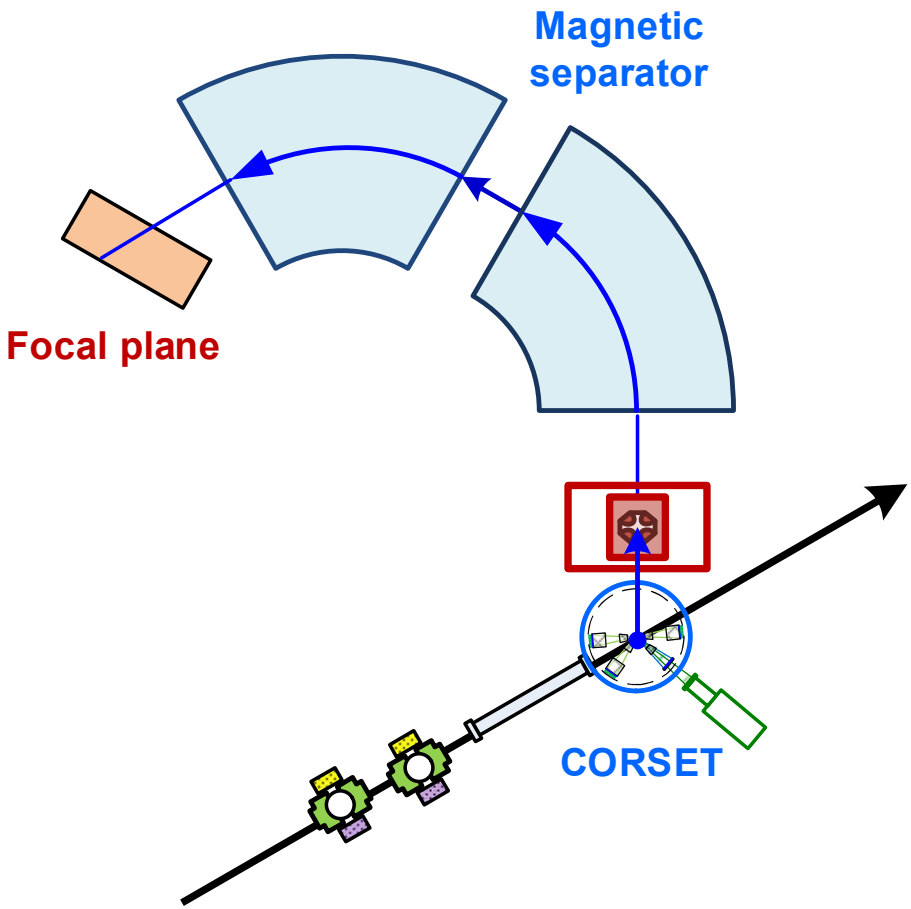


System for Correlated Investigation of Fragments (SCIF)

Study of mechanisms of fusion-fission and incomplete fusion reactions

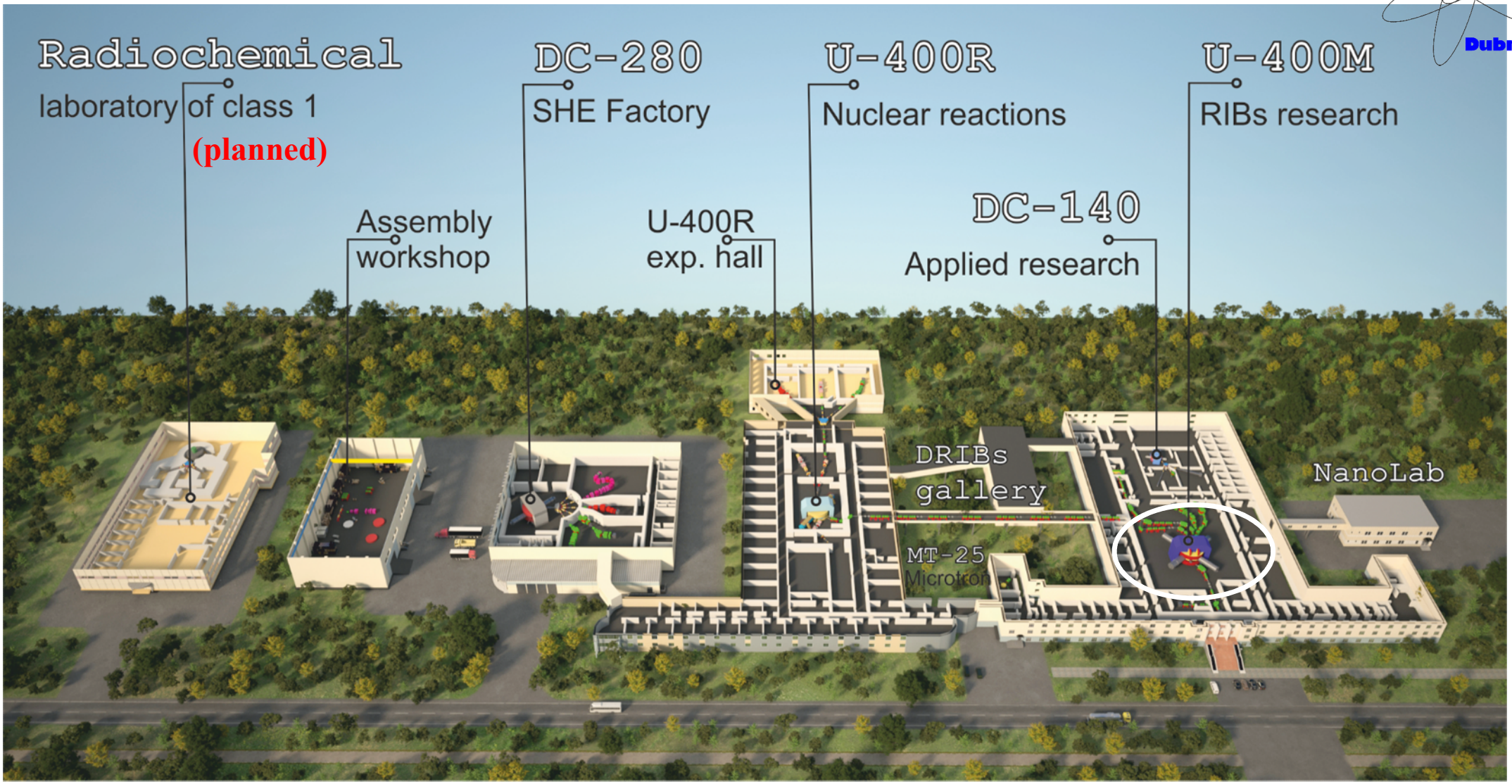
SCIF consists of:

- **CORSET** spectrometer - measuring mass-energy and angular distributions of reaction fragments;
- **Bragg chambers** - measuring of charge distributions of reaction fragments;
- **Magnetic spectrometer** providing precise (A,Z) identification of fragments with masses up to 200 a.m.u.;
- etc.



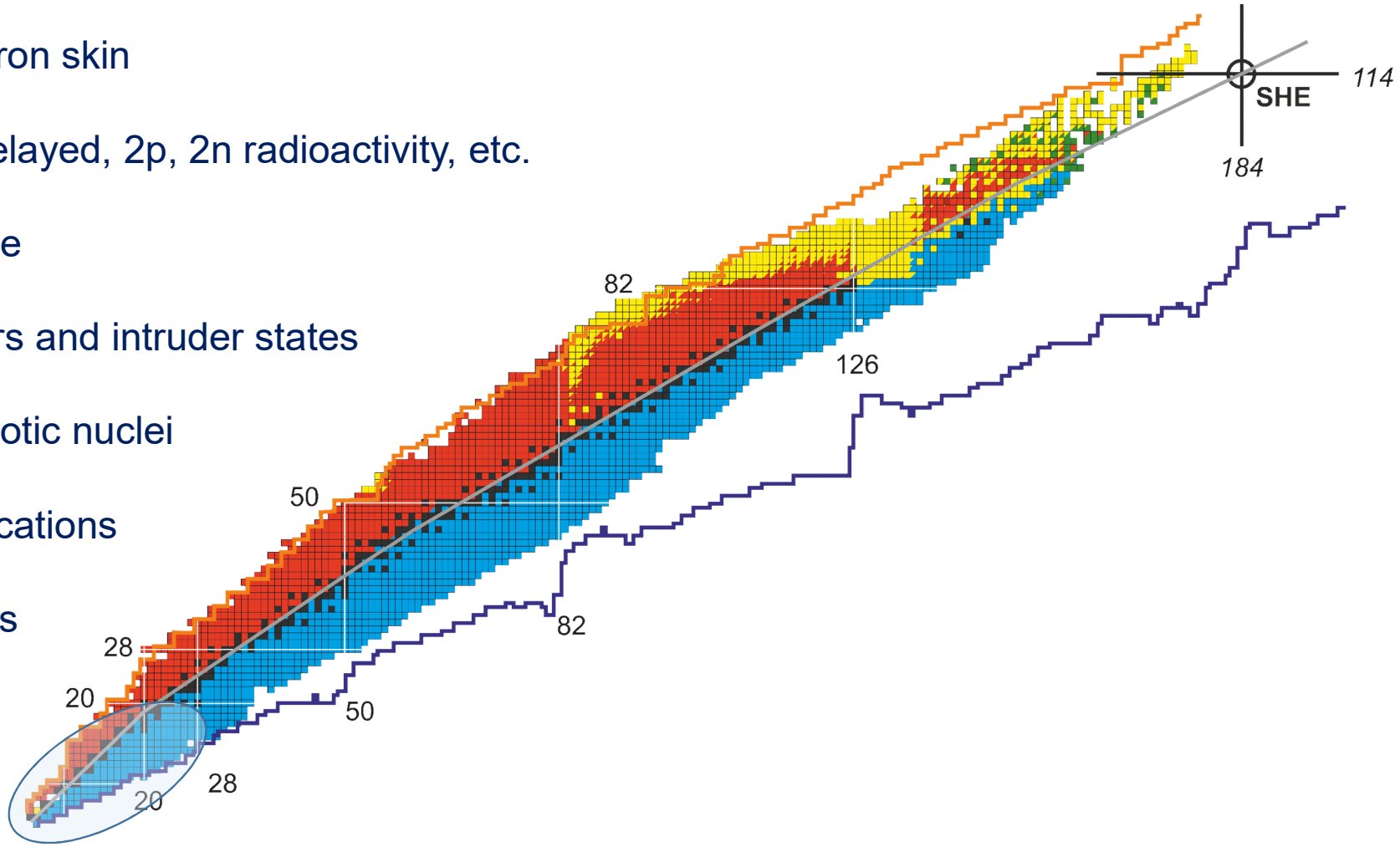
Study of exotic nuclei close and beyond the nucleon stability limits

FLNR ACCELERATOR COMPLEX



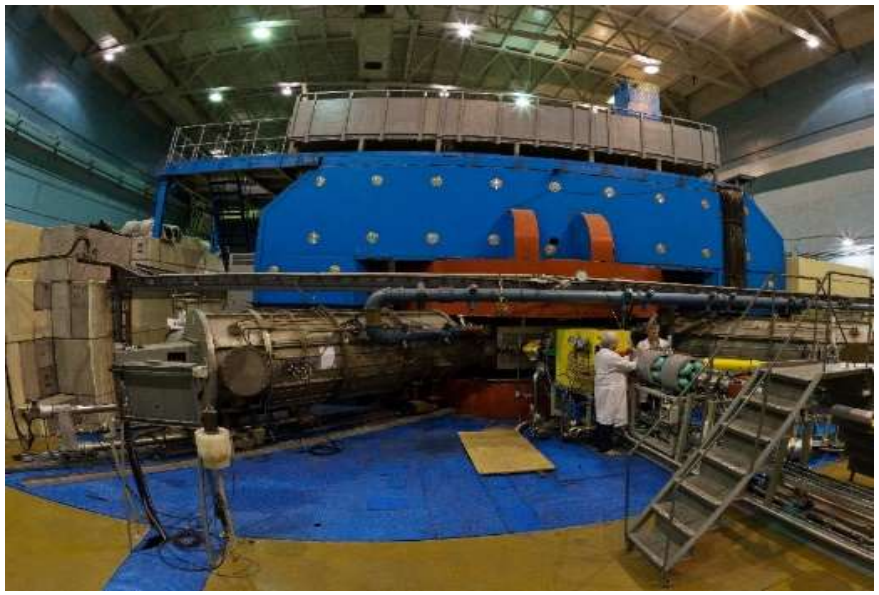
Experimental program with exotic nuclei

- Nucleon halo, neutron skin
- Exotic decays: β-delayed, 2p, 2n radioactivity, etc.
- Soft excitation mode
- New magic numbers and intruder states
- Spectroscopy of exotic nuclei
- Astrophysical applications
- Reactions with RIBs
- Cluster states



Cyclotron U400M

commissioned after modernization in 2025



ACCULINNA-II

In-flight fragment-separator



Primary beams

HI	E(AMeV)	I(pμA)
^{7}Li	39	10
^{11}B	34	6
^{15}N	51	2
^{18}O	40	1.5
^{20,22}Ne	54/50	1
^{32,36}S	52/44	0.2

Secondary beams

RI	Y, pps	P, %
^{8}He	$6*10^{5}$	90
^{11}Li	$3*10^{4}$	80
^{14}Be	$2*10^{3}$	85
^{13}O	$2*10^{5}$	55
^{24}O	$7*10^{2}$	50
^{17}Ne	$5*10^{5}$	80
^{28}S	$1.2*10^{4}$	70



2017: ACCULINNA-II is launched

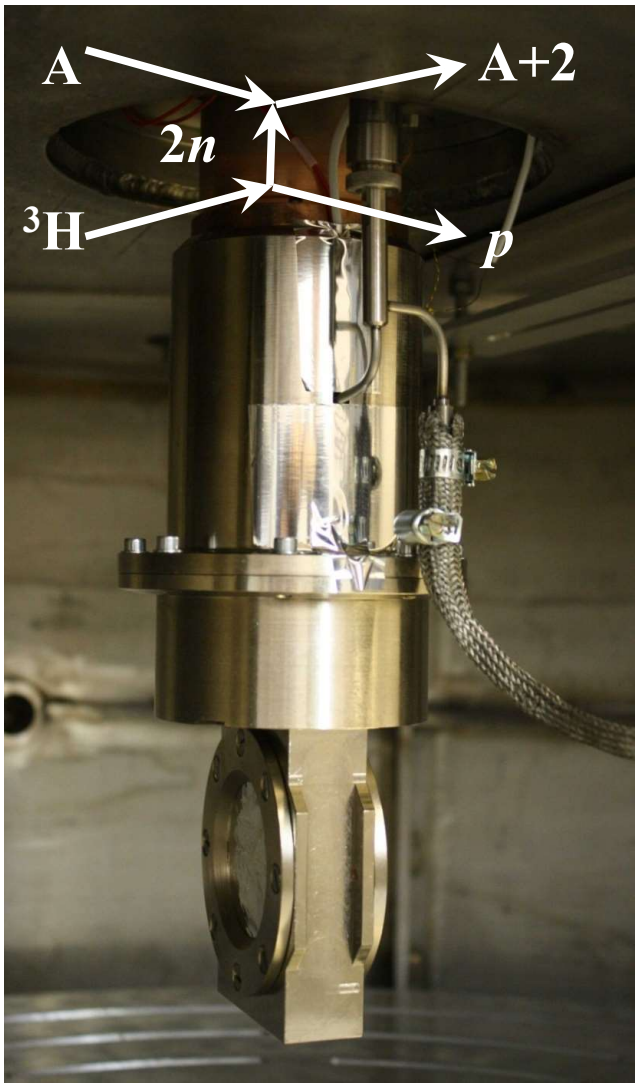


2019: RF kicker



2017: Zero-degree spectrometer

Cryogenic gas target ^{1,2,3}H, ^{3,4}He



Why tritium?

- Required excess of neutrons – 2 neutrons can be transferred;
- Energy of separation of two neutrons from triton (~ 8.4 MeV) is the minimum possible;
- Recoil is a proton which can be detected in a low-background kinematic range where it is emitted in the angular range close to 180° in respect to the beam direction.

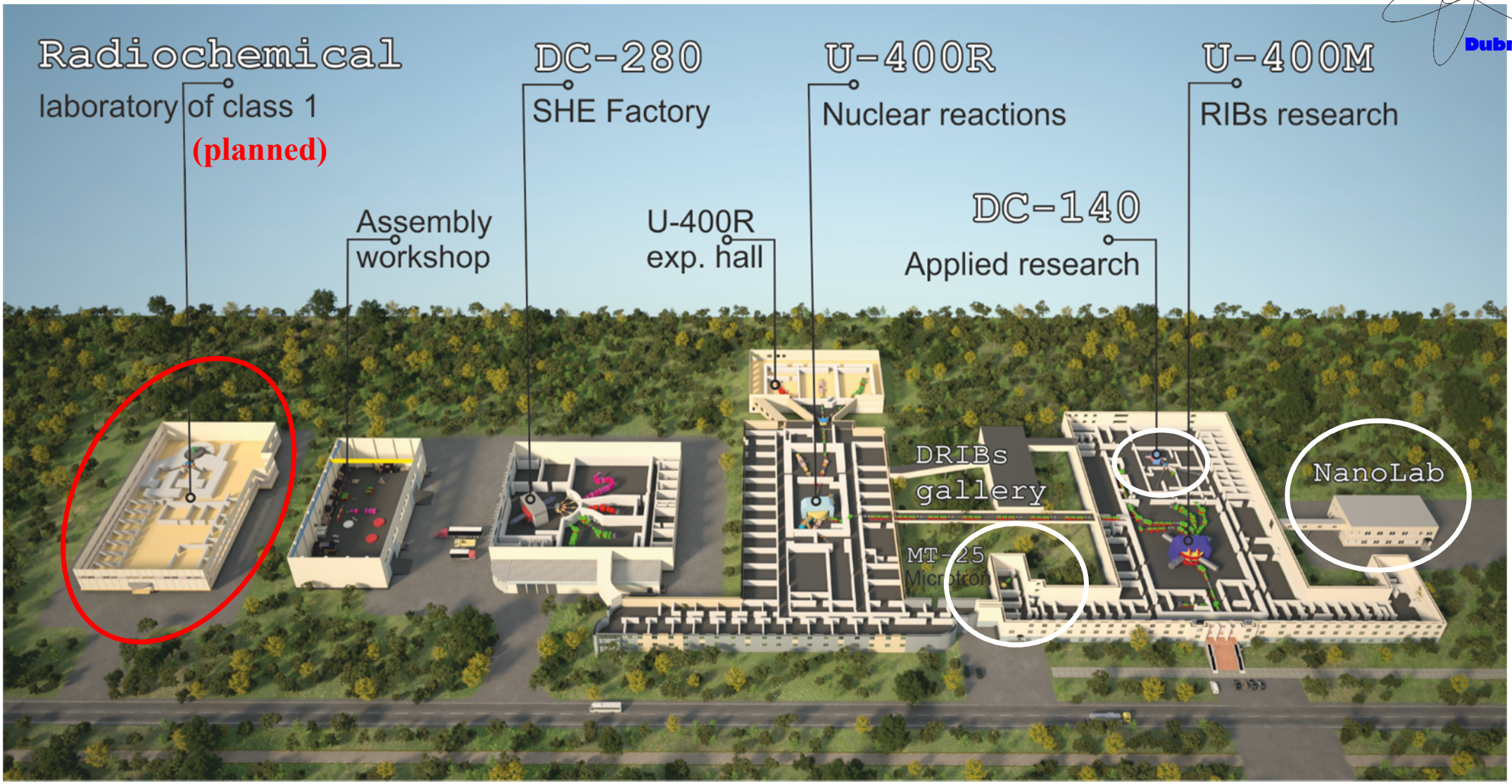
The cell can also be filled with H, D_2, ^{3}He, ^{4}He.

Tritium:

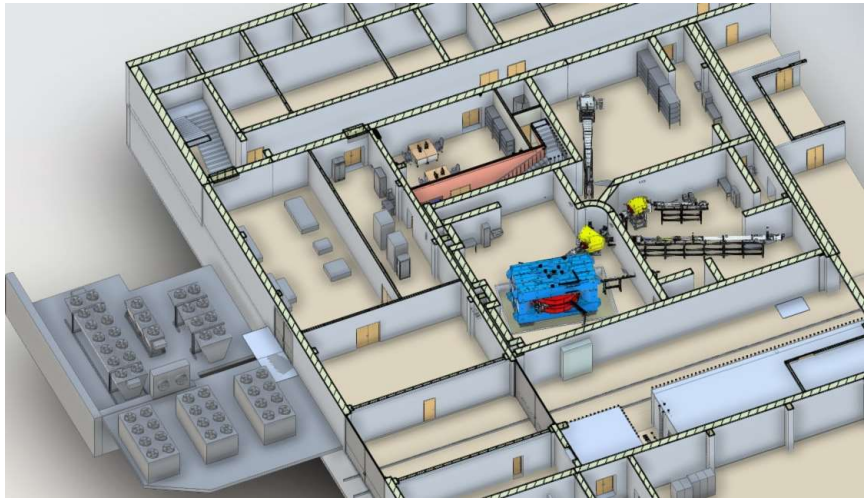
- 1 kCi T_2;
- Liquid (T~25 K): h=0.4 mm;
  Gas: h=4 mm;
- Three stages of radiation protection;
- Radiation safety control;
- Automatic control and parameter setting;

Applied research

FLNR ACCELERATOR COMPLEX



Applied studies with heavy ion beams
Cyclotron DC-140 to be launched in 2026





Principal tasks

1. Testing electronic chips ~3000 h/y.
2. Radiation material science ~1500 h/y;
3. Irradiation of polymer films ~1500 h/y.

Technical parameters of DC-140:

Magnetic field:	1.377 - 1.554 T;
Frequency:	8.452 MHz;
Ions:	O – Bi;
Energy:	2.1 MeV/n (A/Z=7.35 – 8.25)
	4.8 MeV/n (A/Z=4.9 - 5.5)
Beam intensity:	$10^5 \div 10^{12}$ s^{-1}



NANOLAB



Projects:

- Radiation tolerance of materials to high intensity heavy ion beams impact;
- Nanocomposite and functional track-etched membranes;
- High-sensitivity sensor based on molecular recognition for viruses detection.

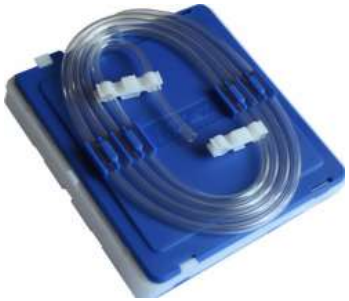
Available equipment

- Two scanning electron microscopes (Hitachi SU8020 and S3400N) with a number of options (X-ray microanalysis, cathodoluminescence, etc)
- Transmission electron microscope Talos F200i (Thermo Fisher Scientific)
- Atomic force microscope with Raman spectrometer NTEGRA Spectra
- X Ray photoelectron spectroscopy (K-Alpha instrument)
- Fourier-transform IR spectrophotometer Nicolet 6700 UV-Vis spectrophotometer Evolution 600
- Capillary flow porometer Porolux 1000 and other equipment for membrane testing
- Raman spectrometer R-532 (EnSpectr)
- Thermogravimetry instrument: TG 209 F1 Libra (Netzsch)
- Differential scanning calorimetry instrument: DSC 3 (Mettler Toledo)
- Particle analyzer: Zetasizer Nano ZSP (Malvern)
- Nanofiber electrospinning machine: Nanon-01A (MECC)
- Inductively coupled plasma atomic emission spectrometer EXPEC-600

Track membrane-based products with pores 0.2-0.4 μm



Water filter«Krymskaya rosinka» (Simferopol)



Water filter Nerox



Plasmafilter «Rosa», SPA «Alpha» (Dubna)



Multi-layer modules for cross-flow micro filtration (Vladisart, Vladimir)



Water filters NAQWA (Obninsk)



Plasmafilter «PFN-500» (Saint-Petersburg)



Infusion filters (China)



Cancer diagnostics (China)



Multifunctional filter cartridges (China)

Thank you for your attention!

