Evolution of the new experimental set ups for studies of transfermium elements in the reactions with heavy ions at FLNR JINR.

Yeremin A.V.

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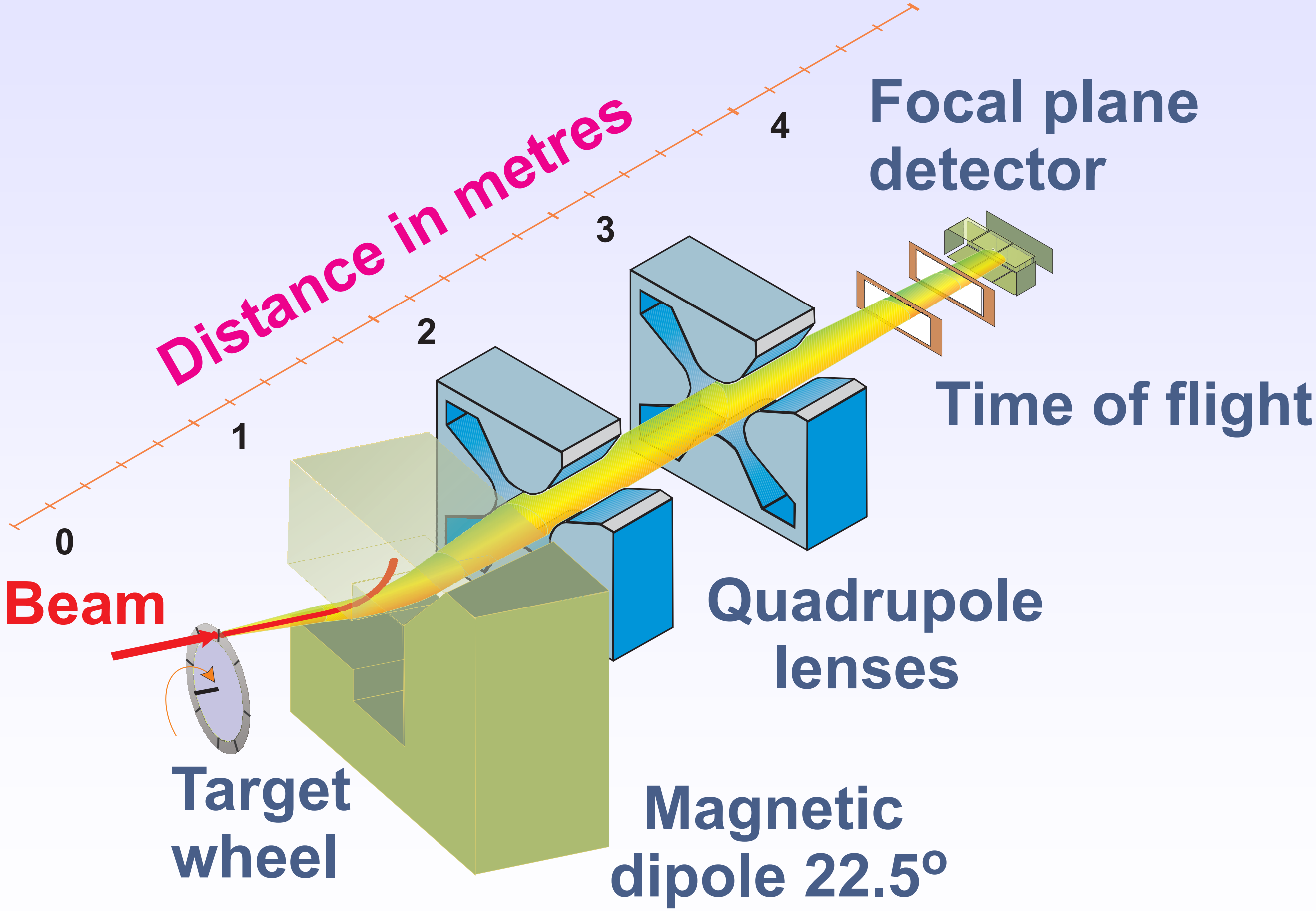
eremin@jinr.ru

Presently Working Experimental Set Ups

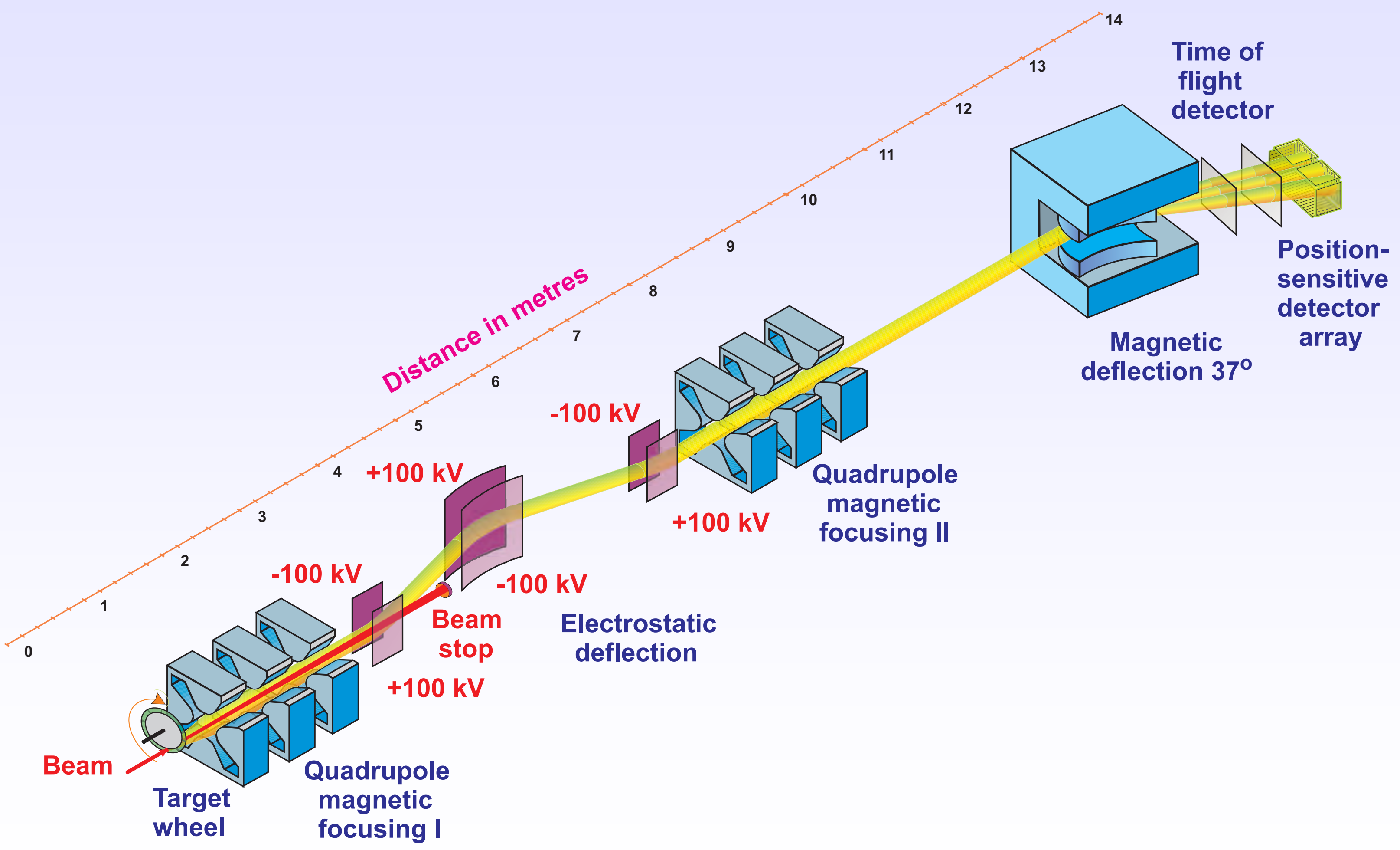
Set up	Heavy element research	Spectroscopy studies
Dubna Gas Filled Separator (Russia)	★	
SHIP (Darmstadt, Germany)	★	✦
Berkeley Gas Filled Separator (USA)	★	
GARIS (Saitama, Japan)	★	
VASSILISSA (Dubna, Russia)	★	✦
LIZE3 (GANIL, France)	★	✦
RITU (JYFL, Finland)		✦
FMA (Argonne, USA)		✦
JAERI-RMS (Tokai, Japan)	★	

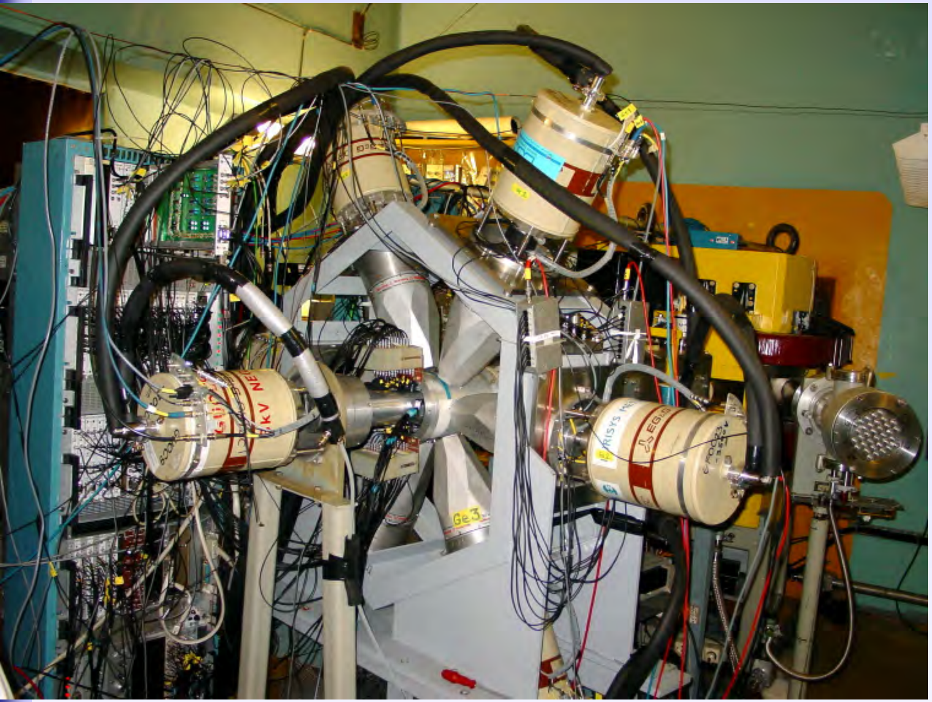
★ Heavy element research ✦ Spectroscopy studies

Dubna Gas Filled Recoil Separator (DGFRS)



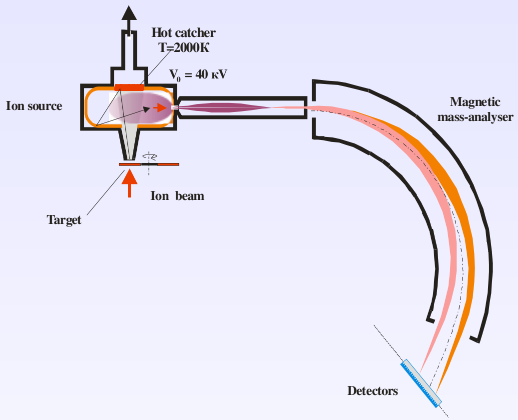
Electro Static separator VASSILISSA

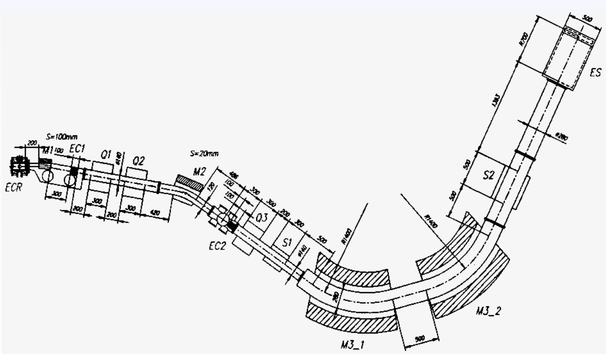




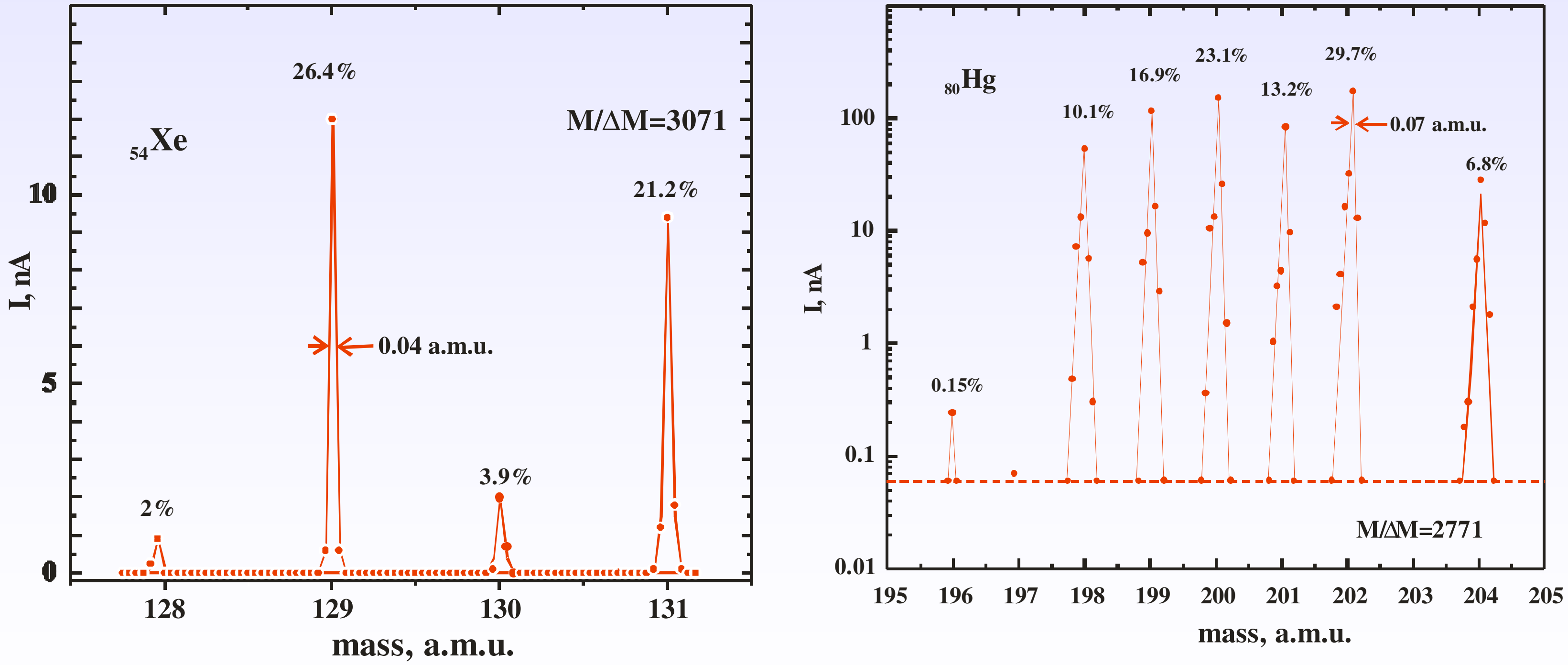
GABRIELA Gamma Alpha Beta Recoil Investigation with the Electromagnetic Analyser

Mass Analyzer of Super Heavy Atoms





MASHA test with ^{nat}Xe and ^{nat}Hg isotopes



Bottom lines:

- During past 25 years 10 new elements (107 – 116) were synthesized.
- Experimental set ups used – kinematic separators.
- Methods of synthesis: "Cold fusion" – the use of Pb, Bi targets (E* ~ 10 – 20 MeV); "Hot" fusion – the use of U, Pu, Cm, Cf targets (E* ~ 30 – 50 MeV).
- Main method of identification – registration of α and SF (Generic decay links).

Synthesis of transfermium elements: reaction dynamics - conclusions

- Big charge and/or mass asymmetry at the entrance channel increases formation cross section
- Closed shells increases fusion probability
- High T_z in the projectile or in the target increases fusion probability
- Neutron excess (the increase of isospin T_z) in the CN increases the survival probability

★ Perspectives of the experiments to study reaction dynamics and spectroscopy studies:

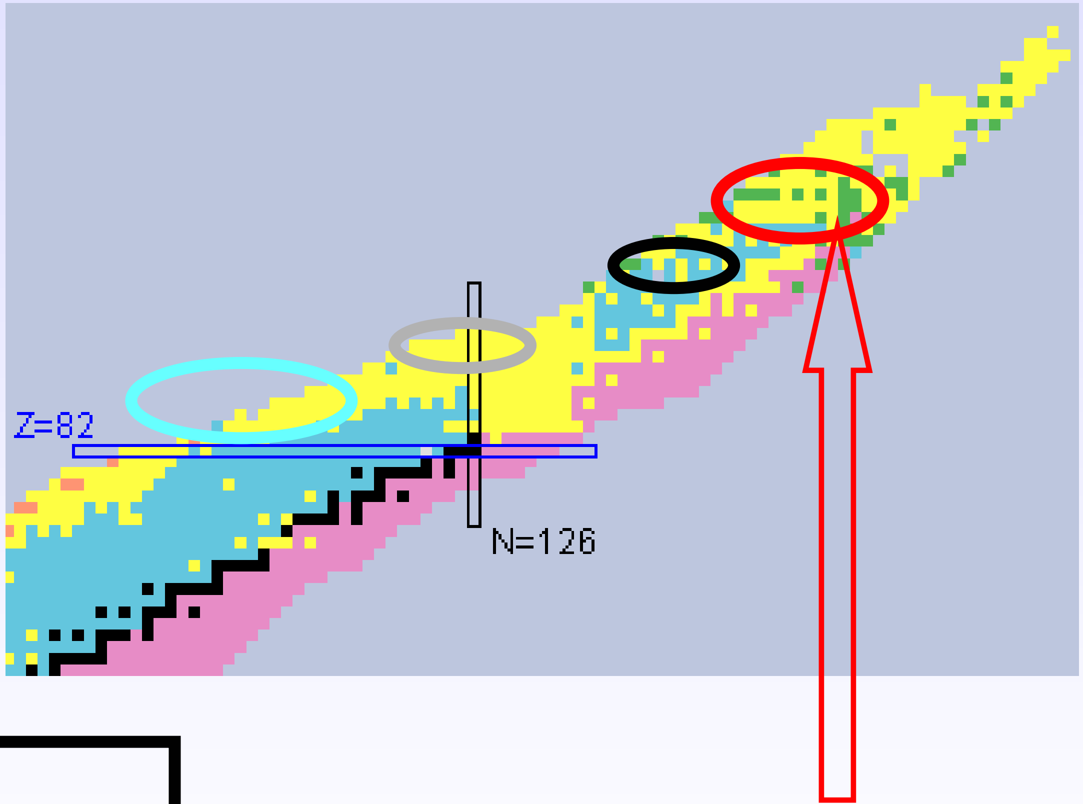
★ Stable beams + exotic targets

Study of the fusion dynamics of nuclei with closed shells (^{136}Xe + ^{136}Xe).
Study of the reaction dynamics with stable beams of $^{62,64}Ni$, $^{84,86}Kr$, $^{134,136}Xe$
Focal plane spectroscopy studies with stable beams of ^{22}Ne, ^{26}Mg, $^{34,36}S$, $^{44,48}Ca$ and exotic targets ^{236}U, $^{242,244}Pu$, ^{243}Am, ^{248}Cm
Kinematic separator, gas – jet technique

★ Exotic beams + stable targets

Study of the reaction dynamics: formation cross sections, influence of the closed shells, check of the superheavies – bridge between results of“cold” and “hot” fusion.
Spectroscopy studies: new neutron rich isotopes, detailed study of the nuclear structure in vicinity of N = 162 subshell

Regions of interests in spectroscopy with kinematic separators



New neutron deficient isotopes in polonium region (strong change of deformation, break of G-N law, shape coexistence,…)

Isomer study in radium - uranium region

Study of new neutron deficient plutonium - curium isotopes (fission barrier,…)

Spectroscopy in fermium region (K-isomers, single particle level systematic, decay properties…)

Future possible experiments with Ge and electron detectors at focal plane in Dubna

Study of decay properties and /or γ and/or electron spectroscopy in two regions: Rn - U and Fm – Sg

Advantages of Dubna:

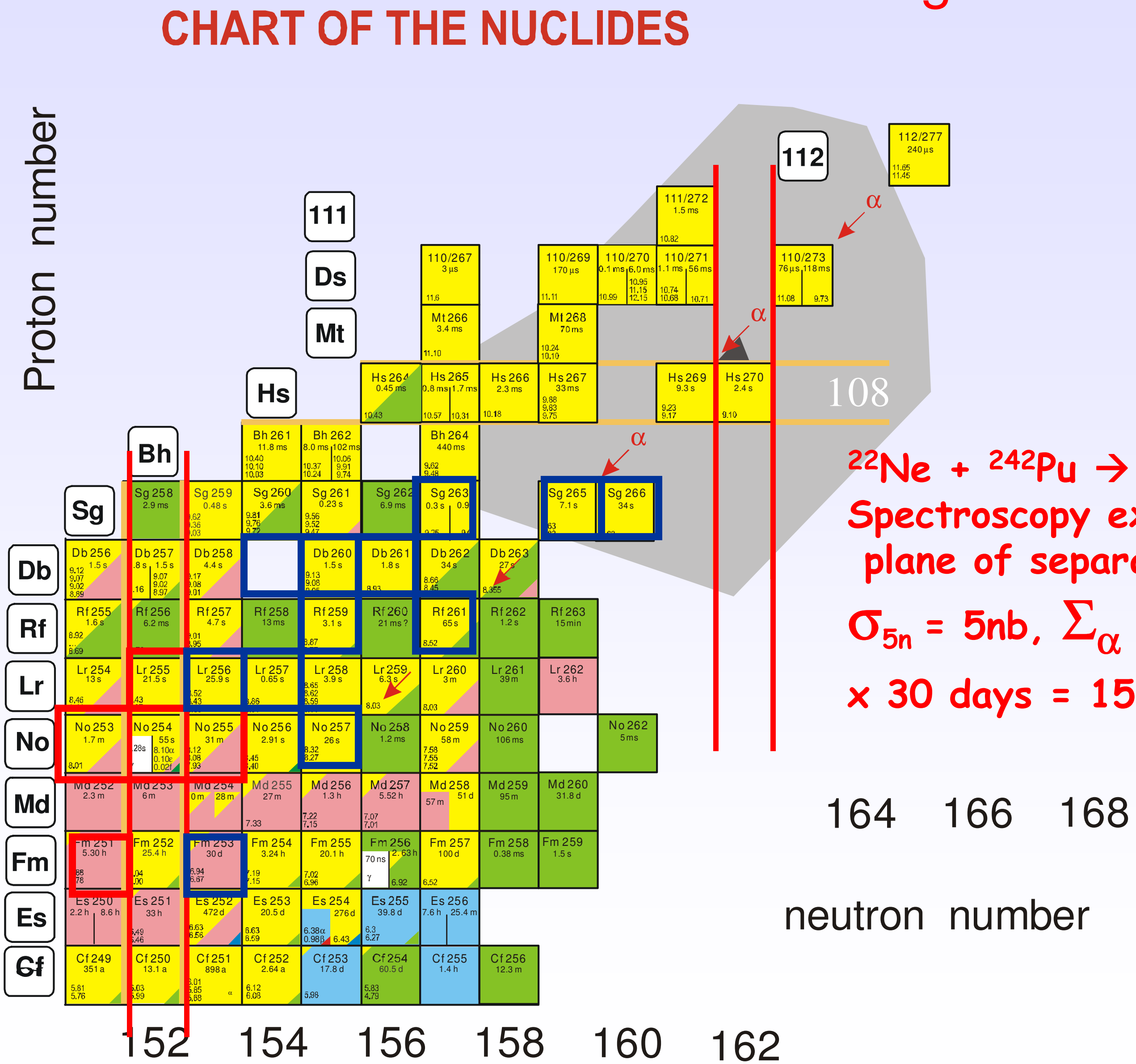
Radioactive targets : → more neutron rich nuclei

Prospective reactions

Mother		Daughter
$^{238}U(^{26}Mg,5n)^{259}Rf$	1.1 nb	$^{255}No_{153}$ (Z=102)
$^{242}Pu(^{22}Ne,5n)^{259}Rf$	5.0 nb	$^{255}No_{153}$ (Z=102)
$^{248}Cm(^{18}O,5n)^{261}Rf$	13 nb	$^{257}No_{155}$ (Z=102)
$^{244}Pu(^{22}Ne,5n)^{261}Rf$	5.0 nb	$^{257}No_{155}$ (Z=102)
$^{243}Am(^{22}Ne,5n)^{260}Db$	2.0 nb	$^{256}Lr_{153}$ (Z=103)
$^{243}Am(^{22}Ne,4n)^{261}Db$	1.5 nb	$^{257}Lr_{154}$ (Z=103)
$^{248}Cm(^{22}Ne,5n)^{265}Sg$	1.3 nb	$^{261}Rf_{157}$(Z=104)

Unique radioactive targets, such as ^{210}Pb, $^{242,244}Pu$, ^{243}Am, ^{248}Cm are available in Dubna and could be used in order to populate excited states in the heavy neutron rich nuclei. This offers the opportunity to give insight into the single neutron and proton structure.

Possible spectroscopy experiments with stable beams and exotic targets



$^{22}Ne + ^{242}Pu \rightarrow ^{259}Rf + 5n$

Spectroscopy experiments at the focal plane of separator.

σ_{5n} = 5nb, Σ_{α} = 50 /day (I_{Ne} = 1pμA)

× 30 days = 1500 α's

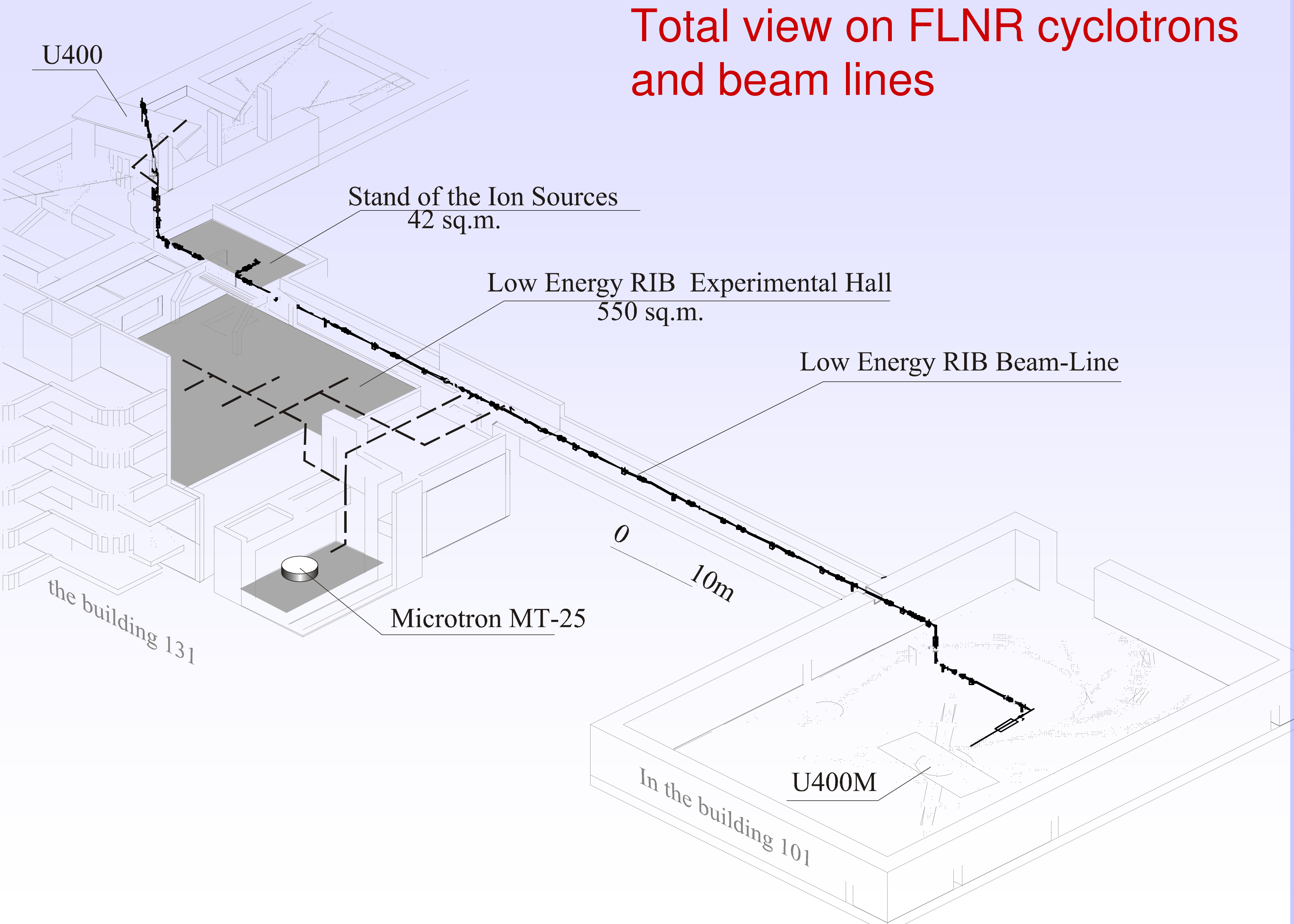
Way to the asymmetric combinations

- Achievement: neutron rich isotopes, that could not be reached in more symmetric combinations.
- Disadvantage: very broad energy and angular distributions of recoils => low transmission of the kinematic separators

Possible solutions

- Design of new kinematic separator for asymmetric combinations. Modernization of the existing set up.
- Modernization of the accelerators
- Alternative experimental installations (gas jet, gas jet + ISOL)

Total view on FLNR cyclotrons and beam lines



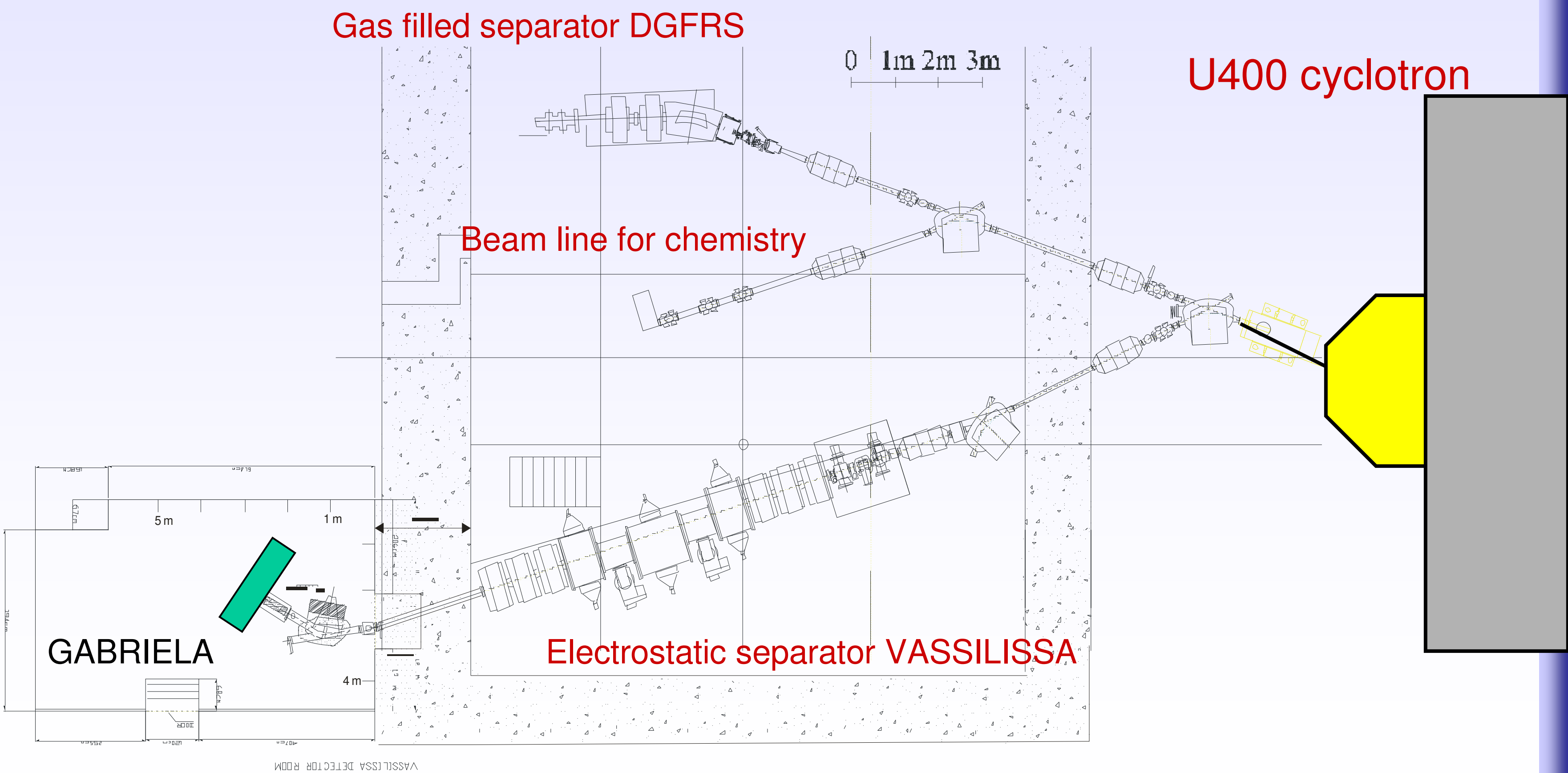
Modernization of the U400M cyclotron (march – october 2007)

- to accelerate “low” (6÷15 MeV/A) energy ions (to move some experiments from U400 to U400M),
- to extract the “low energy” beams to the opposite direction and to organize new experimental hall.

Modernization of the U400 cyclotron (year 2009)

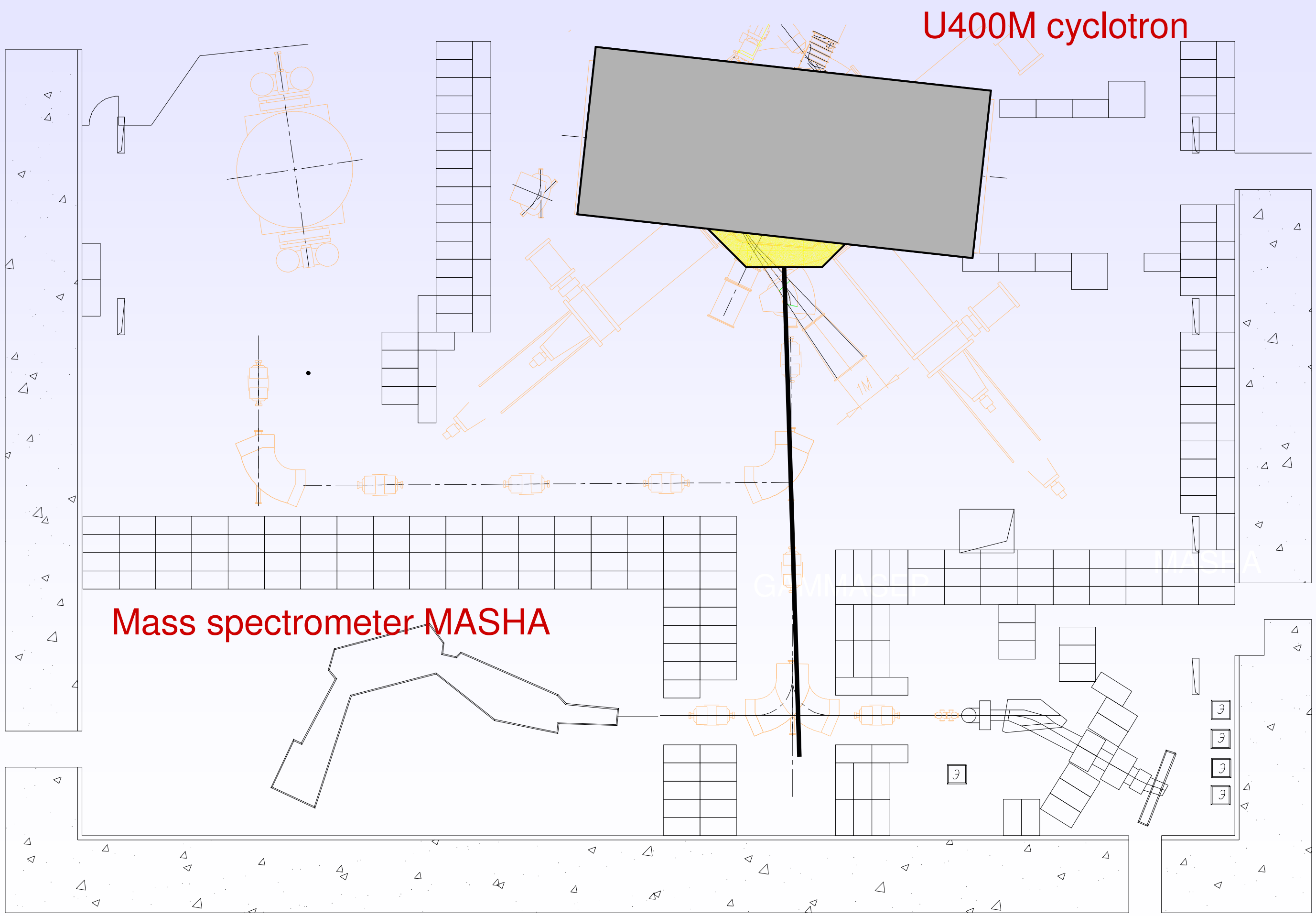
- to increase the ion beam intensity up to $10^{13} – 10^{14}\ s^{-1}$,
- to improve the beam energy resolution up to $5{\cdot}10^{-4}$,
- to vary smoothly the beam energy in the range 0.8 ÷ 10 A·MeV,
- to decrease the power consumption from 1 to 0.25 MWatt.

Installation configurations at U400 cyclotron



Possible installation configurations at U400M cyclotron

Installation: low energy beam line of the U400M



Experimental tests for asymmetric combinations

1) VASSILISSAToF : 2 thin foils (20 μg each)

$^{22}Ne + ^{197}Au \longrightarrow ^{214}Ac + 5n \quad \varepsilon = 2\ \%$

2) VASSILISSA ToF : 1 thin foils

$^{22}Ne + ^{197}Au \longrightarrow ^{214}Ac + 5n \quad \varepsilon = 5\ \%$

1) VASSILISSA ToF : 1 thin foil

$^{22}Ne + ^{238}U \longrightarrow ^{255}No + 5n \quad \varepsilon = 1.5\ \%$

2) VASSILISSA ToF : without foils

$^{22}Ne + ^{238}U \longrightarrow ^{255}No + 5n \quad \varepsilon = 2\ \%$

1) DGFRS

$^{22}Ne + ^{197}Au \longrightarrow ^{214}Ac + 5n \quad \varepsilon = 12 \pm 3\%$

2) DGFRS

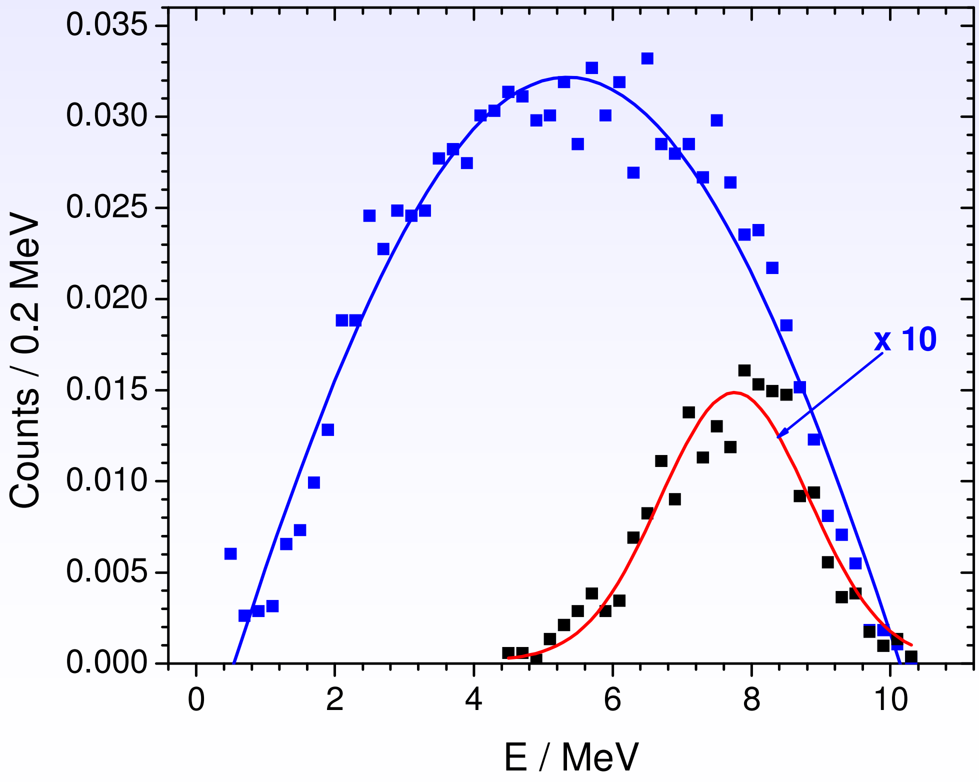
$^{22}Ne + ^{238}U \longrightarrow ^{255}No + 5n \quad \varepsilon = 6 \pm 2\ \%$

1) SHIP: ToF : without foils

$^{22}Ne + ^{238}U \longrightarrow ^{255}No + 5n \quad \varepsilon = 3 \pm 1\ \%$

Calculations : VASSILISSA

$^{22}Ne + ^{238}U \longrightarrow ^{255}No + 5n \quad \varepsilon = 2\ \%$

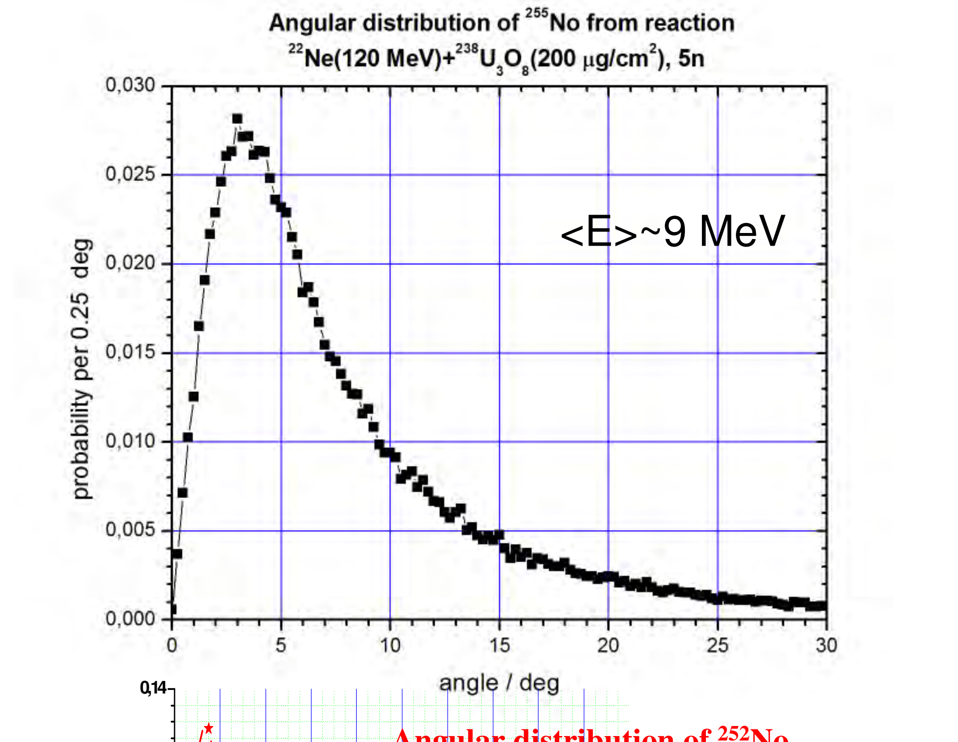


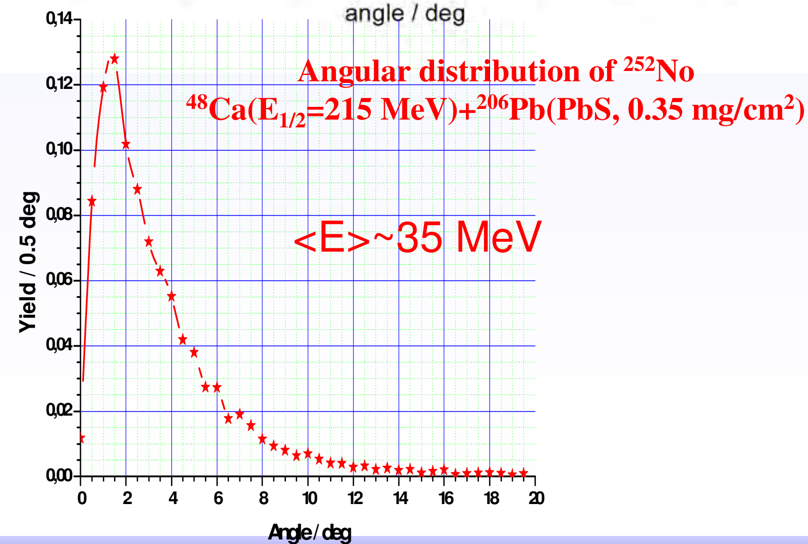
Requirements for new separator

- Increased transmission & detection of recoils produced in asymmetric reactions induced by light ions

=> larger acceptance
=> minimization of scattering/straggling through matter
=> additionnal focussing onto focal plane detector

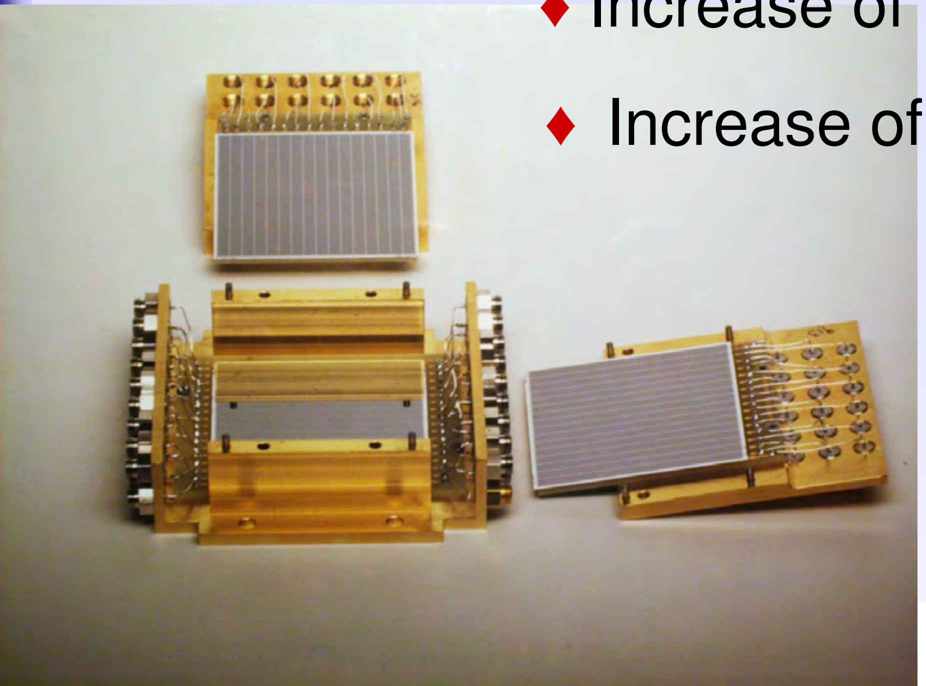
Shielding of target-position as well as focal-plane detectors from beam dump and background from separator





For asymmetric combinations –

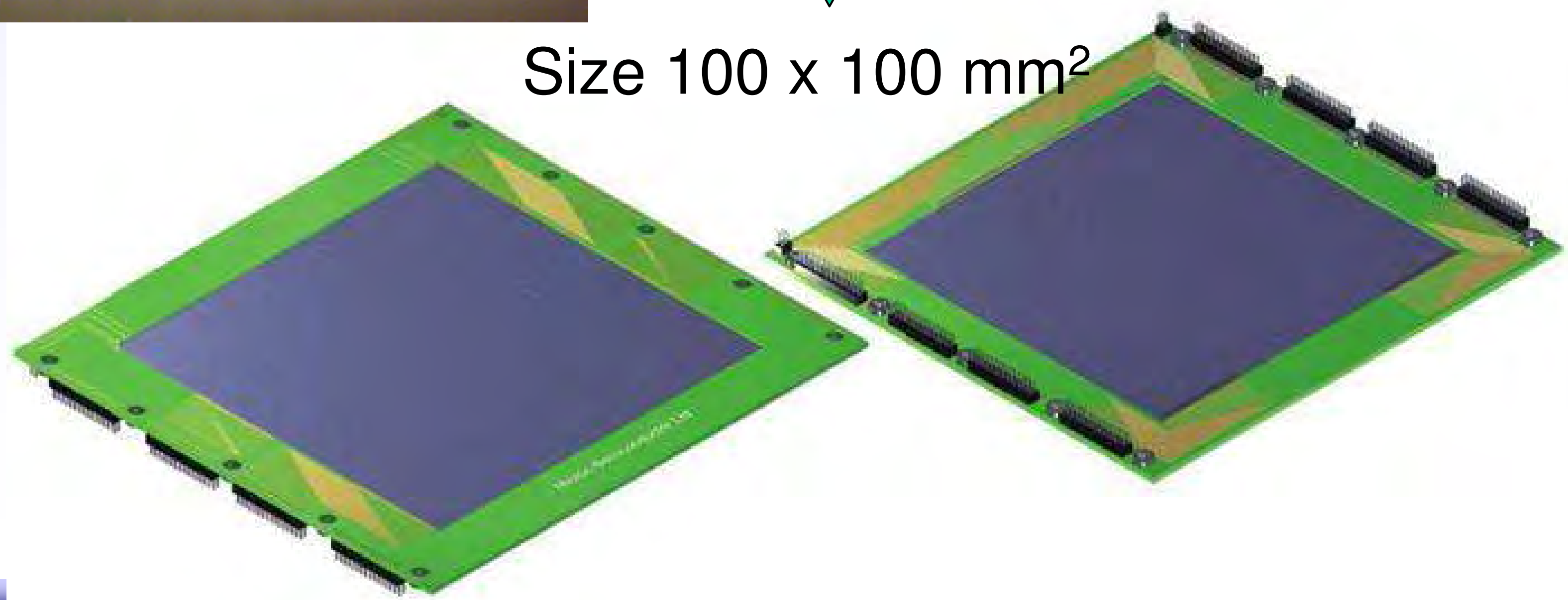
- ♦ Increase of the quadrupole lens aperture
- ♦ Increase of the focal plane detector size



Size 60 x 60 mm^2

Factor of 2 in transmission

Size 100 x 100 mm^2



$^{22}Ne + ^{238}U \longrightarrow ^{260}No^*$

Nucleus	E(MeV)	Bρ (vacuum T·m)	Bρ (He. T·m)	Bρ (H_2. T·m)	V (cm/ns)	E/q (MV) vacuum
^{22}Ne	112.4	0.76	0.76	0.76	3.14	11.7
^{260}No	9.5	0.74	1.82	2.45	0.26	0.99
^{238}U	34.8	0.72	1.89	2.01	0.53	1.93
^{4}He	58.5		1.1		5.3	

Distance between plates 20 cm; High voltage ± 100 kV:
Plate length ~ 15 cm;
Electric rigidity accepted => 1.5 MV

$^{48}Ca + ^{244}Pu \longrightarrow ^{292}114^{*}$

Nucleus	E(MeV)	Bρ (vacuum T·m)	Bρ (He. T·m)	Bρ (H_2. T·m)	V (cm/ns)	E/q (MV) vacuum
^{48}Ca	236	0.88	0.94	0.94	3.1	13.0
$^{292}114$	38.8	0.79	2.0	2.18	0.51	2.0
^{244}Pu	129.7	0.83	1.65	1.49	1.0	4.2
^{4}He	67		1.2		5.7	

Distance between plates 15 cm; High voltage ± 150 kV:
Plate length ~ 15 cm;
Electric rigidity accepted => 2 MV

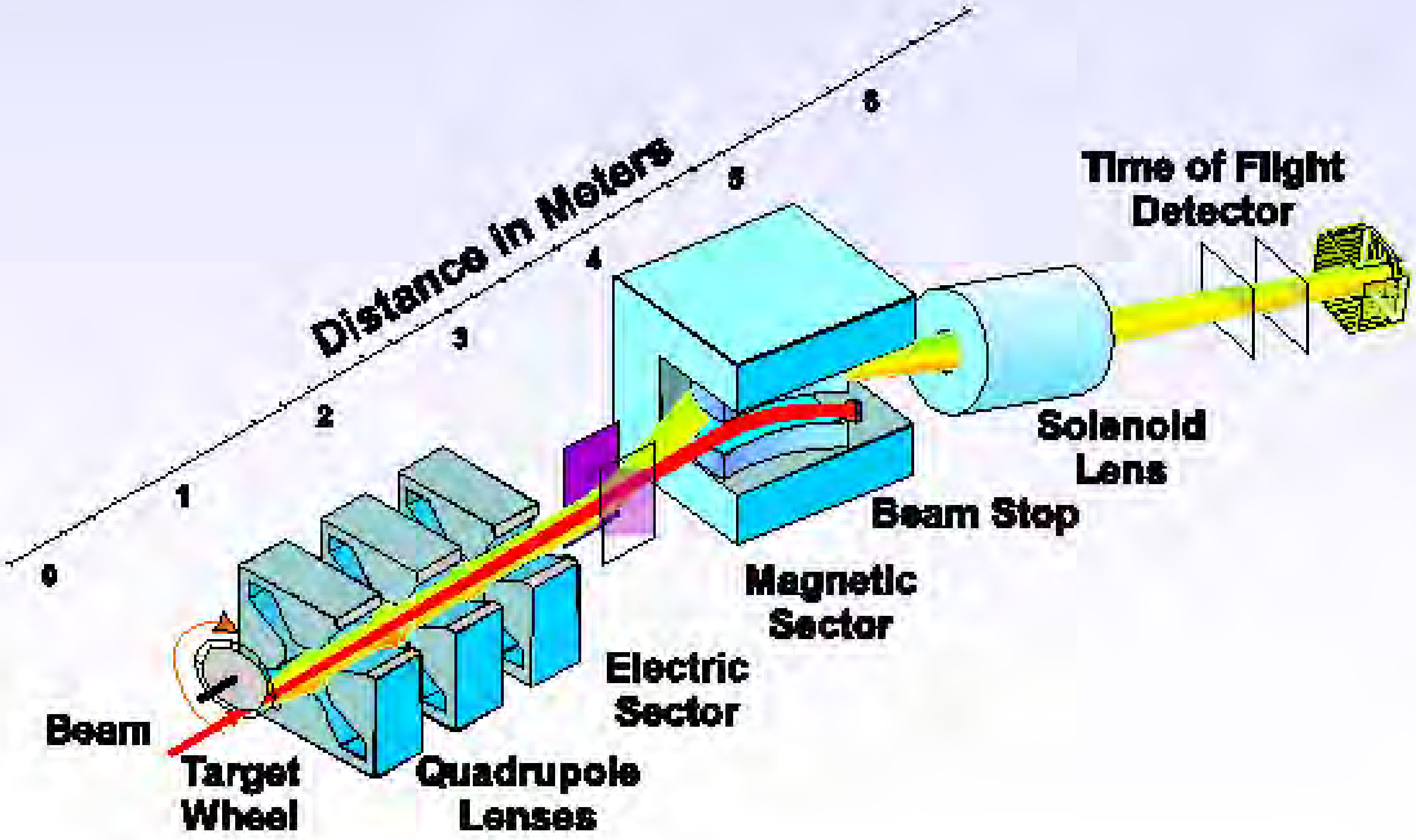
$^{136}Xe + ^{136}Xe \longrightarrow ^{272}Hs^*$

Nucleus	E(MeV)	Bρ (vacuum T·m)	Bρ (He. T·m)	Bρ (H_2. T·m)	V (cm/ns)	E/q (MV) vacuum
^{136}Xe	600	1.1	1.38	1.38	3.0	15.7
^{272}Hs	300	0.95	1.39	1.21	1.46	6.85
^{136}Xe	600	1.1	1.38	1.38	3.0	15.7
^{4}He	66.6		1.2		5.7	

Distance between plates 10 cm; High voltage ± 200 kV:
Plate length ~ 50 cm;
Electric rigidity accepted => 8 MV

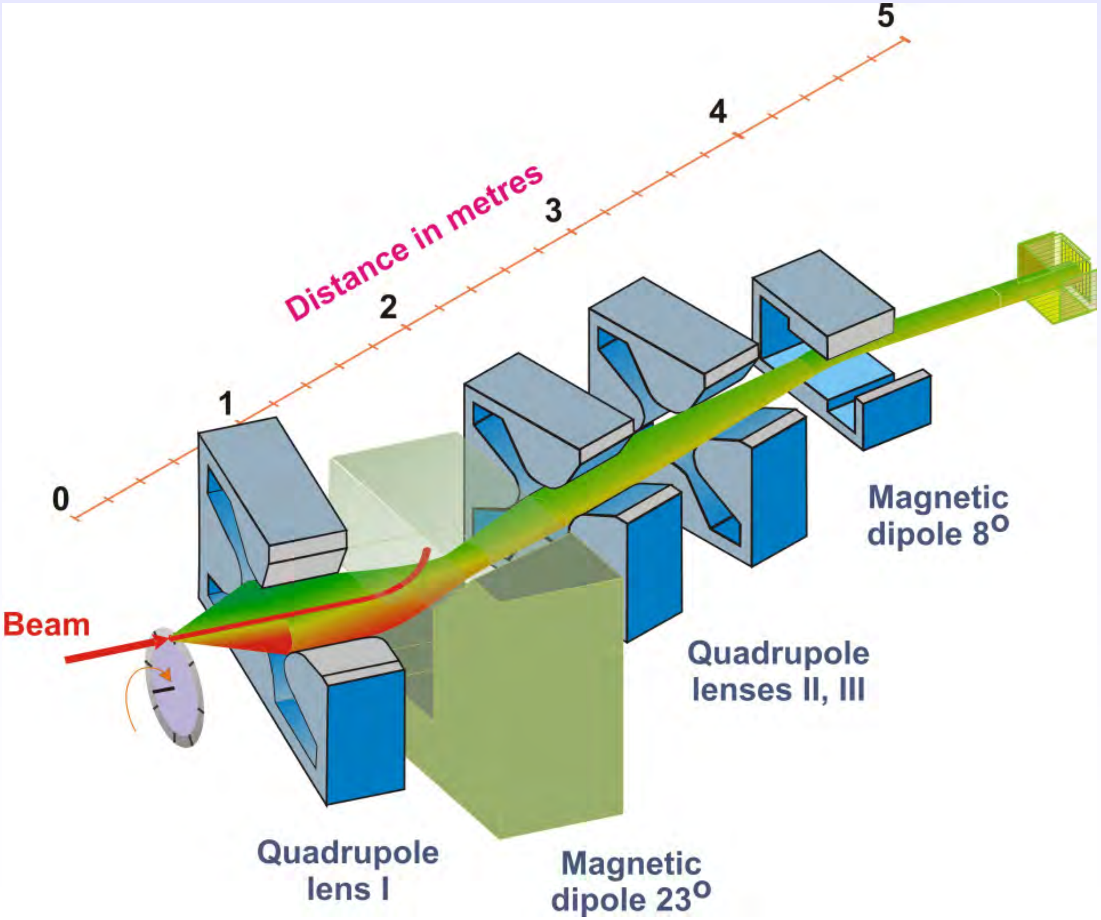
Separator for TransActinide Research
"STAR"

Layout of the MQh-MQv-MQh-ES-MS-CMS – vacuum separator.



Separator for TransActinide Research "STAR"

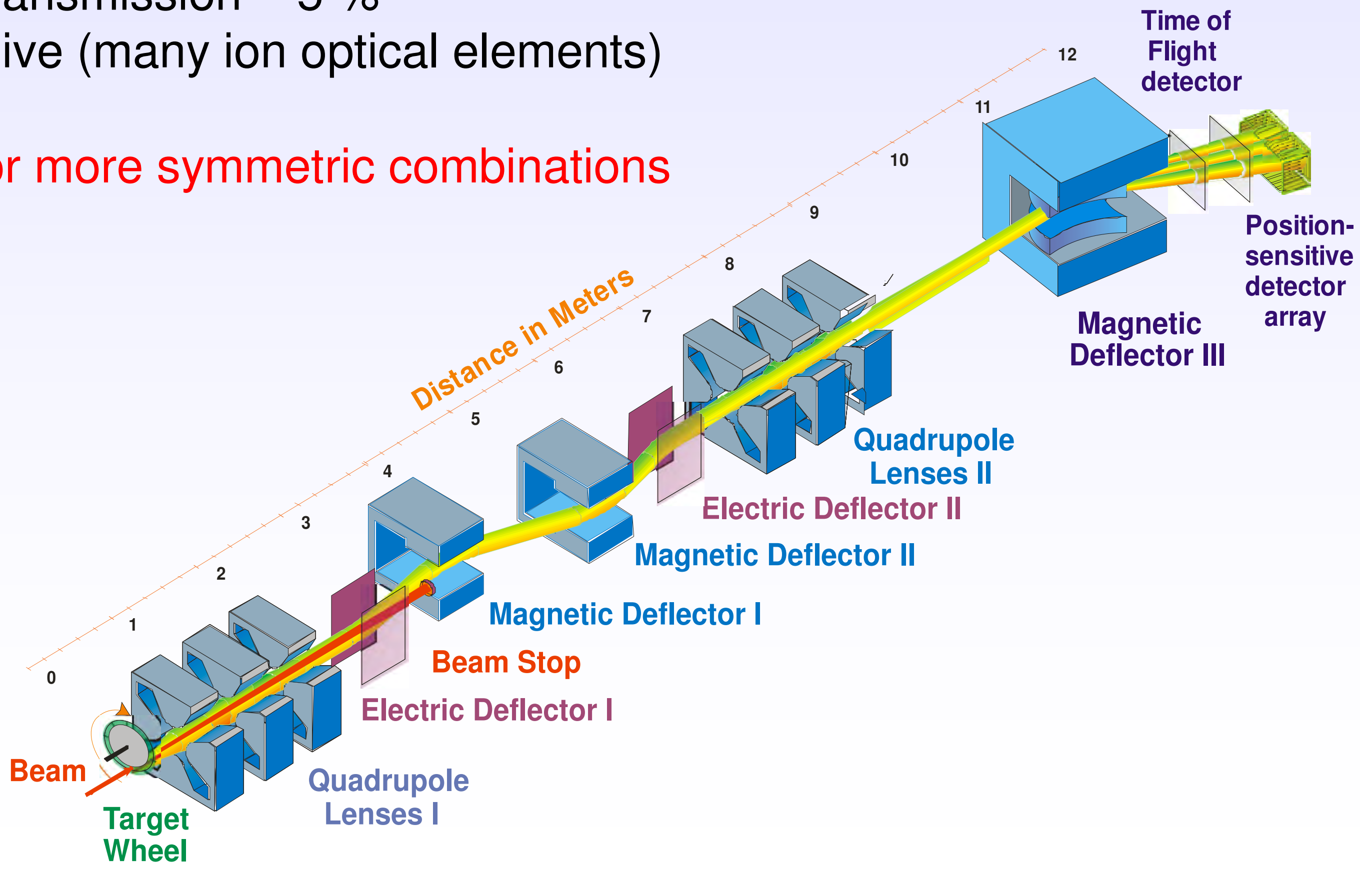
Layout of the gas filled separator



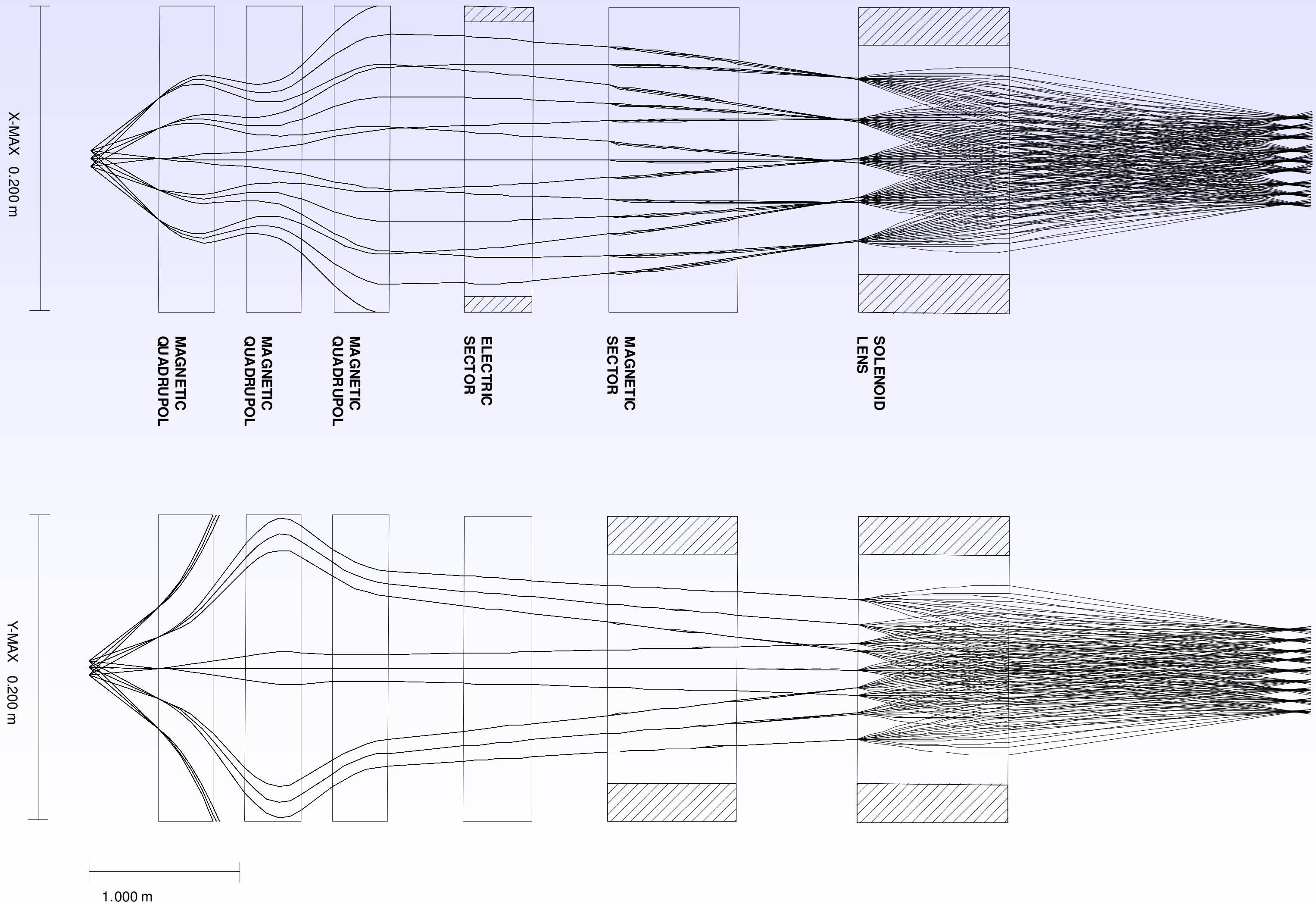
Velocity filter for asymmetric combinations (modernization of VASSILISSA)

Excess in suppression factors
Rather small transmission ~ 5 %
Rather expensive (many ion optical elements)

More proper for more symmetric combinations



$Q_hQ_vQ_h$EDS - GICOSY beam plot

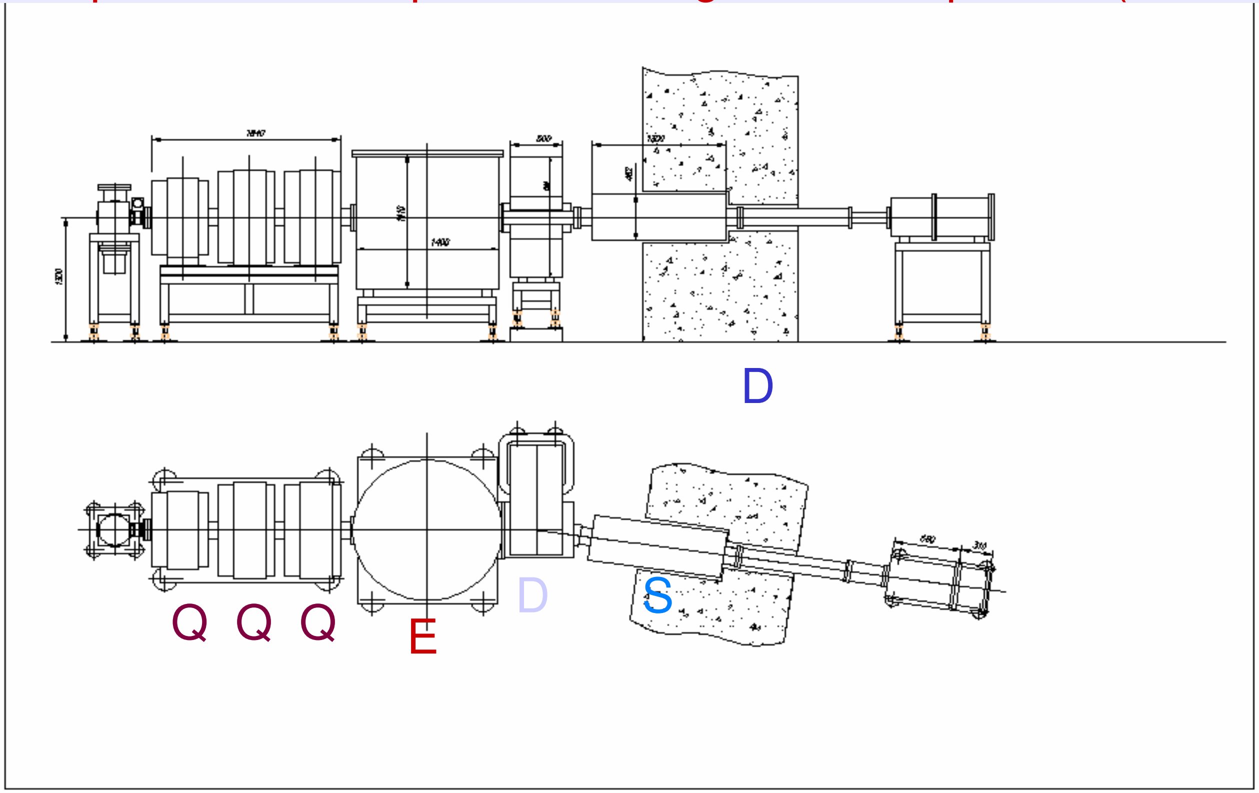


Preliminary separator design

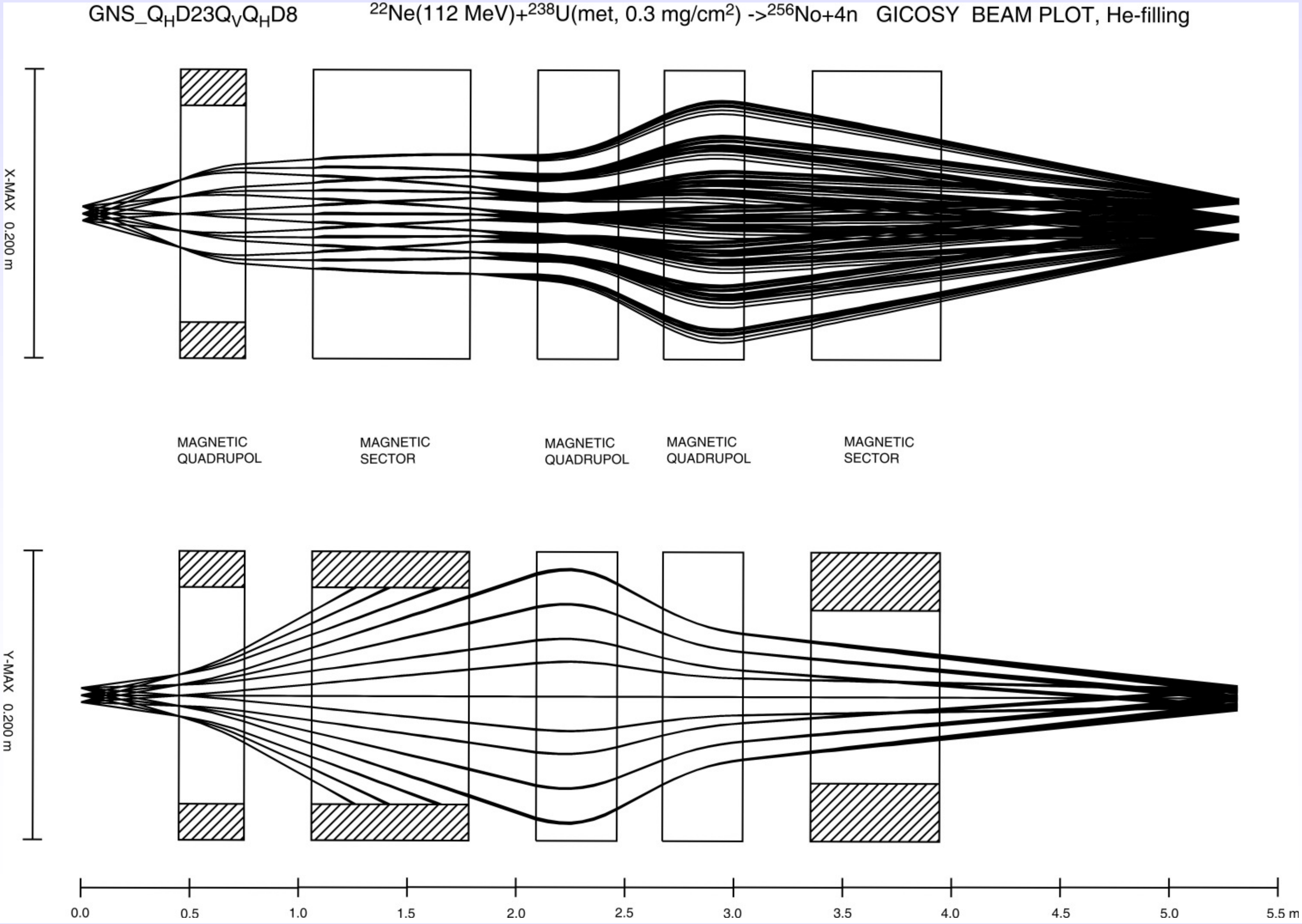
Example of envisaged configuration: vacuum QQQEDS   Length: ~ 8 m
estimated transmission efficiency for $^{22}Ne+^{238}U$: 10 – 15 %
(VASSILISSA 2 %, DGFRS 6 %)

♦ NO problems with timing detectors

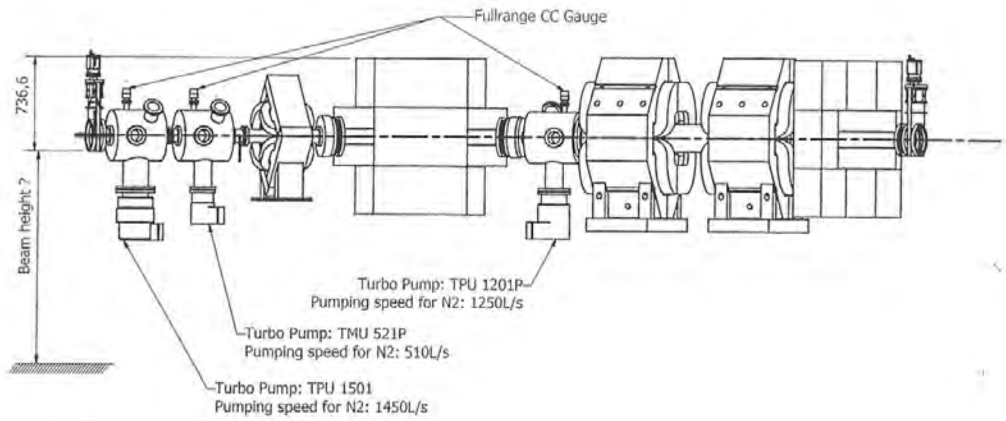
♦ More expensive in comparison withngas filled separator (factor of 1.5)

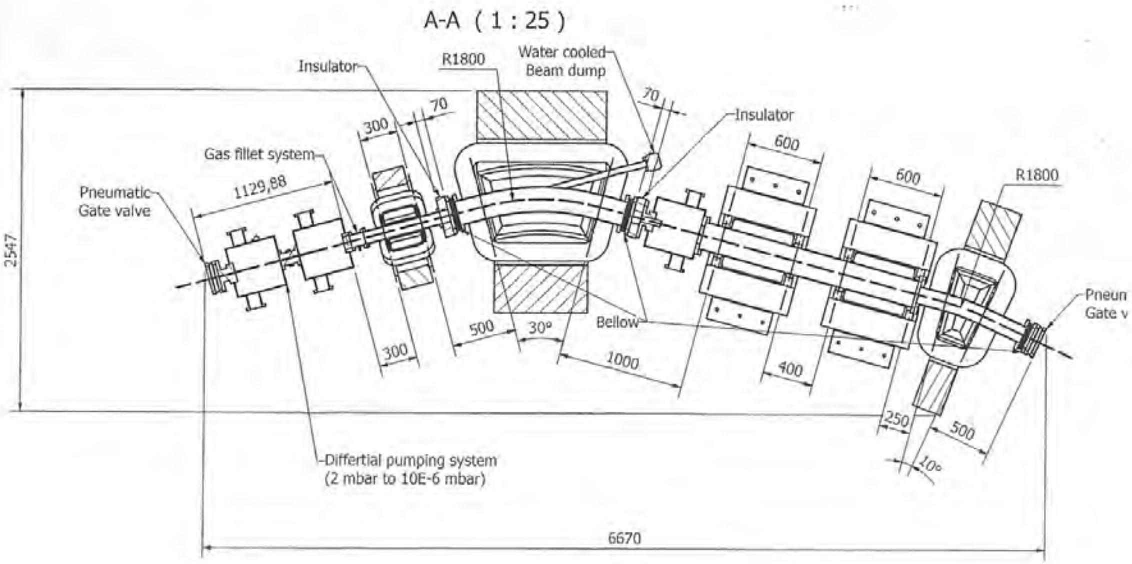


$Q_hDQ_vQ_hD$ - GICOSY beam plot



Preliminary separator design



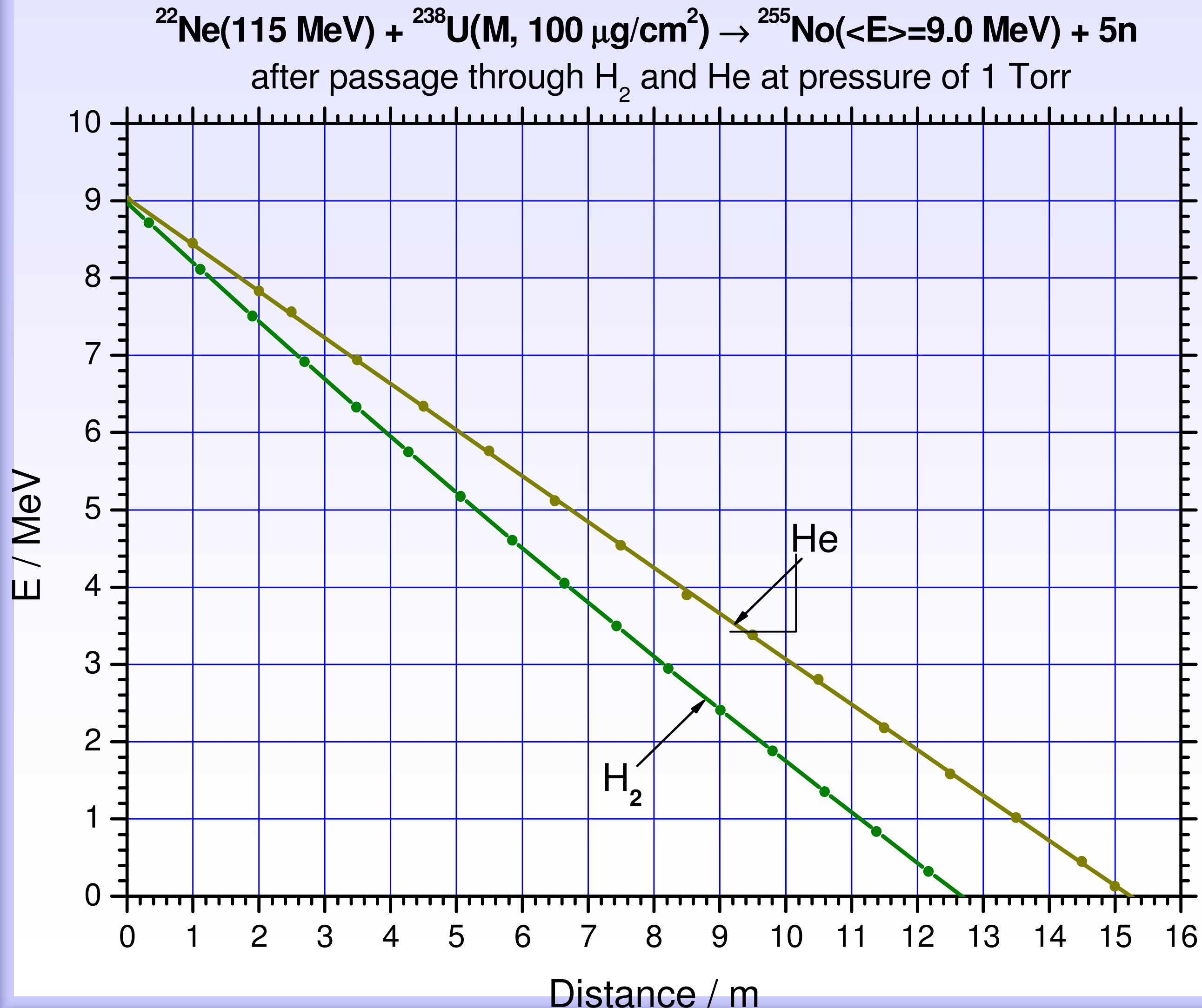


Example of envisaged configuration: gas filled QDQQD   Length: ~ 6.6 m estimated transmission efficiency for $^{22}Ne+^{238}U$: 10 – 15 % (Vassilissa 2 %, DGFRS 6 %)

- ♦ Problems with timing detectors
- ♦ More cheap in comparison with vacuum separator (factor of 1.5)

Gas filled separators for asymmetric combinations

- Range of ^{238}U (10 MeV) – 7.8 m in He (2 mbar)
- After the flight path of 5 m – ion energy is about 2 MeV, too small for timing detectors.



In the case of the use Pentane gas at the timing detector - Problem for the cooling of the electron detectors

Comparison of the different types of the separators

Separator / Reaction	VASSILISSA after modernization QQQEDDEQQQ	Vacuum type separator Q-Q-Q-E-D-S	Gas filled separator Q-D-Q-Q-D
Symmetric Ap/At > 0.6	Fine transmission, acceptable suppression factors	Fine transmission, poor suppression factors	Could not be used because Bρ of beam in gas is close to Bρ of ERs
Intermediate 0.2 < Ap/At < 0.6	Fine transmission, fine suppression factors	Fine transmission, fine suppression factors	Fine transmission, fine suppression factors
Asymmetric Ap/At < 0.2	Acceptable transmission, fine suppression factors	Fine transmission, fine suppression factors	Fine transmission, fine suppression factors

Main properties of the new separator "STAR" (vacuum type)

Magnetic dipole

Deflection angle	16^0
Radius of curvature	3.1 m
Maximum field	1.2 T

Electric dipole

Deflection angle	8^0
Radius of curvature	3.2 m
Maximum field	40 kV/cm

Quadrupole lens

Effective length	0.37 m
Bore diametr	0.2 m
Maximum field	13.0 T/m

Solenoid lens

Effective length	1 m
Bore diameter	0.15 m
Maximum field	1.0 T

Main properties of the new separator “STAR” (gas filled type)

Main magnetic dipole

Deflection angle	30^0
Radius of curvature	1.8 m
Maximum field	1.8 T

First quadrupole lens

Effective length	0.3 m
Bore diameter	0.11 m
Field gradient	10.0 T/m

2^{nd} and 3d quadrupole lenses

Effective length	0.6 m
Bore diameter	0.22 m
Field gradient	9.0 T/m

2^{nd} magnetic dipole

Deflection angle	10^0
Radius of curvature	1.8 m
Maximum field	1.7 T

Alternative developments

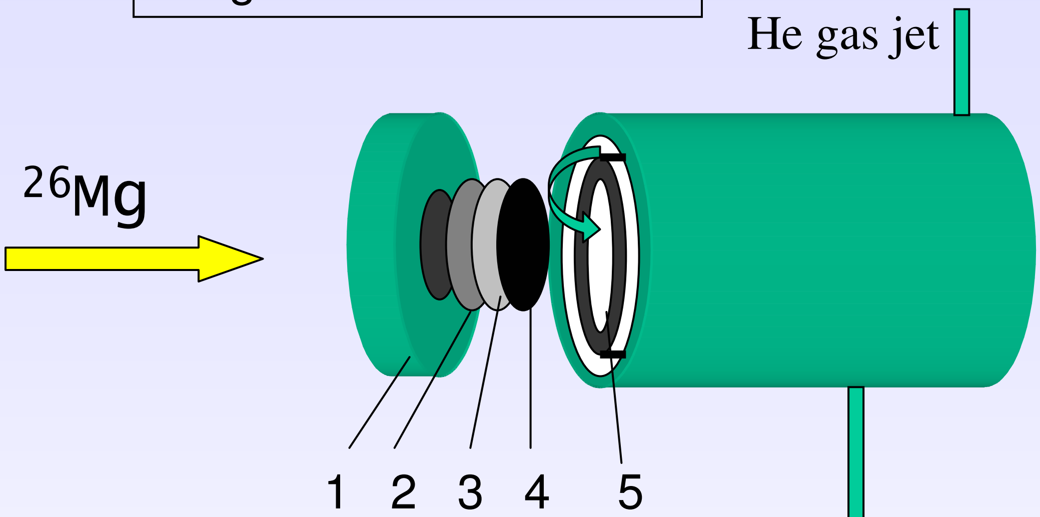
- Gas jet (aerosol) + filters

Low detection efficiency, rather bad resolution, unstable efficiency

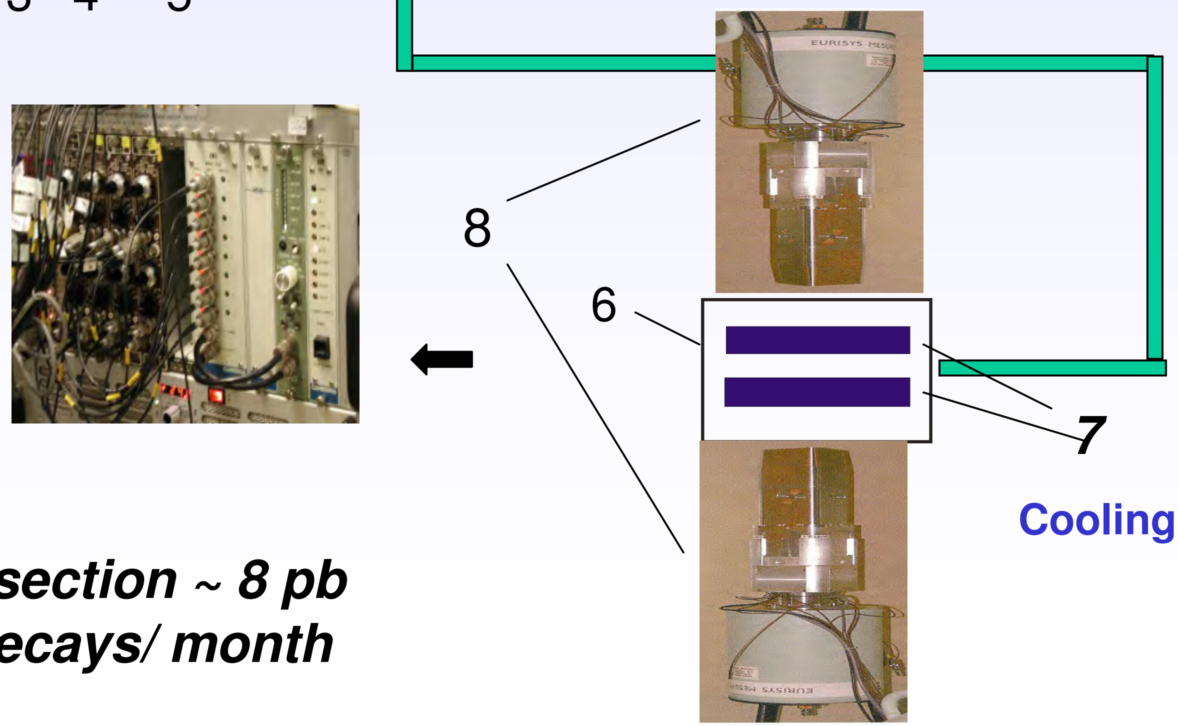
- Gas jet (aerosol) + ISOL (efficiency for ^{257}No from ^{13}C + ^{248}Cm reaction – 0.46 %) M. Asai et. al., PRL 95 (2005) 102502

Good for very asymmetric combinations.

$^{26}Mg + ^{248}Cm \rightarrow ^{274-xn}Hs$



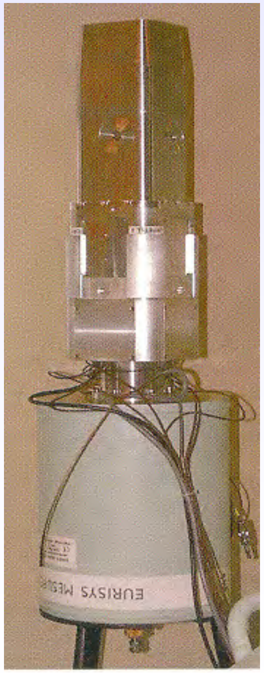
1 - collimator
2 - vacuum window
3 - degrader foil(s)
4 - target
5 - recoil chamber
6 - detector chamber
7 - Si α,β detectors
8 - Clover γ detectors



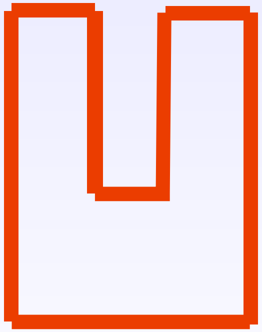
Cross section ~ 8 pb
50 α decays/ month

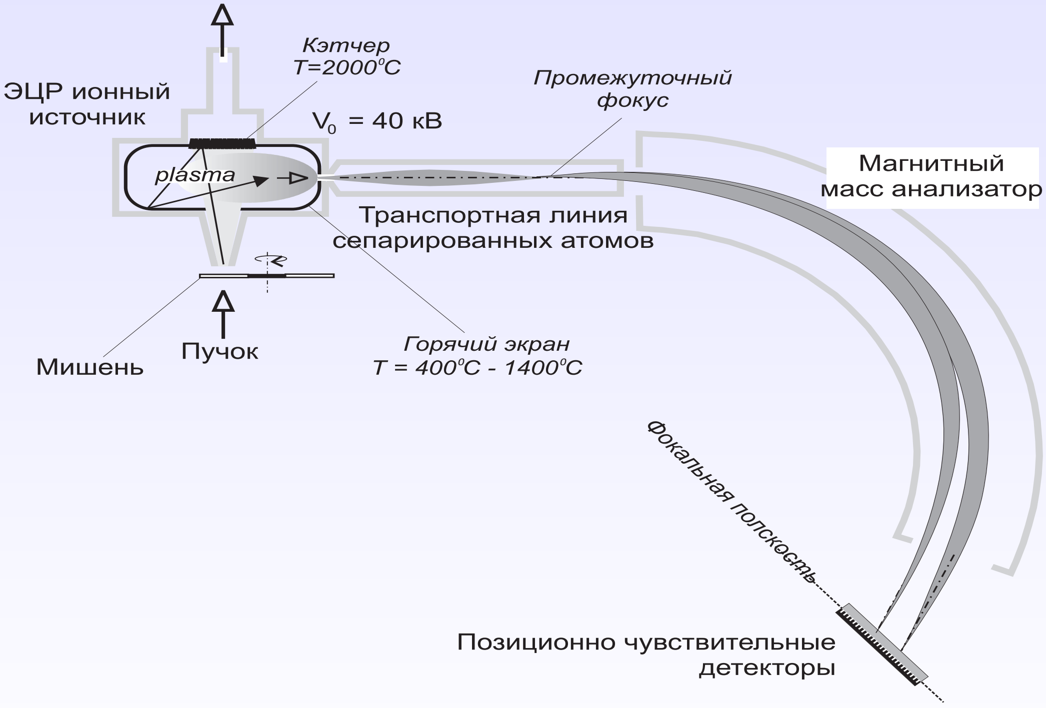
Future developments: γ spectroscopy of superheavies

High detection efficiency



16 mm hole





40 mm in size Ge Well detector at the focal plane of MASHA for γ detection, 80 % detection efficiency