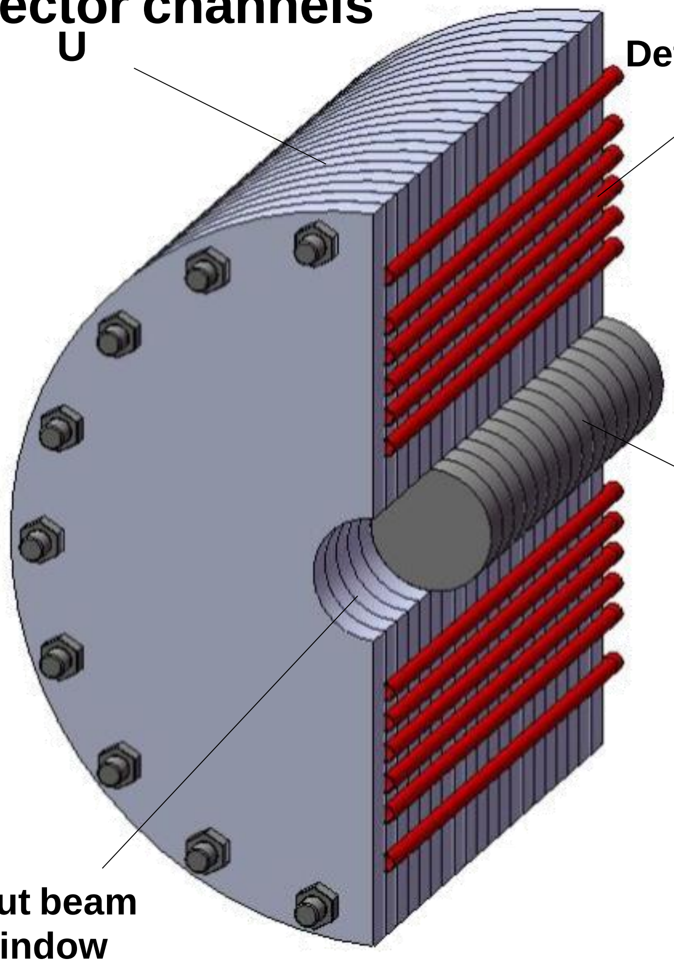
Compapison of the spallation neutron field on the surface of Carbon and Lead Target under 660 MeV protons irradiation

J.Adam, L. Zavorka, A.A.Baldin, W.Furman, S.Gustov, K.Katovsky, J.Khushvaktov, D.Kral, A.Solnyshkin, J.Svoboda, P.Tichy, S.Tyutyunnikov, J.Vrzalova, V.Wagner, M. Zeman

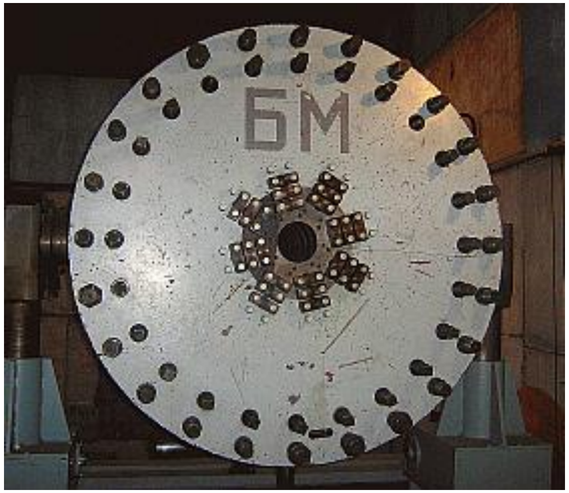
Joint Institute for Nuclear Research at Dubna, Moscow region, Russia

Quasi-infinite depleted uranium target (BURAN) with replacement central zone

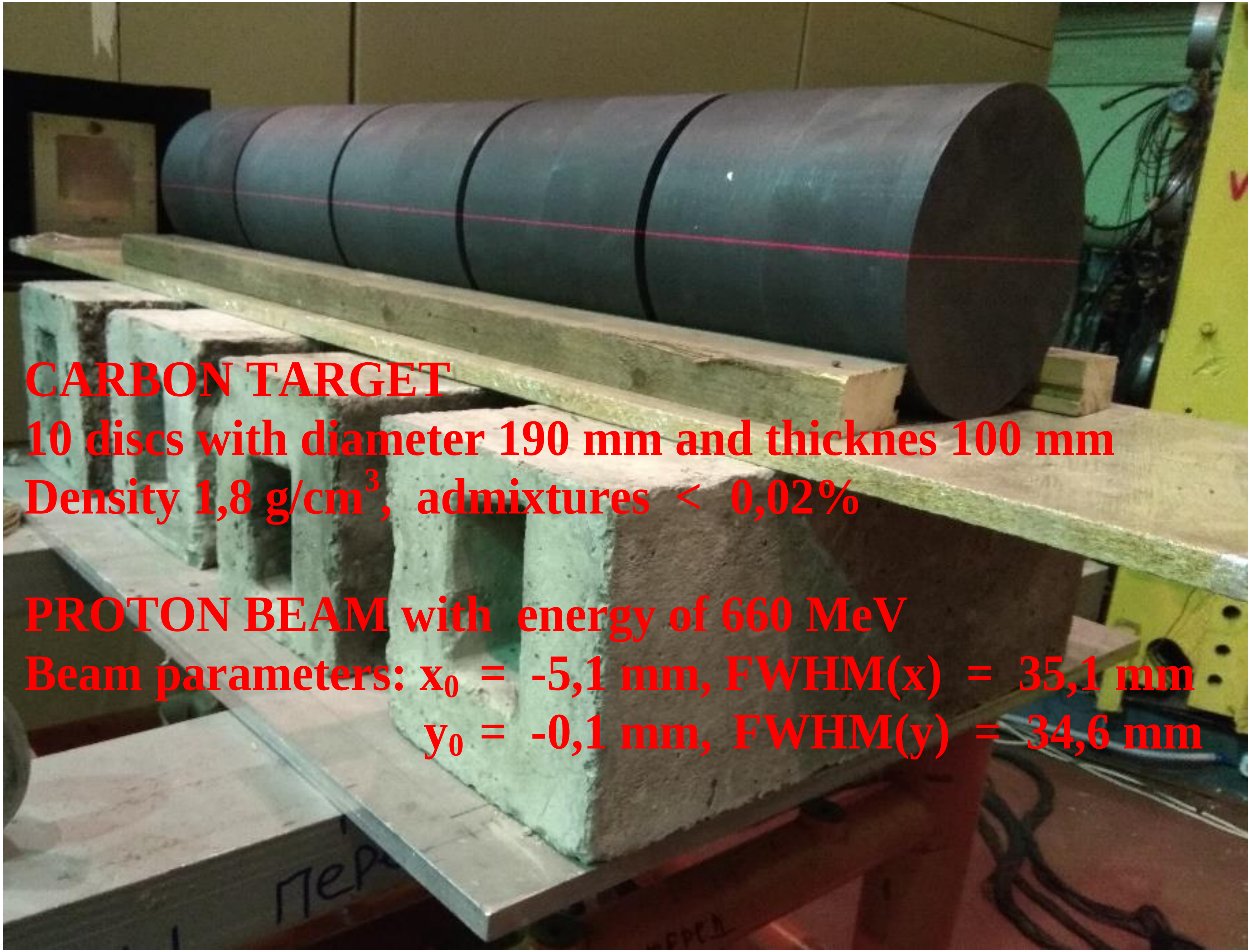
Longitudinal section of TA BURAN together with central zone and detector channels



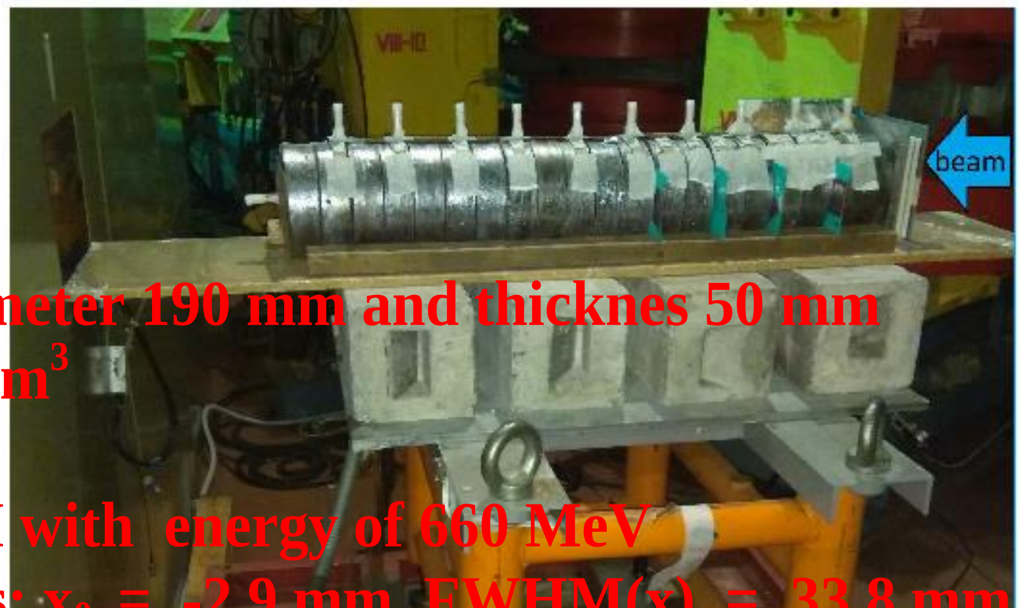
Front view photo



Rear view photo


CARBON TARGET
10 discs with diameter 190 mm and thicknes 100 mm
Density 1,8 g/cm^3, admixtures < 0,02%
PROTON BEAM with energy of 660 MeV
Beam parameters: x_0 = -5,1 mm, FWHM(x) = 35,1 mm
y_0 = -0,1 mm, FWHM(y) = 34,6 mm

LEAD target setup



LEAD TARGET

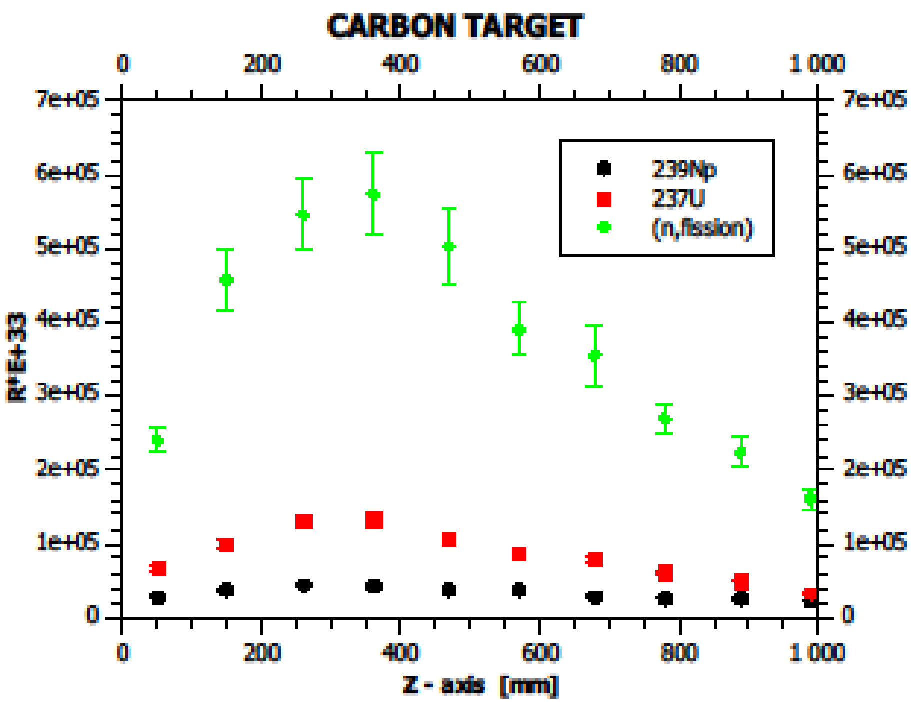
20 discs with diameter 190 mm and thicknes 50 mm

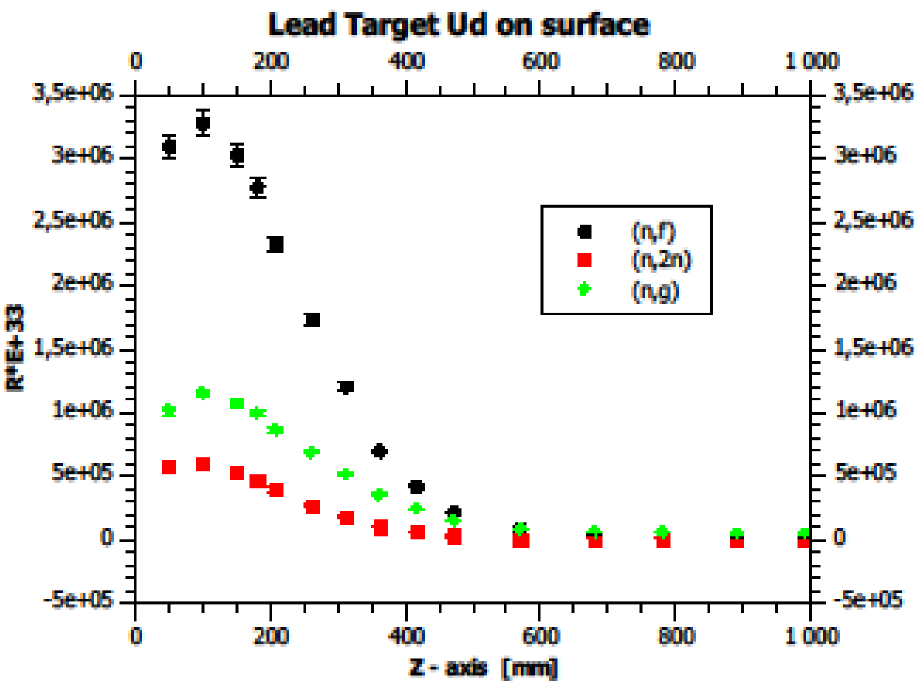
Density 11,35 g/cm^3

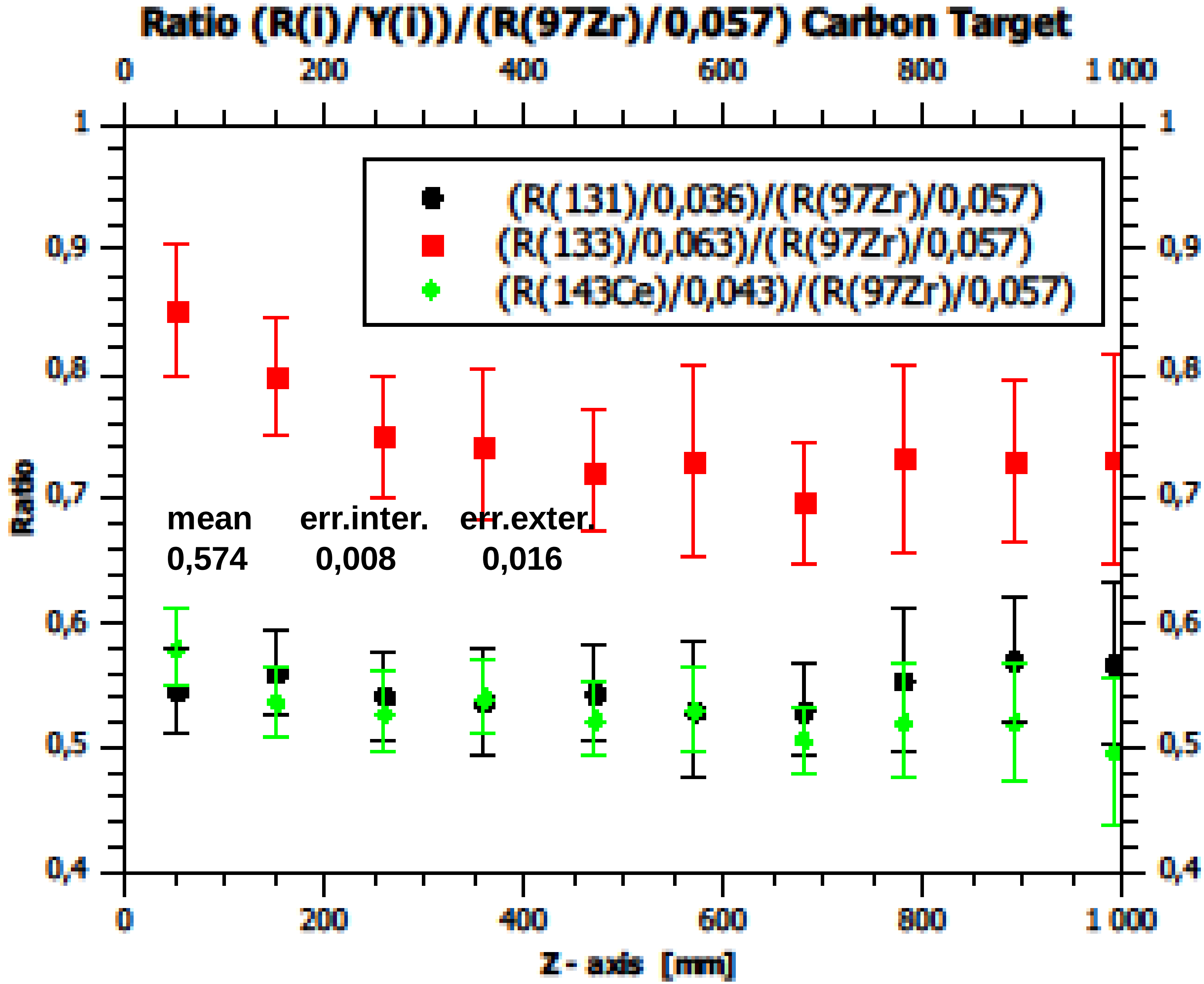
PROTON BEAM with energy of 660 MeV

Beam parameters: x_0 = -2,9 mm, FWHM(x) = 33,8 mm

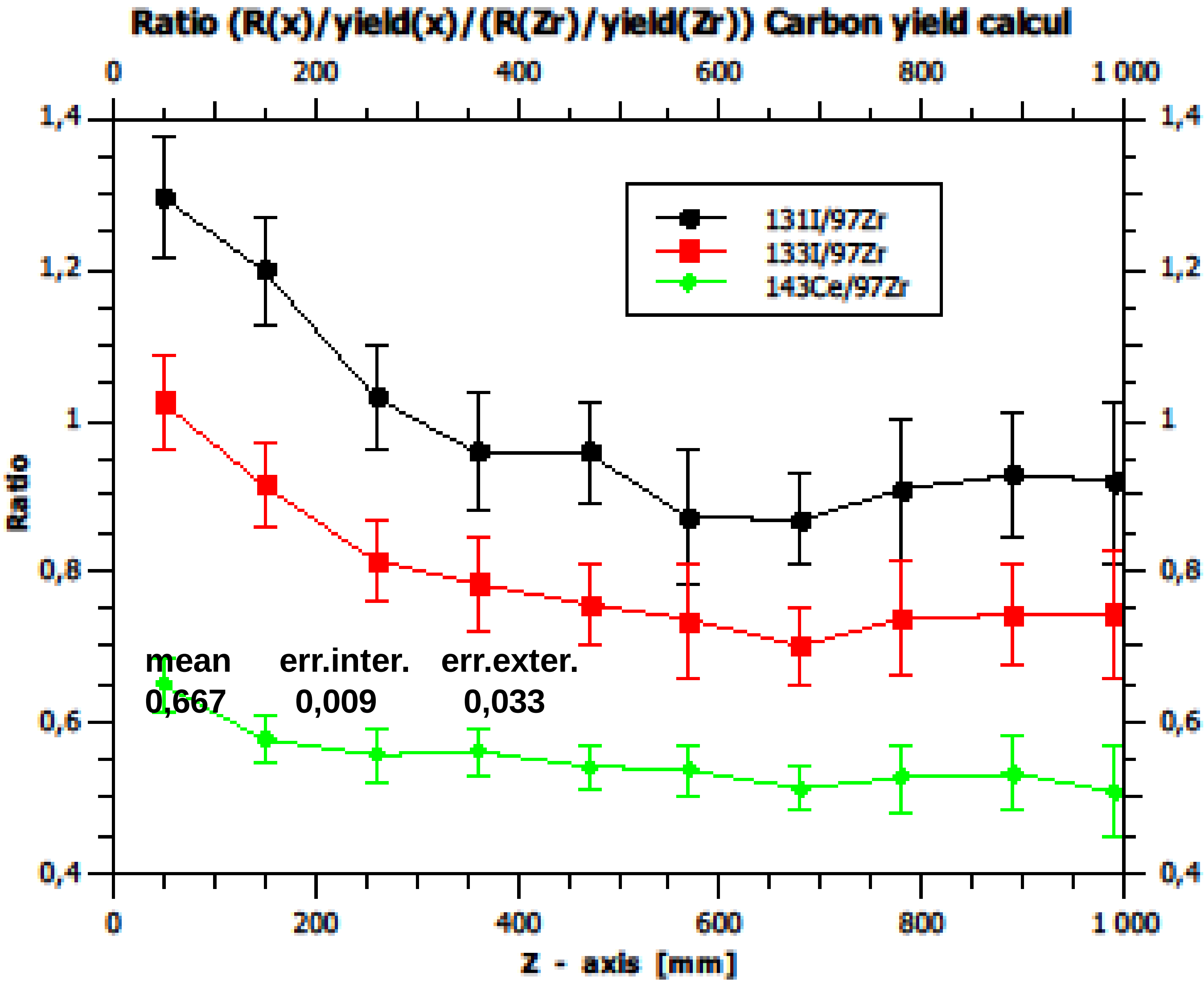
y_0 = -0,6 mm, FWHM(y) = 37,1 mm

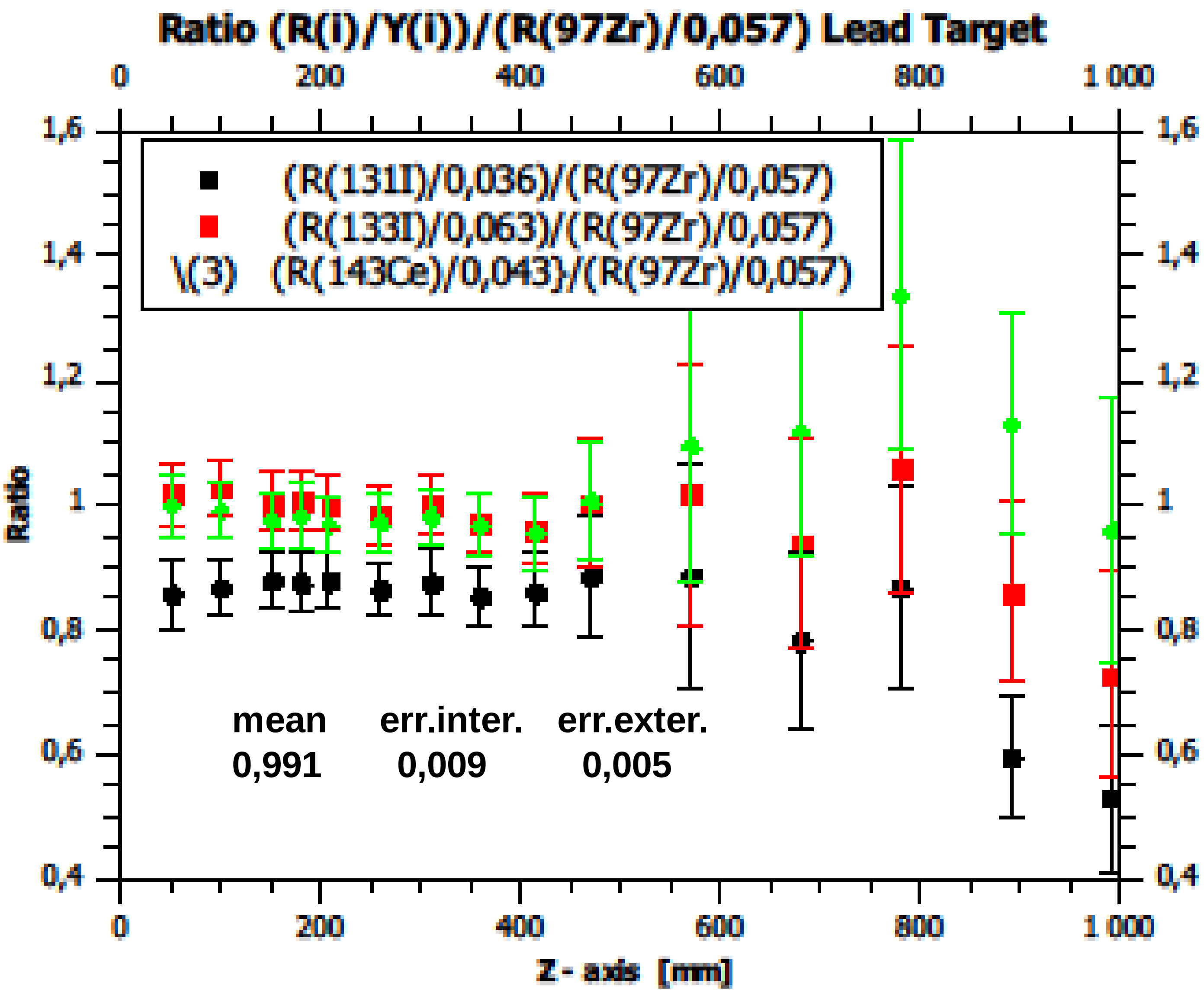

CARBON TARGET
239Np
237U
(n,fission)
R*E+33
Z - axis [mm]

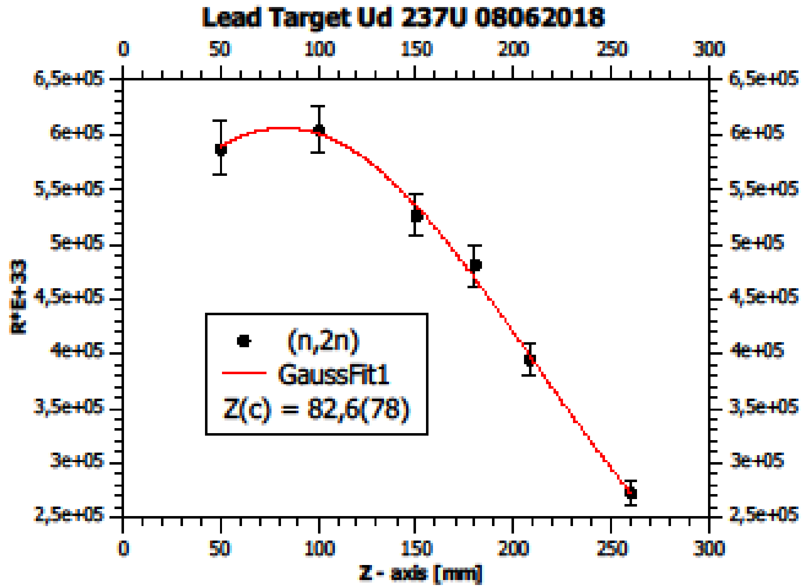

Lead Target Ud on surface
(n,f)
(n,2n)
(n,g)
R*E+33
Z - axis [mm]

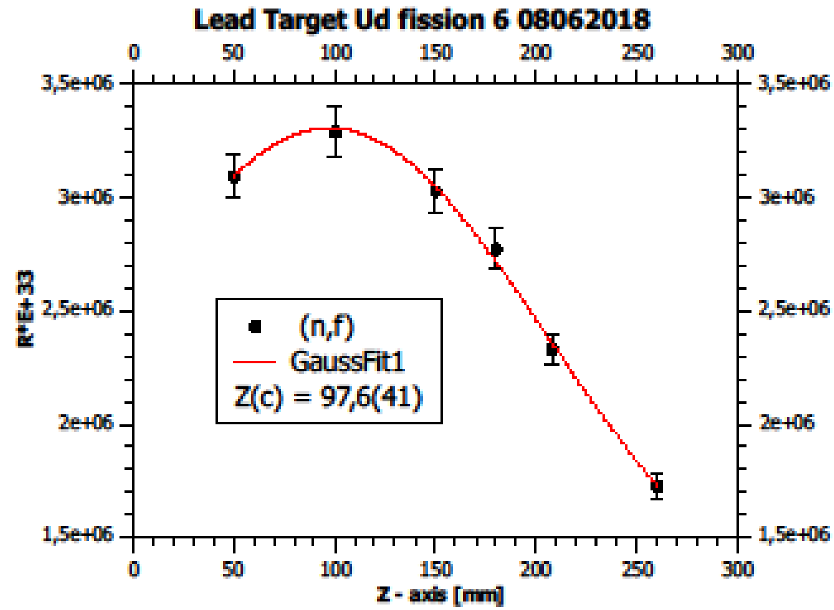


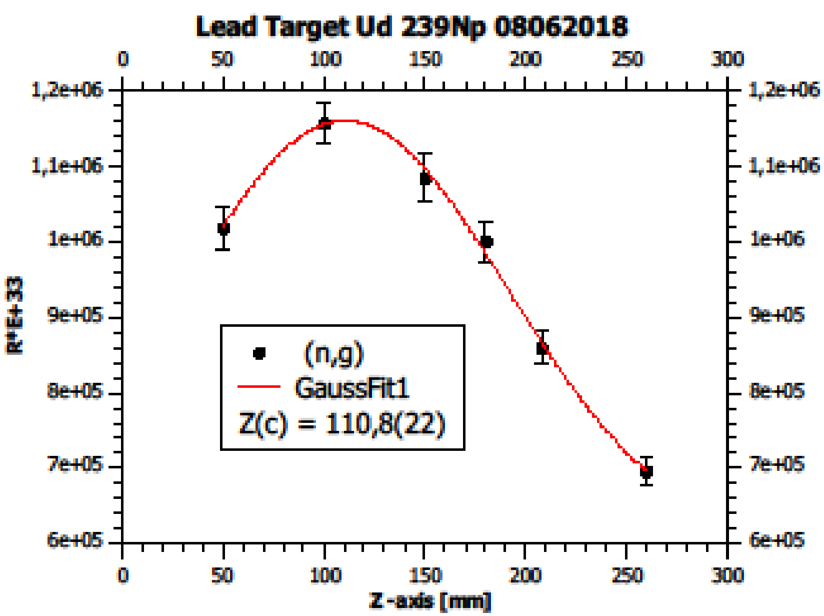
Ratio (R(i)/Y(i))/(R(97Zr)/0,057) Carbon Target
(R(131)/0,036)/(R(97Zr)/0,057)
(R(133)/0,063)/(R(97Zr)/0,057)
(R(143Ce)/0,043)/(R(97Zr)/0,057)
mean
0,574
err.inter.
0,008
err.exter.
0,016
Ratio
Z - axis [mm]
0
200
400
600
800
1 000
0,4
0,5
0,6
0,7
0,8
0,9
1

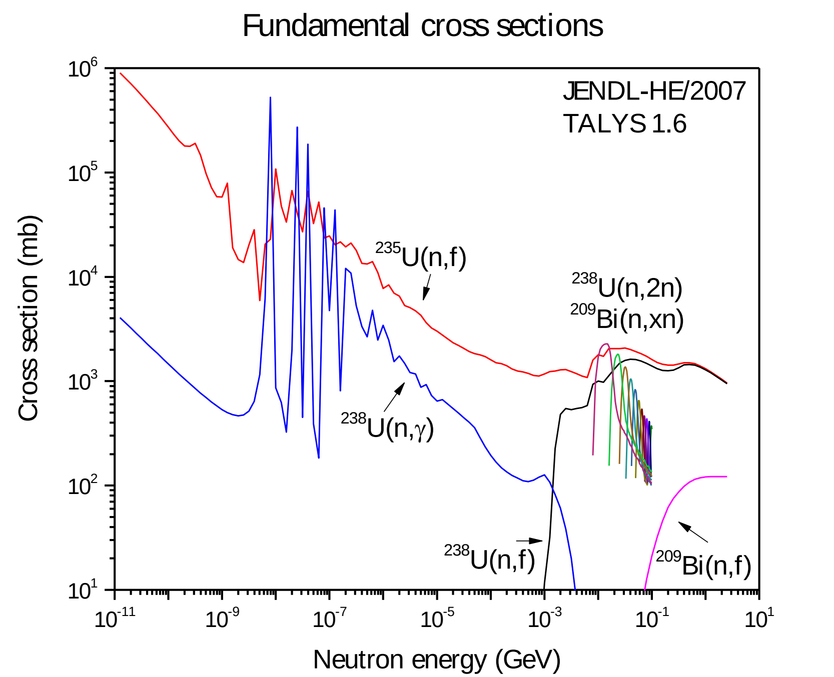

Ratio (R(x)/yield(x)/(R(Zr)/yield(Zr)) Carbon yield calcul
0
200
400
600
800
1 000
1,4
1,2
1
0,8
0,6
0,4
Ratio
131I/97Zr
133I/97Zr
143Ce/97Zr
mean
0,667
err.inter.
0,009
err.exter.
0,033
Z - axis [mm]

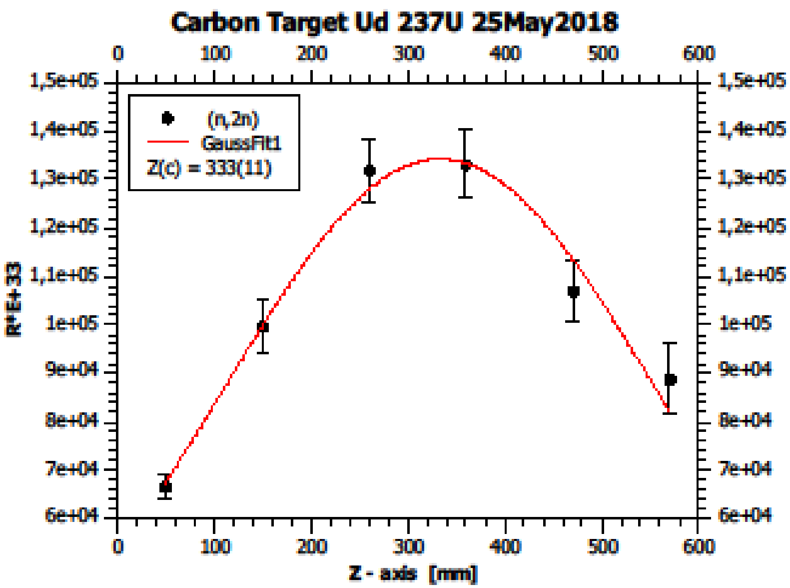

Ratio (R(i)/Y(i))/(R(97Zr)/0,057) Lead Target
(R(131I)/0,036)/(R(97Zr)/0,057)
(R(133I)/0,063)/(R(97Zr)/0,057)
\(3) (R(143Ce)/0,043)/(R(97Zr)/0,057)
mean 0,991
err.inter. 0,009
err.exter. 0,005
Ratio
Z - axis [mm]
0
200
400
600
800
1 000
0,4
0,6
0,8
1
1,2
1,4
1,6

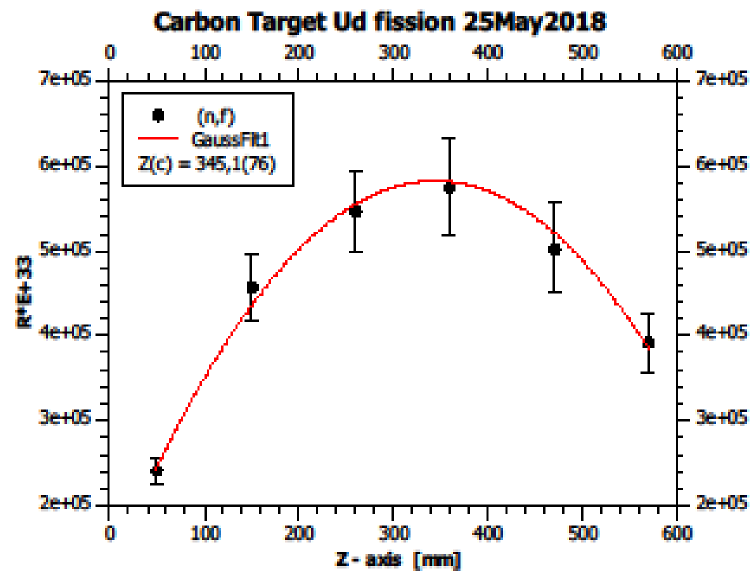

Lead Target Ud 237U 08062018
R*E+33
Z - axis [mm]
(n,2n)
GaussFit1
Z(c) = 82,6(78)

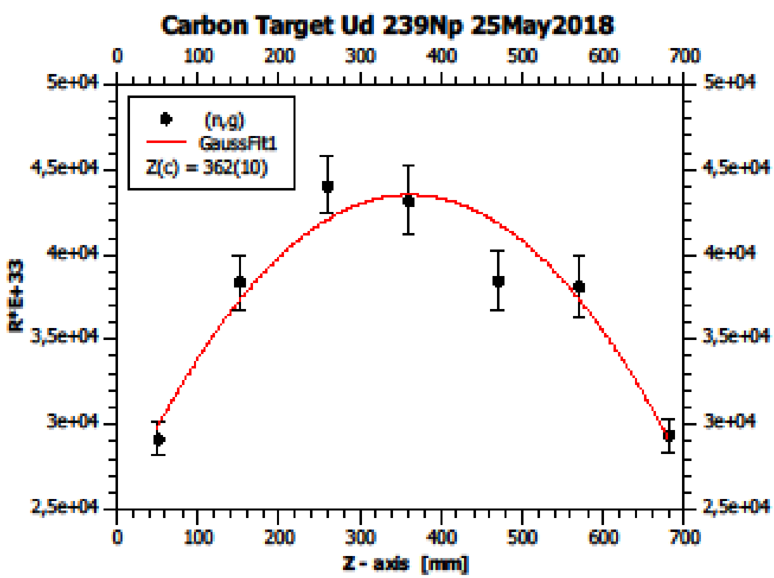

Lead Target Ud fission 6 08062018
R*E+33
Z - axis [mm]
(n,f)
GaussFit1
Z(c) = 97,6(41)

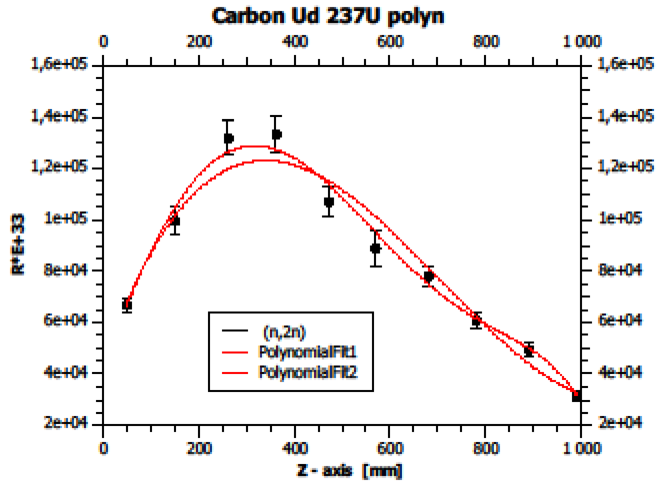

Lead Target Ud 239Np 08062018
R*E+33
Z -axis [mm]
(n,g)
GaussFit1
Z(c) = 110,8(22)

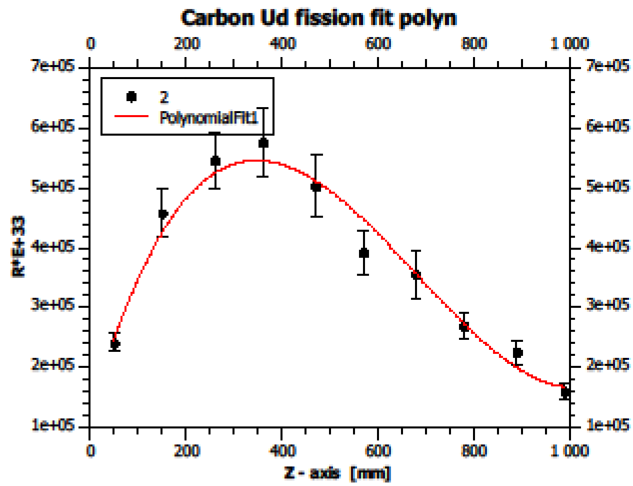

Fundamental cross sections
JENDL-HE/2007
TALYS 1.6
Cross section (mb)
Neutron energy (GeV)
235U(n,f)
238U(n,2n)
209Bi(n,xn)
238U(n,γ)
238U(n,f)
209Bi(n,f)

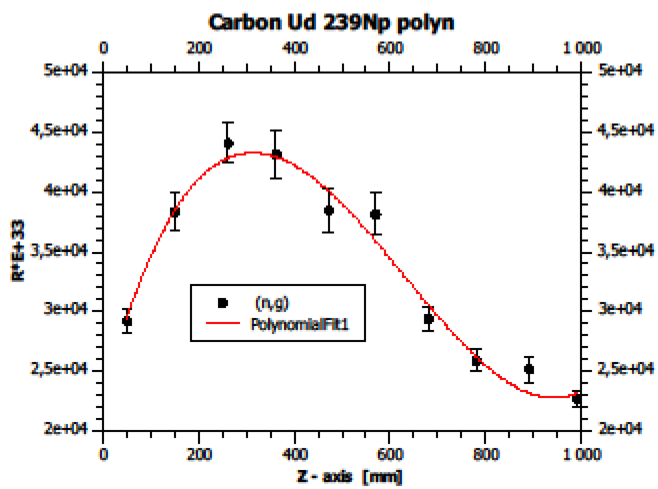

Carbon Target Ud 237U 25May2018
(n,2n)
GaussFit1
Z(c) = 333(11)
R*E+33
Z - axis [mm]

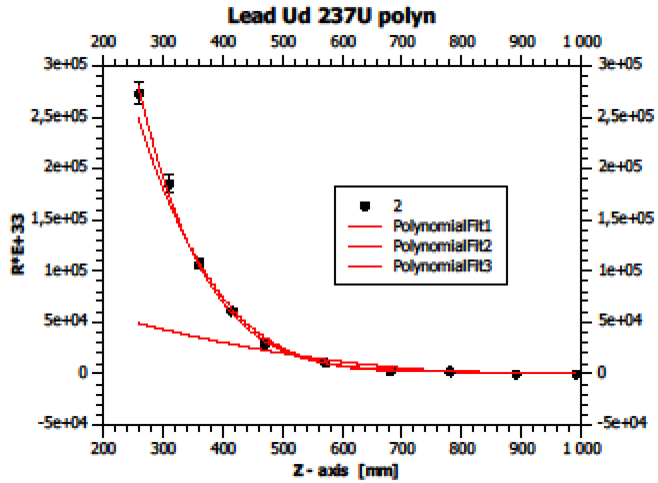

Carbon Target Ud fission 25May2018
(n,f)
GaussFit1
Z(c) = 345,1(76)
R*E+33
Z - axis [mm]

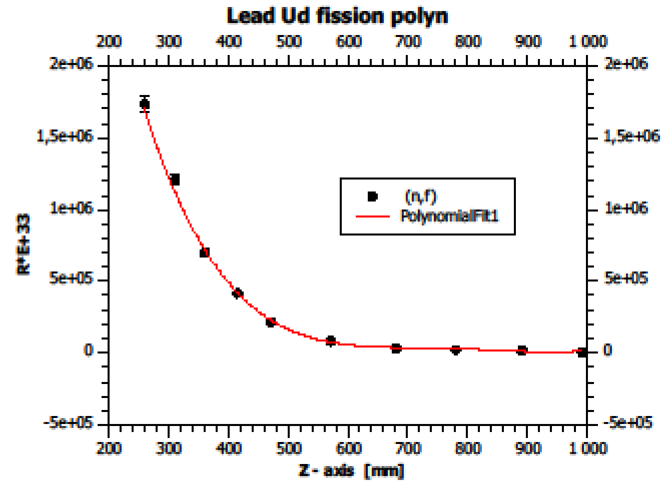

Carbon Target Ud 239Np 25May2018
(n,g)
GaussFit1
Z(c) = 362(10)
R*E+33
Z - axis [mm]

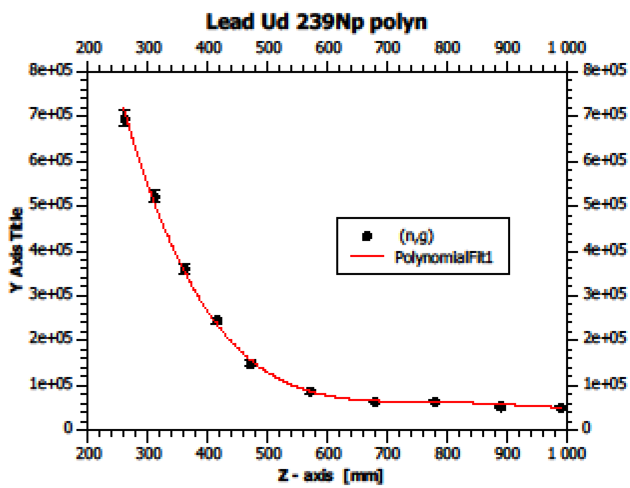

Carbon Ud 237U polyn
R*E+33
Z - axis [mm]
(n,2n)
PolynomialFit1
PolynomialFit2


Carbon Ud fission fit polyn
R*E+33
Z - axis [mm]
2
PolynomialFit1


Carbon Ud 239Np polyn
R*E+33
Z - axis [mm]
(n,g)
PolynomialFit1


Lead Ud 237U polyn
R*E+33
Z - axis [mm]
2
PolynomialFit1
PolynomialFit2
PolynomialFit3


Lead Ud fission polyn
R*E+33
Z - axis [mm]
(n,f)
PolynomialFit1


Lead Ud 239Np polyn
Y Axis Title
Z - axis [mm]
(n,g)
PolynomialFit1

CARBON TARGET

Gauss Fit: $y_0 + A^* \text{sqrt}(2/\pi) / w^* \exp(-2^* ((x-x_c)/w)^2)$
From x = 50 mm to x = 990 mm

Reaction	A(area)	z_c (center)	w (width)
U_d (n,2n)	9,3(38)E7	403(23)	692(160)
U_d (n,f)	2,24(44)E8	406(22)	452(71)
U_d (n,f)new	2,73(66)E8	417(27)	427(82)
U_d (n,γ)	1,14(13)E7	355(14)	426(38)

Polynomial Fit : $a_0+a_1*x+a_2*x^2+a_3*x^3$
From x = 50 mm to x = 990 mm

	a_0	a_1	a_2	a_3
U_d (n,2n)	4,37(40)E4	5,23(45)E2	-1,02(10)	4,80(58)E-4
U_d (n,f)	1,21(25)E5	2,76(32)E3	-5,33(73)	2,62(44)E-3
U_d (n,f)new	1,14(63)E5	3,93(74)E3	-7,4 (17)	3,6(10)E-3
U_d (n,γ)	2,28(14)E4	1,46(14)E2	-0,31(3)	1,65(18)E-4

Integral = $\{ a_0*x+a_1*x^2/2+a_2*x^3/3+a_3*x^4/4\}_0^{1000}$

Integral	Fission old	Fission new	(n,2n)	(n,γ}
Gauss	3,696E-25	4,971E-25	8,669E-26	3,374E-26
Polynom	3,827E-25	5,093E-25	8,693E-26	3,364E-26
Average	**3,762E-25**	**5,032E-25**	**8,681E-26**	**3,369E-26**

LEAD TARGET

Gauss Fit: $y_0 + A * \mathrm{sqrt}(2/\pi) / w * \exp(-2* ((x-x_c)/w)^2)$
From x = 50 mm to x = 260 mm

Reaction	A(area)	z_c (center)	w (width)
U_d (n,2n)	1,65(59)E8	82,6(78)	251(46)
U_d (n,f)	6,3(16)E8	97,6(41)	216(30)
U_d (n,γ)	1,13(13)E8	110,8(22)	160(12)

Polynomial Fit : $a_0+a_1*x+a_2*x^2+a_3*x^3+a_4*x^4$
From x = 260 mm to x = 990 mm

	a_0	a_1	a_2	a_3	a_4
U_d (n,2n)	1,20(4)E6	-6,03(21)E3	11,3(4)	-9,40(40)E-3	2,91(13)E-6
U_d (n,f)	8,63(26)E6	-4,45(16)E4	85,9(37)	-7,33(36)E-2	2,33(13)E-5
U_d (n,γ)	3,09(15)E6	-1,48(10)E4	26,8(25)	-2,15(26)E-2	6,42(98)E-6

Integral = $\{ a_0*x+a_1*x^2/2+a_2*x^3/3+a_3*x^4/4+a_4*x^5/5\}_{260}^{1000}$

Integral	Fission	(n,2n)	(n,γ}
Gauss	**7,275E-25**	**1,103E-25**	**2,555E-25**
Polynom	**1,911E-25**	**2,794E-26**	**2,836E-26**
Sum	**9,187E-25**	**1,383E-25**	**3,713E-25**

The experimental rates of reactions

	U_d(n,fission)	U_d(n,2n)	U_d(n, γ)
CARBON TARGET	5,093E-25	8,693E-26	3,364E-26
LEAD TARGET	9,187E-25	1,383E-25	3,713E-25
Ratio C/L	**0,554**	**0,629**	**0,091**

CALCULATION

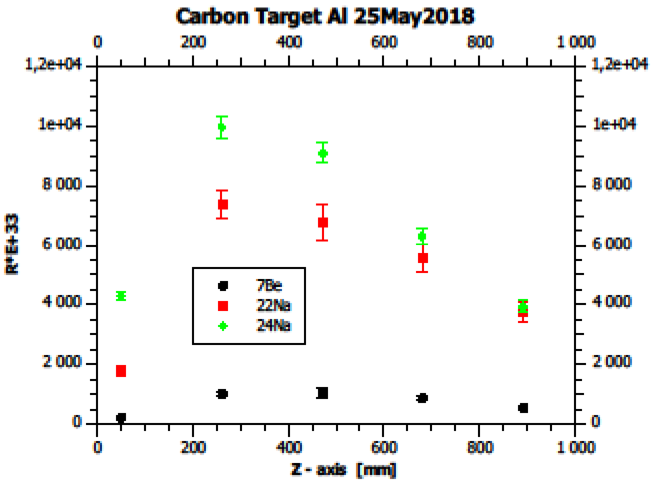
The reaction rates and the neutron fluxes were calculated with the radiation transport code **MCNPX2.7.0**
The cross sections were extracted from
the intranuclear cascade model **INCL4.2**,
from **TALYS-1.8** code,
and the evaluated nuclear data file **TENDL-2015s**.

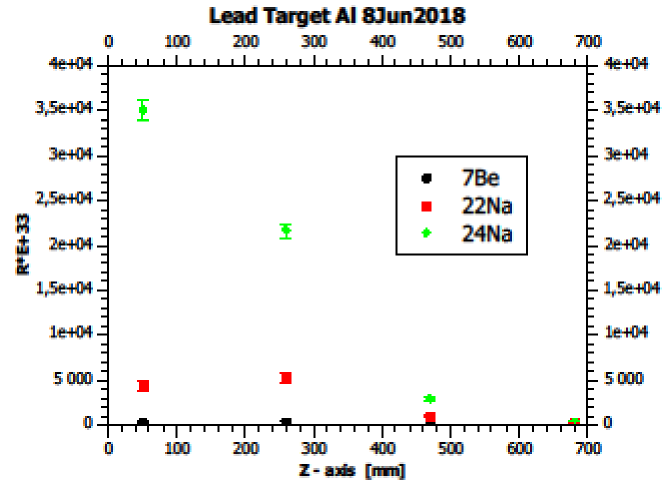
CARBON TARGET

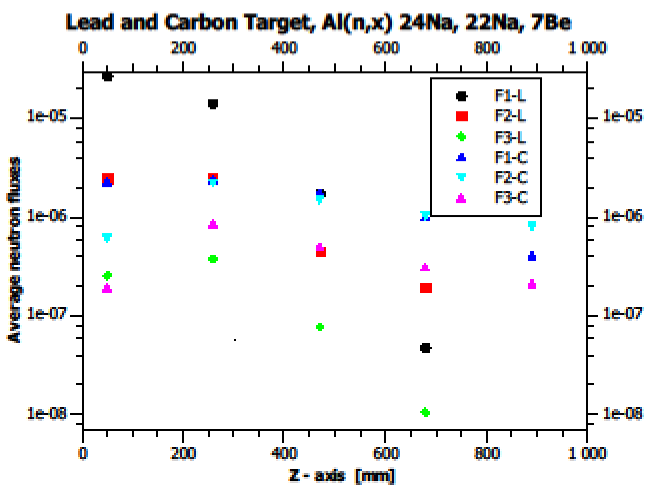
.

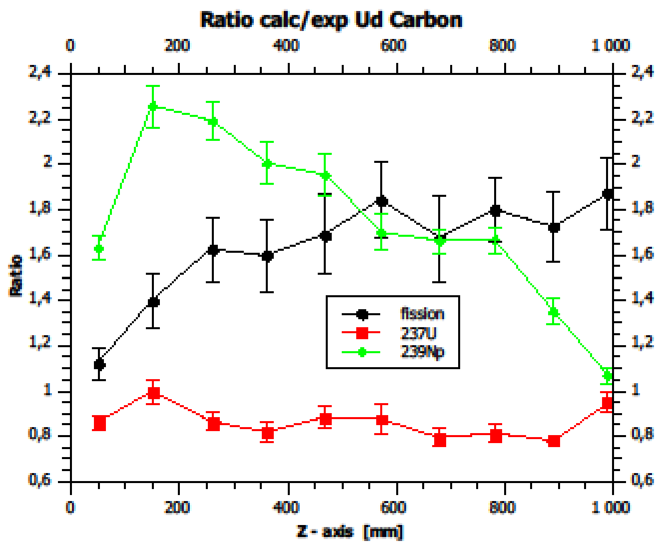
Dist. [mm]	Fis. – n [%]	Fis. – p [%]	<En> [MeV]	<Ep> [MeV]	N yield [%]	P yield [%]	YIELD* [%]
50	91	9	19,5	86,8	5,15	2,86	4,95
150	78	22	27,7	135,4	4,83	2,74	4,37
260	70	30	34,5	184,4	4,66	2.82	4,10
360	67	33	38,6	201,0	4,49	2,77	3,93
470	65	35	41,4	206,8	4,49	2,77	3,89
570	65	35	43,0	200,3	4,26	2,77	3,73
680	63	37	43,7	189,7	4,26	2,77	3,71
780	62	38	44,0	176,0	4,26	2,82	3,71
890	59	41	44,0	156,3	4,26	2,83	3,68
990	58	42	45,2	128,8	4,26	2,74	3,62

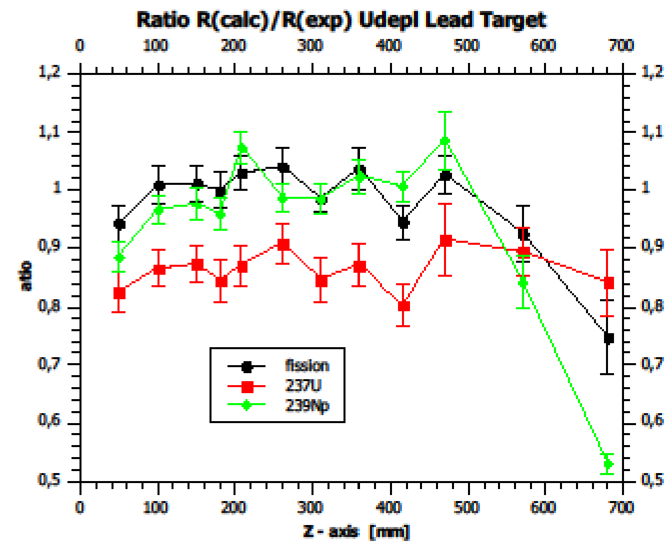
*) Here are values for 97Zr,
for 131I, 133I, and 143Ce the calculations are also done

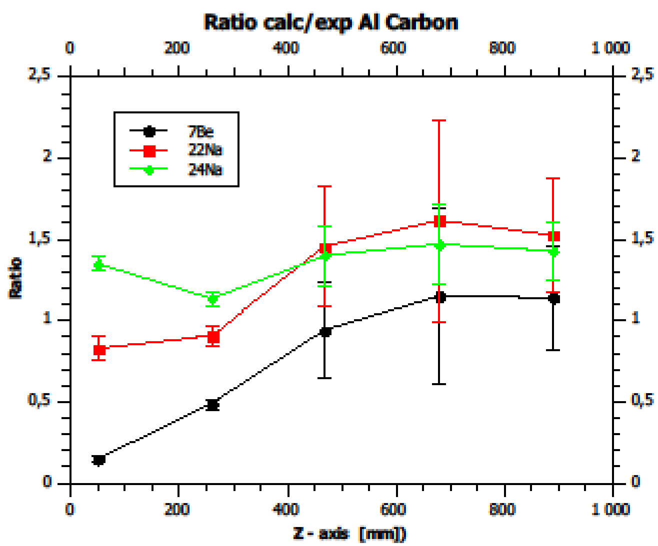

Carbon Target Al 25May2018
R*E+33
Z - axis [mm]
7Be
22Na
24Na

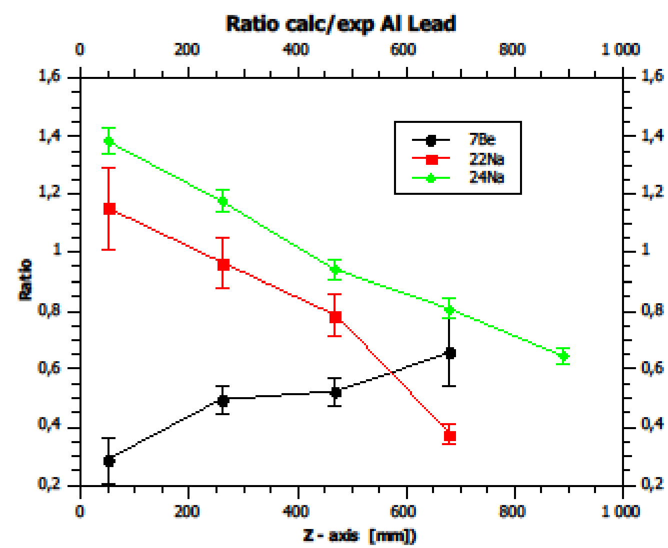

Lead Target Al 8Jun2018
R*E+33
Z - axis [mm]
7Be
22Na
24Na

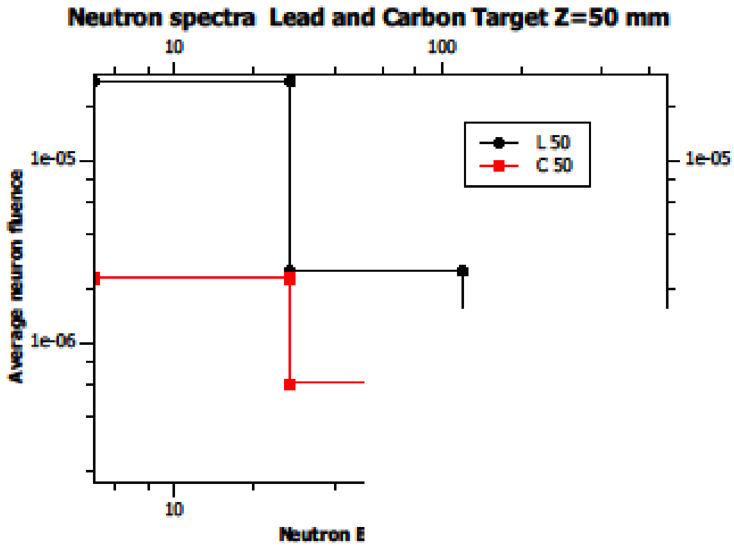

Lead and Carbon Target, Al(n,x) 24Na, 22Na, 7Be
Average neutron fluxes
Z - axis [mm]
F1-L
F2-L
F3-L
F1-C
F2-C
F3-C

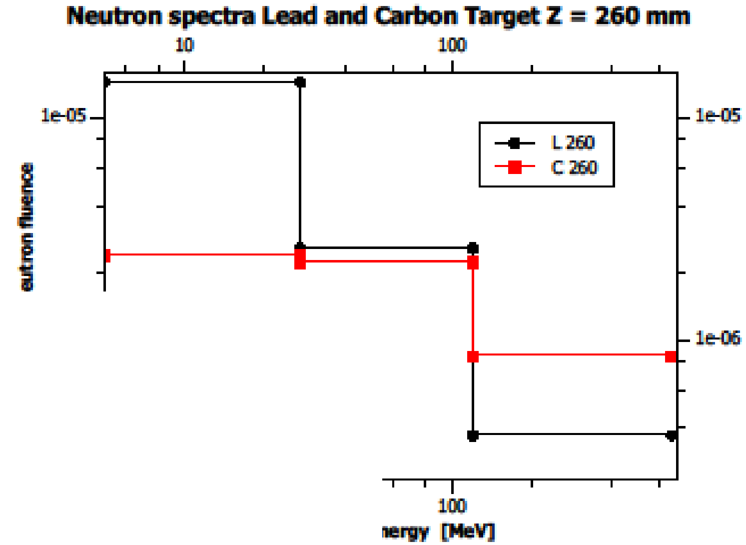

Ratio calc/exp Ud Carbon
Ratio
Z - axis [mm]
fission
237U
239Np

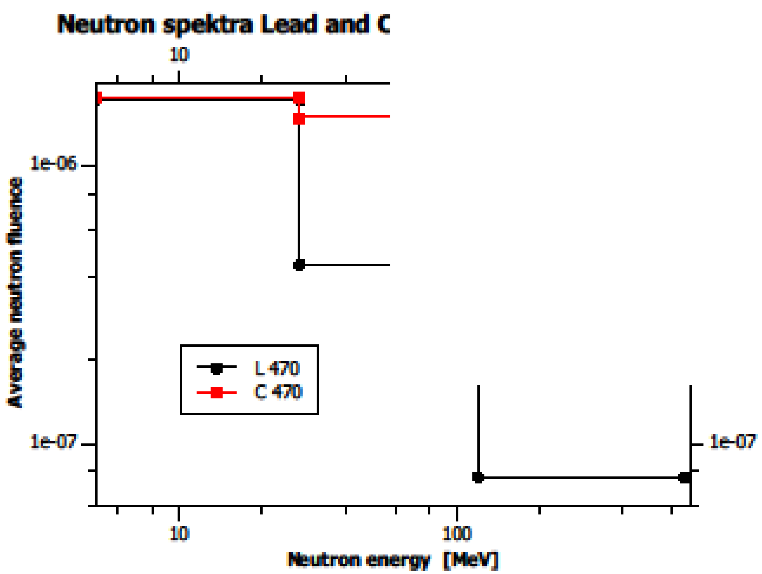

Ratio R(calc)/R(exp) Udepl Lead Target
atio
Z - axis [mm]
fission
237U
239Np

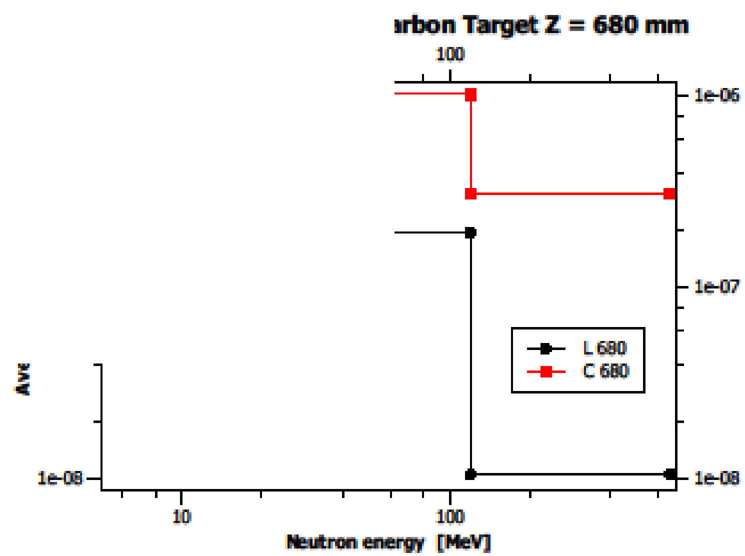

Ratio calc/exp Al Carbon
Ratio
Z - axis [mm])
7Be
22Na
24Na


Ratio calc/exp Al Lead
Ratio
Z - axis [mm])
7Be
22Na
24Na


Neutron spectra Lead and Carbon Target Z=50 mm
Average neuron fluence
L 50
C 50
1e-05
1e-06
10
100
Neutron E


Neutron spectra Lead and Carbon Target Z = 260 mm
utron fluence
L 260
C 260
1e-05
1e-06
10
100
ergy [MeV]


Neutron spektra Lead and C
Average neutron fluence
L 470
C 470
1e-06
1e-07
10
100
Neutron energy [MeV]


rbon Target Z = 680 mm
Ave
L 680
C 680
1e-06
1e-07
1e-08
10
100
Neutron energy [MeV]

CONCLUSIONS

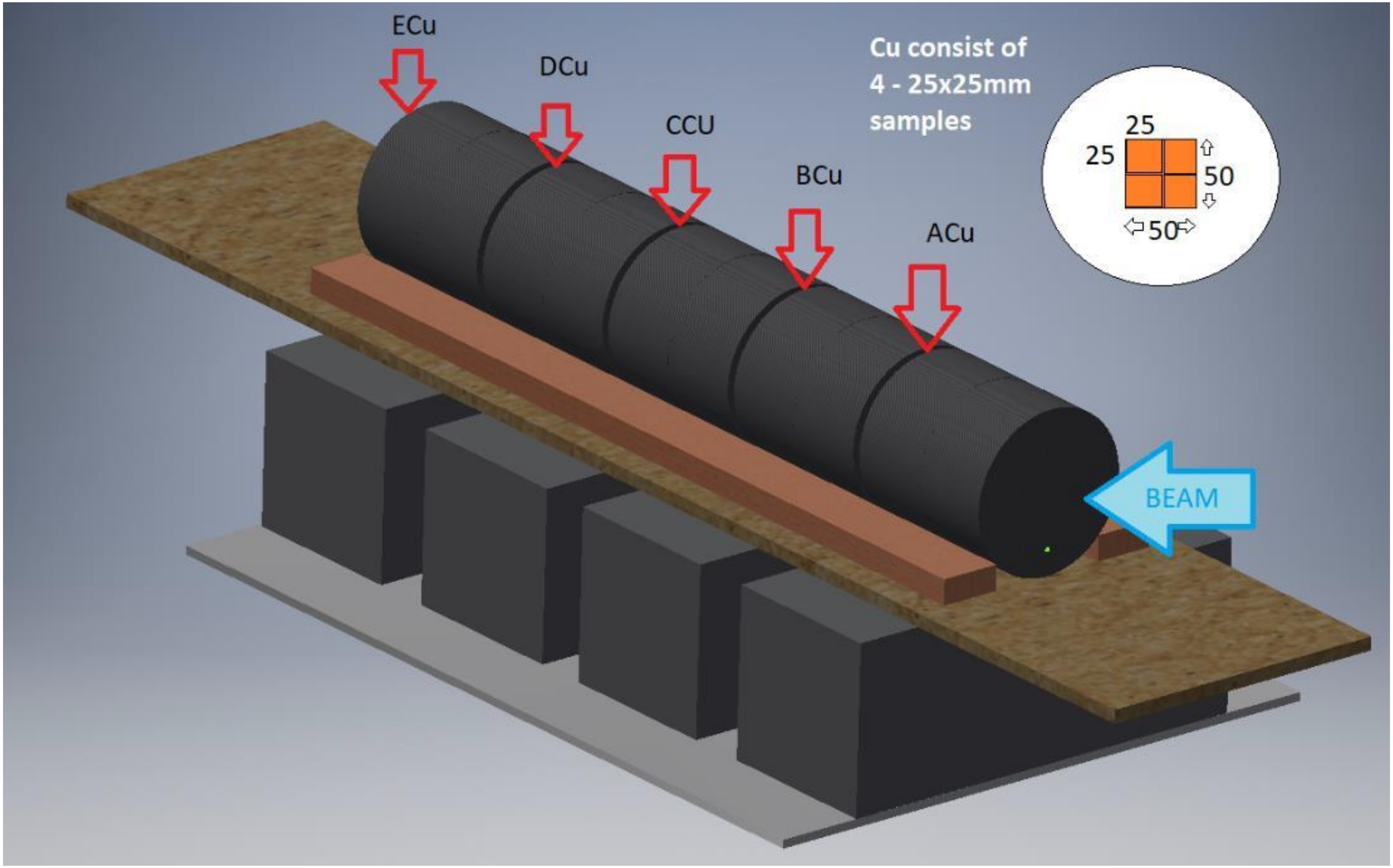
Yields for 97Zr, 131I, 133I, 143Ce
for Carbon target we must know most precise

Almost 40% protons escape for Carbon
We can try propose configuration
Lead + Carbon

We must finished calculation of neutron
spectra for all samples of Ud and threshold
detector

It interesting to study experimentaly
Be target with diameter 190 mm and length 1000 mm

THANK YOU
FOR YOUR
ATTENTION!



ECu
DCu
CCU
BCu
ACu
Cu consist of
4 - 25x25mm
samples
25
25
50
50
BEAM

Target «Quinta-M»

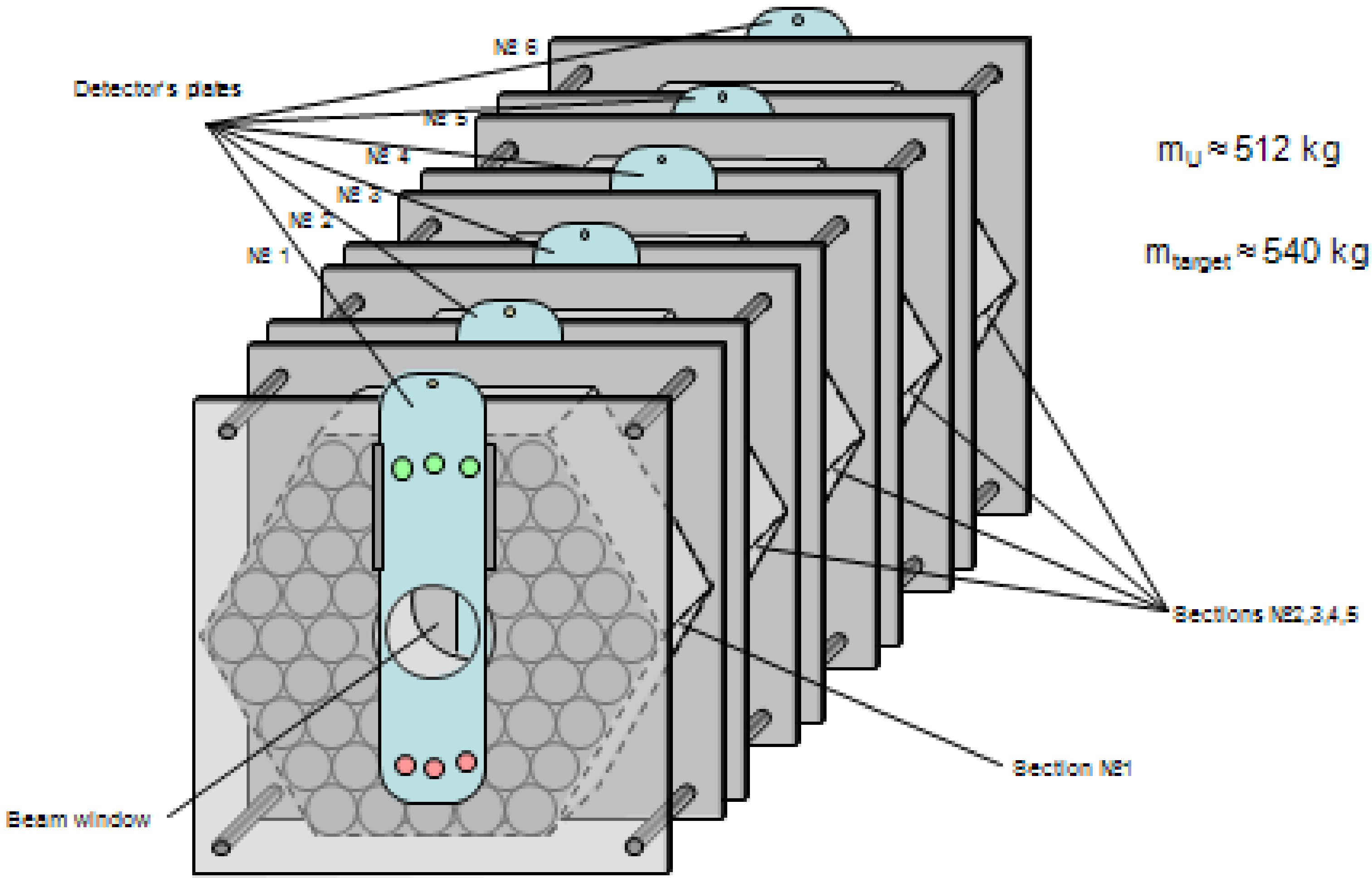
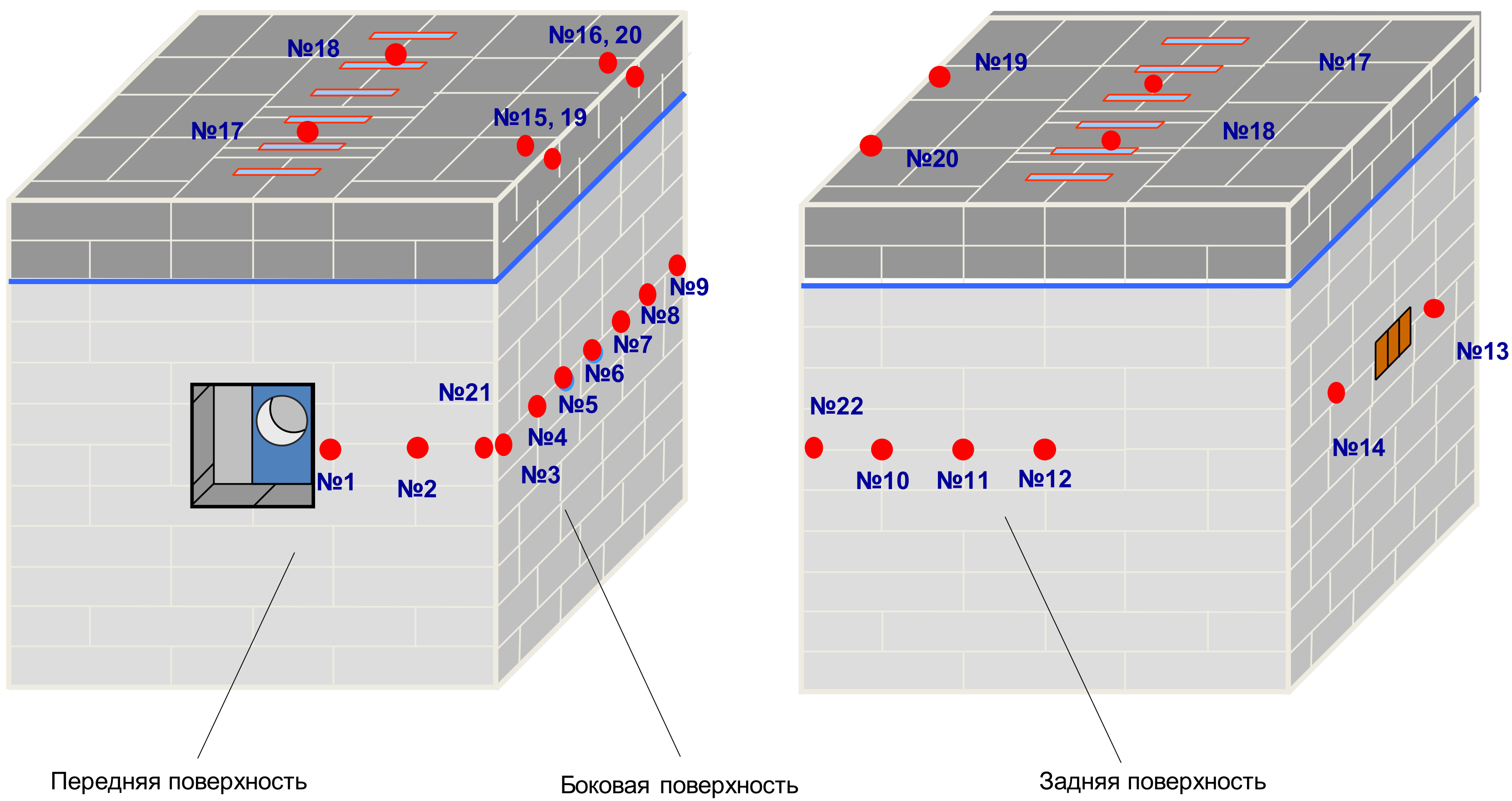
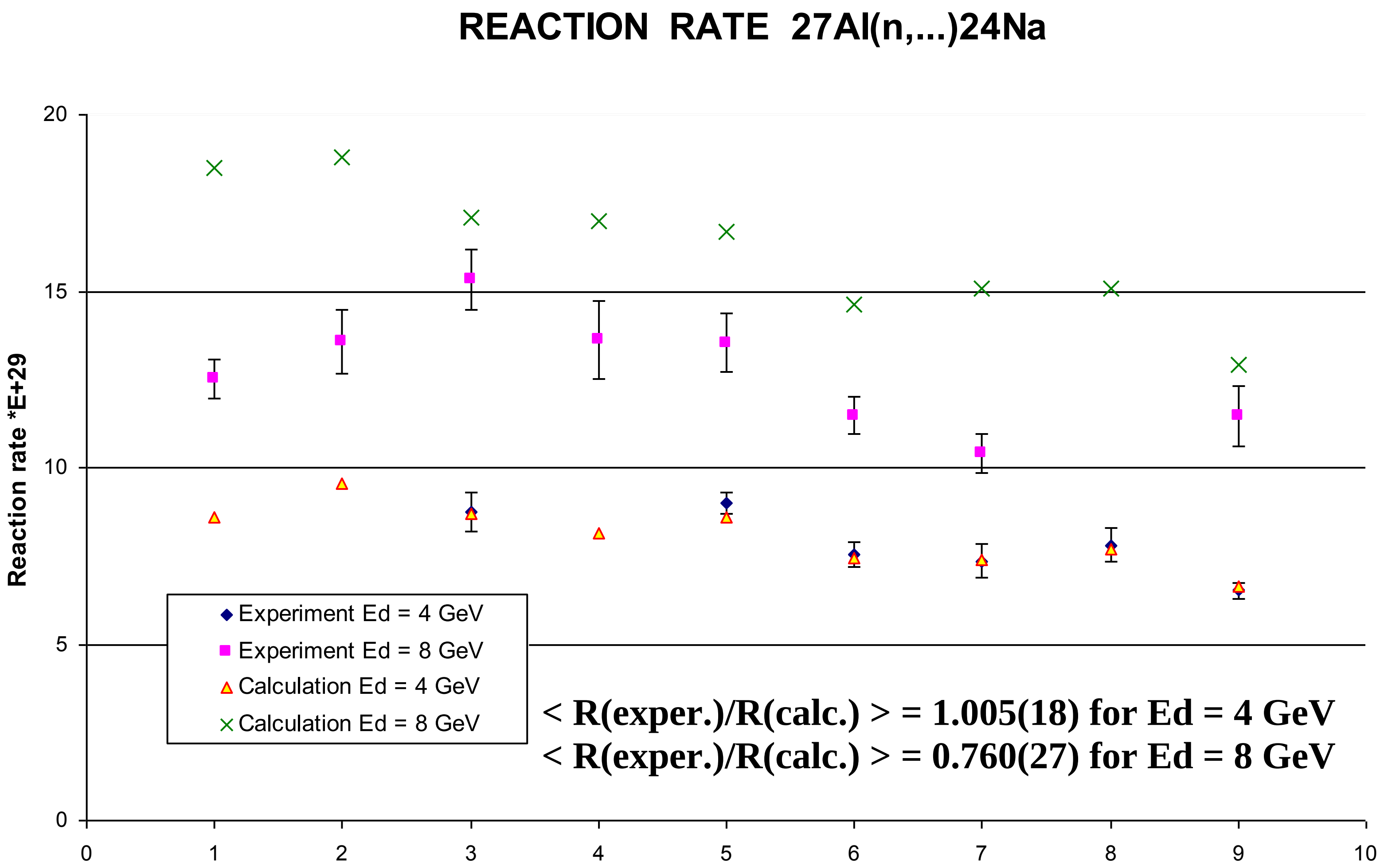


Fig. 1

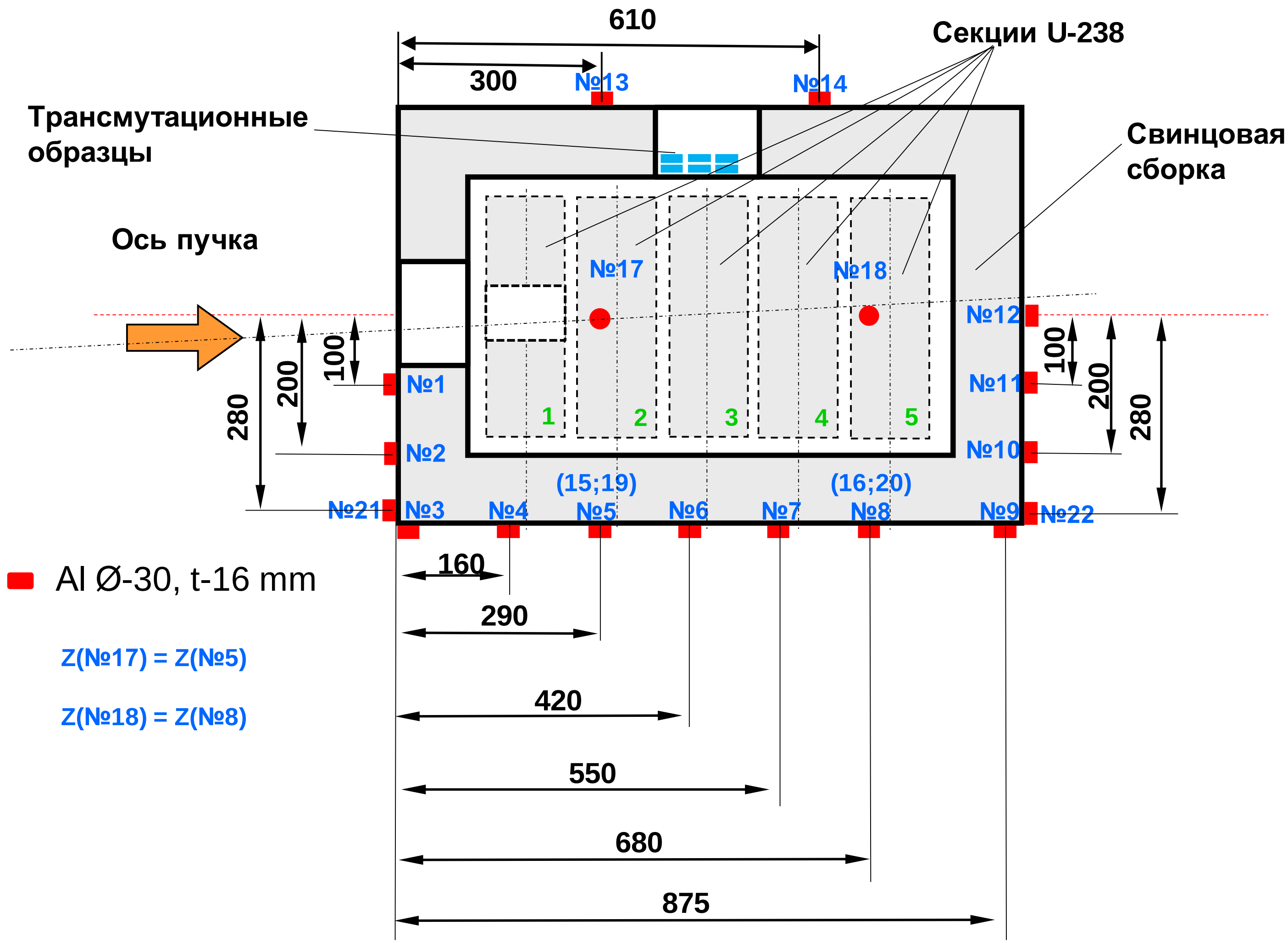
Схема расположения Al-детекторов на поверхности свинцовой сборки установки «Квинта»

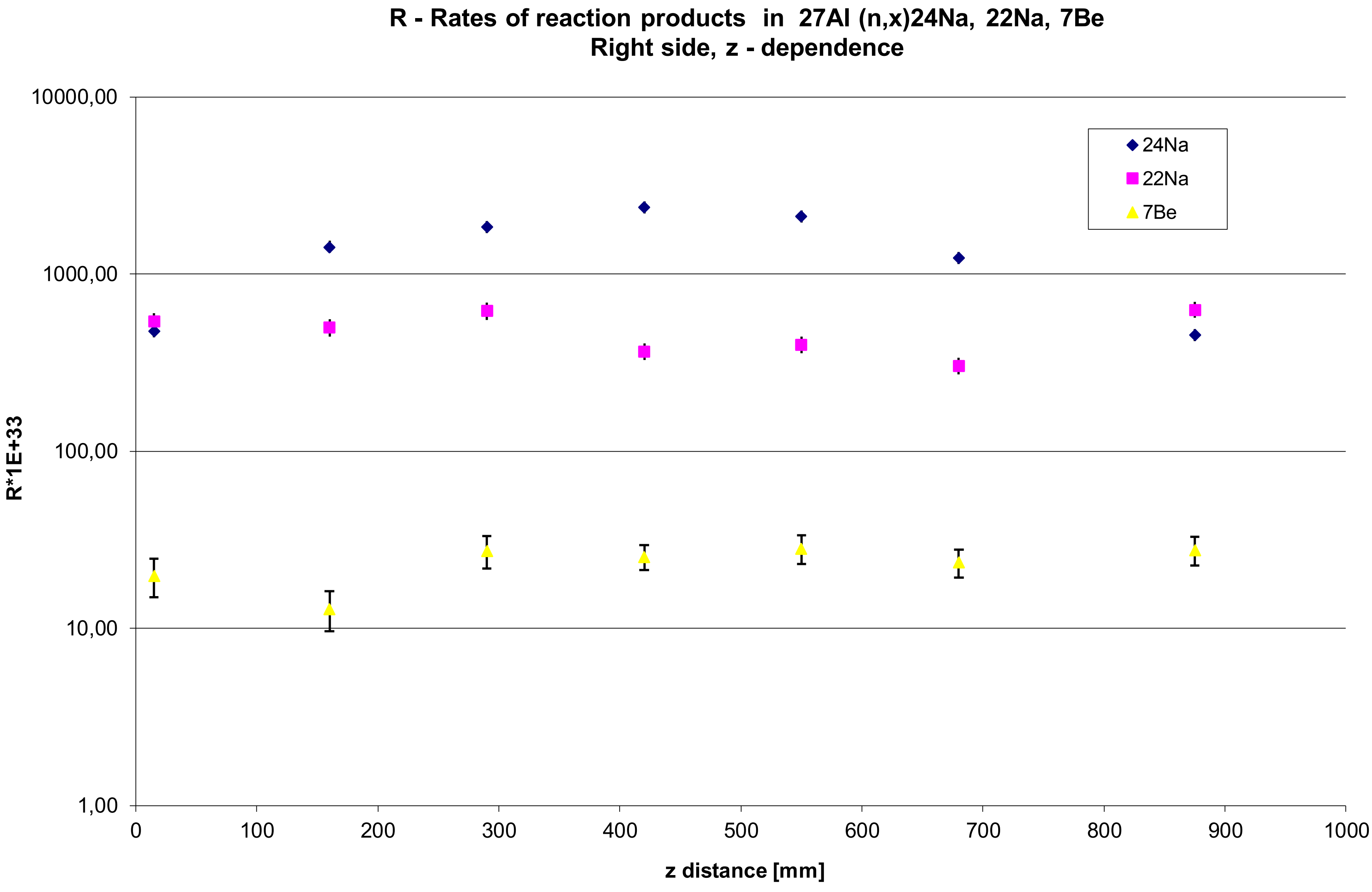


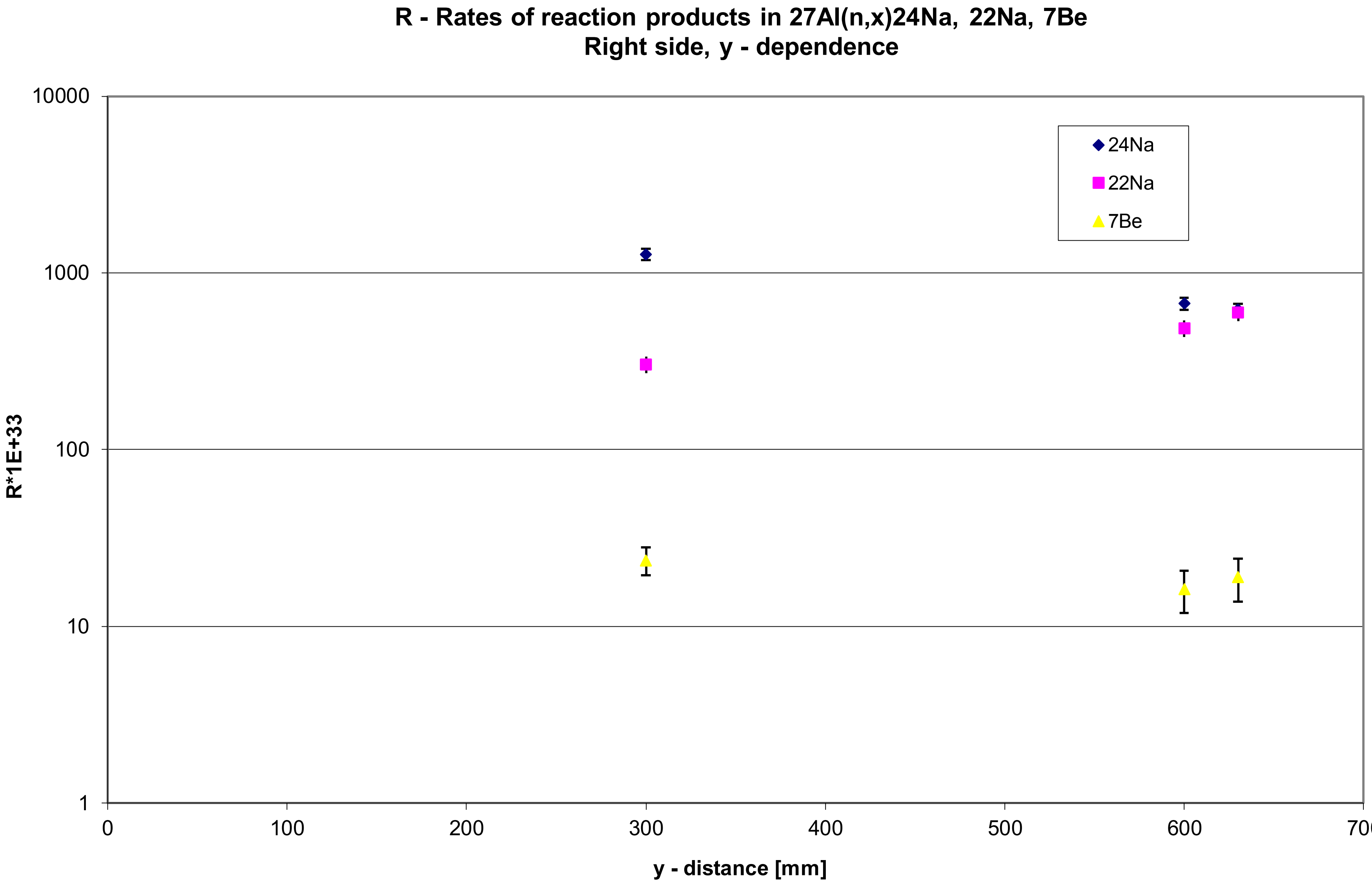


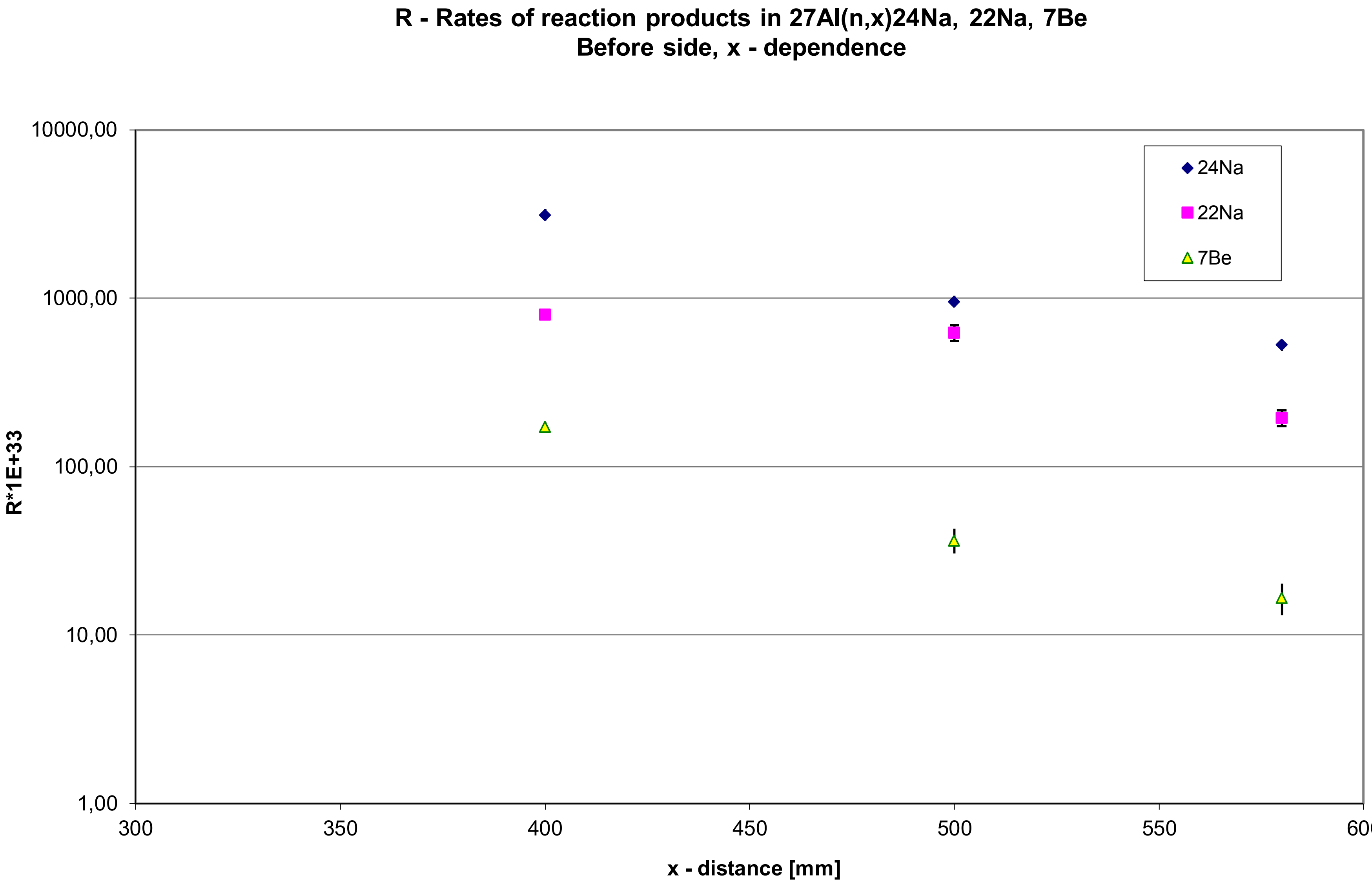
REACTION RATE 27Al(n,...)24Na
Reaction rate *E+29
20
15
10
5
0
0
1
2
3
4
5
6
7
8
9
10
Experiment Ed = 4 GeV
Experiment Ed = 8 GeV
Calculation Ed = 4 GeV
Calculation Ed = 8 GeV
< R(exper.)/R(calc.) > = 1.005(18) for Ed = 4 GeV
< R(exper.)/R(calc.) > = 0.760(27) for Ed = 8 GeV

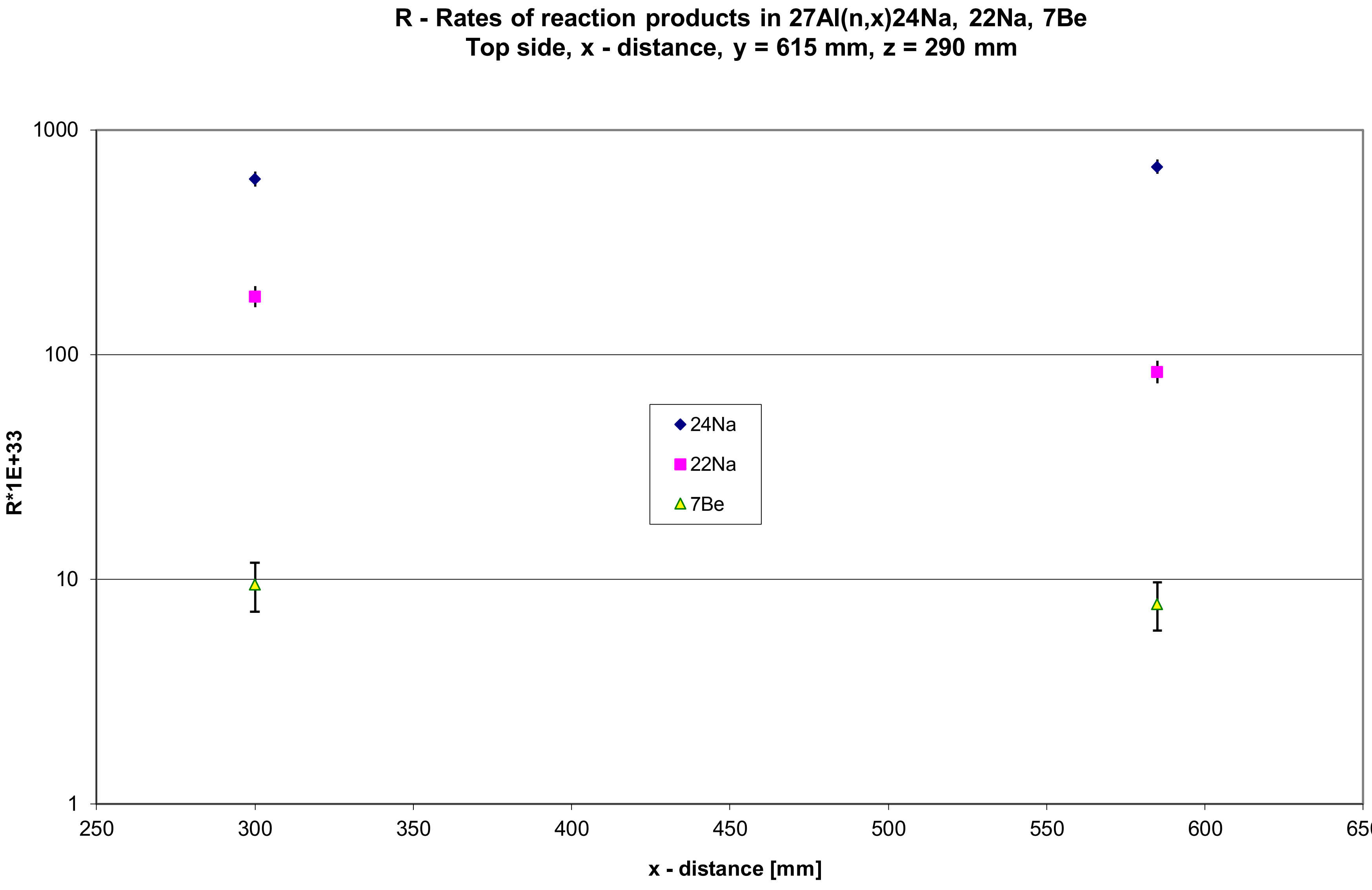
Расположение Al-детекторов на поверхности свинцовой сборки установки «Квинта»
(Крышка установки условно не показана).

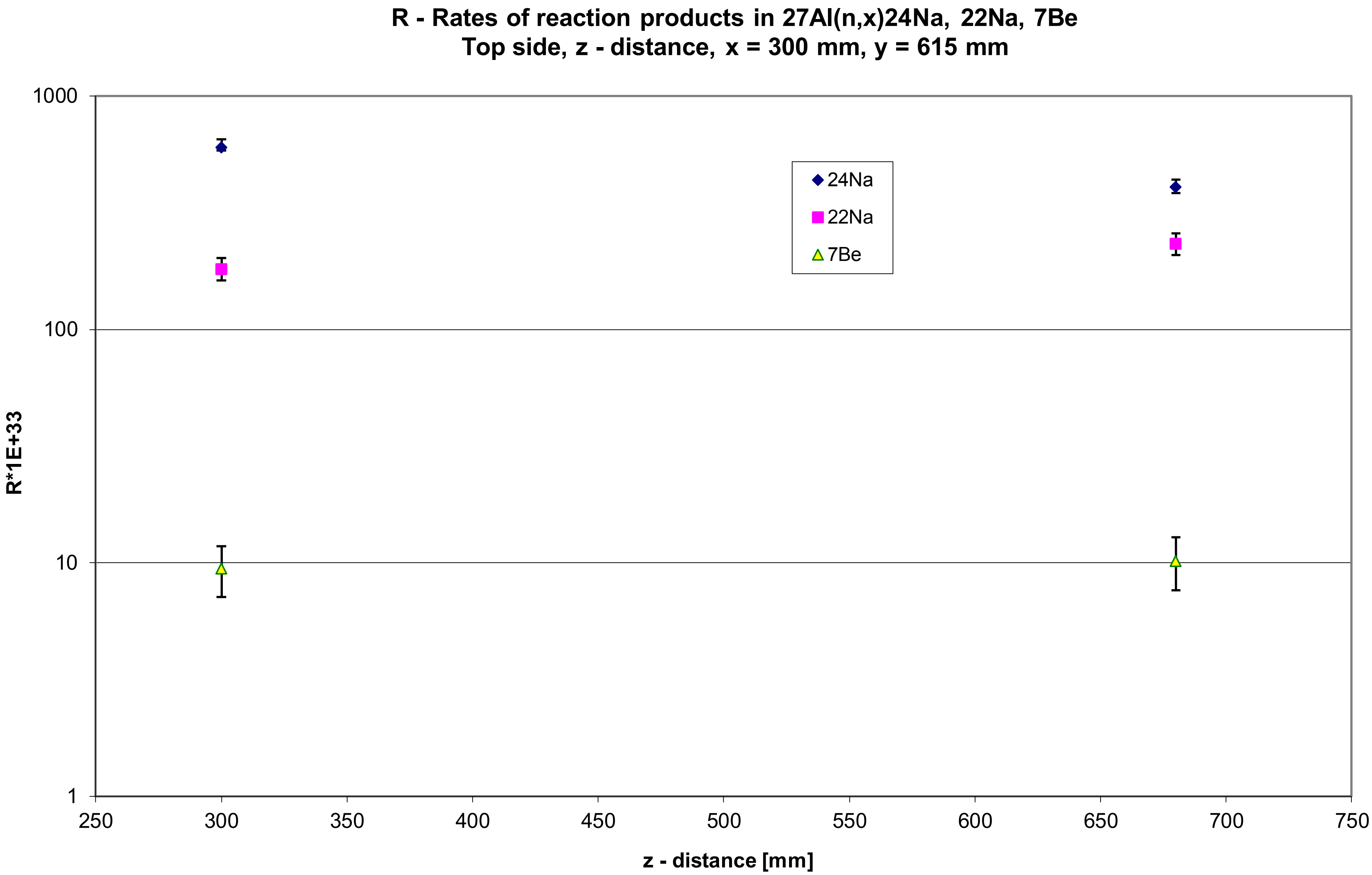



R - Rates of reaction products in 27Al (n,x)24Na, 22Na, 7Be
Right side, z - dependence
10000,00
1000,00
100,00
10,00
1,00
R*1E+33
0
100
200
300
400
500
600
700
800
900
1000
z distance [mm]
24Na
22Na
7Be


R - Rates of reaction products in 27Al(n,x)24Na, 22Na, 7Be
Right side, y - dependence
24Na
22Na
7Be
R*1E+33
10000
1000
100
10
1
0
100
200
300
400
500
600
700
y - distance [mm]


R - Rates of reaction products in 27Al(n,x)24Na, 22Na, 7Be
Before side, x - dependence
24Na
22Na
7Be
R*1E+33
10000,00
1000,00
100,00
10,00
1,00
300
350
400
450
500
550
600
x - distance [mm]


R - Rates of reaction products in 27Al(n,x)24Na, 22Na, 7Be
Top side, x - distance, y = 615 mm, z = 290 mm
1000
100
10
1
R*1E+33
24Na
22Na
7Be
250
300
350
400
450
500
550
600
650
x - distance [mm]



R - Rates of reaction products in 27Al(n,x)24Na, 22Na, 7Be
Top side, z - distance, x = 300 mm, y = 615 mm
1000
100
10
1
R*1E+33
250
300
350
400
450
500
550
600
650
700
750
z - distance [mm]
24Na
22Na
7Be

Reaction rate for 27Al(n,…)24Na, 27Al(n,…)22Na and 27Al(n,…)7Be experimental and calculated

Resid. nuclei	Data	Ed = 4 GeV		Ed = 8 GeV		R(8GeV)/R(4GeV)
		R [E-29]	d(R) [E-29]		R [E-29]	d(R) [E-29]
Na24	Exper.	7.48	0.43	12.23	0.54	1.64(12)
	Calcl.	7.473		16.75		2.24
	Exp/cal	1.00	0.06	0.73	0.03	
Na22	Exper.	0.522	0.029	2.73	0.22	5.23(51)
	Calcul.	0.71		1.73		2.43
	Exp/cal	0.73	0.04	1.58	0.13	
Be7	Exper.	0.069	0.011	0.471	0.083	6.84(150)
	Calcul.	0.0274		0.0736		2.69
	Exp/calc	2.51	0.38	6.40	1.13	

Calculation of average neutron fluence from reaction reaction rate of Be-7, Na-22 and Na-24

$$R_3 = \int_3^4 \sigma_3(E)\phi_3(E)dE \cong \phi_3 \sum_3^4 \sigma_3(E)\Delta E = \phi_3 X_{34}(3)$$

R3 = F3*X34(3)

R2 = F2*X23(2) + F3*X34(2)

R1 = F1*X12(1) + F2*X23(1) + F3*X34(1)

F3 = R3 / X34(3)

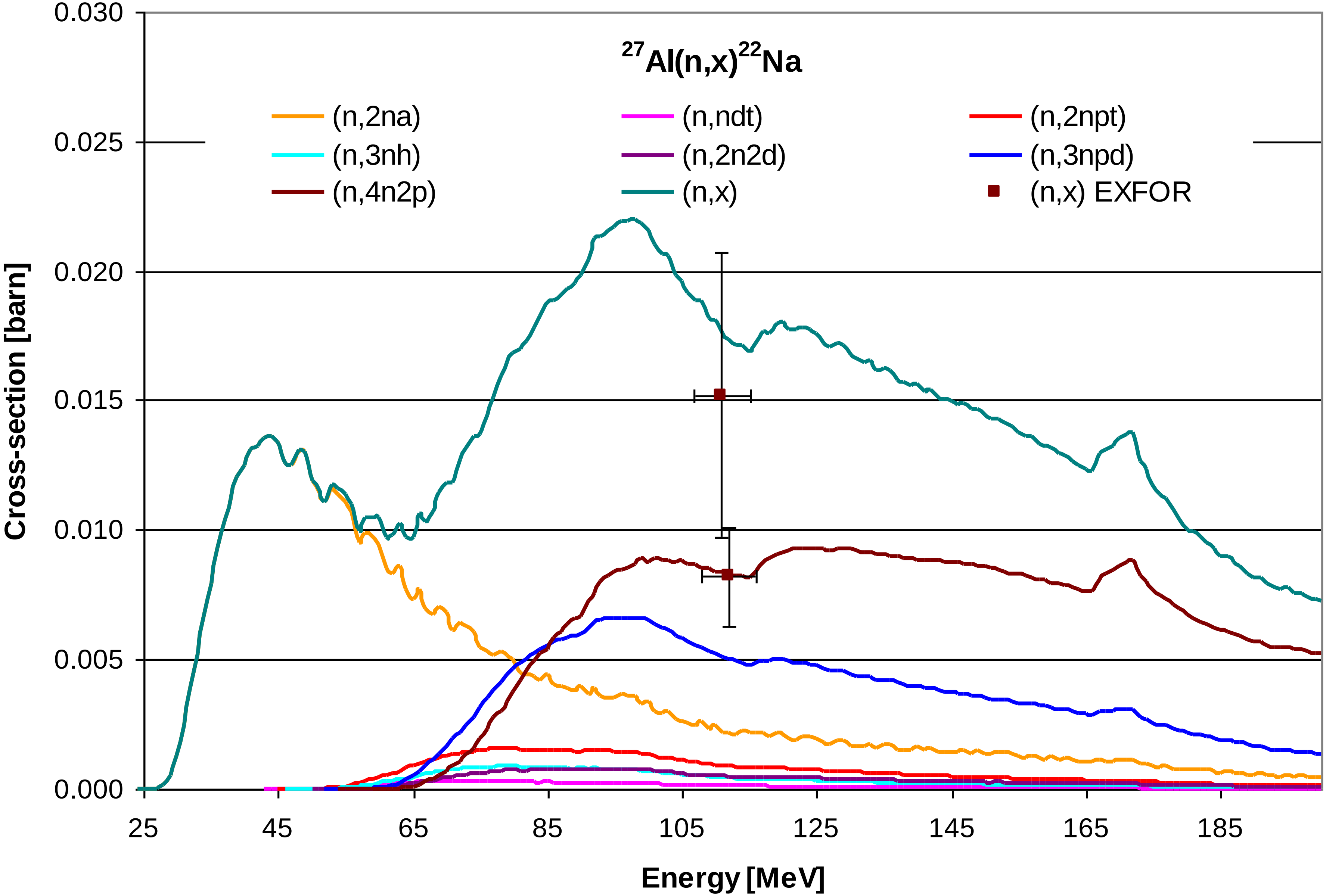
F2 = (R2 - F3* X34(2)) / X23(2)

F1 = (R1 - F2* X23(1) - F3*X34(1)) / X12(1)

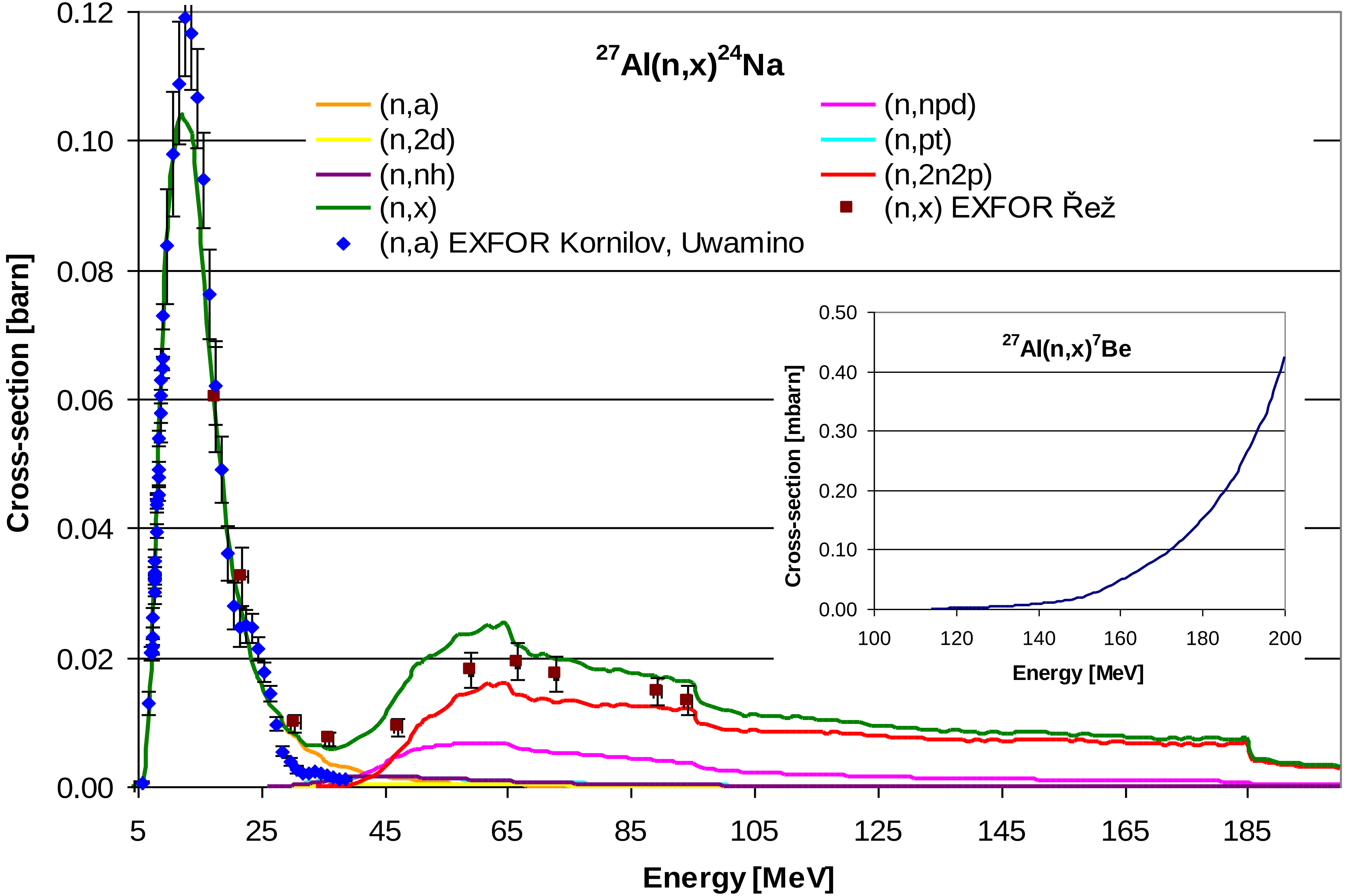
Sum of cross-section

X12(1) X23(i) X34(i)b X34(i)c

Residual Nuclei	Threshold [MeV]	No.	5->27 [barn]	27->119 [barn]	119->800 [barn]	119->1000 [barn]
24Na	5	1	1.12	1.38	1.925	3.132
22Na	27	2		1.32	7.891	10.690
7Be	119	3			5.386	7.663



$^{27}Al(n,x)^{22}Na$
(n,2na)
(n,ndt)
(n,2npt)
(n,3nh)
(n,2n2d)
(n,3npd)
(n,4n2p)
(n,x)
(n,x) EXFOR
Cross-section [barn]
0.030
0.025
0.020
0.015
0.010
0.005
0.000
25
45
65
85
105
125
145
165
185
Energy [MeV]



$^{27}Al(n,x)^{24}Na$
(n,a)
(n,2d)
(n,nh)
(n,x)
(n,a) EXFOR Kornilov, Uwamino
(n,npd)
(n,pt)
(n,2n2p)
(n,x) EXFOR Řež
Cross-section [barn]
Energy [MeV]
0.00
0.02
0.04
0.06
0.08
0.10
0.12
5
25
45
65
85
105
125
145
165
185
$^{27}Al(n,x)^{7}Be$
Cross-section [mbarn]
Energy [MeV]
0.00
0.10
0.20
0.30
0.40
0.50
100
120
140
160
180
200

Measured average neutron fluences [neutrons/(cm2.MeV.deuteron)] x10-5

in case of two beam energies, 4 and 8 GeV

Product	Data	E_d = 4 GeV Fluence ϕ [E-5]	E_d = 8 GeV Fluence ϕ [E–5]	ϕ (8GeV)/ϕ(4GeV)
^{24}Na	Exp. Calc. exp/calc	4.734(243) 5.160 0.917	8.521(511) 12.91 0.660	1.800 2.502
^{22}Na	Exp. Calc. exp/calc	0.182(12) 0.261 1.077	0.851(69) 0.550 2.706	4.676 2.107
^{7}Be	Exp. Calc. exp/calc	0.0358(57) 0.00748 4.786	0.150(27) 0.00749 20.03	4.190 0.999

Results of analysis of γ-ray spectra of **U**$_{\textbf{nat.}}$ after irradiation with secondary neutrons from E_d = 1.60 GeV. All corrections are included. (+) denotes mixing due to other nuclide.

Isotope Energy[keV]	**Activity[Bq]** I_g [%]	**$T_{1/2}$(Library)** $T_{1/2}$(Exper.)	**<B>** B	**<R>** R	Number of spectra
Np-239	**849(40)**	**2.3565(4) d**	**7.51(35)-05**	**2.97(14)E-26**	31-X,16-C
106.125	27.2	2.388(15) d	6.76(30)E-05	2.67(12)E-26	6-X
106.125	27.2	2.39(6) d	6.51(40)E-05	2.64(16)E-26	3-C
209.753	3.42	2.36(5) d	9.54(43)E-05	3.77(17)E-26	5-X
209.753	3.42	2.44(10) d	9.00(52)E-05	3.56(21)E-26	3-C
228.183	10.76	2.45(6) d	8.86(37)E-05	3.50(15)E-26	6-X
228.183	10.76	2.49(4) d	8.51(54)E-05	3.36(21)E-26	3-C
277.599	14.38	2.35(3) d	7.37(33)E-05	2.91(13)E-26	5-X
277.599	14.38	2.45(9) d	7.47(53)E-05	2.96(21)E-26	3-C
315.879	1.60	1.8(3) d	7.70(63)E-05	3.04(25)E-26	4-X
315.879	1.60	2.30(12)d	7.12(64)E-05	2.81(25)E-26	2-C
334.309	2.07	2.04(14) d	6.25(52)E-05	2.47(21)E-26	5-X
334.309	2.07	3.2 d	5.15(51)E-05	2.03(20)E-26	2-C
Mo-99	**14.1(16)**	**2.7475(4) d**	**1.45(17)E-06**	**5.74(65)E-28**	3;7X,7C
Te-132	**11.5(10)**	**3.204(2) d**	**1.38(12)E-06**	**5.46(46)E-28**	7:12X,18C
I-133	**35(18)**	**20.8(1) h**	**8.0(41)E-07**	**3.2(16)E-28**	1:2X,2C
I-135	**175(14)**	**6.57(2) h**	**1.80(26)E-06**	**7.13(57)E-28**	6;6C
Xe-135	**152(58)**	**9.14(2) h**	**2.04(109)E-06**	**8.6(38)E-28**	1;3X,2C
Ba-140	**3.38(10)**	**12.752(3) d**	**1.62(5)E-06**	**6.40(19)E-28**	5;1X,15C
Ce-143	**24.5(54)**	**33.039(6) h**	**1.26(27)E-06**	**5.0(11)E-28**	3;4X,7C

Group weight factors for calculations of total number of fissions

$$w_j(t) = \frac{\int_{a(j)}^{a(j+1)} \sigma_j(t, E_n)\Phi(E_n)dE_n}{\int_{a(1)}^{a(4)} \sigma_j(t, E_n)\Phi(E_n)dE_n} \qquad (16)$$

* thermal, epithermal and resonance – from $a(1) = 10^{-5}$ eV to $a(2) = 126$ keV
* unresolved resonance and fast – from $a(2) = 126$ keV to $a(3) = 4.57$ MeV
* fast and high energy neutrons – from $a(3) = 4.57$ MeV up to $a(4) =$ beam energy

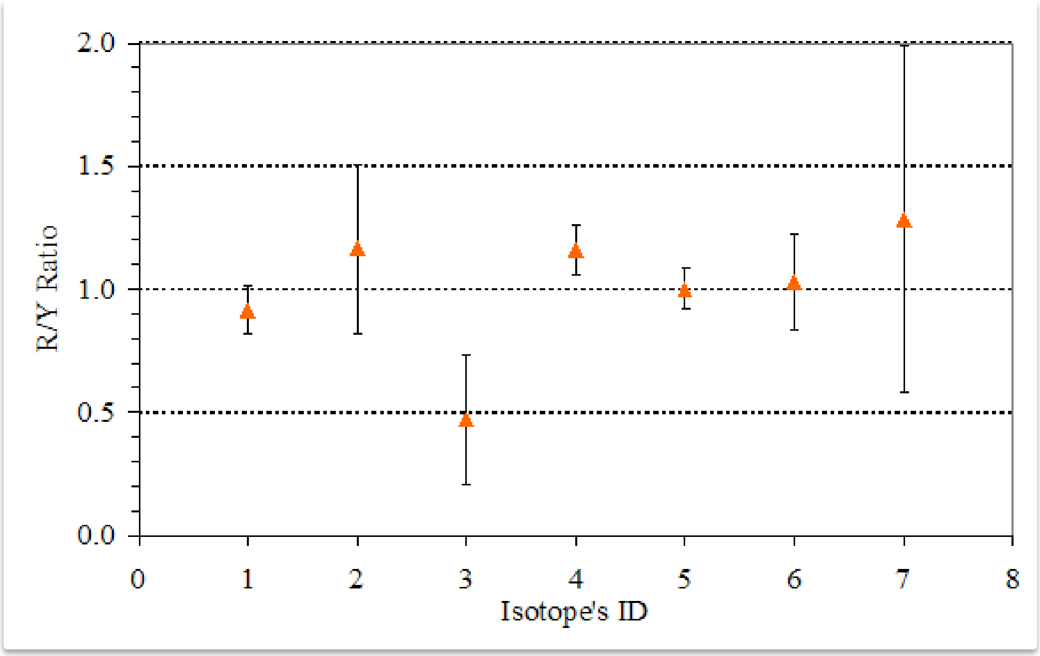
$$Y_{cum}(Th, {}^{99}Mo) = w_2(Th).Y_{cum}(Th, {}^{99}Mo, 2) + w_3(Th).Y_{cum}(Th, {}^{99}Mo, 3)$$

$$\begin{aligned} Y_{cum}(U_{nat}, r) = {} & [0.007204\,(w_1({}^{235}U).Y_{cum}({}^{235}U, r, 1) + w_2({}^{235}U).Y_{cum}({}^{235}U, r, 2) + \\ & + w_3({}^{235}U).Y_{cum}({}^{235}U, r, 3))] + \\ & + [0.992742((w_2({}^{238}U).Y_{cum}({}^{238}U, r, 2) + (w_3({}^{238}U).Y_{cum}({}^{238}U, r, 3))] \end{aligned}$$

where r = ^{99}Mo, ^{132}Te, ^{133}I, ^{135}I, ^{135}Xe, ^{140}Ba and ^{143}Ce.

E_n	^{232}Th	^{235}U	^{238}U	^{nat}U
Epithermal	$6.72.10^{-7}$	0.636	$7.12.10^{-5}$	$4.65.\ 10^{-3}$
Resonance	0.663	0.318	0.715	0.712
Fast	0.337	0.046	0.285	0.283

The relative ratio of R_{exp} (^{nat}U,r) / (Y_{cum}(^{nat}U,r)



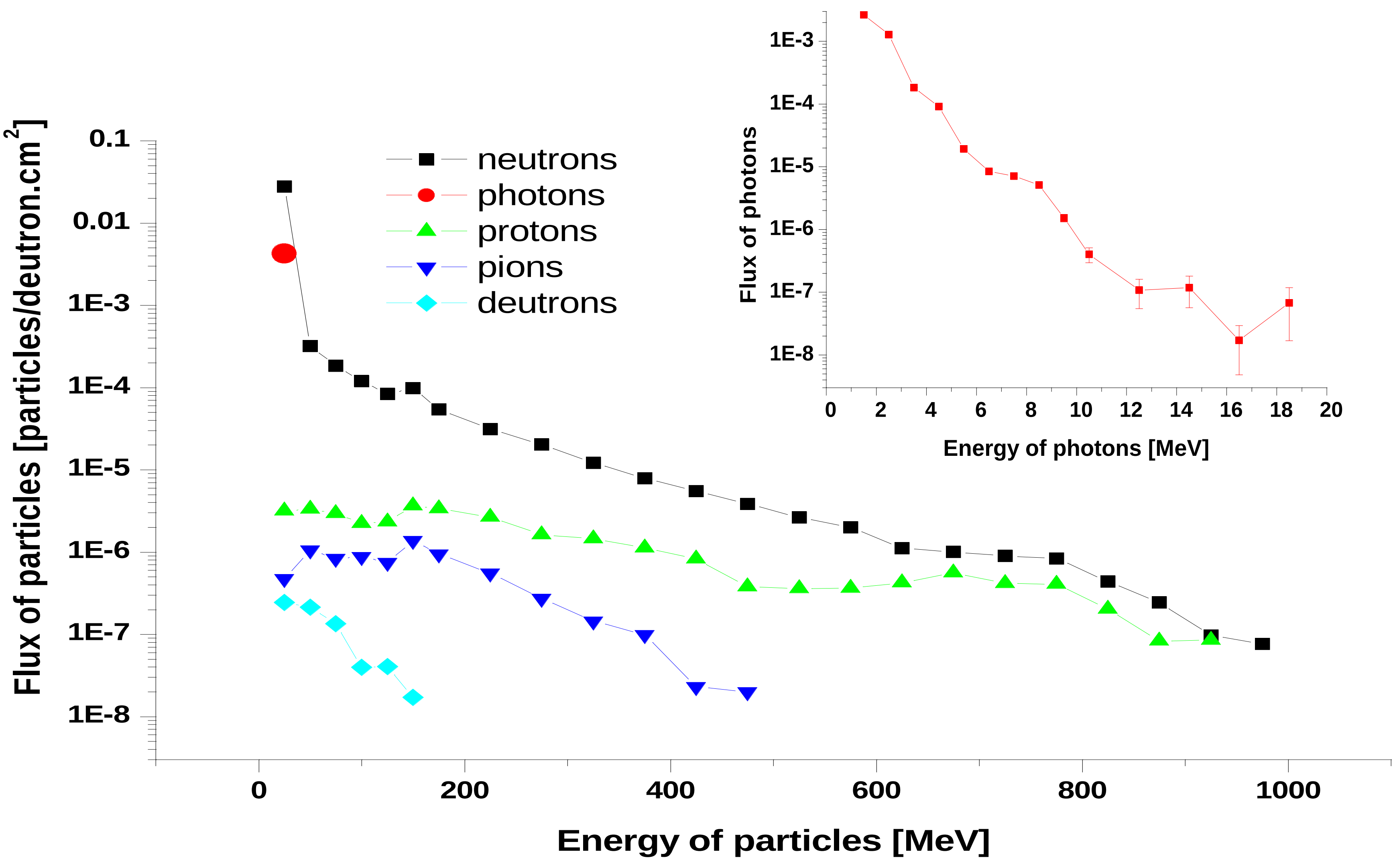
X-axis 1 = ^{99}Mo, 2 = ^{132}Te, 3 = ^{133}I, 4 = ^{135}I, 5 = ^{135}Xe, 6 = ^{140}Ba, and 7 = ^{143}Ce

Calculation of neutron spectra and reaction rates.

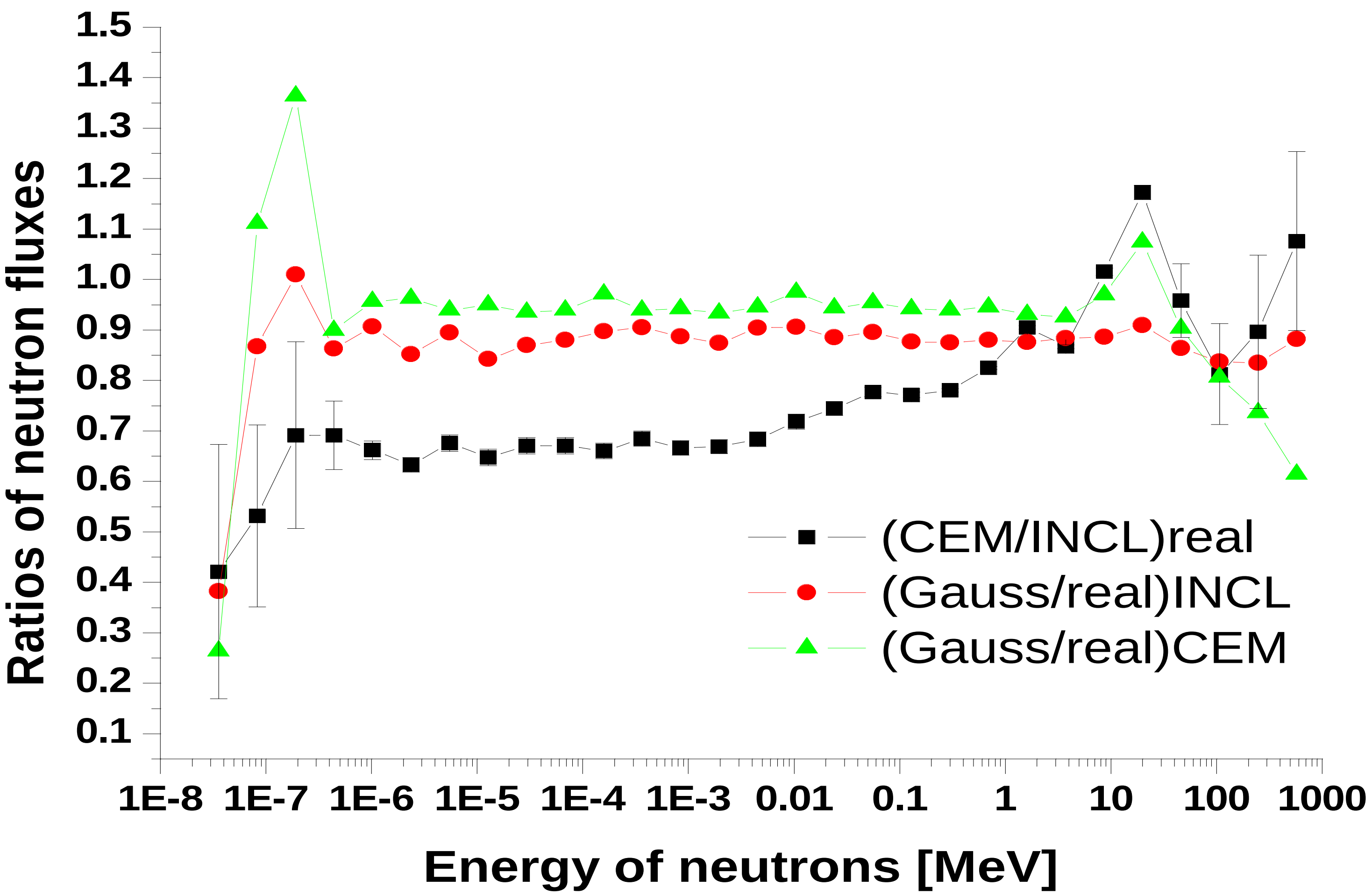
- MCNPX 2.6.C
- Neutron flux, 4 cells 36*36*15 mm on top of 2nd section
- Setup: lead target, uranium rods in hexagonal lattice, polyethylene box with cadmium shielding, metal and aluminum holders and wooden plates
- Realistic size of beam: Xc = -0.64 cm, Yc = -0.39 cm, FWHM – X = 2.87 cm, Y = 1.92 cm

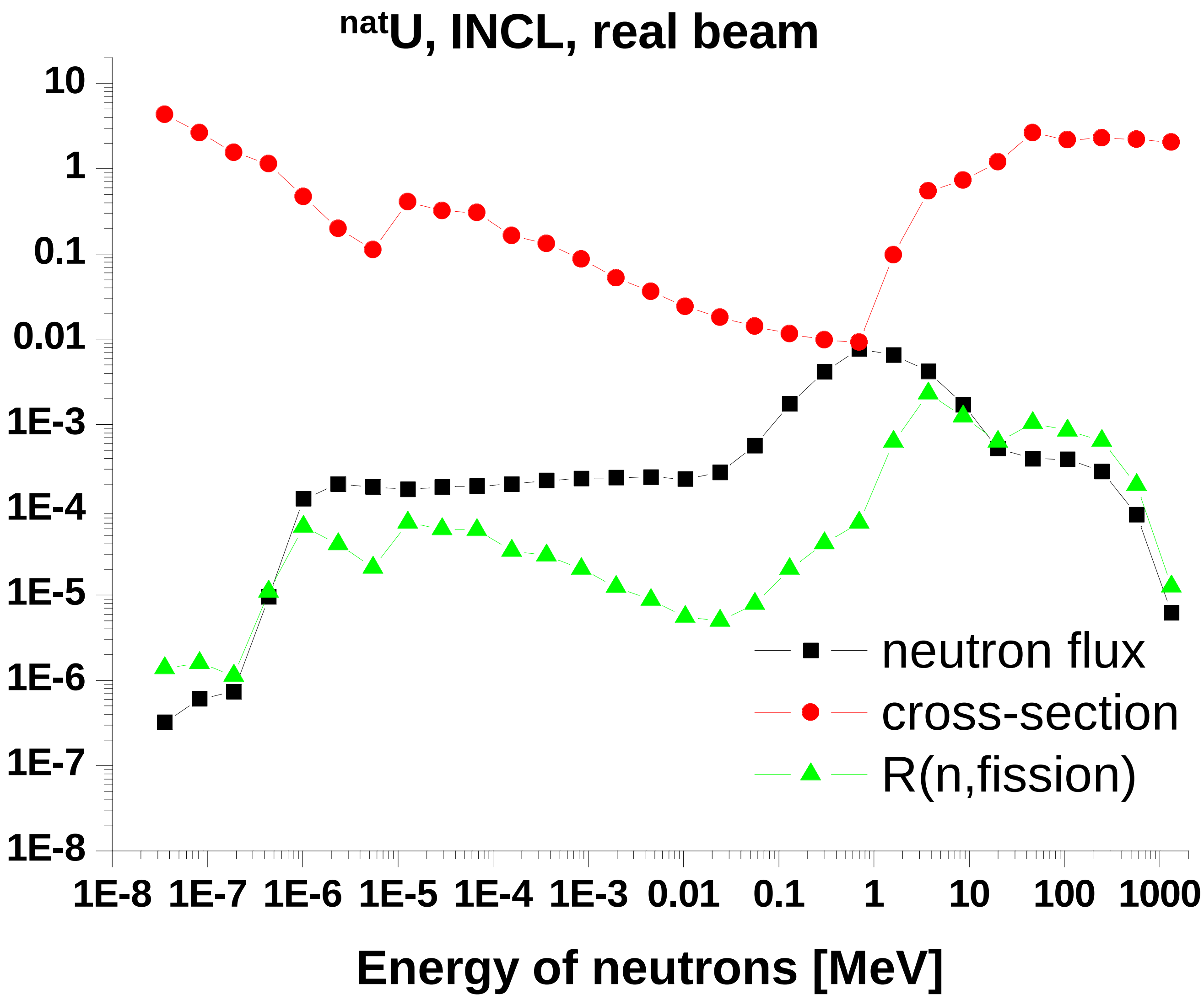
  Gauss: Xc = Yc = 0, FWHM – X = Y = 4.00 cm
- CEM, INCL model with the LA150N and LA150H libraries
- 3.2*10^7 of incident particles were used for each calculation

The simulated particles spectra on top of second section of our setup using “INCL” model and “real” beam

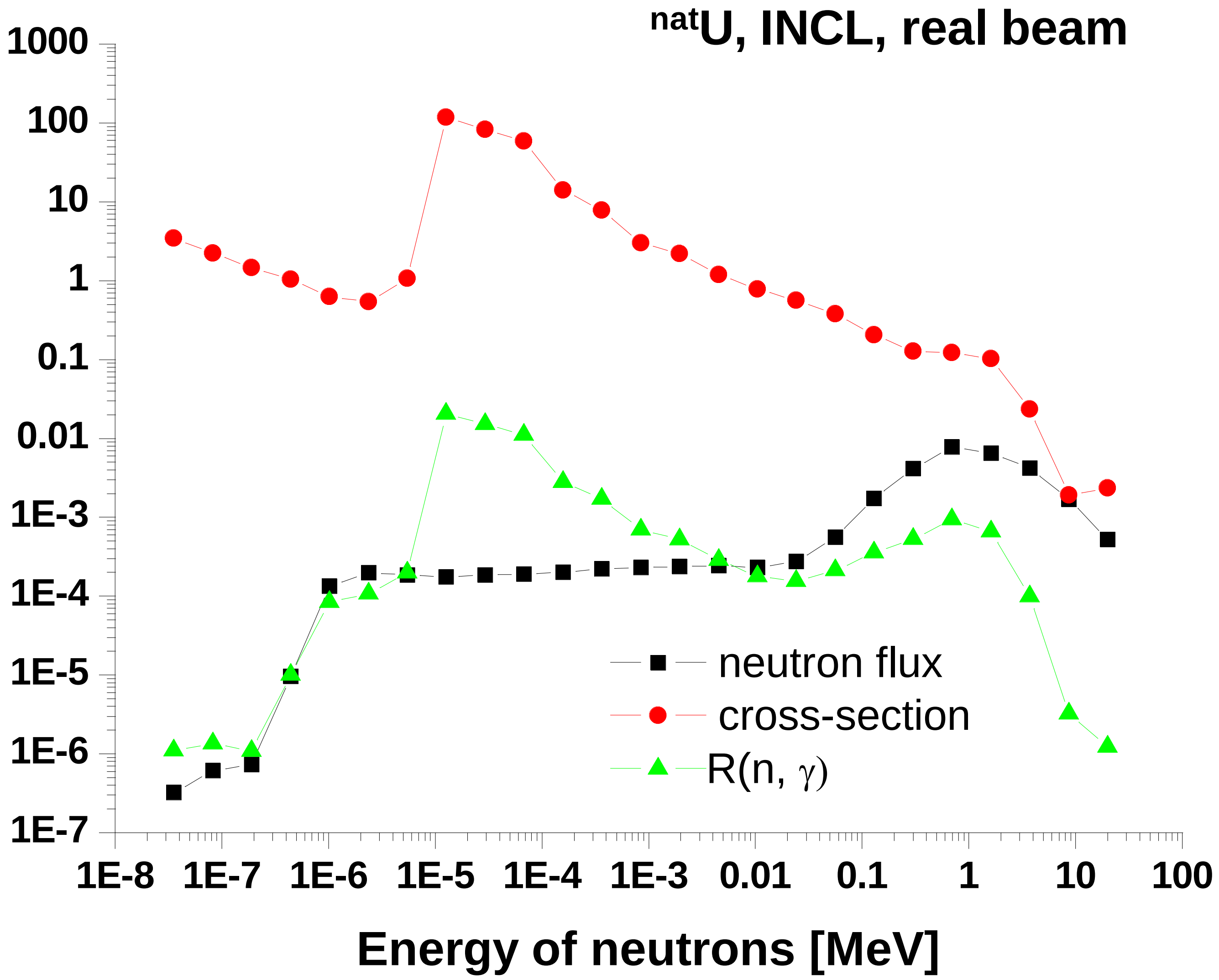


Ratio of neutron flux simulated in box 3 (uran) with different combination of intra-nuclear model and shape of beam.





^{nat}U, INCL, real beam
10
1
0.1
0.01
1E-3
1E-4
1E-5
1E-6
1E-7
1E-8
1E-8 1E-7 1E-6 1E-5 1E-4 1E-3 0.01 0.1 1 10 100 1000
Energy of neutrons [MeV]
neutron flux
cross-section
R(n,fission)



natU, INCL, real beam
1000
100
10
1
0.1
0.01
1E-3
1E-4
1E-5
1E-6
1E-7
1E-8
1E-7
1E-6
1E-5
1E-4
1E-3
0.01
0.1
1
10
100
Energy of neutrons [MeV]
neutron flux
cross-section
R(n, γ)

	232Th			Unat	
Reaction	**(n,g)**	**(n,f)**	**(n,2n)**	**(n,g)**	**(n,f)**
Reaction Rate, exper.	**3.03(10)E-26**	**5.89(60)E-27**	**1.60(16)E-27**	**2.97(14)E-26**	**2.24(10)E-26**
R(CEM-Gauss)	2.35E-26	2.38E-27	9.95E-28	5.87E-26	1.02E-26
R(CEM-real)	1.75E-26	1.83E-27	1.16E-27	3.66E-26	7.26E-27
R(INCL-Gauss)	2.74E-26	2.10E-27	1.09E-27	5.16E-26	7.80E-27
R(INCL-real)	2.49E-26	2.03E-27	1.06E-27	5.49E-26	7.93E-27
R(C-G)/R(C-r)	1.34	1.30	0.86	0.62	1.40
R(C-G)/R(I-r)	0.94	1.17	0.94	1.07	1.29
R(C-r)/R(I-r)	0.70	0.77	1.09	0.67	0.92
R(I-G)/R(I-r)	1.10	1.04	1.03	0.94	0.98
R(exper.)/R(I-r,calc.)	**1.22(4)**	**2.90(30)**	**1.51(15)**	**0.54(3)**	**2.82(13)**

C-G sign CEM-Gauss, C-r _ CEM-real, I-G _ INCL-Gauss, I-r _ INCL-real

$P(A_r, Z_r)$ - Transmutation rate.

$$P(A_r, Z_r) = m(A_r, Z_r,) / m(A_t, Z_t)$$

$$P(A_r, Z_r) = R(A_r, Z_r)\, N_d(\text{integral})\, (A_r / A_t)$$

With normalization to 10^9 beam particles

$$P_{norm}(A_r, Z_r) = 10^9\, P(A_r, Z_r) / N_d(\text{integral})$$

232Th (n,γ)233Th (β- decay,T1/2 = 22.3 min) → 233Pa (β- decay,T1/2 = 26.967 d) → 233U

232Th (n,2n)231Th(β-, 25.52 h) →231Pa(β-, 32760 y) →231U(n,γ) → 232U (T1/2 = 68.9 y)

238U (n,γ) 239U (β-, 23.4 min) →239Np(b-,2.4 d) → 239Pu (alpha, 24110 y) → 235U

Reaction	our		TARC	
	$P_{norm.}$ [10^{-17}g/g]	D_c [cm]	$P_{norm.}$ [10^{-17}g/g]	D_c [cm]
^{232}Th(n,γ)	3.09(13)	13.1	3.8(3)	122
			1.0(2)	150
^{238}U(n,γ)	2.87(9)	13.8	1.1(3)	107
			7.7(2)	94

Reaction $^{232}Th(n,2n)^{231}Th$

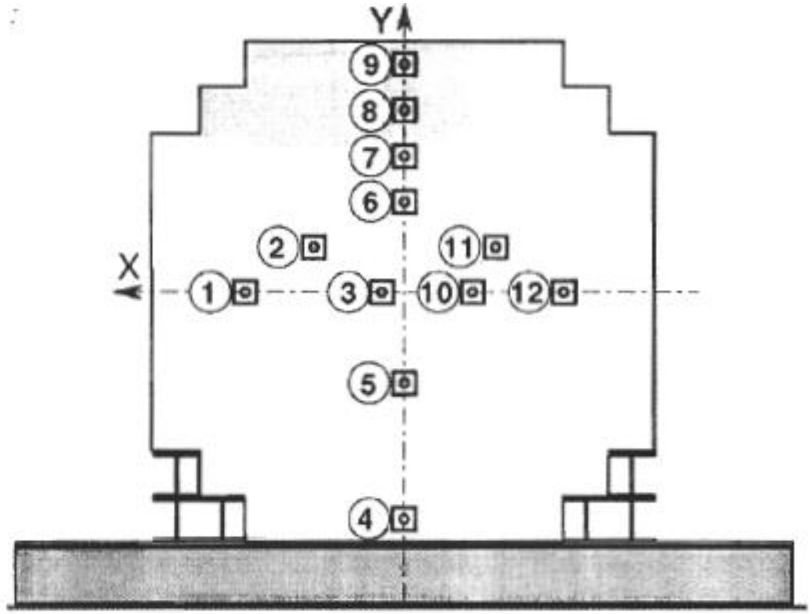
E_γ [keV]	our		TARC	
	B [10^{-6}]	D_c [cm]	B [10^{-6}]	D_c [cm]
25.646	3.96(51)	13.1	0.635(63)	4.0
84.216	4.47(65)		1.32(13)	
25.646			1.05(16)	8.5
84.216			2.11(32)	

$P_{norm}(^{231}Th) = 1.59(15)10^{-18}$ [g/g] our

	Th - foils			Unat. - foils	
	our	TARC		our	TARC
	(n, γ),(n, 2n)	(n, γ)	(n, 2n)	(n, γ)	(n, γ)
Weight (No.1)(mg)	**93.2**	**132**	**158**	**172**	**290**
Weight (No.2)(mg)			**678**		
Diameter (No.1)(mm)	**15**	**12.7**	**12.5**	**15**	**12.7**
Square (No.2)(mm)			**30x29**		
Thickness (No.1)(µm)	**45.0**	**88.9**	**110.3**	**52.0**	**127**
Thickness (No.2)(µm)			**66.5**		
Activity (No.1)(Bq)	**378**	**536**	**624**	**2244**	**3783**
Activity (No.2)(Bq)			**2753**		
Radial distance (No.1) Center - sample [mm]	**131**	**1220**	**~ 40**	**138**	**1070**
Radial distance (No.2) Center – simple(mm)		**1500**	**~ 85**		**940**
Beam particle	**deuteron**	**proton**	**proton**	**deuteron**	**proton**
Beam energy	**1.6 GeV**	**3.5 GeV /c**	**2. 5 GeV /c**	**1.6 GeV**	**3.5 GeV /c**
Sum of particle	$1.93.10^{13}$	$2.14.10^{13}$		$1.93.10^{13}$	$2.14.10^{13}$
Sum of particle (No.1)			$4.80.10^{12}$		
Sum of particle (No.2)			$9.01.10^{12}$		
Irradiation time (h)	6.65	8.5		6.65	8.5

TARC – Transmutation by Adiabatic Resonance Capture

The 334 t lead assembly, ~ cylinder diam. 3.3 m and length 3m



Summary of the coordinates of the centres of the 12 instrumented holes in the 334 t lead assembly volume. The beam is introduced through a 77.2 mm diameter and 1.2 m long blind hole

Hole no.	x (m)	y (m)	Hole no.	x (m)	y (m)
1	1.05	0.00	2	0.60	0.30
3	0.15	0.00	4	0.00	−1.50
5	0.00	−0.60	6	0.00	0.60
7	0.00	0.90	8	0.00	1.20
9	0.00	1.50	10	−0.45	0.00
11	−0.60	0.30	12	−1.05	0.00

Summary:

Measurements and analyzing

32 Spectra – monitor Al, sample ^{232}Th, ^{nat}U

133 peaks – calculated E_γ, I_γ, $T_{1/2}$ – determined reaction products A_r, Z_r

Experimental Reaction rate

Th: ^{233}Pa, ^{231}Th, ^{99}Mo

U: ^{239}Np, ^{99}Mo, ^{132}Te, ^{133}I, ^{135}I, ^{135}Xe, ^{140}Ba, ^{143}Ce

Estimate: R(Th(n,fission)) and R(U(n,fission))

Calculation with MCNPX 2.6C – CEM, INCL, real, Gauss. Neutron flux, Reaction rate, Th, U, (n,γ), (n,2n) (n,fission)

Calculation of Transmutation rate: Th, U with (n,γ), (n,2n) and comparisson with TARC data

THANK YOU FOR YOUR ATTENTION!