Experimental Measurement of the Level of Transmutation and Neutron Flux Density in Subcritical Nuclear Reactors ADS

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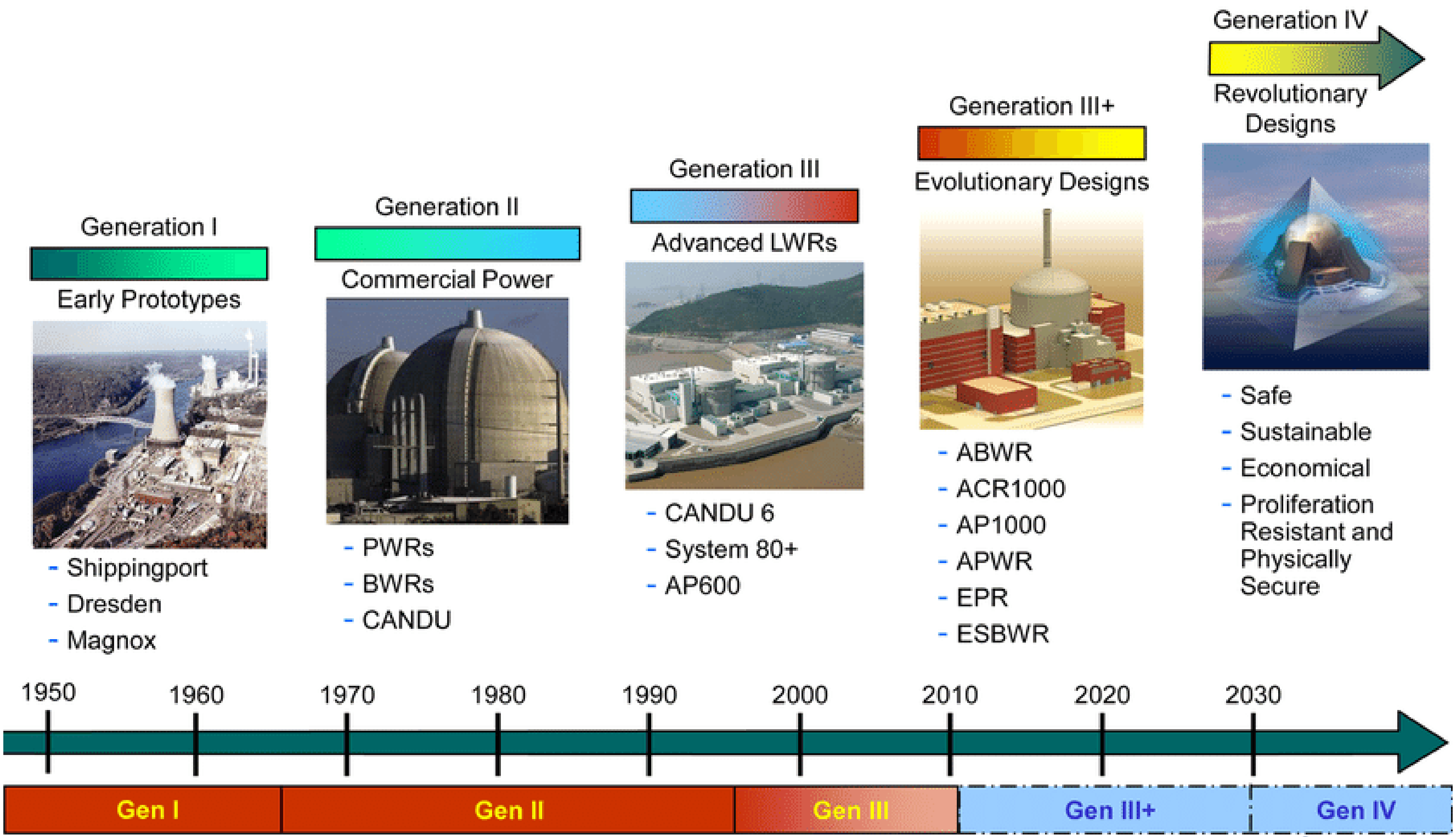
Outline

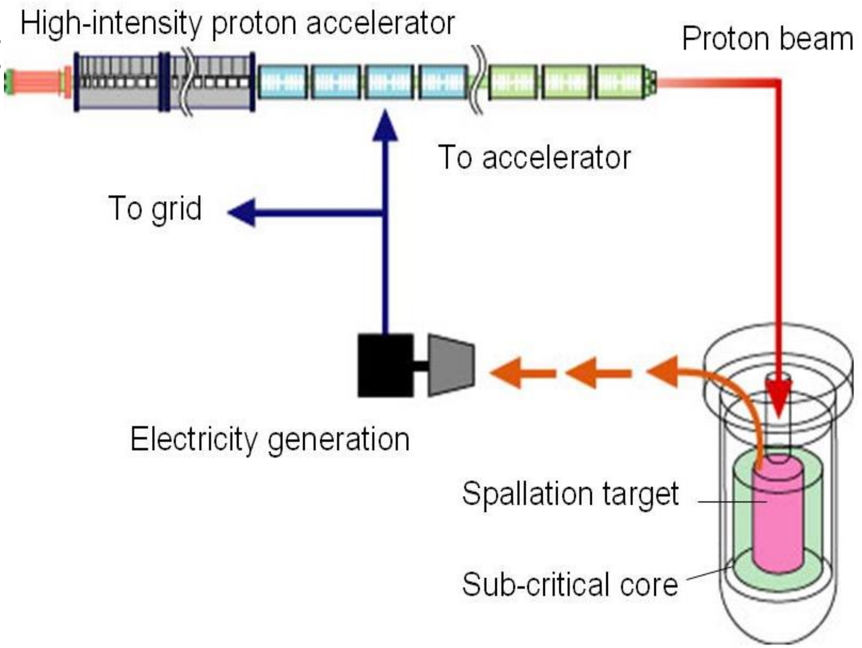
- Study motivation. ADS systems
- «Quinta» experiment definition
- DEIMOS and efficiency calibration
- Determine parameter B and results from Yttrium
- Neutron flux calculation
- Steel results
- Conclusion

Evolution of Nuclear Power



Accelerator-Driven System

- Subcritical system
  - $k_{ef} = \frac{number\ of\ neutrons\ in\ one\ generation}{number\ of\ neutrons\ in\ preceeding\ generation} < 1$
- Neutron source
  - Accelerator + spallation target
- Core can include
  - MA + LLFP
  - Weapons-grade plutonium
  - Thorium

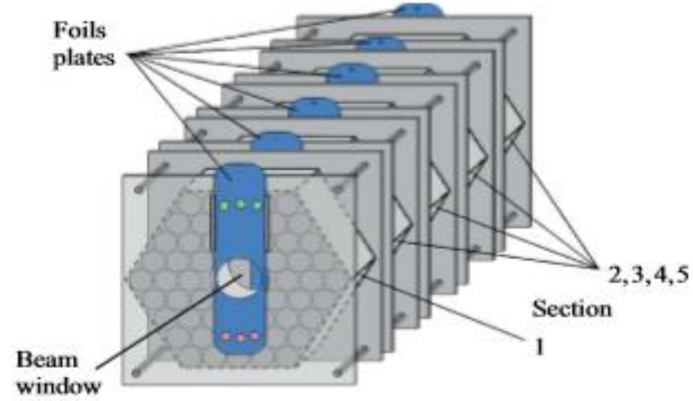


Purpose of the experiment

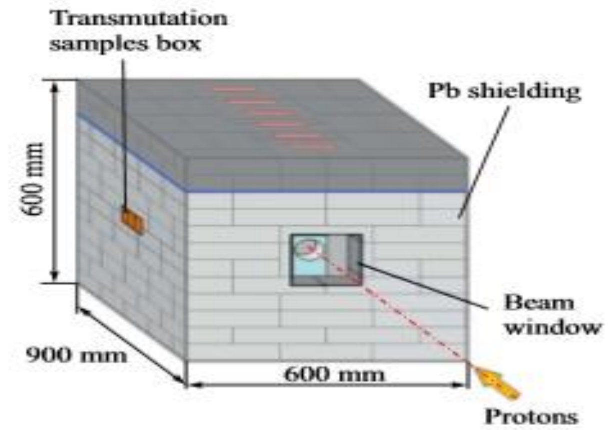
The main goal of the experiment is to determine the density of fast neutron fluxes in **QUINTA** experiment using the level of transmutation in subcritical reactors, which can be determined by using **neutron activation method**.

The experimental assembly - Quinta

- Consist of about 512 kg natural uranium
- Divided into 5 section
- Each section consist uranium cylindrical rods in the aluminium cover (1 – 51 ,2-5 – 61)
- Surrounded by lead bricks cover



Scheme of uranium core of the Quinta set. [1]



Scheme of Quinta assembly surrounded by the lead bunker. [1]

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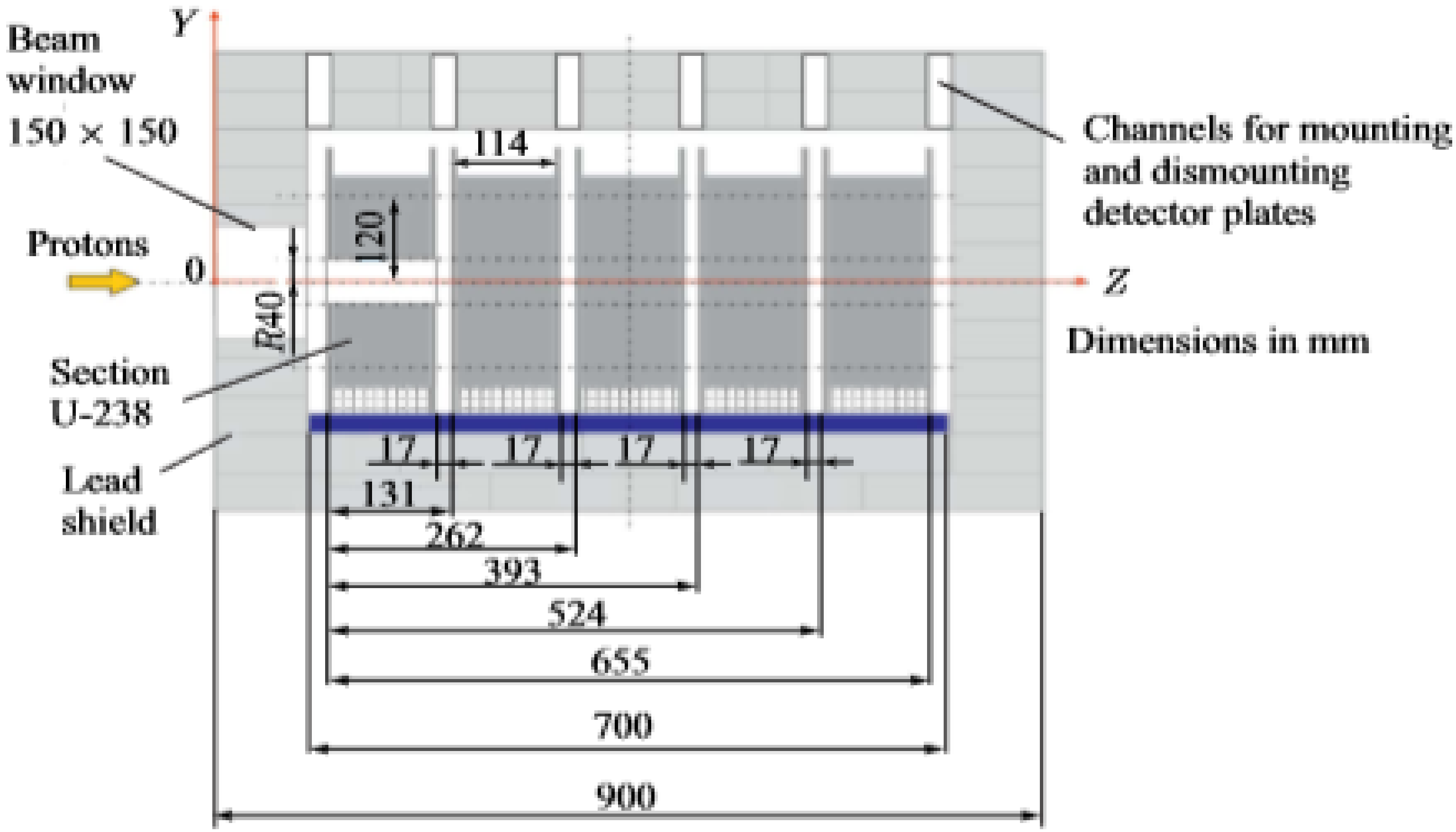
Experiment Quinta



View of experimental system along with the lead shield along the beam axis. [1]

Sample – Yttrium

- Natural yttrium with a purity of 99,99%
- Abudance of only one isotope Y-89
- Sufficient half-life to measure products of Y-89 (n,xn) reactions

Samples of Yttrium.

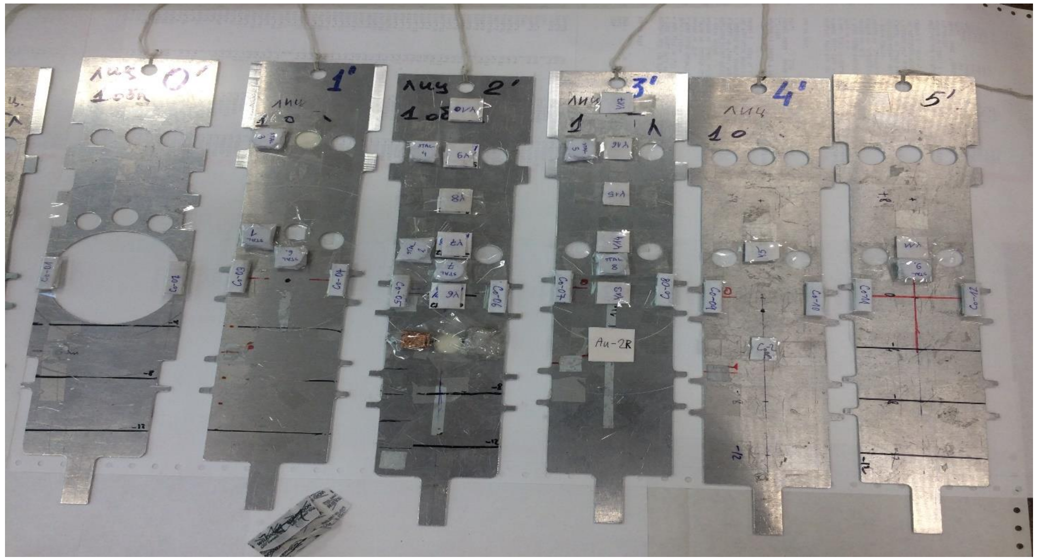
Sample – Stainless steel

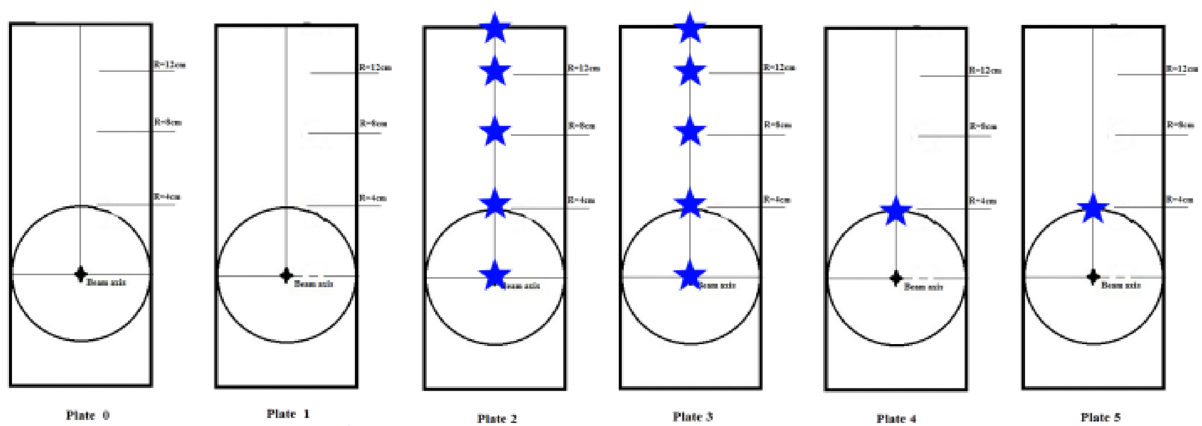
- The most common and widely used stainless steel

Elements	AISI304 [%]	Maximum value [%]
Carbon (C)	<0.08	0.2
Chromiuim (Cr)	17.50-20.00	28.00
Manganese (Mn)	<2.00	10.50
Sillicon (Si)	<1.00	4.50
Molybdenum (Mo)	-	8.00
Copper (Cu)	-	3.50
Nickel (Ni)	8.00-11.00	36.00
Niobium (Nb)	-	1.00
Tungsten (W)	-	2.5
Iron (Fe)	Balance	Balance
P, S, N, B, Ti, Ce	-	<0.8

Compositon of stainless steel.

Experiment Quinta





★ - Y89 sample, 5 hours irradiation.

The placement of the Y-89 and stainless steel on the aluminium plates.

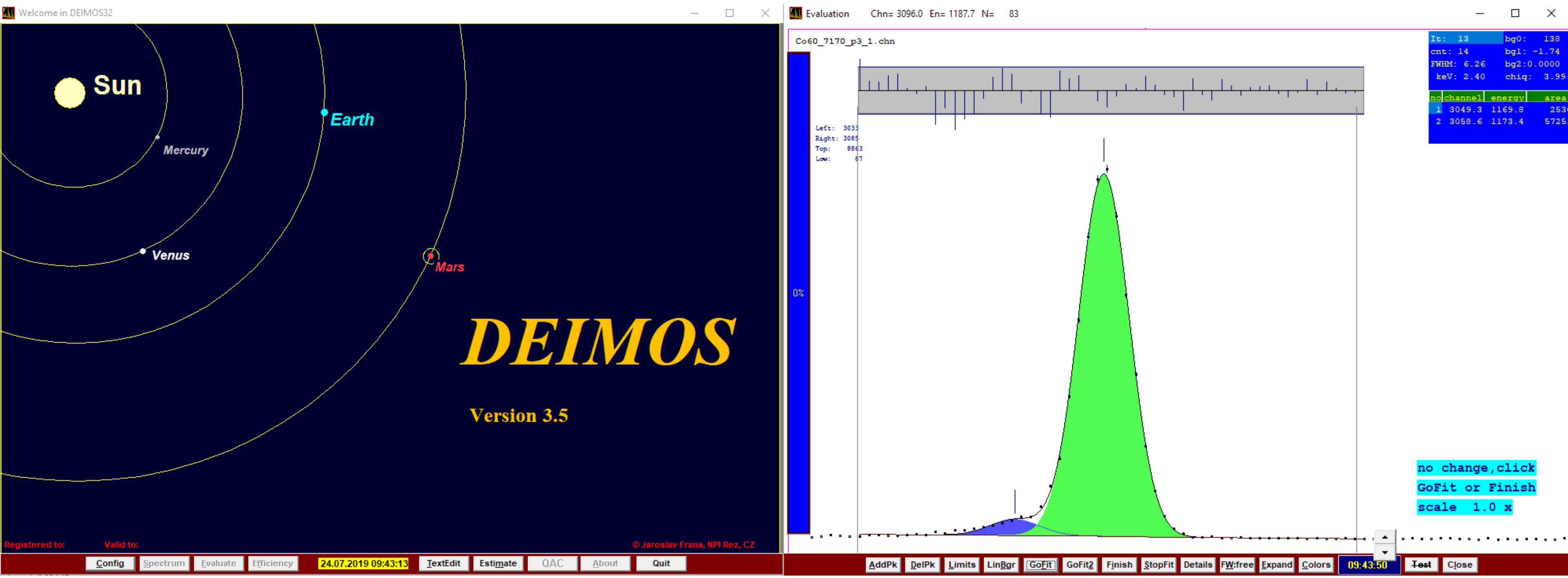
Gamma Spectrometry System

- High Purity Germanium (HPGe) detector with liquid nitrogen cooling
- HPGe consists of
  - Ge crystal
  - Lead shielding
  - Dewar container
  - Electronics and PC

HPGe gamma spectormetry system.

Software DEIMOS and energy calibration

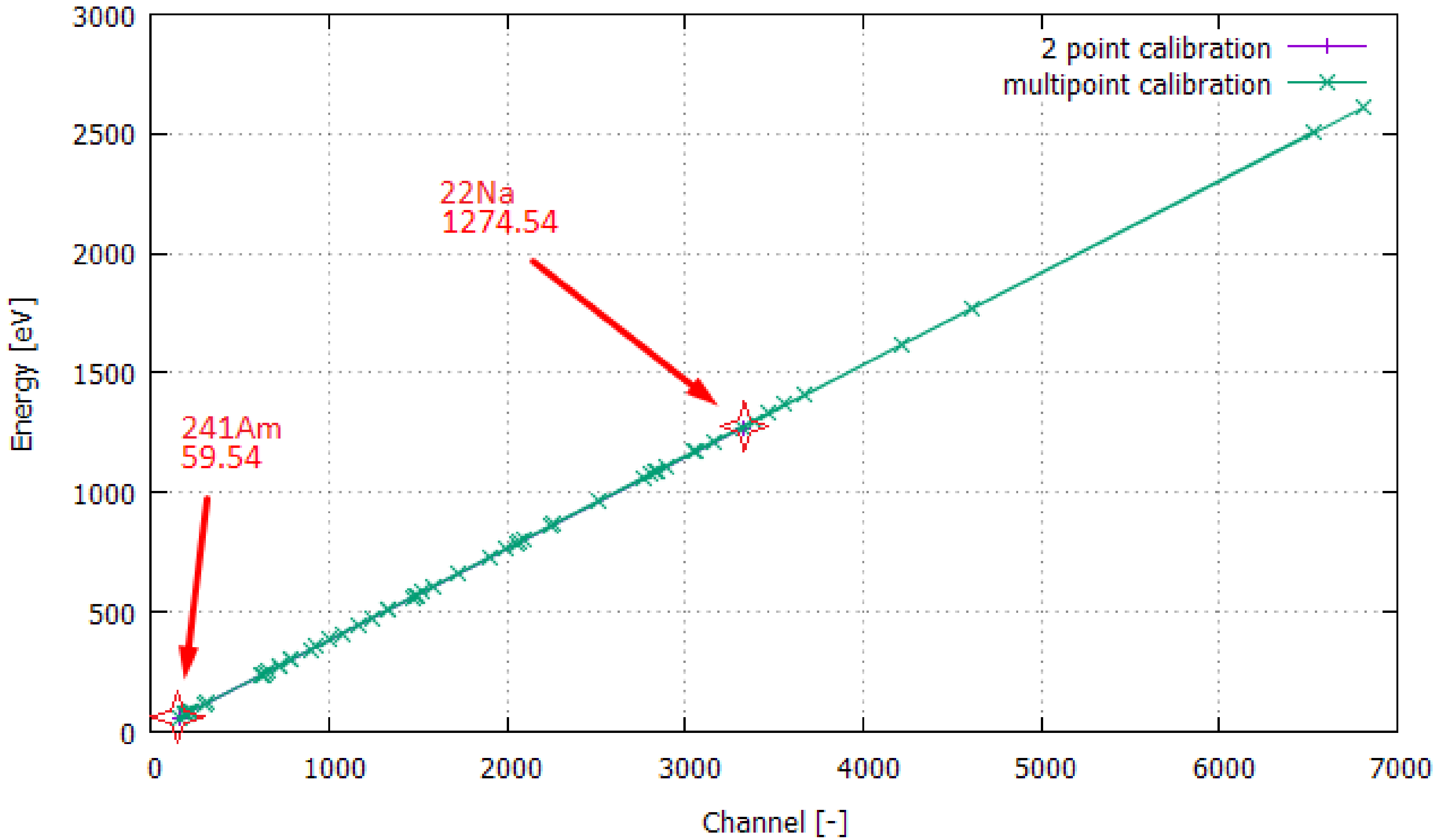
- Software for spectra analysis
- Developed in UJV Rez in the Czech Republic



Screens from DEIMOS

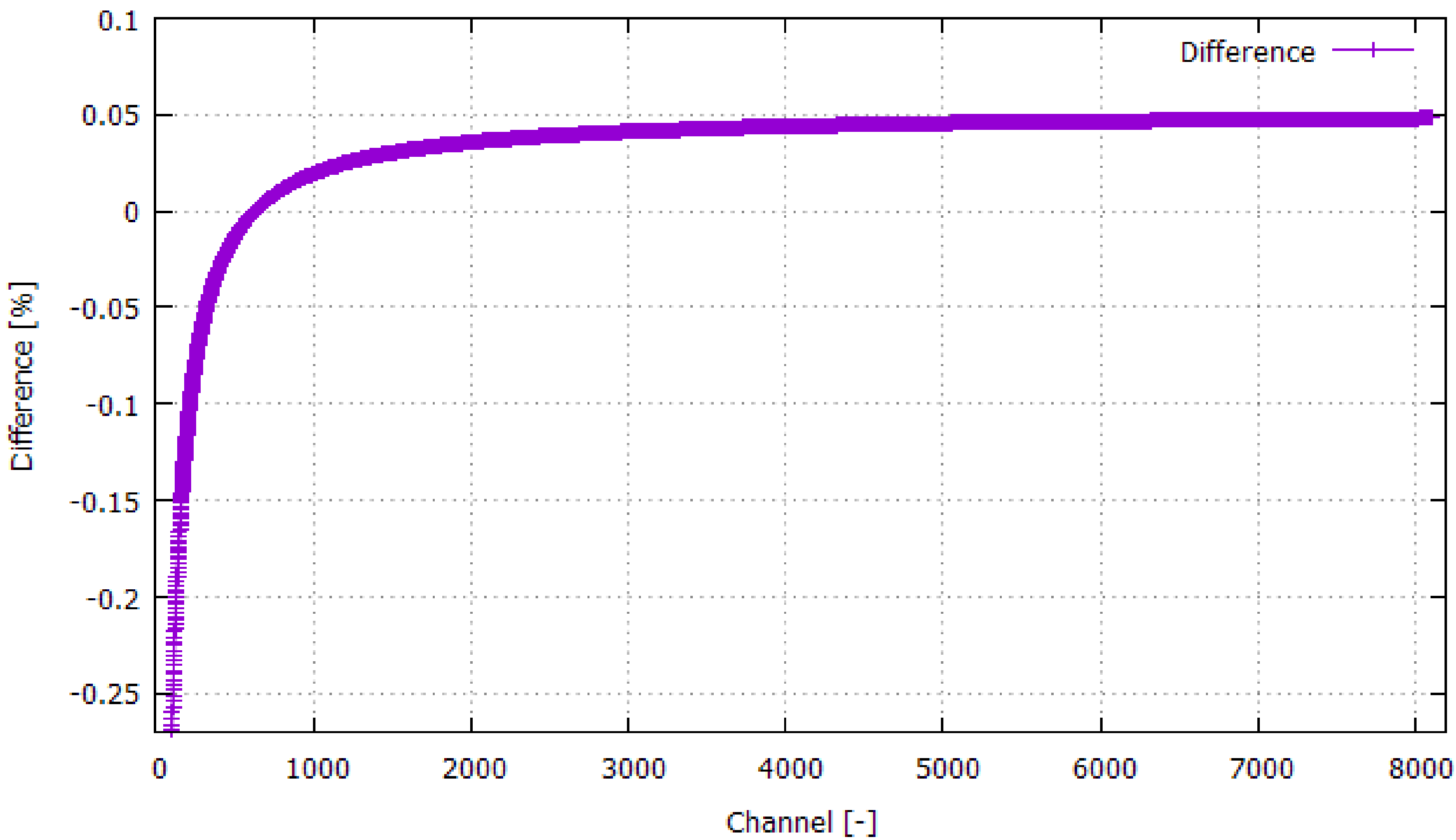
Energy calibration

Comparison of two ways of enegry calibration in DEIMOS.



Difference between 2-point and multi-point calibration

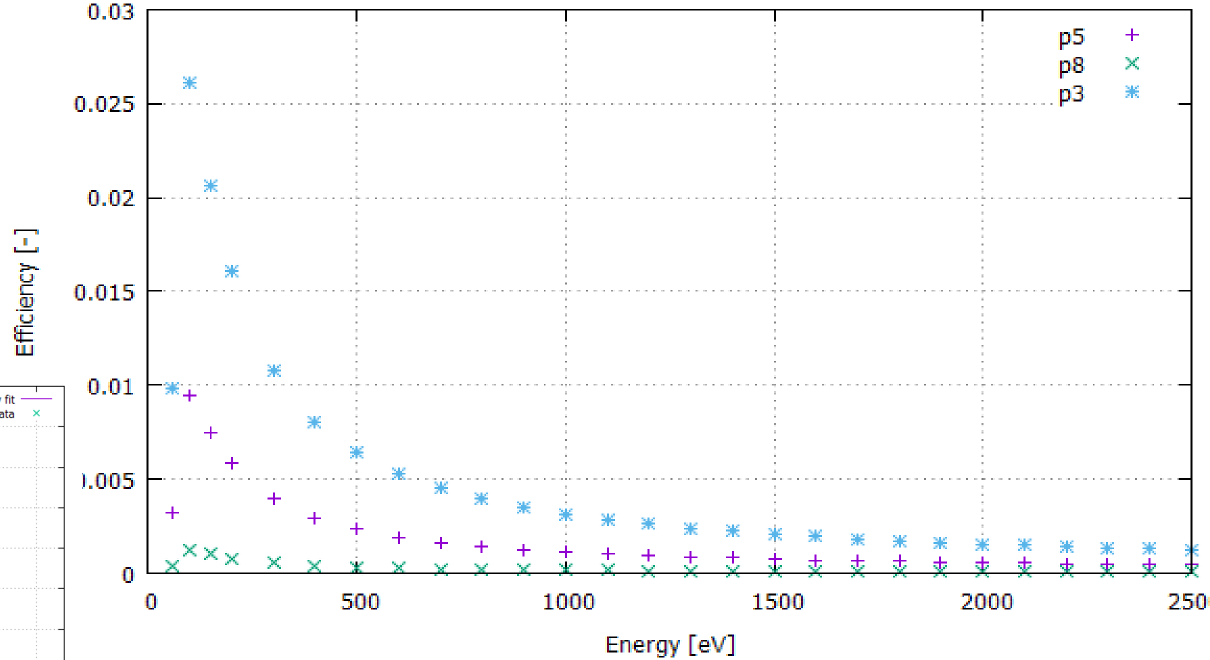
Comparison of two ways of enegry calibration in DEIMOS.

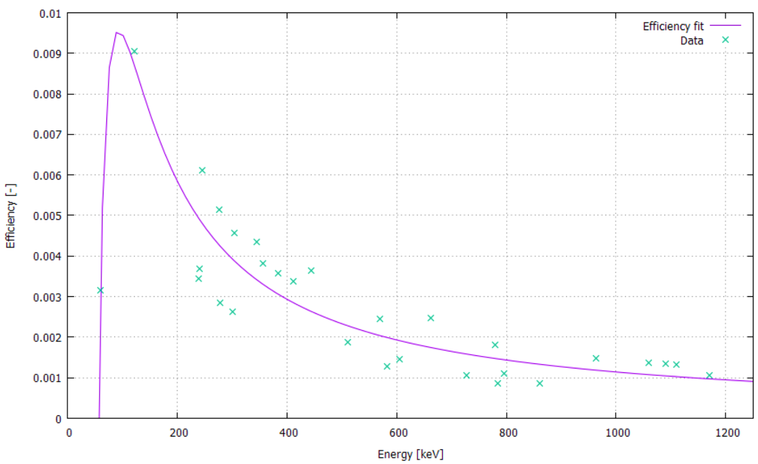


Detector efficiency

- For fitting was used GNU-PLOT
- Energy range: 59 – 2500 keV
- Sources:
  Am241, Ba133, Bi207, Co60, Cs134, Cs137, Eu152, Na22, Th228

$$y = \frac{a}{x} + \frac{b}{x^2} + \frac{c}{x^3}$$





Data analysis – Parameter B

$$B = N_i \frac{1}{m \cdot I} \cdot \frac{\Delta S(G) \cdot \Delta D(E)}{\frac{N_{abs}}{100} \cdot \varepsilon_p(E) \cdot COI(E,G)} \cdot \frac{\lambda \cdot t_{ira}}{1 - exp(-\lambda \cdot t_{ira})} \cdot exp(\lambda \cdot t_+) \cdot \frac{\frac{t_{real}}{t_{live}}}{1 - exp(-\lambda \cdot t_{real})}$$

- B – numer of nuclei per 1 g of sample and per 1 nucleus from the accelaerator
- N_1 – area of the peak (number of counts)
- N_{abs} – absolute intensity of the line in percentage
- $E_p(E)$ – detector effciency in the energy function
- COI(E,G) – cascade effects in the energy and geometry function
- I – absolute numer of nuclei in the beam from the accelerator
- m - mass of the sample

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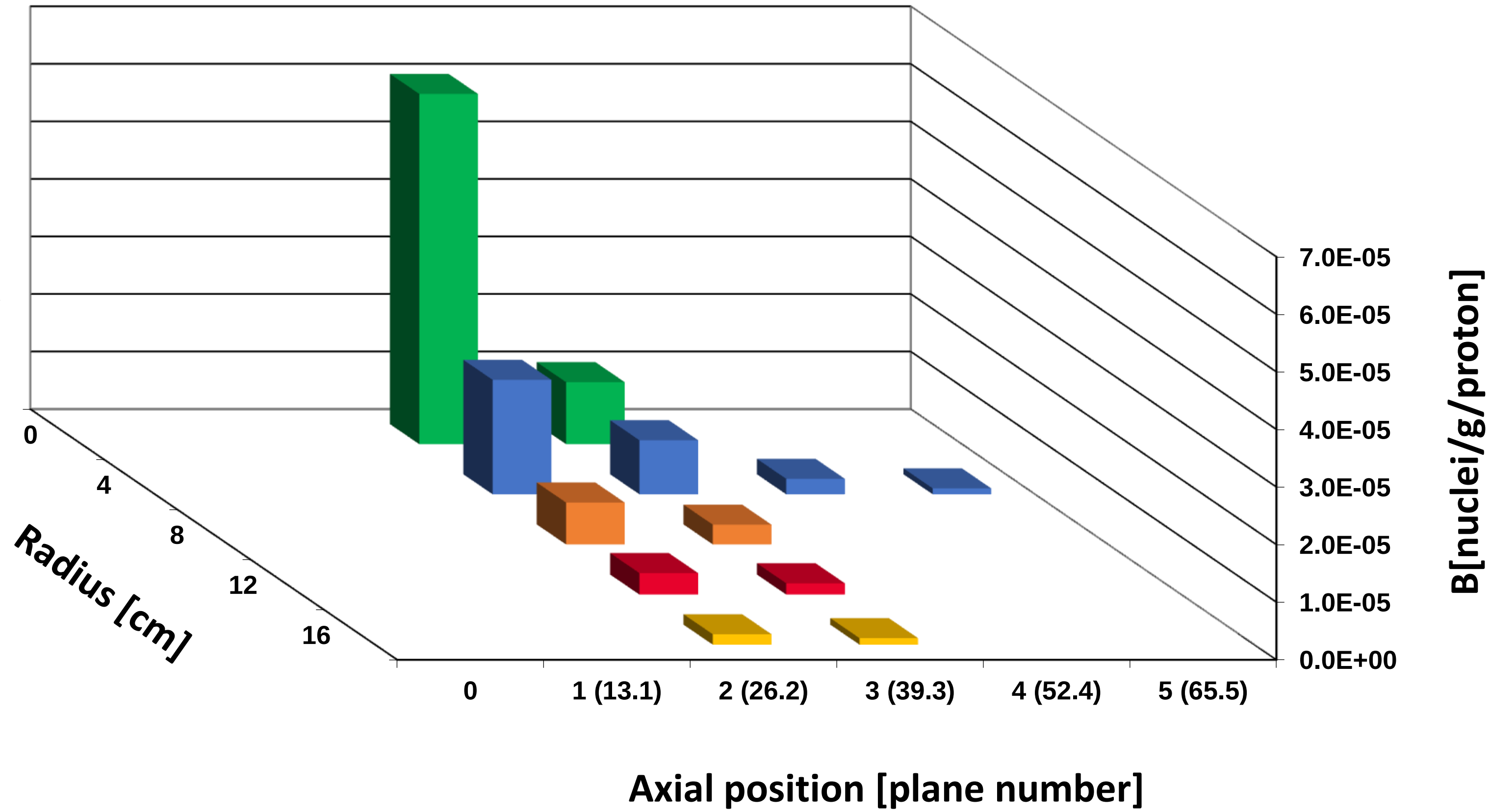
- △S(G) – sample area correction in the geometry function
- △D(E) – self-absorption correction in the energy function
- λ – decay constant
- $t_{1/2}$ – half time period
- t_{ira} – irradiation time
- t_+ – time between the end of the experiment and the start of the measurement

Production of Y-88

Y-88 spatial distribution based on lines 898.042 and 1836.063 keV

660 MeV proton beam



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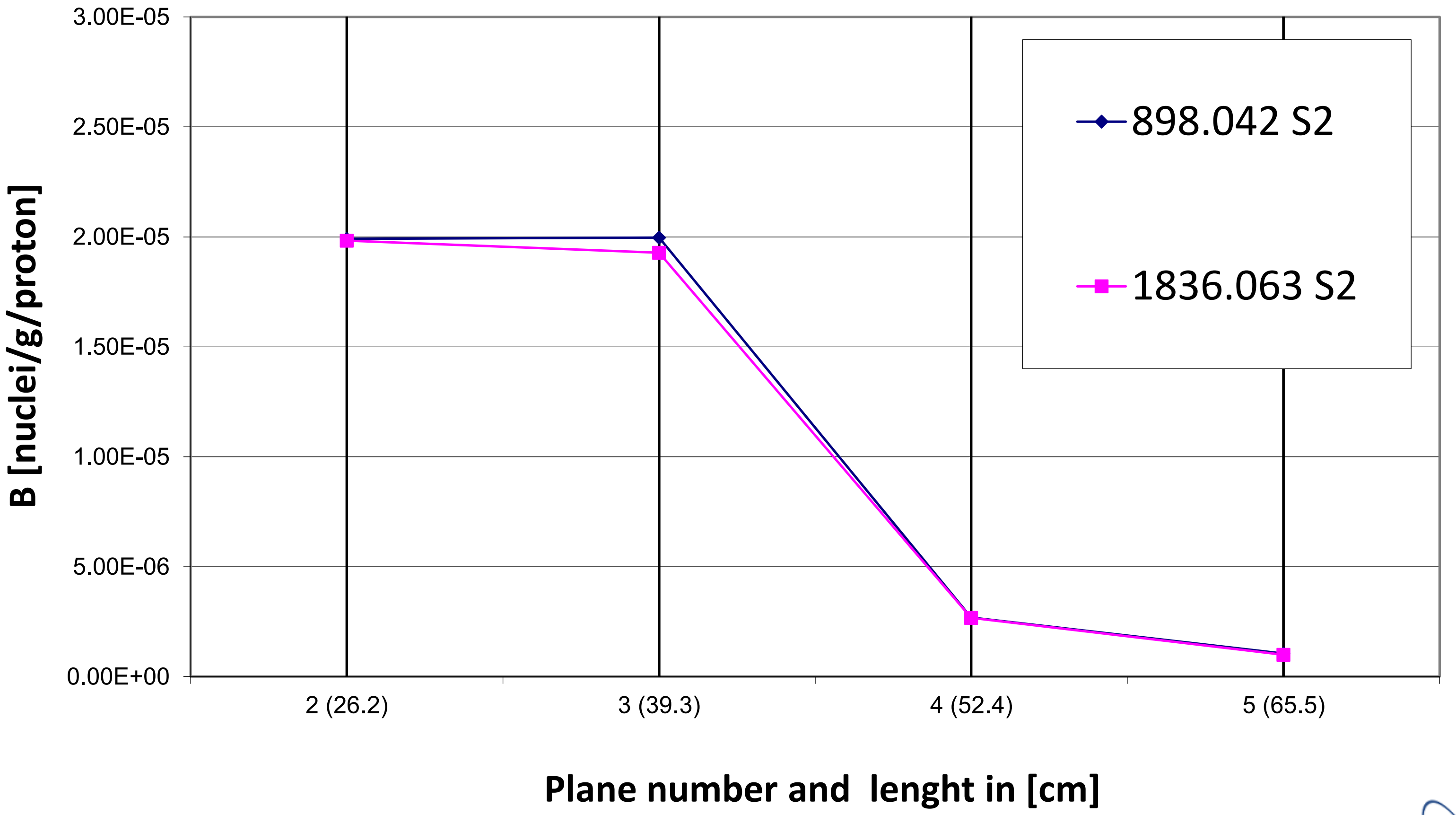
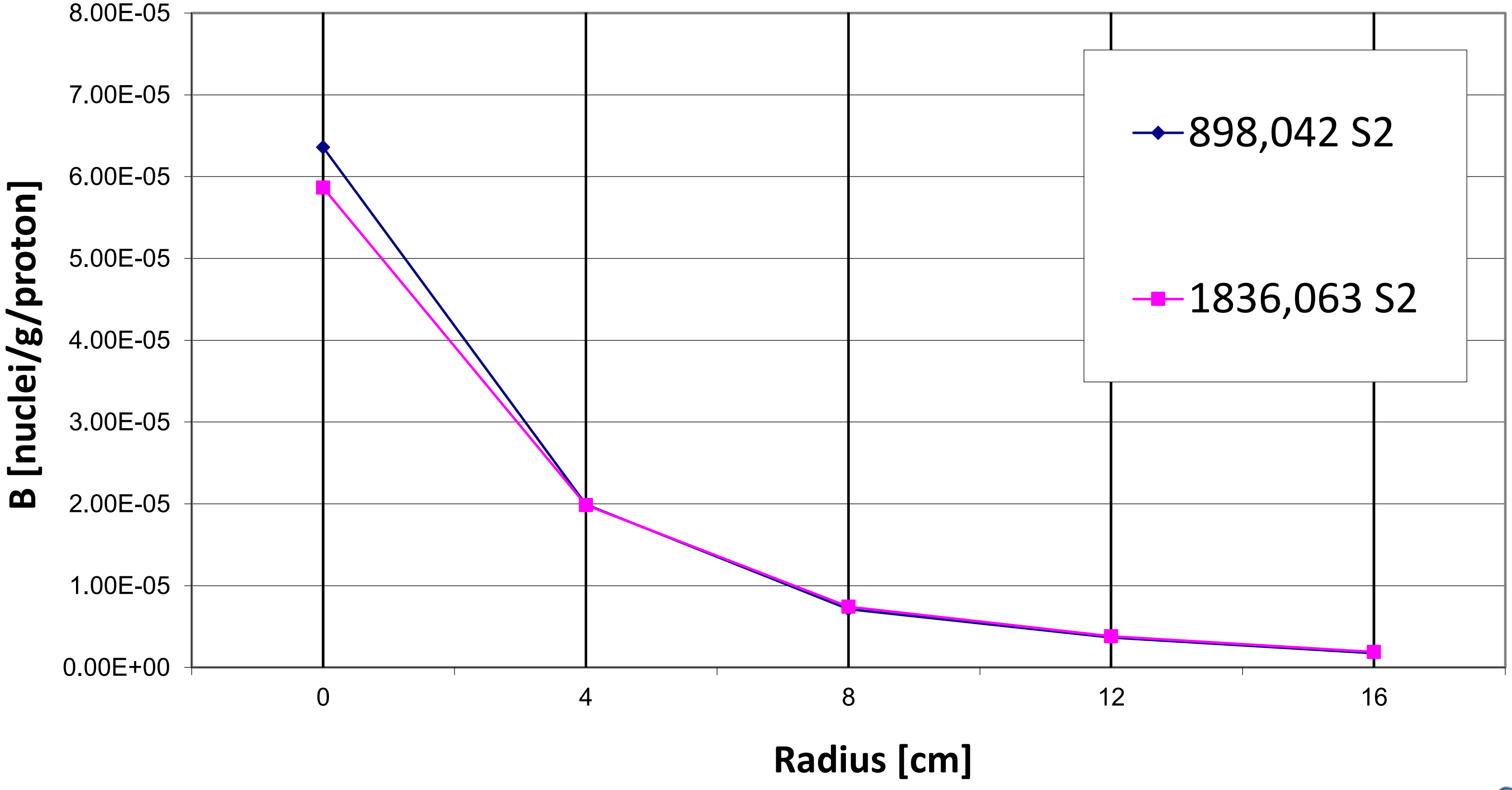
Production of Y-88 in R=4 cm axial distribution



Production of Y-88 plane 2 radial distribution



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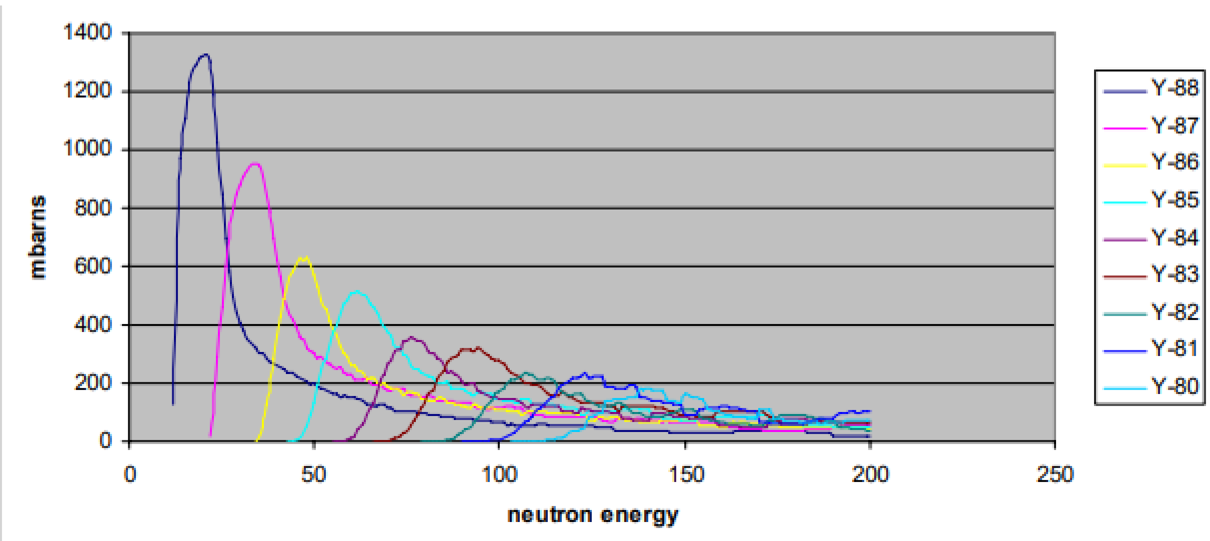
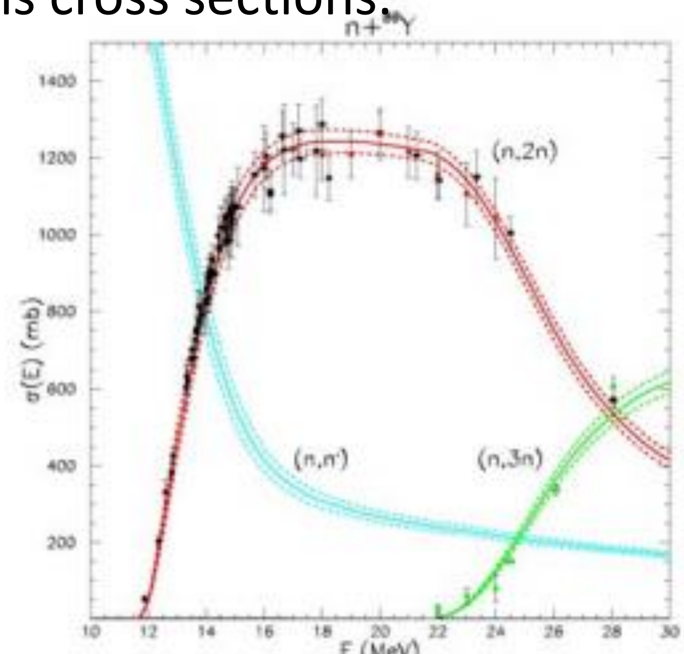
Neutron flux calculation

- To evaluate the high energy neutron field we need to know the microscopic cross section for the (n,xn) reaction of 89Y. The available experimental data of microscopic cross section for the reaction 89Y(n, 2n)88Y and the small part for reaction 89Y(n, 3n)87Y are going from EXFOR data base. Since the nuclear data libraries are poor TALYS code was used for calculation of (n,xn) reactions cross sections.



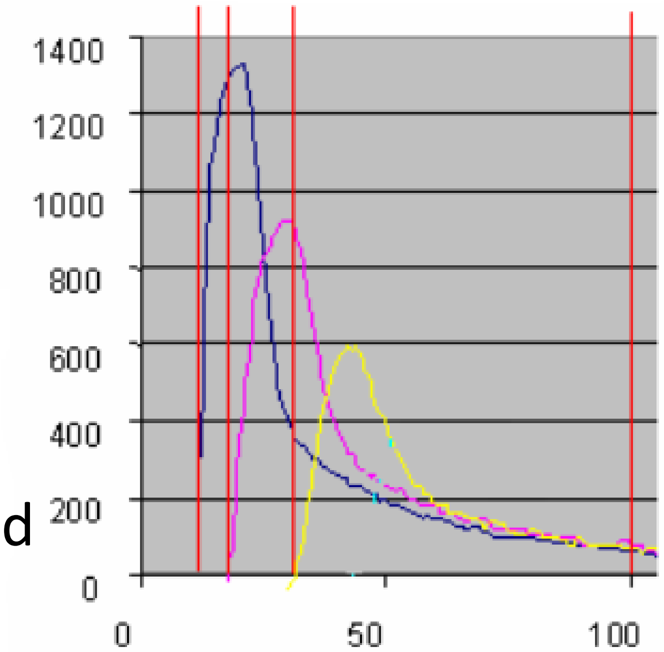


Neutron flux calculation

- Reaction Y-89 (n,xn):

- Y-89 (n,2n) Y-88 E_{th}=11,5 MeV
- Y-89 (n,3n) Y-87 E_{th}=20,8 MeV
- Y-89 (n,4n) Y-86 E_{th}=32,7 MeV

- Interval for neutron flux was divided into 3 groups according to the threshold energy
- 11.5 – 20.8 MeV
- 20.8 – 32.7 MeV
- 32.7 – 100 MeV



Neutron flux calculation

$$B^{88}\,C = \overline{\phi}_1\,\overline{\sigma}_{11} + \overline{\phi}_2\,\overline{\sigma}_{12} + \overline{\phi}_3\,\overline{\sigma}_{13}$$

$$B^{87}\,C = 0 + \overline{\phi}_2\,\overline{\sigma}_{22} + \overline{\phi}_3\,\overline{\sigma}_{23}$$

$$B^{86}\,C = 0 + 0 + \overline{\phi}_3\,\overline{\sigma}_{33}$$

$$C = \frac{S\,G^{89}}{A\,t}$$

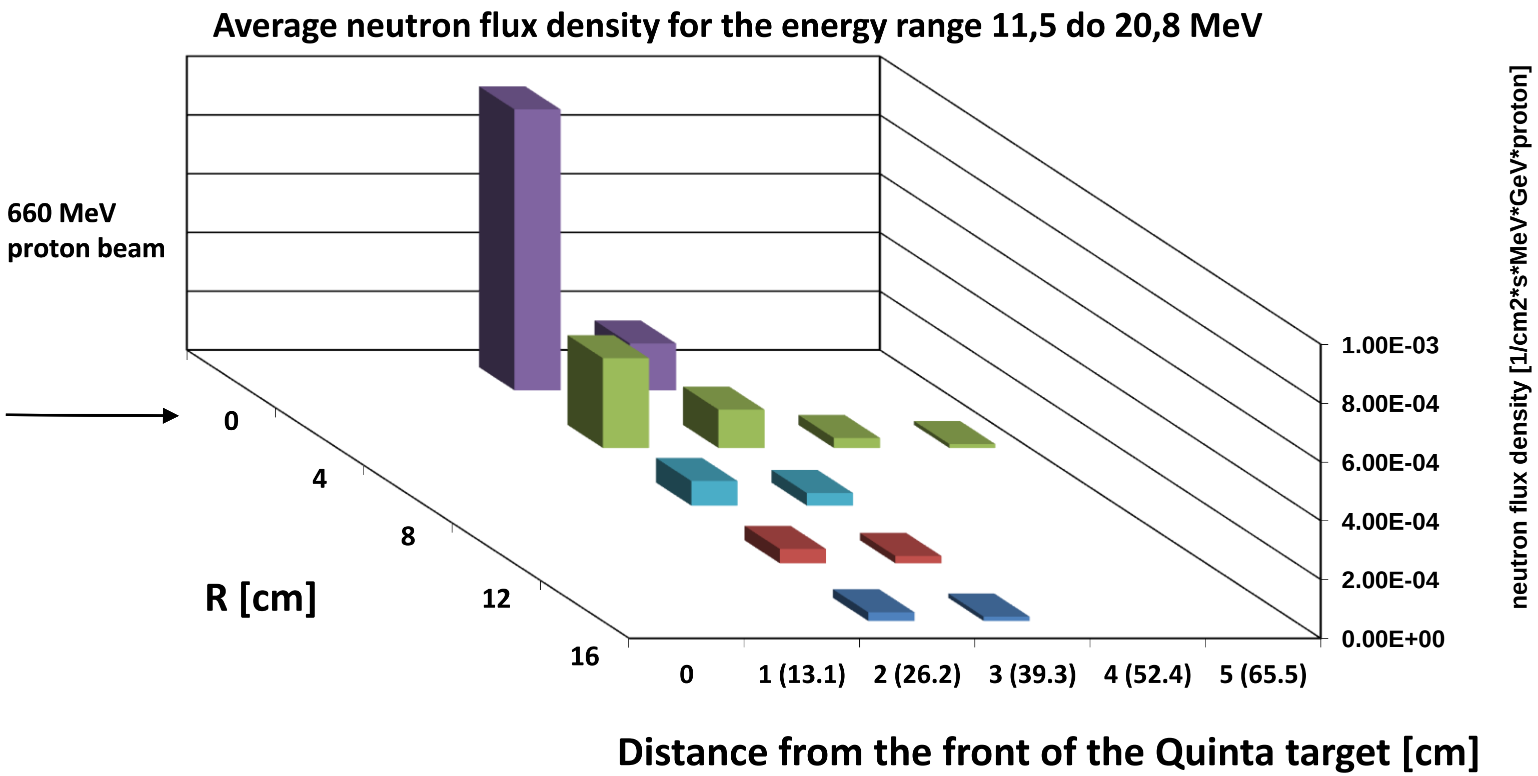
$$\overline{\phi}_1 = \frac{C}{\overline{\sigma}_{11}}\left[B^{88} - B^{87}\frac{\overline{\sigma}_{12}}{\overline{\sigma}_{22}} + B^{86}\left(\frac{\overline{\sigma}_{23}\,\overline{\sigma}_{12}}{\overline{\sigma}_{33}\,\overline{\sigma}_{22}} - \frac{\overline{\sigma}_{13}}{\overline{\sigma}_{33}}\right)\right]$$

$$\overline{\phi}_2 = \frac{C}{\overline{\sigma}_{22}}\left[B^{87} - B^{86}\frac{\overline{\sigma}_{23}}{\overline{\sigma}_{33}}\right]$$

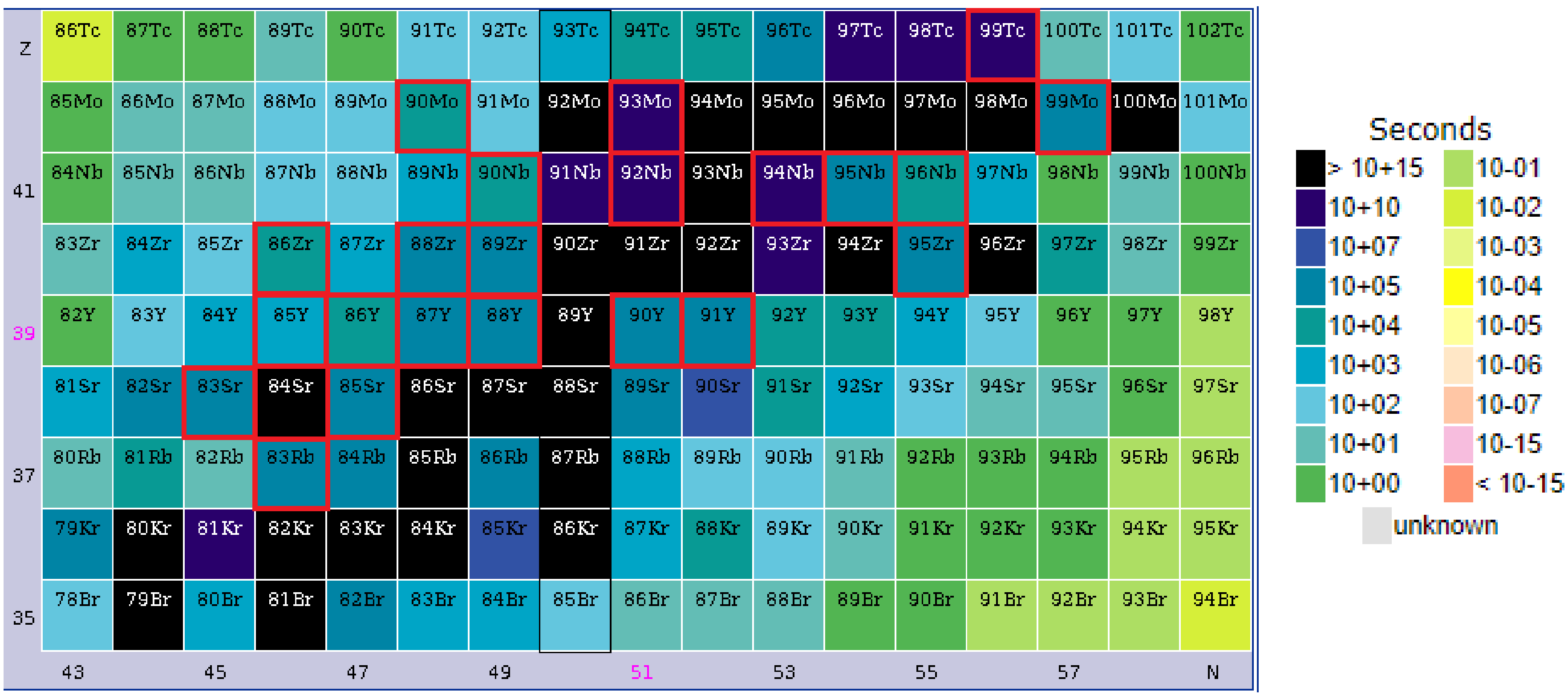
$$\overline{\phi}_3 = \frac{C}{\overline{\sigma}_{33}}B^{86}$$

- B - parameter B for the isotope
- S - total number of protons from accelerator, which interact with the detector during the experiment
- A - Avogadro constans
- t - time of irradiation [s]
- σ - average cross-section for reaction (n,xn) in particular energy range [barn]
- G - atomic mass of the isotope

Neutron flux density for the energy range per primary particle - results



Isotopes found in steel samples



Conclusion

- The purpose of the project was the research of neutron flux that was caused by high energy proton beam created by accelerator in the experimental assembly containing natural uranium (**Quinta** experiment)
- **Fast neutron flux** is used to plan further ADS subcritical experiments and future nuclear power plants especially their fuel cycle
- DEIMOS: **two point** energy calibration is enough
- Detector efficiency was successfully fitted by known standards
- Production of Yttrium isotopes **decreases** with **increasing** distance from the source of primary neutrons
- Neutron flux **peak** is for the second plane for closest position to the target because of construction of assembly
- Data of activation of steel samples will be analyzed **later** that will mainly improve knowledge about construction materials for fast reactors

Thank you for attention!

Questions?

References

1. M. Bielewicz, T. Hanusek, A. Jaskulak, M.Peryt, S.Tiutiunnikov, Determining the fast neutron flux density and transmutation level measurements in ADS bythe use of a threshold nuclear reaction, September 2018.
2. Source of image on slide 3: https://www.researchgate.net/figure/The-evolution-of-nuclear-power_fig9_325855950
3. Source of image on slide 4: https://nsec.jaea.go.jp/ndre/ndre3/trans/objective-e.html