



- Nuclear Physics Institute, Academy of Sciences of Czech Republic
- Department of Nuclear Reactors, Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague

Cross-section measurements of the (n,xn) threshold reactions

1.6 GeV deuteron irradiation of the
Energy plus Transmutation setup

Ondřej Svoboda



Outline

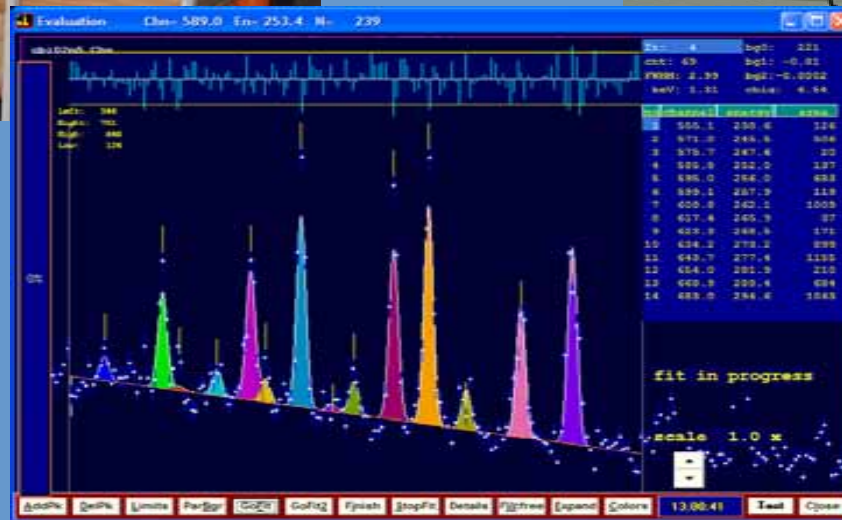
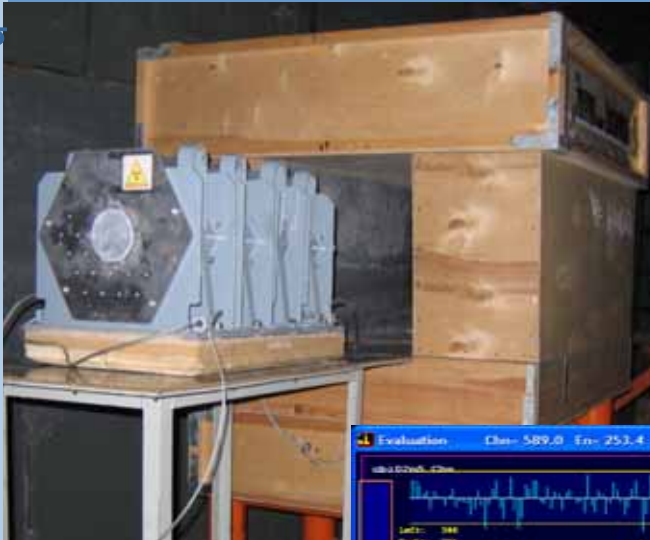
- Motivation for σ measurements
- Requirements
- TSL Uppsala
- Cyclotron Řež
- σ conclusion
- E+T: 1.6 GeV d+
- Simulations & comparisons
- Data share
- E+T conclusion

- Motivation for σ measurements
- Requirements for σ measurements
- TSL Uppsala experiment
- Experiments on Cyclotron in Řež
- Cross-section conclusion
- 1.6 GeV deuteron E+T experiment
- Simulations and comparisons of Exp \times Sim
- Data share space
- E+T conclusion



Motivation for σ measurement – E+T

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 - Energy plus Transmutation
 - Yield to neutron flux
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$$N_{yield} = \frac{S_p \cdot C_{abs} \cdot C_{irr}}{I_\gamma \cdot \epsilon_P(E) \cdot C_{oi} \cdot C_{area}} \cdot \frac{t_{real}}{t_{live}} \cdot \frac{1}{m_{foil}} \cdot \frac{e^{(\lambda \cdot t_0)}}{1 - e^{(-\lambda \cdot t_{real})}} \cdot \frac{\lambda \cdot t_{irr}}{1 - e^{(-\lambda \cdot t_{irr})}}$$



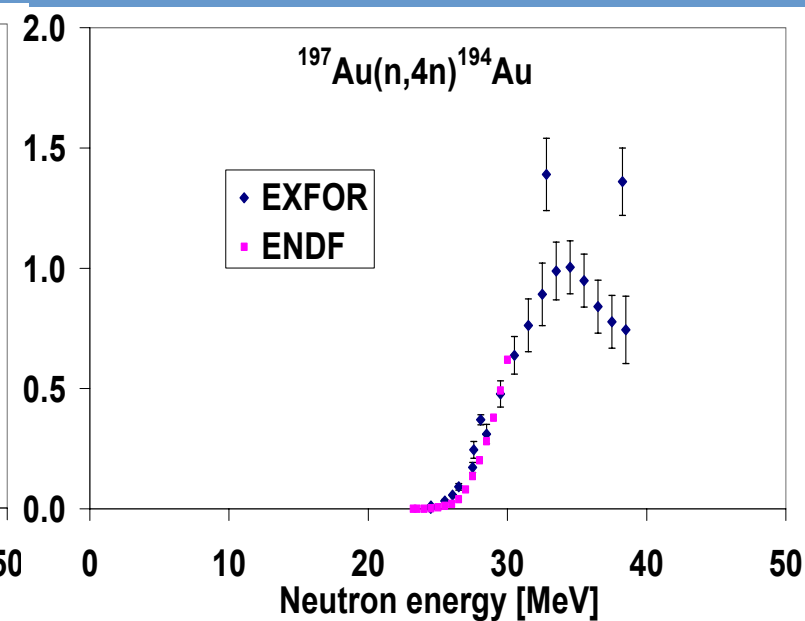
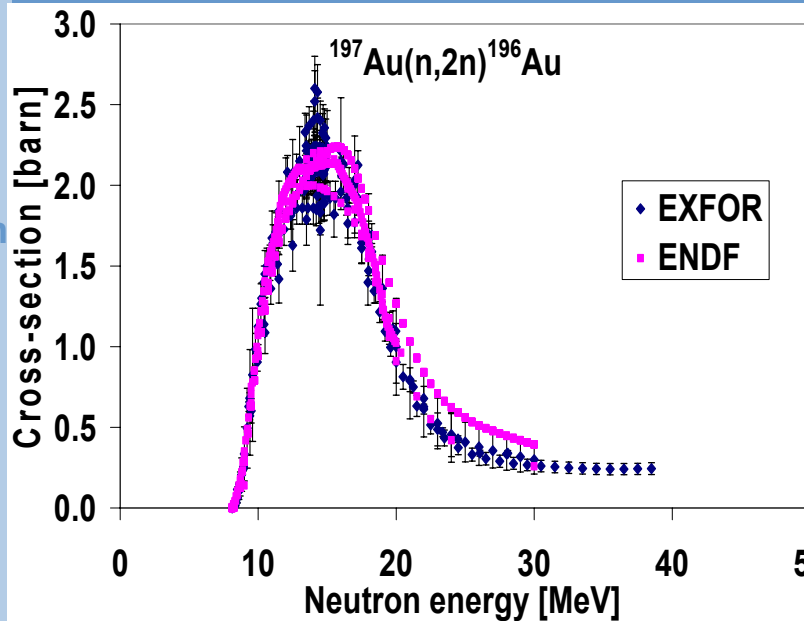
Yield to neutron flux problem

Solving a Fredholm equation we can find $\Phi(E)$:

Measured in E+T $\leftarrow N_{yield} = \int_{E_{thresh}}^{E_{beam}} \Phi(E) \sigma(E) dE$

We would like to find!
(Up to know only MCNPX simulation)

Poor knowledge of σ
We want to measure



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Requirements for σ measurements

Requirements for σ -measurements by activation method:

- high energy neutron source with good intensity
- (quasi)monoenergetic neutrons with well known spectrum
- pure monoisotopic samples
- good spectroscopic equipment – γ and X-rays spectrometers
- knowledge about the corrections on beam fluctuation, self- absorption, non-point like emitters...

Evaluation process:

Irradiation \rightarrow HPGe \rightarrow Spectra evaluation \rightarrow Corrections \rightarrow N_{Yield}

$$\sigma = \frac{N_{yield} \cdot S \cdot A}{N_n \cdot N_A}$$



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Measured materials

- Motivation for σ measurements

- Requirements

- Equipment
- *Materials*

- TSL Uppsala

- Cyclotron Řež

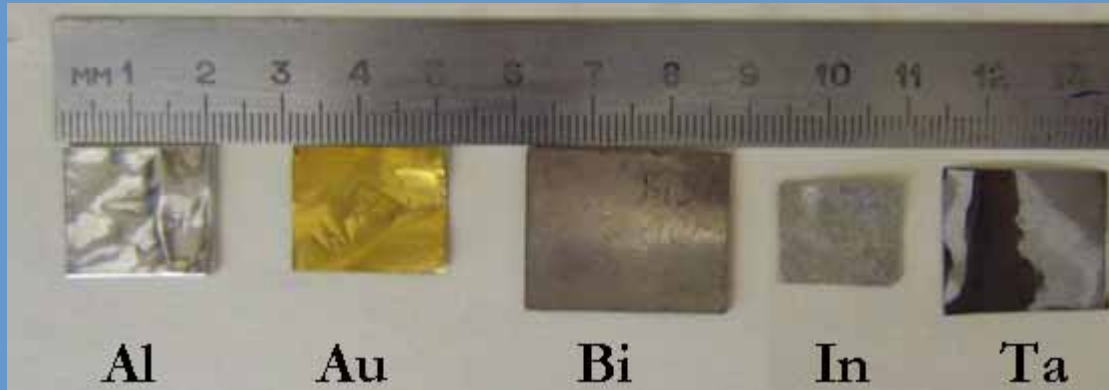
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iodine
(KIO_4)

Reaction	E_{thresh} [MeV]	Half-life
$^{197}\text{Au} (n,2n) ^{196}\text{Au}$	8.1	6.183 d
$^{197}\text{Au} (n,3n) ^{195}\text{Au}$	14.8	186.1 d
$^{197}\text{Au} (n,4n) ^{194}\text{Au}$	23.2	38.02 h
$^{197}\text{Au} (n,5n) ^{193}\text{Au}$	30.2	17.65 h
$^{197}\text{Au} (n,6n) ^{192}\text{Au}$	38.9	4.94 h
$^{197}\text{Au} (n,7n) ^{191}\text{Au}$	45.7	3.18 h

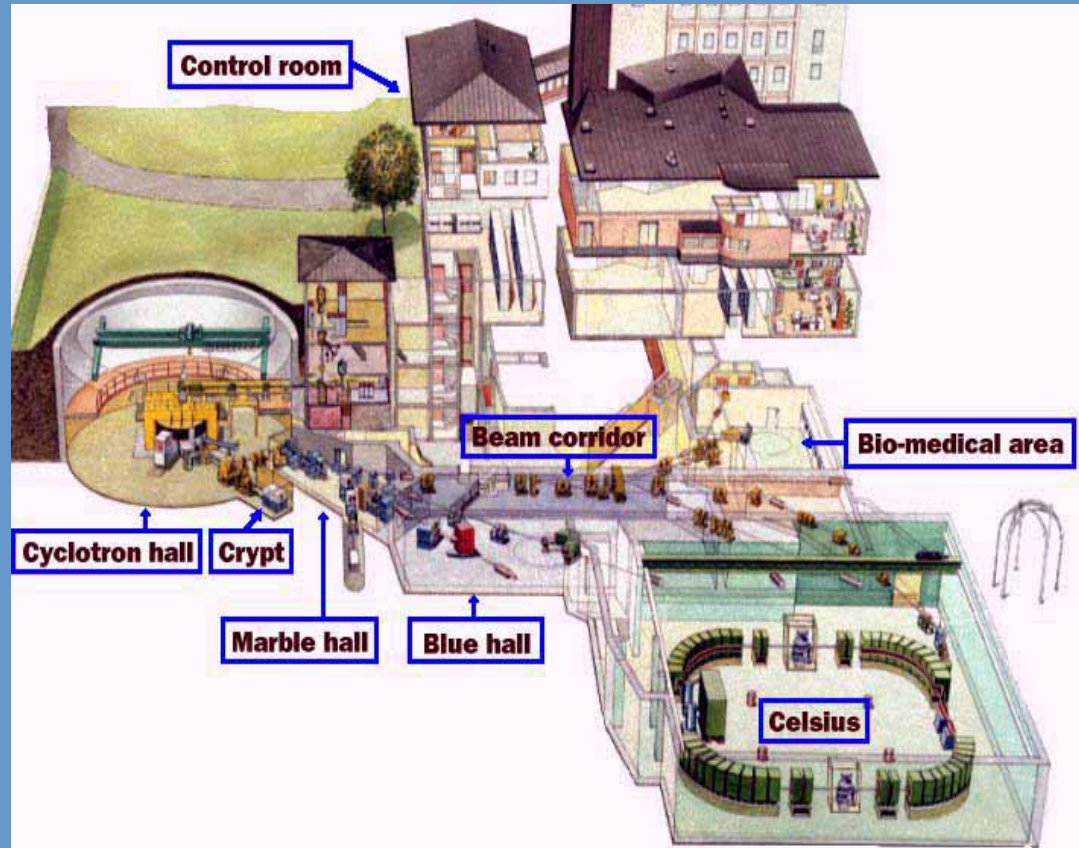
In Řež also measured:

Mg, Ni, Fe, Zn



TSL Uppsala

- Protons on Li target or spallation source
- Neutrons with energies 11-174 MeV
- Well known beam and neutron spectrum



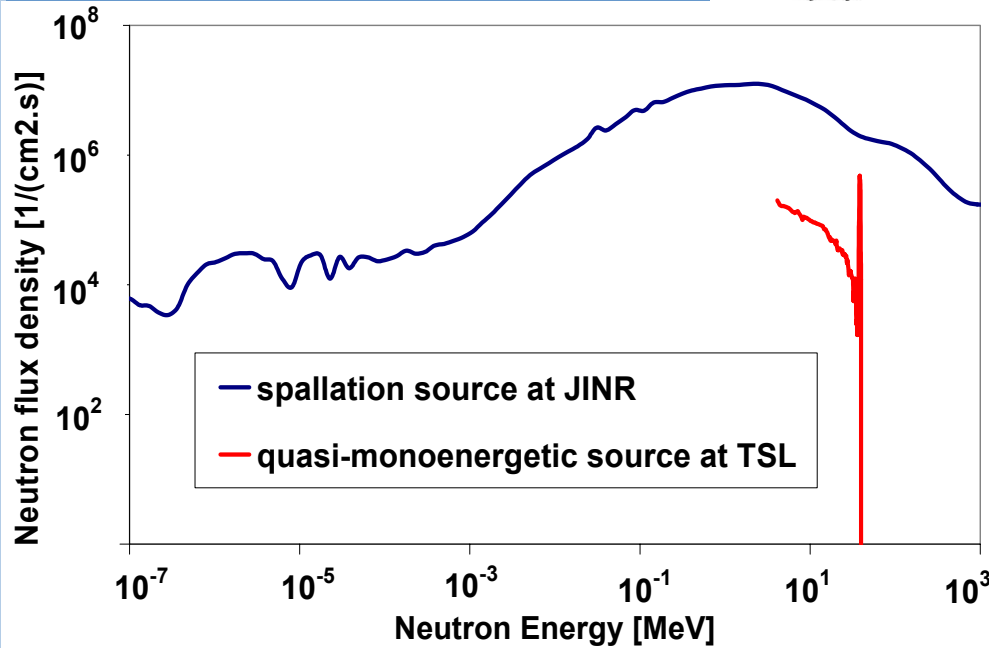
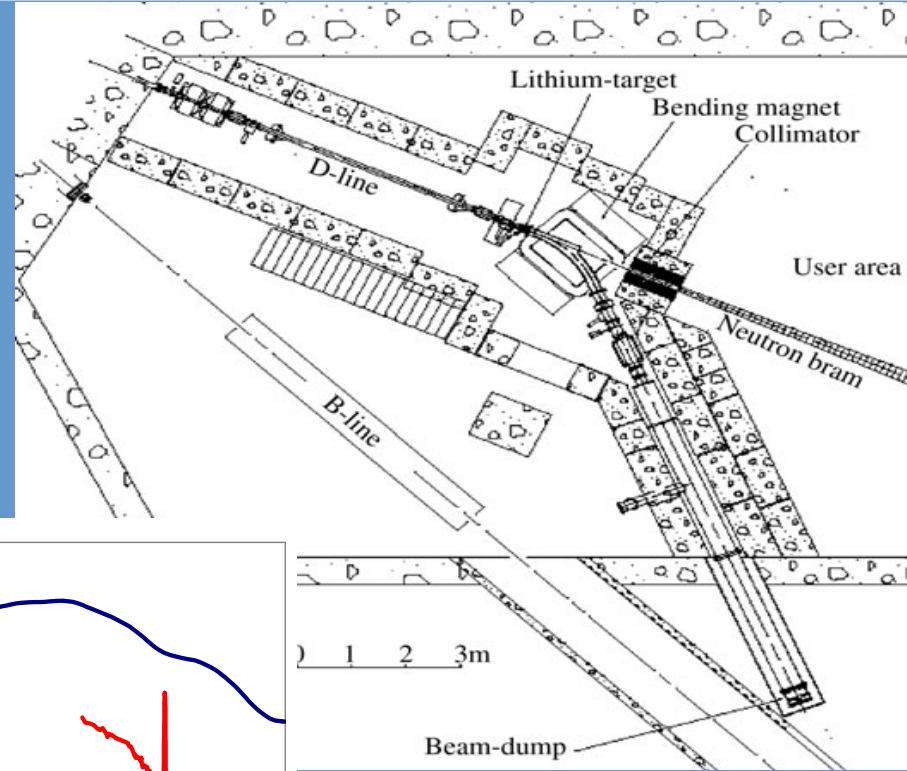
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TSL Uppsala – Blue hall

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Experimental setup in the Blue hall



Neutron spectra



TSL Uppsala - irradiations

- 3 irradiations on the Li target – 25, 50, and 100 MeV p+

Proton beam energy [MeV]	24.68 ± 0.04	49.5 ± 0.2	97.9 ± 0.3
Li-target thickness [mm]	2	4	8.5
Proton beam current [μA]	10	10	5
Average energy of peak neutrons [MeV]	21.8	46.5	94.7
Fraction of neutrons in the peak [%]	50	39	41
Peak neutron flux density [$10^5 \text{ cm}^{-2} \text{ s}^{-1}$]	1.3	2.9	4.6

- one irradiation on the ANITA spallation target – 180 MeV p+

June 2008, supported by
EFNUDAT program



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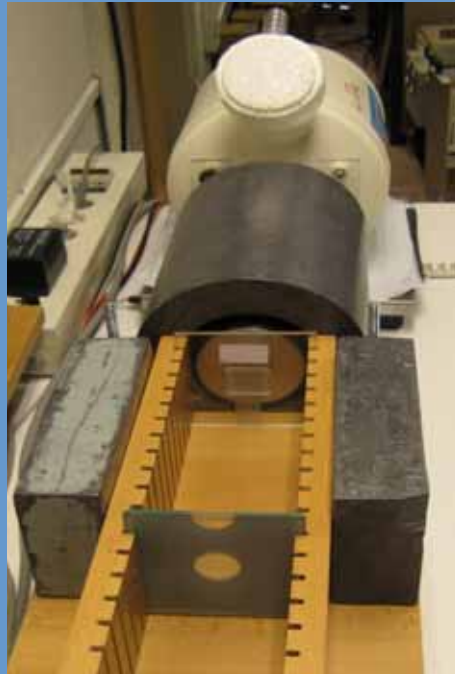


TSL Uppsala – spectroscopic measurements

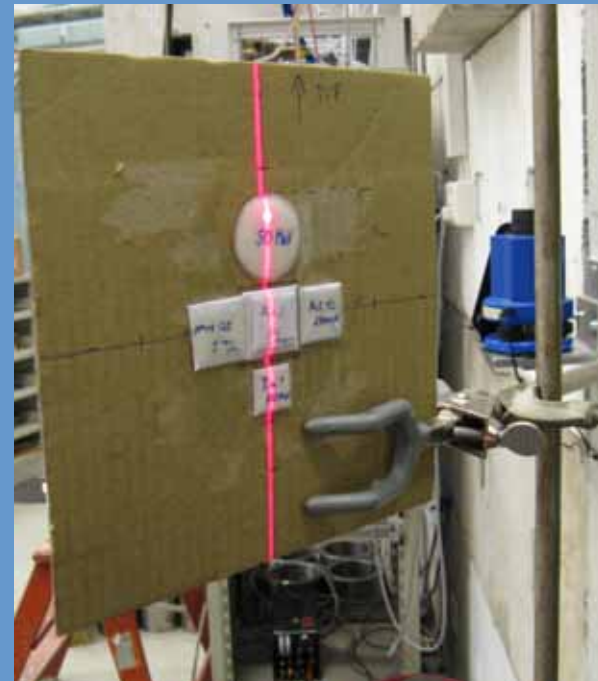
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- 8 hours each irradiation

- one day of spectroscopic measurements after each irradiation



Au, Al, Bi, In, Ta, I samples



Present status:

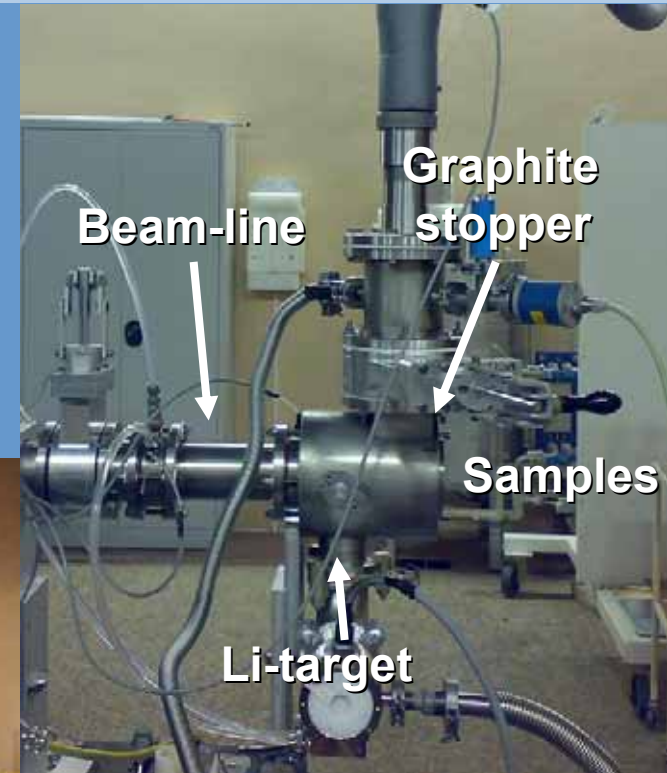
Finished yields evaluation, waiting for the beam data...
to be completed soon



Cyclotron Řež

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- Protons on Li target
- Neutrons with energies 10-37 MeV
- Good intensities: $10^8 \text{ n cm}^{-2} \text{ s}^{-1}$
- Well equipped spectroscopic laboratory (NSD-NPI)



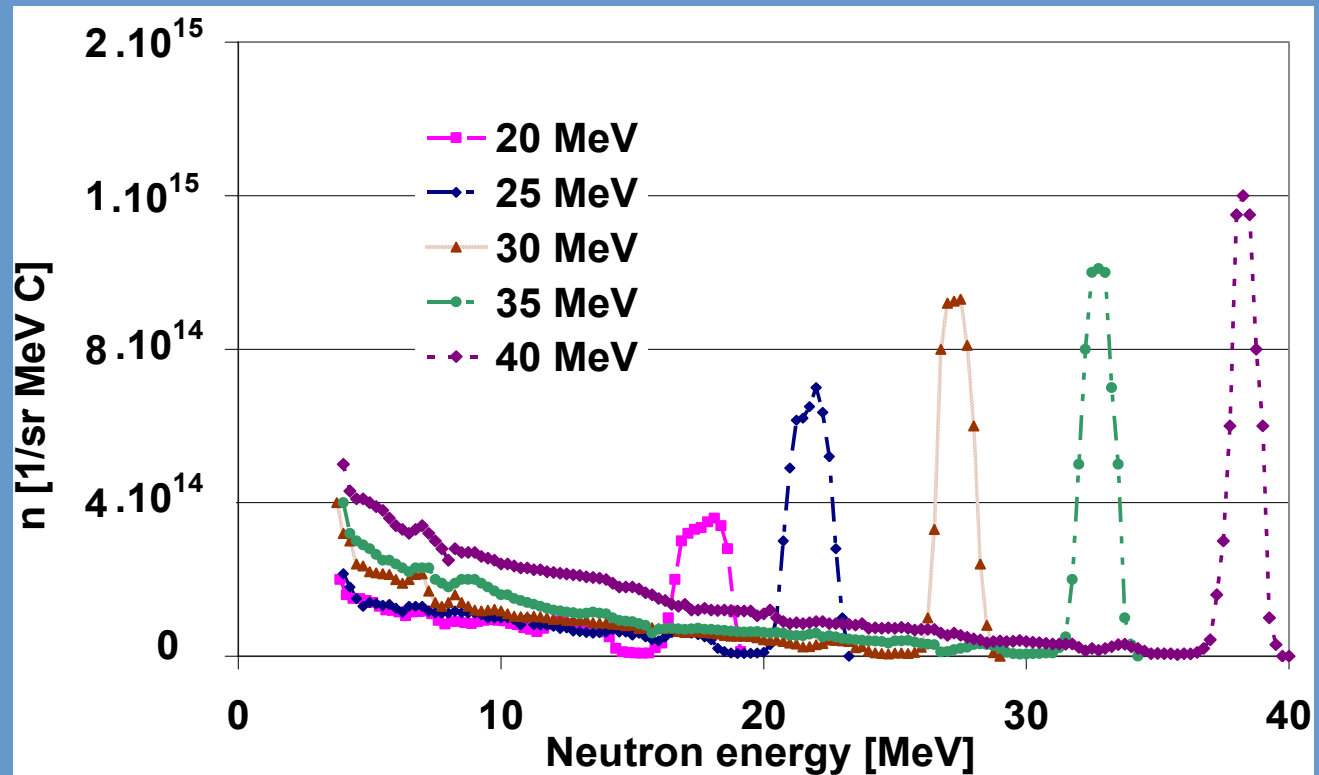


Cyclotron Řež – experiments

- Up to now 2 experiments: 20 and 25 MeV

- Au, Al, Bi, In, Ta, I, Ni, Fe, Mg, Zn

- next irradiations planned on October 2008



- Motivation for σ measurements

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- Introduction
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- Preliminary results

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- E+T: 1.6 GeV d+

- Simulations & comparisons

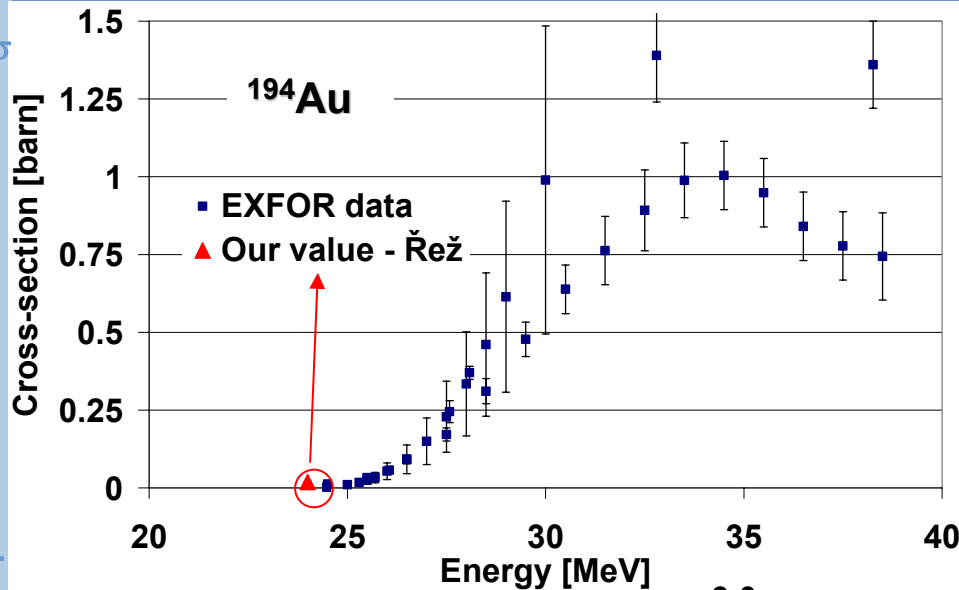
- Data share

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Cyclotron Řež – experimental results

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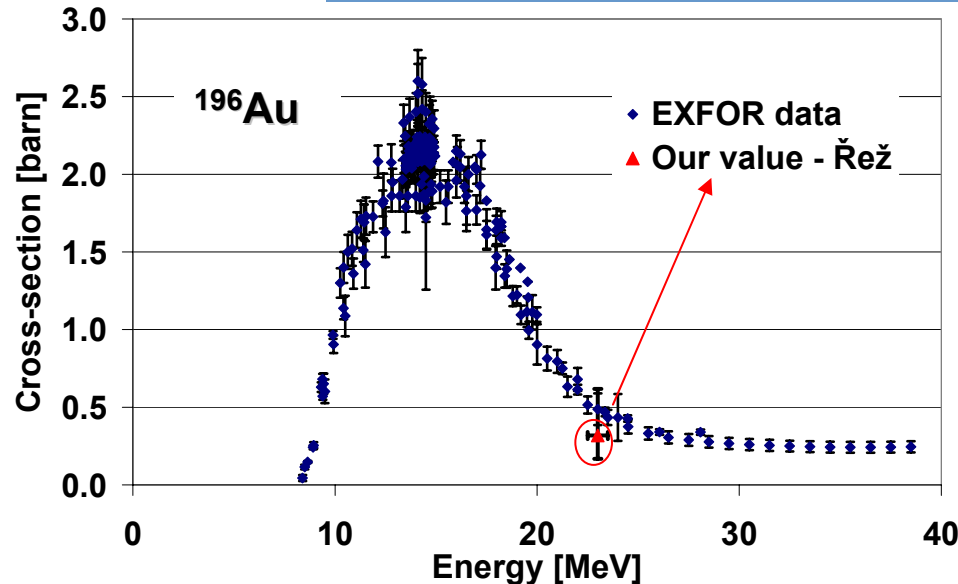


$$\sigma = \frac{N_{yield} \cdot S \cdot A}{N_n \cdot N_A}$$

Number of neutrons in peak

Tentative data!

Evaluation not yet ready...





Conclusion – cross-sections

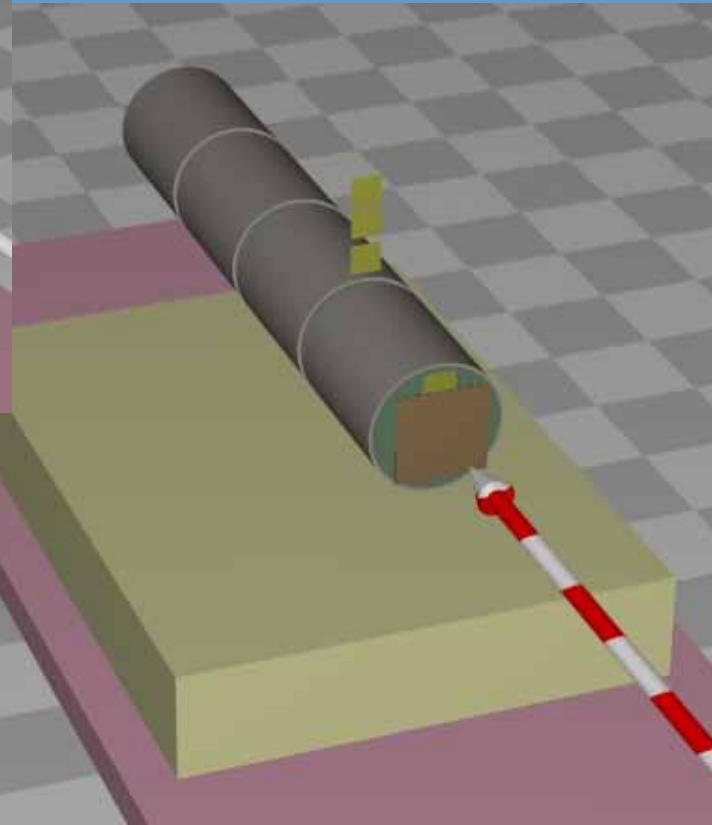
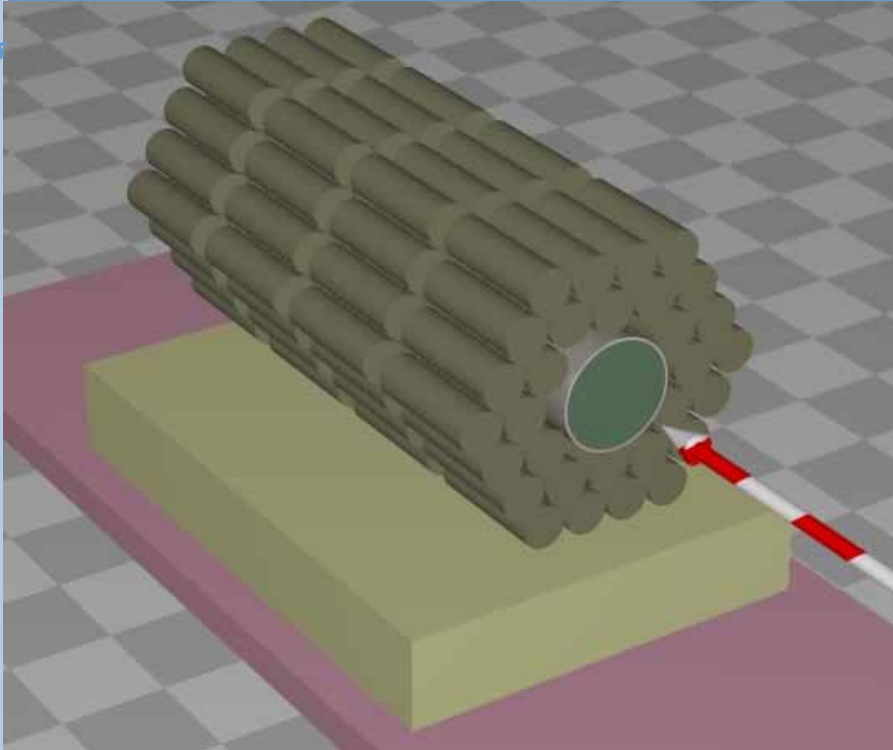
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- Uppsala and Řež cross-section measurements covered wide spectrum of energies (20-100 MeV)
- Preliminary results show we are close to known cross-section values
- Near future – finalize experiment analysis
 - next experiments at Řež
- Farther future – next experiments at Uppsala
 - application of the results on the E+T experiments
 - publish the measured cross-sections with respect to be involved in the EXFOR library if possible



Energy plus Transmutation - setup

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 - Setup - videos
 - Longitudinal results
 - Radial results
 - Spectral index
 - d x p – longitud
 - d x p - radial
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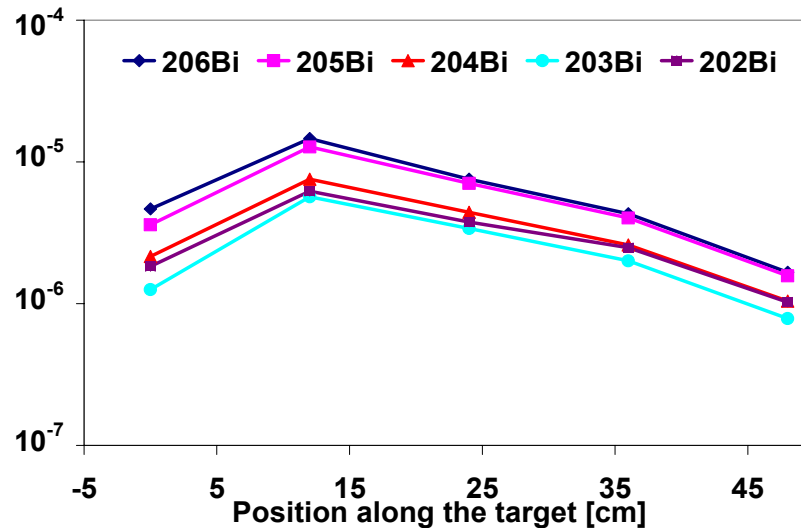
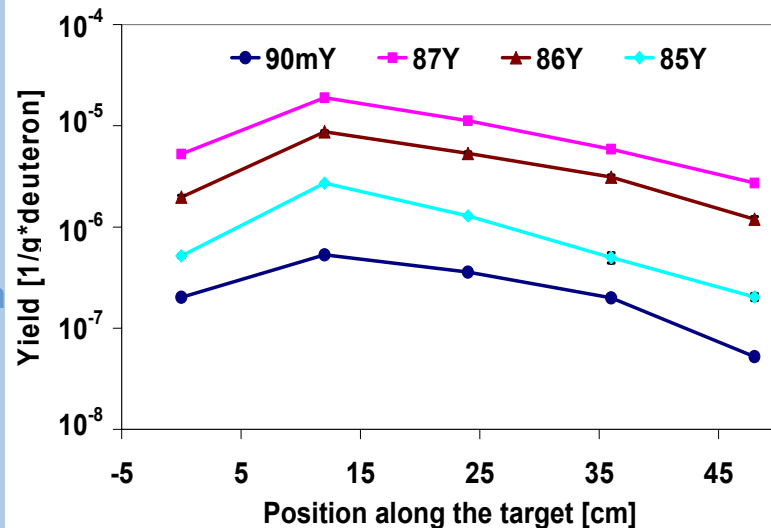
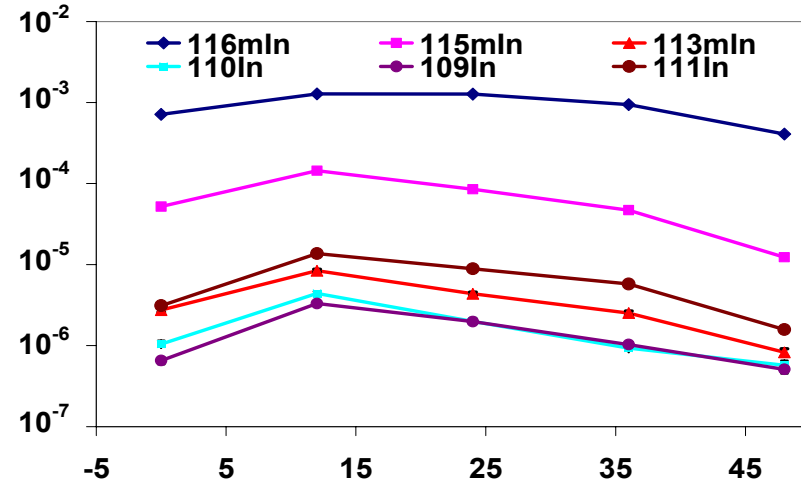
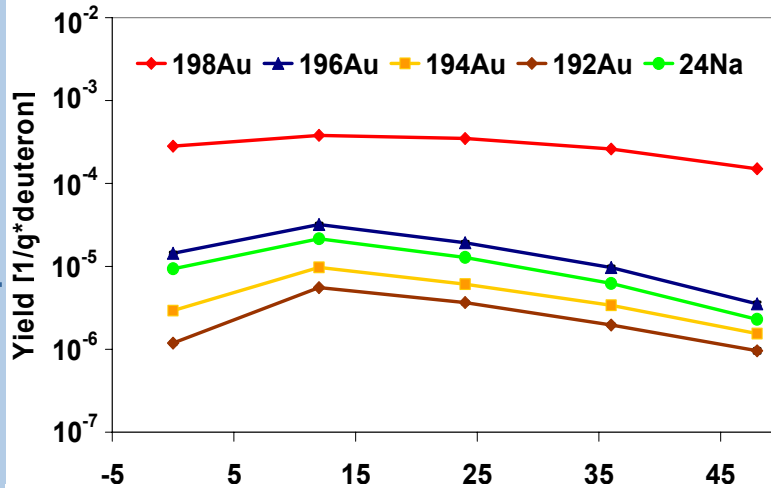


**Povray code –
renders pictures from
input files**



Longitudinal distributions of isotopes – at 3 cm

- produced in Au, Al, Bi and In foils, 1.6 GeV deuterons

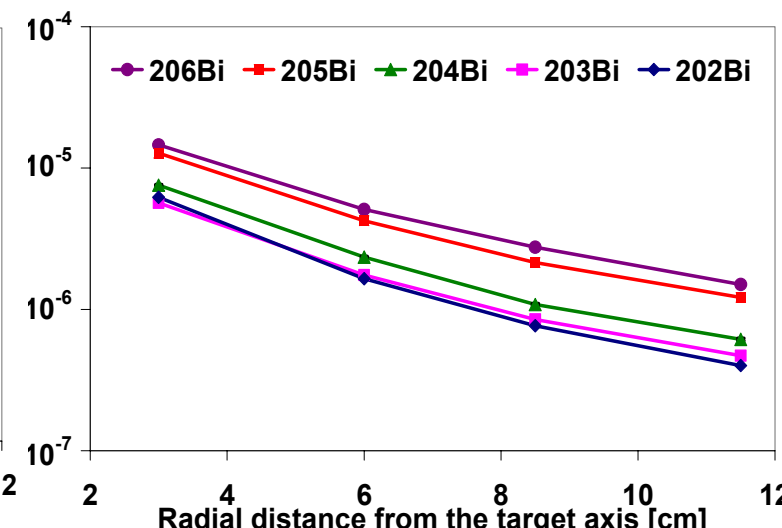
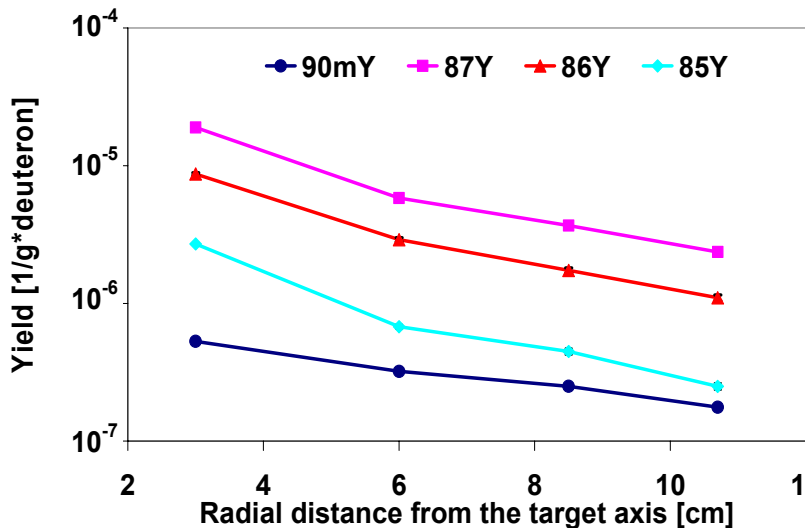
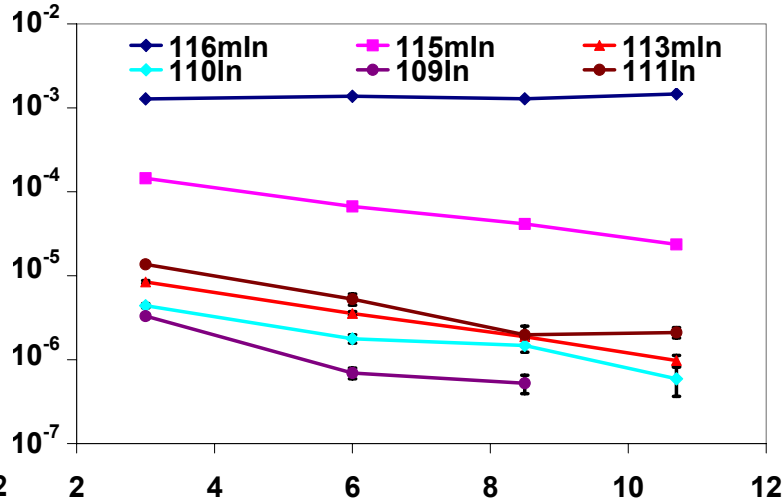
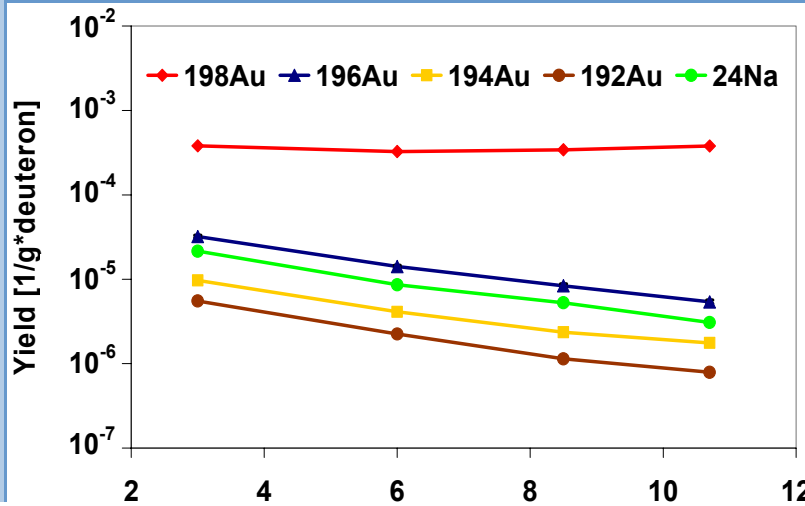


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Radial distributions of isotopes – 1st gap

- produced in Au, Al, Bi and In foils, 1.6 GeV deuterons

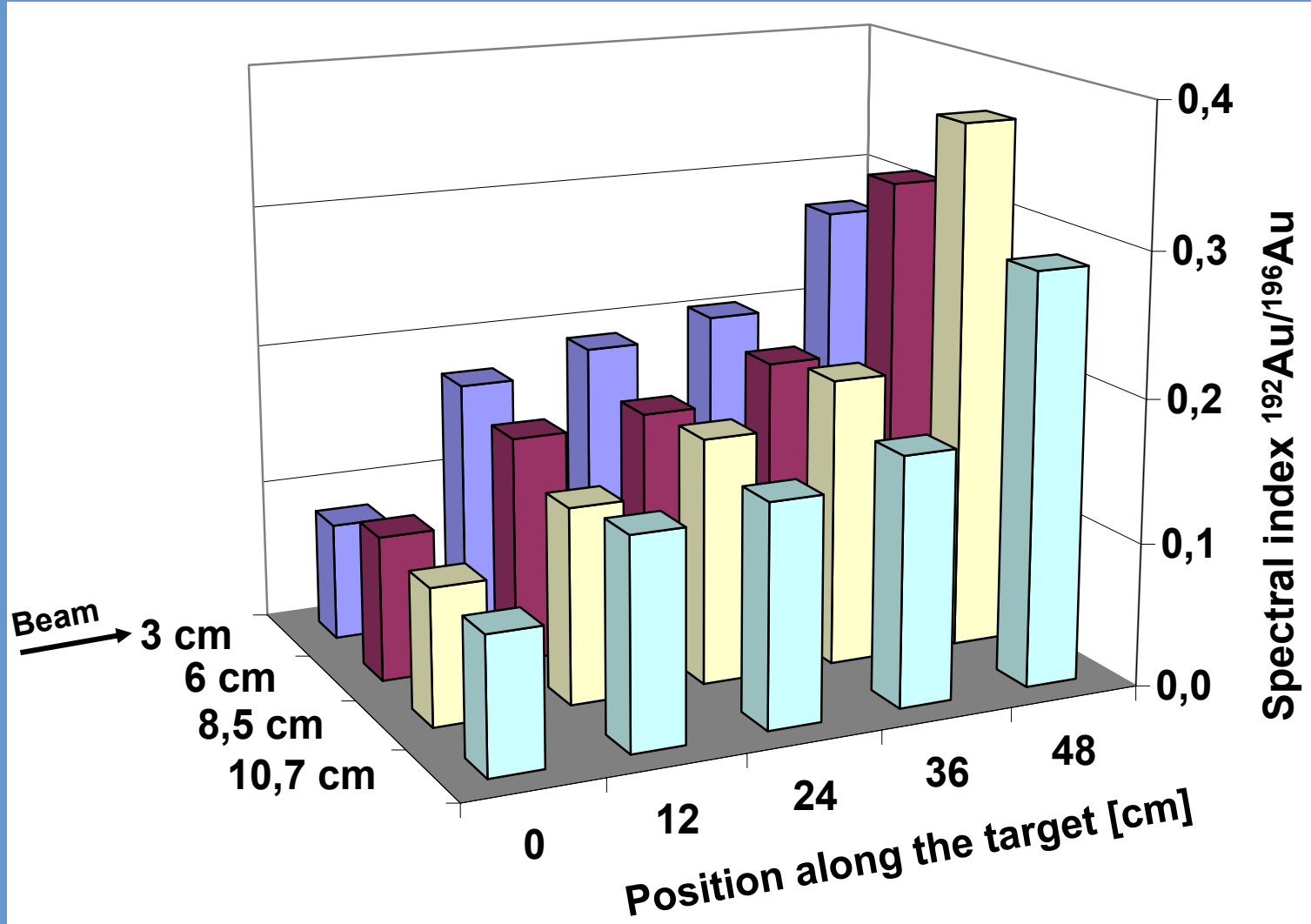


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Spectral index - $^{192}\text{Au}/^{196}\text{Au}$

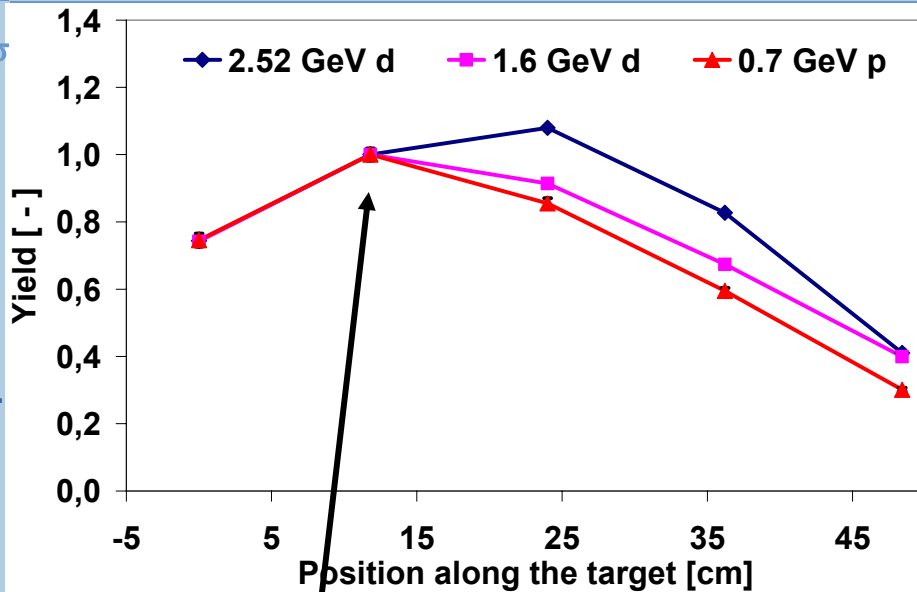
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Comparison between experiments - longitudinal

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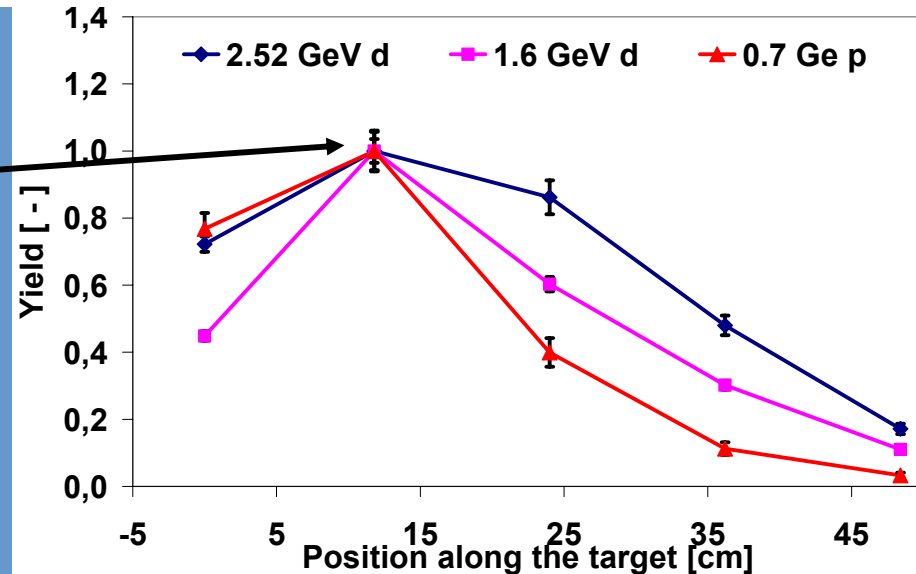


Experiment	^{198}Au yield
0.7 GeV p	0.7 ± 0.5
1.6 GeV d	3.3 ± 0.7
2.52 GeV d	3.8 ± 0.3

^{198}Au

^{196}Au

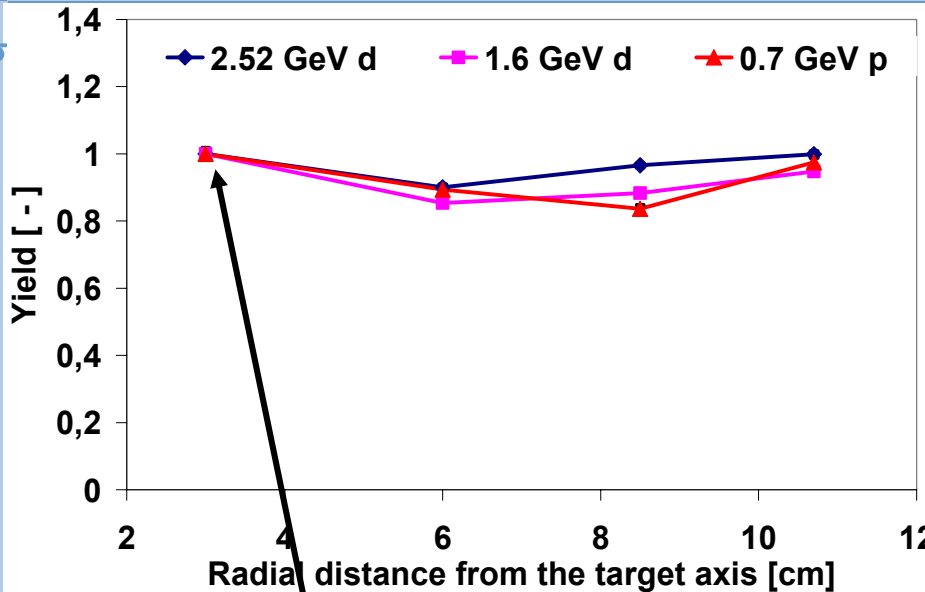
Yields normalized
to the second foil
in each experiment





Comparison between experiments - radial

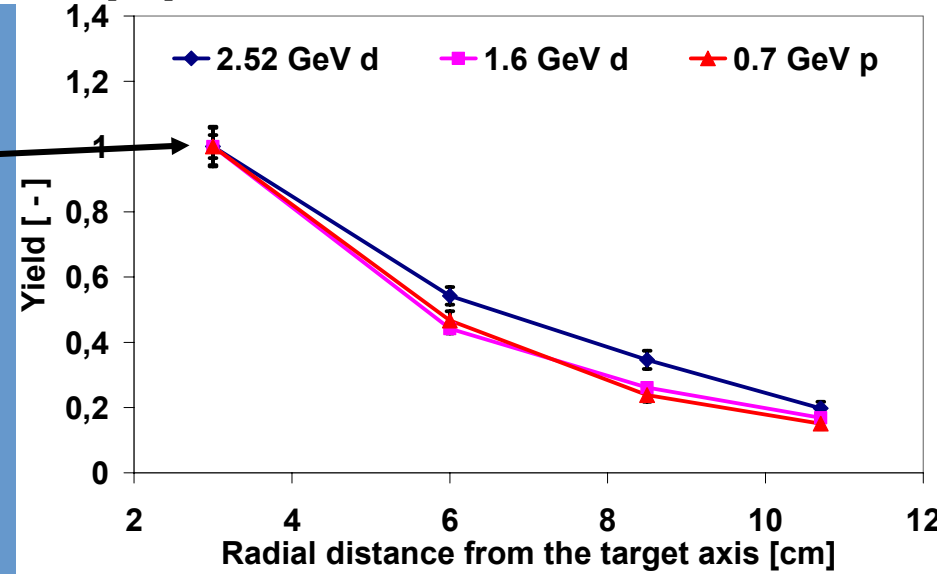
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^{198}Au

^{196}Au

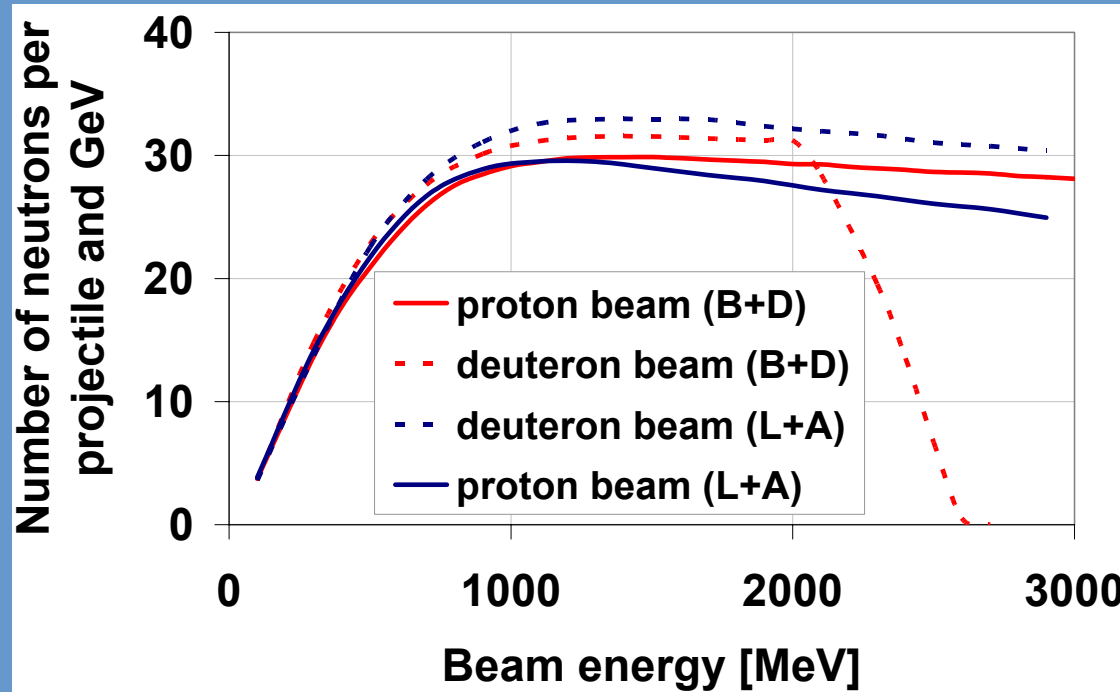
**Yields normalized
to the first foil
in each experiment**





Simulations – MCNPX 2.6.E

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- different INC+evaporation models available
 - only INCL4+ABLA can simulate deuterons with $E > 2 \text{ GeV}$

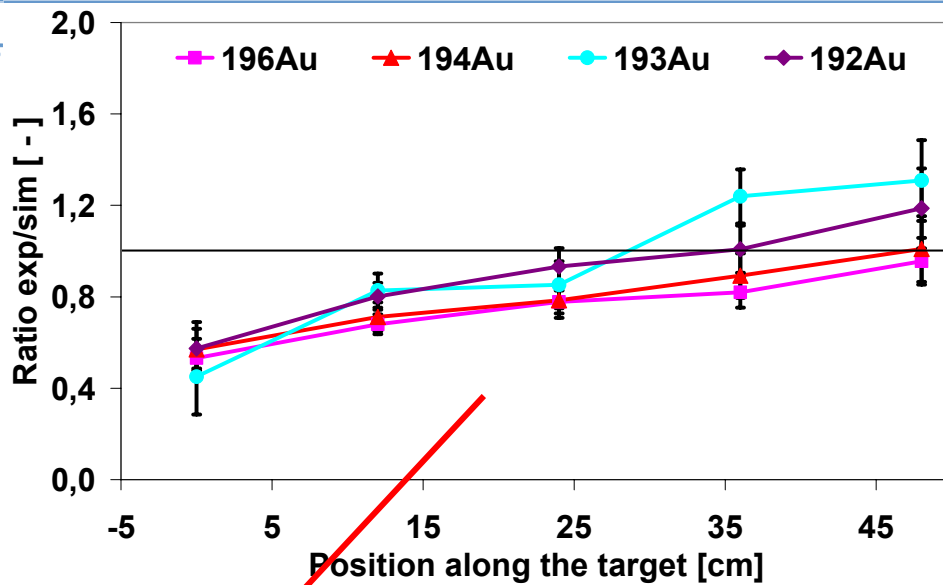


But INCL4+ABLA needs 10x more time
=> solved thanks CESNET METACentrum

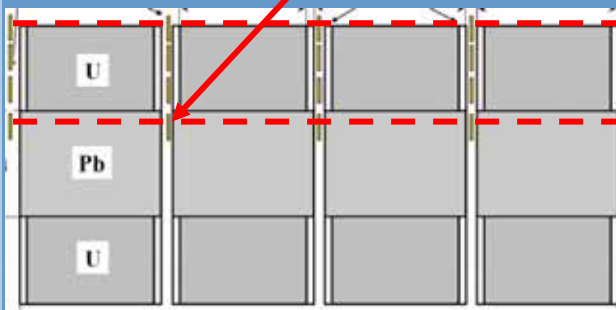


Exp versus Sim – longitudinal

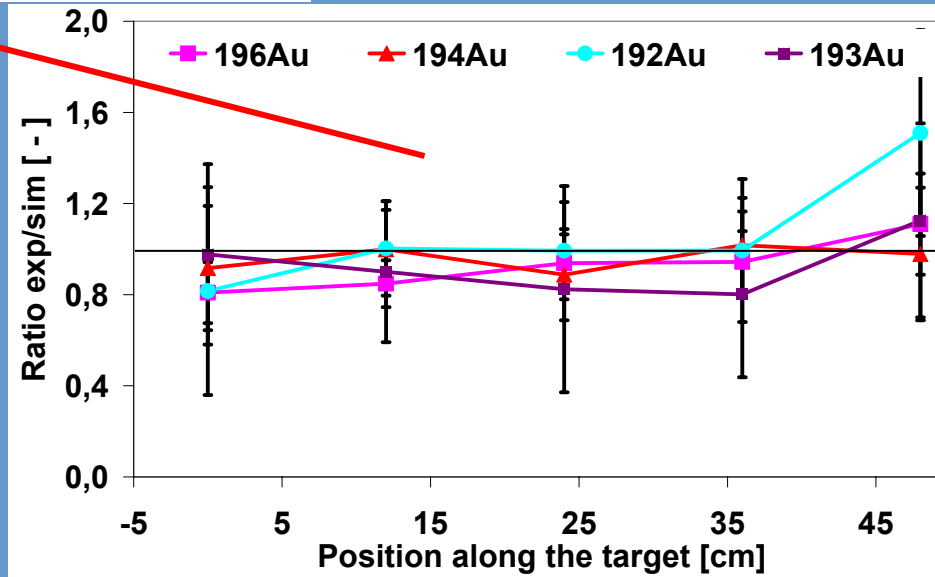
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- 3 cm over the target axis



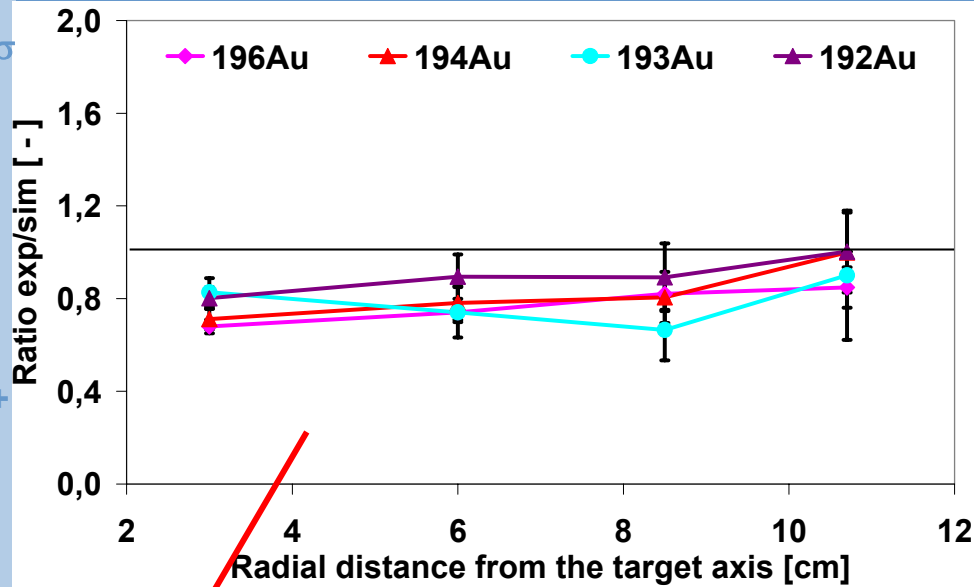
- 10.7 cm over the target axis





Exp versus Sim - radial

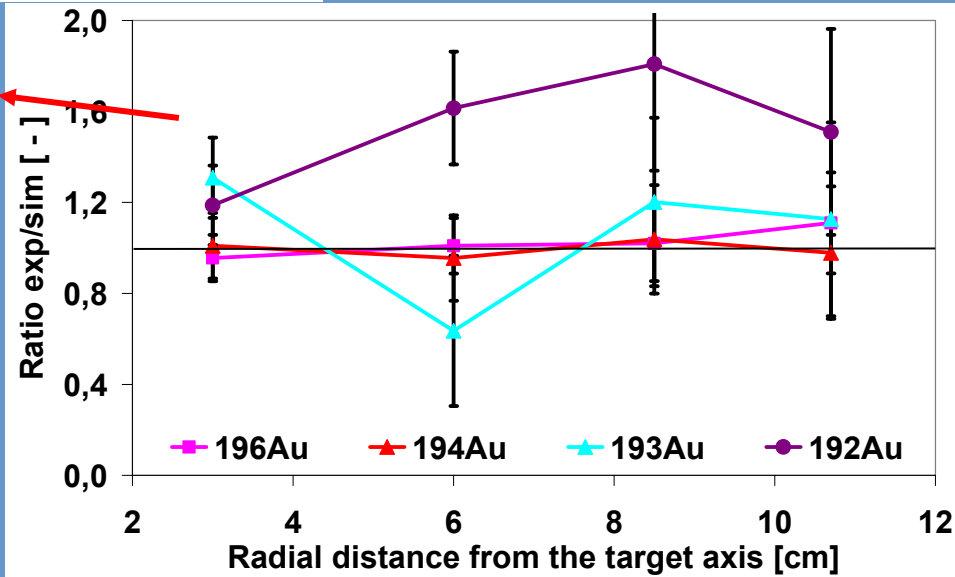
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- first gap



- behind the target





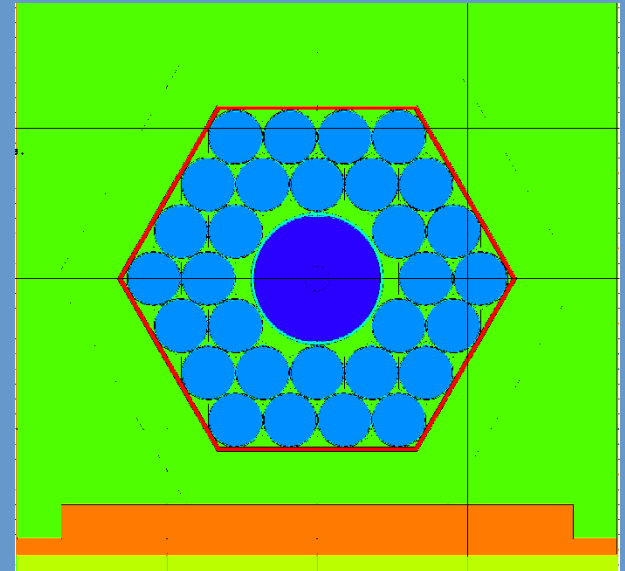
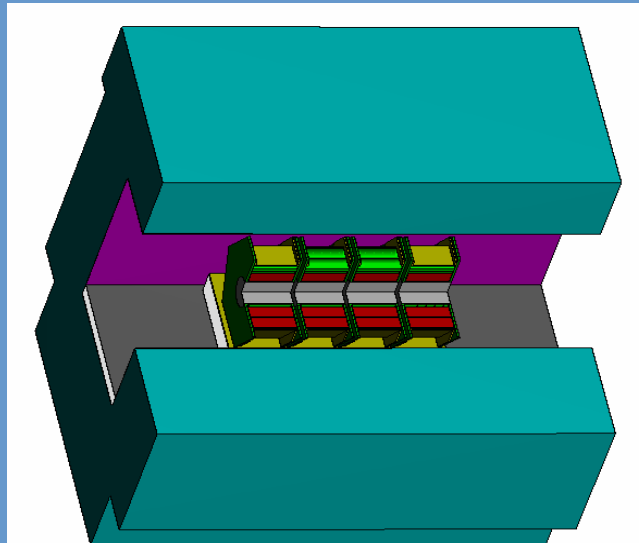
Data share

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- **Exact setup description in the codes**
 - **MCNPX, FLUKA, TALYS**
 - **Huge computing power - CESNET**
- } We can simulate various problems

We offer help and space for collecting your E+T results, perform calculations and make comparisons within the collaboration!!

<http://ojs.ujf.cas.cz/~mitja/jinr/experiments>





Energy plus Transmutation - conclusion

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- Analysis of previous E+T experiments finished, simulations performed
- Published JINR preprints: E15-2007-81 – 1 GeV p
E15-2007-82 – MC simulations
E1-2005-46 – 1.5 GeV p
- Preprints 0.7 & 2 GeV p, 2.52 & 1.6 GeV d will follow
- In October – defense of Antonín Krása PhD. thesis
- Future plans:
 - Next E+T experiments – this November?
 - Further cross-section measurements
 - Application of measured cross-section data to E+T data

Thank you for your attention..