# Lead target for the study of accelerator driven subcritical reactors

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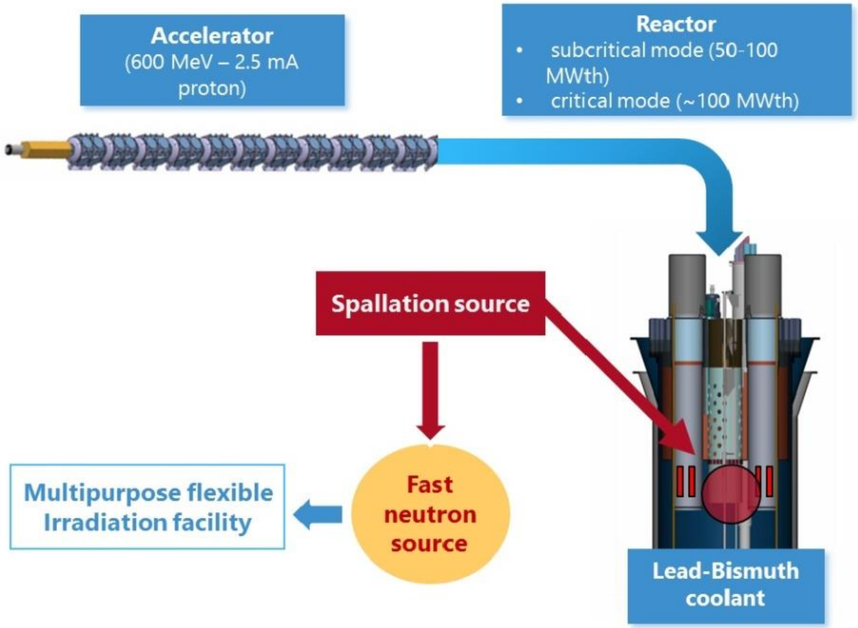
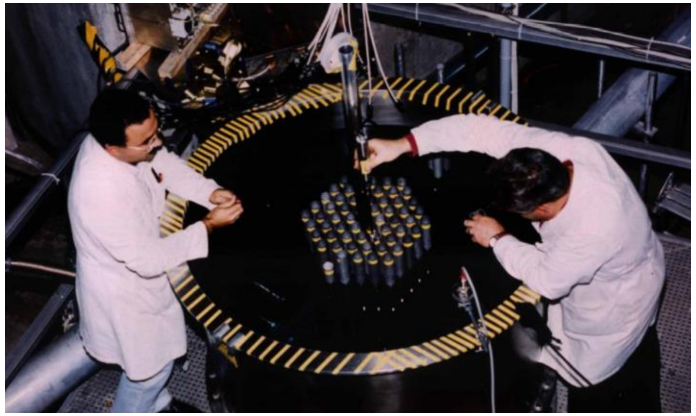
ARIADNA Collaboration, JINR

# ADS projects in the world

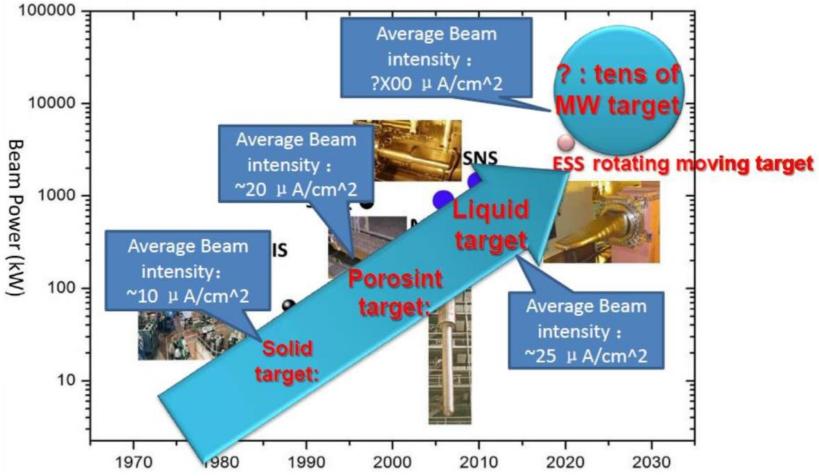
## Project MYRRHA




## FEAT experiment (CERN)



## Chinese ADS project




## European Spallation Source

Linear accelerator – 2 GeV proton,
Beam intensity $1.5 \cdot 10^{16}$

| Particle | Proton | |
|---|---|---|
| Energy | 1.5 | GeV |
| Current | 10 | mA |
| Beam power | 15 | MW |
| Frequency | 162.5/325/650 | MHz |
| Duty factor | 100 | % |
| Beam loss | <1 (or 0.3) | W/m |
| Beam trips /year | <25000<br><2500<br><25 | 1s<t<10s<br>10s<t<5m<br>t>5m |

All these projects plan to use proton beams and a lead-bismuth eutectic (LBE) cooled subcritical reactor.

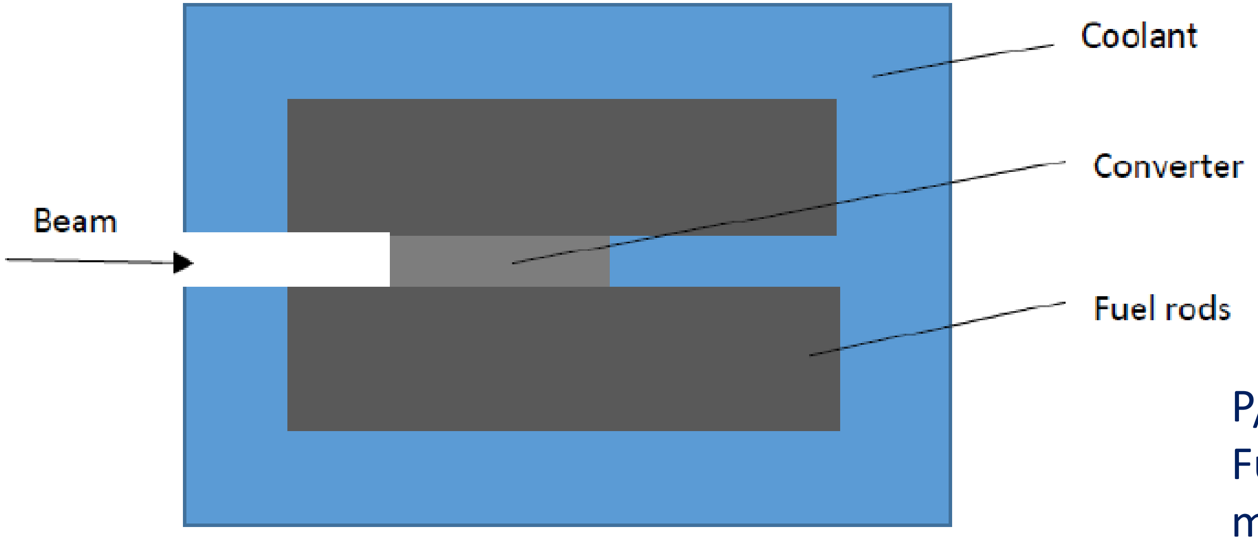
# ADSR as energy amplifier

**Advantages:**
**- the reactor works in subcritical regime – enhanced Safety**
**- harder neutron spectrum – better for actinide burning**

**Factors which influence the efficiency of ADSR**

- factors related with the core structure and composition:
  - the material for the converter
  - the value of the criticality coefficient $k_{eff}$
  - the level of enrichment
- particle beam and energy
- accelerator type

**M. Paraipan, V. M. Javadova, S. I. Tyutyunnikov, *Aspects of target optimization for ADS with light ion beams at energies below 0.5 AGeV,* Progr. Nucl. En. 120 (2020) 103221**




**M. Paraipan, V. M. Javadova & S. I. Tyutyunnikov , *Influence of Particle Beam and Accelerator Type on ADS Efficiency*, Nuclear Science and Engineering, 198 1 (2024), p. 109-120**

P/D ~ 2
Fuel rods –diameter 9 mm, length 160 cm gap 0.15 mm, clad T91 0.6 mm

**The scheme of the target.**

# Safe exploitation – optimal value of $k_{eff}$

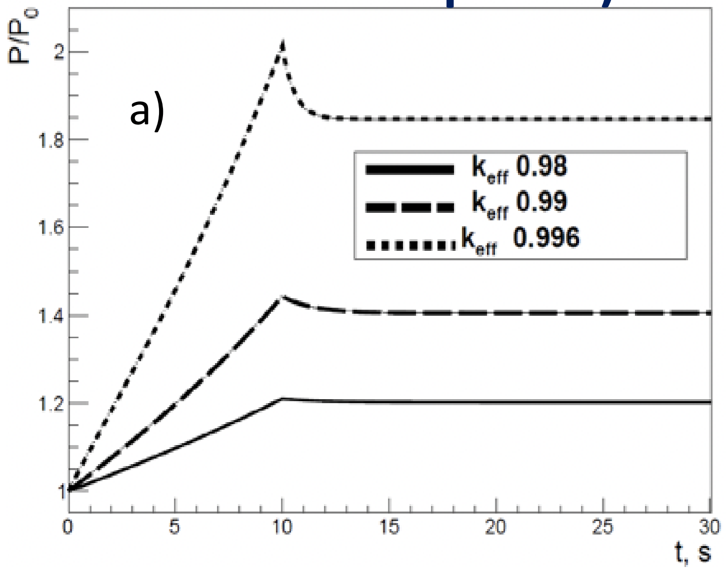
**Transients with positive reactivity insertion**

- the accidental withdrawal of the control rods
- pin failure
- core compaction.

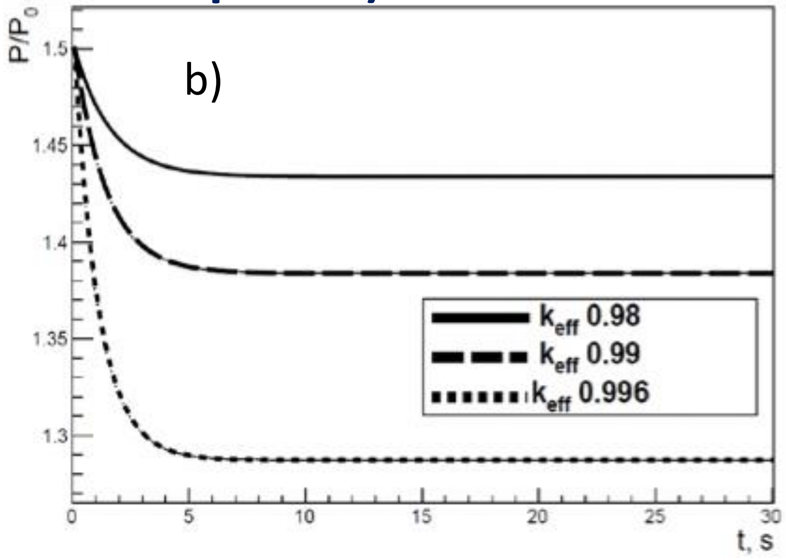
**Reactivity insertion < 400 pcm**

**Paraipan M., Kryachko I. A., Javadova V. M., Levterova E. A., Tyutyunnikov S. I., Main Results of Neutronical Study about ADS with Ion Beams and Implications on Experiments Planning, Phys. Part. Nucl. Lett. 19 2 (2022) p. 129-144**

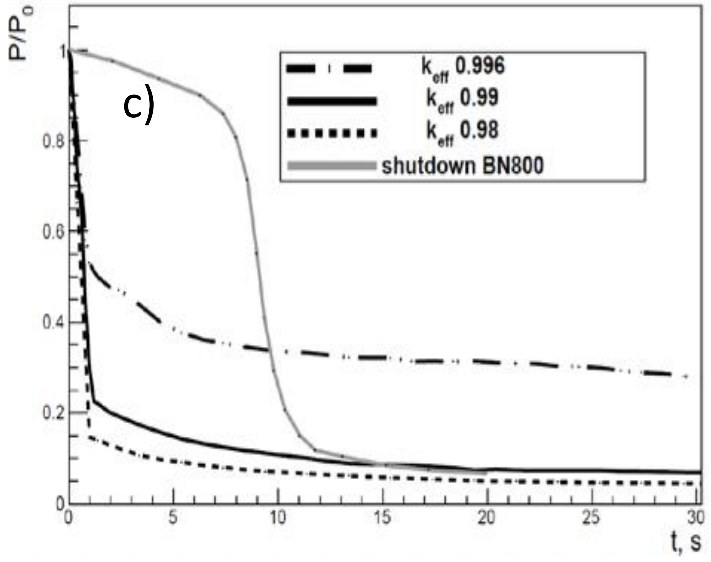
## UTOP (unprotected transient overpower)




## UBOP (unprotected beam overpower)




## Beam shutdown

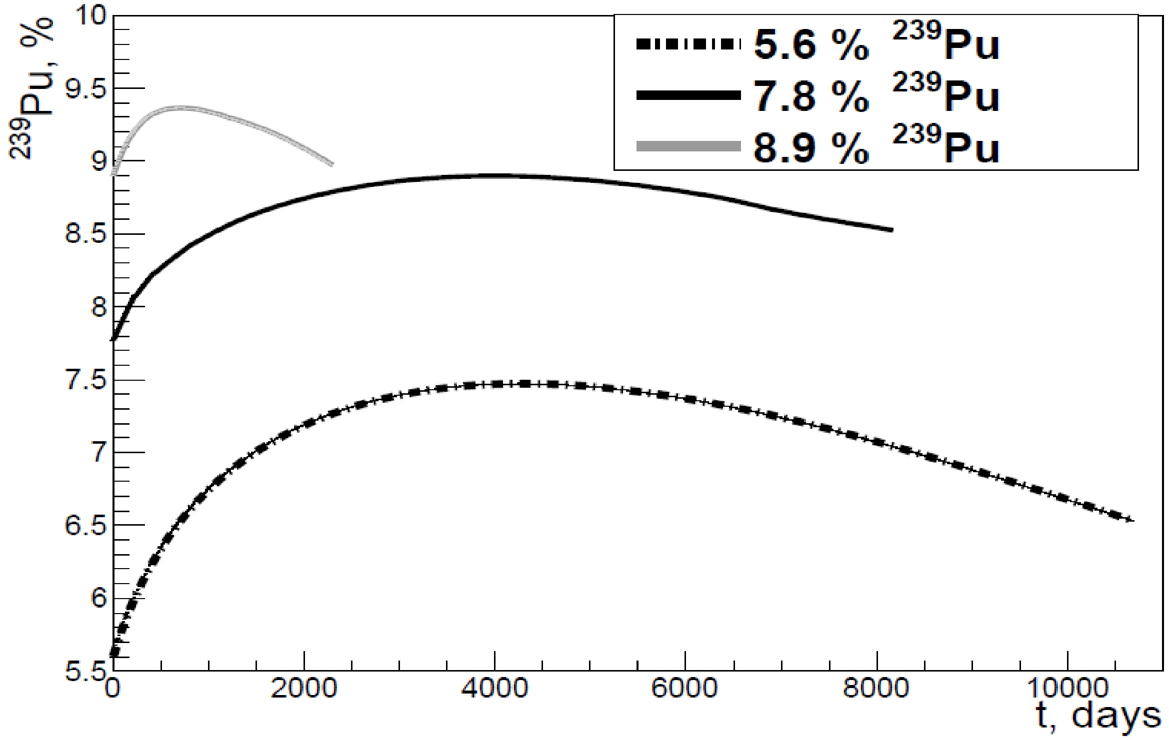



The power evolution in UTOP (a), in UBOP (b) transients and after the beam turn off (c) in ADS with U-Pu-10%Zr fuel and $k_{eff}$ 0.98, 0.99, 0.996.

**A working value of 0.985-0.988 for $k_{eff}$ would be safe enough.**

# Level of enrichment and actinide burning

**With a proper core configuration, the fuel allows to burn in ADS 15-20 % from actinides in one cycle, in comparison with 6-7 % in a fast reactor.**

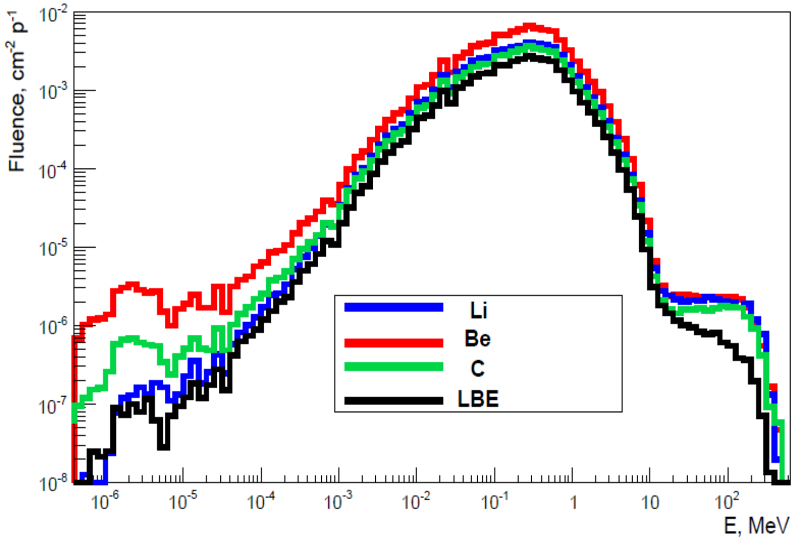



The evolution of $^{239}$Pu in cores with 5.6%, 7.8% and 8.9% $^{239}$Pu, irradiated with a beam of $^{7}$Li with energy 0.25 AGeV and intensity $1.25 \cdot 10^{16}$.

# The choice of the converter

- Heavy metals (W, Pb, LBE) for protons

- Light materials are preferable especially for ion beams at low energy.
- The best results are obtained with Be converter.

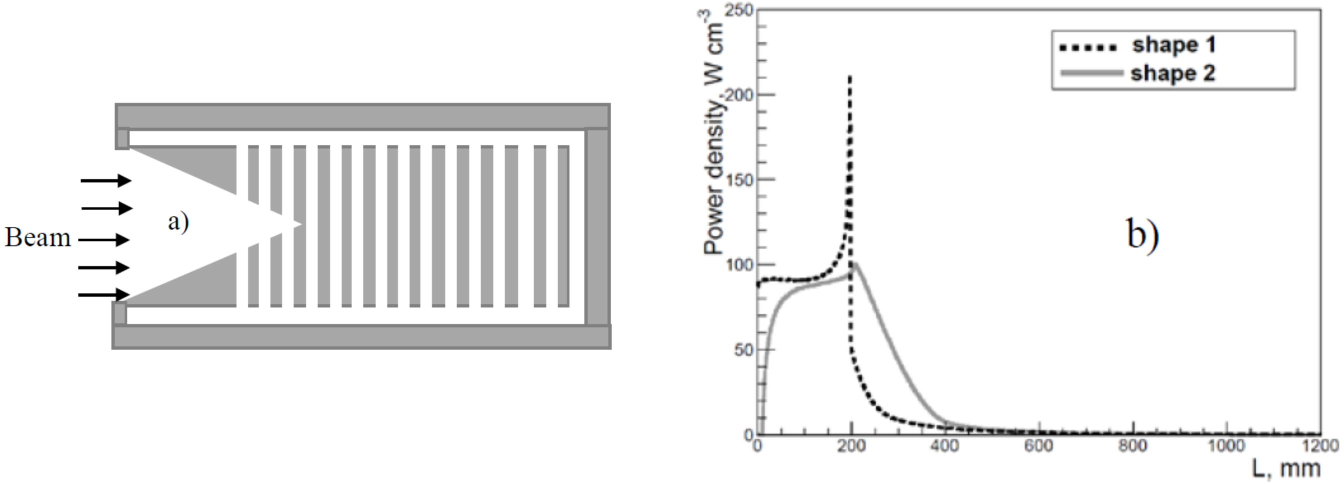



The neutron spectra in fuel blanket with Li, Be, C and LBE converters, irradiated with a beam of $^7$Li with energy 0.3 AGeV.

The total energy of the escaped neutrons Etot, and the energy released $E_{dep}$ in core with keff 0.988, irradiated with protons and $Li^7$

| Particle/Energy (GeV/n) | Converter Material | $E_{tot}$ (MeV) | $E_{dep}$ (MeV) |
|---|---|---|---|
| P 1 | Be | 202.1 | 1.971e5 |
| | LBE | 205.2 | 2.145e5 |
| P 1.5 | Be | 323 | 3.041e5 |
| | LBE | 349.6 | 3.543e5 |
| $^7$Li 0.25 | Be | 292.5 | 3.05e5 |
| $^7$Li 0.3 | Be | 442.9 | 3.933e5 |

## Optimization of the shape of the Be converter

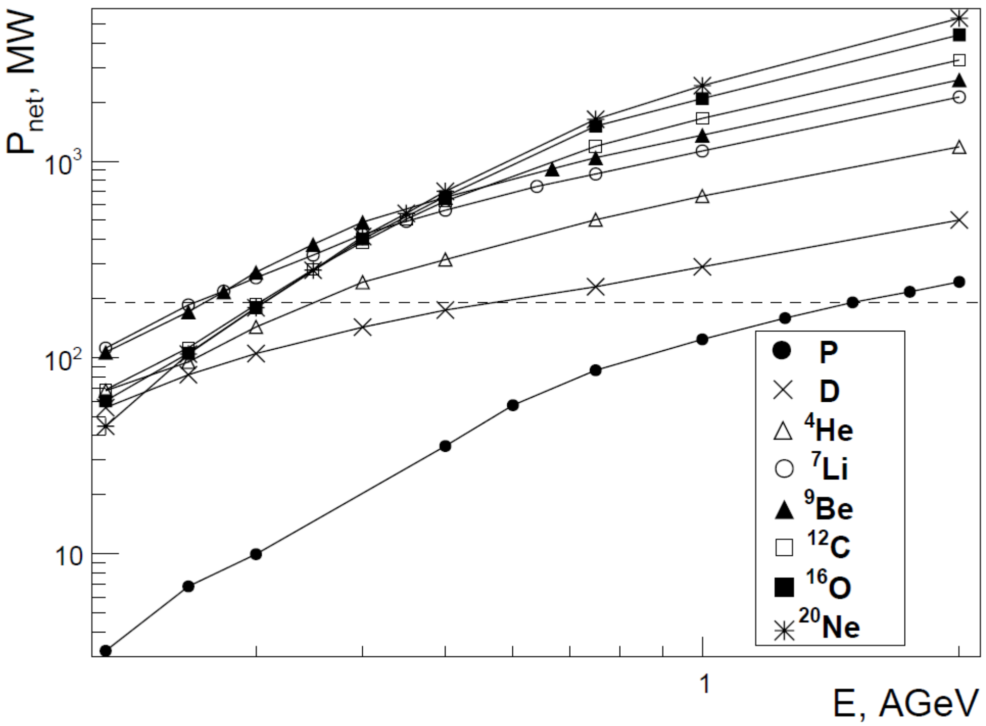



Proposed shape of the converter with a wedge part (a), the distribution of power density in cylindrical converter (shape 1) and with the proposed shape (shape 2) irradiated with $^7$Li 0.25 AGeV (b).

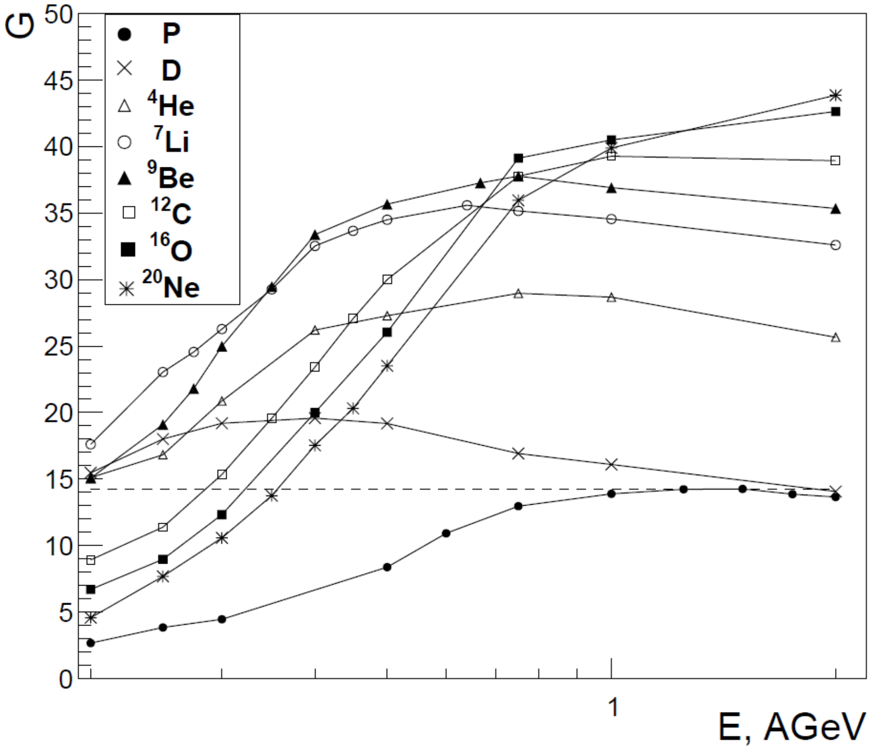
**One relevant advantage of a Be converter with high dimensions is the fact that allows to diminish the level of enrichment, increasing the period of functioning without refueling and consequently, the burn-up.**

# The comparative study on the energy efficiency of proton and ion beams

- metallic rods U-Pu-Zr, LBE coolant, Be converter with a length of 110 cm, $k_{eff}$ 0.985.
- core irradiated with protons and ion beams from D to $^{20}$Ne, energies from 0.2 AGeV to 2 AGeV and beam intensity $1.5 \cdot 10^{16}$ p/s.




The net electrical power as a function of projectile mass number and beam energy.




$$G = \frac{P_{prod}}{P_{spent}}$$

**A beam of 0.25 – 0.3 AGeV $^7$Li realizes the same $P_{net}$ as a beam of 1-1.5 GeV proton with the minimal length of the accelerator (length 2 times smaller than for proton).**

# Planned experiments

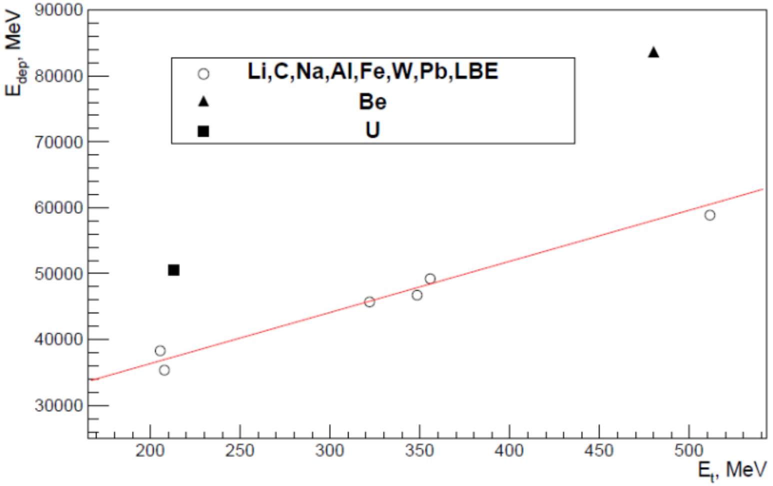
## Neutron yield from converters

$^{7}$Li with energy 0.3 AGeV

- converter cylinder with radius 10 cm and length equal with the ion range in the given material.
- U-Pu-Zr target with 8.9 % $^{239}$Pu

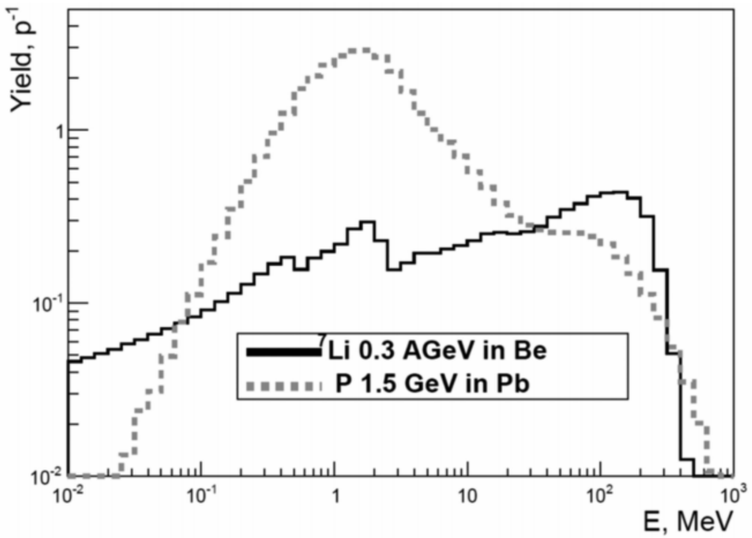
**The neutron yield, the total energy of the escaped neutrons $E_{tot}$, and the energy released $E_{dep}$**

| Converter material | Neutron yield | | | $E_{tot}$, MeV | $E_{dep}$, MeV |
|---|---|---|---|---|---|
| | total | E>10MeV | E>100MeV | | |
| Li | 6.36 | 4.53 | 2.08 | 511.4 | 5.887e4 |
| Be | 8.44 | 4.33 | 1.95 | 480 | 8.366e4 |
| C | 4.48 | 3.13 | 1.45 | 355.7 | 4.922e4 |
| Na | 4.56 | 3.17 | 1.4 | 348.4 | 4.673e4 |
| Al | 4.96 | 2.95 | 1.27 | 321.9 | 4.57e4 |
| Fe | 5.88 | 2.31 | 0.894 | 235.2 | 3.346e4 |
| W | 13.6 | 2.51 | 0.631 | 196.5 | 3.392e4 |
| Pb | 14.55 | 2.75 | 0.627 | 207.8 | 3.535e4 |
| LBE | 13.95 | 2.75 | 0.619 | 205.4 | 3.806e4 |
| U | 24.04 | 2.96 | 0.578 | 212.8 | 5.173e4 |




The dependence of the energy released on the total energy carried out by the neutrons.

Neutron yield from $^{7}$Li 0.3 AGeV in extended Be converter, and from P 1.5 GeV in Pb. The dimensions of the converters: radius 10 cm, length 120 cm.

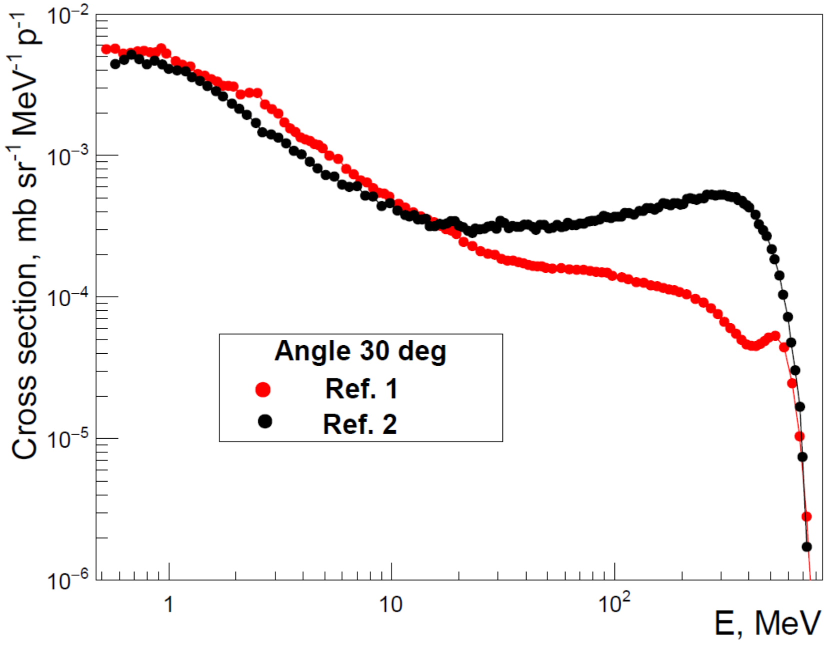


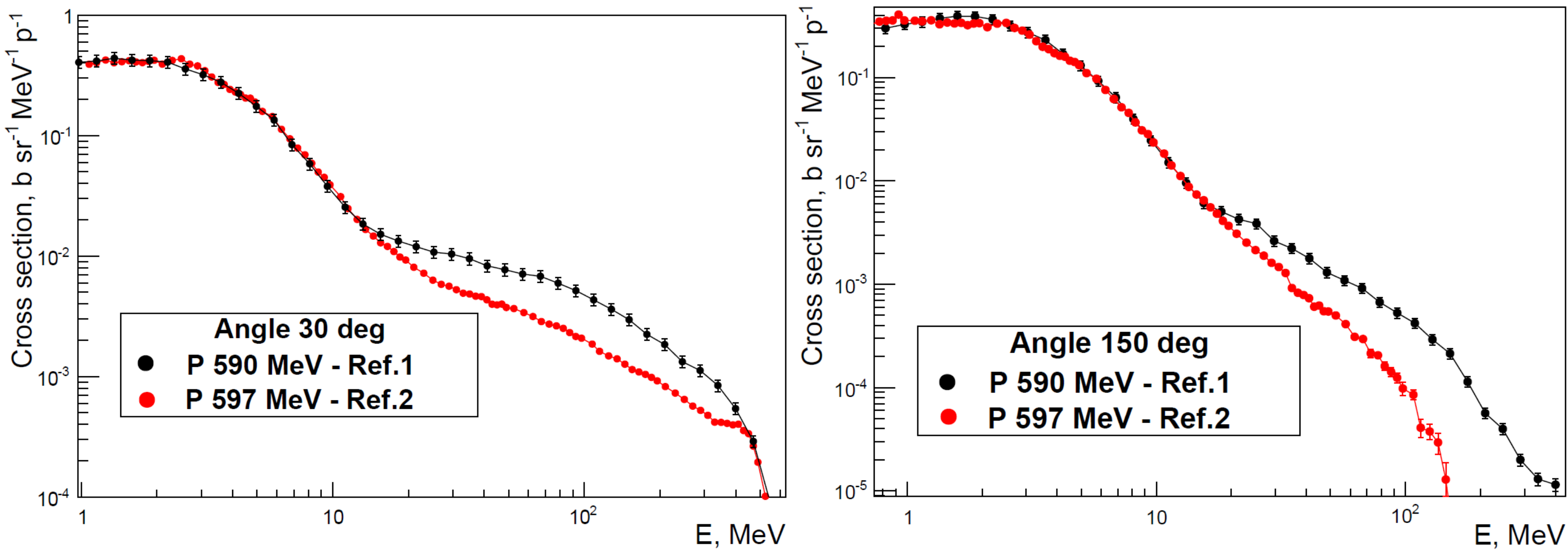

**- $^{7}$Li - neutrons with E>100 MeV - 70 % from the total kinetic energy**
**- P – 53%**

**Paraipan M., Kryachko I. A., Javadova V. M., Levterova E. A., Tyutyunnikov S. I., Main Results of Neutronical Study about ADS with Ion Beams and Implications on Experiments Planning, Phys. Part. Nucl. Lett. 19 2 (2022) p. 129-144**

## Double differential cross section of neutrons from P 800 MeV in Be

## Double differential cross section of neutrons from P 590 MeV in U



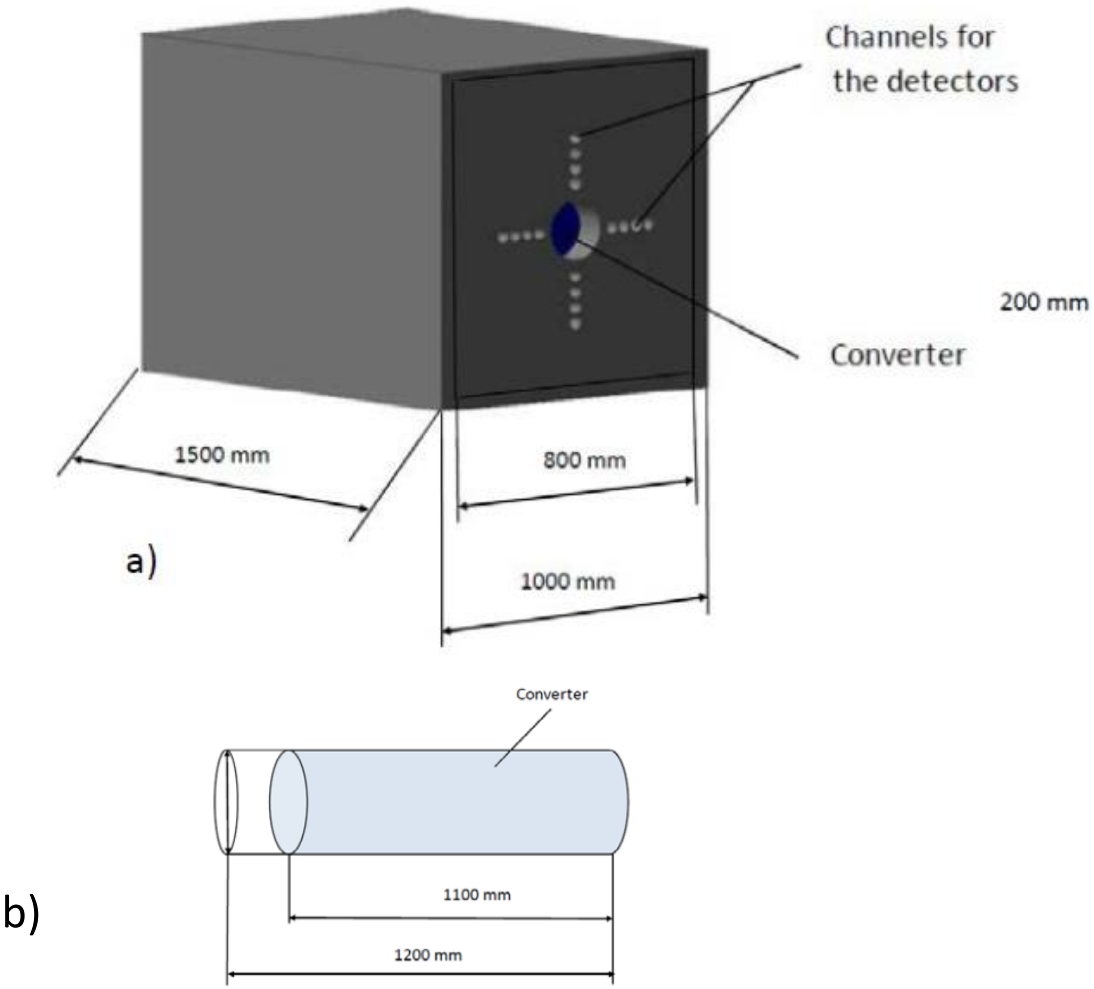





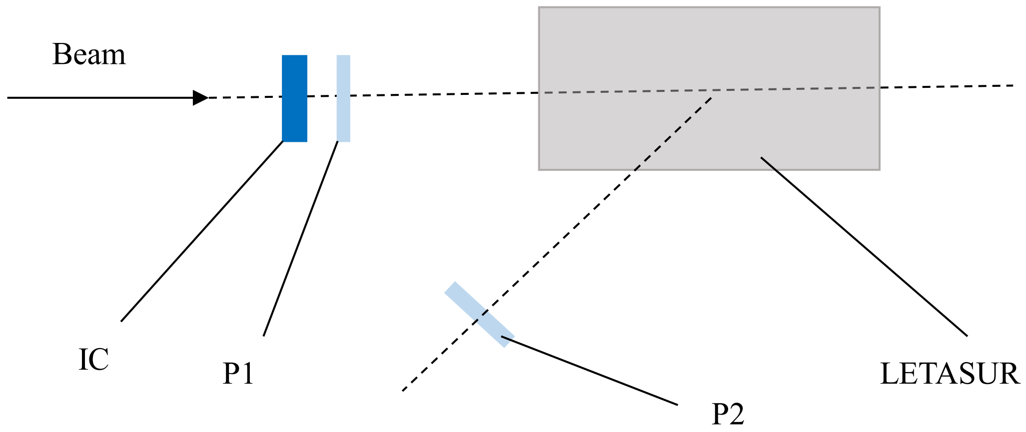
1. W.B.Amian et al., Differential Neutron Production Cross Sections for 800-MeV Protons, Nucl. Sci. Eng., Vol.112, p.78 (1992)
2. D.A.Lind, Charge-exchange studies at the Los Alamos Meson Physics Facility, Canadian Journal of Physics, Vol.65, p.637 (1987)

1. D. Filges et al., Validation of the intra-nuclear cascade evaporation model for particle production, Kernforschungszentrum Karlsruhe Reports, No.3779, p.11 (1984)
2. W. B. Amian et al., Differential Neutron Production Cross Sections for 597-MeV Protons, Nucl. Sci. Eng,, Vol.115, p.1 (1993)

# Configuration of the extended Pb target LETASUR




The scheme of the target (100x100x150 cm) (a) and converter (b )

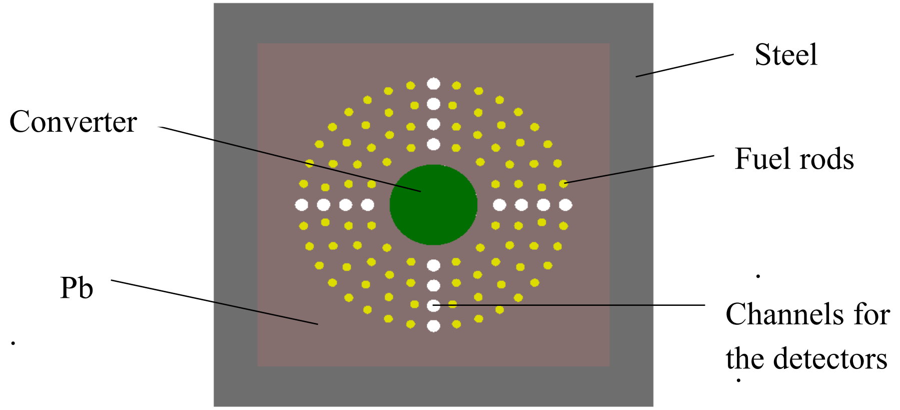



## The experimental set-up in Nuclotron, JINR

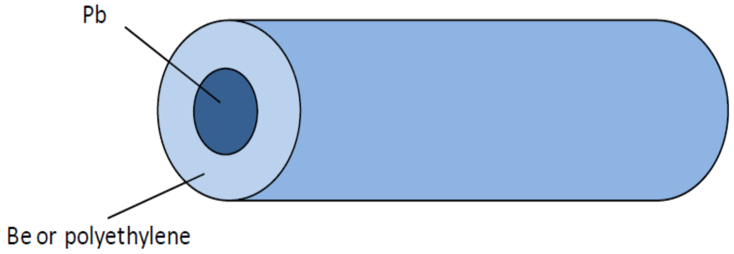
- Proton beams: 0.5 – 2 GeV.
- Ion beams ($He^4$-$C^{12}$): 0.25 – 0.75 GeV.
- Beam intensity: ~ $10^9$ p/s within 10 h.
- Measured with an ionization chamber IC and calibrated with thin plastic scintillators P1 and P2.
- Cylindrical 10% $U^{235}$ samples: R = 5 mm, T=1 mm
- Fission rates measured with HPGe detectors.

**Paraipan, M., et al (2025). Extended Lead Target for Studying the Perspectives of the Accelerator-Driven Subcritical Reactor. Nuclear Science and Engineering, 1–13**

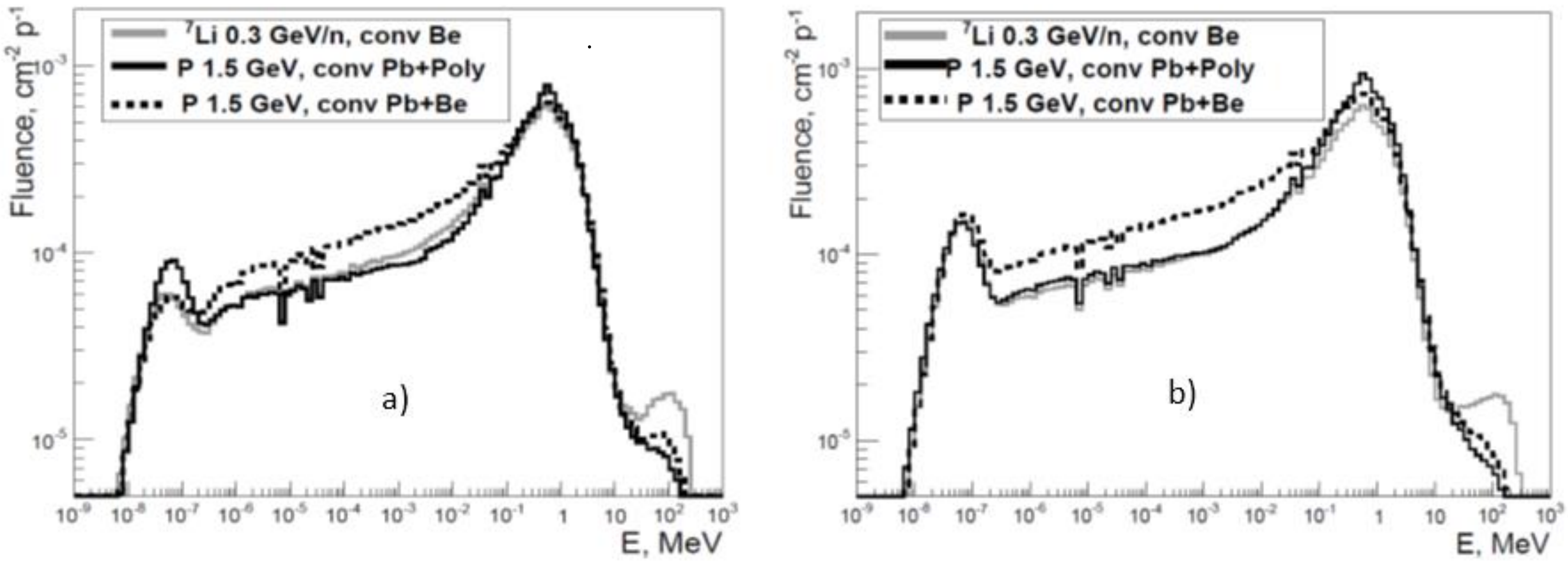
# Design of combined converters




The placement of fuel rods inside the target, $k_{eff}$ = 0.42



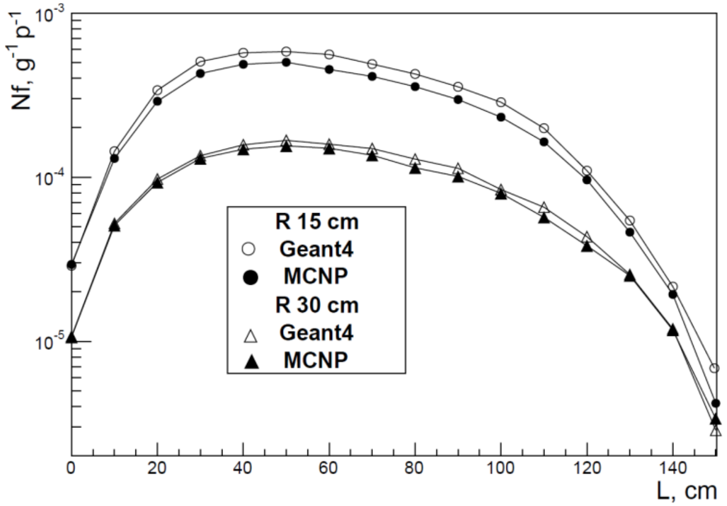

Converter Pb-Be: 4.5 cm Pb+5.5 cm Be
Converter Pb-$CH_2$: 9.3 cm Pb+0.7 cm $CH_2$

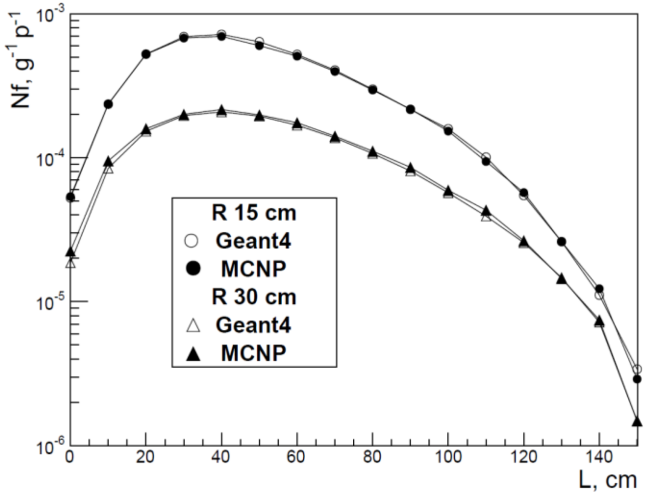



Mean neutron spectra for $^{7}$Li 0.3 AGeV with Be converter and P 1.5 GeV with combined converters predicted with Geant4 (a), and with MCNP (b)

# Measurements of fission distribution in extended Pb target LETASUR

Longitudinal fission distribution is registered in samples of enriched U with Be converter, irradiated with Li 0.3 GeV/n (left), combined Pb+Be converter, irradiated with P 1.5 GeV (right)




| Part/E, AGeV | Code | Conv. Be | | Conv. Pb+Be | | Conv. Pb+Poly | |
|---|---|---|---|---|---|---|---|
| | | Nat U | 10%$^{235}$U | Nat U | 10%$^{235}$U | Nat U | 10%$^{235}$U |
| P 1 | Geant4 | 48.6 | 433 | 65.8 | 550.4 | 62.1 | 601.5 |
| | MCNP | 65.2 | 585.6 | 73.2 | 677.8 | 68.2 | 608 |
| P 1.5 | Geant4 | 74.9 | 661 | 97.1 | 998.1 | 105.2 | 1014.8 |
| | MCNP | 94.7 | 857.2 | 109.4 | 1101.7 | 105.2 | 997.4 |
| $^{7}$Li 0.2 | Geant4 | 43.5 | 389.9 | 15.5 | 145.8 | 15.1 | 139.8 |
| | MCNP | 42.7 | 387.3 | 13.6 | 122.5 | 13.4 | 115.9 |
| $^{7}$Li 0.25 | Geant4 | 79.1 | 760 | 24.9 | 220.3 | 26.8 | 249.7 |
| | MCNP | 70.5 | 639.3 | 24 | 216.2 | 24.2 | 205.4 |
| $^{7}$Li 0.3 | Geant4 | 110.3 | 1055.9 | 39.2 | 368.5 | 42 | 394.2 |
| | MCNP | 103.7 | 936.5 | 30.8 | 344.6 | 37.4 | 325.4 |

We can demonstrate the equivalence between Li 0.25 (0.3) AGeV and P 1 (1.5) GeV

Total number of fission per projectile in LETASUR with different converter LETASUR

# Conclusions

- The conditions that maximize the energy efficiency of ADSR were investigated. The main factors related with the core, relevant for the ADSR efficiency are the core, $k_{eff}$, the material used for the converter and the level of the enrichment.
- The optimal value of $k_{eff}$ is in the range 0.985 - 0.988, ensuring a safe operation.
- The optimal energy for proton is 1-1.5 GeV. Ion beams starting with $^4$He realize higher energy gain than protons. The best choice is a beam of Li7 with energy 0.25-0.3 AGeV.
- The use of LBE converter is preferable for proton beams, and for ion beams it is Be.
- Large configurations that allow to obtain the needed value of $k_{eff}$ with lower enrichment are preferable, giving the possibility to realize longer cycles and to burn 15-20% from the actinides during cycle.
- With beam intensities above $10^{16}$ energy gain higher than 15 is obtained which makes ADSR an efficient source of energy.
- The analysis of various experiments meant to compare the efficiency of different beams concludes that the most reliable results can be obtained by measuring the distribution of fissions.
- We propose a lead target LETASUR with large dimensions 100x100x150 cm, with central hole for the converter, and vertical and horizontal holes for the detectors.

# Thank you for attention!