Theoretical and experimental investigation on the optimization of accelerator driven subcritical reactors ADSR

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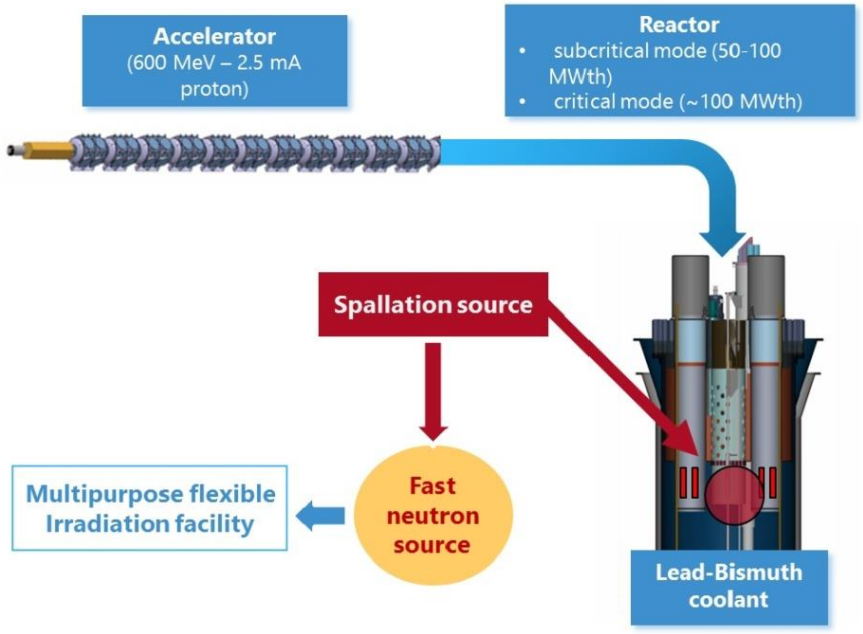
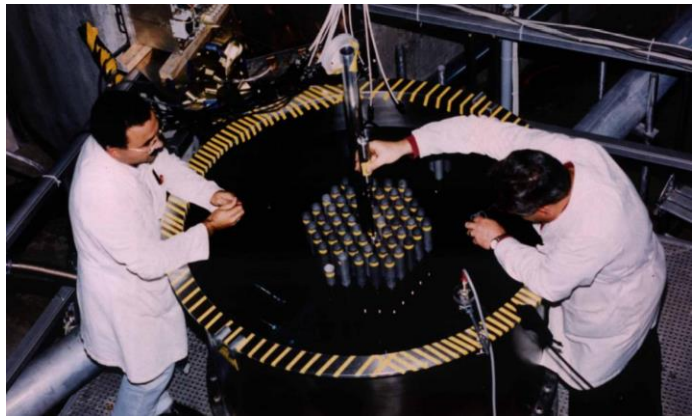
ADS projects in the world

- ADS as a solution for problem of nuclear radioactive waste since the hard neutron spectrum allows better burning of actinides.
- Source of energy.

Project MYRRHA



FEAT experiment (CERN)



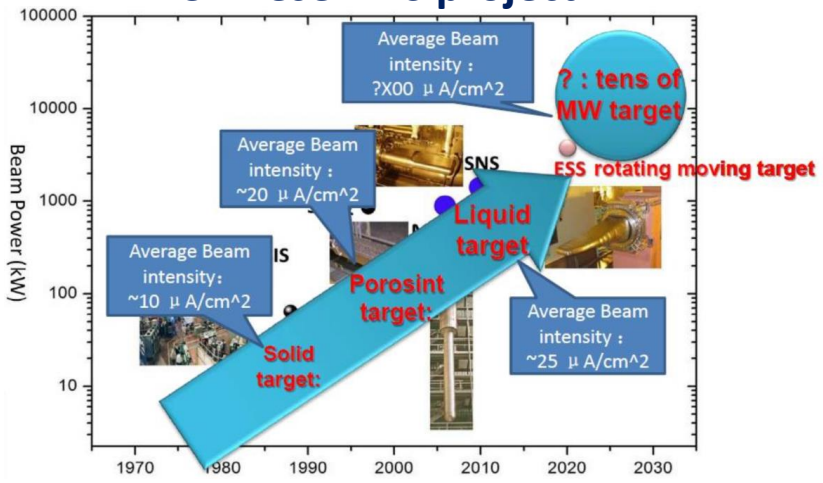
European Spallation Source



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 <2500 <25	1s<t<10s 10s<t<5m t>5m

Chinese ADS project



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

ADSR as energy amplifier

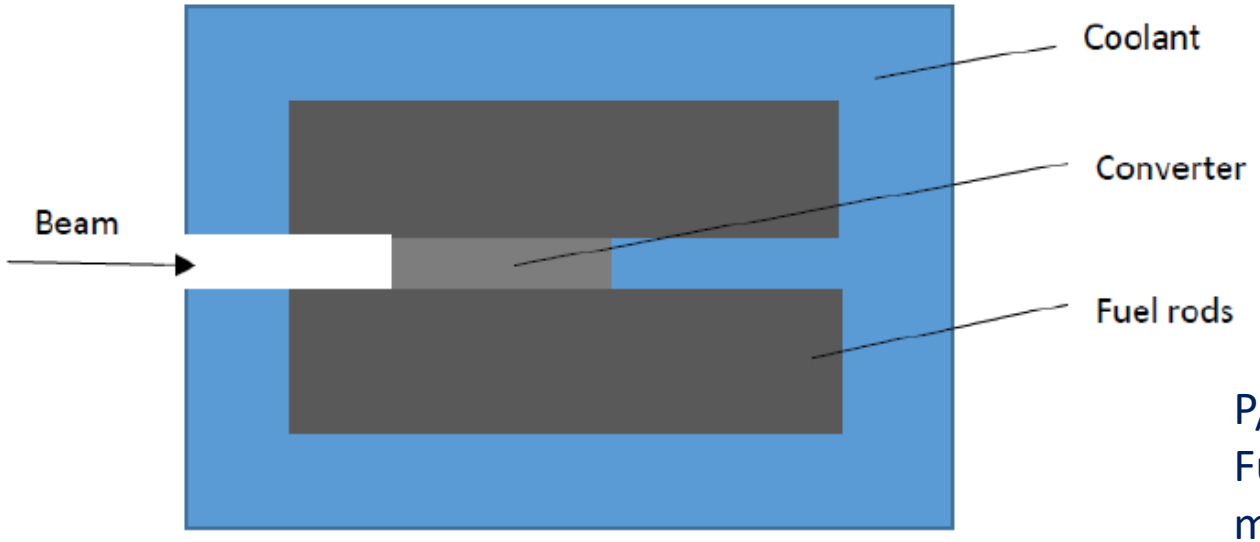
Advantages:

- 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



The scheme of the target.

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

Safe exploitation – optimal value of k_{eff}

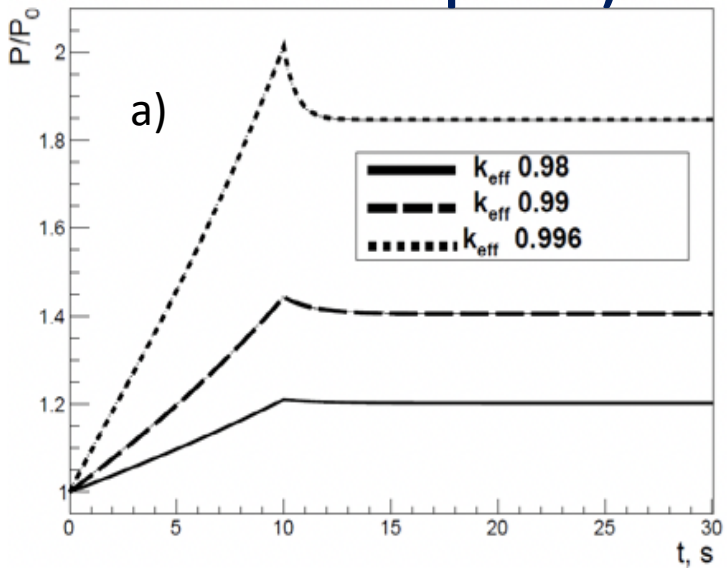
Transients with positive reactivity insertion

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

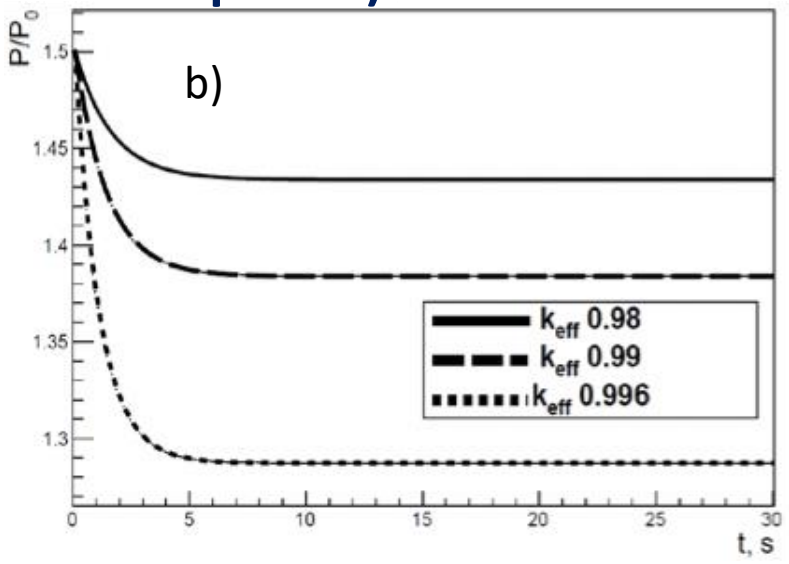
Reactivity insertion < 400 pcm

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

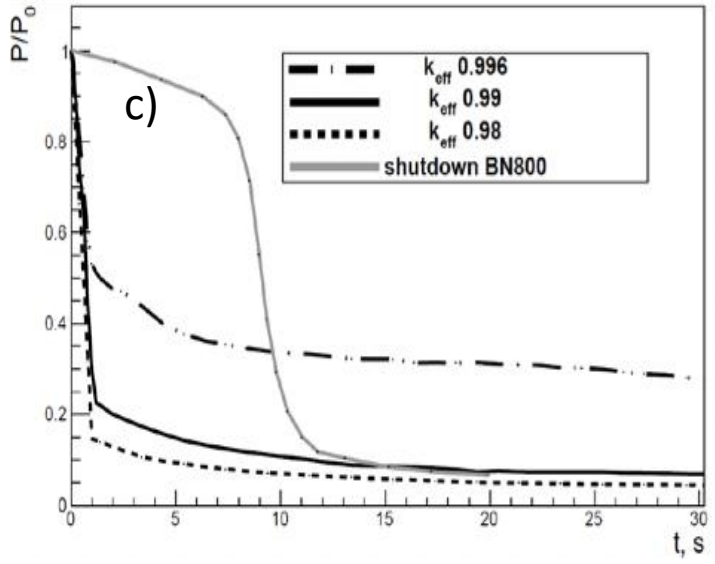
UTOP (unprotected transient overpower)



UBOP (unprotected beam overpower)



Beam shutdown



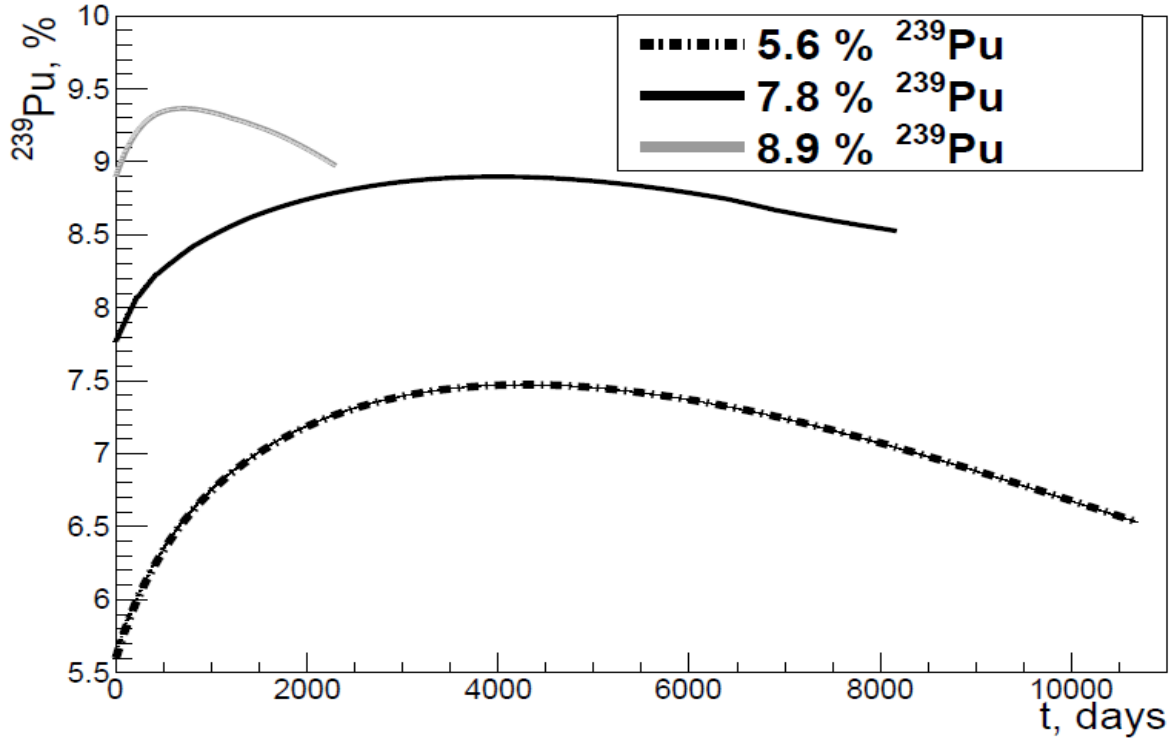
The power evolution in UTOP (a), in UBOP (b) transients and after the beam turn off (c) in ADS with U-Pu-10%Zr fuel and k_{eff} 0.98, 0.99, 0.996.

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

Level of enrichment and actinide burning

- **A larger configuration of ADSR is preferable , that allows reaching the needed value of keff with lower enrichment and longer period of working time**

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

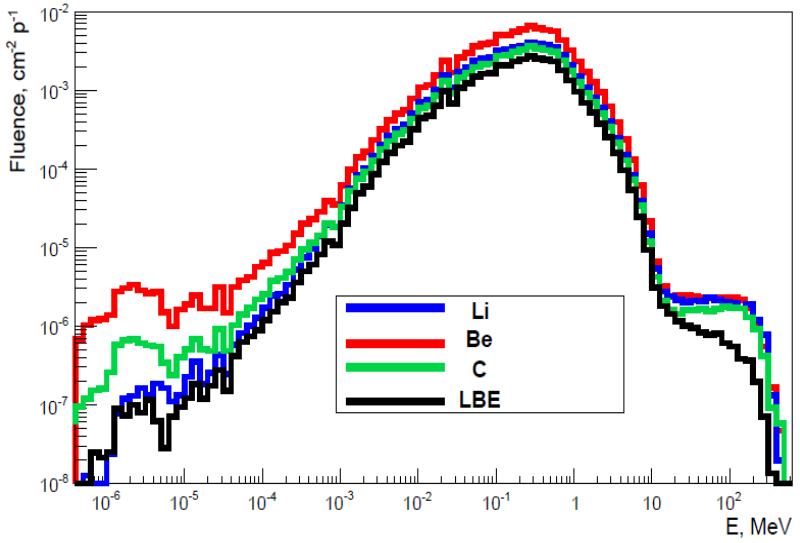


The evolution of ^{239}Pu in cores with 5.6%, 7.8% and 8.9% ^{239}Pu, irradiated with a beam of ^{7}Li with energy 0.25 AGeV and intensity $1.25 \cdot 10^{16}$ p/s.

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.

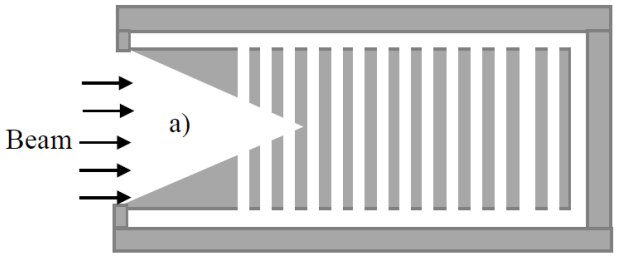


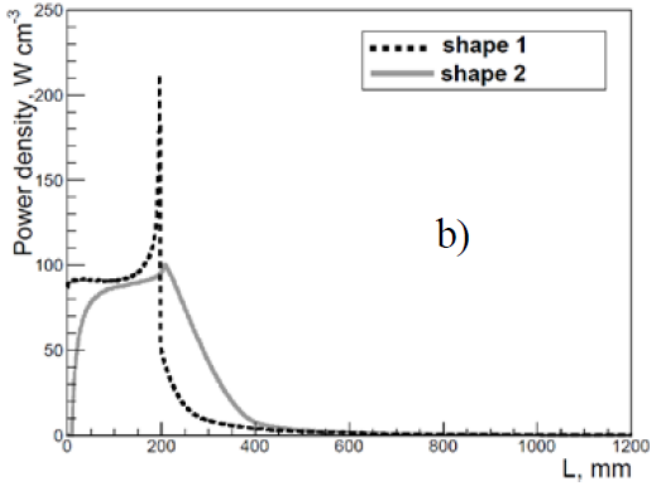
The neutron spectra in fuel blanket with Li, Be, C and LBE converters, irradiated with a beam of ^{7}Li with energy 0.3 AGeV.

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

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



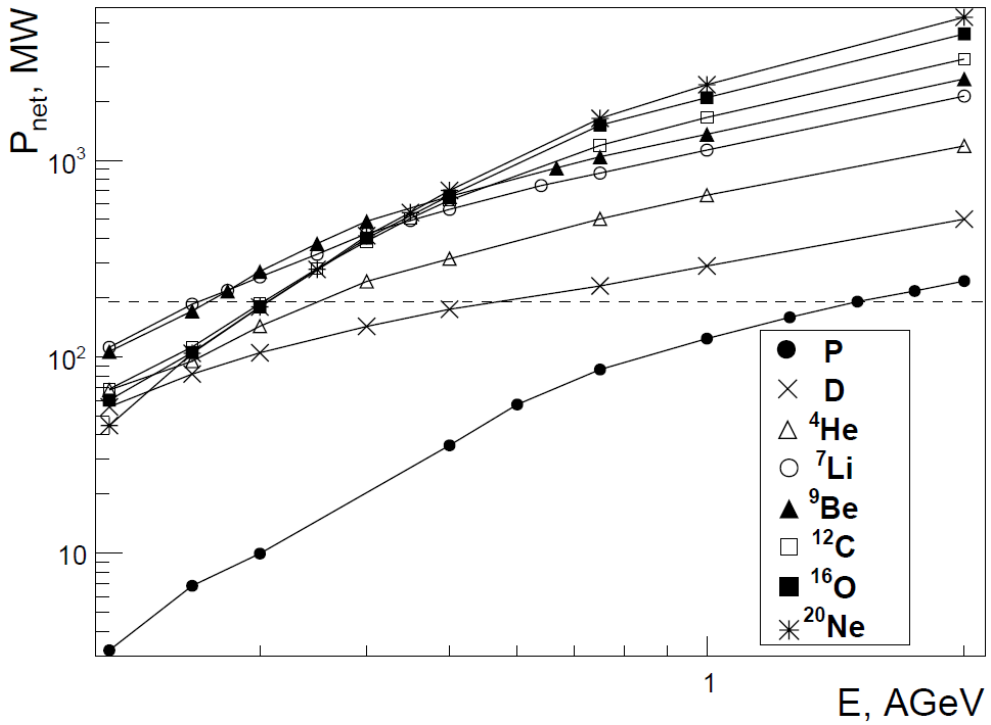


Proposed shape of the converter with a wedge part (a), the distribution of power density in cylindrical converter (shape 1) and with the proposed shape (shape 2) irradiated with ^{7}Li 0.25 AGeV (b).

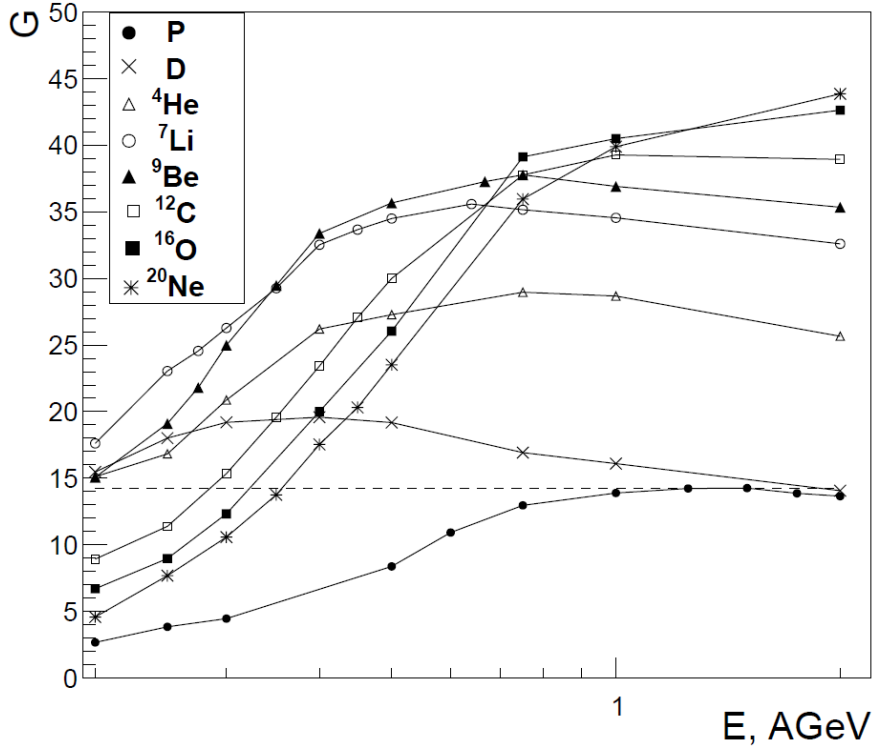
One relevant advantage of a Be converter with high dimensions is the fact that allows to diminish the level of enrichment, increasing the period of functioning without refueling and consequently, the burn-up.

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 produces the same P_{net} as a beam of 1-1.5 GeV proton with the minimal length of the accelerator (length 2 times shorter than for protons).

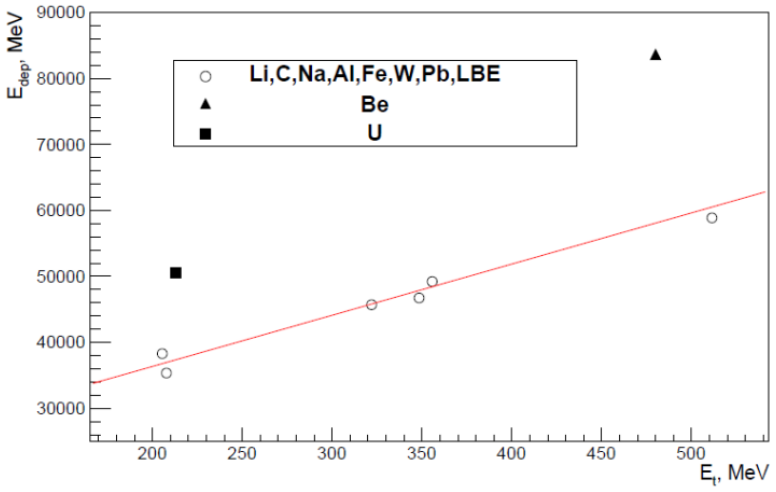
Planned experiments

Theoretical results from simulation:

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

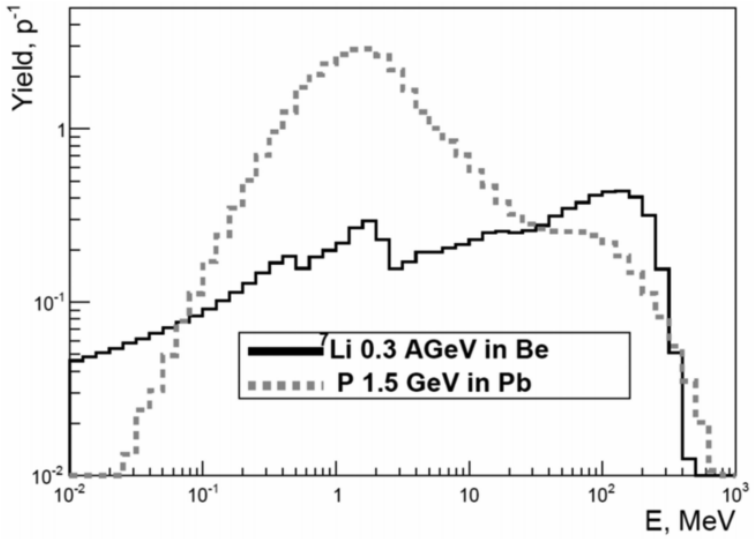


The dependence of the energy released on the total energy carried out by the neutrons.

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

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.

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

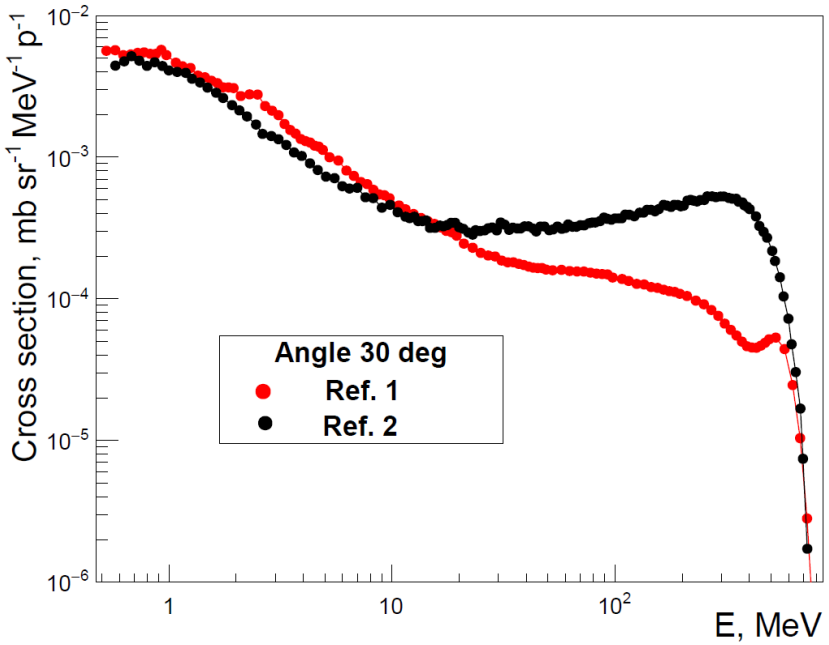


- ^{7}Li - neutrons with E>100 MeV - 70 % from the total kinetic energy

- P – 53%

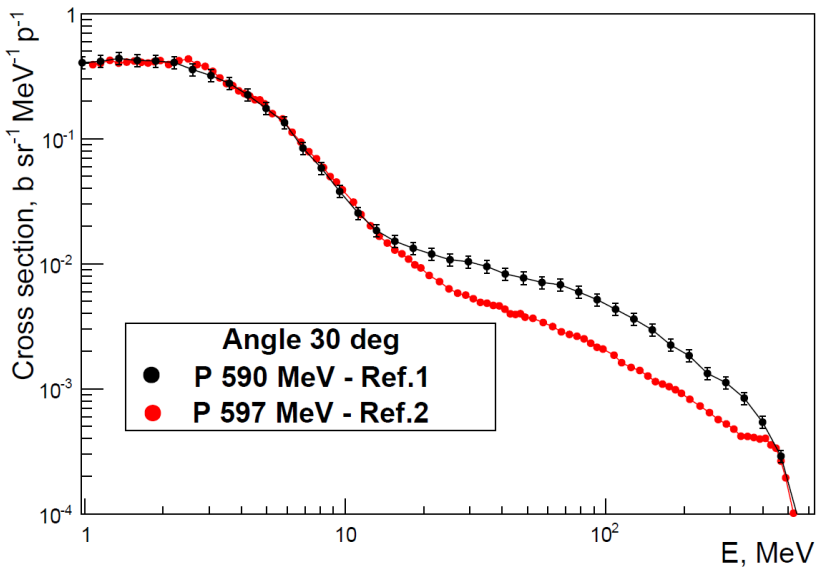
Paraipan M., Kryachko I. A., Javadova V. M., Levterova E. A., Tyutyunnikov S. I., Main Results of Neutronical Study about ADS with Ion Beams and Implications on Experiments Planning, Phys. Part. Nucl. Lett. 19 2 (2022) p. 129-144

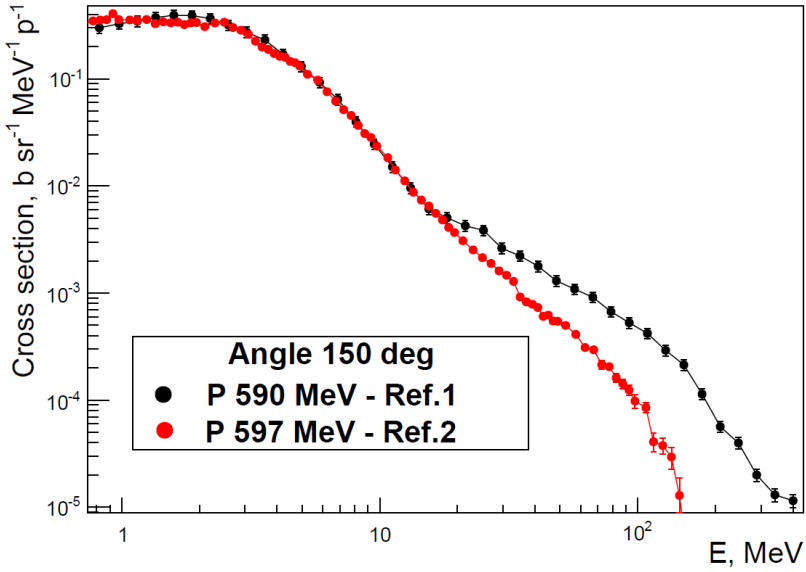
Double differential cross section of neutrons from P 800 MeV in Be



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)

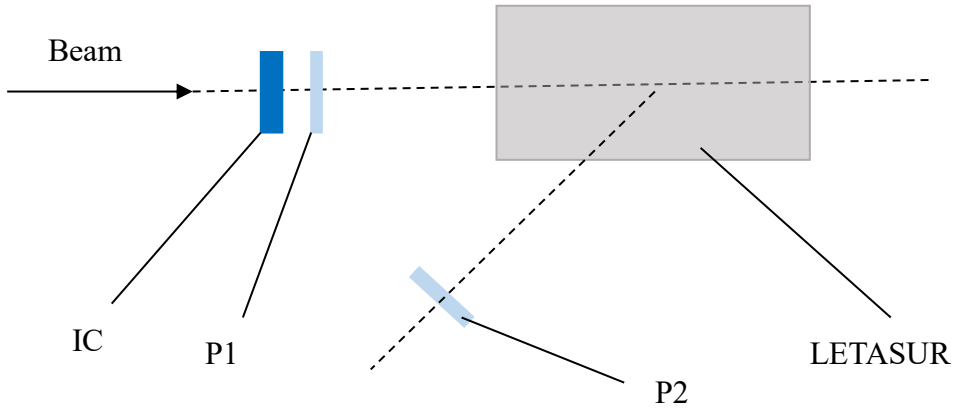
Double differential cross section of neutrons from P 590 MeV in U

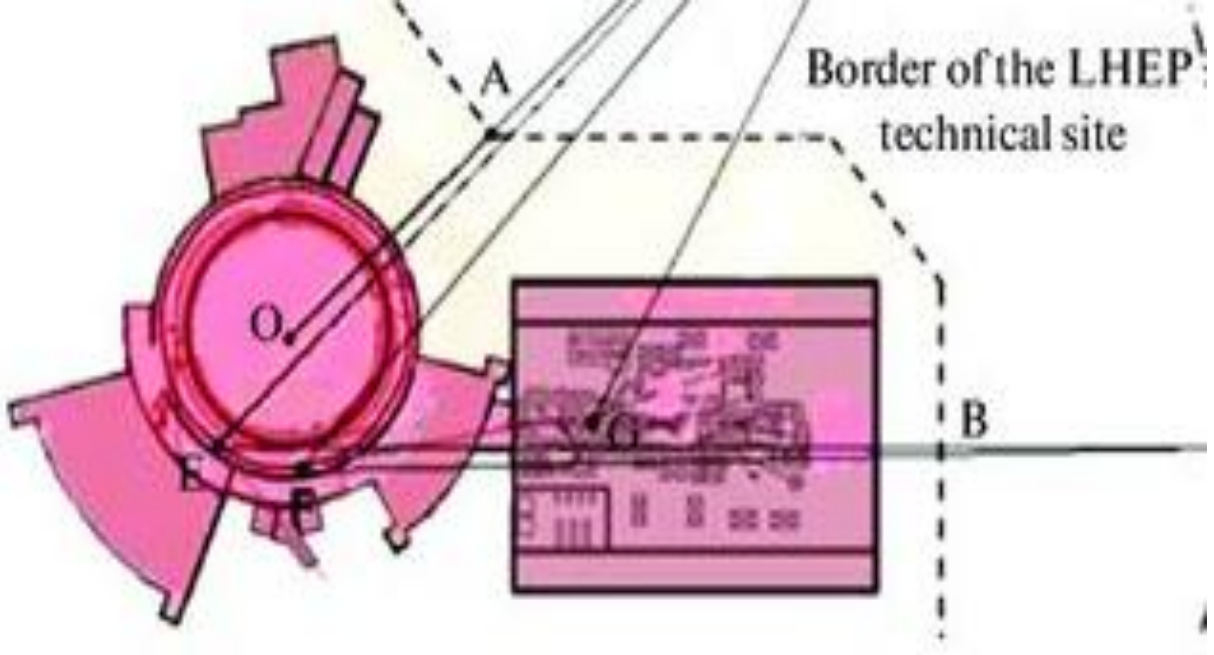




1. D. Filges et al., Validation of the intra-nuclear cascade evaporation model for particle production, Kernforschungszentrum Karlsruhe Reports, No.3779, p.11 (1984)
2. W. B. Amian et al., Differential Neutron Production Cross Sections for 597-MeV Protons, Nucl. Sci. Eng,, Vol.115, p.1 (1993)

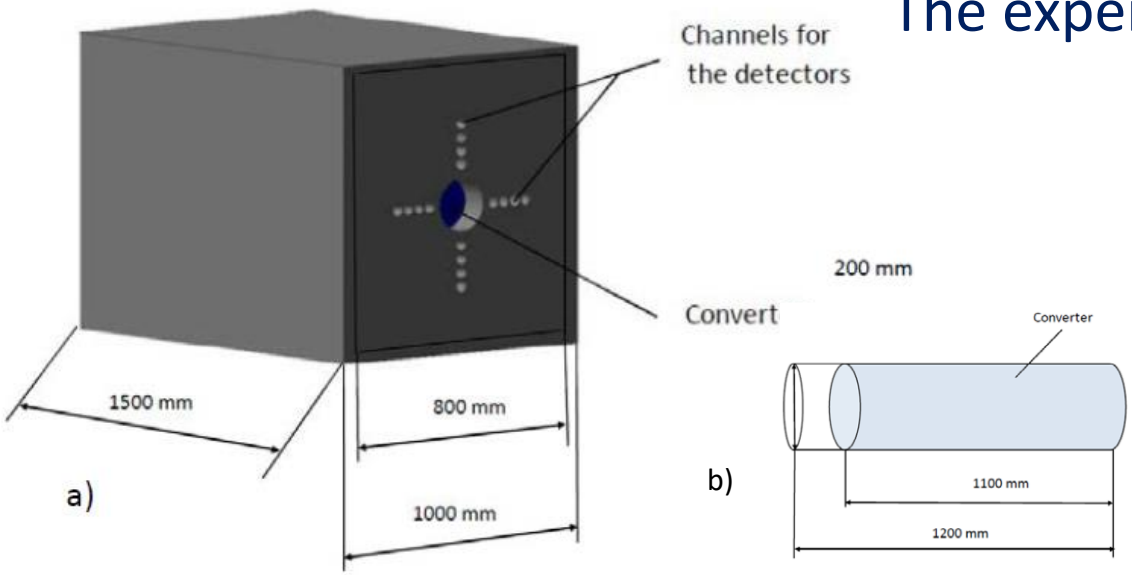
Configuration of the extended Pb target LETASUR





The experimental set-up at NICA complex, JINR

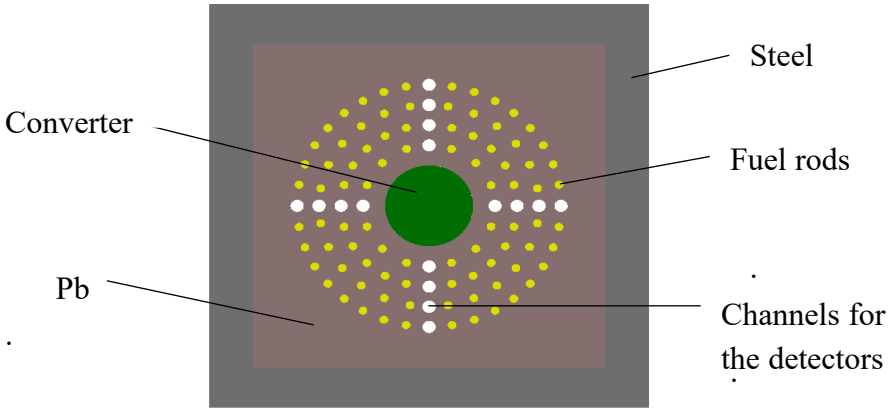
- Proton beams: 0.5 – 2 GeV.
- Ion beams (He^4-C^{12}): 0.25 – 0.75 GeV.
- Beam intensity: ~ 10^9 p/s within 10 h.
- Measured with an ionization chamber IC and calibrated with thin plastic scintillators P1 and P2.

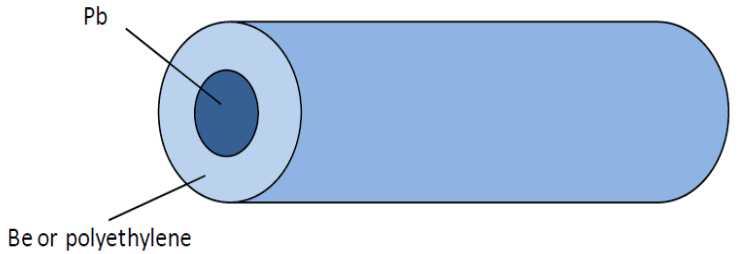


The scheme of the target (100x100x150 cm) (a), converter (b)

Paraipan, M., et al (2025). Extended Lead Target for Studying the Perspectives of the Accelerator-Driven Subcritical Reactor. Nuclear Science and Engineering, 1–13. doi.org/10.1080/00295639.2025.2522570

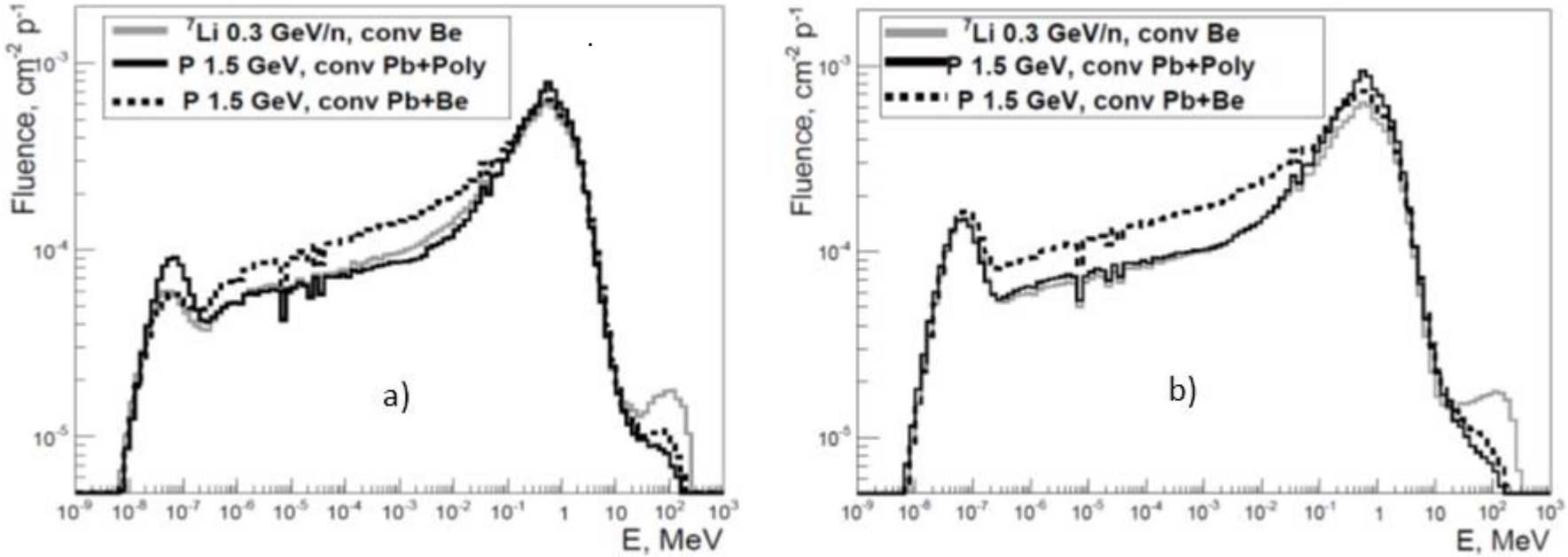
Design of combined converters





The placement of fuel rods inside the target, k_{eff} = 0.42 for Be converter.

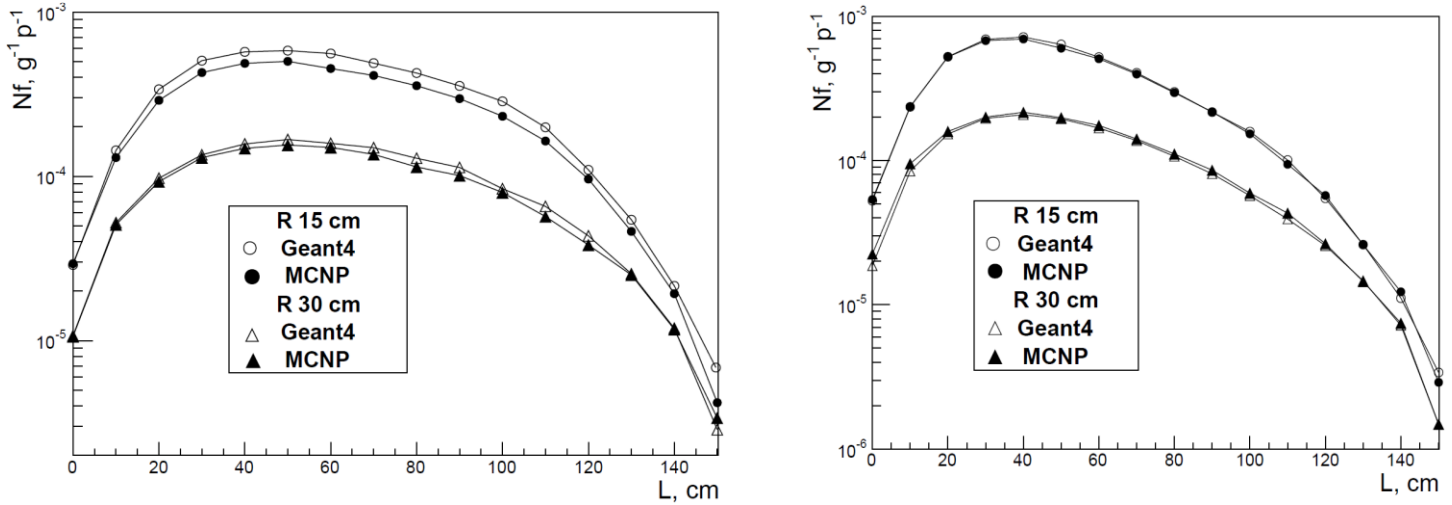
Converter Pb-Be: 4.5 cm Pb+5.5 cm Be
Converter Pb-CH_2: 9.3 cm Pb+0.7 cm CH_2



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)

Calculated 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

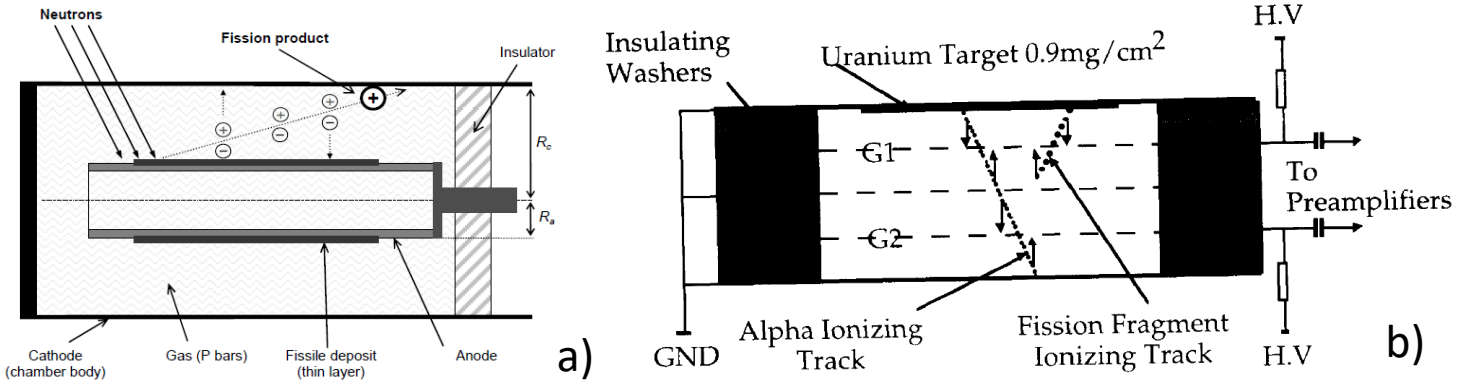
Experimental methods for the measurement of the fission distribution

Activation method

- Cylindrical 10% U^{235} samples: R = 5 mm, T=1 mm
- Fission rates measured with HPGe detectors.

Fission ionization chambers

- parallel or cylindrical configuration of the electrodes, with dimensions small enough to enter in the channel, and the extension on the length of the channel <100 mm
- the chambers must work in pulse mode
- sealed chambers without gas flow



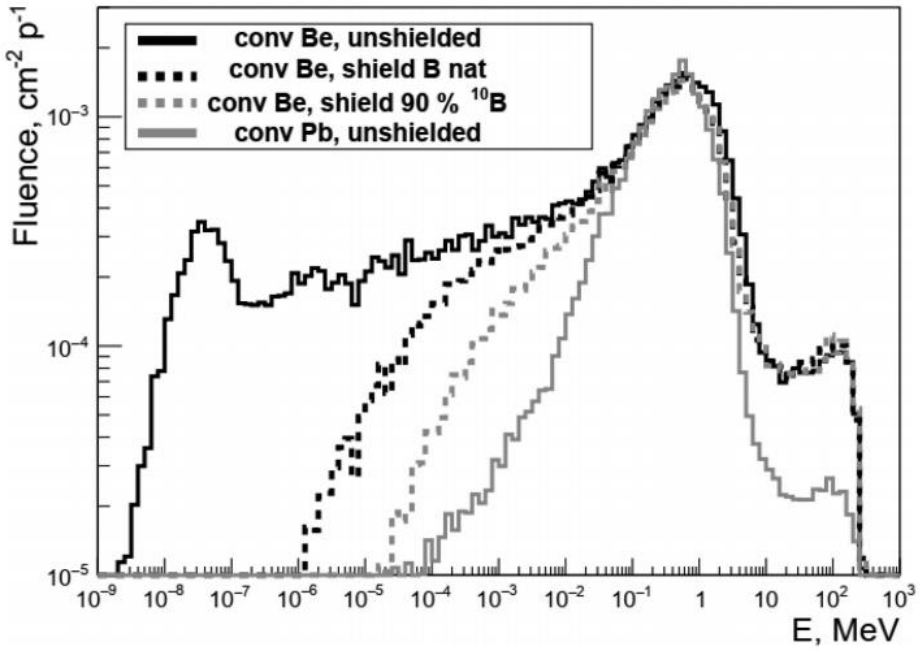
The scheme of fission chamber in cylindrical (a) and parallel (b) geometry.

TFBC (thin film breakdown counters)

- used in experiments with Quinta target
- **they did not give reliable results**

A. A. Baldin, A. I. Berlev, I. A. Kryachko, E. A. Levterova, M. M. Paraipan, *c*, A. M. Prokoshin, A. N. Smirnov, A. A. Solnyshkin, T. N. Tran*a*, S. I. Tyutyunnikov, Using Thin-Film Breakdown Counters for the Neutron Field Characterization in Experiments on "Quinta" Setup, *Physics of Particles and Nuclei, 2021, Vol. 52, No. 6, pp. 1033–1043*

Neutron spectra and actinide transmutation



Various shapes of neutron spectrum.

The hard neutron spectrum obtained in FR realizes a higher breeding ratio than in thermal reactors
Neutron spectra with intermediate shape conduce to higher breeding ratio than in FR.

The breeding characteristic of neutron spectra will be estimated through the ratio of the neutron capture in ^{238}U to the fission in ^{239}Pu.

- foils of Au, Mo, W, Ni, Co and Bi will be irradiated in the same conditions as the ^{238}U and ^{239}Pu samples
-radiative capture reactions: ^{197}Au(n,γ)^{198}Au, ^{98}Mo(n,γ) ^{99}Mo, ^{186}W(n,γ)^{187}W, ^{59}Co(n,γ)^{60}Co will be used for the low energy part of the neutron spectrum.
- the accumulation rates of isotopes with different threshold energies in Co and Bi samples for the high energy part of the spectrum.

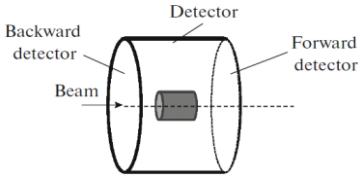
The ratio capt^{238}U/fis^{239}Pu for different shapes of neutron spectrum

	Converter Be Unshield	Converter Be Shield ^{nat}B	Converter Be Shield 90% ^{10}B	Converter Pb Unshield
capt^{238}U/fis^{239}Pu	0.063	0.524	0.31	0.227

Radiation exposure and shielding calculation

Source term

other planned experiments at **SHINE (СИЯЭТ)** room
- Pb cylinder R 10cm, L 50 cm, irradiated with 10 GeV protons and 1 GeV/n ^{12}C

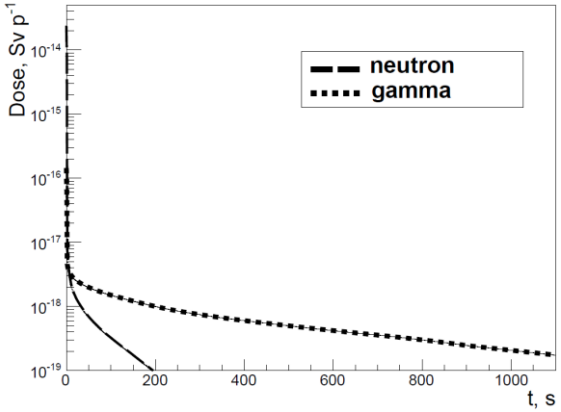


The set-up used for the simulation of the source term.

Doses for different beam-target combinations.

Target	Particle/E, AGeV	Dose back, Sv/p	Dose forw, Sv/p	Dose lat, Sv/p	Dose mean, Sv/h
Pb cylinder	P/10	1.94e-14	2.08e-14	3.04e-14	0.97
	^{12}C/1	1.89e-14	1.76e-14	2.67e-14	8.6e-2
LETASUR	P/2	8.59e-15	6.97e-16	2.4e-15	1.1e-2
	^{12}C/0.75	5.96e-15	9.12e-15	8.05e-15	2.8e-2

Target activation



- The evolution of the neutron and gamma doses after the irradiation of the target with ^{12}C 0.75 AGeV, beam intensity $1 \cdot 10^9$ p/s.
- 15 min after irradiation, dose is below 1 μSv/h

We can safely use beam intensities of $1 \cdot 10^9$ p/s.

Doses in the experimental area



maximal doses limits in the Russian Federation (ОСПОРБ-99/2010)
-12 μSv/h in zones with temporary presence of the personnel group A
- 6 μSv/h for the zones with permanent presence of the personnel group A
- 1.2 μSv/h for the personnel group B
- 0.06 μSv/h for population

The doses registered when the target LETASUR is irradiated with ^{12}C 0.75 AGeV, beam intensity $1 \cdot 10^9$ p/s.

Detector	Door 2m concrete		Door 50 cm steel		Door unshielded	
	Dose		Dose		Dose	
	Sv/p	μSv/h	Sv/p	μSv/h	Sv/p	μSv/h
1	7.7e-19	27.7	2.43e-17	87.6	1.19e-15	4.3e3
2	4.19e-21	1.5e-2	2.03e-20	7.3e-2	8.59e-19	3.08
3	5.93e-20	0.21	6.54e-20	0.23	3.28e-18	11.8
4	3.14e-19	1.13	3.54e-18	12.7	3.12e-16	1.12e3
5	1.5e-21	5.4e-3	7.29e-22	2.62e-3	3.4e-19	1.22
6	7.91e-20	0.28	9.03e-19	3.26	1.27e-16	4.56e2
7	1.36e-19	0.49	7.99e-19	2.88	6.69e-17	2.46e2
8	2.5e-19	0.9	4.56e-21	1.6e-2	2.82e-20	1.02
9	4.04e-20	0.14	4.32e-21	1.5e-2	3.49e-19	1.26
10	1.46e-19	0.53	2.09e-20	7.54e-2	1.41e-18	5.06

Future plans

1. To continue the theoretical study about the optimization of ADSR:
    - the influence of the fuel type on the maximum power
    - possibilities to vary the shape of the energy density in the active zone
    - modeling the neutron spectrum in order to obtain longer cycle

2. Participation in experiments and data analysis

3. Prepare materials for PhD thesis.

Thank you for attention!