Perspectives of ADSR. The target LETASUR.

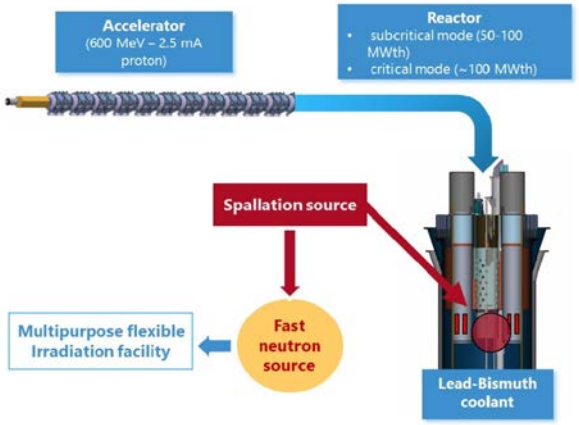
Mihaela Paraipan

On behalf of the ARIADNA-NPT Collaboration

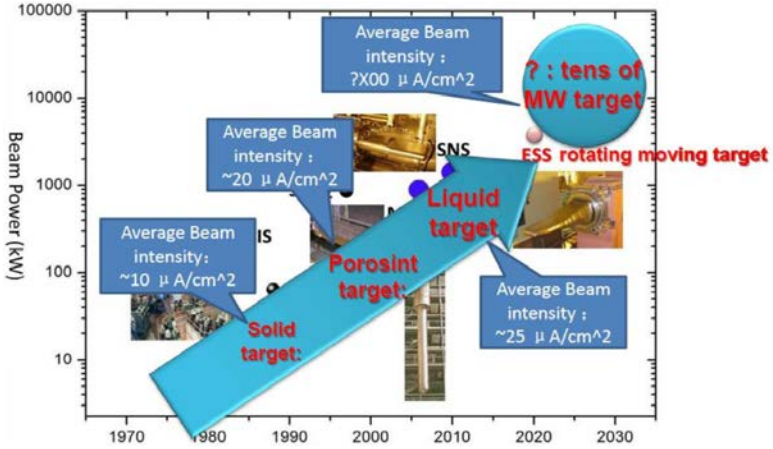
ADSR as energy amplifier

Advantages:
- the reactor works in subcritical regime – safer exploitation
- harder neutron spectrum – better incineration of the actinides

Project MYRRHA



Chinese ADS project



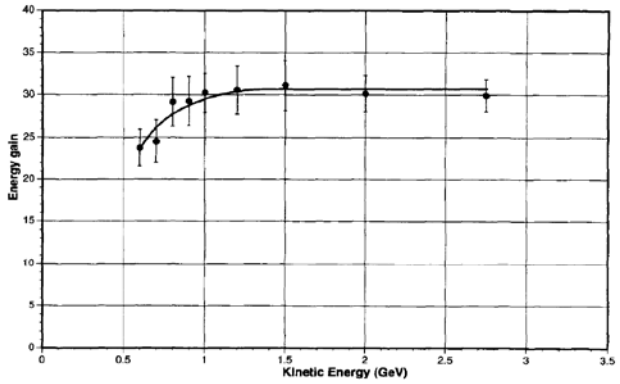
All these projects plan to use proton beams and a lead-bismuth eutectic (LBE) cooled subcritical reactor.

Goals:

- Review of main results of our theoretical study about the factors that influence the efficiency of ADSR (factors related with the core structure and composition, particle beam and energy, accelerator type), with the main conclusion:
  - ADSR represents an efficient source of energy with energy gain G>15 for protons
  - ion beams starting with Li7 are more efficient than protons (G>20)
  - the mass of the actinides burned in one cycle 2-3 times higher than in fast reactors
- Analysis of possible experiments meant to compare the energy efficiency of different beams
- Description of the extended lead target LETASUR (**LE**ad **T**arget for the study of **A**ccelerator driven **SU**bcritical **R**eactors)

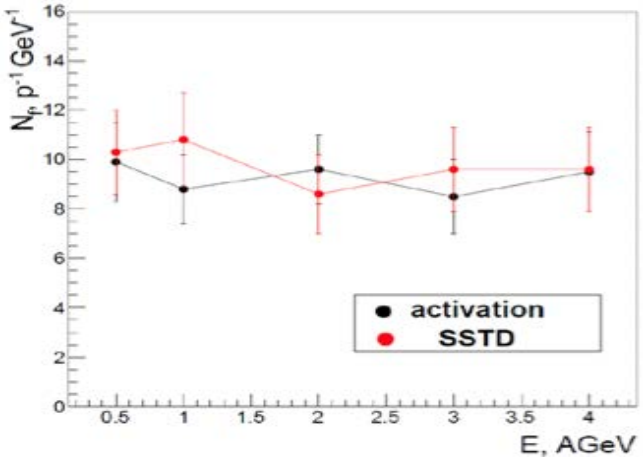
Proton and deuteron

FEAT experiment



The energy gain as function on proton kinetic energy.

E&T collaboration



The dependence of the number of fissions on the deuteron beam energy (target QUINTA)

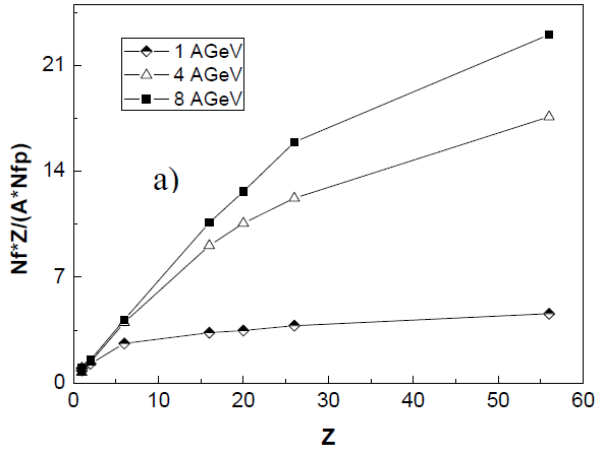
Heavier ions

D. G. Koshkarev, N. M. Sobolevskii, A. V. Barkhudaryan, "Use of the electronuclear method in power generation," At. Energy 105,225 (2008)

They recommend optimal beam Ne with energy 3 GeV/n, beam current 30 mA

Incorrect method to calculate the energy gain by normalizing to the beam energy

Correct calculation of the energy gain G is is the ratio of the produced electrical power $\mathbf{P_{prod}}$ to the power spent to accelerate the beam $\mathbf{P_{spent}}$



M. Paraipan, A. A. Baldin, M. G. Kadykov, S. I. Tyutyunikov, Investigation of the possibility to use ion beams for ADS through simulation in GEANT4, *PoS (Baldin ISHEPP XXI)* 088 (2012)

The number of fission reported to the energy consumed for the acceleration of the charged particles and to the number of fissions obtained with protons with the same energy on nucleon

Calculated energy gain

The energy gain factor G is the ratio of the produced electrical power $\mathbf{P_{prod}}$ to the power spent to accelerate the beam $\mathbf{P_{spent}}$:

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

$$P_{prod} = \eta_{el} \cdot E_{dep} \cdot I_{beam} \qquad \eta_{el} = 0.4$$

$$P_{spent} = P_{beam} + P_{acc}$$

M. Paraipan, A. Baldin, E. Baldina, S. Tyutyunnikov, Light Ion Beams for Energy Production in ADS, Proceedings MMCP 2017, https://doi.org/10.1051/epjconf/201817304011

M. Paraipan, A. Baldin, E. Baldina, S. Tyutyunnikov, Conceptual design of accelerator driven systems with light ion beams, IL NUOVO CIMENTO 42 C (2019) 66

Linear accelerator

$Pacc \sim A \cdot E/Z$

$$P_{spent} = A \cdot E \cdot I_b \left[1 + \left(\frac{1}{\eta_0} - 1\right) \frac{Z_0}{Z} \frac{I_{b0}}{I_b}\right]$$

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

A is the mass number, Z the atomic number, E is the energy per nucleon and p the momentum per nucleon
Index 0 for the reference particle

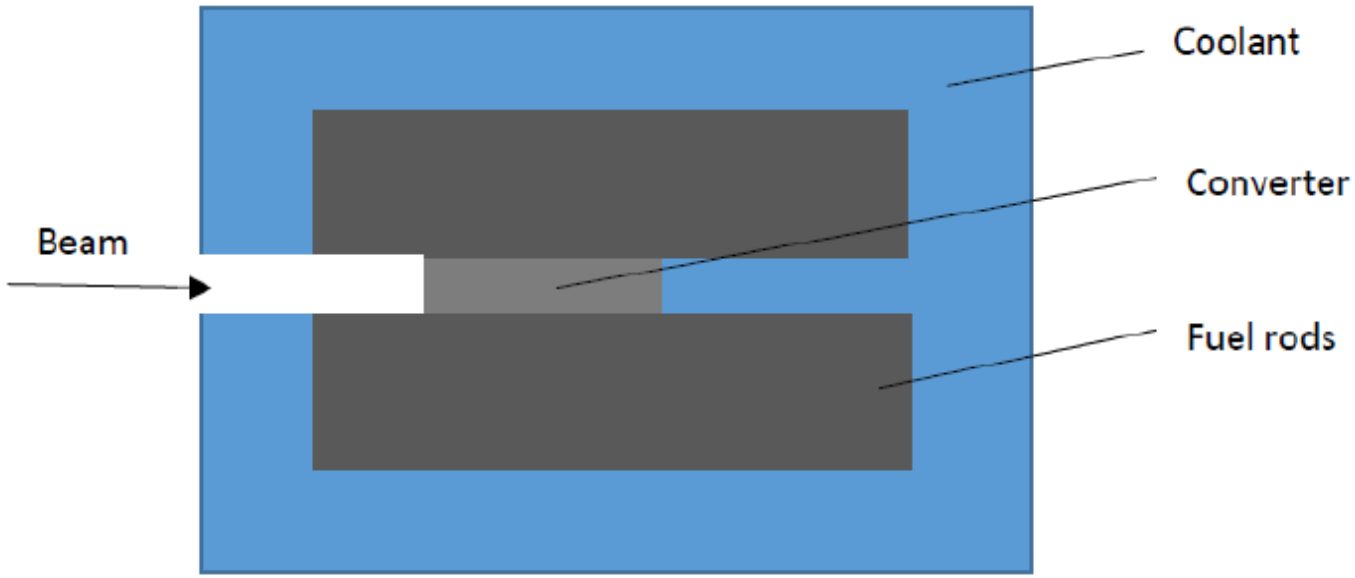
Cyclotron

$Pacc \sim (A \cdot p/Z)2$

$$P_{spent} = A \cdot E \cdot I_b \left[1 + \left(\frac{1}{\eta_0} - 1\right) \frac{E_0}{E} \frac{A}{A_0} \frac{I_{b0}}{I_b} \left(\frac{Z_0}{Z} \frac{p}{p_0}\right)^2\right]$$

Factors related with the core structure and composition

- the value of the effective multiplication factor k_{eff}
- the level of enrichment
- the material for the converter



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}

$$P(t) = P_0(t)\frac{\rho_0}{\rho(t)} \qquad \rho = \frac{k_{eff}^{-1}}{k_{eff}}$$

$P_0(t)$ is the uncorrected power, ρ_o is the reactivity in steady-state, and $\rho(t)$ is the reactivity at time t

Transients with positive reactivity insertion and beam transients

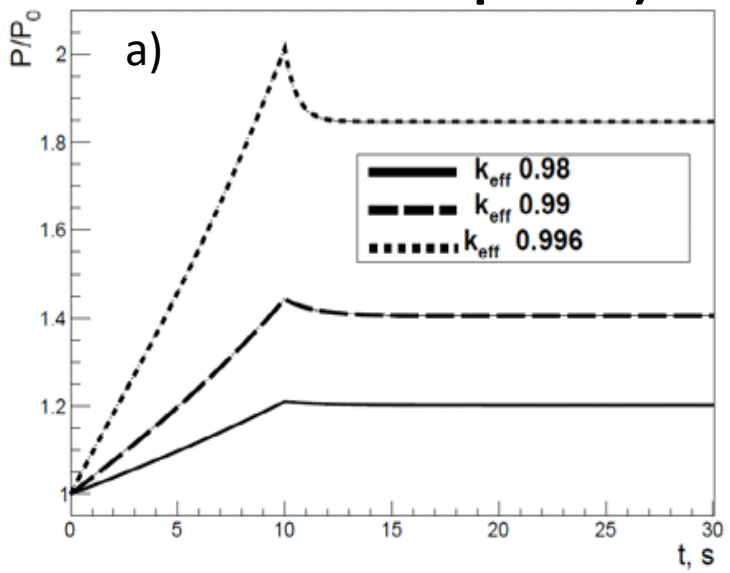
- the accidental withdrawal of the control rods - reactivity insertion < 150 pcm
- pin failure
- core compaction.

} reactivity insertion < 400 pcm

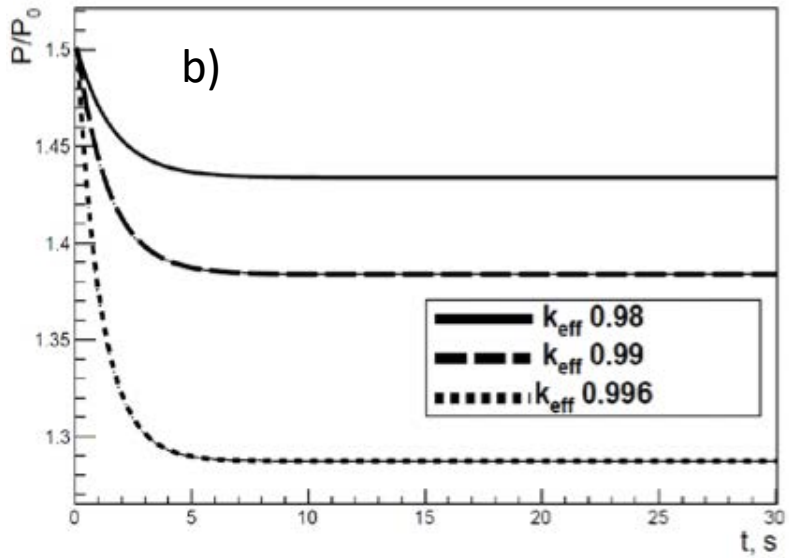
1 pcm=1e-5
(per cent mille)

k_{eff}	0.996	0.988	0.985
ρ [pcm]	-401.6	-1214.6	-1522.8

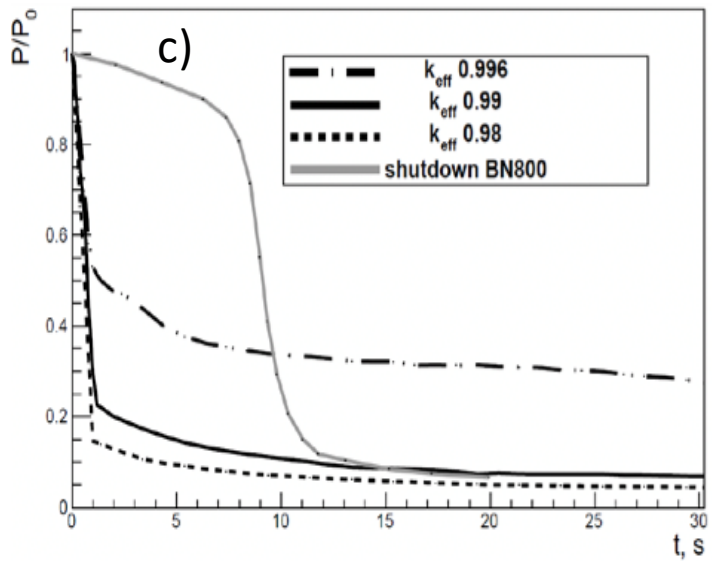
UTOP (unprotected transient overpower)



UBOP (unprotected beam overpower)



Beam shutdown



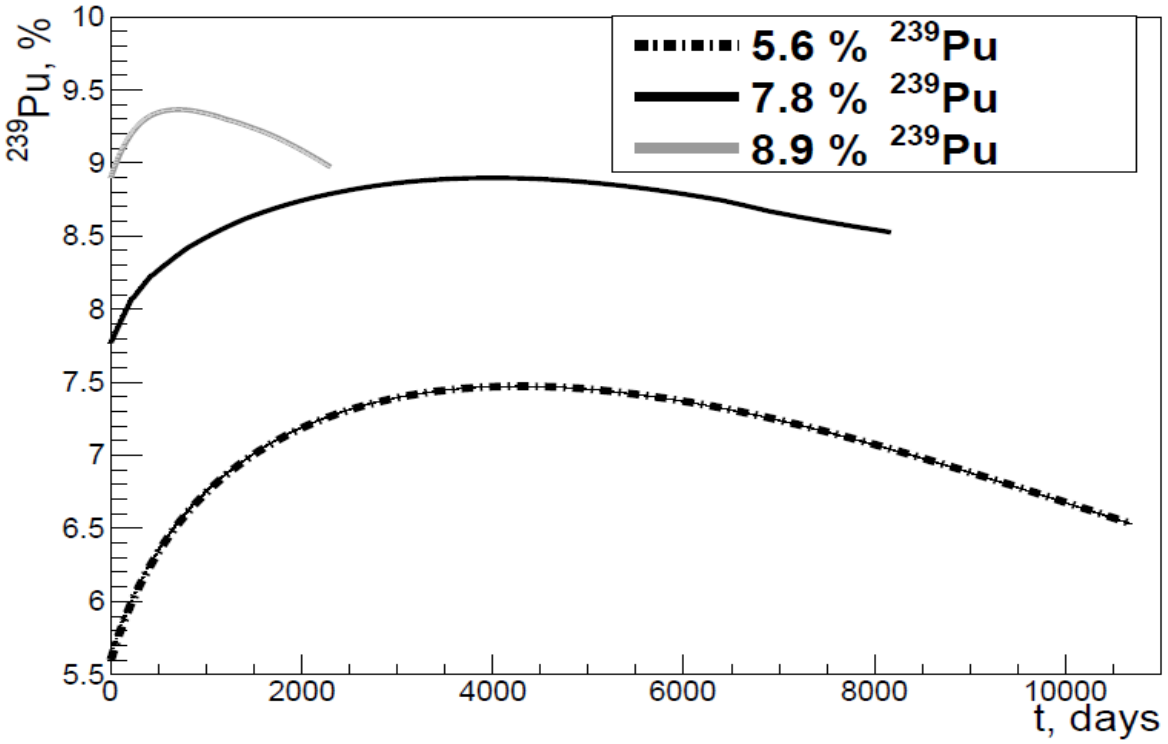
The power evolution in UTOP (a), in UBOP (b) transients and after the beam turn off (c) in ADS with U-Pu-10%Zr fuel and k_{eff} 0.98, 0.99, 0.996.

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

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

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.



Clad resistance:
-the coolant velocity below 2 m/s.
-radiation damage < 200 displacements per atom (dpa)

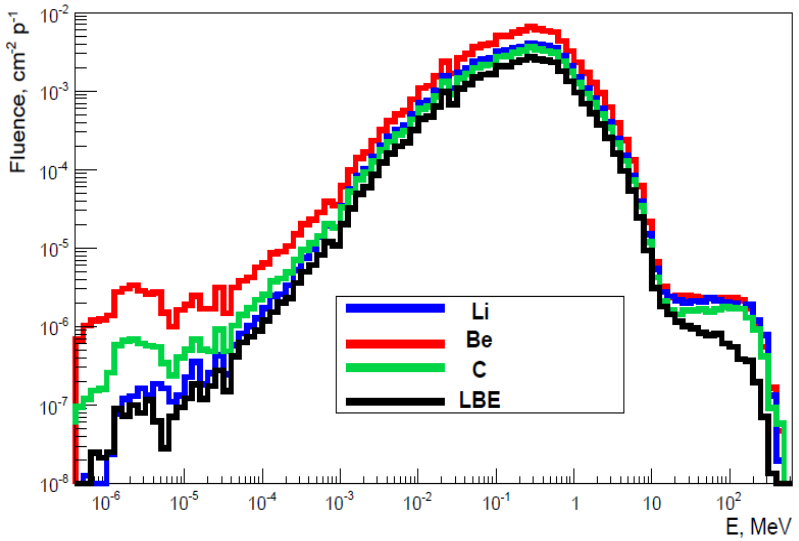
Calculated amount dpa during cycle:
- 89 dpa (8.9% ^{239}Pu)
- 122 dpa (7.8% ^{239}Pu)
- 202 dpa (5.6% ^{239}Pu)

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

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.

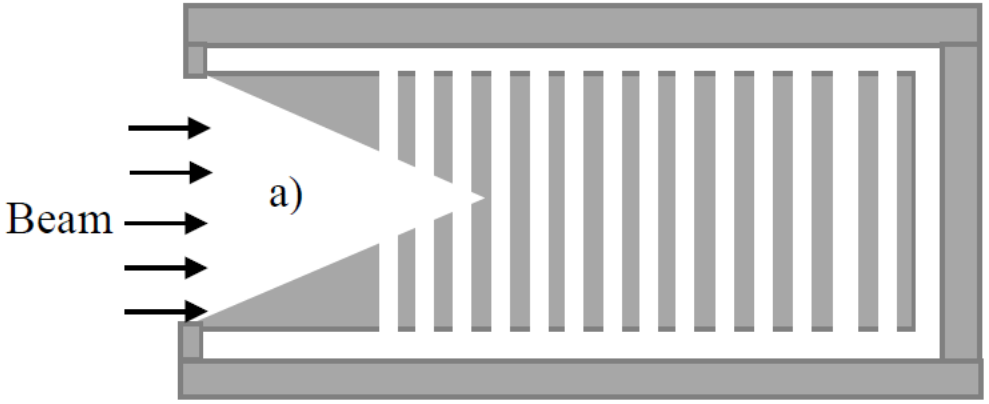
The choice of the converter

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

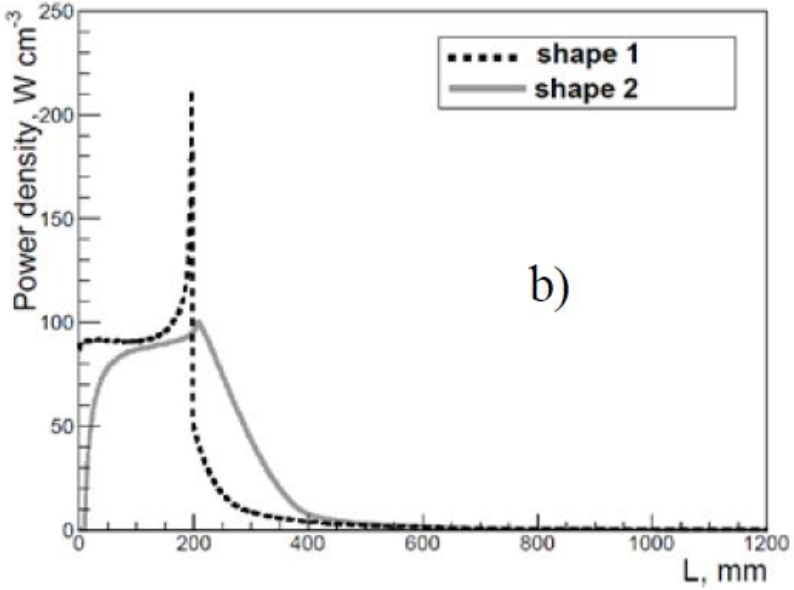


The neutron spectra in fuel blanket with Li, Be, C and LBE converters, irradiated with a beam of ^{7}Li with energy 0.3 AGeV.

Optimization of the shape of the Be converter



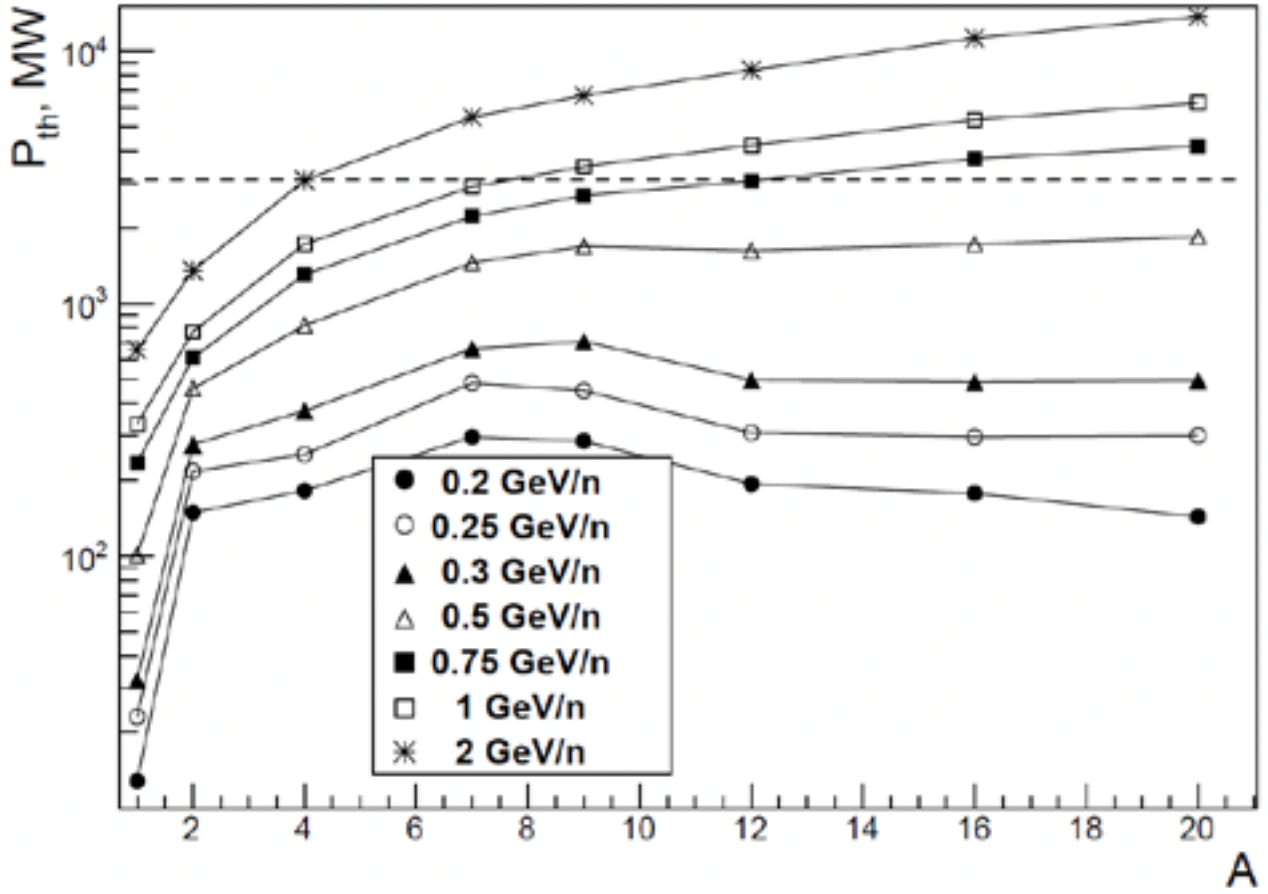
Proposed shape of the converter (a), the distribution of power density in cylindrical converter (shape 1) and with the proposed shape (shape 2) irradiated with ^{7}Li 0.25 AGeV (b).



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.

Beam and accelerator

- metallic rods U-Pu-Zr, LBE coolant, Be converter with length 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.



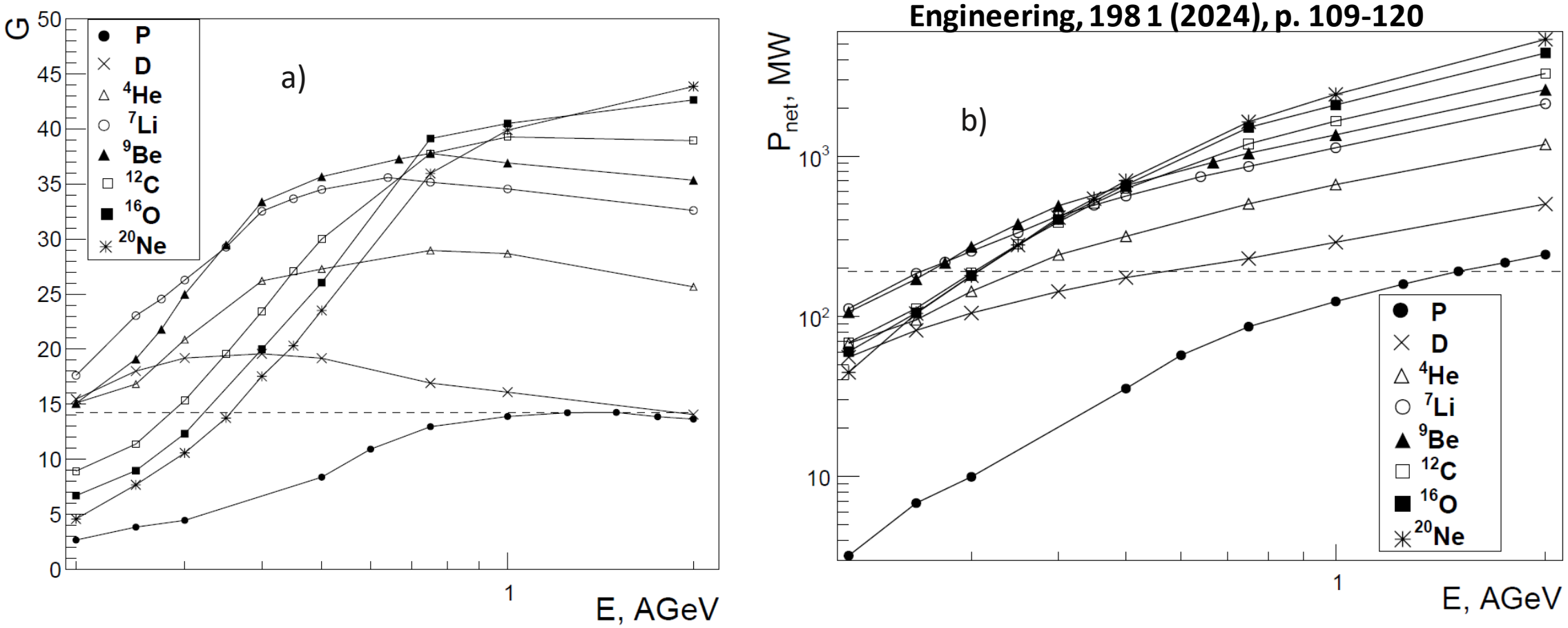
The thermal power as a function of projectile mass number and energy.

Calculated energy gain and net power

Linear accelerator

reference particle – proton 2 GeV, $\eta_0 = 0.18$
ESS Technical Design Report April 23, ESS-doc-274 (2013)

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



G (a) and P_{net} (b) as a function of projectile energy for particles accelerated in a linac, core with k_{eff} 0.985.

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).

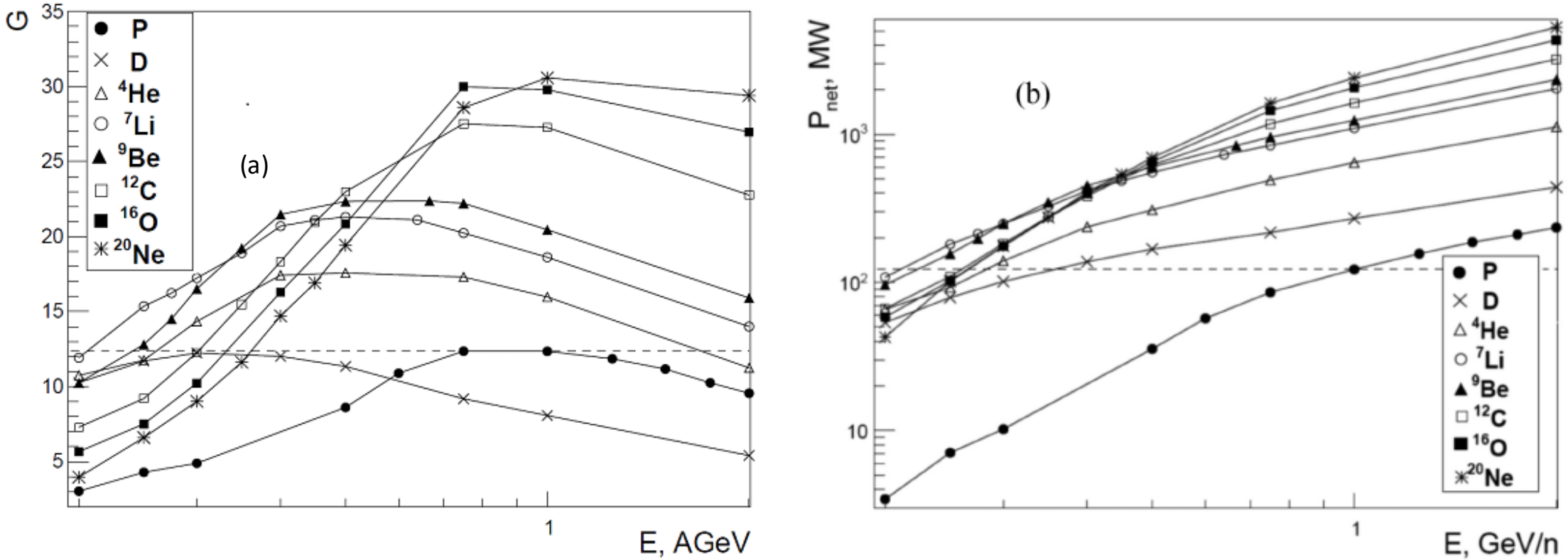
Cyclotron

reference particle – proton 0.59 GeV, η_0= 0.25

D. KISELEV et al., "Status and Future Projects of the PSI High Intensity Proton Accelerator," *JPS Conf. Proc.*, **33**, 011004 (2021); https://doi.org/10.7566/ JPSCP.33.011004

fixed field alternating gradient accelerators will be able to produce high-intensity ion beams at energies of a few GeV/n –

*M. K. CRADDOCK and K. R. SYMON, "Cyclotrons and Fixed-Field Alternating-Gradient Accelerators," Rev. Accel Sci. Technol., **1**, 65 (2008); https://doi.org/10.1142/ S1793626808000058.21*



Value of *G* (a) and *Pnet* (b) as a function of projectile energy for particles accelerated in a cyclotron, core with *keff* of 0.985.

Comparison with fusion power plants

ITER project – magnetic plasma confinement G ~ 3

Table 1
Energy-related parameters of the DEMO2 fusion power plant reference model.

Fusion power	3255	MW
Thermal power[a]	4149	MW
Gross electric power	1660	MW
Net electric power	953	MW
Plant self-consumption[b]	707	MW
Plant availability fraction	75	%

Entler S., Horacek J., Dlouhy T., Doctal V., Approximation of the economy of fusion energy, Energy 152 (2018) 489-497

LIFE project – laser inertial plasma confinement G ~ 4

Table 1
LIFE plant parameters.

Conversion efficiency, %	45	47
Gross power, MWe	595	1217
Laser electrical power input, MWe	124	248
In-plant power load, MWe	34	64
Net electric power, MWe	437	905

Meier W.R. et al., Fusion technology aspects of laser inertial fusion energy (LIFE), Fusion Engineering and Design 89 (2014) 2489-2492

G that could be achieved in ADSR is significantly higher that the values estimated for fusion power plant.

Requests for the accelerator

- Beam intensity > 10^{16} p/s - acceleration of the ^{7}Li beam with intensity 7 ×10^{16} p/pulse is reported

  M. OKAMURA et al., "Demonstration of an Intense Lithium Beam for Forward-Directed Pulsed Neutron Generation," *Sci. Rep.*, 12, 14016 (2022); https://doi.org/ 10.1038/s41598-022-18270-0.22

- Beam stability – limitation of beam trip frequency

Acceptable frequency of the beam trips according to the beam trip duration

Criteria	Acceptable value (times/year)	Component or condition that imposed limits
$0\ sec. \leq T \leq 10\ sec.$	25,000	Inner barrel
$10\ sec. < T \leq 5\ min.$	2,500	Inner barrel, Reactor vessel
$T > 5\ min.$	43	system availability

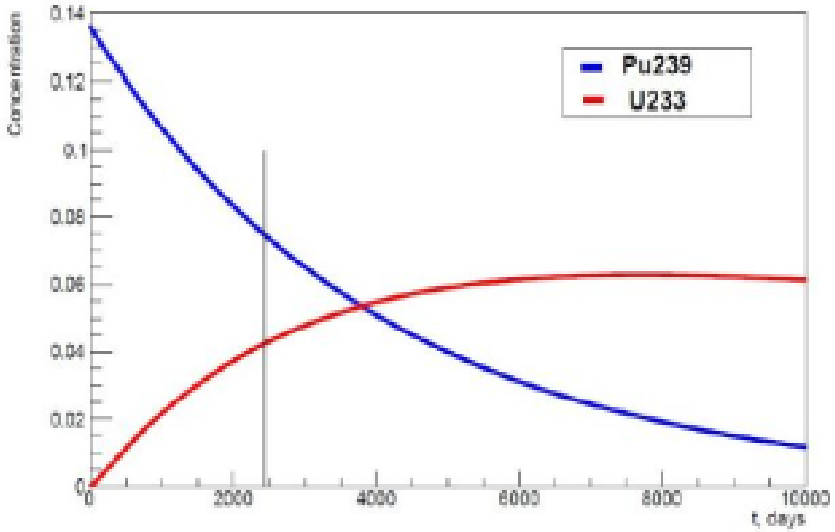
H. Takei et al., Estimation of acceptable beam trip frequencies of accelerators for ADS and comparison with experimental data of accelerators, //www-pub.iaea.org/MTCD/publications/PDF/P1433_CD/datasets/papers/ads_p4-06.pdf

Thorium fuel

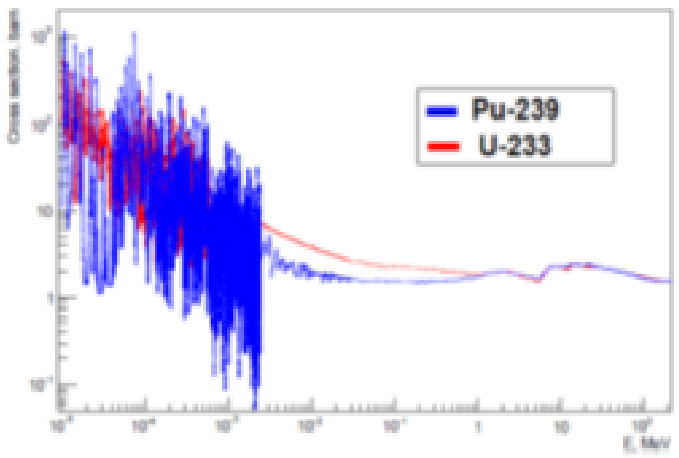
Metallic core with k_{eff} 0.96, the same geometry:

- U-Pu 9.2 % Pu239 - cycle length 5000 days
- Th-Pu 13.6 % Pu239 - cycle length 2200 days

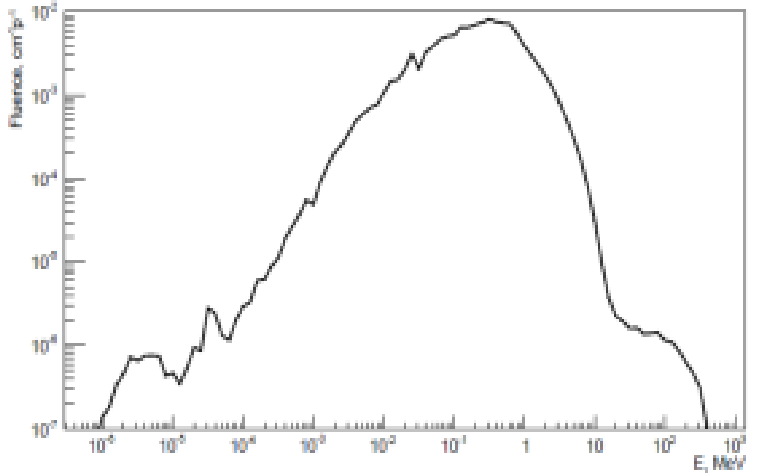
M. Paraipan, A. A. Baldin, E. G. Baldina, S. I. Tyutyunikov, Beam and target optimization for energy production in accelerator driven systems, DOI: https://doi.org/10.1051/epjconf/201920404001 (2019)



The time evolution of the Pu239 and U233 under irradiation with a beam of ^{7}Li 0.35 GeV/n, with intensity $1.25 \cdot 10^{16}$ p/s.



Fission cross section of neutrons in U233 and Pu239



Neutron spectrum under irradiation with Li-7

A thorium core needs a higher level of enrichment for the same geometry and a shorter period between refueling, comparing with uranium core.

Mean fission cross section:

- 2.38 barn in U233
- 1.66 barn in Pu239

Analysis of possible experiments

1. Neutron yield from converters

The neutron multiplicity does not correlate with the energy released in the active zone.

The total kinetic energy of escaped neutrons correlates with the energy released.

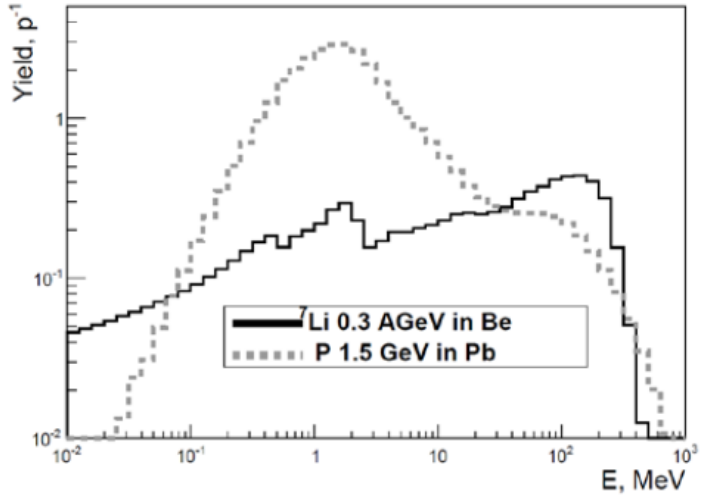
^{7}Li with energy 0.3 AGeV

- 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

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



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%

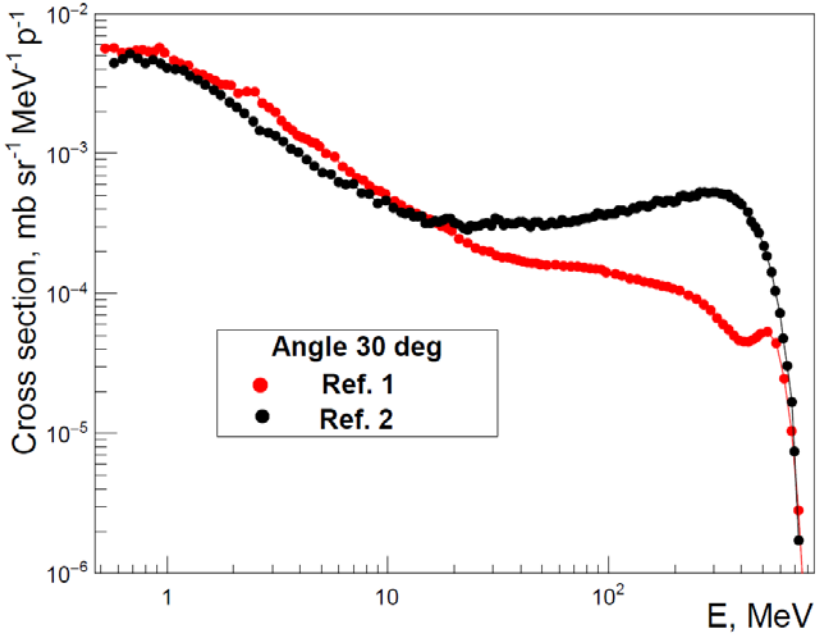
The neutron yield, the total energy of the escaped neutrons E_{tot}, and the energy released E_{dep} in core with keff 0.988, irradiated with protons and ^{7}Li

Particle/Energy (GeV/n)	Converter Material	Neutron Yield			E_{tot} (MeV)	E_{dep} (MeV)
		Total	E > 10 MeV	E > 100 MeV		
P 1	Be	3.06	1.32	0.64	202.1	1.971e5
	LBE	22.1	2.49	0.5	205.2	2.145e5
P 1.5	Be	3.76	1.7	0.86	323	3.041e5
	LBE	33.66	4.24	0.9	349.6	3.543e5
^{7}Li 0.25	Be	8.75	3.58	1.12	292.5	3.05e5
^{7}Li 0.3	Be	11.01	4.72	1.76	442.9	3.933e5

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

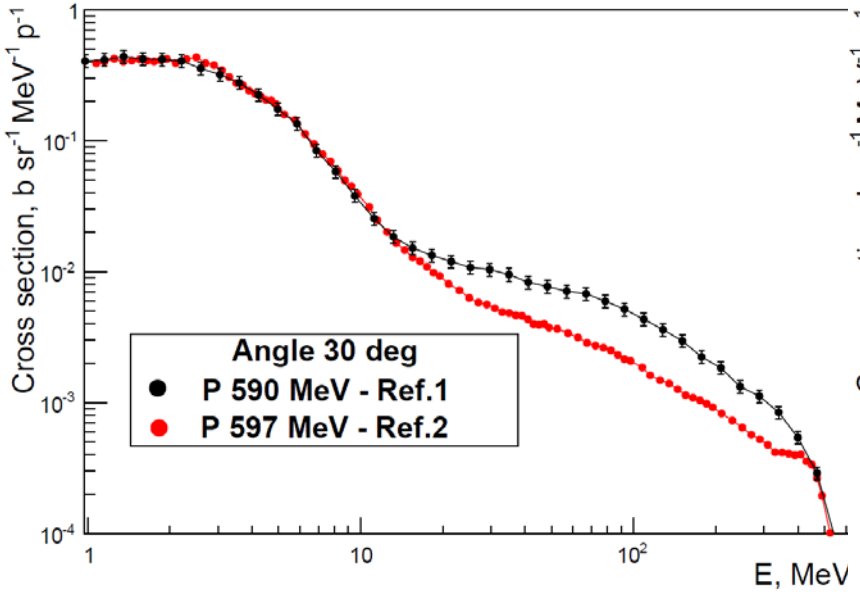
Paraipan M., et al., Extended Lead Target for Studying the Perspectives of the Accelerator-Driven Subcritical Reactor, *Nuclear Science and Engineering*, 1–13 (2025) https://doi.org/10.1080/00295639.2025.2522570

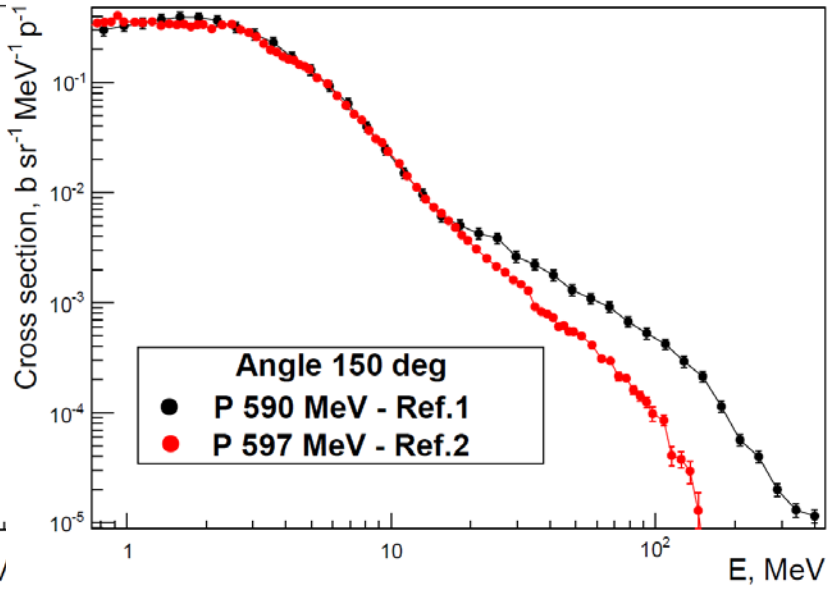
Double differential cross section of neutrons from P 800 MeV in Be



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, Can. J. Phys., 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)

Measurements and integration of neutron spectra cannot offer reliable results.

2. Registration of the overall effect - fission distributions

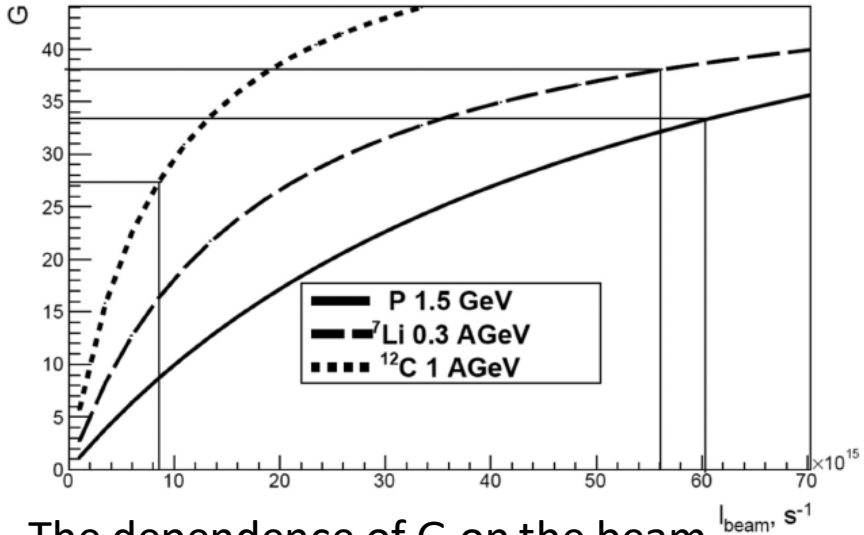
measurements only at the surface of the converter overestimate the fission realized with low energy ion beam, in comparison with 1-2 GeV proton beam

The ratio between the integral number of fissions obtained with ^{7}Li 0.3 AGeV (converter Be), and P 1.5 GeV (converter Pb).

Nfis-Li/Nfis-P	Detectors Natural U	Detectors Enriched U (10% ^{235}U)
Only converter	2.69	2.4
LETASUR	1.28	1.31
ADSR	1.17	

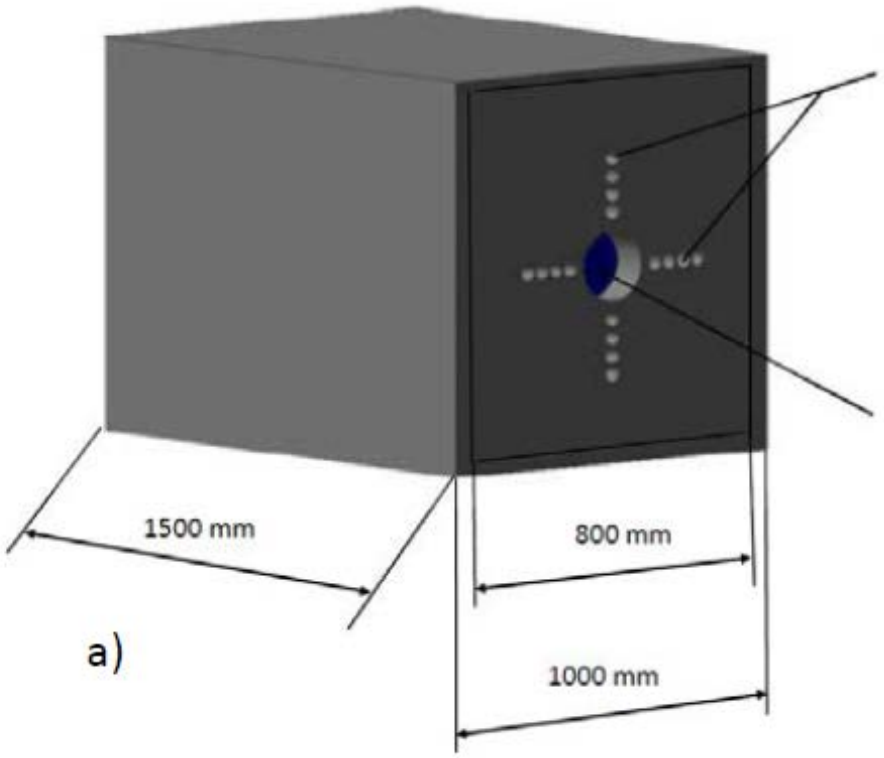
We propose measurements of the fission distribution inside an extended target surrounding the converter.

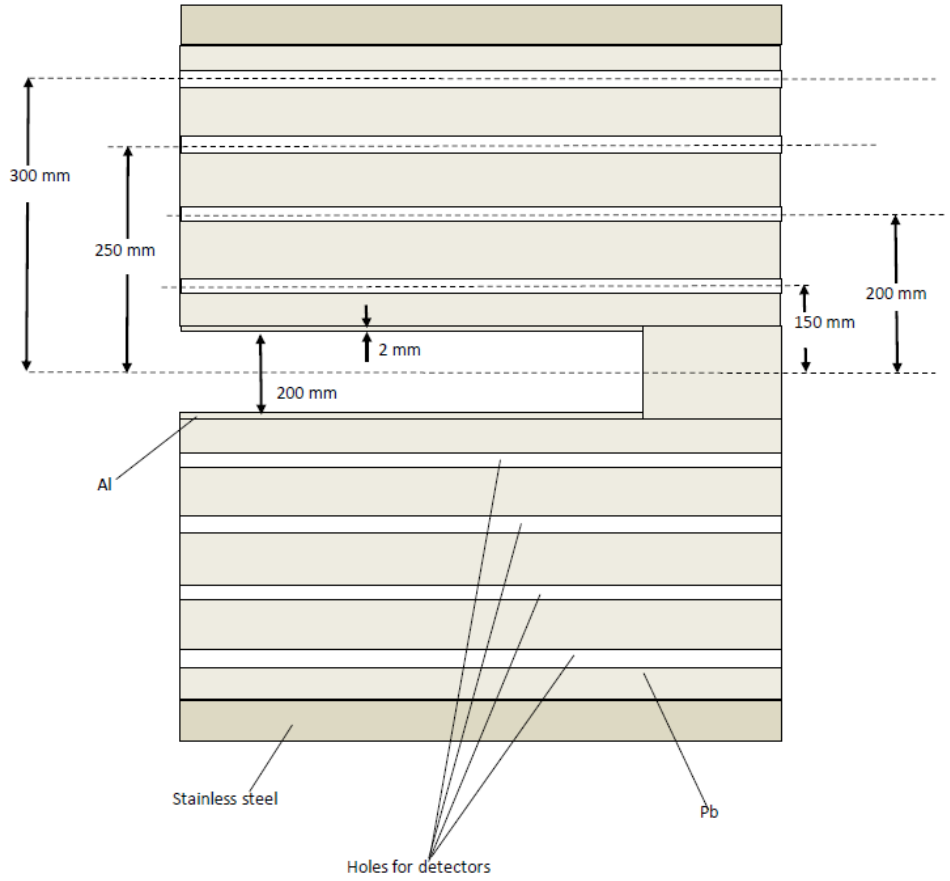
Experiments at the SHINE channel in LHEP
Protons with energies 0.5-2 GeV
Ions until ^{12}C and energies from 0.25 GeV/n to 0.75 GeV/n



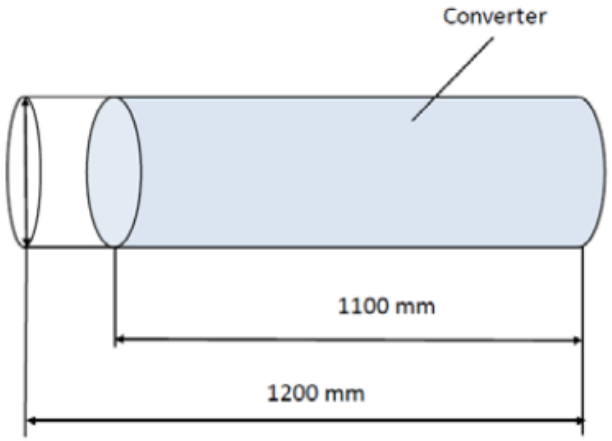
The dependence of G on the beam intensity in core with k_{eff} 0.985.

The design of the target LETASUR





b)

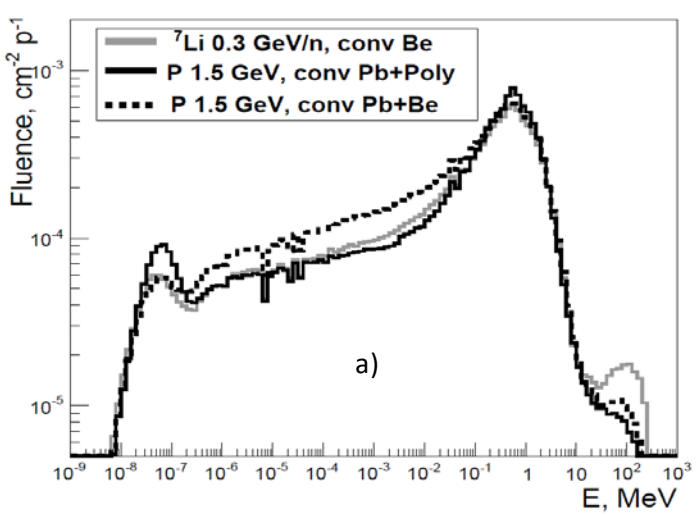


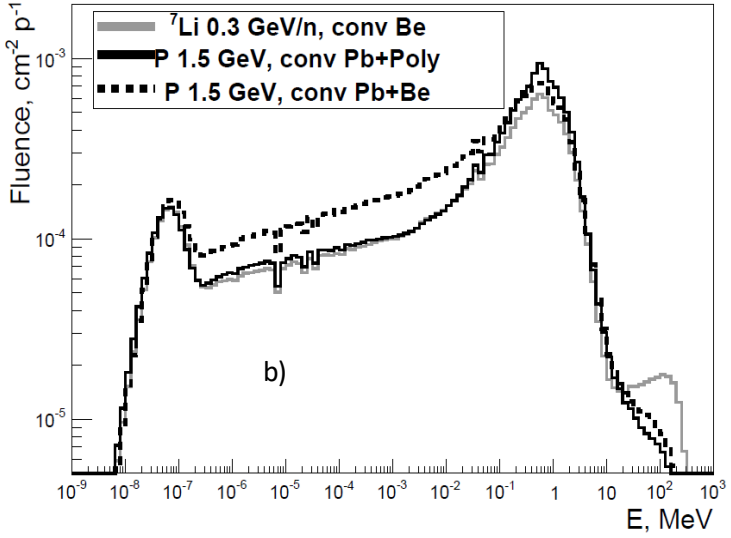
c)

The scheme of the target (a), sectional view (b), and of the converter (c).

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

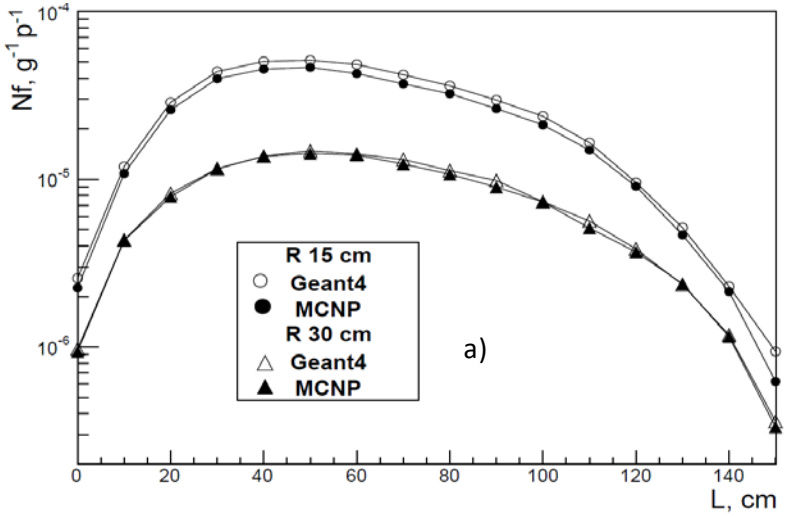
Combined converter to compensate k_{eff}

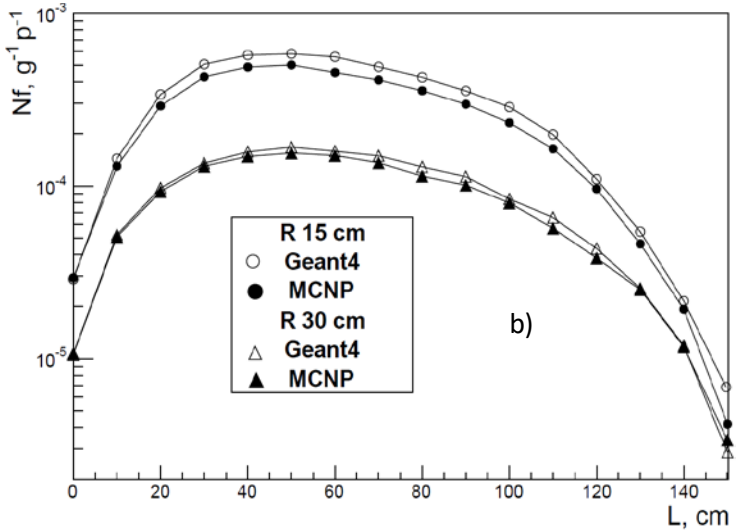




Mean neutron spectra for ^{7}Li 0.3 AGeV with Be converter and P 1.5 GeV with combined converters predicted with Geant4 (a), and with MCNP (b).

Samples of natural U or enriched U





Longitudinal fission distribution in target with Be converter, irradiated with Li 0.3 GeV/n, registered in samples of natural U (a) and enriched U (b).

Calculated fission distribution in extended Pb target LETASUR

Total number of fission per projectile in LETASUR

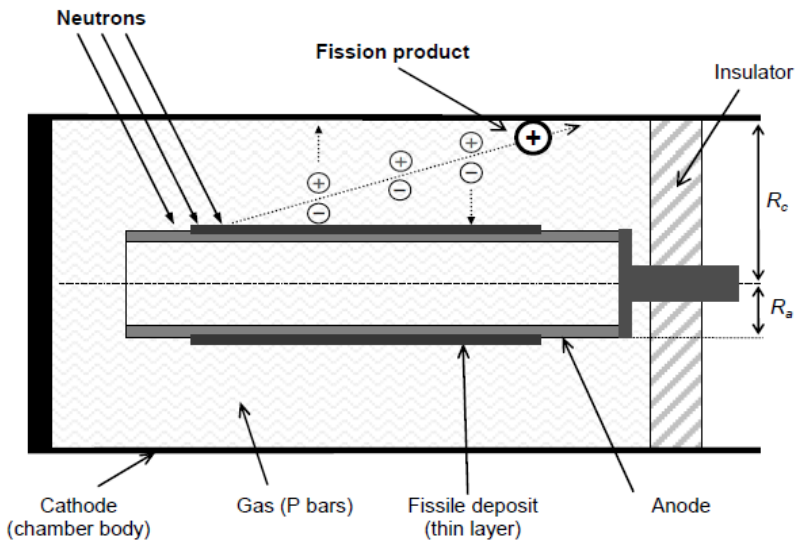
Part/E, AGeV	Code	Conv. Be		Conv. Pb+Be		Conv. Pb+Poly	
		Nat U	10%^{235}U	Nat U	10%^{235}U	Nat U	10%^{235}U
P 1	Geant4	48.6	433	65.8	550.4	62.1	601.5
	MCNP	65.2	585.6	73.2	677.8	68.2	608
P 1.5	Geant4	74.9	661	97.1	998.1	105.2	1014.8
	MCNP	94.7	857.2	109.4	1101.7	105.2	997.4
^{7}Li 0.2	Geant4	43.5	389.9	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

Fission ionization chambers

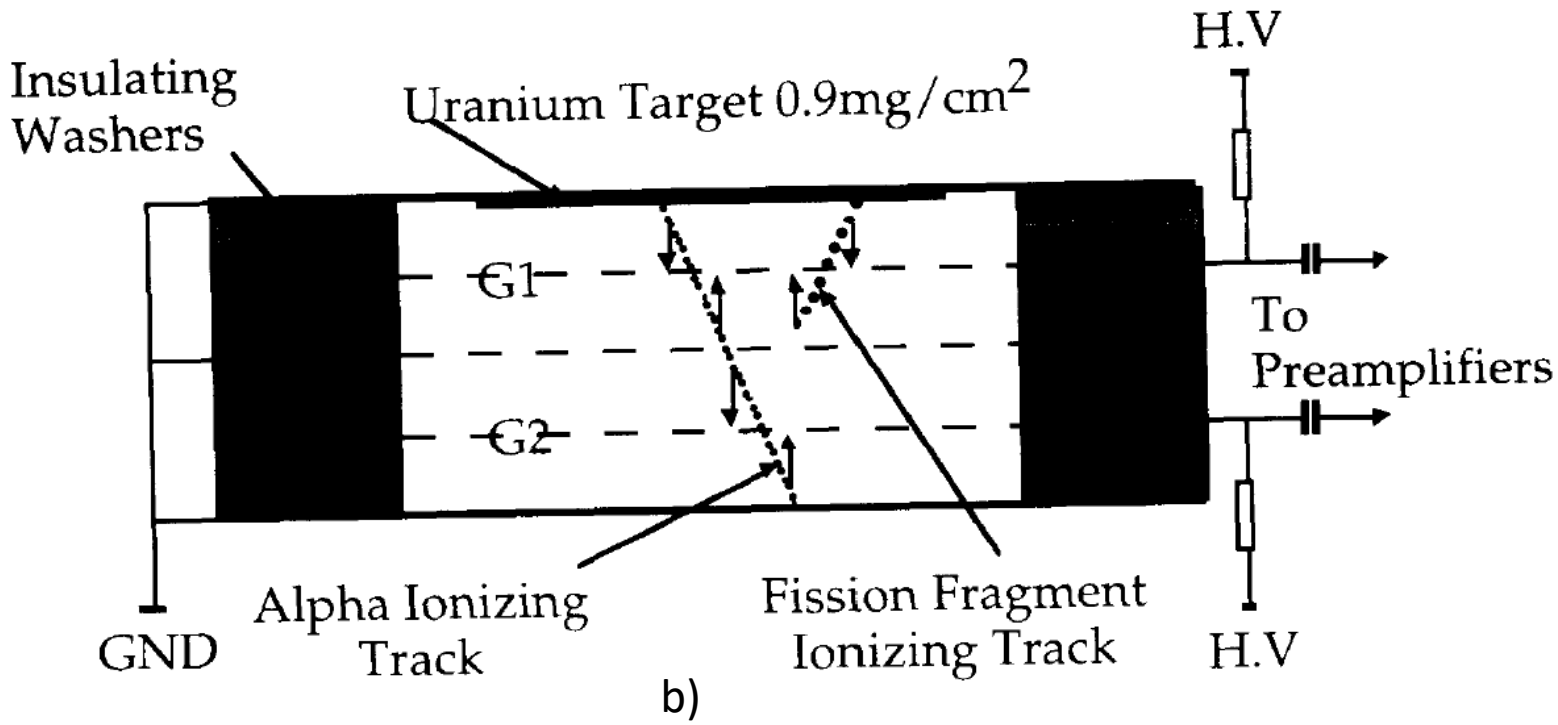
- parallel or cylindrical configuration of the electrodes, with dimensions small enough to enter in the channel, and the extension on the length of the channel <100 mm

- the chambers must work in pulse mode

- sealed chambers without gas flow



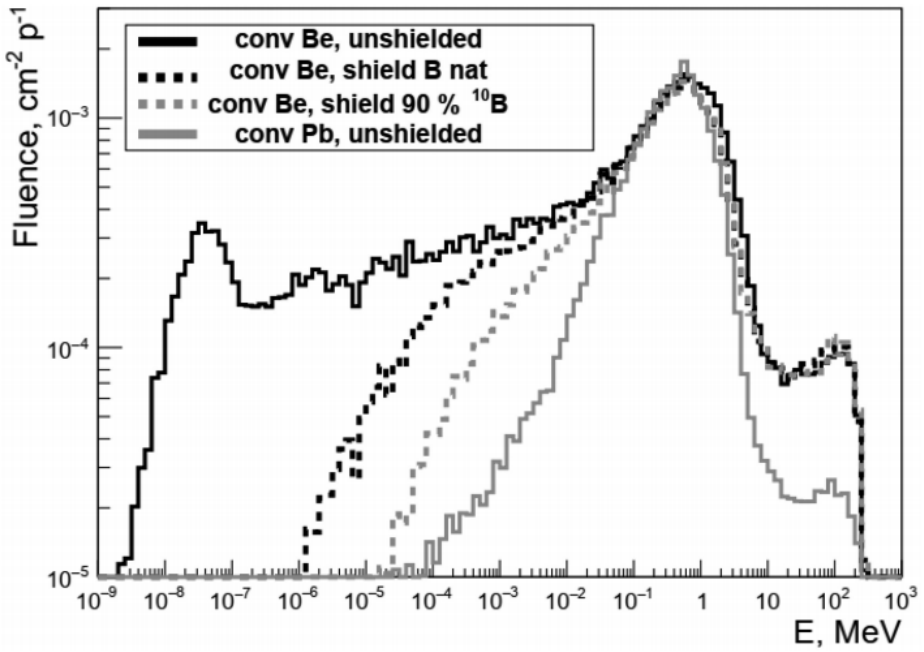
a)



b)

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

Neutron spectra and actinide transmutation



Various shapes of neutron spectrum.

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.

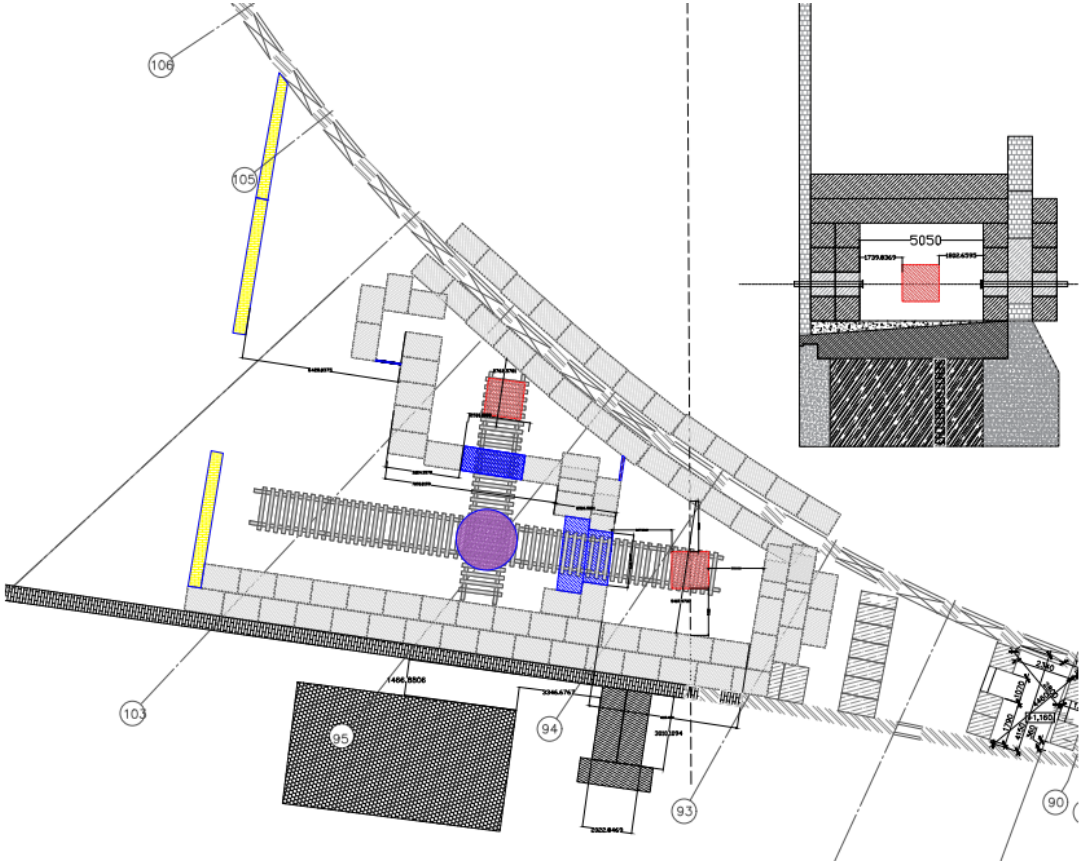
- foils of Au, Mo, W, Ni, Co and Bi will be irradiated in the same conditions as the ^{238}U and ^{239}Pu samples
-radiative capture reactions: ^{197}Au(n,γ)^{198}Au, ^{98}Mo(n,γ) ^{99}Mo, ^{186}W(n,γ)^{187}W, ^{59}Co(n,γ)^{60}Co will be used for the low energy part of the neutron spectrum.
- the accumulation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

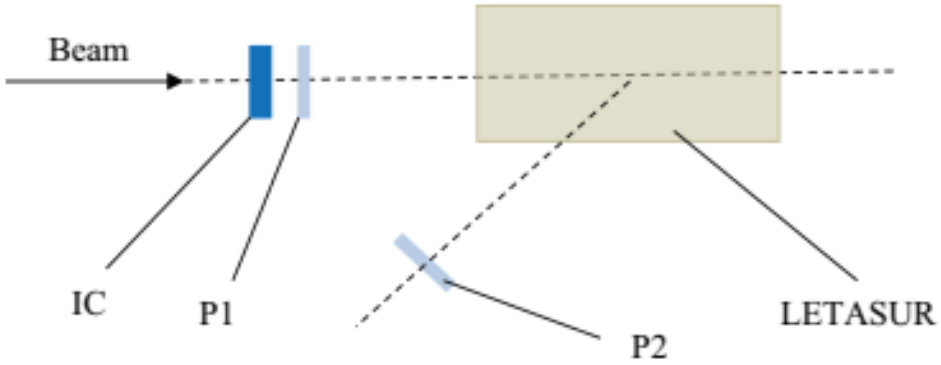
	Converter Be Unshield	Converter Be Shield ^{nat}B	Converter Be Shield 90% ^{10}B	Converter Pb Unshield
capt^{238}U/fis^{239}Pu	0.063	0.524	0.31	0.227

Experiments planning

SHINE channel



The scheme of the experimental room



The experimental setup

Conclusions

The conditions that maximize the energy efficiency of ADSR are reviewed.

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 ^{7}Li with energy 0.25-0.3 GeV/n.

The use of LBE converter is preferable for proton beams, and Be converter for ion beams.

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 $1 \cdot 10^{16}$ p/s 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!