Accelerator driven subcritical reactors: Status and perspectives

Mihaela Paraipan[1,2], Oleg V. Belov[1], Vafa M. Javadova[1], Toan N. Tran[1,3], Sergey I. Tyutyunnikov[1]

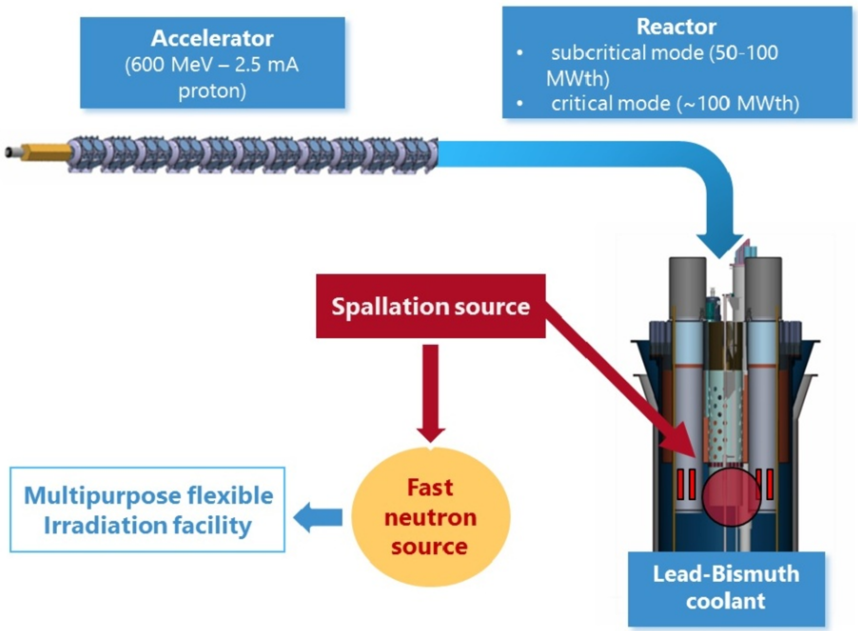
[1] Joint Institute for Nuclear Research, 6 Joliot-Curie st., Dubna, Russia, 141980

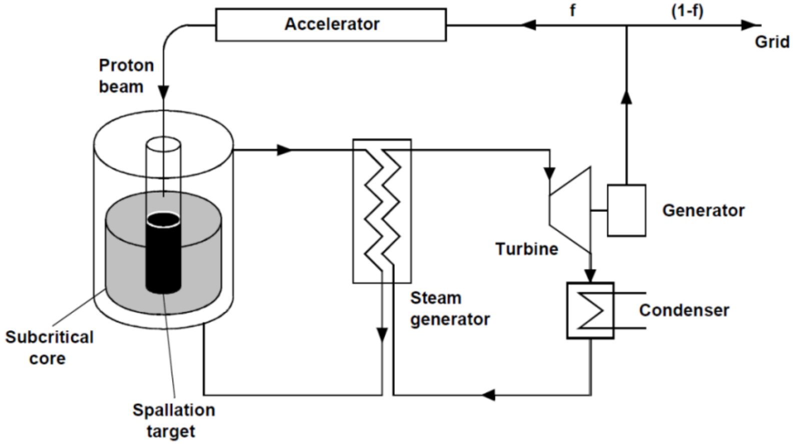
[2] Institute of Space Science, 409 Atomistilor st., Magurele, Ilfov, Romania, 077125

[3]Institute of Physics of the Vietnam Academy of Science and Technology (IP VAST), Hanoi, Vietnam

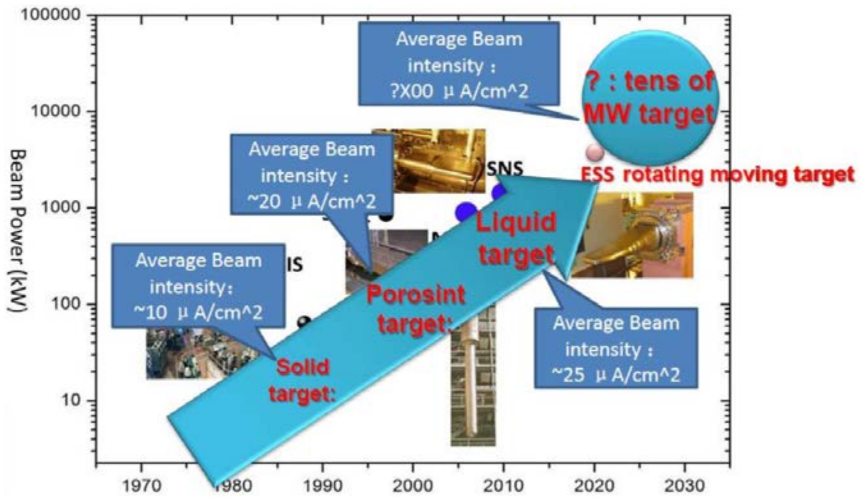
ADS projects in the world

Project MYRRHA





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

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

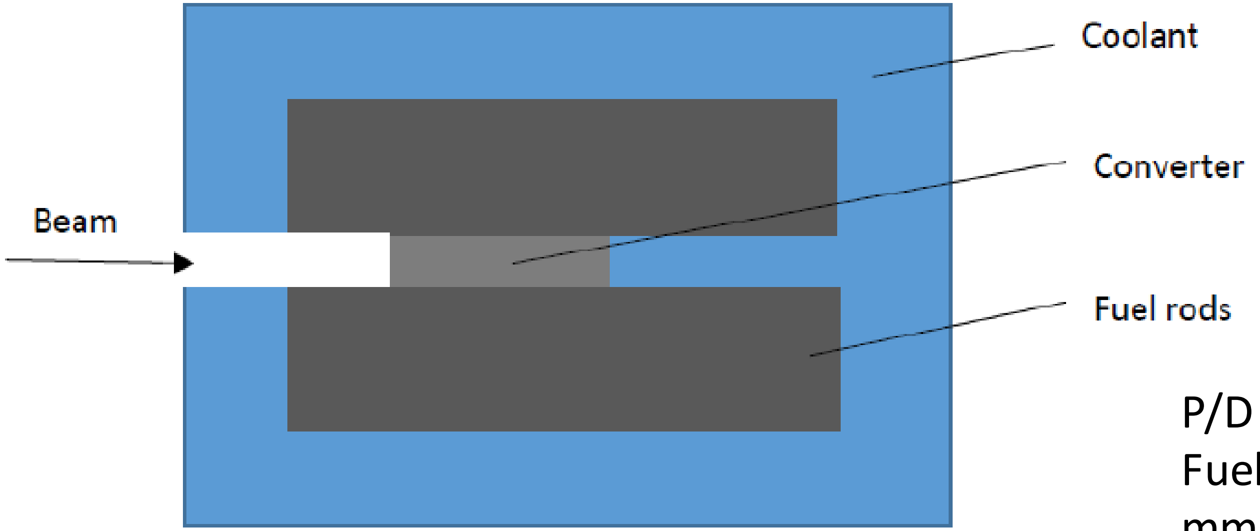
ADSR as energy amplifier

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

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



The scheme of the target.

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}

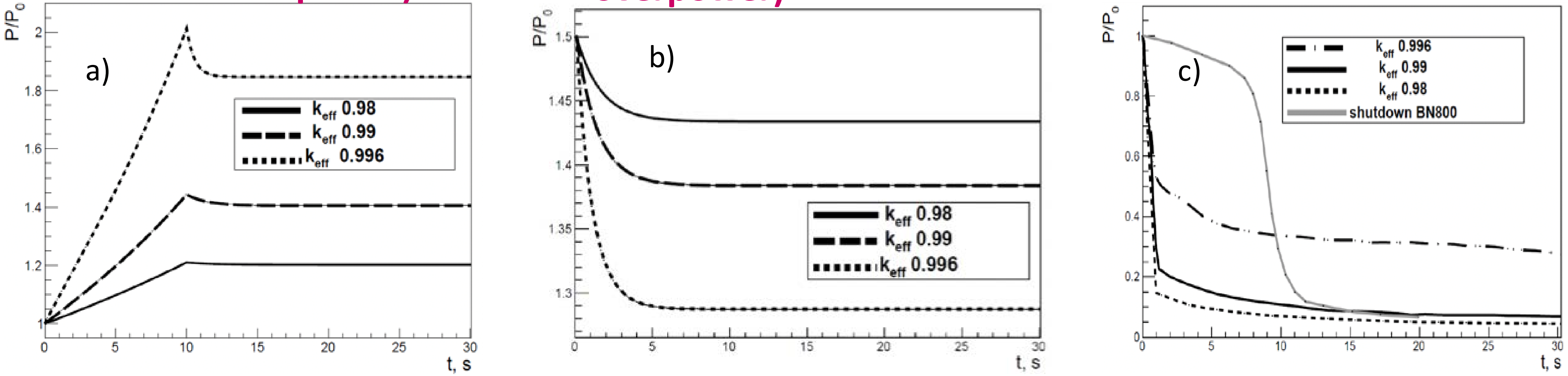
Transients with positive reactivity insertion

- 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**

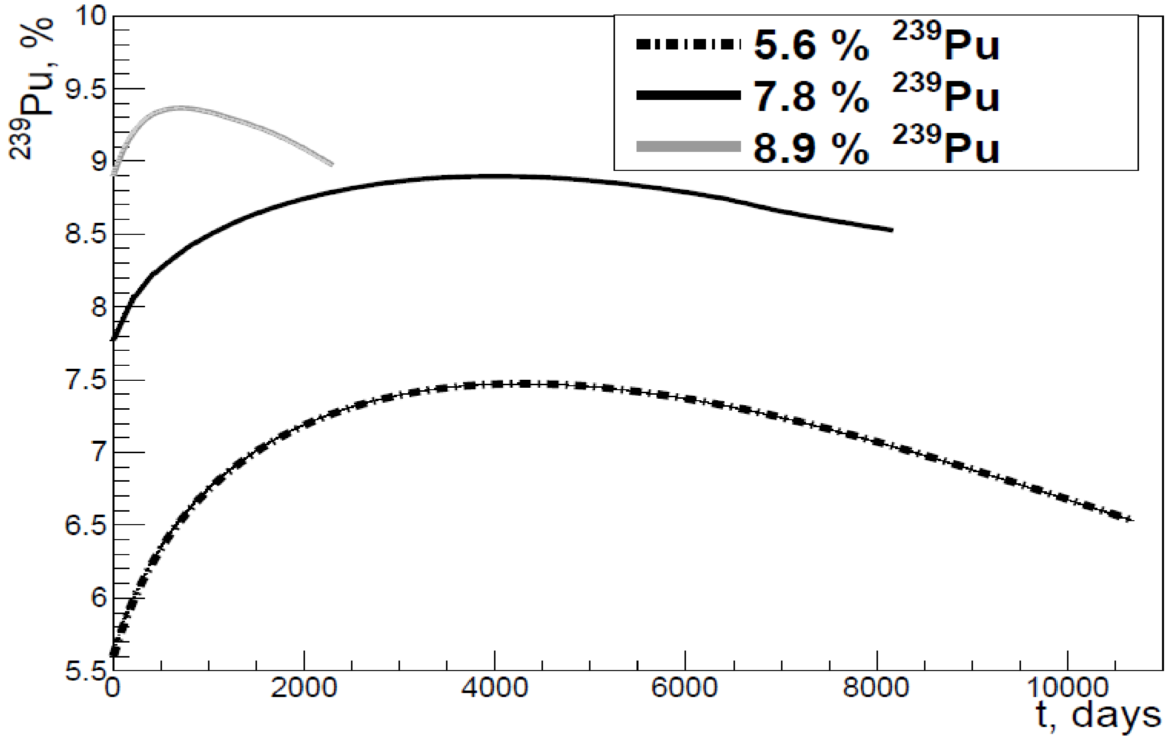


The power evolution in UTOP (a), in UBOP (b) transients and after the beam turn off (c) in ADS with U-Pu-10%Zr fuel and k_{eff} 0.98, 0.99, 0.996.

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

Level of enrichment and actinide burning

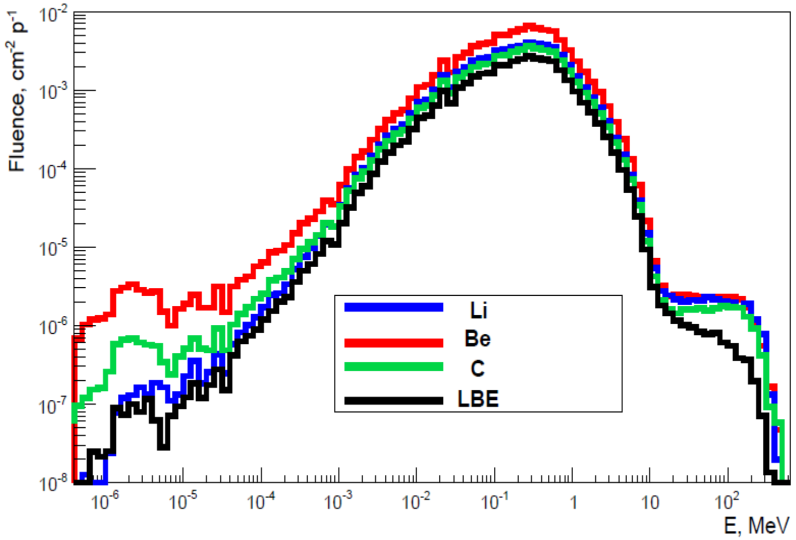
With a proper core configuration the fuel allows to burn in ADS 15-20 % from actinides in one cycle, in comparison with 6-7 % in a fast reactor.



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 $1.25 \cdot 10^{16}$.

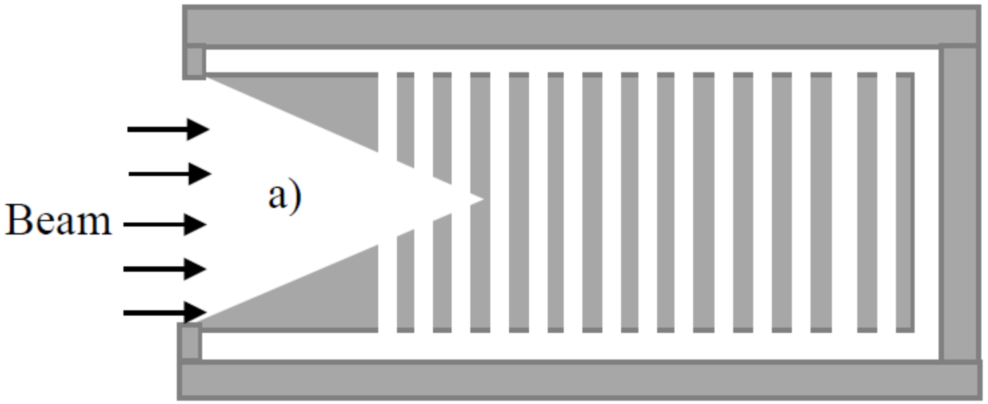
The choice of the converter

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

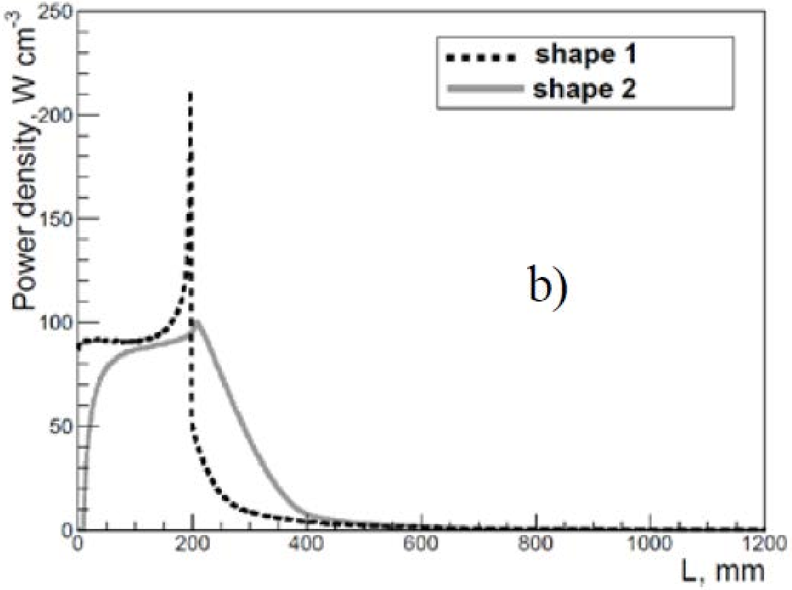


The neutron spectra in fuel blanket with Li, Be, C and LBE converters, irradiated with a beam of ^{7}Li with energy 0.3 AGeV.

Optimization of the shape of the Be converter



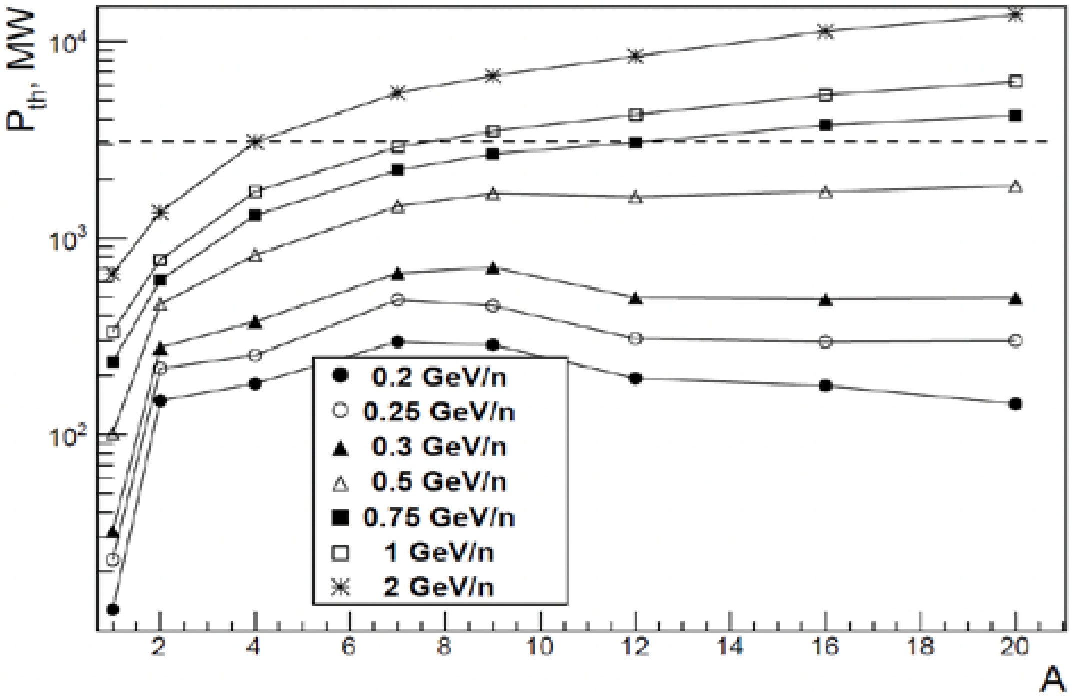
Proposed shape of the converter (a), the distribution of power density in cylindrical converter (shape 1) and with the proposed shape (shape 2) irradiated with ^{7}Li 0.25 AGeV (b).



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.

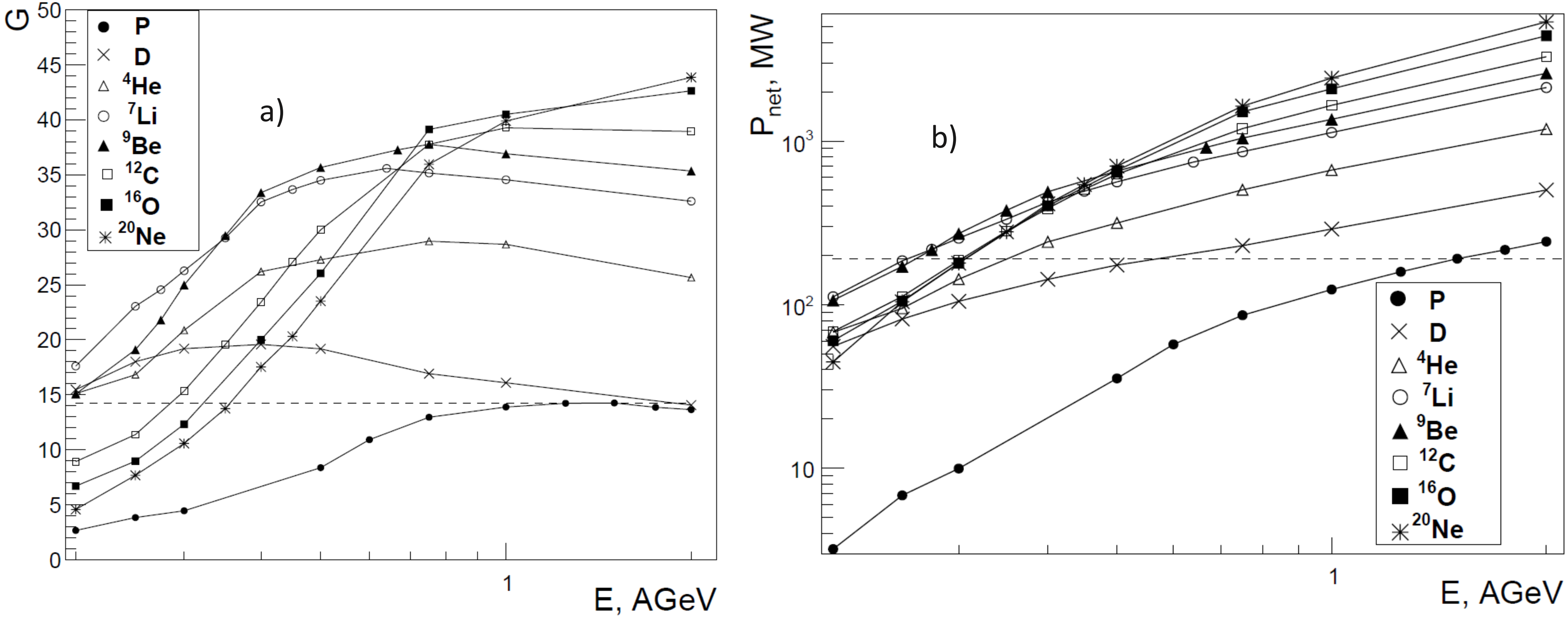


The thermal power as a function of projectile mass number and energy.

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

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

Linear accelerator



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).

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	%

[a] The reactor thermal power includes the fusion power, the power released during a tritium breeding, and the reradiated heating power.
[b] The self-consumption includes among others the plasma heating and current drive system.

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

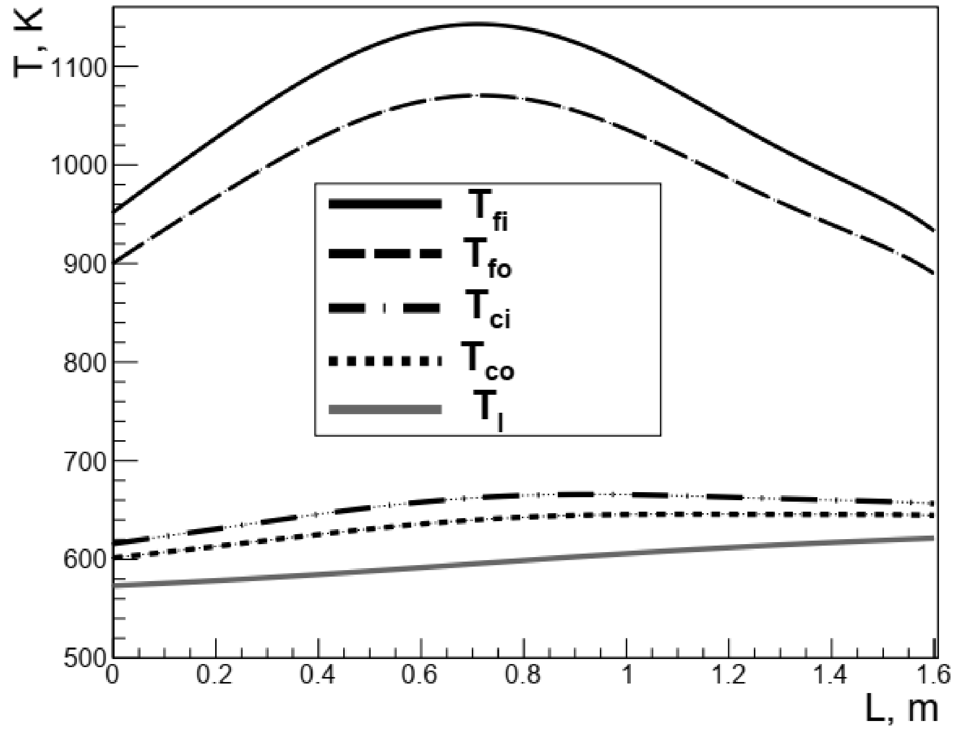
The values of energy gain that could be achieved in ADSR are significantly higher that the G values estimated for fusion power plant.

The maximum power and fuel type

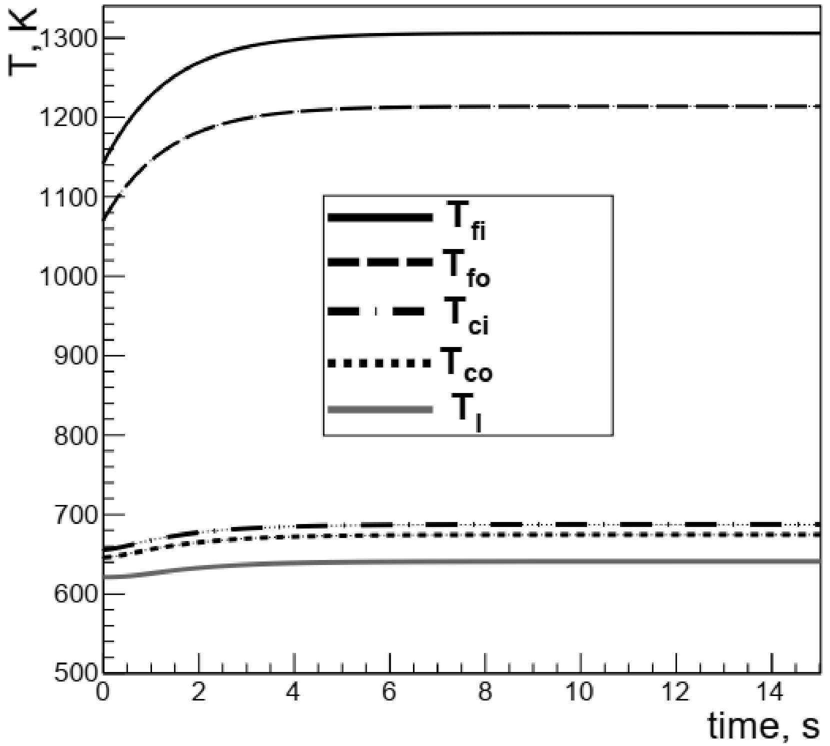
The maximum power is limited by the temperature in the hottest channel during UBOP
The fuel temperature with 100 K below the melting temperature during transients.
The outer clad temperature below 923 K

Metal (U-Pu-Zr)

Tmelt 1390 K
P 1.5 GeV, converter LBE, Ibeam 9e15



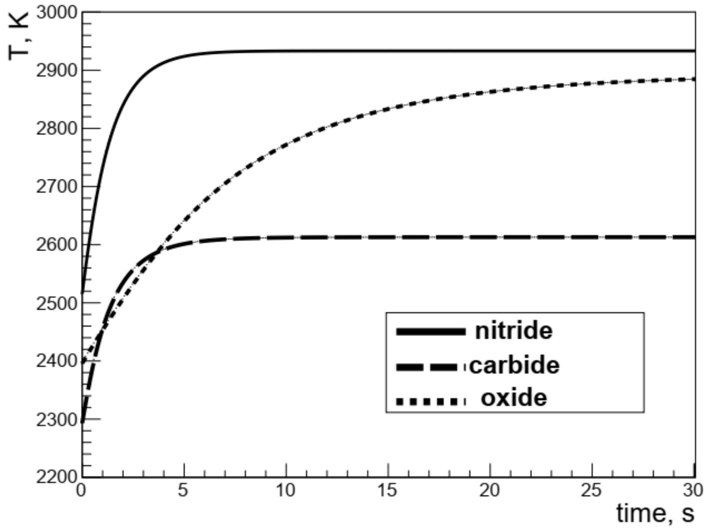
The initial temperature distribution in the hottest channel



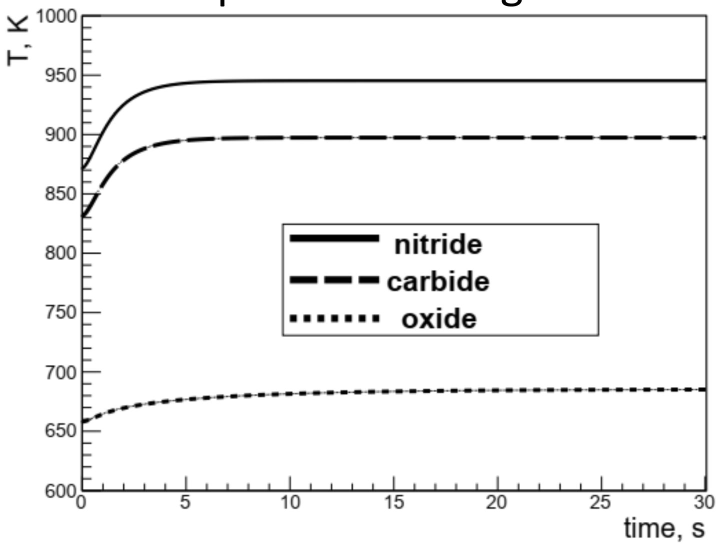
The evolution of the maximum temperature in the hottest channel, during UBOP.

Oxide, carbide, nitride

The evolution of the maximum fuel temperature during UBOP.



The evolution of the maximum clad temperature during UBOP



Oxide - Tmelt 3023 K
Carbide - Tmelt 2700 K
Nitride – Tmelt 3050 K

The dependence of maximal beam intensity and electrical power on the fuel type

Particle/Energy, GeV/n	Fuel	$I_{beam\ max}$, s^{-1}	P_{el}, MW
P 1	metal	1.35e16	200.4
	oxide	1.6e16	237.6
	carbide	4.8e16	712.7
	nitride	5.6e16	811.5
P 1.5	metal	9e15	202.8
	oxide	1.05e16	236.6
	carbide	3.2e16	721.1
	nitride	3.7e16	813.8
Li 0.25	metal	1.6e16	190.8
	oxide	1.85e16	220.5
	carbide	5.4e16	673.8
	nitride	6.3e16	781.1
Li 0.3	metal	1.05e16	188.9
	oxide	1.25e16	224.9
	carbide	3.7e16	685.6
	nitride	4.3e16	793.6

Planned experiments

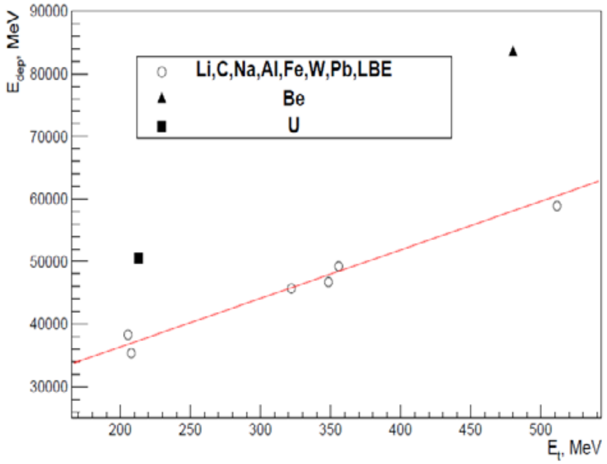
Neutron yield from converters

^{7}Li with energy 0.3 AGeV

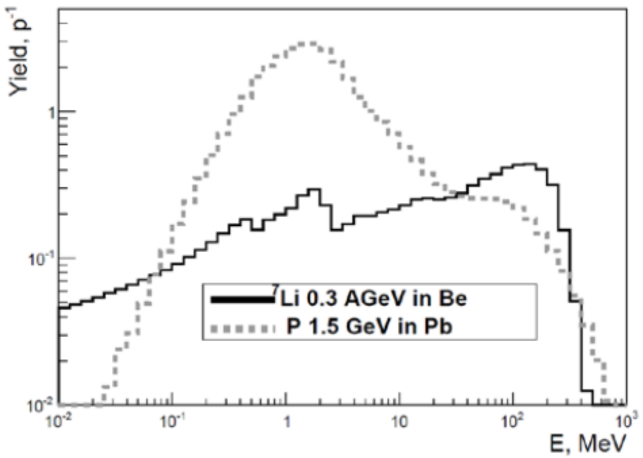
- converter cylinder with radius 10 cm and length equal with the ion range in the given material.
- U-Pu-Zr target with 8.9 % ^{239}Pu

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.

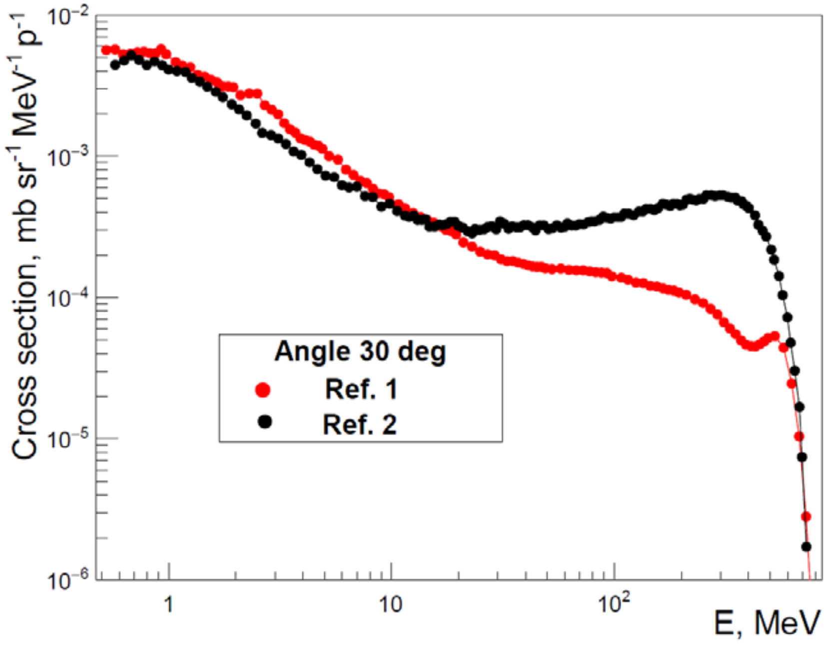


Neutron yield from ^{7}Li 0.3 AGeV in extended Be converter, and from P 1.5 GeV in Pb. The dimensions of the converters: radius 10 cm, length 120 cm.

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

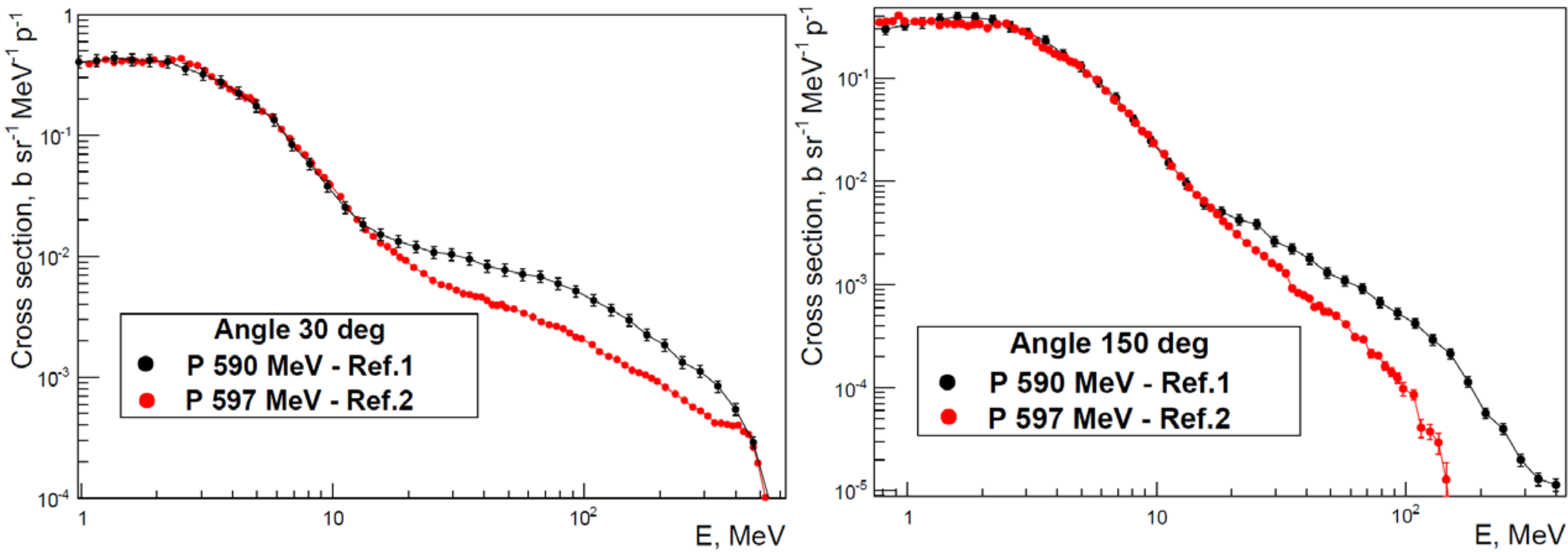
Paraipan M., Kryachko I. A., Javadova V. M., Levterova E. A., Tyutyunnikov S. I., Main Results of Neutronical Study about ADS with Ion Beams and Implications on Experiments Planning, Phys. Part. Nucl. Lett. 19 2 (2022) p. 129-144

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



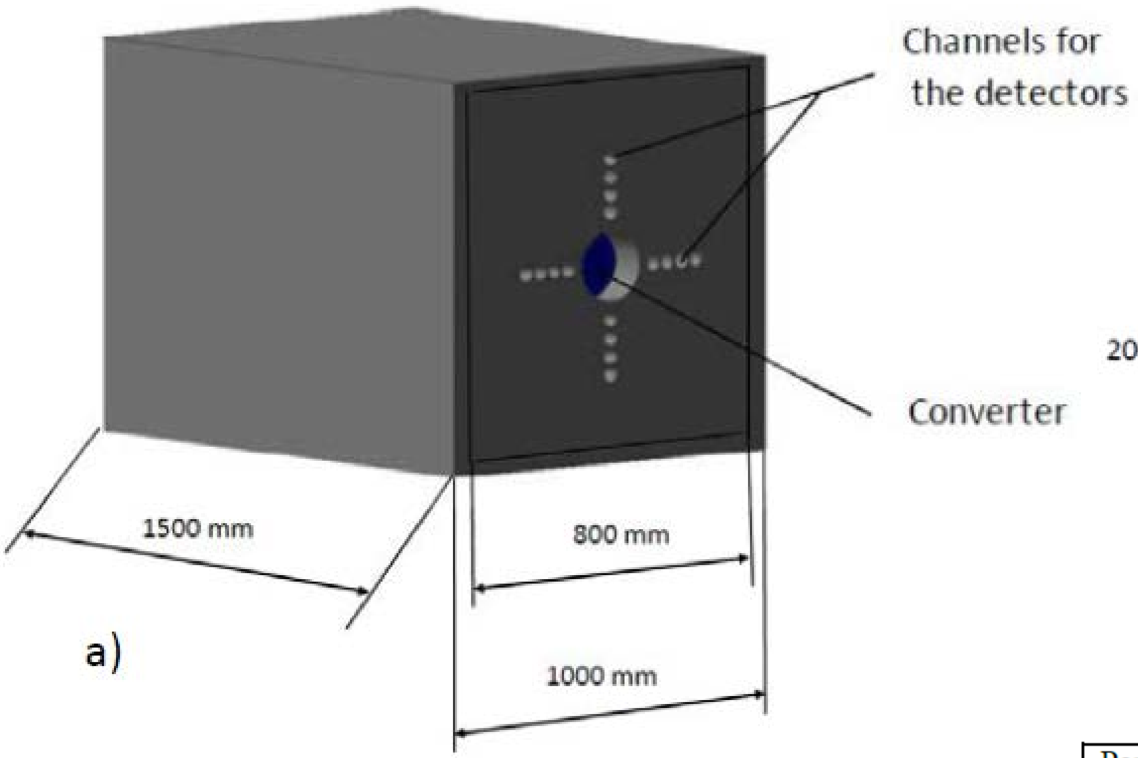
1. W.B.Amian et al., Differential Neutron Production Cross Sections for 800-MeV Protons, Nucl. Sci. Eng., Vol.112, p.78 (1992)
2. D.A.Lind, Charge-exchange studies at the Los Alamos Meson Physics Facility, Canadian Journal of Physics, Vol.65, p.637 (1987)

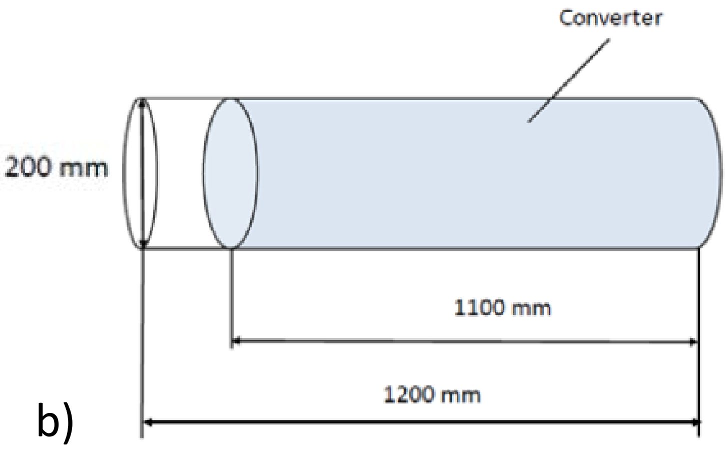
Double differential cross section of neutrons from P 590 MeV in U



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)

Measurements of fission distribution in extended Pb target LETASUR





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

Total number of fission per projectile in LETASUR with different converters.

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

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 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 relize longer cycles and to burn 15-20% from the actinides during cycle.

Carbide and nitride fuels are advantageous for ADSR, allowing higher reactor power. Electrical power of 750-800 MW can be obtained.

With beam intensities above 1e16 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!