Neutron Sources for Neutrino Investigations (as Alternative for Nuclear Reactors)

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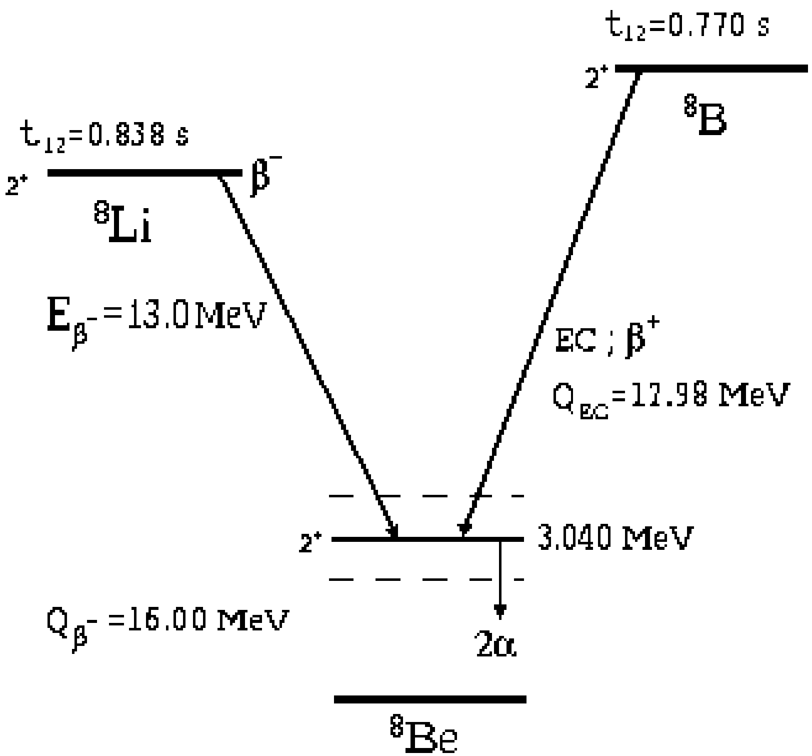
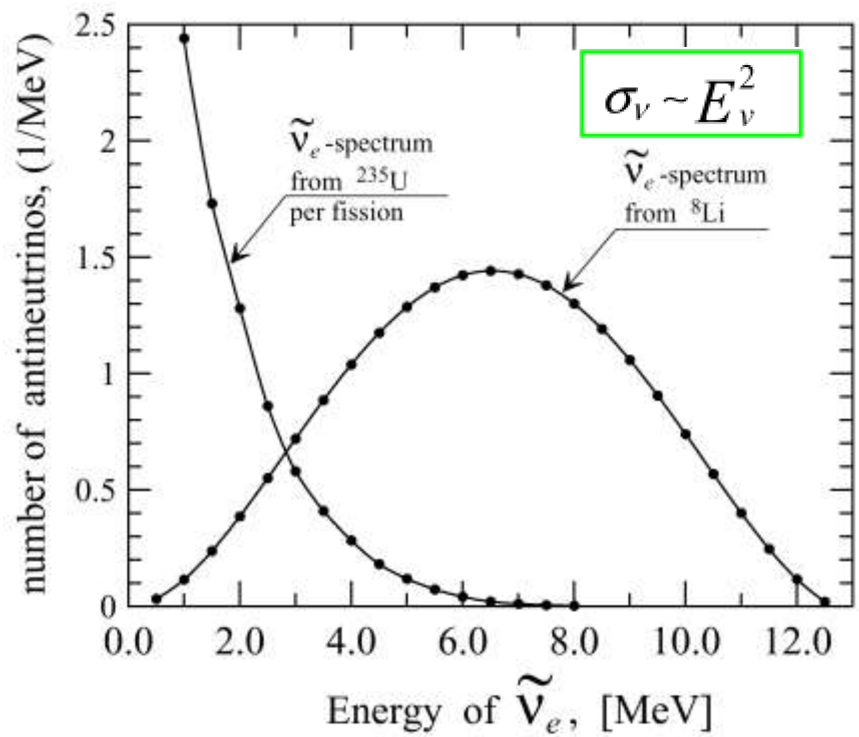
IDEA of the LITHIUM CONVERTER

Alongside with the obvious advantage on a neutrino flux the nuclear reactor has a disadvantage - too-small hardness of -spectrum. This disadvantage can be filled having realized the idea to use a high-purified isotope of ^{7}Li for engineering of a reactor neutrons-to-antineutrino converter, which is located close to the active zone of a reactor. The idea of neutrino source based on $^{7}Li(n,\gamma)^{8}Li$ reaction and ^{8}Li β^{-}–decay was proposed by **L.A. Mikaelian, P.E. Spivak and V.G.Tsinoev (1965).**





Reactor RING (РИНГ).

Plan of `Kurchatov Institute` 1974

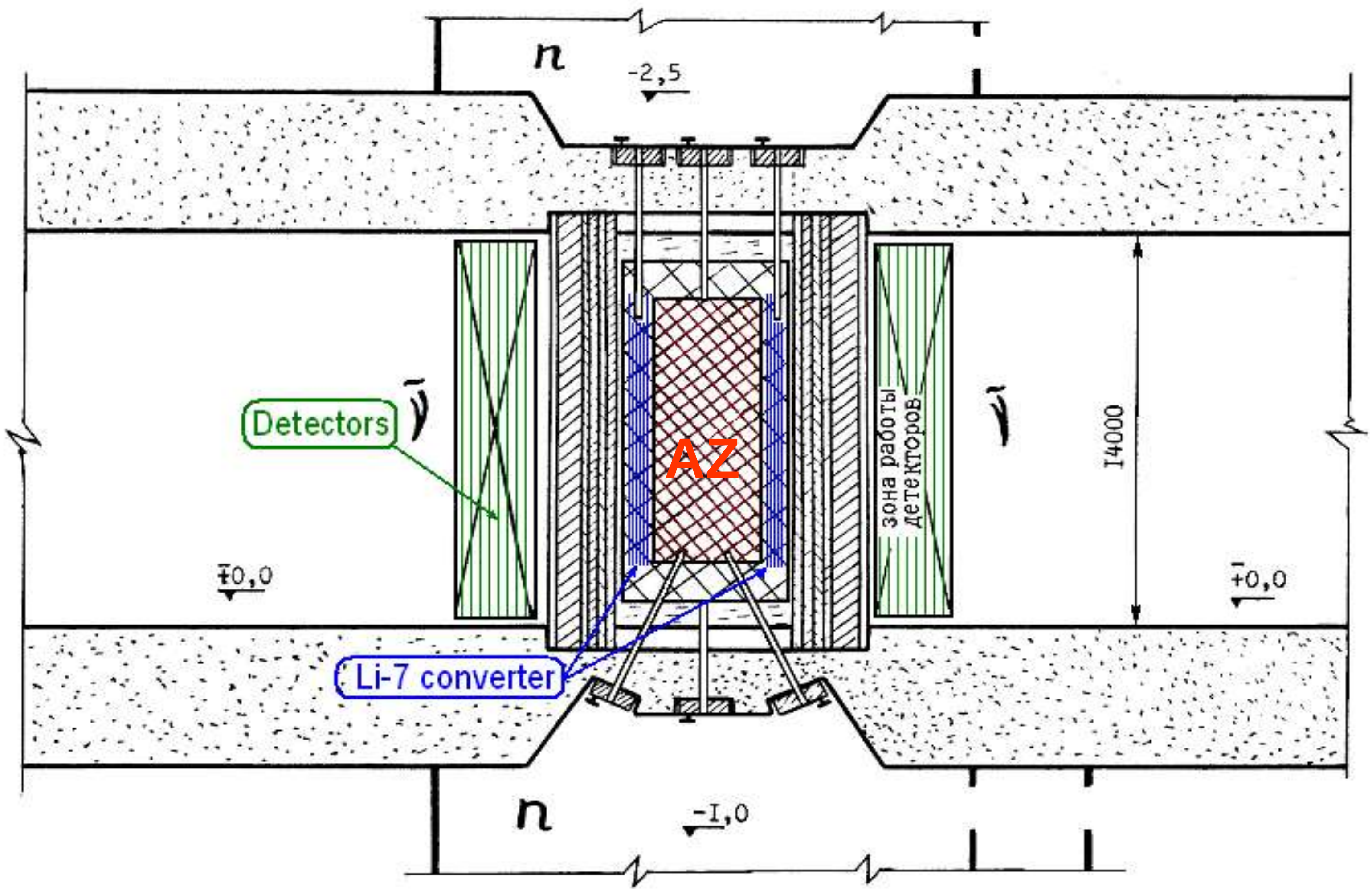
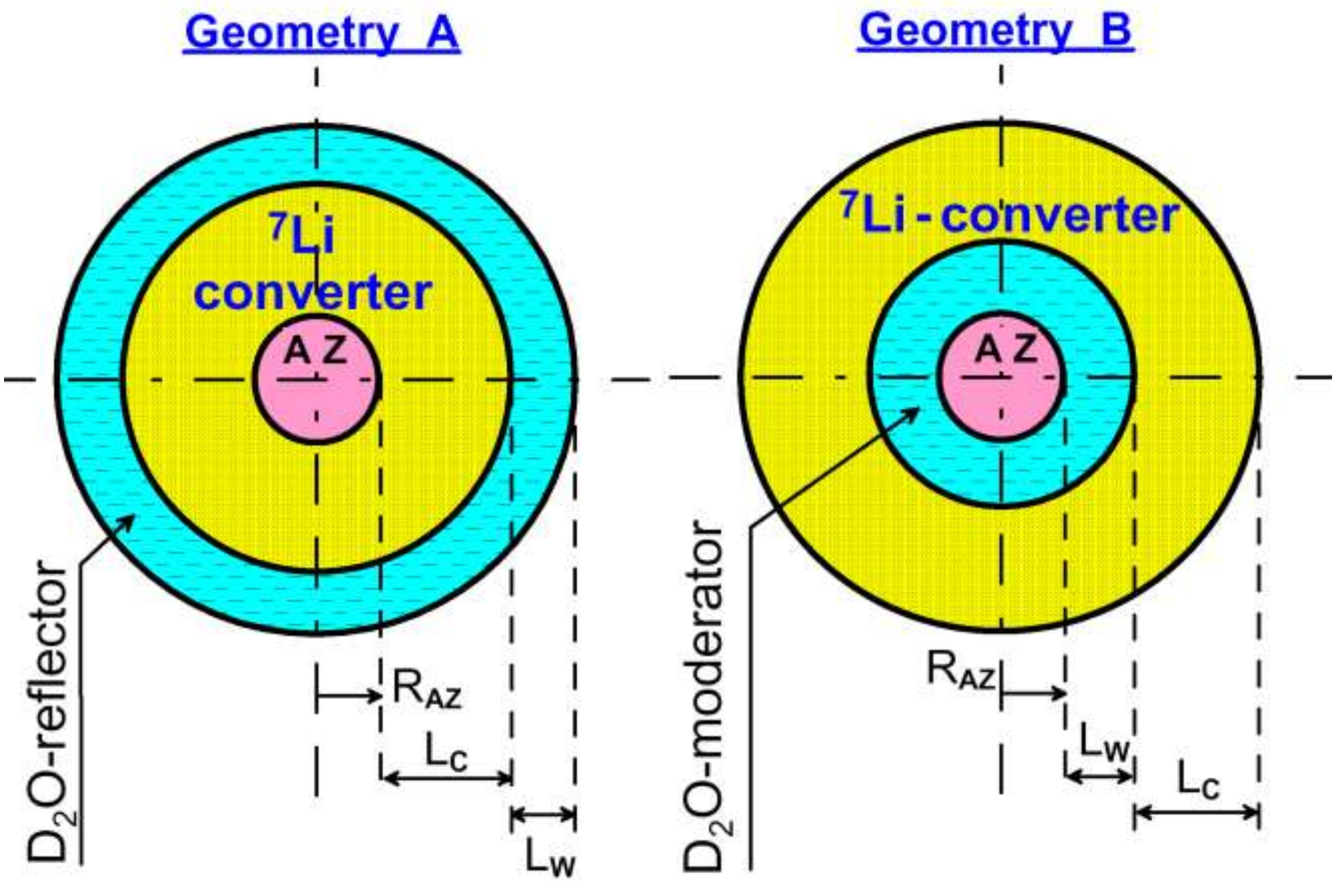


Рис. 2. План размещения нейтринных и нейтронных залов.

STATIC REGIME of the OPERATION

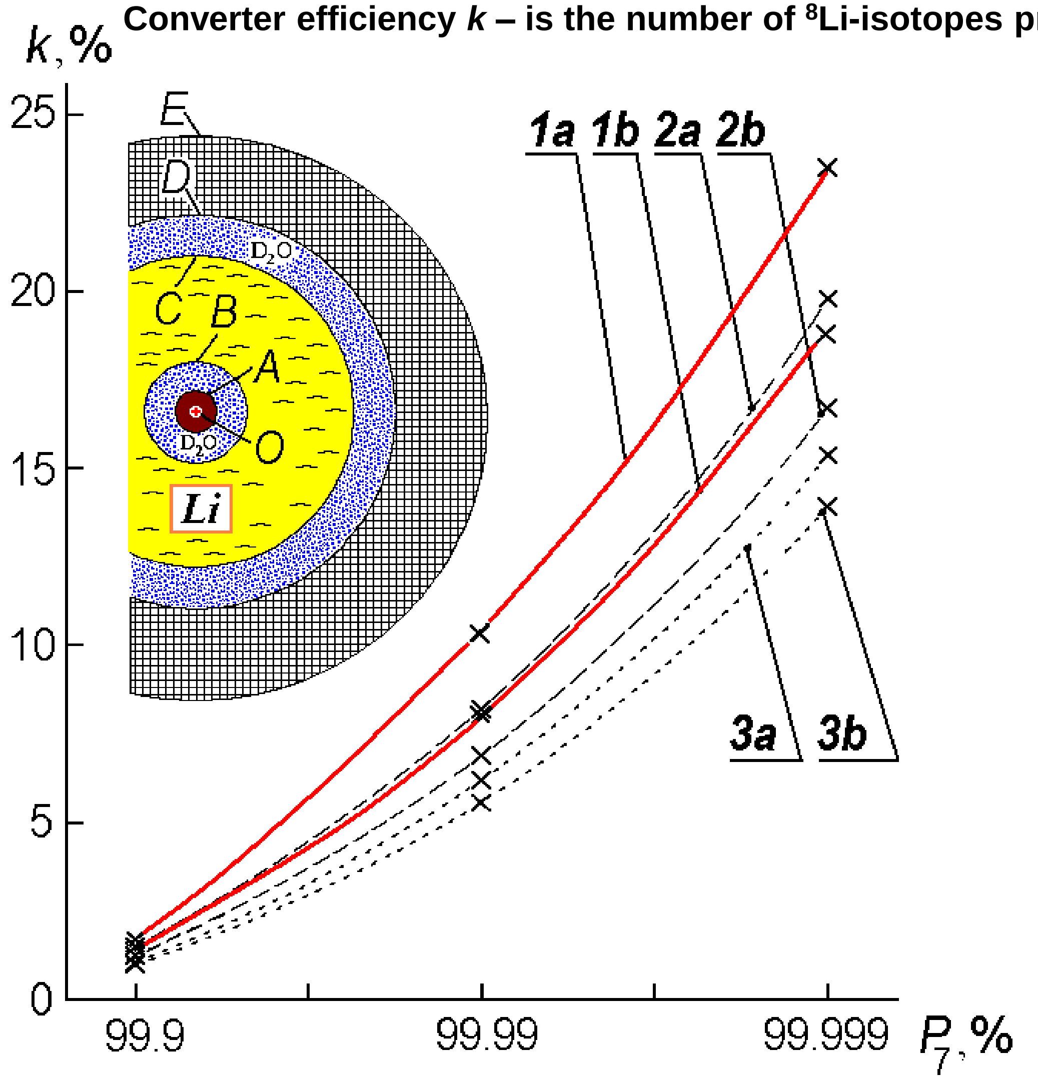


In a reactor neutrons flux a short-lived isotope ^{8}Li(T_S= 0.84 s) is created in the reaction ^{7}Li(n,γ)^{8}Li and at β^--decay emits hard antineutrinos $\tilde{\nu}_e$ of a well determined spectrum with the maximum energy $E_{\tilde{\nu}}^{max}$=13.0 MeV and mean energy $\overline{E}_{\tilde{\nu}}$ = 6.5 MeV.

In the calculation it was considered the next values: L_c = 130, 150, 170 cm, L_w = 30, 15 cm. R_{AZ} = 23 cm (as for the reactor PIK. It was assumed that one fission-spectrum neutron was escaped from active zone per fission in the active zone. The D_2O acts as a reflector in the geometry **A** and as an effective moderator in geometry **B**.

DEPENDANCE of EFFICIENCY *k* from the ^7Li PURITY

Converter efficiency *k* – is the number of ^8Li-isotopes produced per neutron of the source.

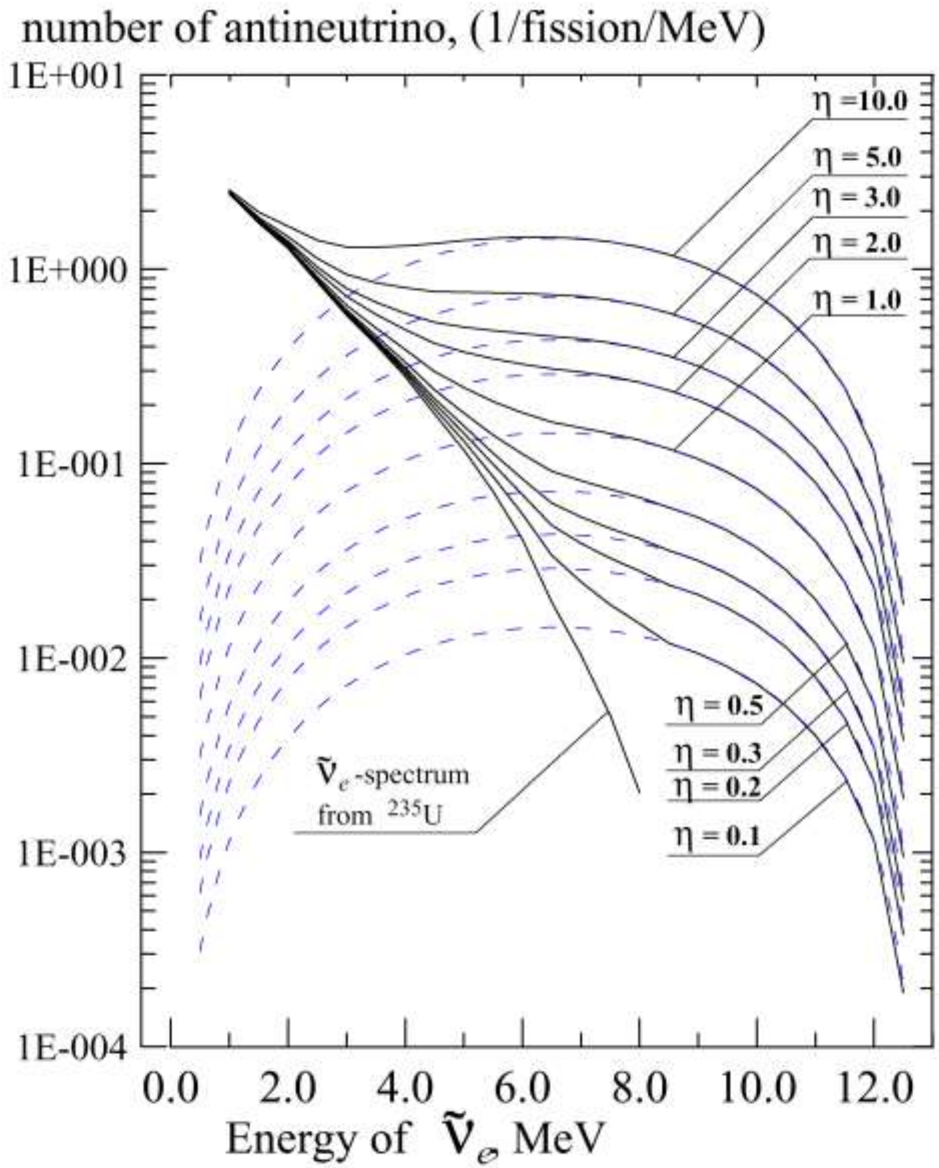


The best variant with geometry *1a* c L_{AB}= 15 sm, L_{BC} = 170 sm, L_{CD} = 30 sm. With purity for ^7Li eq. P_7=99.999% efficiency eq. *k=24%*; for P_7=99.99% *k=10%*

Contents of 7Li in nature lithium is 92,41%.

Spherical geometry: (O-A) – active zone; (A-B) – D_2O moderator; (B-C) – purified ^7Li; (C-D) – D_2O reflector and (D-E) – protection. Variants of Monte-Carlo calculations: 1a – (15,170,30) sm., 1b – (15,150,30) sm.; 2a – (0,170,30) sm., 2b – (0,150,30) sm.; 3a – (15,170,0) sm., 3b – (15,150,0) sm.

SUMMARY ANTINEUTRINO SPECTRUM



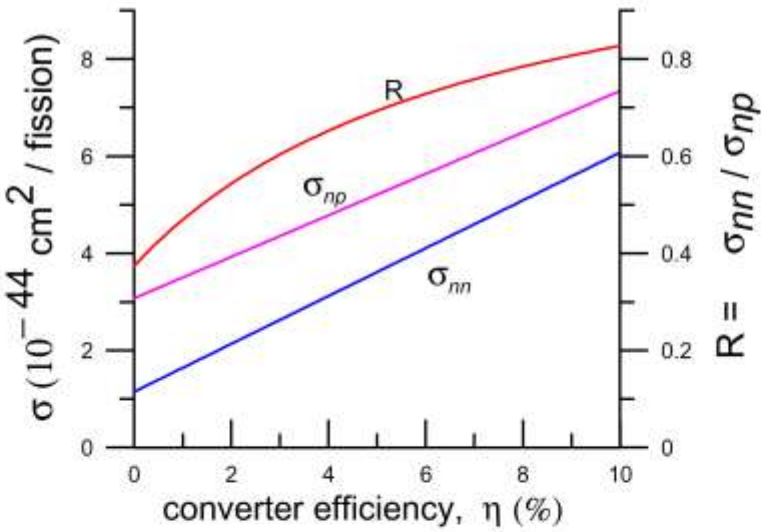
Antineutrino spectrum:

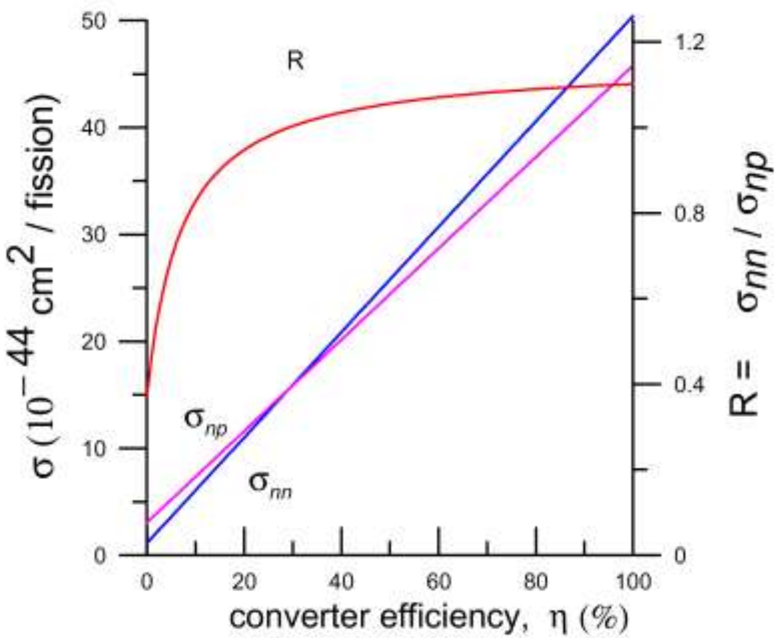
1 – from ^{235}U,

2 – solid line: summary antineutrino spectrum from the active zone and lithium converter for different values of the converter efficiency,

3 – neutrino spectrum from the converter (dotted line) for different converter efficiency.

SOME PHYSICAL ASPECTS





The total number of antineutrinos from the installation is:

$$N_{\tilde{\nu}_e} = N_{AZ} + \eta \bullet (N_{AZ} / n),$$

where N_{AZ} is number of antineutrinos from the active zone, η - converter efficiency, n – number of antineutrinos from active zone per fission ; n ≅ 6.13). So, the second summand determines the number of lithium antineutrinos.

For reaction i , the cross section (normalized per one fission) for the summary neutrino spectrum is also an additive value:

$$\sigma_i = \sigma_i^{AZ} + \eta \bullet \sigma_i^{\text{converter}},$$

where the cross section of antineutrinos from the active zone σ_i^{AZ} and from the converter are calculated separately: each with its own spectrum.

Some reaction, investigated in the neutrino reactor experiments:

$(\tilde{\nu}_e + p \rightarrow n + e^+)$ (1)

$(\tilde{\nu}_e + d \rightarrow n + p + \tilde{\nu}_e)$ ($\sigma_{np,}$ **neutral channel**) (2)

$(\tilde{\nu}_e + d \rightarrow n + n + e^+)$ ($\sigma_{nn,}$ **charged channel**) (3)

Cross section for the reactor antineutrino:

(1) (4.3 to 6.9) 10^{-43} cm^2/fission
(2) (1.1 to 1.9) 10^{-45} cm^2/$\tilde{\nu}_e$
(3) (2.9 to 4.7) 10^{-45} cm^2/$\tilde{\nu}_e$

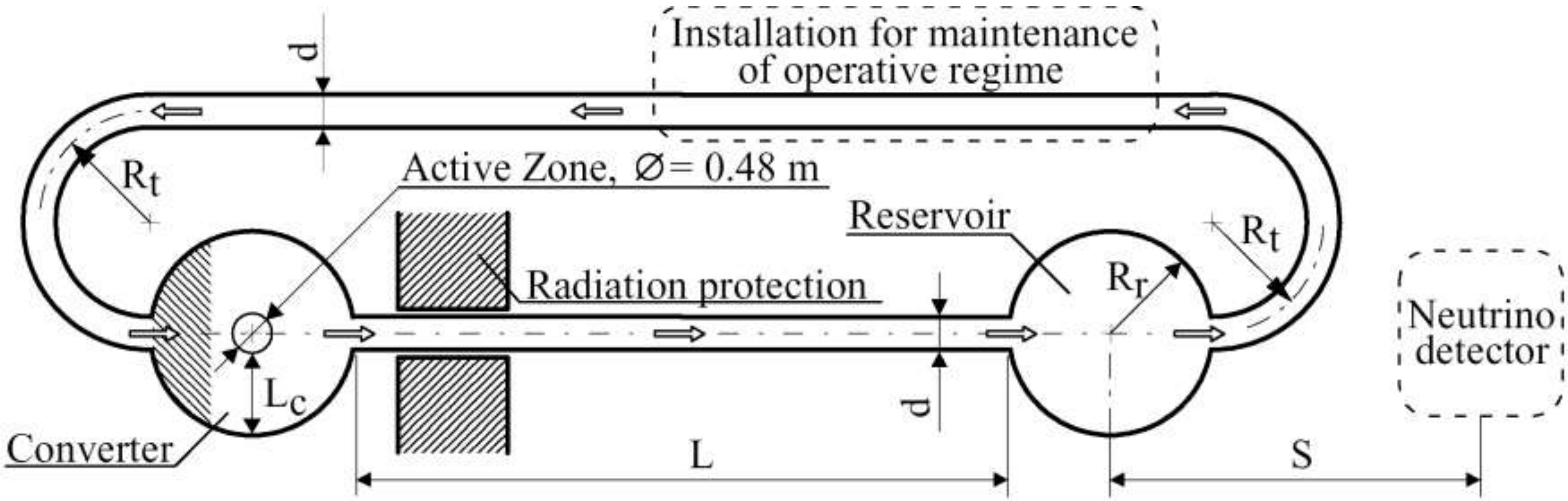
Hard-spectrum lithium antineutrinos allow Increase cross section in several times.

CHOISE of CONVETER MATTER

CONVERTER MATERIAL	DENCITY (g/cm^2)	TEMPERATURE OF MELTING (t ^{0}C)	Li mass (in kg) for $\kappa = 9$ % (*$^7Li=99.99\%$*)
^{7}LiD – lithium deuteride	0.89(crystal) 0.80(pressed)	686±5	**>300**
^{7}LiOD – lithium hydroxide	1.495	462÷471 (for LiOH)	**250**
^{7}LiOD·D$_2$O – monohydrate of lithium hydroxide	1.965	>600 (for LiOH·H$_2$O)	**115**
^{7}LiOD–heavy water solution (6%)	~1.1	-	**70**

To increase the converter efficiency by increasing the purity of ^{7}Li to not less than 99.999% value is difficult. The solution is to use not pure ^{7}Li isotope as the converter material, but its chemical compositions, for example the perspective matter is a heavy water solution of lithium hydroxide $LiOD$, $LiOD \cdot D_2O$ and LiD. The results of calculations Li mass for different chemical compositions and other information presented in Table. The most perspective was considered $LiOD$ heavy water solution. Thus, using it permits to reduce the layer thickness L_C up to ≈1m and sharply reduce a required mass of a high-purified lithium. For example, **at the concentration of 9.46 % for the achievement $\kappa = 0.077$ it will be necessary mass in 300 times less than for the converter with lithium only**. Other chemical compositions like Li_2C_2, Li_2CO_3, Li_2O, $LiDCO_3$, LiF, $LiDF_2$ and their heavy water solutions are not so perspective.

DINAMIC REGIME of OPERATION

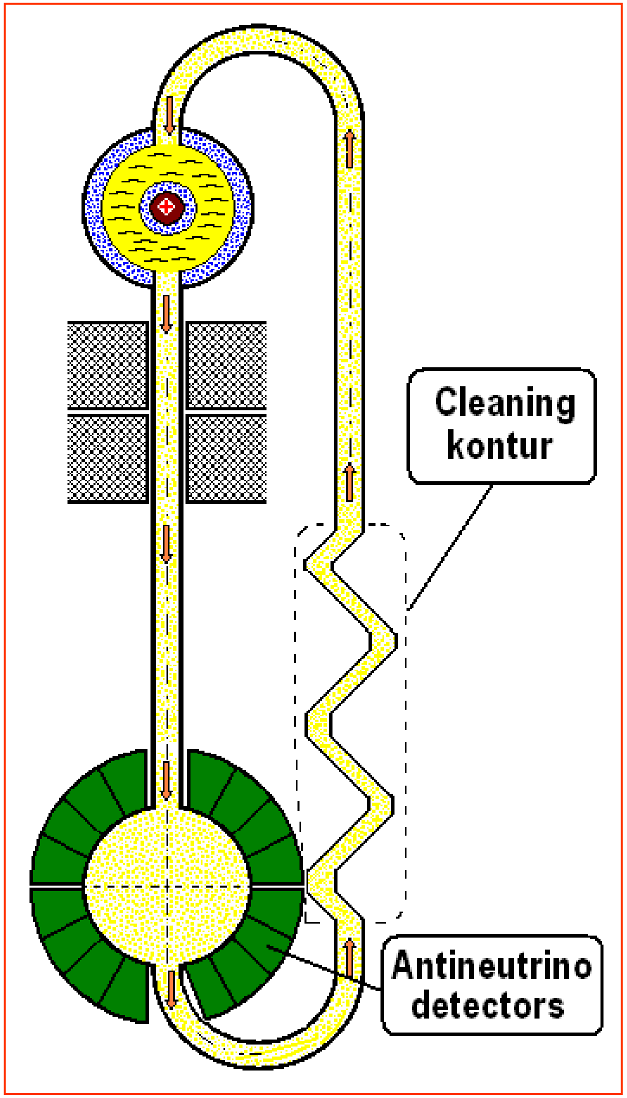


It is possible to supply powerful neutrino fluxes with considerably greater hardness in a facility with a dynamic mode of operation: liquid lithium composition is pumped over in a closed cycle through a converter and further in a direction to a remote neutrino detector. For increasing of a part of hard lithium antineutrinos a being pumped reservoir is constructed near the ν-detector. Such a facility will ensure not only more hard spectrum in the location of a detector but also an opportunity to investigate -interaction at different spectrum hardness.

However, the development of such a facility comes across serious problems connected with necessity of a temperature regime maintenance ($t_{melting}$(Li)=C) and requirement in a large mass of a high-purified lithium. So, at the thickness of converter L_C = 1.5 m it is reaches the efficiency ≅ 0.077 that requires 11.9 t. of lithium with the purity on the isotope ^{7}Li P_7 = 99.99%.

For realization of a dynamic mode it will required lithium about in 2-4 times more.

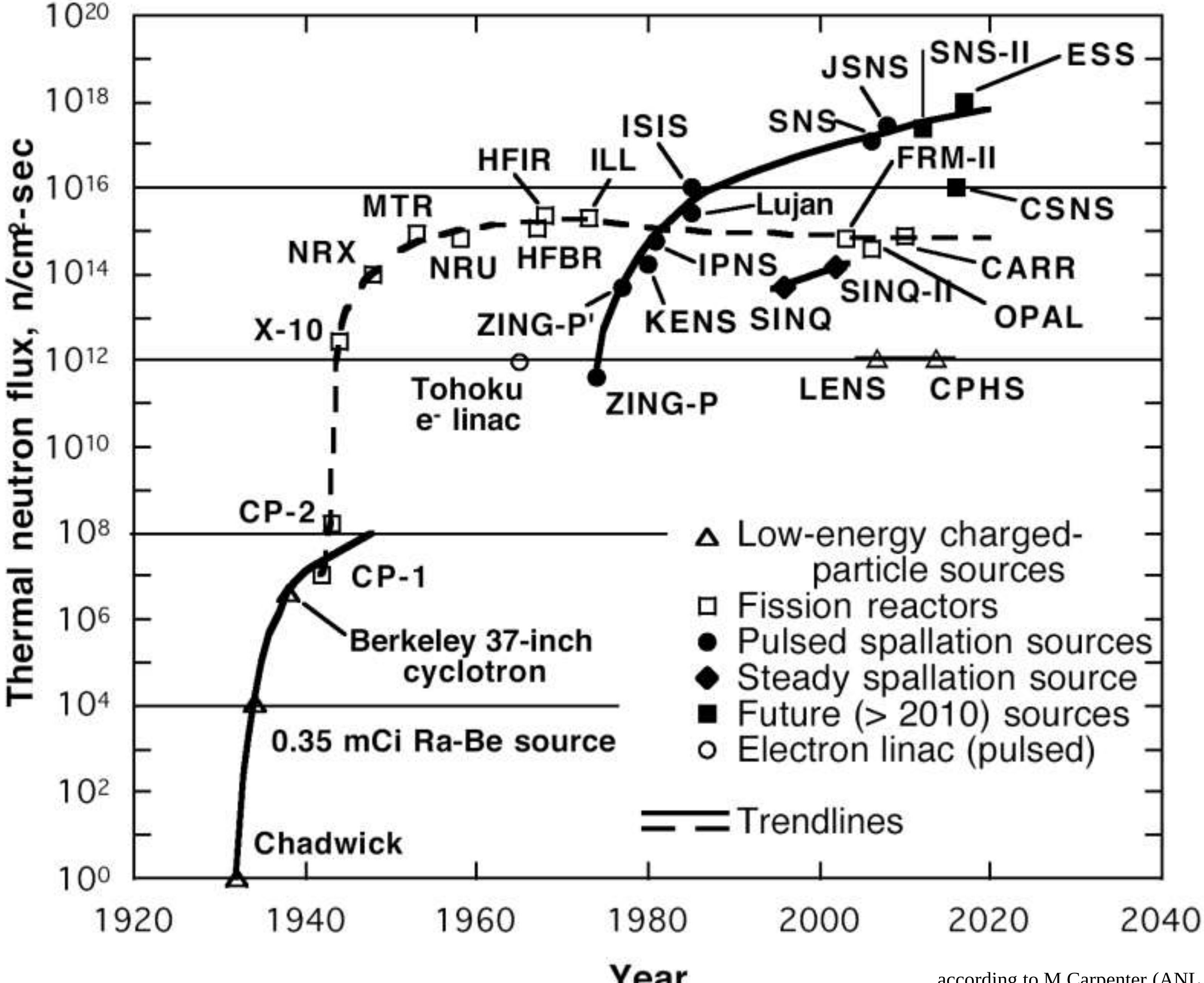
The problem of the requested ^{7}Li mass can be solved with use of lithium heavy water solution



DINAMIC REGIME of OPERATION-2 Vertical scheme

For realization of a dynamic regime it will required lithium about in 2-4 times more.
The problem of the requested ^{7}Li mass can be solved with use of lithium heavy water solution

Neutron Sources (working and developing) (1)

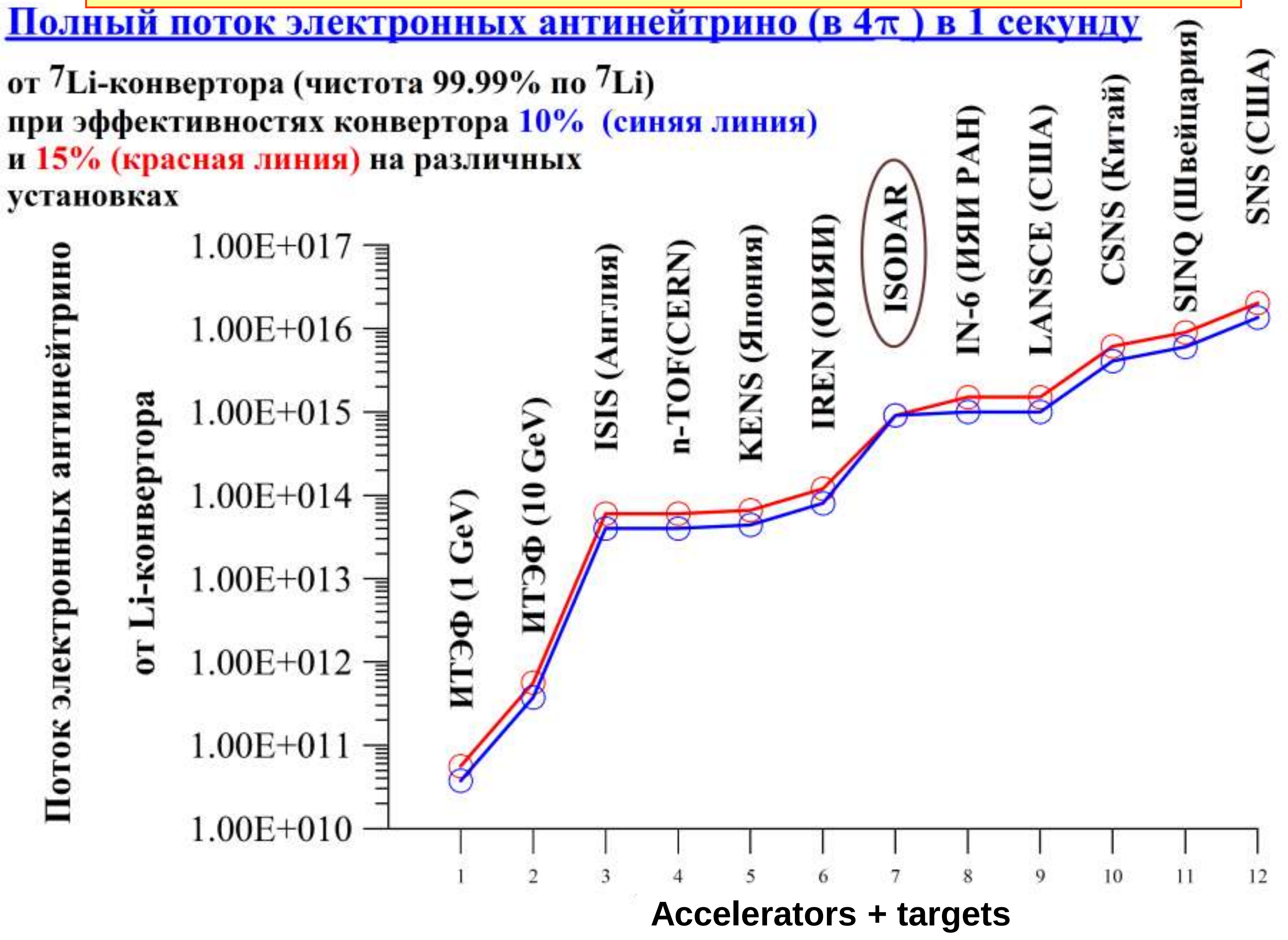


according to M.Carpenter (ANL and ORNL/SNS)

Neutron Sources on the Base of Accelerator + Neutron Producing Target

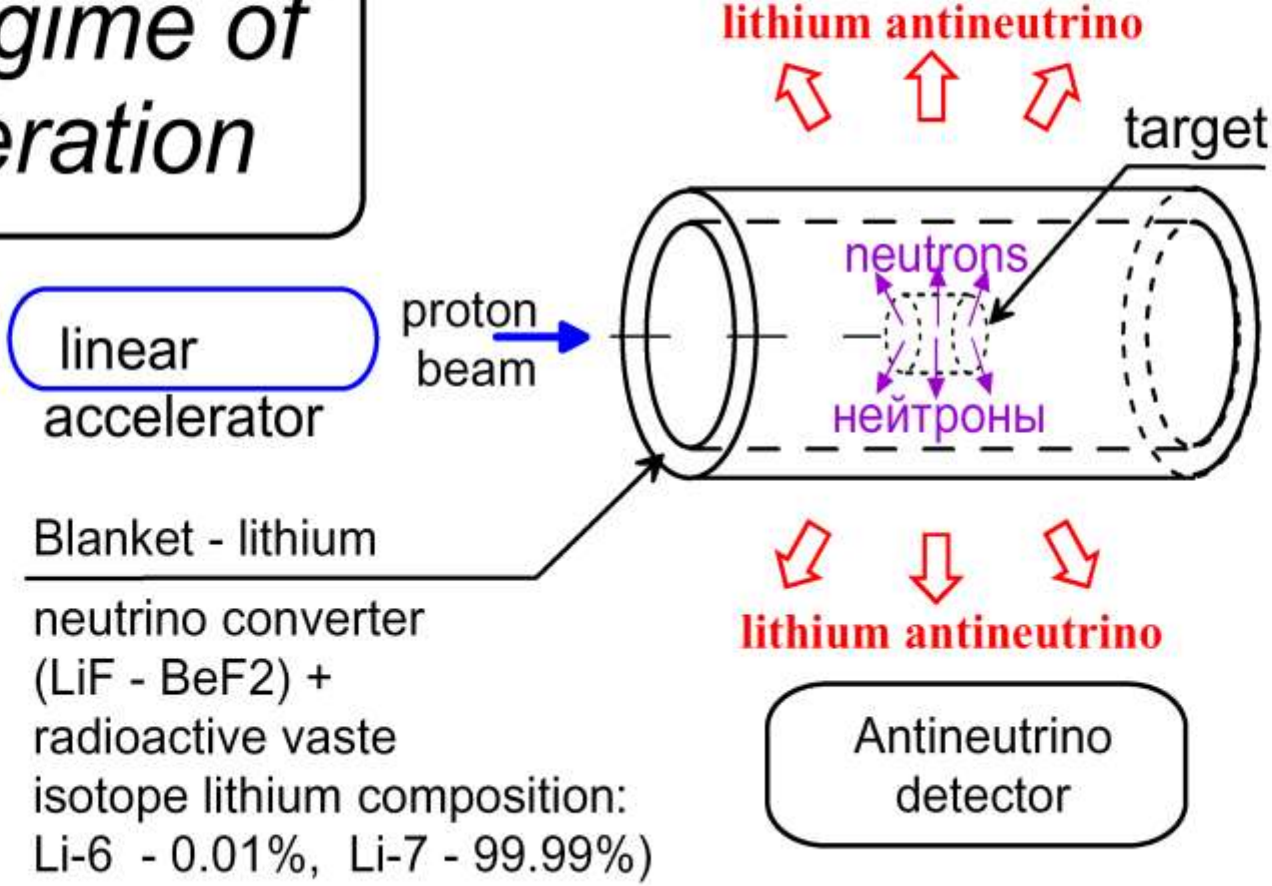
Facility (Country, site, laboratory)	**Beam parameters**: particles, energy, current, frequency (Hz)	**Neutron yield, flux**	**Target; status of the facility**
IN-6 (Russia, Troitsk, INR RAS)	protons, 600 MeV, 0.5 mA (average), 100 Hz (project parameters)	$\sim 1\cdot 10^{16}$ s^{-1}	tungsten (target in block 1); first run in 1998 year
IREN (Russia, Dubna, JINR)	electrons, 200 MeV, 3 A (in the pulse), 150 Hz	$1\cdot 10^{15}$ s^{-1}	Pu (K_{eff} <0.98); under construction: (W-target at 1st stage)
SNS (USA, ORNL)	protons, 1 GeV, 1.4 mA (average), 60 Hz	**(1.8 - 2.7)·10^{17} s^{-1}**	mercury; work since 2006 year
SINQ (Swisserland, Paul Scherrer institut.	protons, 590 MeV, 1.8 mA, steady-state flux	$1\cdot 10^{14}$ cm^{-2}s^{-1}	lead; work since 1998 year
n-TOF (Switzerland, Geneva, CERN)	protons, 20 GeV, 4 Hz	$0.4\cdot 10^{15}$ s^{-1}; at L = 185 m from the target : $4\cdot 10^{5}$ cm^{-2}s^{-1}	lead; work since 2000 year
IFMIF (Italy, Frascati)	deuterons, 40 MeV, 125 mA, steady-state flux	$(4.5\div 10)\cdot 10^{17}$ m^{-2}s^{-1}	Moltem ^{7}Li; under construction
LANSCE (USA, Los-Alamos)	protons, 100-800 MeV, up to 1mA; 20 Hz	$1\cdot 10^{16}$ s^{-1}; for MTS(material test facility): $2\cdot 10^{15}$ cm^{-2}s^{-1} (2012year plan)	tungsten; work since 1985 year
KENS (Japan, Tsukuba, KEK)	protons, 500 MeV 10 μA, 20 Hz	$3\cdot 10^{14}$ cm^{-2}s^{-1}	tungsten (tantalum clad); work since 1980 year
ESS (Sweden, Lund)	protons, 2.5 GeV, 14 Hz	**4·10^{16} cm^{-2}s^{-1}** (peak flux);	tungsten; normal operation in 2019; 44 neutr. instrum. in 2025
CSNS (China, Dongguan)	protons, 1.6 GeV, 62.5 μA, 25 Hz; $1.63\cdot 10^{13}$ proton/pulse, plan-Stage1	$\sim 5\cdot 10^{15}$ cm^{-2}s^{-1}	tungsten; normal operation in 2018 year

ANTINEUTRINO FLUX FROM Li CONVERTOR (in 4π per 1 sec)

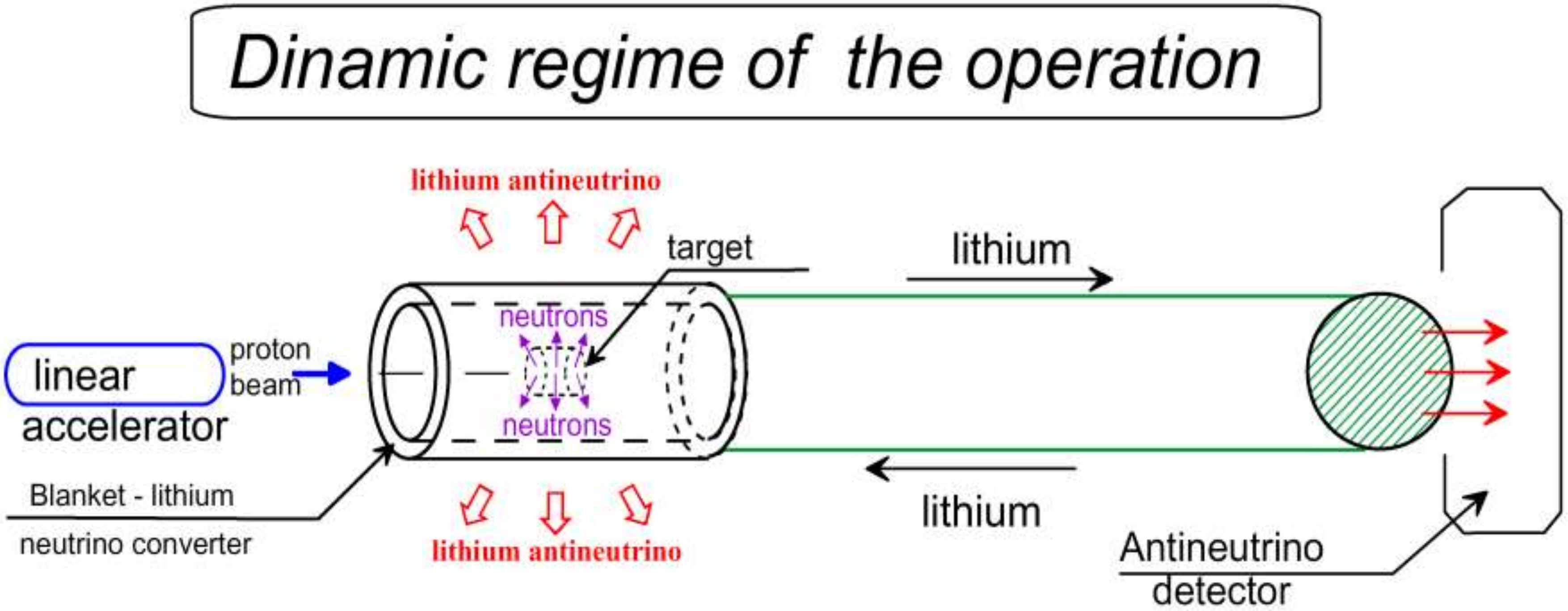


Powerful Lithium Antineutrino Source on the base of the booster for inciniration of radioactive vaste (1)

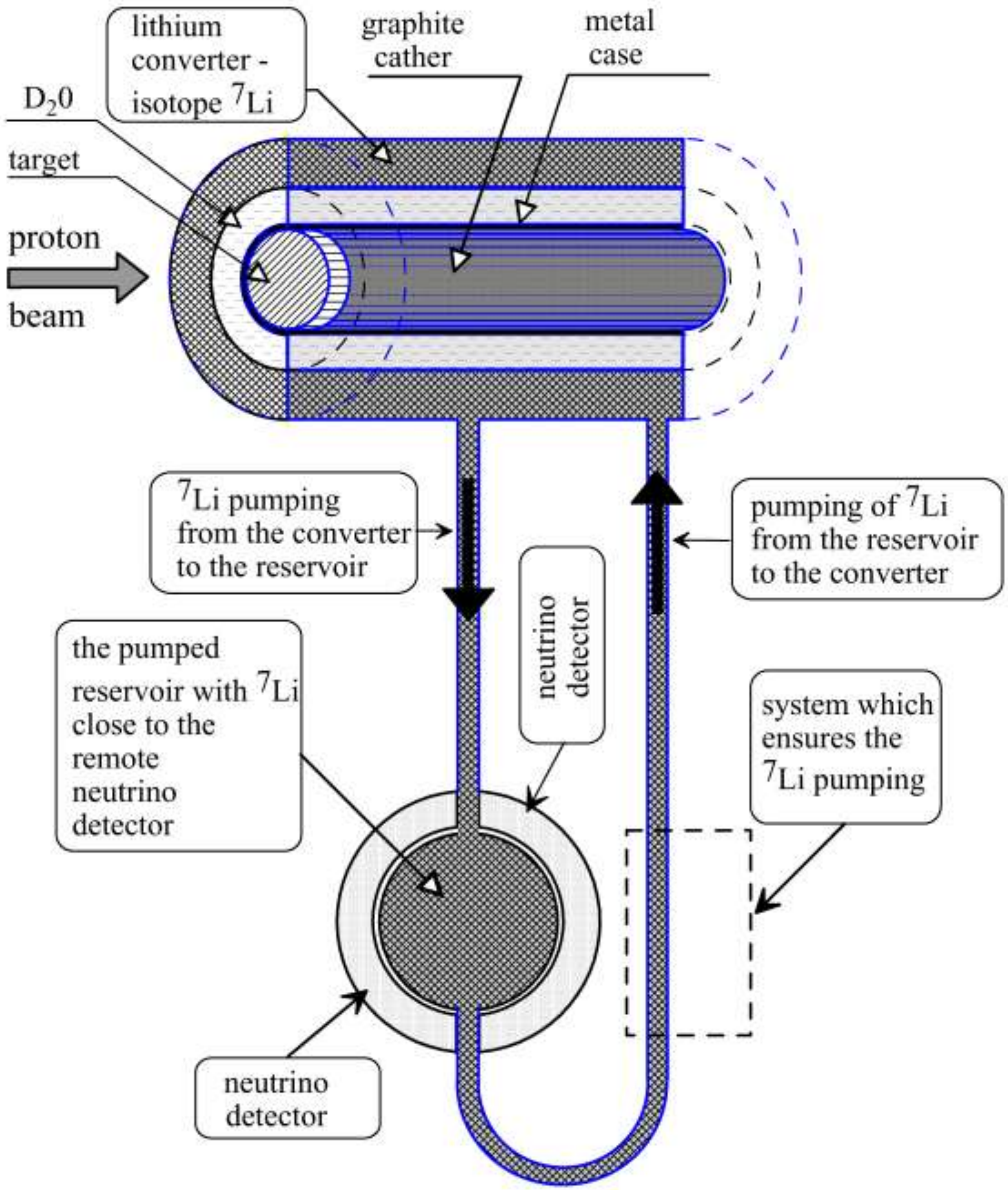
Static regime of the operation



Powerful Lithium Antineutrino Source on the base of the booster for inciniration of radioactive vaste (2)

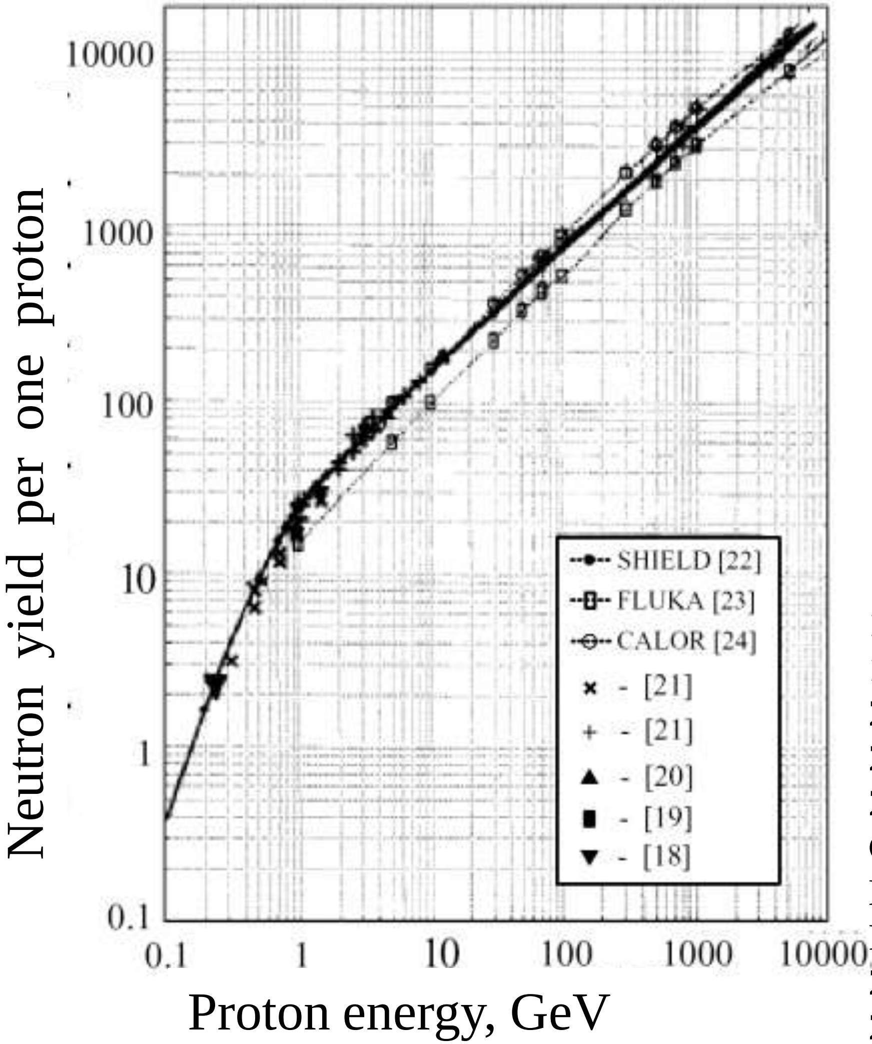


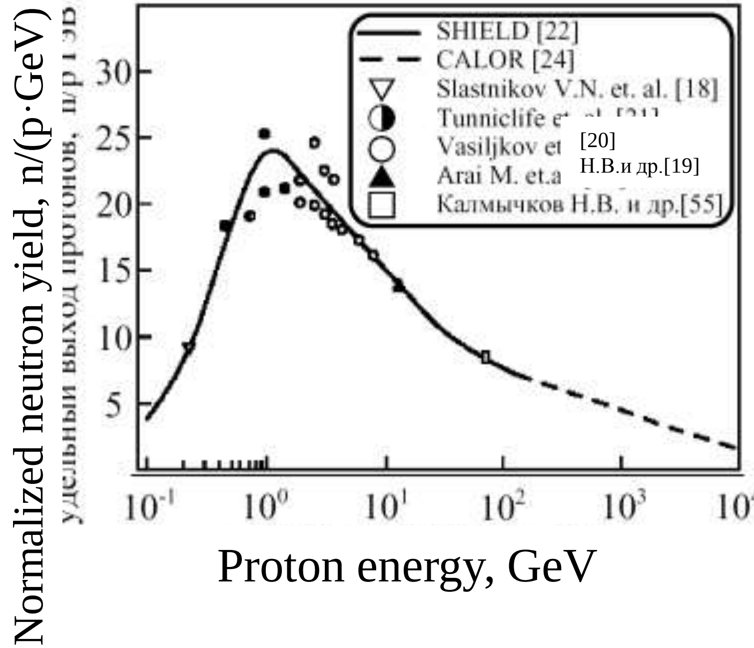
NEUTRINO FACTORY on the BASE of BEAM CATCHER



The scheme of the neutrino factory on the base of the catcher of large accelerators (^{7}Li isotope is activated in (n,γ)-reaction and pumped to the remote detector). Proton beam (from the accelerator is dumped on the heavy neutron-producting target (for example – tungsten) close the graphite catcher. The catcher is placed in the metal cage and is cooled by heavy water (which is the neutron moderator and the 1st cooling contour). The second cooling contour is the lithium (or it's solution) in the pumping regime (dynamic regime).

1. NEUTRON YIELD FRON HEAVY TARGETS (W, Pb)





Стависский Ю.И.
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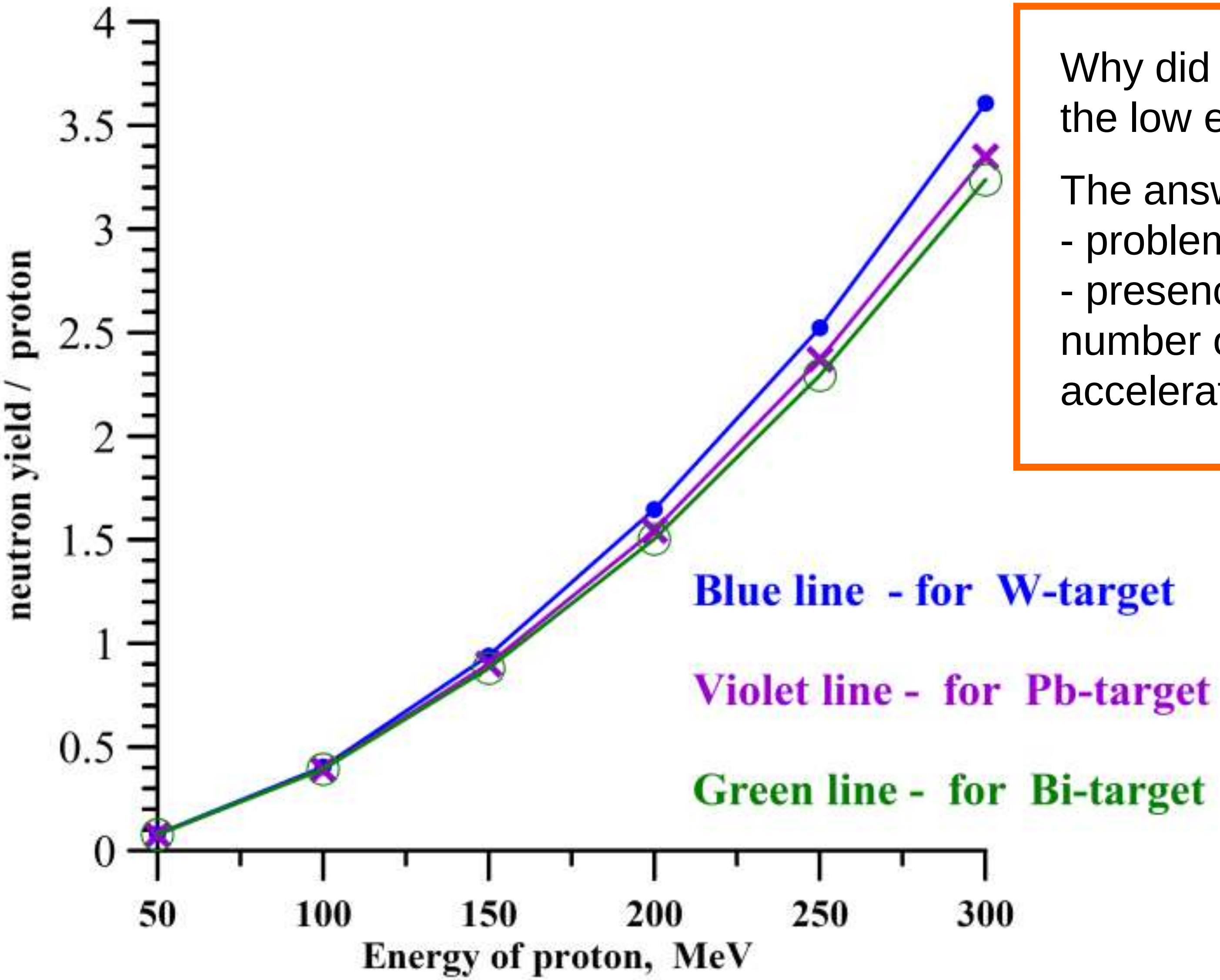
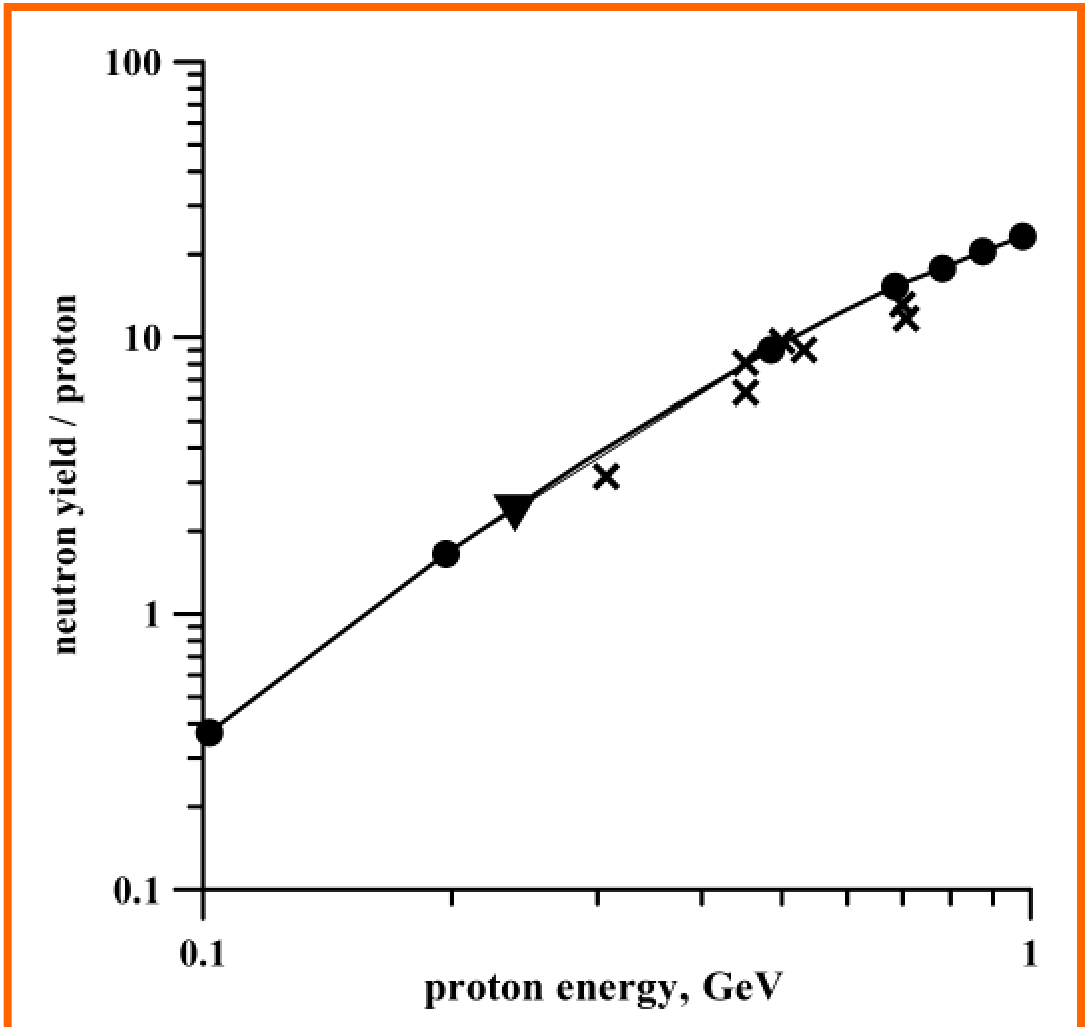
2. NEUTRON YIELD FROM HEAVY TARGETS (W, Pb, Bi)

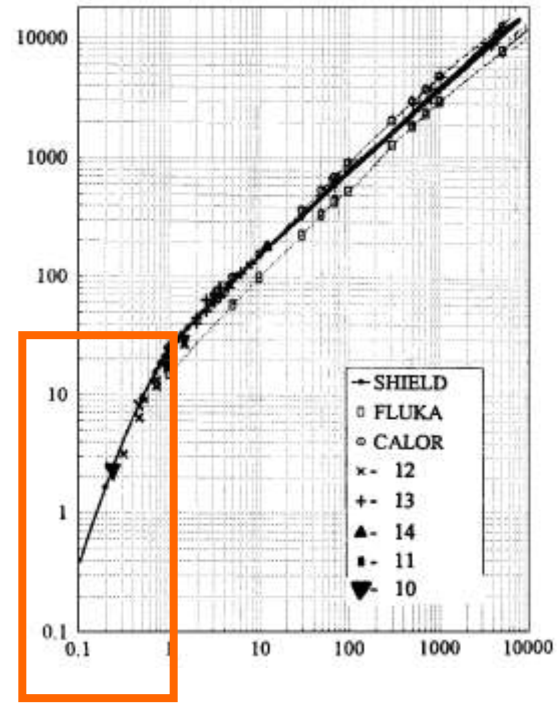


Why did we considered the low energy interval ?

The answer:
- problems of background
- presence significant number of low energy accelerators

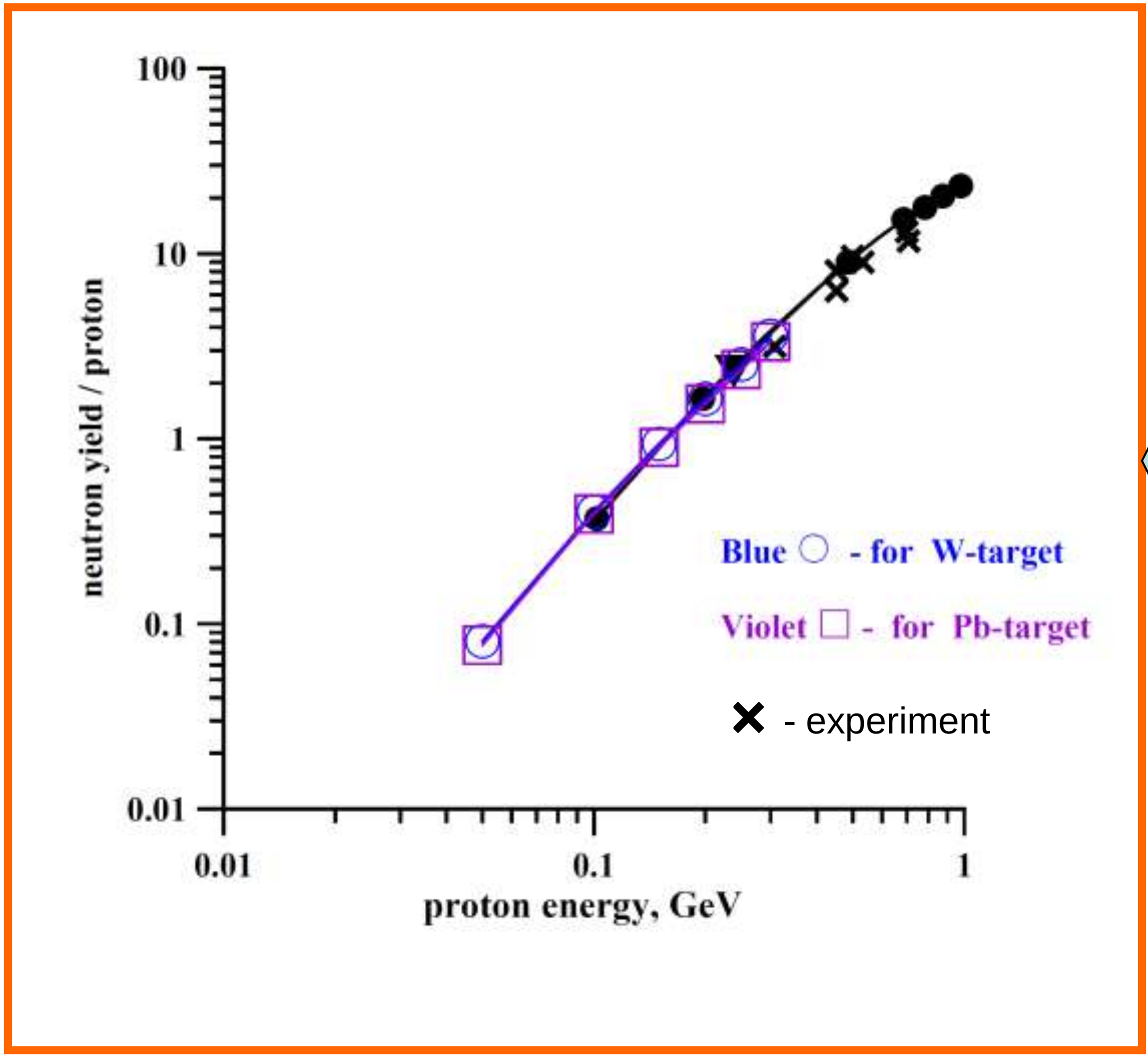
3. NEUTRON YIELD FROM HEAVY TARGETS (W, Pb)
EXPERIMENT

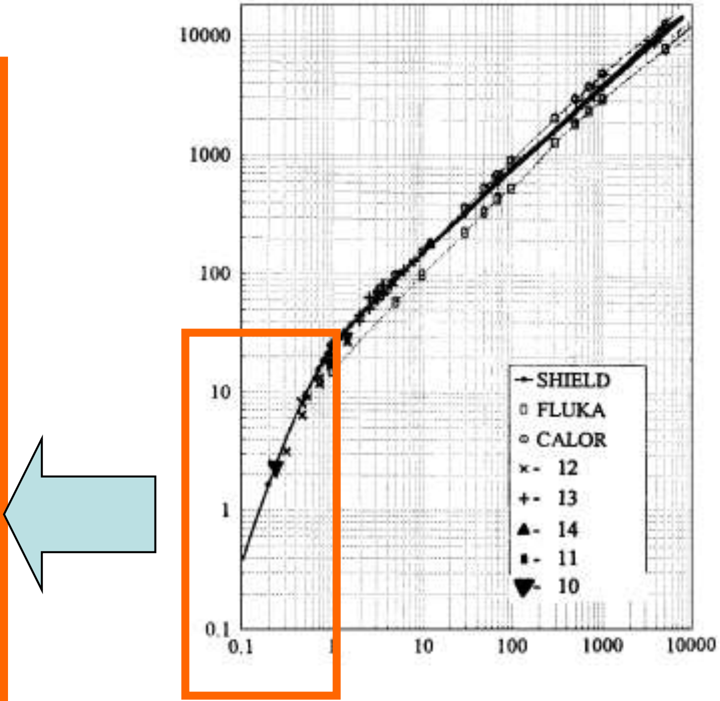




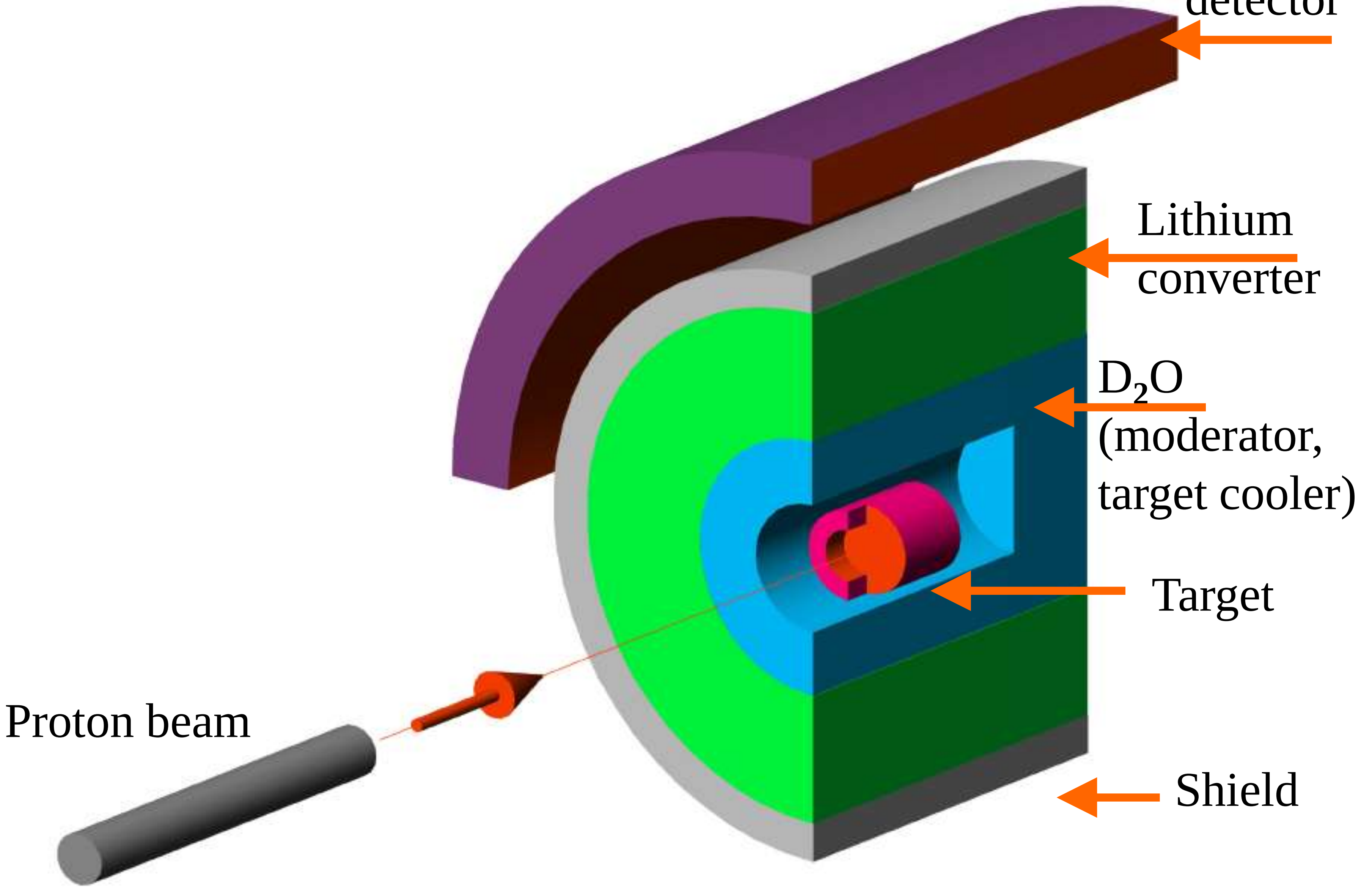
4. NEUTRON YIELD FROM HEAVY TARGETS (W, Pb)

EXPERIMENT + CALCULATIONS



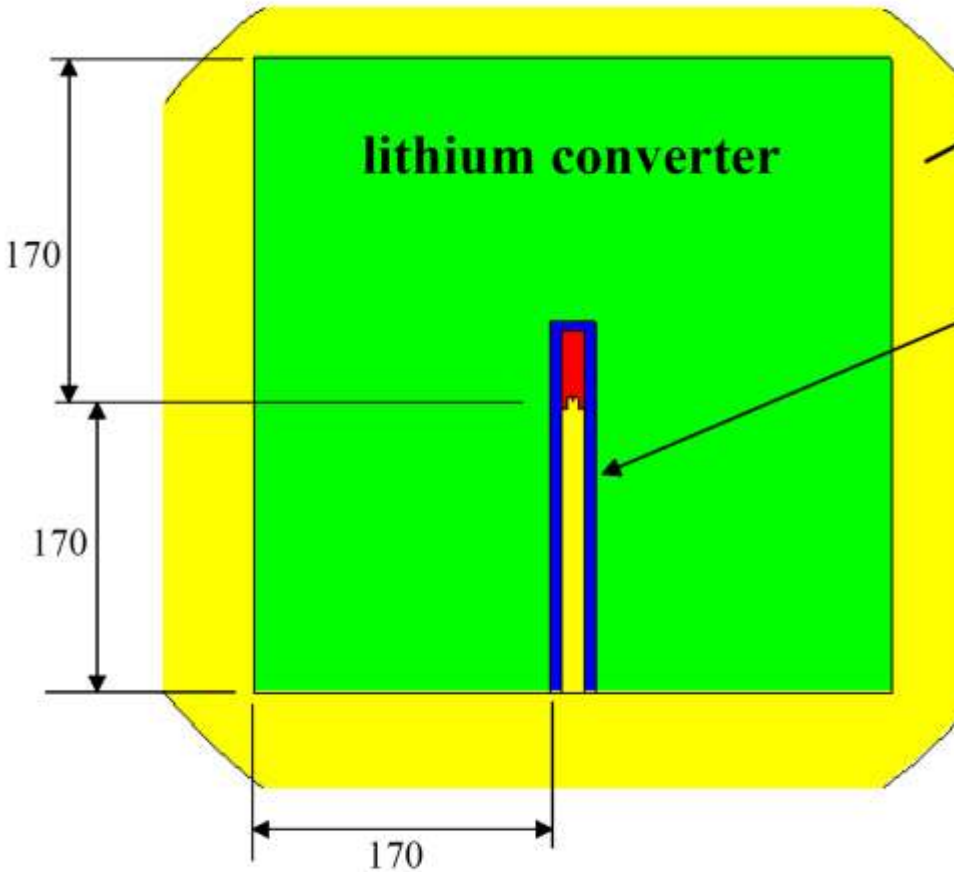


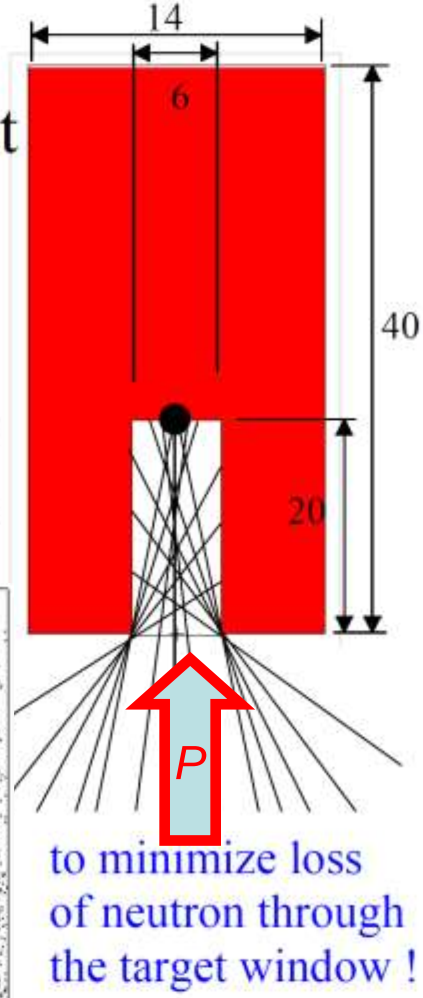
1. Lithium Antineutrino Source in the Cylindrical Geometry

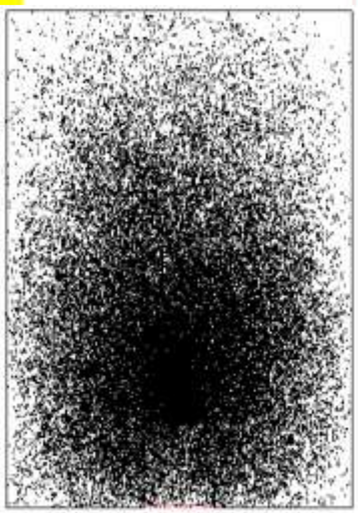


GEOMETRY OF THE INSTALLATION

top view

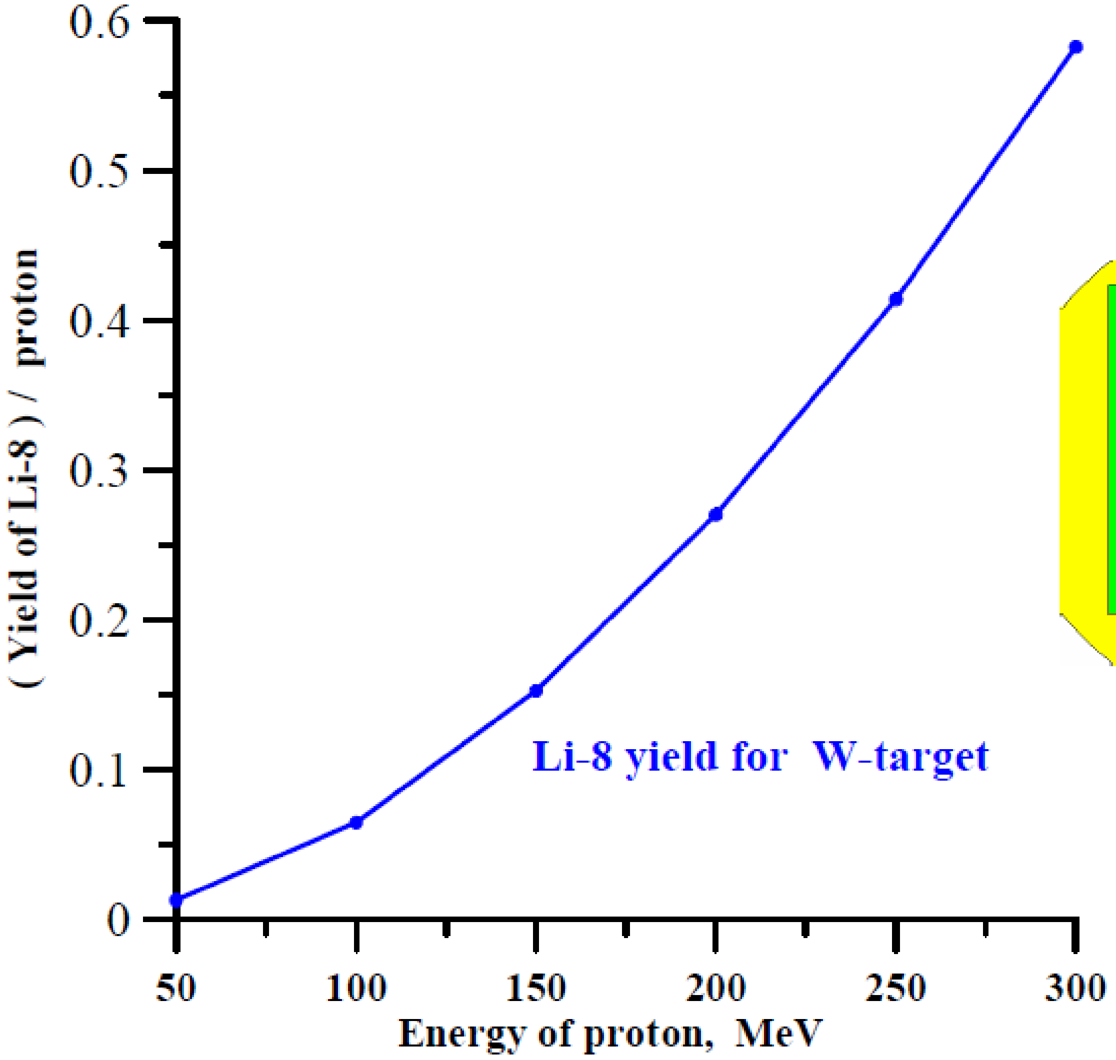




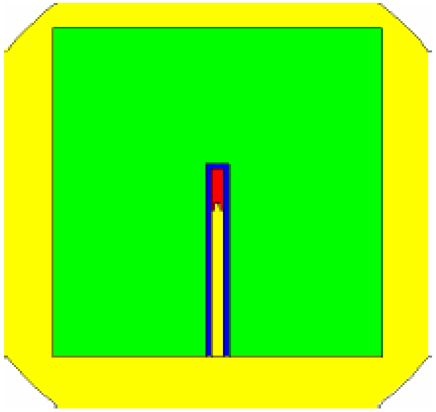


Distribution of neutron collisions

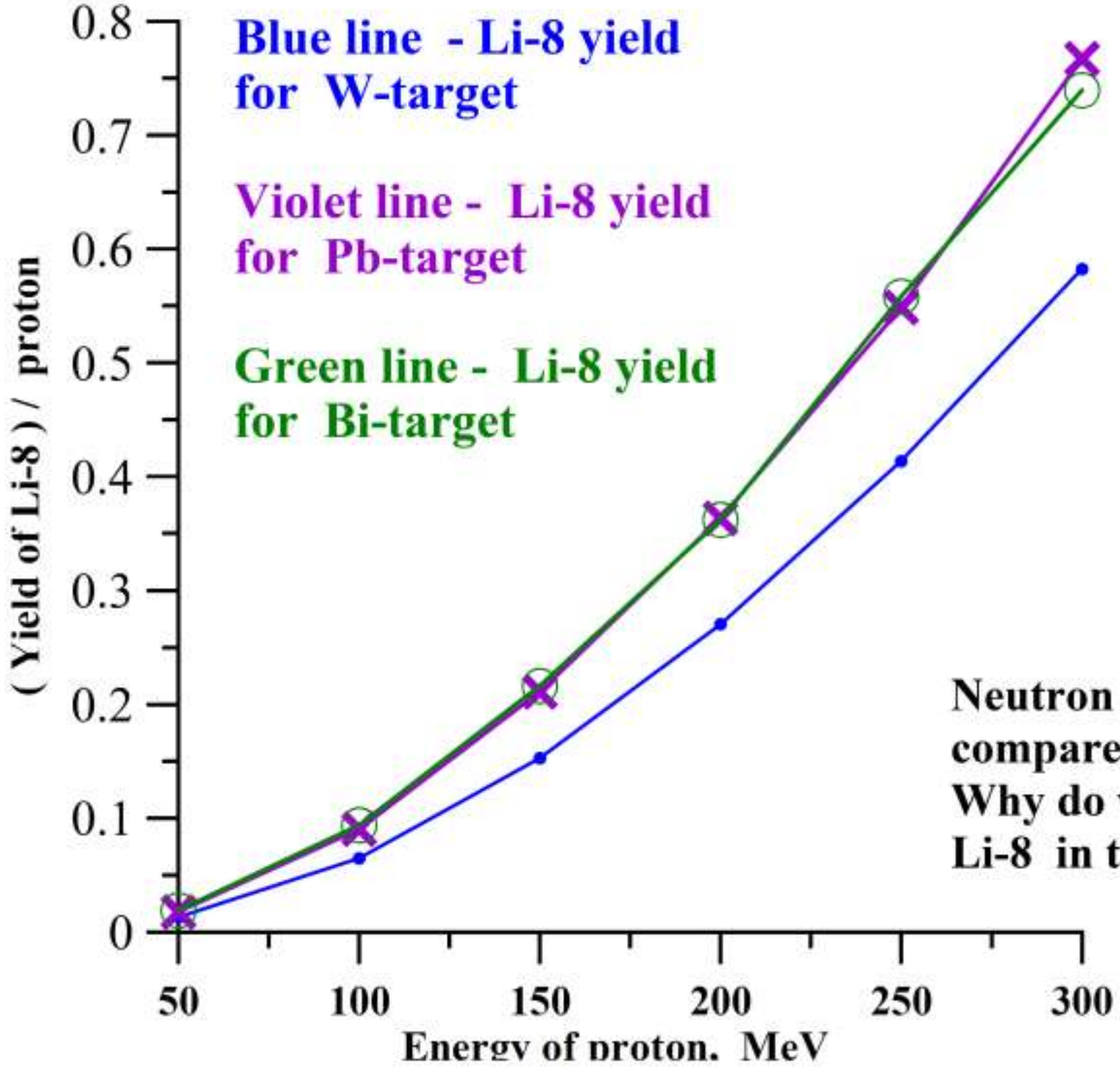
1. EFFICIENCY OF THE LITHIUM ANTINEUTRINO SOURCE IN THE SCHEME OF THE TANDEM OF CONVERTER AND ACCELERATOR PLUS NEUTRON PRODUCING TARGET

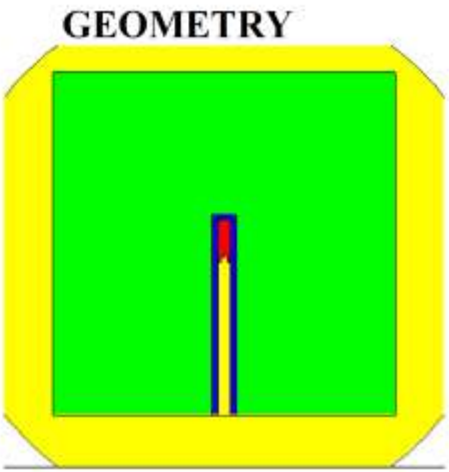


GEOMETRY



2. EFFICIENCY OF THE LITHIUM ANTINEUTRINO SOURCE IN THE SCHEME OF THE TANDEM OF THE CONVERTER AND ACCELERATOR PLUS W, Pb, Bi-TARGET

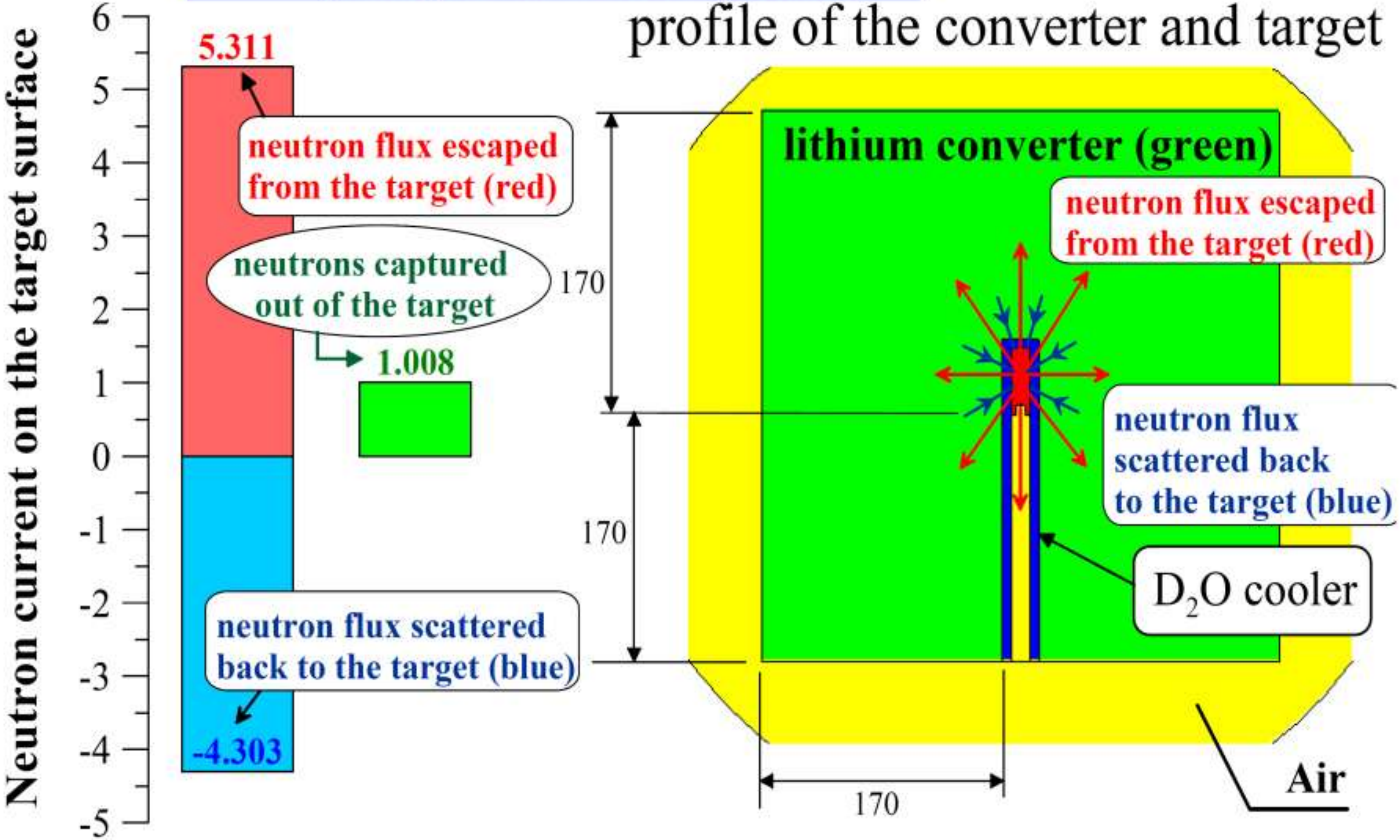




Neutron yield from W-target is larger compare to Pb and Bi-target.
Why do we have inverted yield of Li-8 in the converter ?

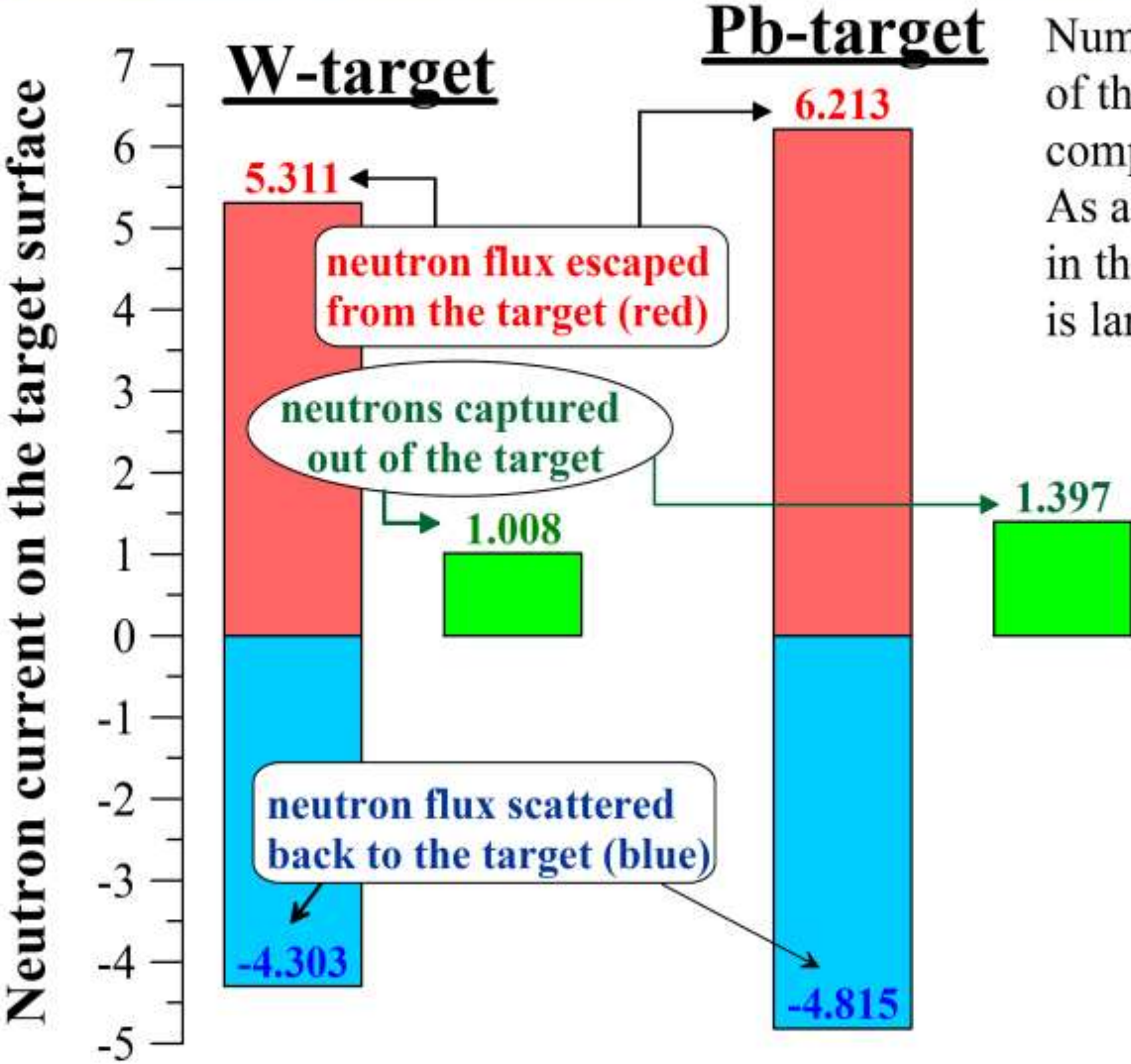
NEUTRON FLUX from the W-TARGET

(example for 200 MeV protons)

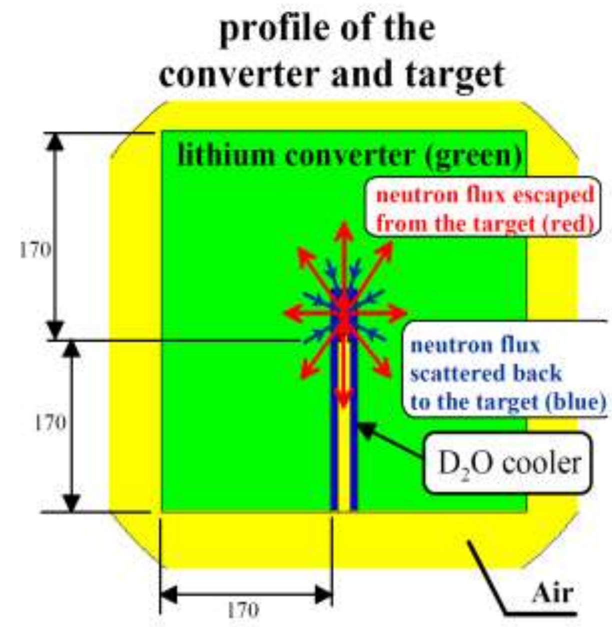


NEUTRON FLUX from the W and Pb -TARGET

(example for 200 MeV protons)

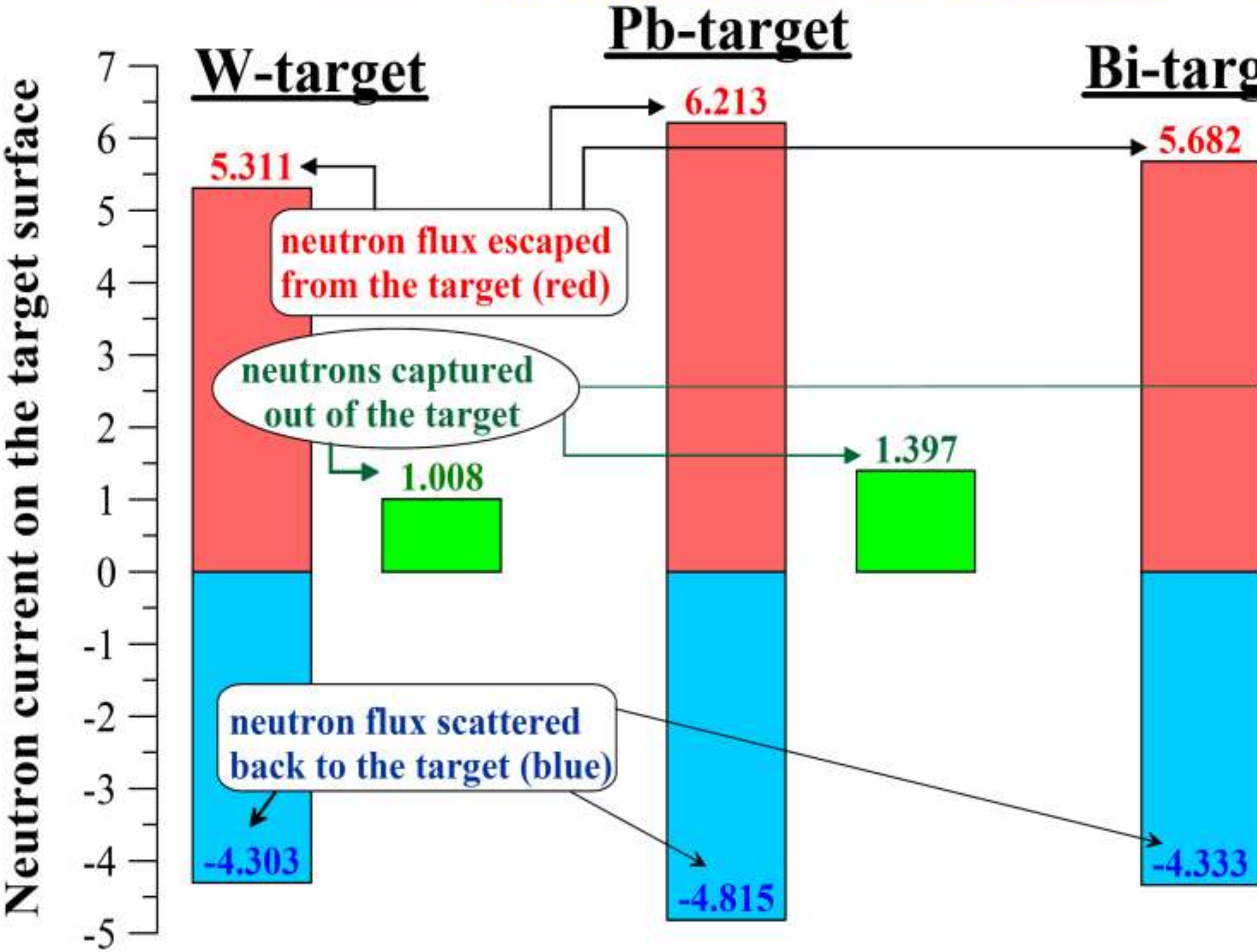


Number of neutrons captured out of the Pb-target (**1.397**) is larger compare to the W-target (**1.008**). As a result, number of Li-8 created in the converter in case of Pb-target is larger compare to the W-target.



NEUTRON FLUX from the W, Pb and Bi -TARGET

(example for 200 MeV protons)



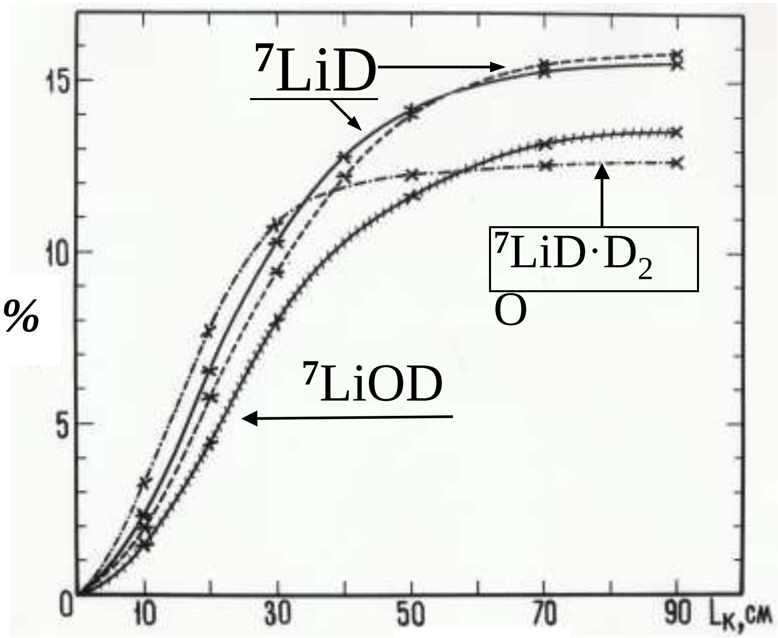
Number of neutrons captured out of the Pb-target (**1.397**) and Bi-target (**1.349**) are close.

EFFICIENCY OF THE LI-8 CREATION IN THE SCHEME OF THE TANDEM OF THE CONVERTER AND ACCELERATOR PLUS W, Pb, Bi-TARGET

	W-target	**Pb-target**	**Bi-target**
Efficiency of Li-8 creation (**per neutron**)	(0.2702 of Li-8 nuclei) / 1.008 neutrons = **0.268**	(0.3634 of Li-8 nuclei) / 1.397 neutrons = **0.260**	(0.3620 of Li-8 nuclei) / 1.348 neutrons = **0.268**
Efficiency of Li-8 creation (***per proton***) (200 MeV)	(0.2702 of Li-8 nuclei) / 1 proton = **0.270**	(0.3634 of Li-8 nuclei) / 1 proton = **0.363**	(0,3620 of Li-8 nuclei) / 1 proton = **0.362**

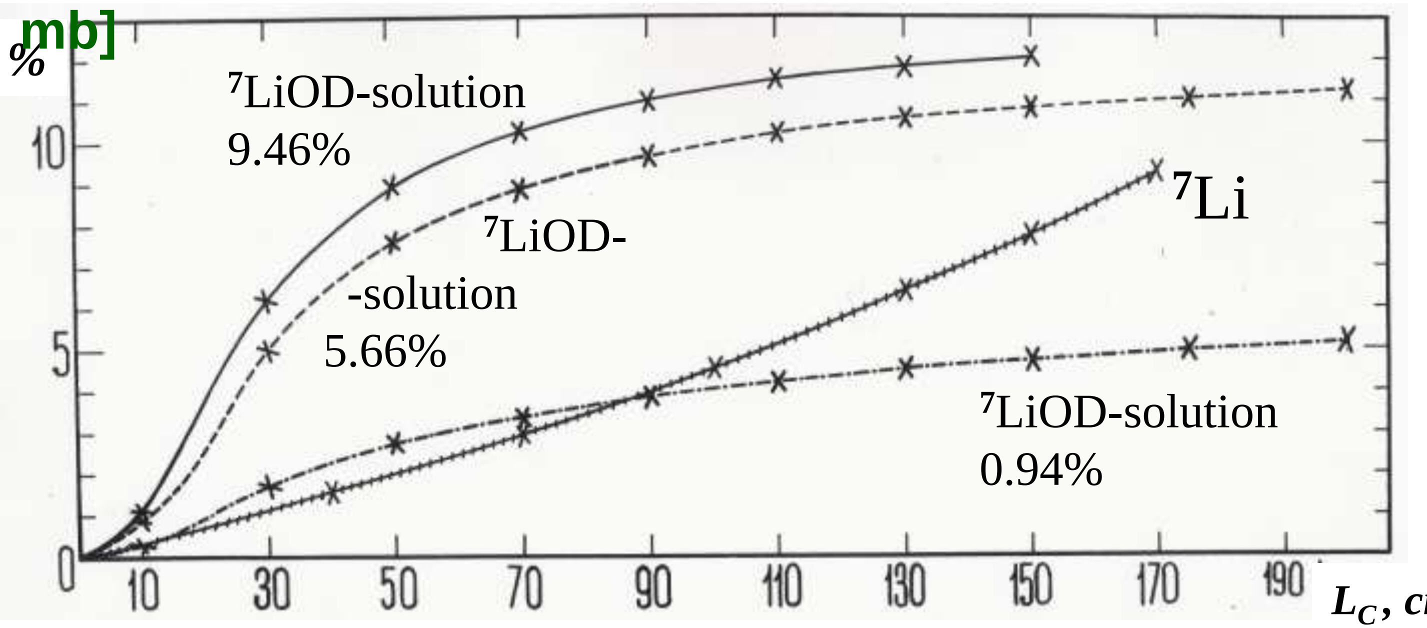
1. Normalization per neutron give the close efficiencies that indicates on similar neutron spectra in the converter for considered heavy targets.
2. Neutron flux analysis significantly corrects the choice of the target.

DEPENDANCE of EFFICIENCY *k* from the THICKNESS L_C of the CONVERETER for DIFFERENT CONVERTER SUBSTANCES (^{7}Li purity – 99.99%)



for the thermal group:

[$\sigma_\alpha(^7Li)$=45 mb] »[σ_α(D)=0.52 mb] >[$\sigma_\alpha(_8O)$=0.19 mb]



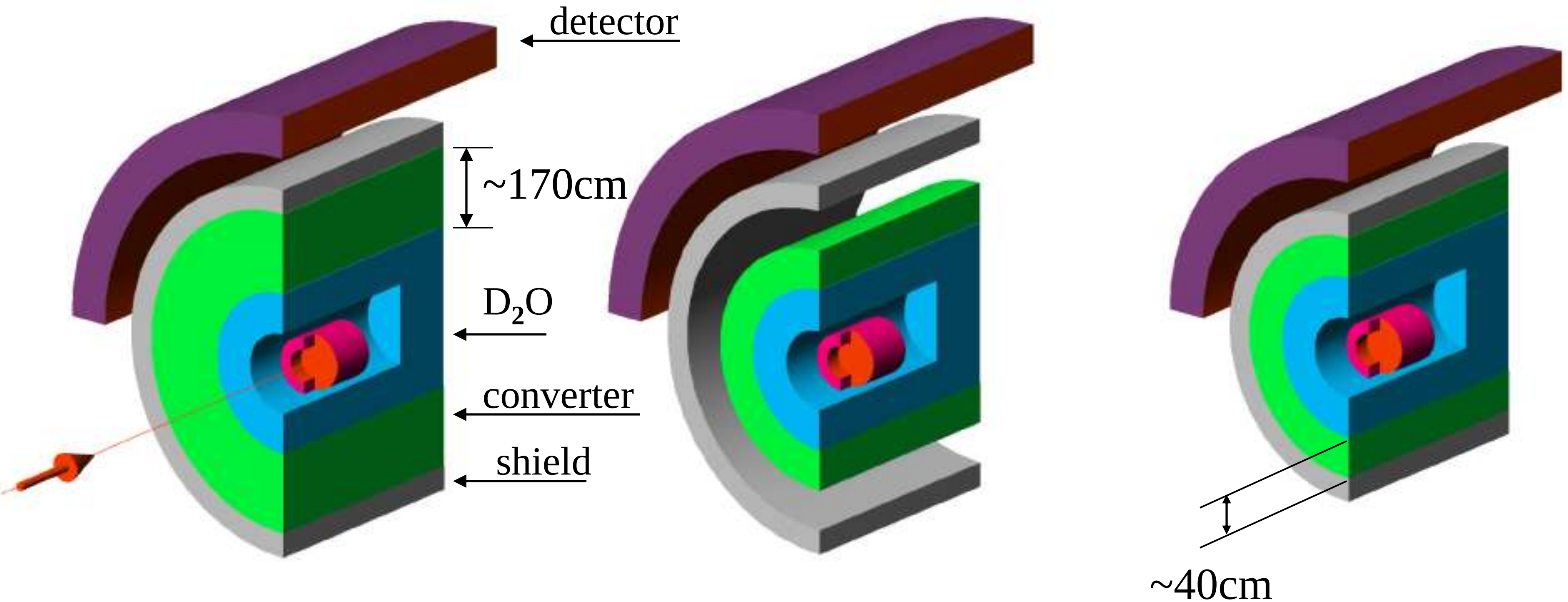
(for the Peak Reactor Geometry)

2. Lithium Antineutrino Source in the Cylindrical Geometry. The Possible Matter of the Converter

Converter: LiOD-solution

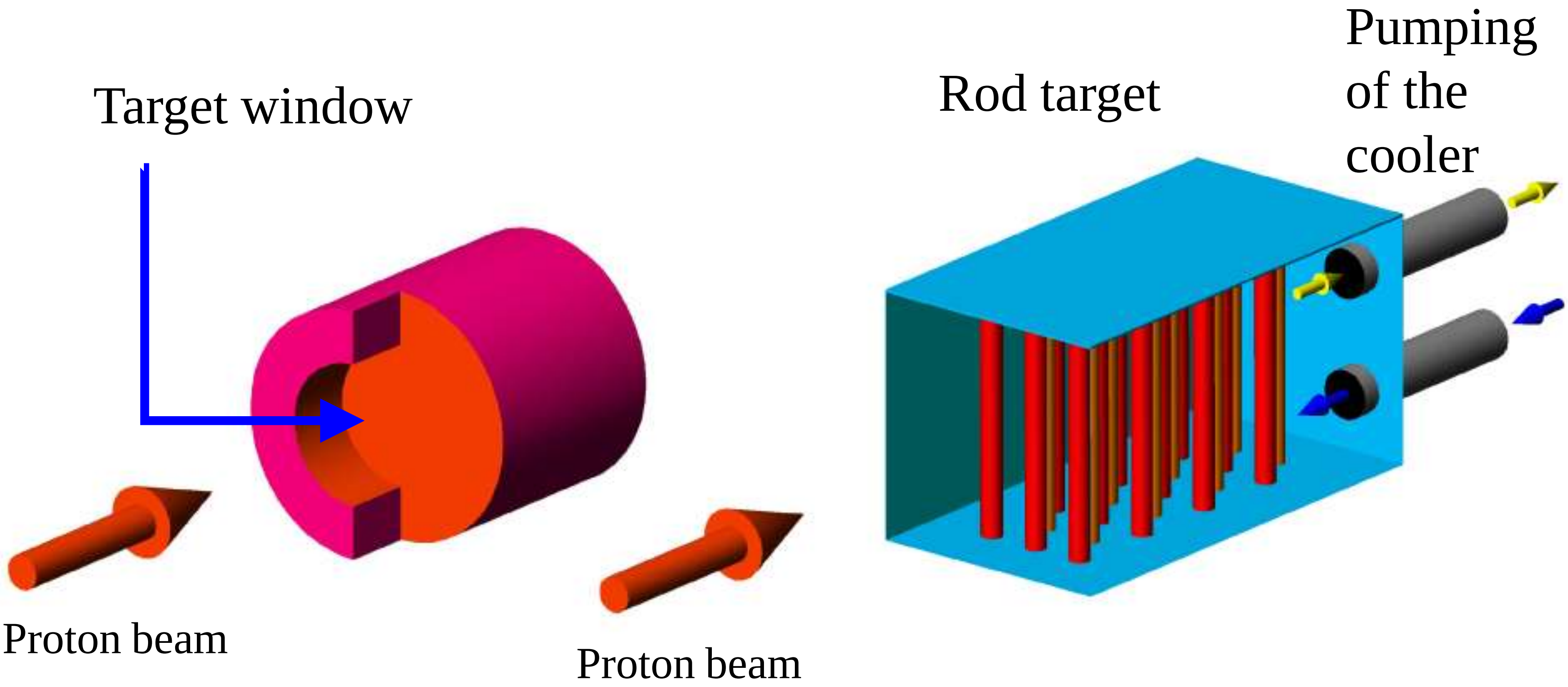
Converter: LiD

Converter: LiD

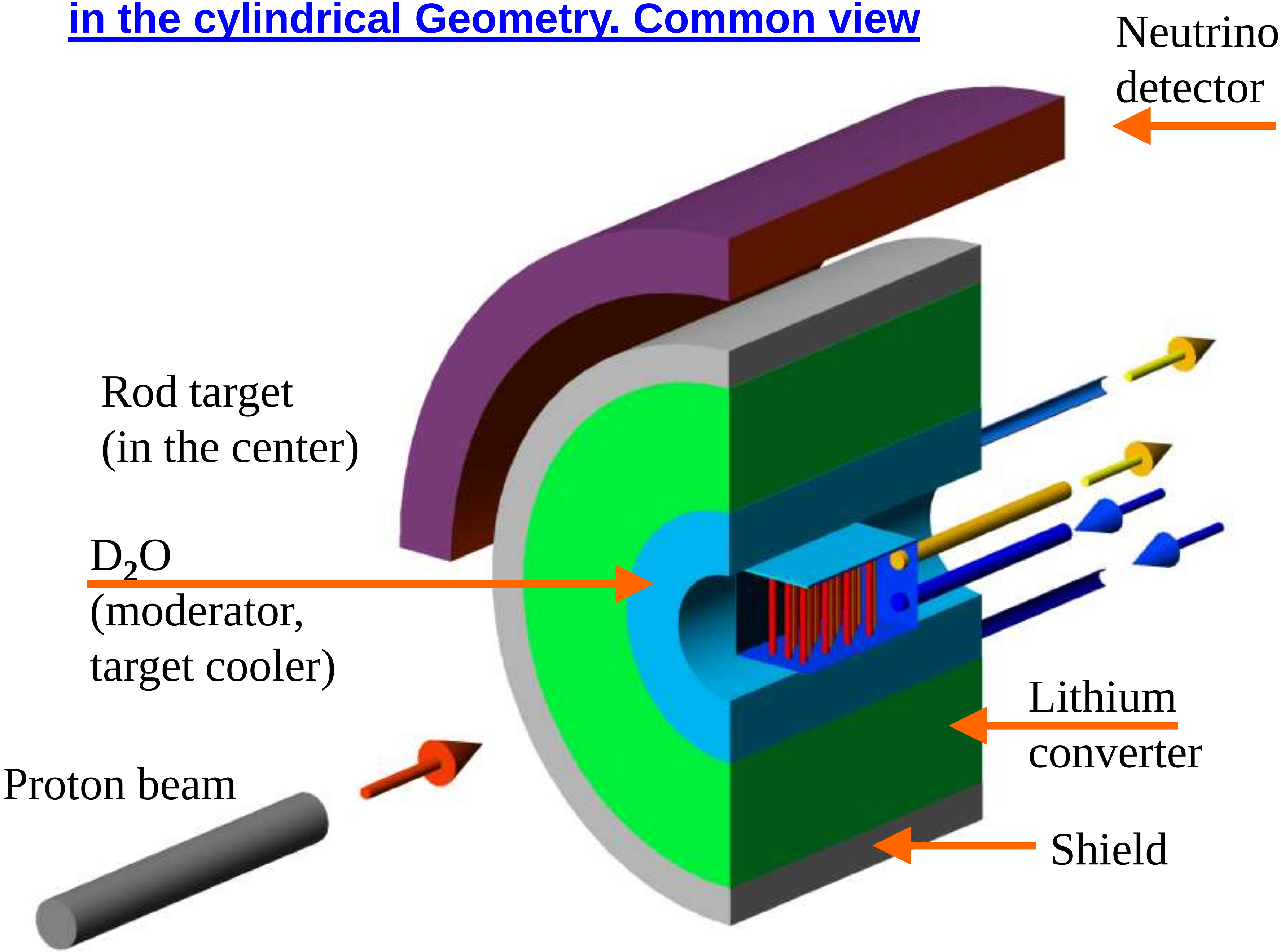


Use of converter substances with more high efficiency ***k*** allows to significantly decrease the dimension of the installation (about two times for k = 10-11% at ^{7}Li purity – 99.99%).

3. Lithium Antineutrino Source in the Cylindrical Geometry. Target realization



4. Lithium Antineutrino Source in the cylindrical Geometry. Common view



International Project of Lithium Antineutrino Source

PRL **109,** 141802 (2012) PHYSICAL REVIEW LETTERS week ending 5 OCTOBER 2012

Proposal for an Electron Antineutrino Disappearance Search Using High-Rate ^{8}Li Production and Decay

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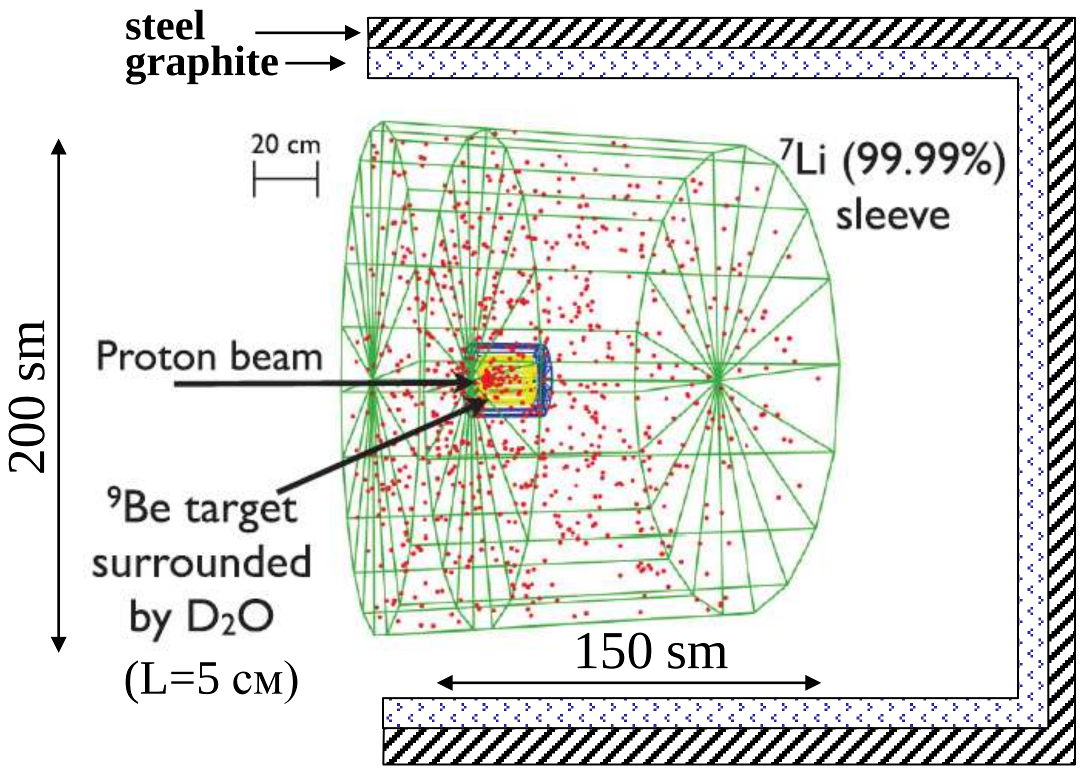
This paper introduces an experimental probe of the sterile neutrino with a novel, high-intensity source of electron antineutrinos from the production and subsequent decay of ^{8}Li. When paired with an existing ~1 kton scintillator-based detector, this $\langle E_\nu \rangle = 6.4$ MeV source opens a wide range of possible searches for beyond standard model physics via studies of the inverse beta decay interaction $\bar{\nu}_e + p \rightarrow e^+ + n$. In particular, the experimental design described here has unprecedented sensitivity to $\bar{\nu}_e$ disappearance at $\Delta m^2 \sim 1$ eV^2 and features the ability to distinguish between the existence of zero, one, and two sterile neutrinos.

Scheme of the Installation with Lithium Converter (named as IsoDAR – Isotope Decay At Rest). The expected parameters



experimental parameters. We note that the geometry design is similar to that described in Ref. [10].

[10] Yu. S. Lutostansky and V. I. Lyashuk, Bull. Russ. Acad. Sci., Phys. **75**, 468 (2011).

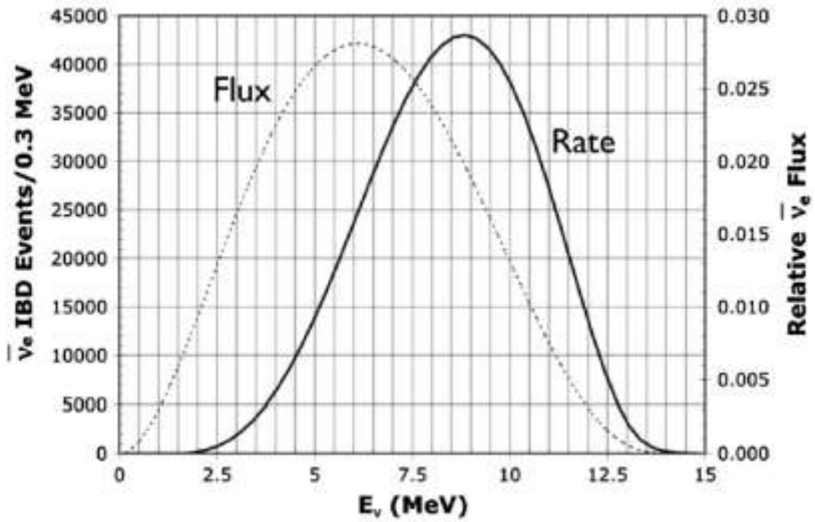
Lithium antineutrino source **IsoDAR**
(Isotope Decay-At-Rest)

Ep = 60 MeV, I=10 mA
-W = 600 kW
- Work cycle (time) – 90%
-Duration of the experiment – 5 years (in fact – 4.5 years)

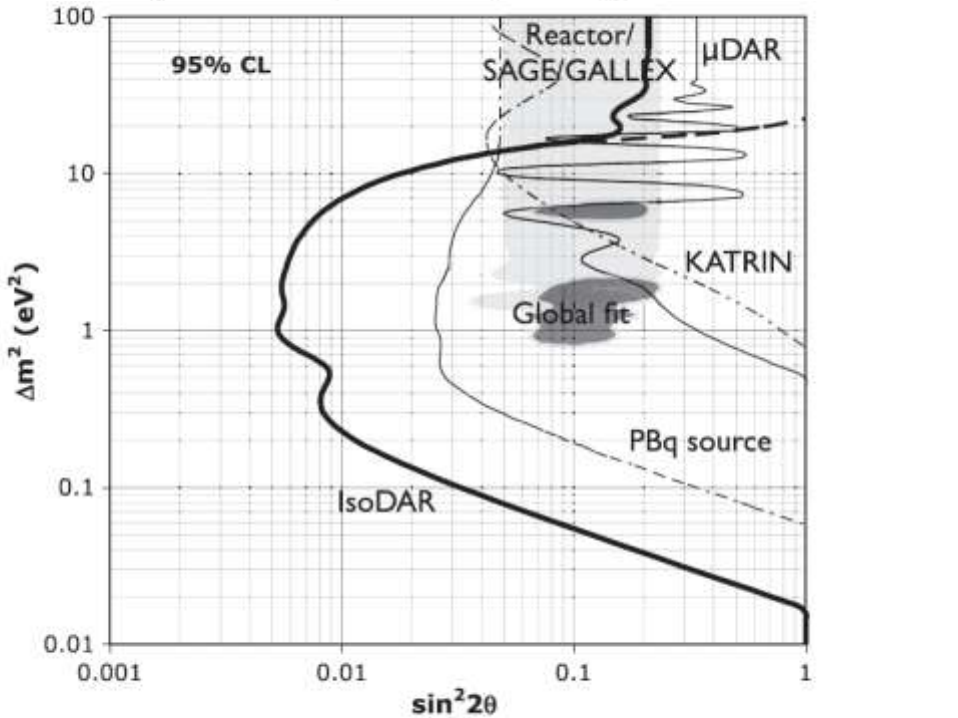
- Yield - 14.6 $\bar{\nu}_e$ /1000 protons
  (Efficiency = 1.46%)
- For 5 years of work - 10^{23} $\bar{\nu}_e$
- Detector - KamLAND
- Sensitive volume – 897 t
- Distance from the target the detector center – 16 m
- Expected statistic of the inverse beta decay (5 years) – 8.2 10^5 events (total) in the detector.
  ν_e- electrons events total 7200

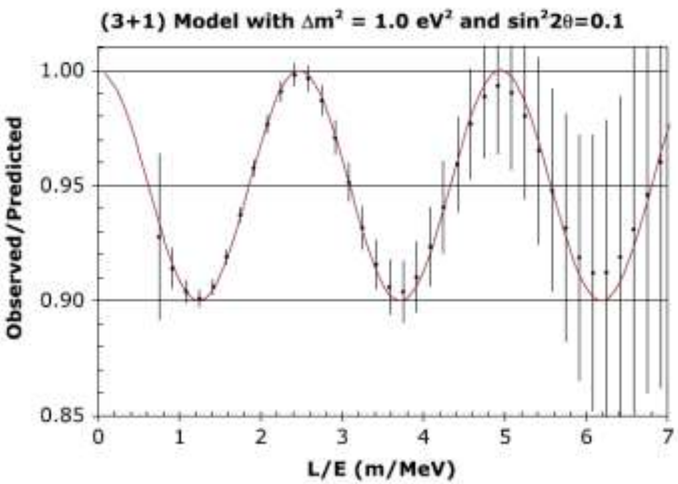
Моделирование для Установки IsoDAR

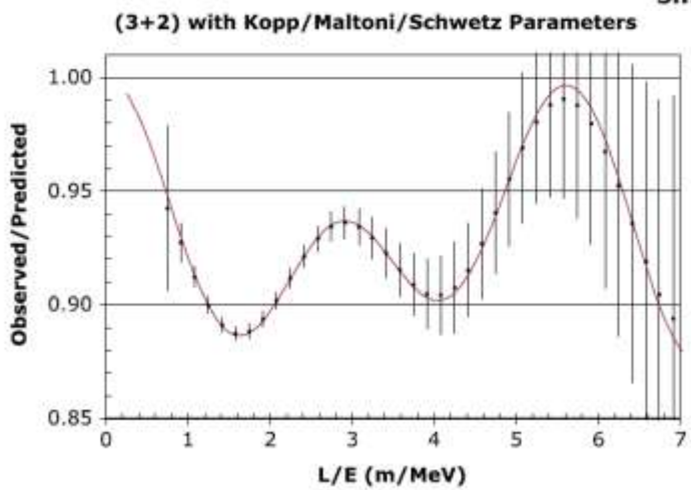
Чувствительность эксперимента через 5 лет. Сплошная линия – с учетом потока и скорости счета. Пунктир – с учетом потока. Указаны ограничения по μDAR, “реакторно-галлиевая ” разрешенная область, ожидаемая чувствительность для PBq источнику и эксперименту KATRIN.



Ожидаемый поток и скорость счета. $8.2 \cdot 10^5$ реконструированных событий от $1.29 \cdot 10^{23}$ литиевых антинейтрино за 5 лет проведения эксперимента.







L/E зависимость для модели осцилляций (3+1) [слева] и (3+2) [справа] с учетом возможного статистического разброса данных.

Perspectives, Risks and Price for IsoDAR project

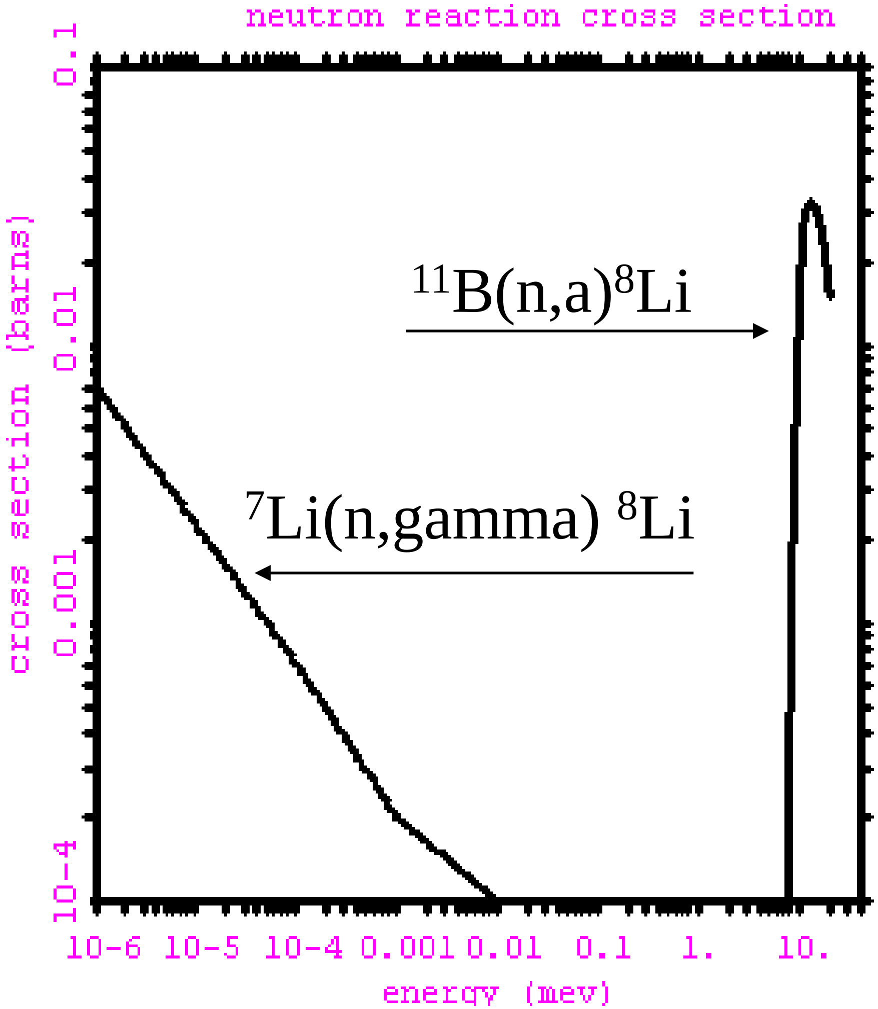
- **Cost: Good: $30M,** Moderate: $50M, *Bad: $100M or higher.*

Assessment

- Good
- Moderate
- Bad

	IsoDAR Base Design	RFQ/Separated Sector Cyclotron	LINAC, 30 MeV, 40 mA	Modified Beta Beam Design	New Detector at Existing Beam
1. Cost	Good	Moderate	Bad	Moderate	Bad
2. $\bar{\nu}_e$ rate	Good	Good	Good	Bad	Good
3. Backgrounds low	Good	Good	Good	Good	Moderate
4. Technical risk	Moderate	Moderate	Moderate	Moderate	Good
5. Compactness	Good	Moderate	Bad	Good	Moderate
6. Simplicity u'ground	Good	Moderate	Moderate	Bad	Moderate
7. Reliability	Good	Good	Good	Bad	Good
8. Value to other exps	Good	Good	Good	Bad	Bad
9. Value to Industry	Good	Moderate	Moderate	Bad	Bad

1. Neutrino Source on the base of 14-MeV Neutron Generator



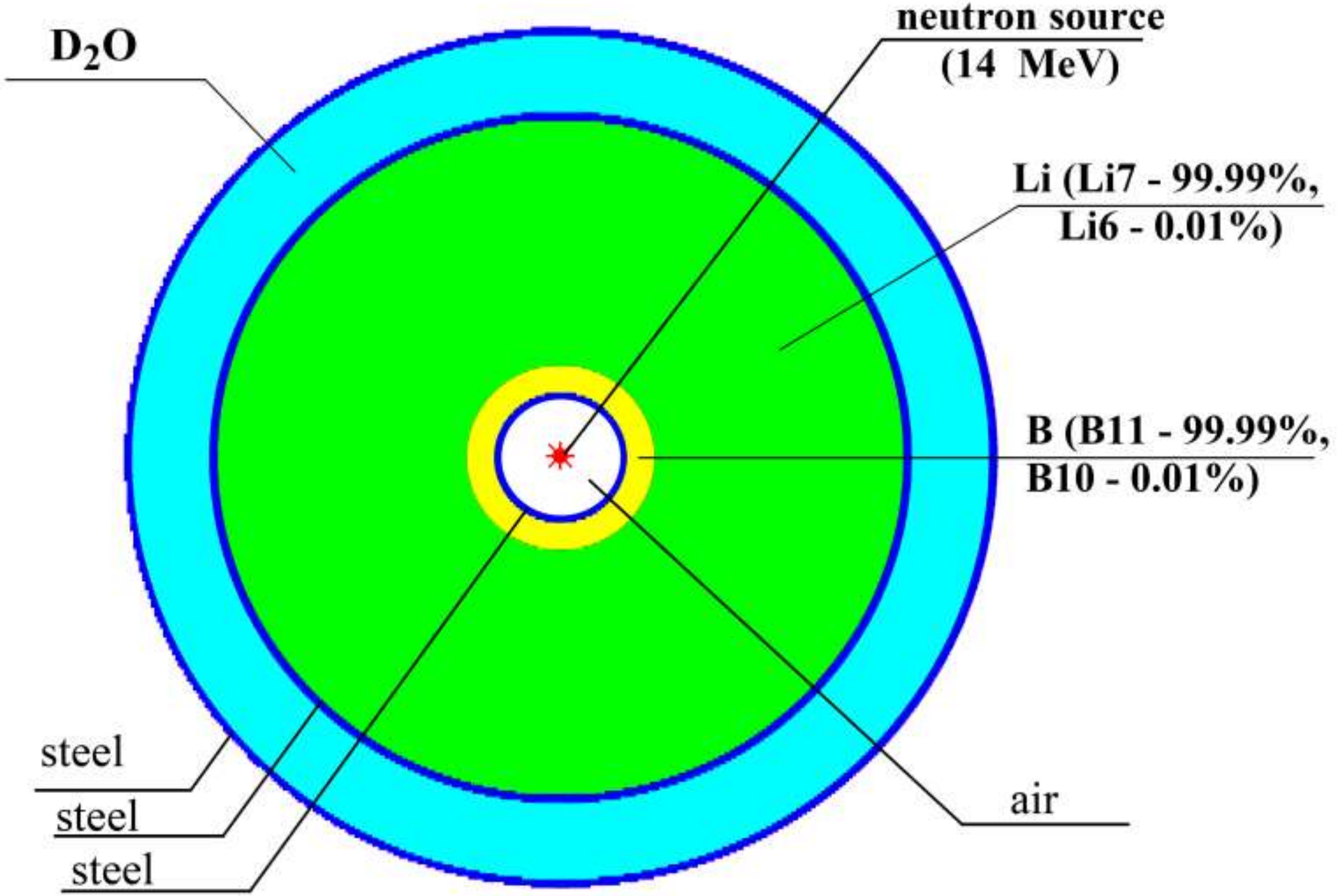
Idea: to use reaction $^{11}B(n,\alpha)^{8}Li$ in the fast part of the neutron spectra ($E_{threshold} \cong 7.4$ МэВ).

See:

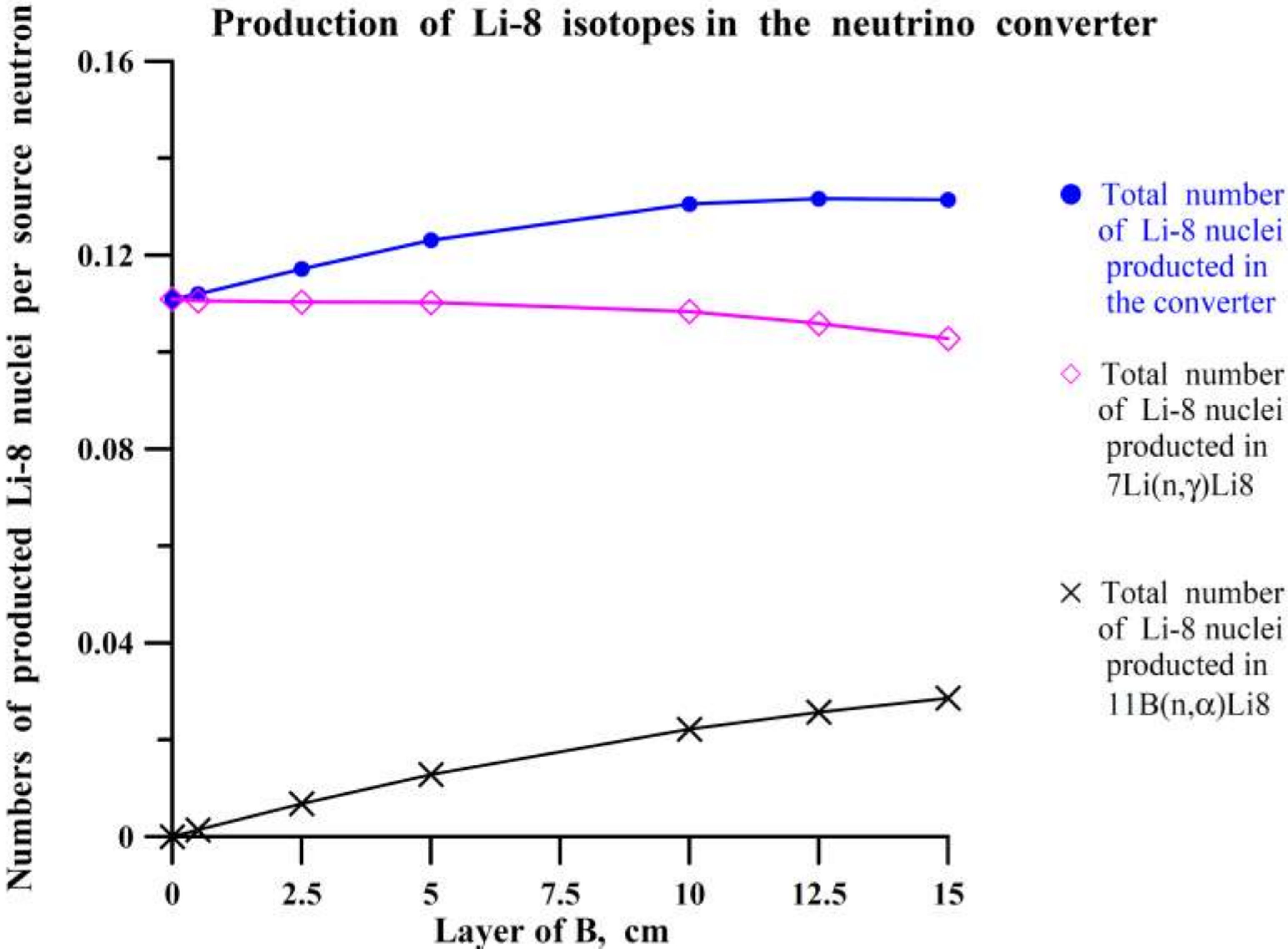
LiB-Neutron converter for Neutrino Source

(LiB-НЕЙТРОННЫЙ КОНВЕРТОР ДЛЯ НЕЙТРИННОГО ИСТОЧНИКА О. М. Горбаченко, В. Н. Кондратьев, Ю. С. Лютостанский, В. И. Ляшук ИЗВЕСТИЯ РАН. Сер ФИЗ., 2014, том 78, № 7, с. 832–836)

2. Neutrino Source
on the base of 14-MeV Neutron Generator.
Geometry of the Model



3. Neutrino Source
on the base of 14-MeV Neutron Generator



CONCLUSION

- It was developed schemes of the powerful neutrino source on the base of **^{7}Li (n,γ)-activation**.

-This source (lithium converter) can be constructed as in **the static as in the dynamic regime**. The converter **efficiency** (for different geometries) were calculated.

- It was obtained the **analytical expression** for neutrino fluxes from the source.

- Different types of matter were investigated for production of neutrino. The **most perspective is the ^{7}LiOD + $D_2$0 solution**.

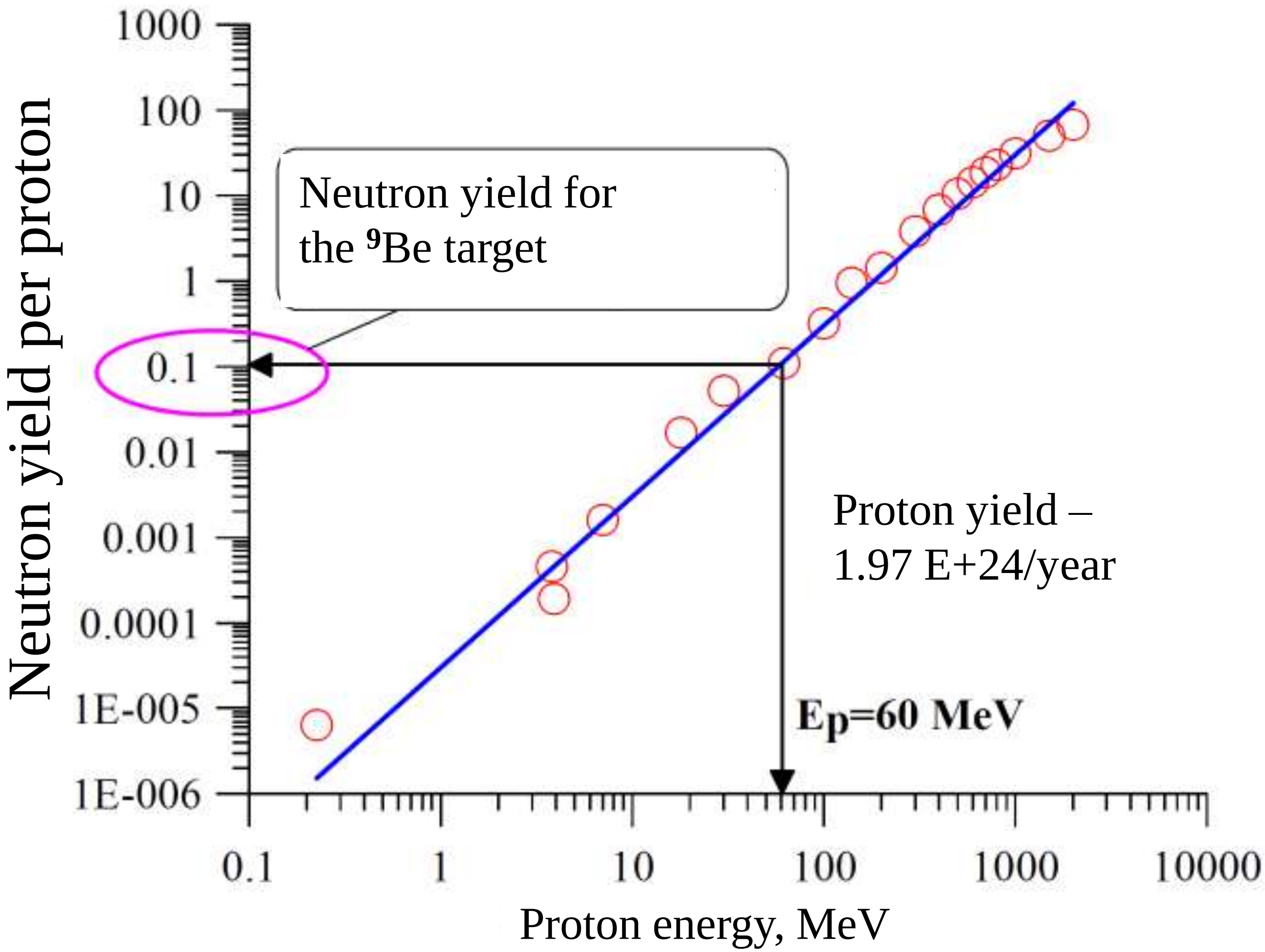
- The **proposed dynamic regime allows** to increase the hardness of the neutrino spectrum and **to vary the neutrino spectrum** for investigated reactions.

-It was considered and proposed **variants of neutrino converters** (neutrino factory) **on the base of different neutron sources**.

-The basic concepts for the proposed neutrino source on the base of lithium converter are included in the IsoDAR project

Thank you a lot !

Neutron Yield for IsoDAR Installation



- arXiv:1210.4454v1 [physics.acc-ph] 16 Oct 2012
- Yves Jongen, Thierry Delvigne, Pascal Cohilis, \Multi-milliampere compact cyclotrons used as neutron sources", Society of Photographic Instrumentation Engineers, Vol 2339, 225-235 (2011)
- R. Alba, M. Barbagallo, P. Boccaccio, A. Celentano, N. Colonna, G. Cosentino, A. Del Zoppo
-A Bungau et al. TARGET STUDIES FOR THE PRODUCTION OF LITHIUM8 FOR NEUTRINO PHYSICS USING A LOWENERGY CYCLOTRON (Proceedings of IPAC2012, New Orleans, Louisiana, USA)