Neutron Sources for Neutrino Factory on the Base of Lithium Converter

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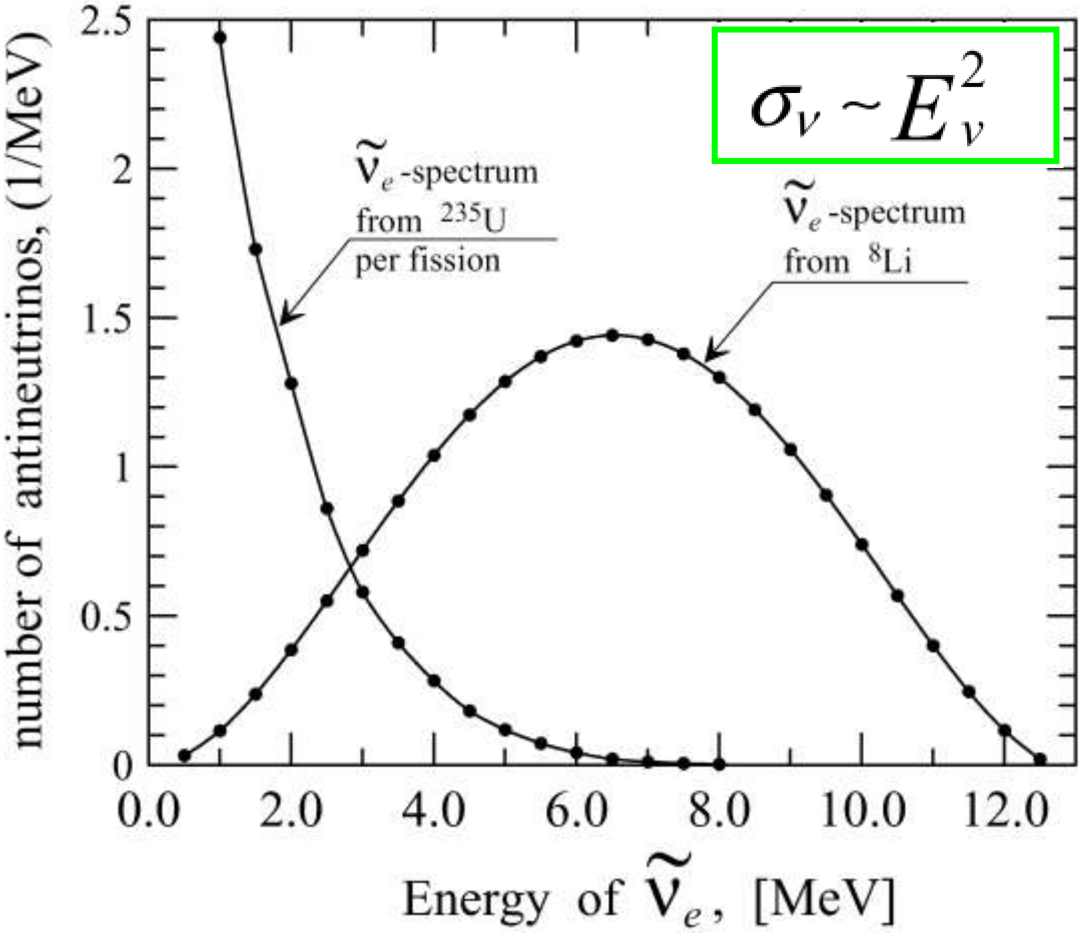
“Fundamental Interactions & Neutrons, Nuclear Structure, Ultracold Neutrons, Related To
Alushta, May 20-25, 2013

IDEA of the LITHIUM CONVERTER

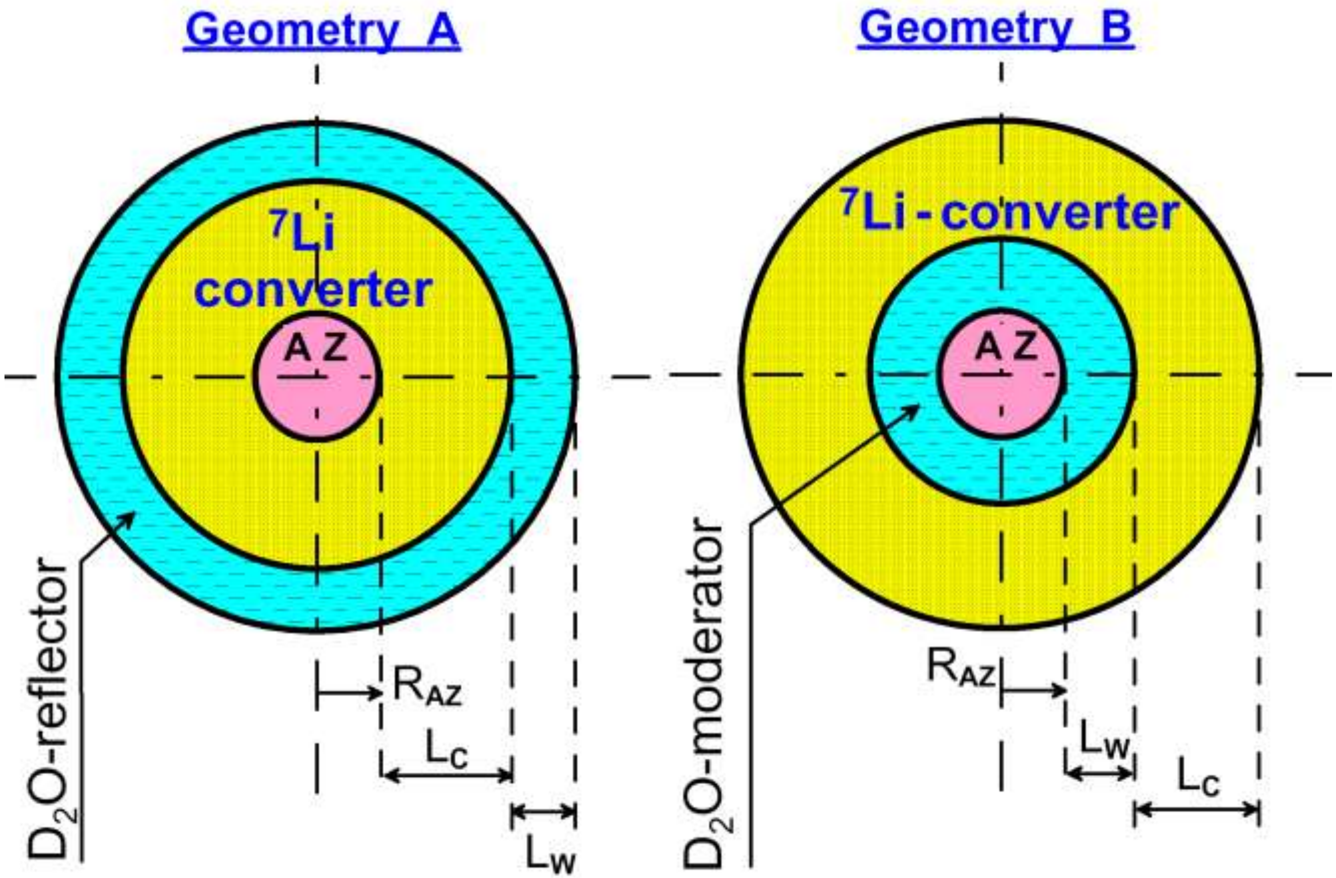
In earthly conditions the Sun, nuclear reactors and accelerators are exceptional on intensive neutrino fluxes. The solar neutrinos fluxes are estimated as $\approx 6.6 \cdot 10^{10}$ cm$^{-2}\cdot$s^{-1}. However, the energy of 98 % of all solar neutrinos does not exceed 0.86 MeV.



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 ^{7}Li for engineering of a reactor neutrons-to-antineutrino converter, which is located close by the active zone of a reactor.

The idea of neutrino source based on ^{8}Li decay originated with **L.A. Mikaelian, P.E. Spivak and V.G.Tsinoev.**

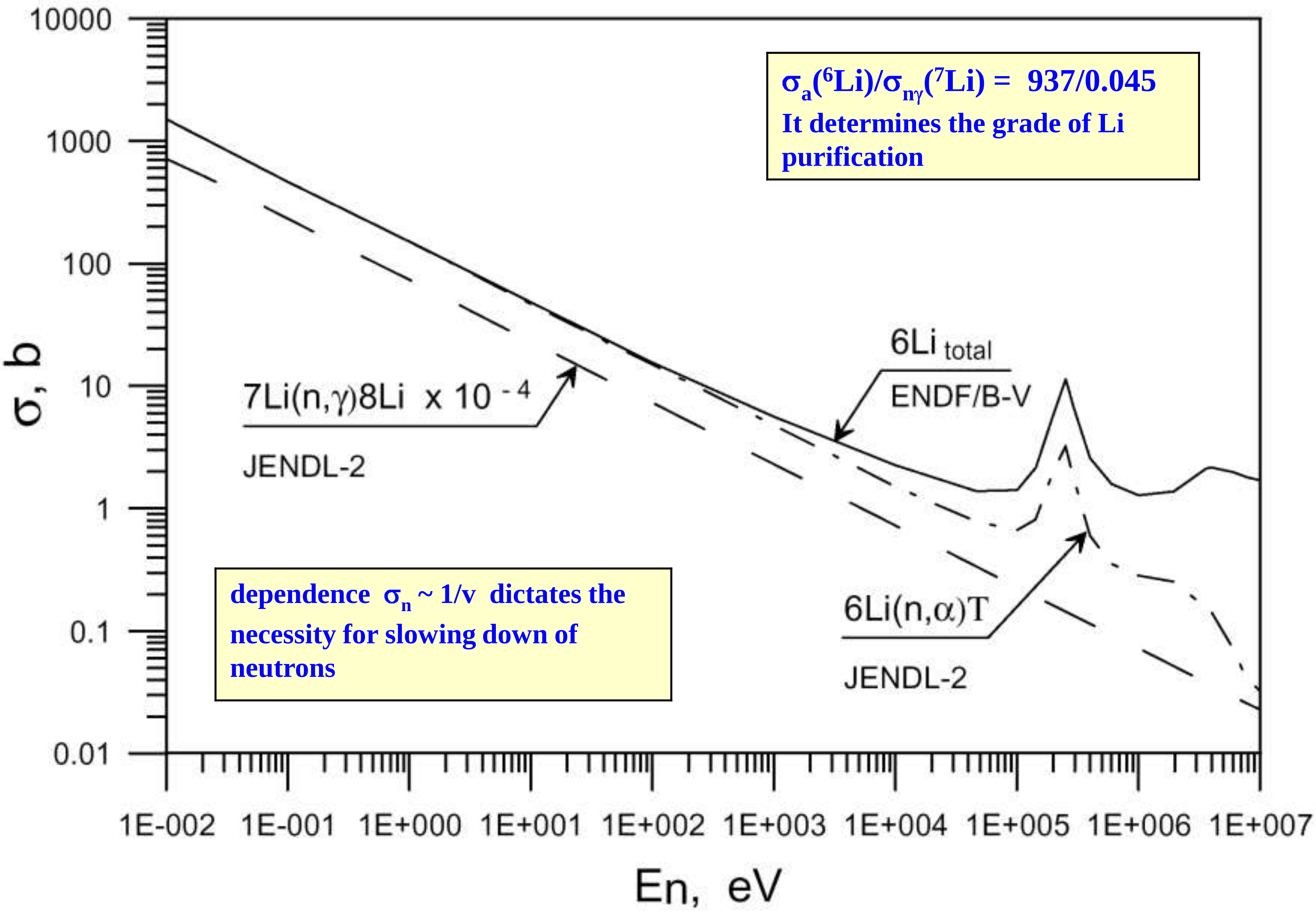
STATIC REGIME of the OPERATION



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**.

NEUTRON CROSS SECTION for ^{6}Li and ^{7}Li

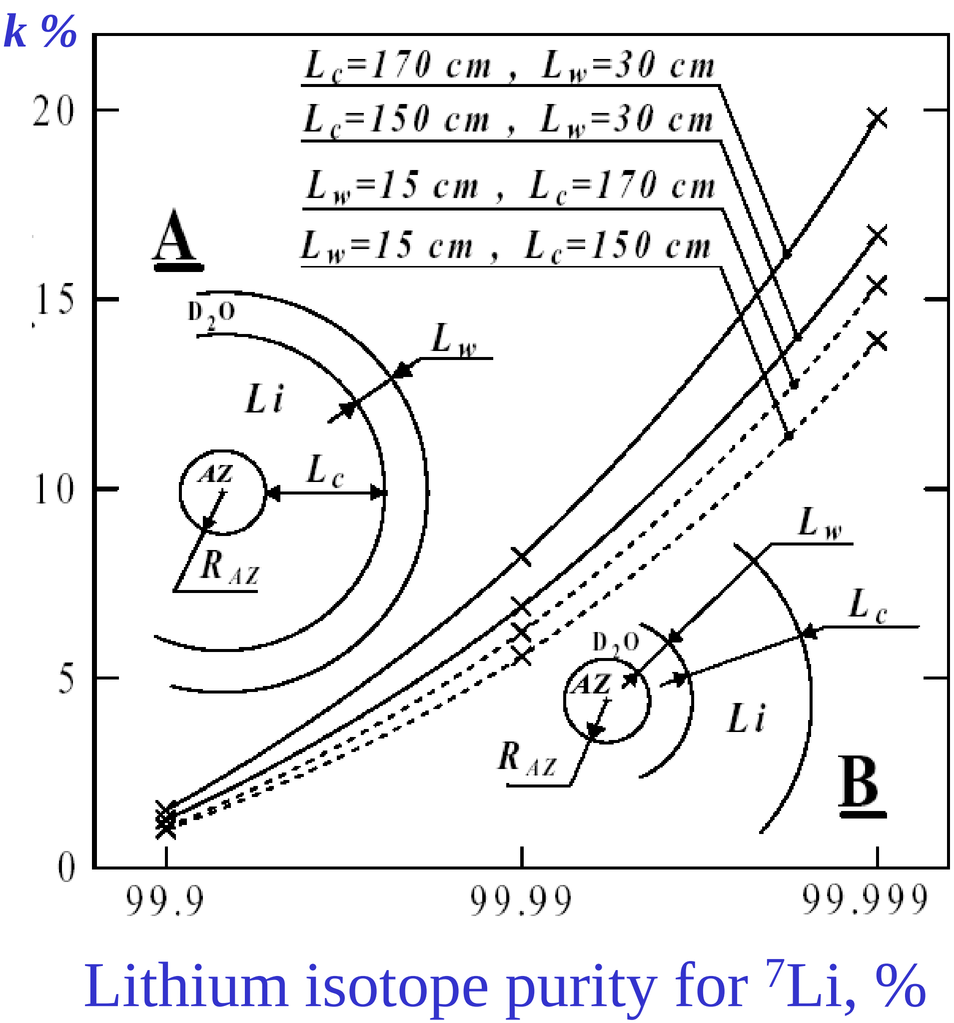


$\sigma_a(^{6}\text{Li})/\sigma_{n\gamma}(^{7}\text{Li}) = 937/0.045$

It determines the grade of Li purification

dependence $\sigma_n \sim 1/v$ dictates the necessity for slowing down of neutrons

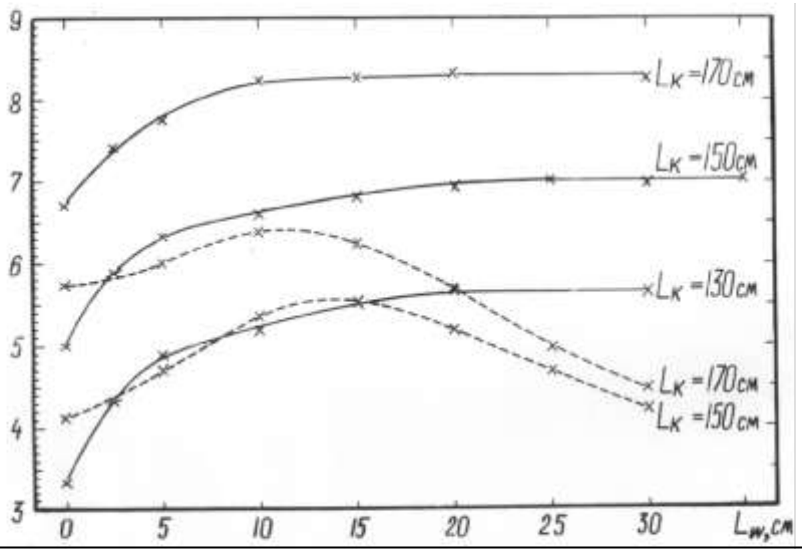
DEPENDANCE of EFFICIENCY k from the ^{7}Li PURITY



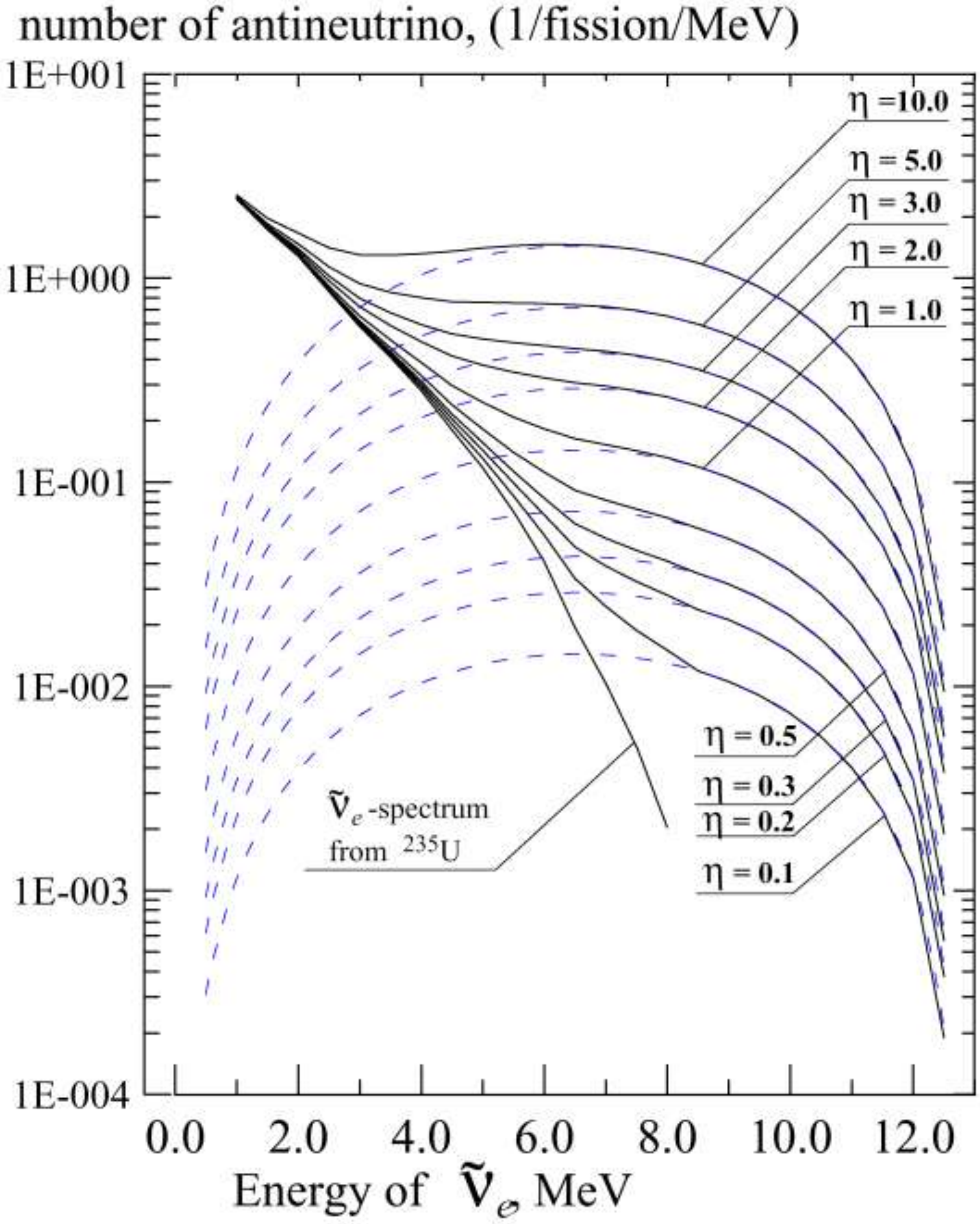
Dependance of the converter efficiency *k* from the ^{7}Li-purity for A-geometry (solid line) and B-geometry (dotted line) in case of different thickness of the converter L_c and for different D_2O thickness L_W.

Contents of ^{7}Li in the nature lithium is 92,41%.

Dependence of the converter efficiency *k(%)* on D_2O layer thickness in geometry A (solid line) and B (dotted line) for converter thickness L_c and Active Zone of the reactor PIC.



SUMMARY ANTINEUTRINO SPECTRUM



Antineutrino spectrum:

1) from ^{235}U,

2) summary antineutrino spectrum from the active zone and lithium converter for different values of the converter efficiency,

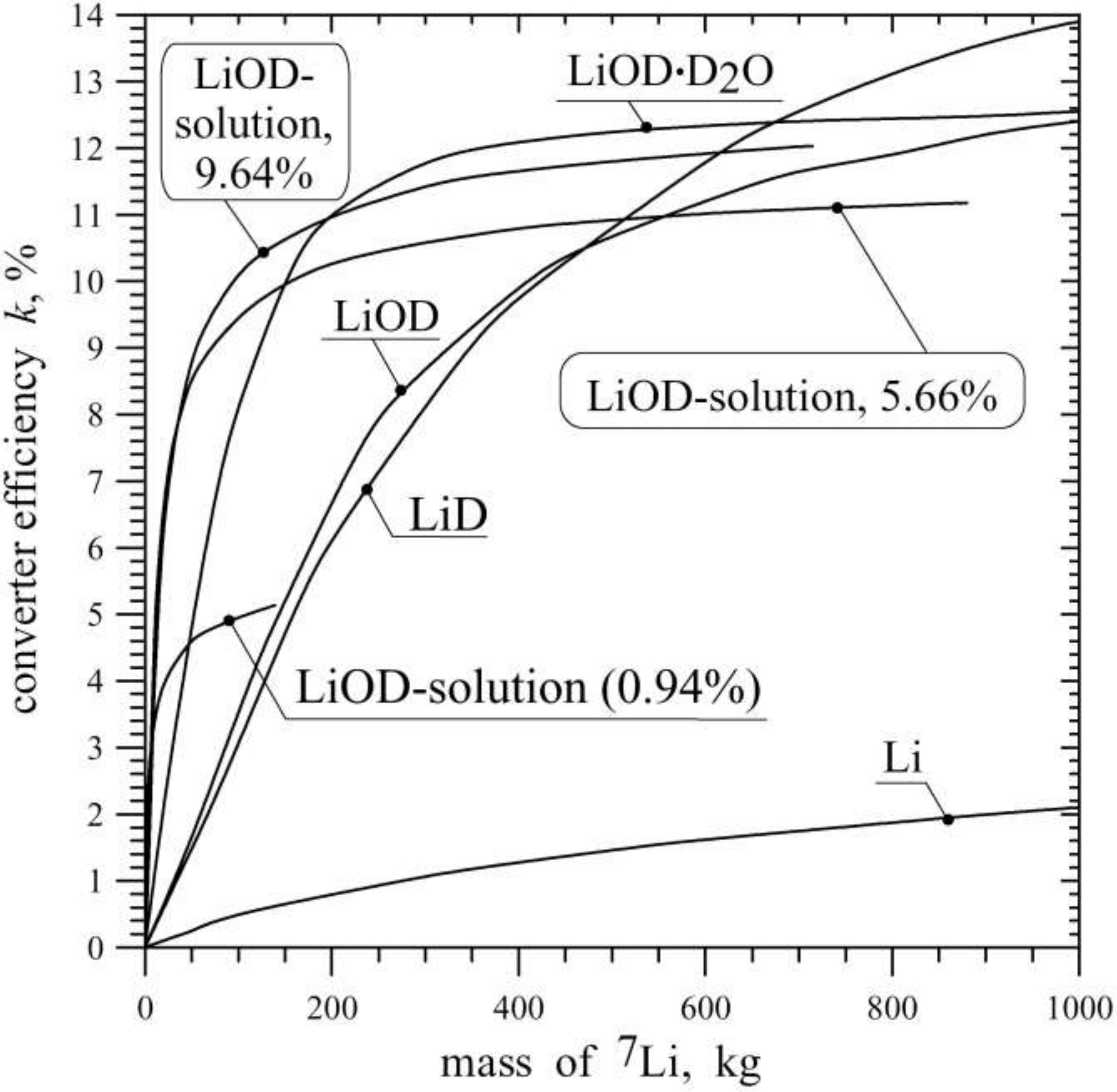
3) neutrino spectrum from the converter (dotted line) for different converter efficiency.

CHOISE of CONVETER MATTER

CONVERTER MATERIAL	DENCITY (g/cm^2)	TEMPERATURE OF MELTING ($t\ ^0C$)	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
$^7LiOD \cdot D_2O$ – monohydrate of lithium hydroxide	1.965	>600 (for $LiOH \cdot H_2O$)	115
^{7}LiOD–heavy water solution (6%)	~1.1	-	70

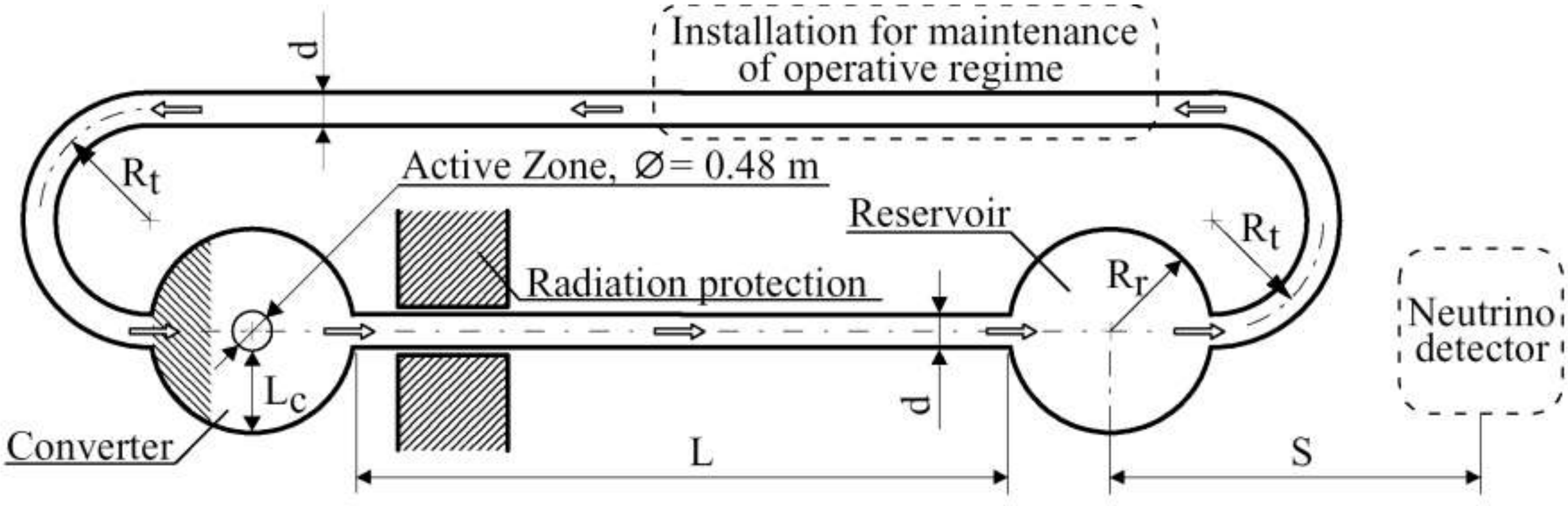
To increase the converter efficiency by increasing the purity of ^{7}Li to not less than 99.999% value is difficult. The solution is to use not pure ^{7}Li isotope as the converter material, but its chemical compositions, for example the perspective matter is a heavy water solution of lithium hydroxide $LiOD$, $LiOD \cdot D_2O$ and LiD [1,6]. 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.

CHOISE of CONVETER MATTER (2)



Dependence of converter efficiency ***k*** on lithium mass m_{Li} for different chemical compositions and heavy water solution of LiOD (with LiOD concentration 0.94, 5.66 and 9.64%).

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 [10]: liquid lithium 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 -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 $\kappa \cong 0.077$ 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

FLUXES of LITHIUM ANTINEUTRINO

Let V_c - converter volume, V_0 - volume of a whole system, w - volume being pumped over in a time unit (flow rate, i.e. circulation rate), then $t_p = V_c / w$ - time of pumping over of converter volume. In a converter we shall allocate some spherical segment with a volume V_s and with a plane of the basis perpendicular to the axis of a delivery channel.

It was obtained integral flux of lithium antineutrinos emited from this spherical segment for a time t :

$$N_S(t) = \frac{t}{t_S}\left(S_1 + \sum_{n=2}^{\infty} S_n\right) = \frac{t}{t_S}\left[S_1 + \frac{S_2}{\varphi(-\lambda_\beta V_0 / w)}\right],$$

where $N_7(t)$ and $N_8(t)$ - number of nucleus ^{7}Li and ^{8}Li at the moment t, $\lambda_{n,\gamma}$, λ_β - rate of (n,γ)-reaction and β^-- decay,

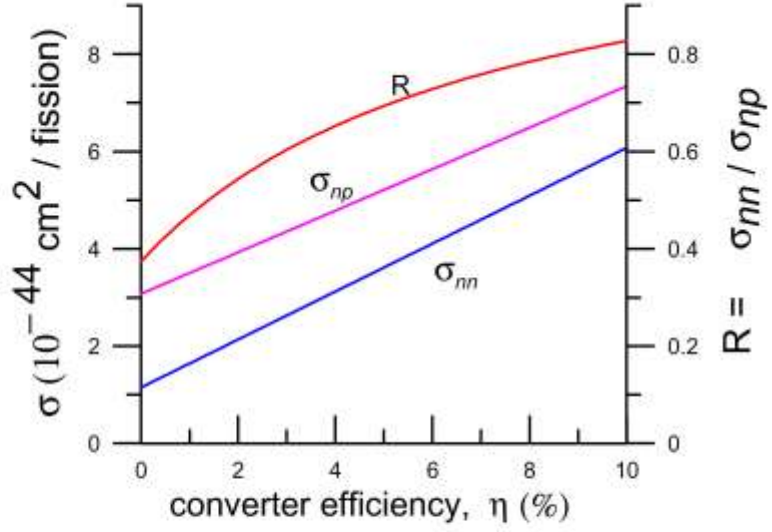
$$S_1 = N_7^0 - N_7(t_S) - N_8(t_S) = \lambda_{n,\gamma} N_7^0 t_S - (\lambda_{n,\gamma} N_7^0 / \lambda_\beta)\varphi(V_S),$$

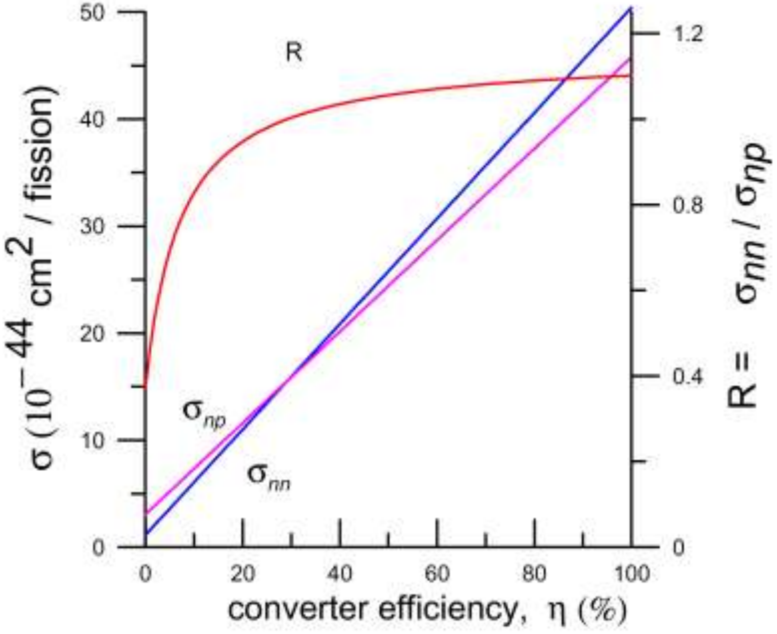
$$S_2 = \frac{\lambda_{n,\gamma} N_7^0}{\lambda_\beta}\varphi(V_C)\left\{\exp\left[-\lambda_\beta (V_0 - V_C)/w\right] - \exp\left[-\lambda_\beta (V_0 - V_C + w t_S)/w\right]\right\},$$

$$\varphi(y) = 1 - \exp(-\lambda_\beta y / w).$$

In the same way it was obtained the expression for the fluxes from the delivery channel and from the pumped reservoir.

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:__

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

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

$(\tilde{\nu}_e + d \to n + n + e^+)$ (σ_{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/$\tilde{\nu}_e$

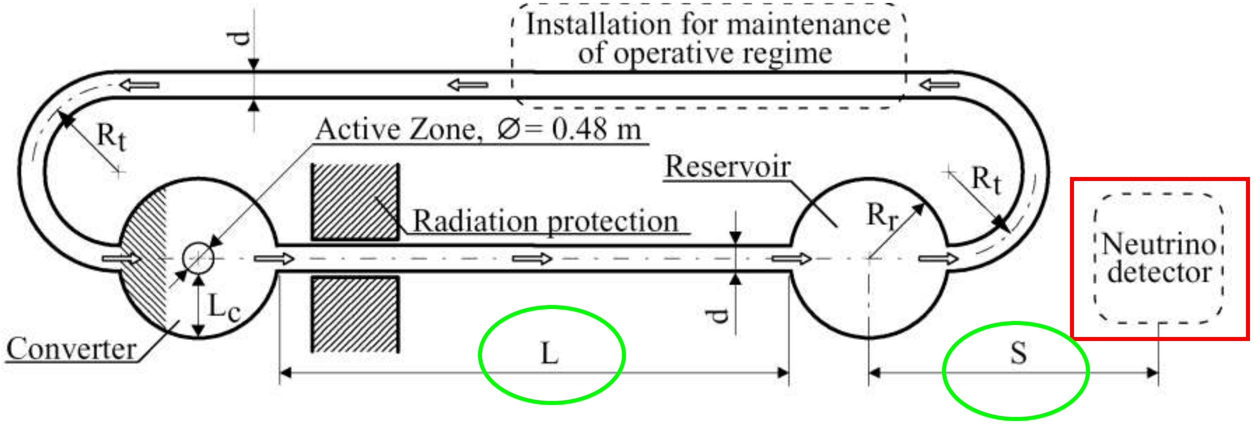
__Hard-spectrum lithium antineutrinos allow Increase cross section in several times.__

HARDNESS OF THE SUMMARY NEUTRINO SPECTRUM

Let $F_{Li}(\vec{r})$ and $F_{AZ}(\vec{r})$ - densities of lithium antineutrinos flux and antineutrino flux from the active zone, $\overline{n}_{\nu}=6.13\div6.14$ - number of reactor antineutrinos emited per one fission in the active zone. Let us consider that the hardness of the summary $\tilde{\nu}_e$- spectrum at the point $\vec{r}$ equals one unit of hardness if the ratio of densities $F_{Li}(\vec{r})/F_{AZ}(\vec{r})$ equals $1/\overline{n}_{\nu}$. Then in common case the hardness of a summary spectrum is defined as:

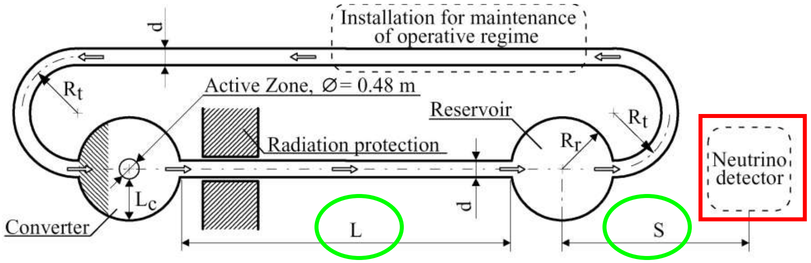
$$H(\vec{r})=\overline{n}_{\nu}\frac{F_{Li}(\vec{r})}{F_{AZ}(\vec{r})}$$

Having know hardness of the summary spectrum (purity of ^{7}Li, parameters of the installation, flow rate w (m3/s))



we can evaluate the expected neutrino cross section for the summary spectrum for this installation.

HARDNESS and EXPECTED CROSS SECTION (1)

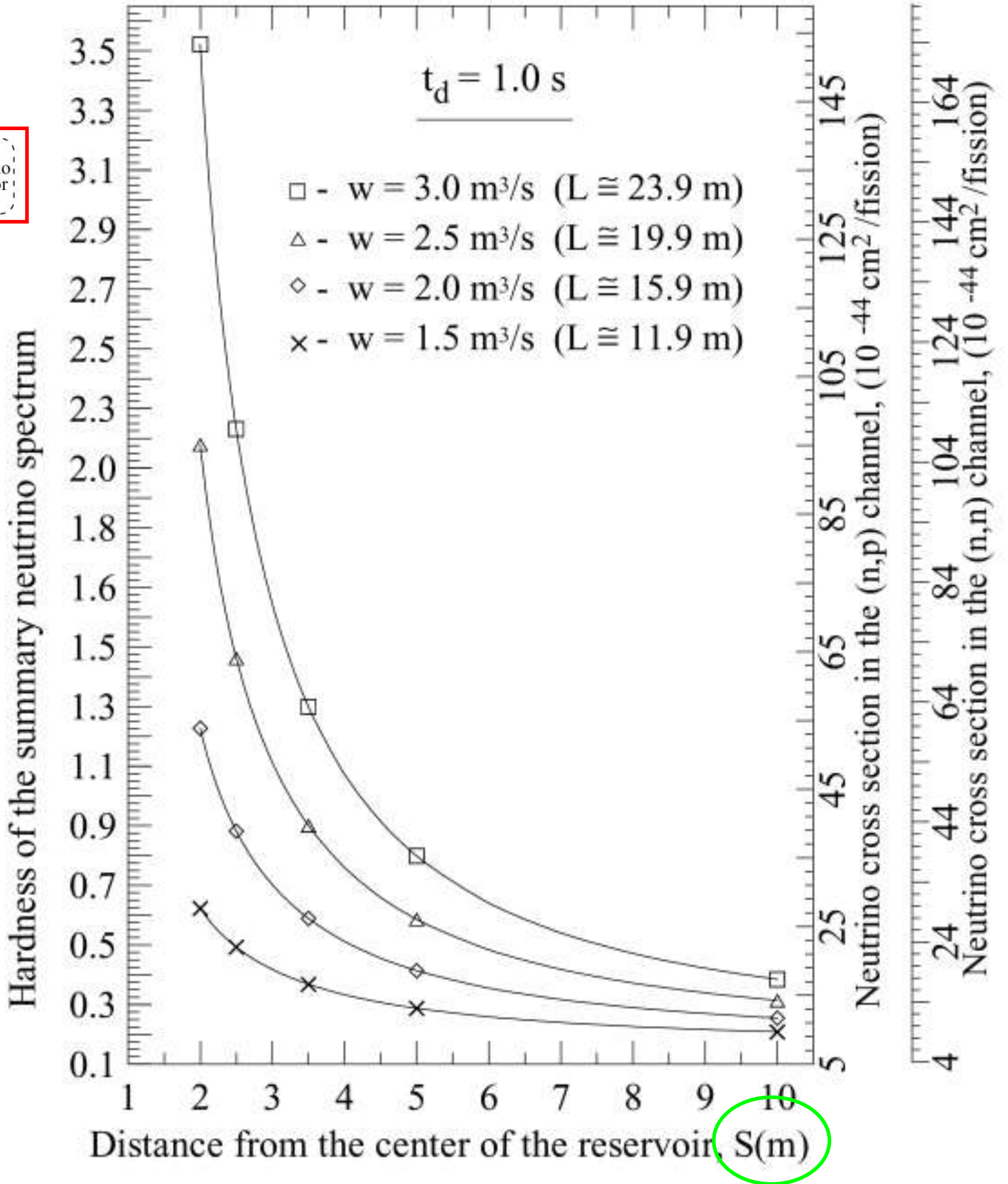


to set (Input data):

hardness of
the summary spectrum
(purity of ^{7}Li, parameters
of the installation,
flow rate w (m3/s))

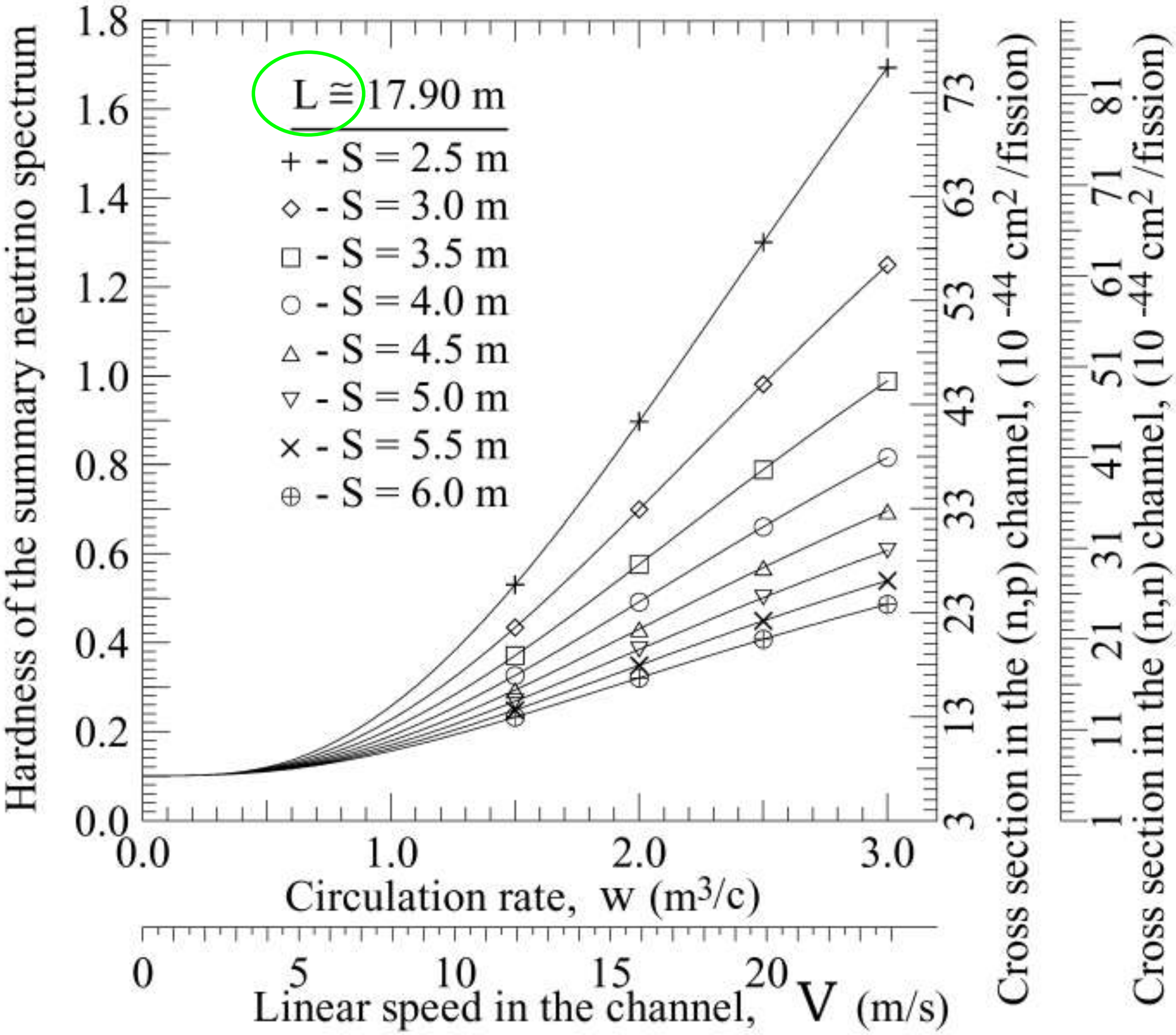
we obtaine (Output data):

hardness of the summary
spectrum, expected cross
sections

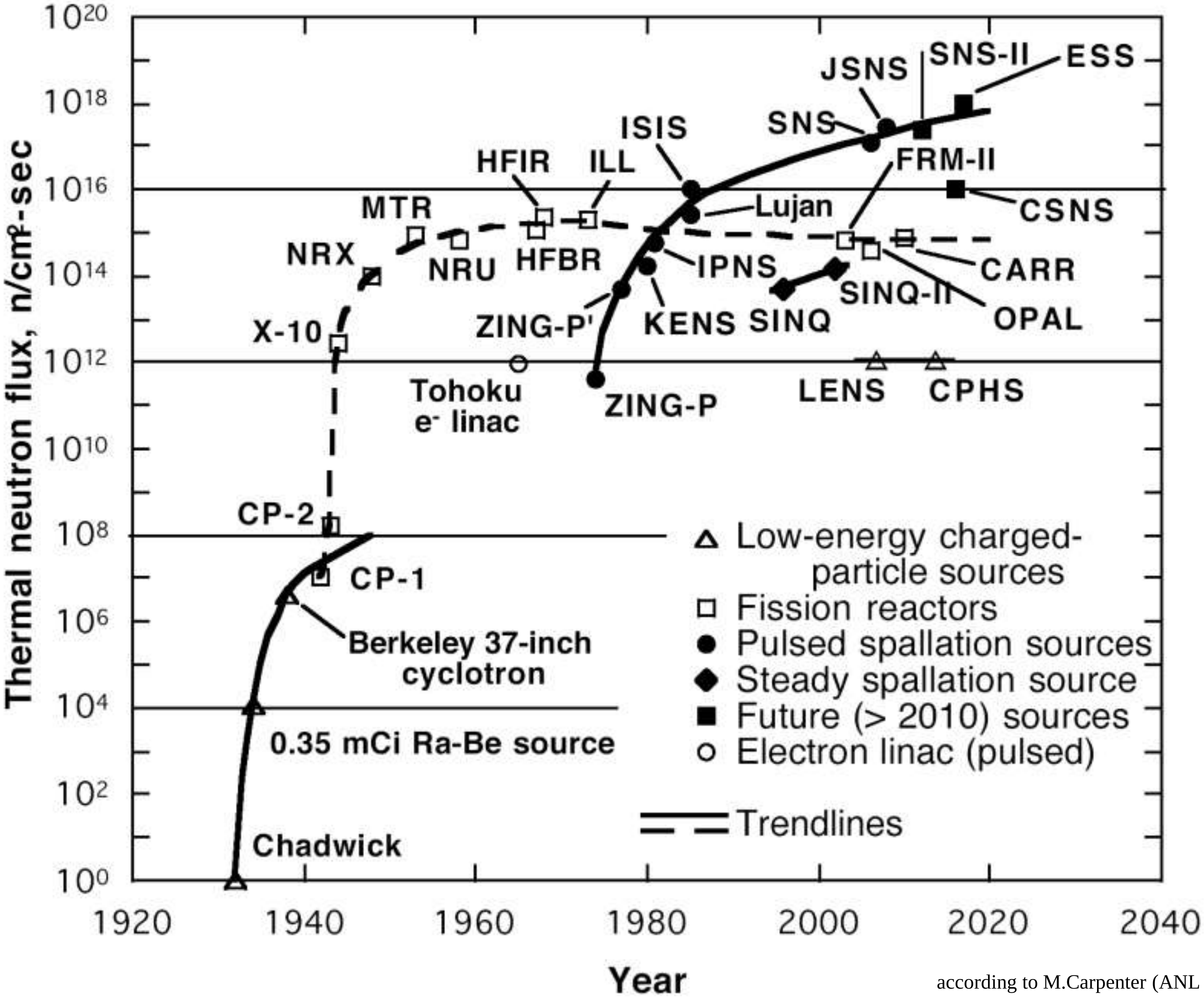


HARDNESS and EXPECTED CROSS SECTION (2)

Variation of neutrino cross section as function of the linear speed of pumping

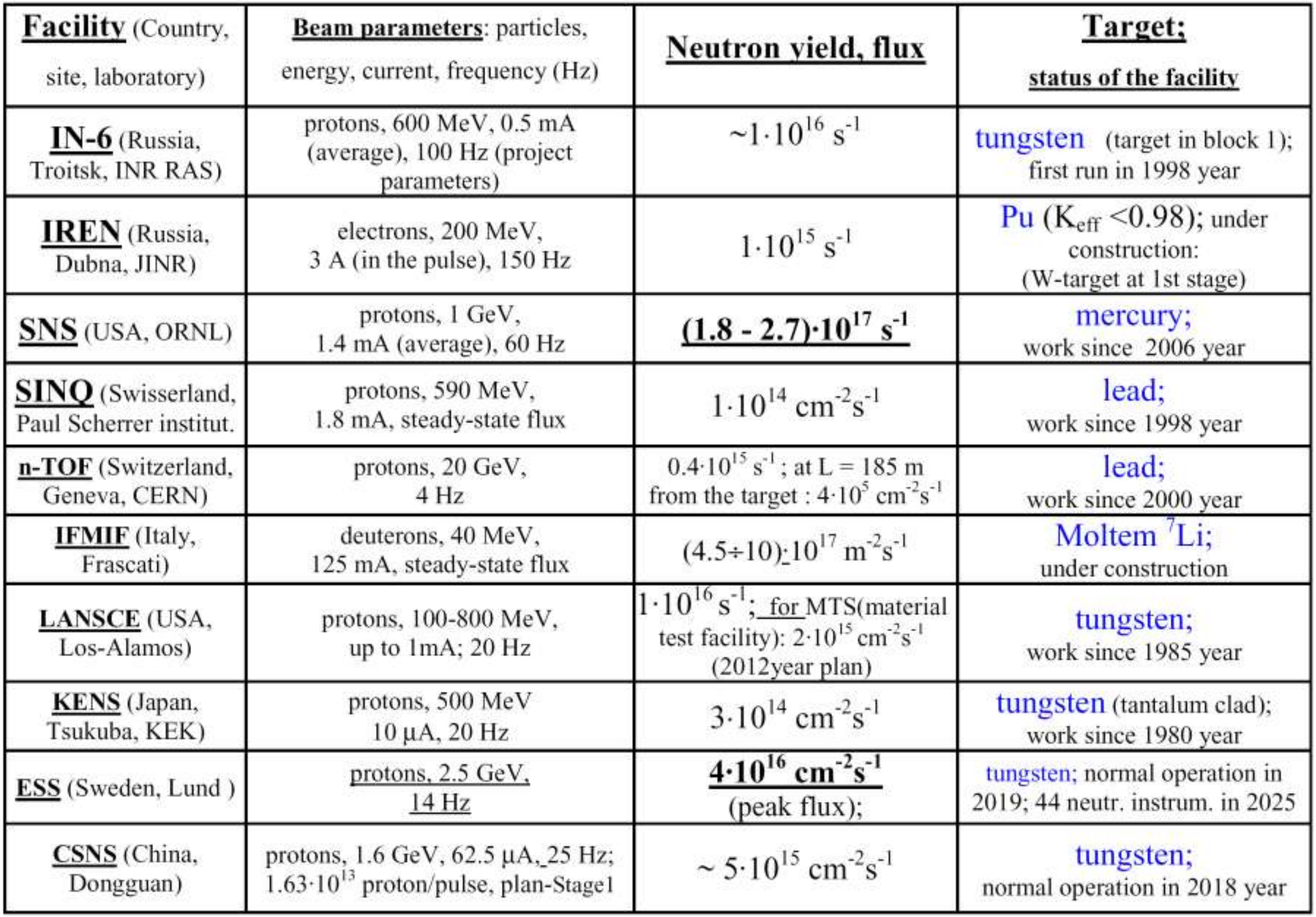


Neutron Sources (working and developing) (1)



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

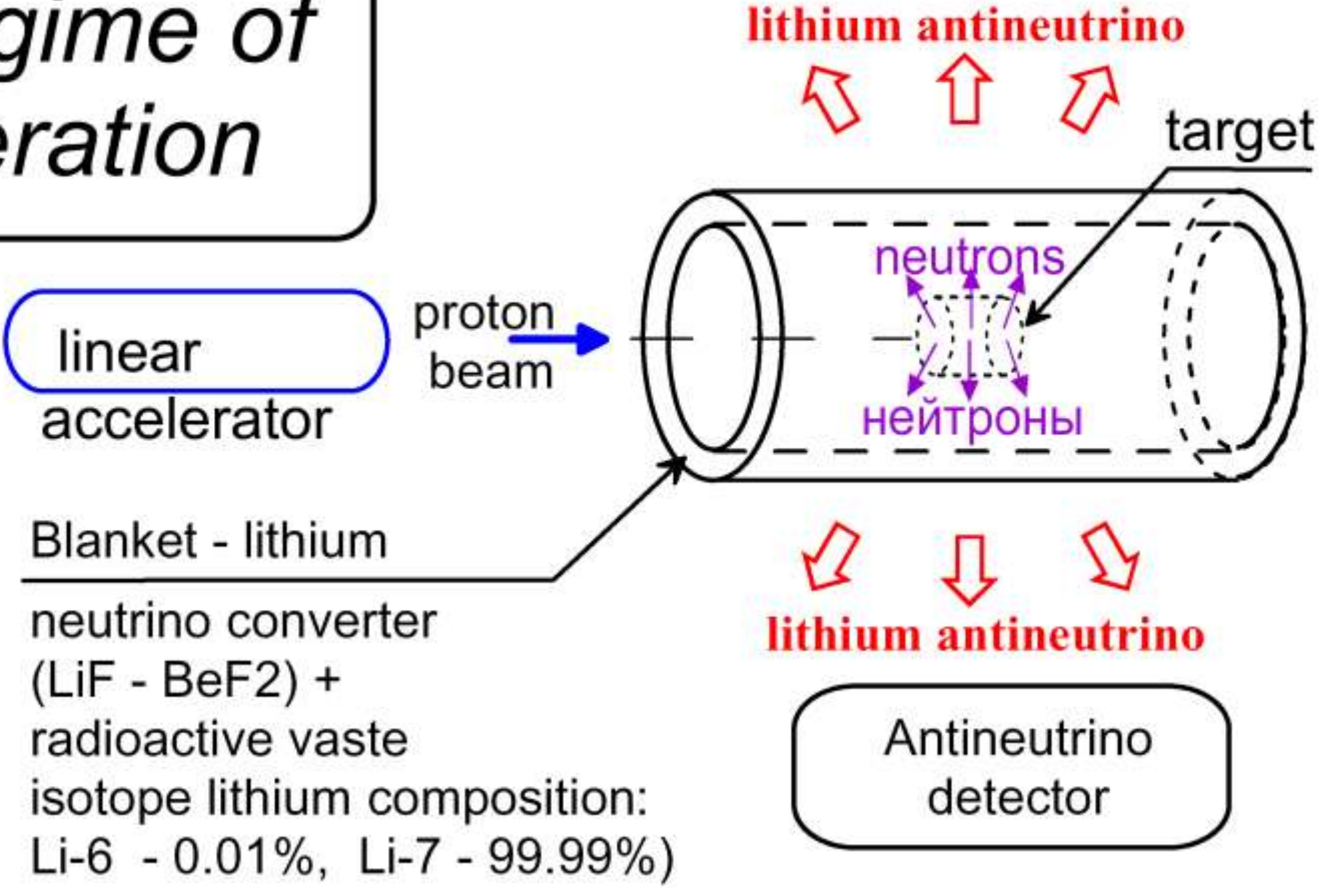
Neutron Sources on the Base of Accelerator + Neutron Producting Target



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	**$(1.8 - 2.7)\cdot 10^{17}\ s^{-1}$**	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	**$4\cdot 10^{16}\ cm^{-2}s^{-1}$** (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

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

Static regime of the operation



lithium antineutrino

target

linear accelerator

proton beam

neutrons

нейтроны

Blanket - lithium

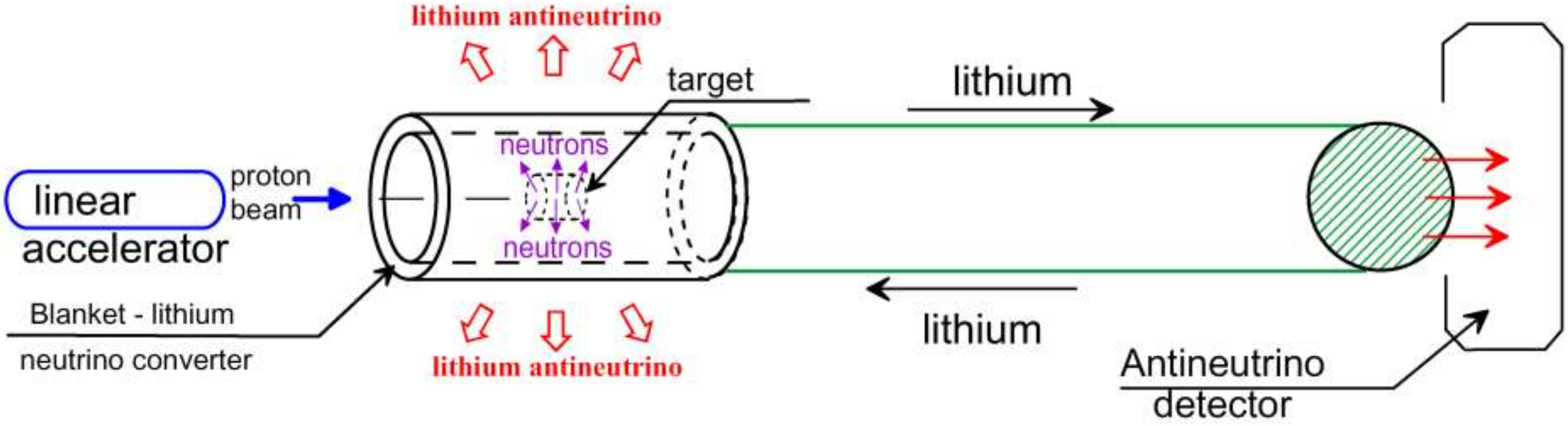
neutrino converter
(LiF - BeF2) +
radioactive vaste
isotope lithium composition:
Li-6 - 0.01%, Li-7 - 99.99%)

lithium antineutrino

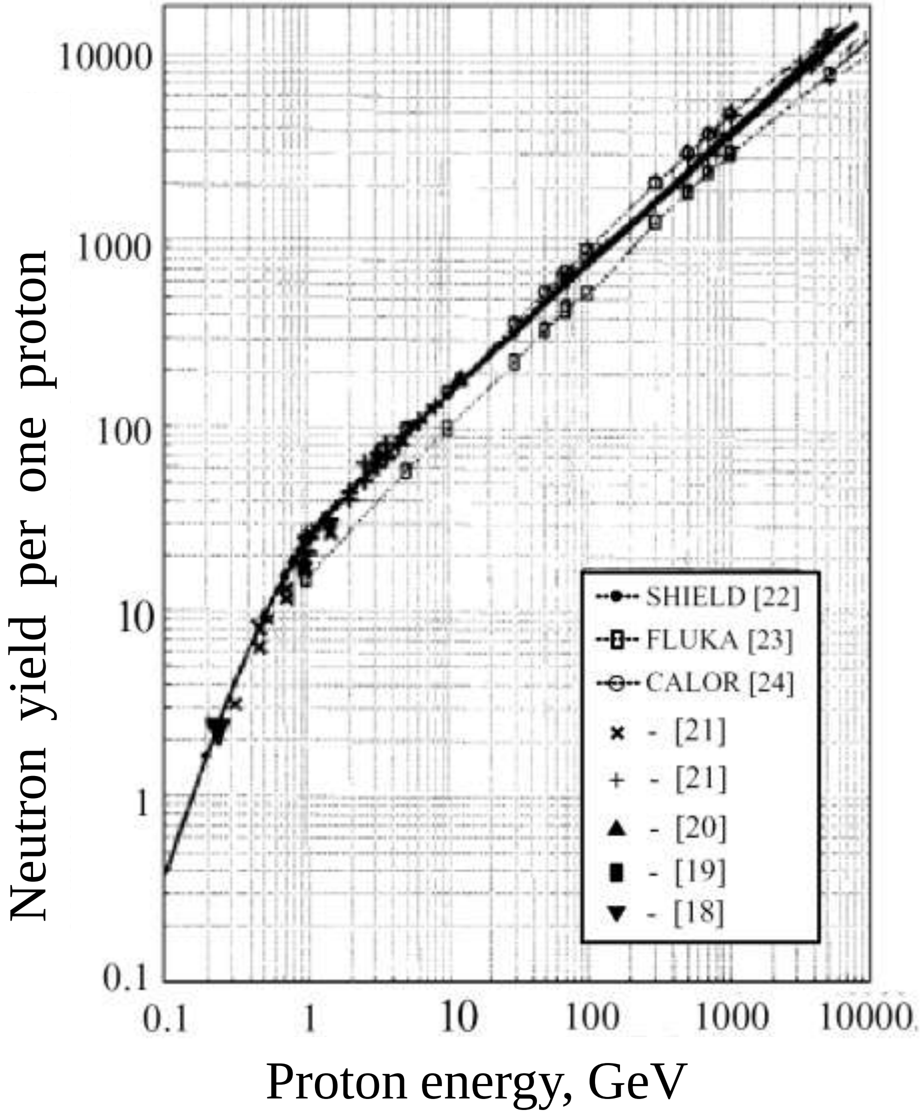
Antineutrino detector

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

Dinamic regime of the operation



NEUTRON YIELD FRON HEAVY TARGETS (W, Pb)



Стависский Ю.И.
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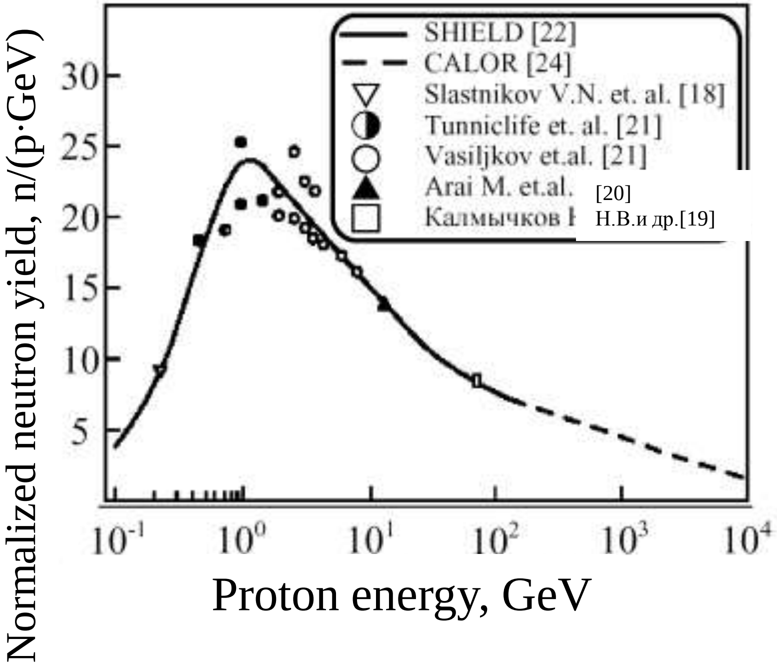

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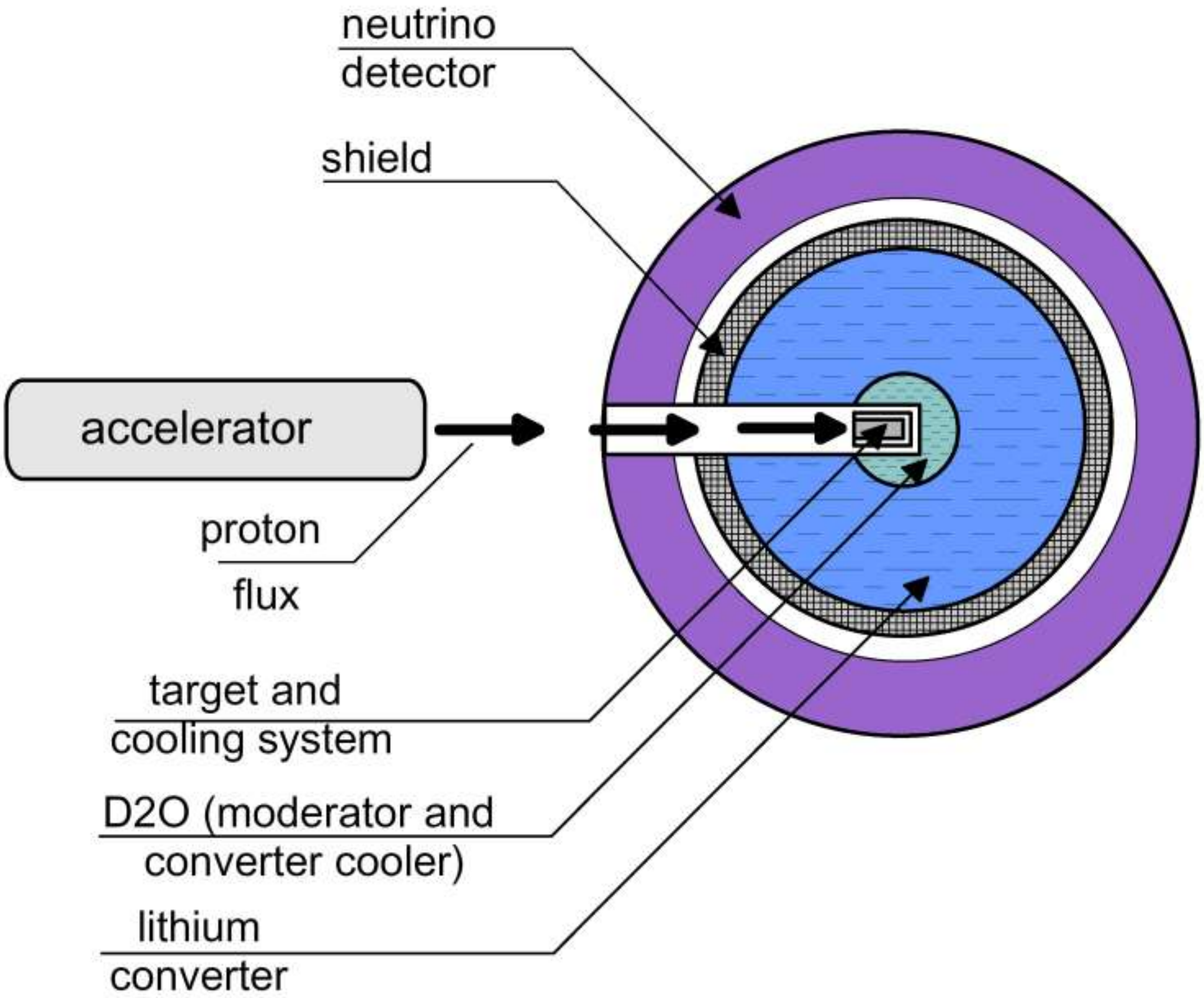
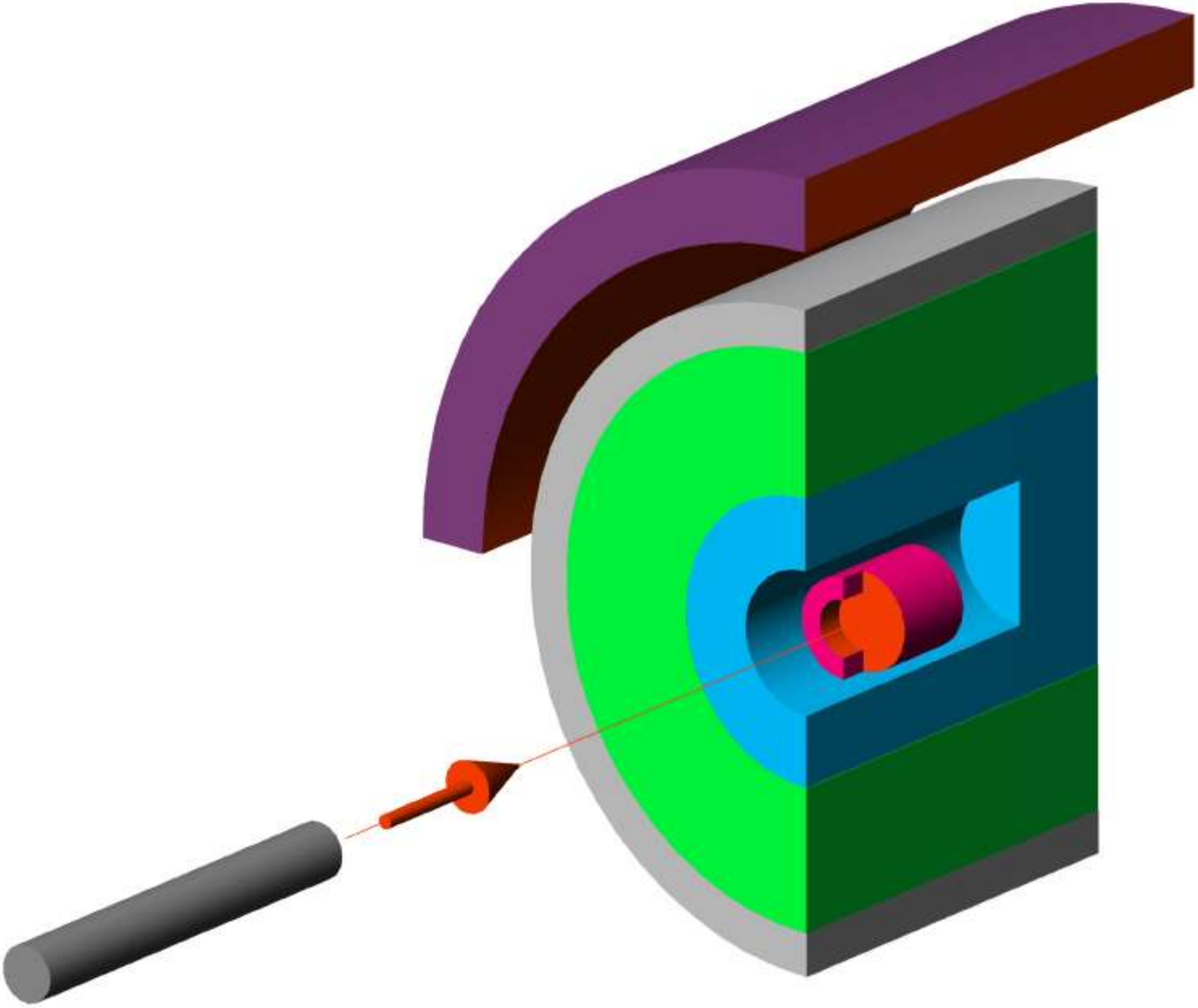
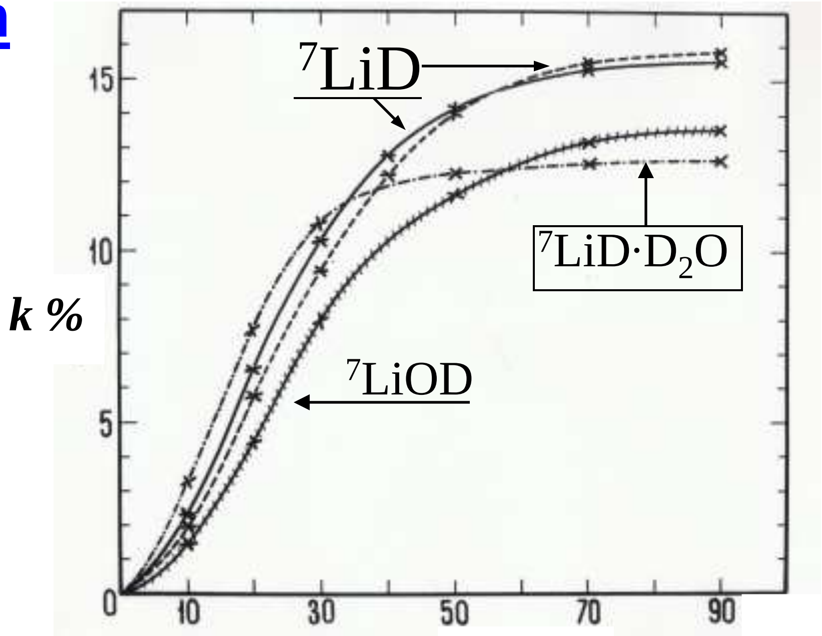
1. Parameters of the Lithium Antineutrino Source. Spherical geometry



2. Parameters of the Lithium Antineutrino Source in the spherical geometry

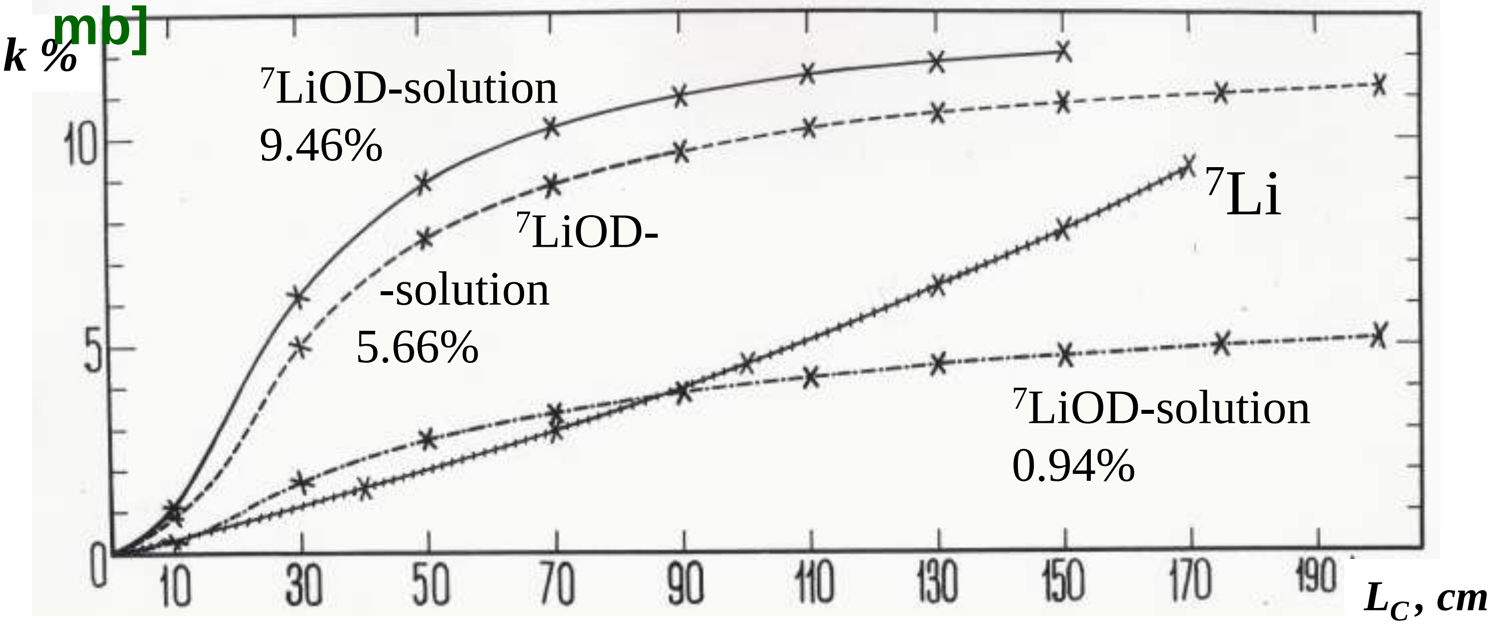


DEPENDANCE of EFFICIENCY *k* from the THICKNESS L_C of the CONVERETER for DIFFERENT CONVERTER SUBSTANCES (^{7}Li purity – 99.99%)



for the thermal group:

[σ_α(^{7}Li)=45 mb] »[σ_α(D)=0.52 mb] >[σ_α($_8$O)=0.19 mb]

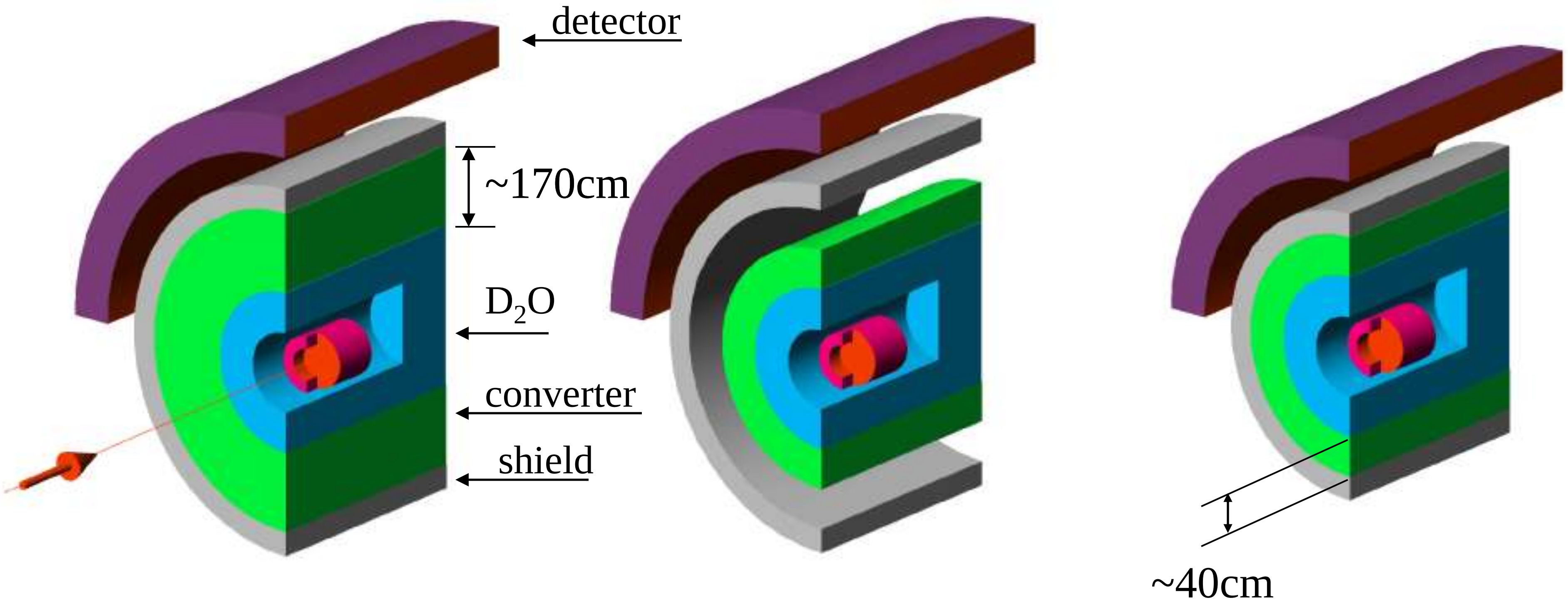


3. Parameters of the Lithium Antineutrino Source

Converter: LiOD-solution

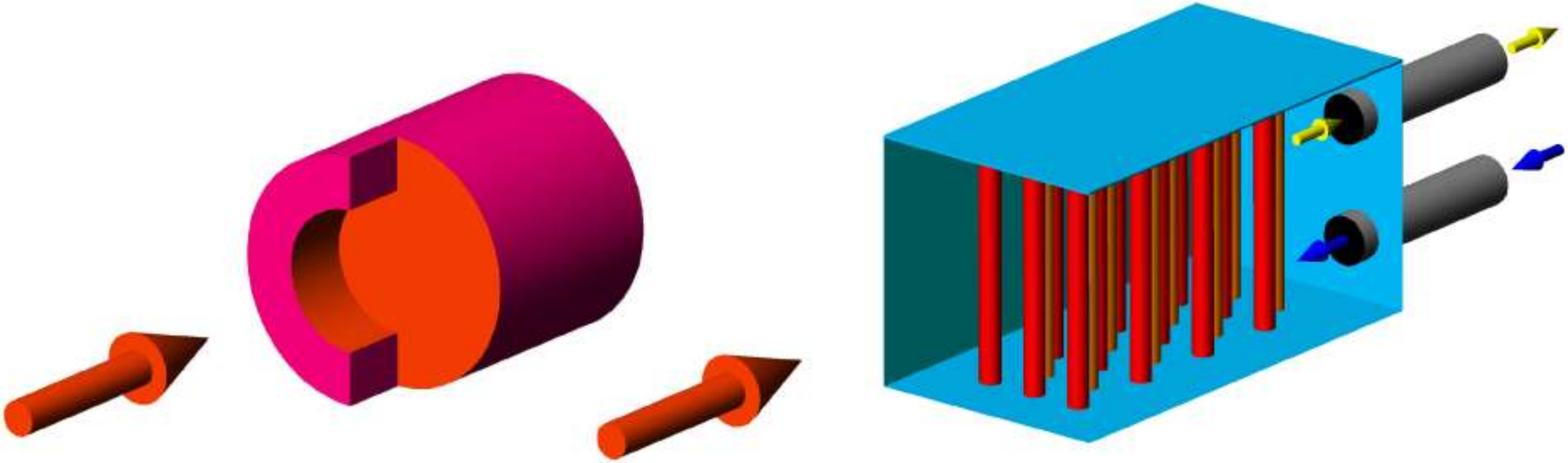
Converter: LiD

Converter: LiD

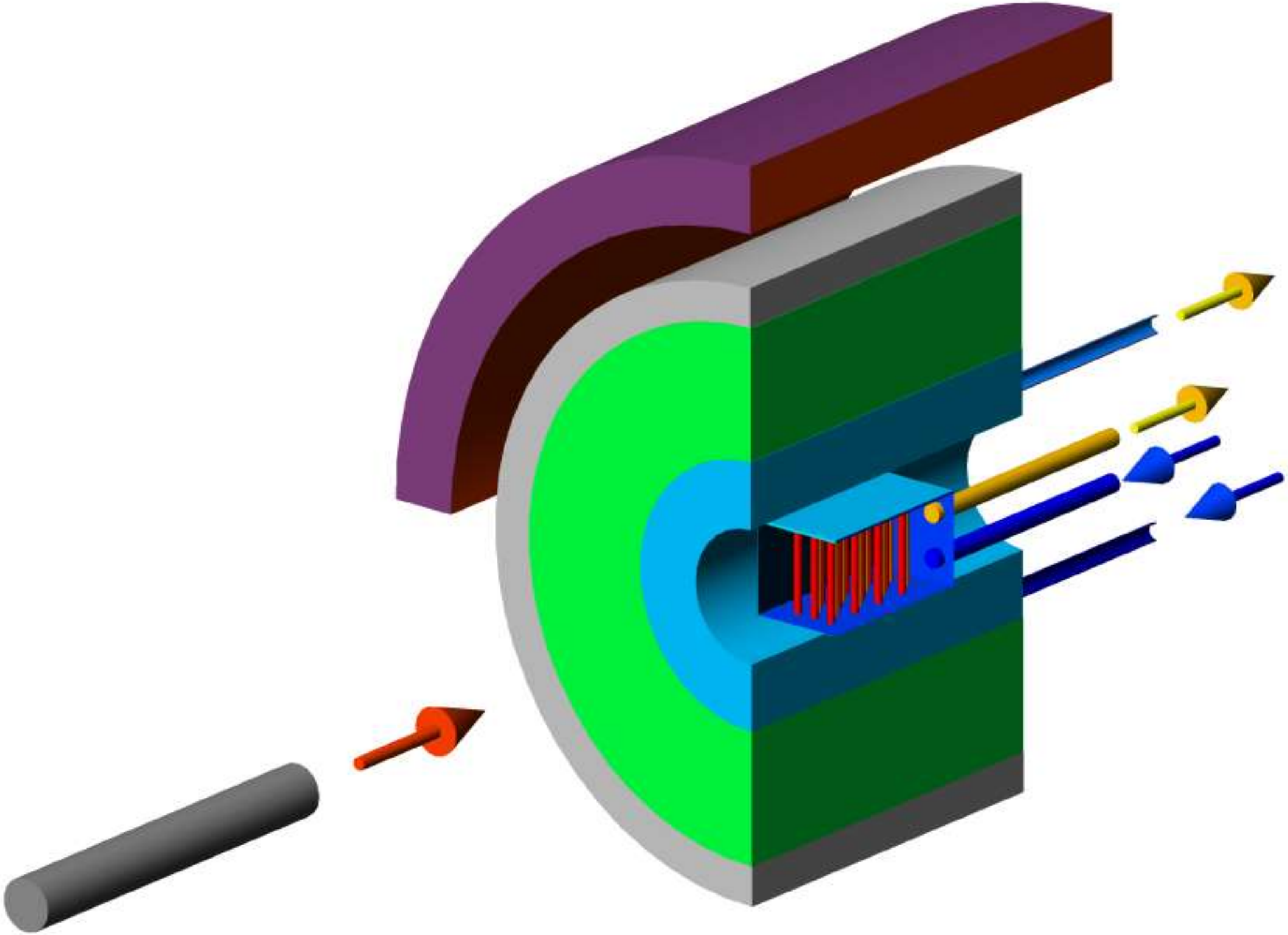


Use of converter substances with more high efficiency ***k*** allows to significantly decrease the dimension of the installation (about two times for *k* = 10-11% at ^{7}Li purity – 99.99%).

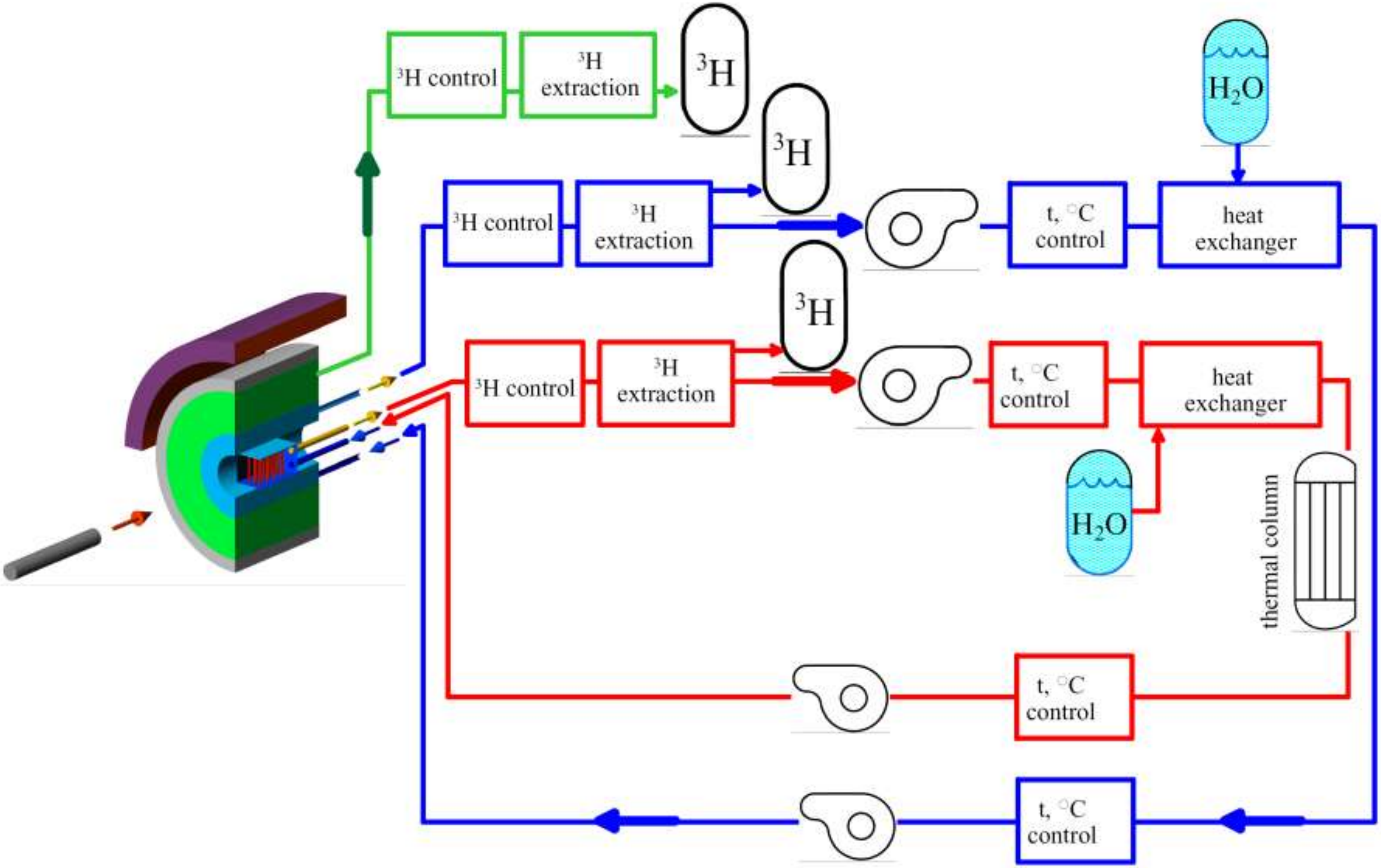
4. Parameters of the Lithium Antineutrino Source in the spherical geometry



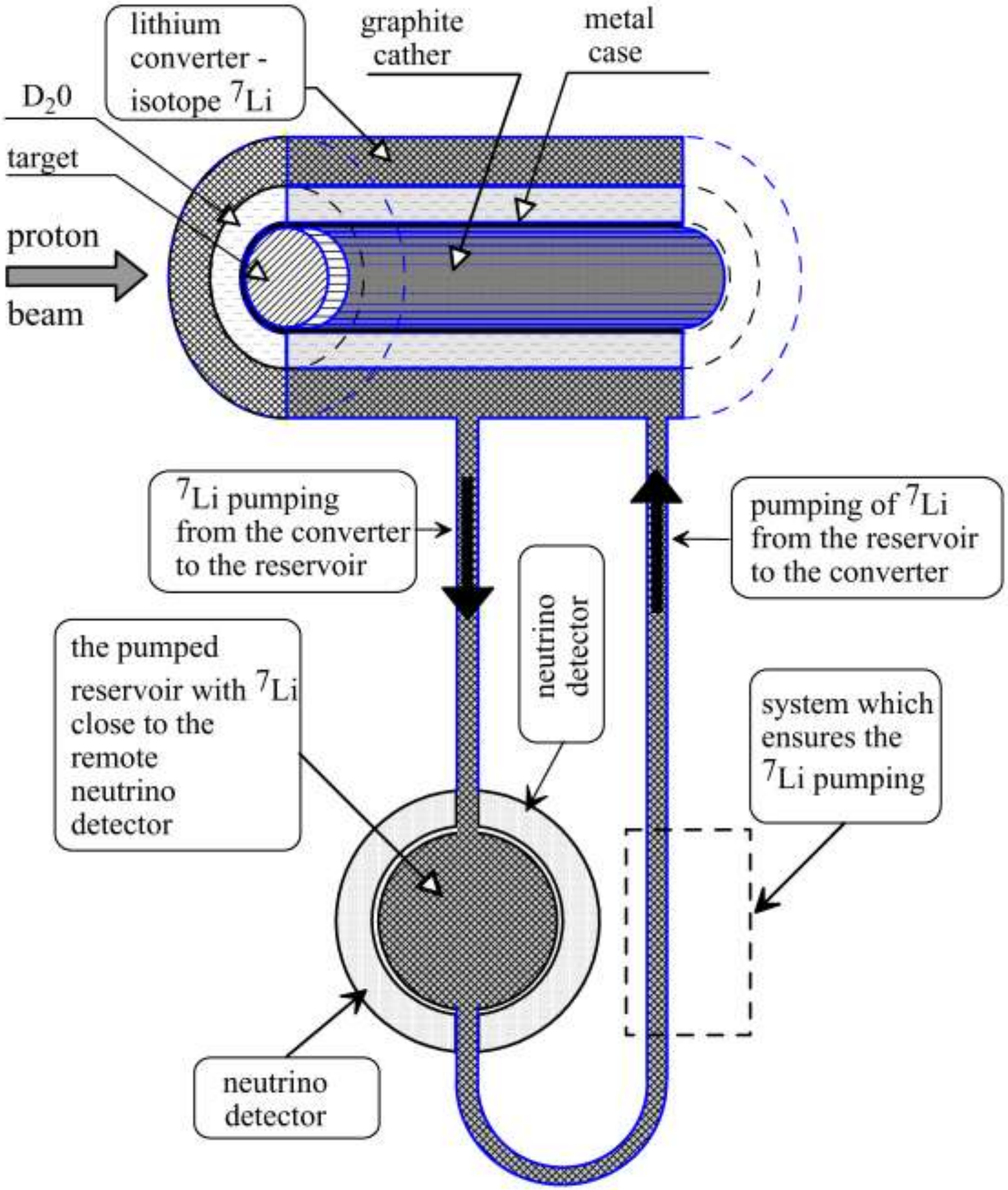
5. Parameters of the Lithium Antineutrino Source in the spherical geometry



5. Functional Scheme of the Antineutrino Source on the Base of Accelerator and Lithium Converter



NEUTRINO FACTORY on the BASE of BEAM CATCHER

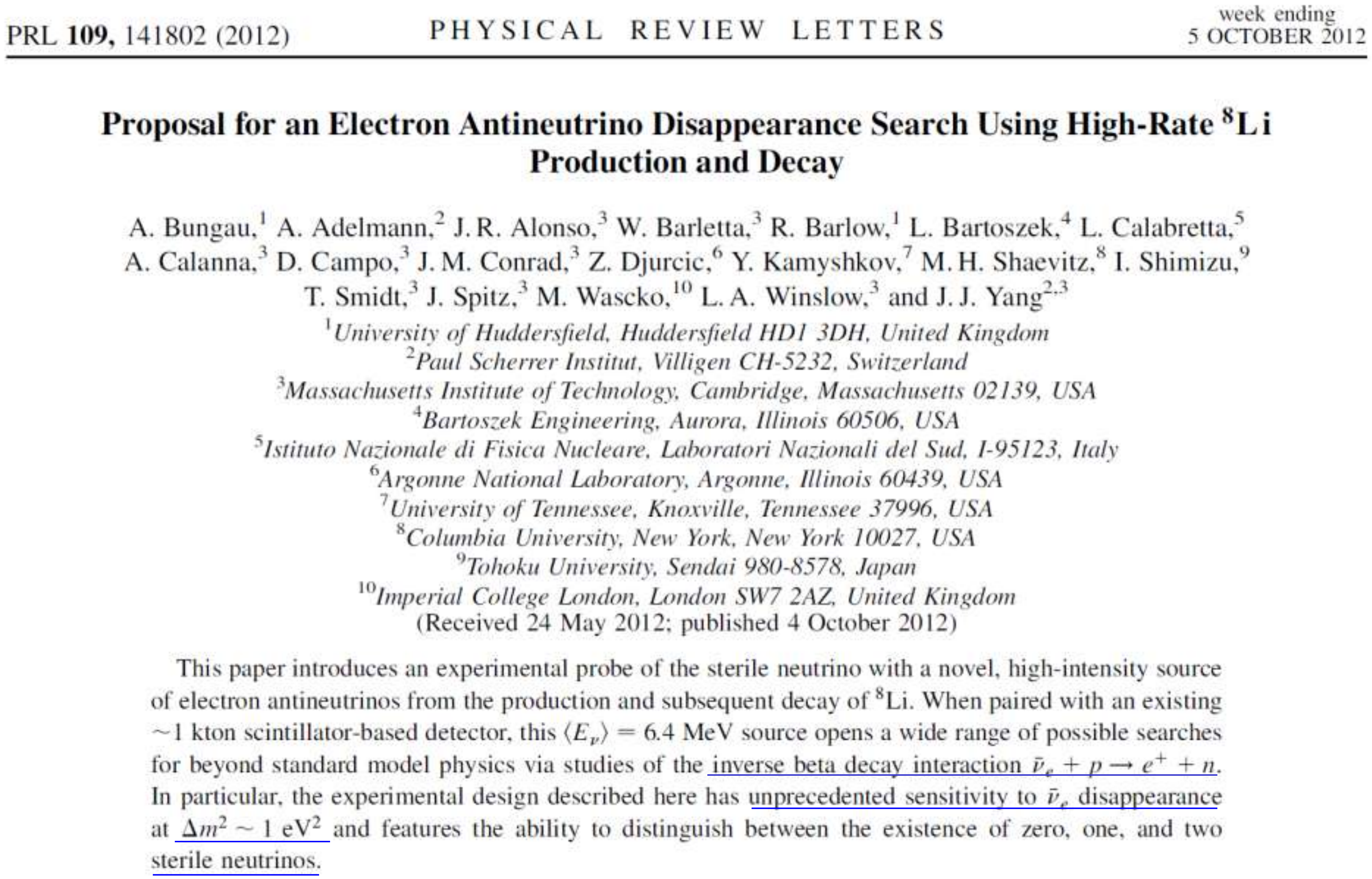


The scheme of the neutrino factory on the base of the catcher of large accelerators (^{7}Li isotope is activateed \ in (n,γ)-reaction and pumped to the remote detector). Proton beam (from the accelerator is dumped on the heavy neutron-producting target (for example – tangsten) close the graphite catcher. 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). The expected flux:

6E+18 neutron/pulse =>

=> 1E+18 neutrino/pulse

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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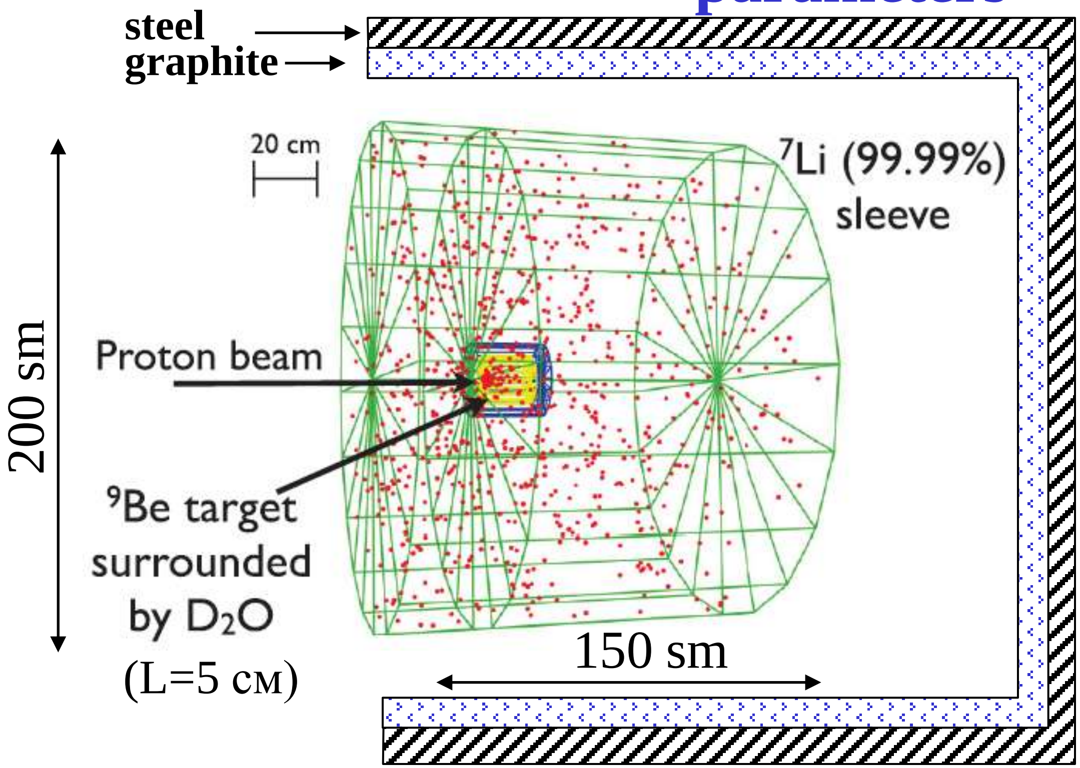
This paper introduces an experimental probe of the sterile neutrino with a novel, high-intensity source of electron antineutrinos from the production and subsequent decay of ^{8}Li. When paired with an existing ~1 kton scintillator-based detector, this $\langle E_\nu \rangle = 6.4$ MeV source opens a 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



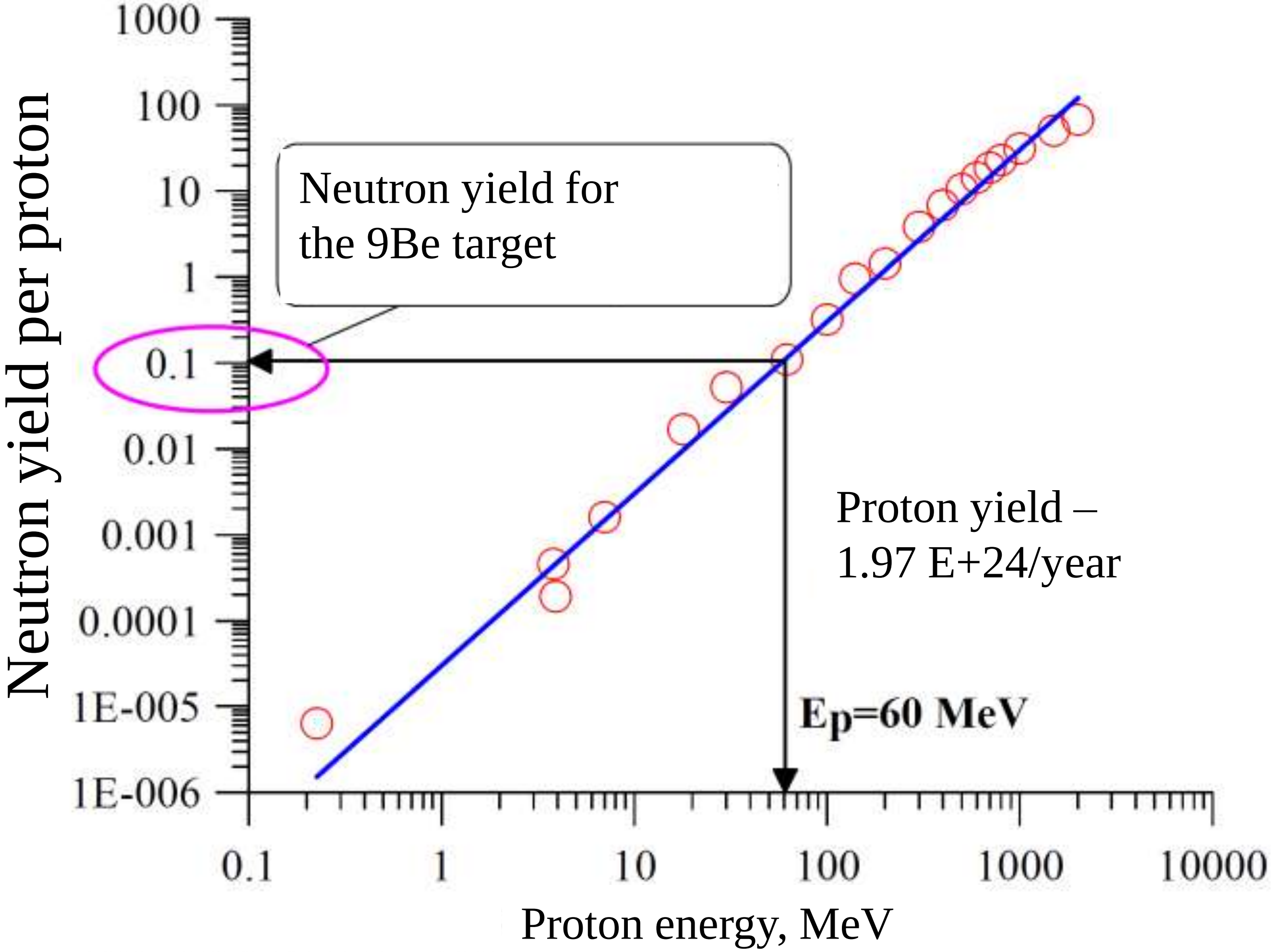
experimental parameters. We note that the geometry design is similar to that described in Ref. [10].

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

Lithium antineutrino source IsoDAR
= =
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) – 8.2E+5

Neutron Yield for IsoDAR Installation



Neutron yield for the 9Be target

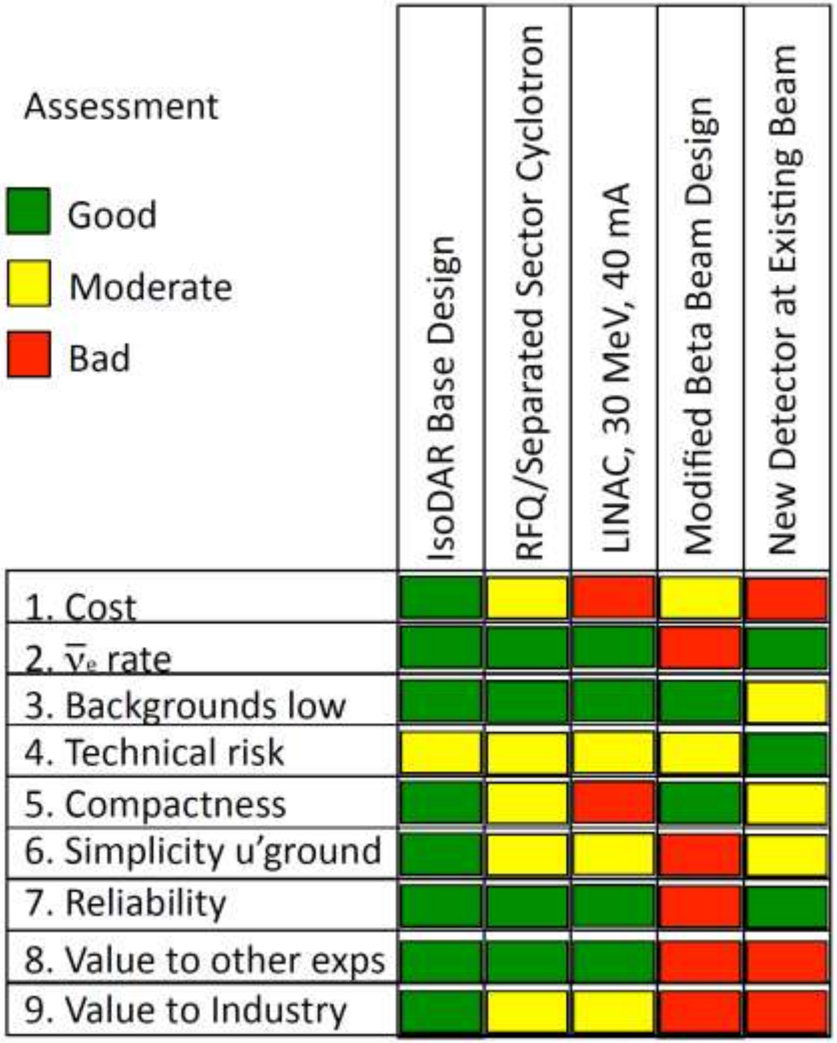
Proton yield – 1.97 E+24/year

Ep=60 MeV

- 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)

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	🟩	🟨	🟥	🟨	🟥
2. $\bar{\nu}_e$ rate	🟩	🟩	🟩	🟥	🟩
3. Backgrounds low	🟩	🟩	🟩	🟩	🟨
4. Technical risk	🟨	🟨	🟨	🟨	🟩
5. Compactness	🟩	🟨	🟥	🟩	🟨
6. Simplicity u'ground	🟩	🟨	🟨	🟥	🟨
7. Reliability	🟩	🟩	🟩	🟥	🟩
8. Value to other exps	🟩	🟩	🟩	🟥	🟥
9. Value to Industry	🟩	🟨	🟨	🟥	🟥

CONCLUSION

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

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

- It was obtaine the **analitical expression** for neutrino fluxes from the source.

- Different types of matter were investigated for production of neutrino. The **most perspective is the heavy water 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**.

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

Thank you a lot !