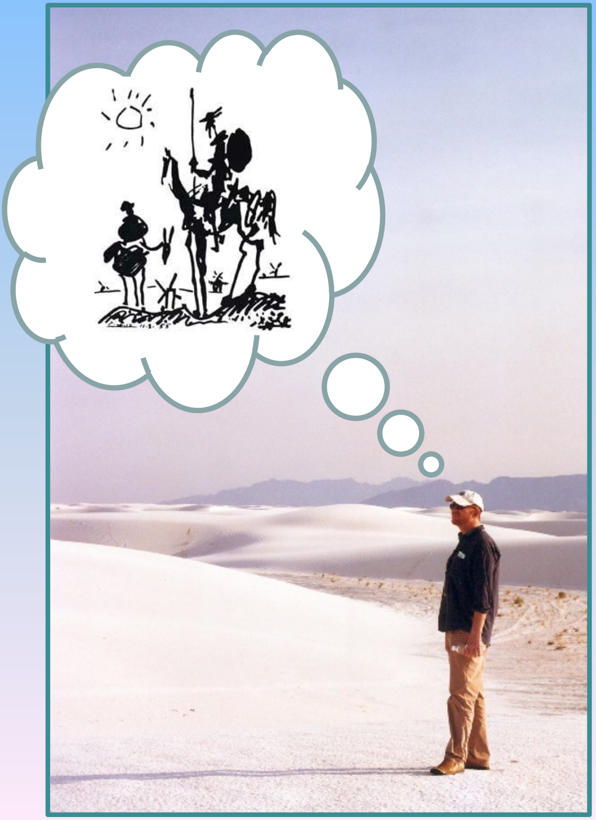
NEPIR: A neutron irradiation facility at the SPES high intensity 70 MeV Cyclotron of LNL

Real Possibility or Fantasy?



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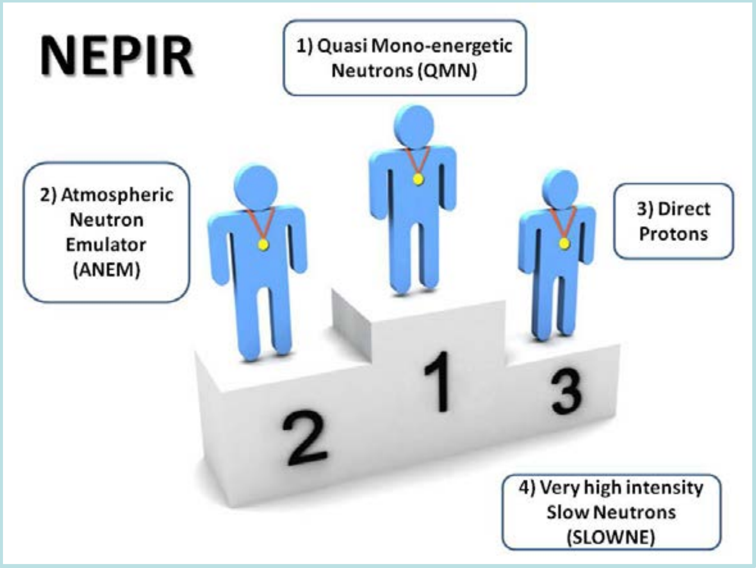
- Introduction and purpose of talk
- NEPIR and its subsystems

    1. QMN quasi mono-energetic neutrons
    2. ANEM atmospheric neutron emulator
    3. PROTON (not this talk)
    4. SLOWNE slow neutrons

- Situation
- discussion



The proposed Neutron and Proton Irradiation (NEPIR) facility would be designed to be useful for the widest scientific community possible, making it unique in Italy and very useful for European research, both applied, industrial and basic.

An opportunity that SHOULD NOT be lost.

Call for collaborators

The **NEPIR** project foresees **4 subsystems**:

- **QMN**:

A source of quasi mono-energetic neutrons (QMN) with a controllable energy peak in the 20-70 MeV energy range; the QMN system would allow correcting data in the forward direction using data taken at angles (wrong-energy tail correction technique)

- **ANEM**: (Atmospheric Neutron Emulator):

A source of ***fast* neutrons (E > 1 MeV)** with a continuous (*white*) energy distribution similar to that of neutrons found at flight-altitudes and at sea-level with an integral neutron flux Φ_n(1 MeV < E_n < 70 MeV) at the test point that is up to 3×10^9 higher than the natural flux at sea level in the same energy range.

- **SLOWNE**:

A high intensity slow neutron source (4π-flux > 10^{14} n/s) for special ***slow* neutron applications**;

- **PROTON**:

a general purpose low intensity beam (max few hundred nA) of direct protons with variable energy in the 20-70 MeV range.

The proton beam line is NOT DISCUSSED in this talk

The original purpose of NEPIR:

The **QMN**, **ANEM** and **PROTON** subsystems will be used for the study of **radiation damage effects in electronic devices and systems** induced by **flight-altitude and sea-level atmospheric neutrons** and **solar protons**.

Neutrons for electronics				
QMN discrete	Energy range 20-70 MeV 😐	Essential to study energy dependencies (cross-section vs energy curves) 😐	Neutron flux at test point is **user controlled**, up to 10^6 n cm^{-2} s^{-1} ☺	Angle correction ☺
ANEM continuous	Energy cut-off 70 MeV ☹	Before full energy tests at very high-energy facilities like Chip-IR (ISIS), it is useful to make flexible studies/checks for unexpected sensitivity to lower energy neutrons 😐 ☞ ☺	Neutron flux at test point is **user controlled**, flux $E_n > 1$ MeV at test point up to $\phi > 10^7$ n cm^{-2} s^{-1} ☺	

QMN

- Interest
- Energy dependent neutron-induced effects in electronics
- Beam-line (vertical plane)
- Angular dependence
- Multi-angle collimators schemes and layouts

  a) iTHEMBA-like (fixed angles)

  b) RIKEN-like (variable angle)

QMN fields with E_n > 20 MeV
are important reference neutron fields

Used to study **energy dependent** neutron interaction mechanisms with matter

USERS:

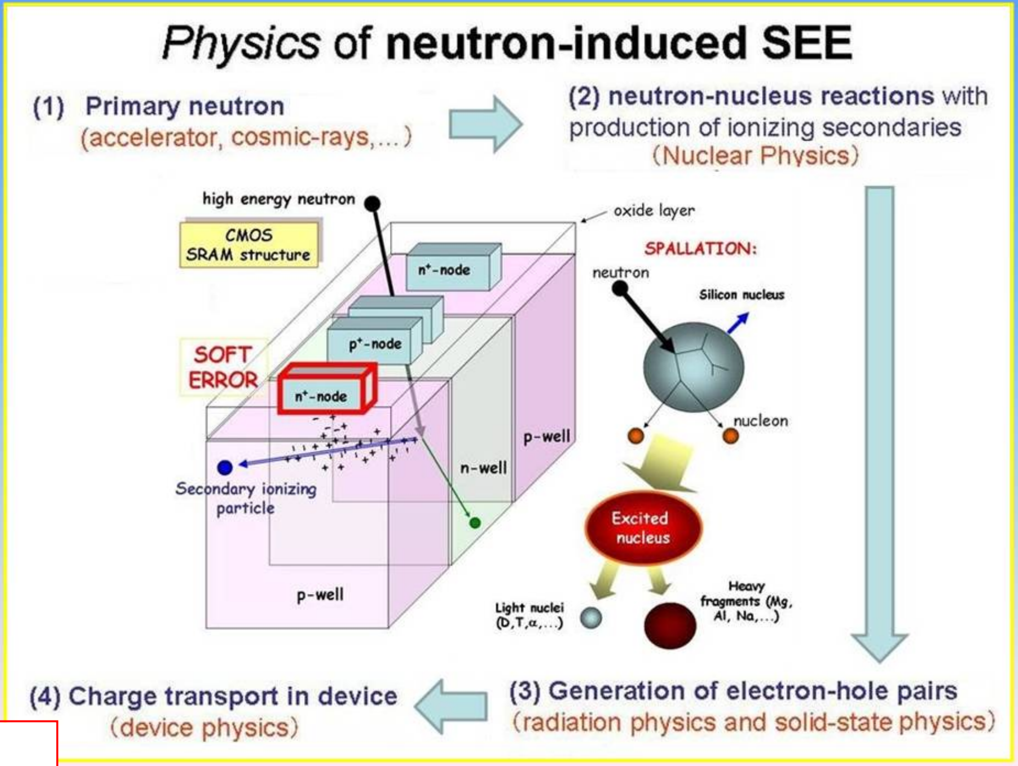
- *electronics industry for critical applications in hostile neutron fields (sensitive electronics anywhere, airlines, accelerator halls in hospitals and industry, space ...);*
- *electronics (ASICs) for HEP and nuclear physics experiments;*

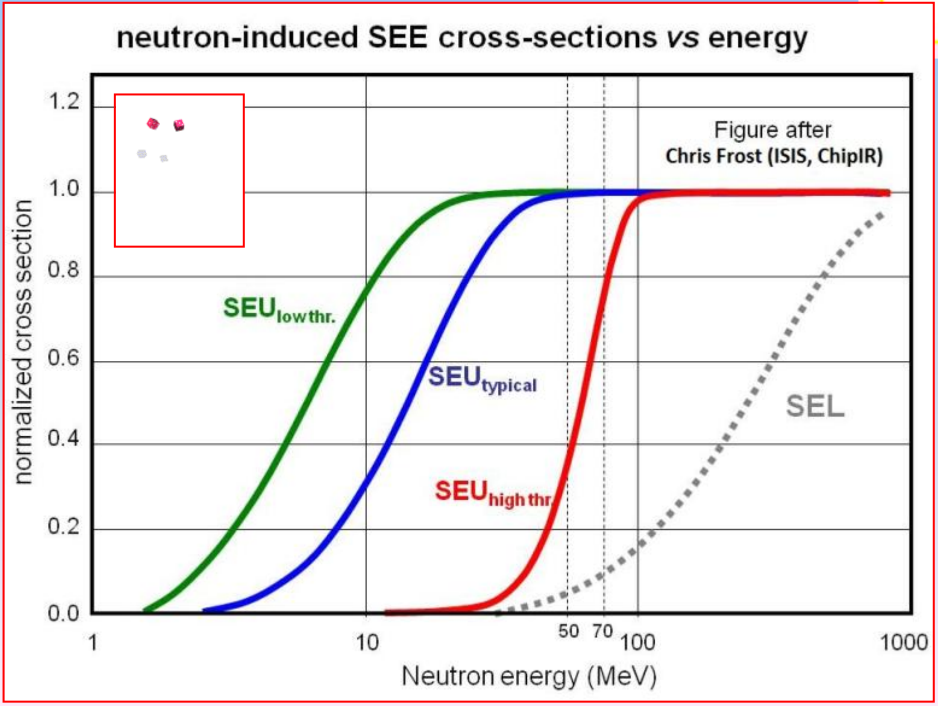
- *high-energy and nuclear physicists (cross-section measurements; MC development);*
- *manufacturers of radiation instrumentation (energy response and calibration);*
- *radiation physicists (studies for: fast neutron treatments; modeling of exposure of patients to secondary neutrons at proton accelerators; bench-mark shielding experiments).*

electronics

If neutron
is fast enough …

a Single Event Effect (SEE)
may occur
(depends on where it strikes)





Reference cross-section for

"Soft Errors" such as **SEUpset**:

σ_{SEU} **= 10^{-14} cm²/bit,**

N_{bits} per device = 4×10^6

(minimum)

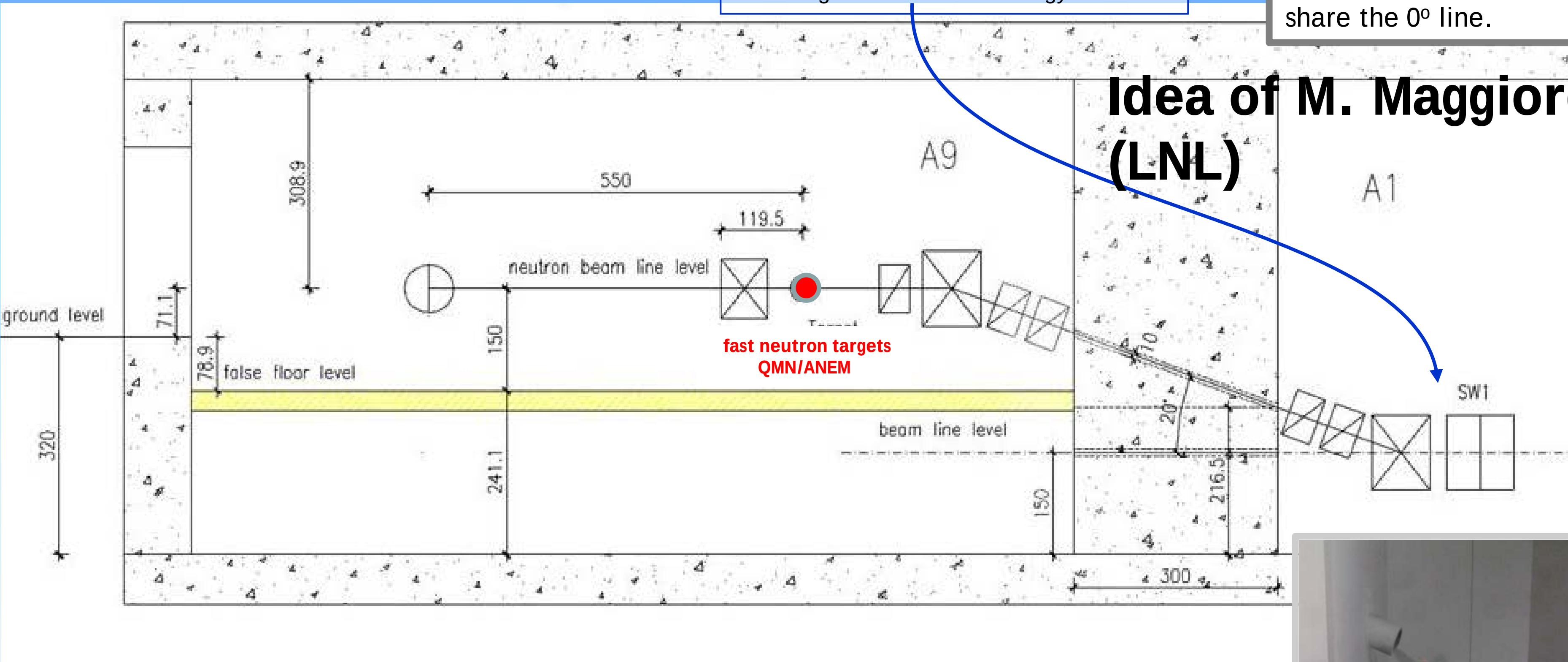
NEPIR fast neutron line (QMN/ANEM)

SPES hall A9, side view

Chicane to:
- avoid neutrons towards cyclotron
- have test point at same distance from floor and ceiling (minimize albedo)
- use degradator for lower energy neutrons

The ANEM target system will exchange position with the QMN multi-target system and will share the 0º line.

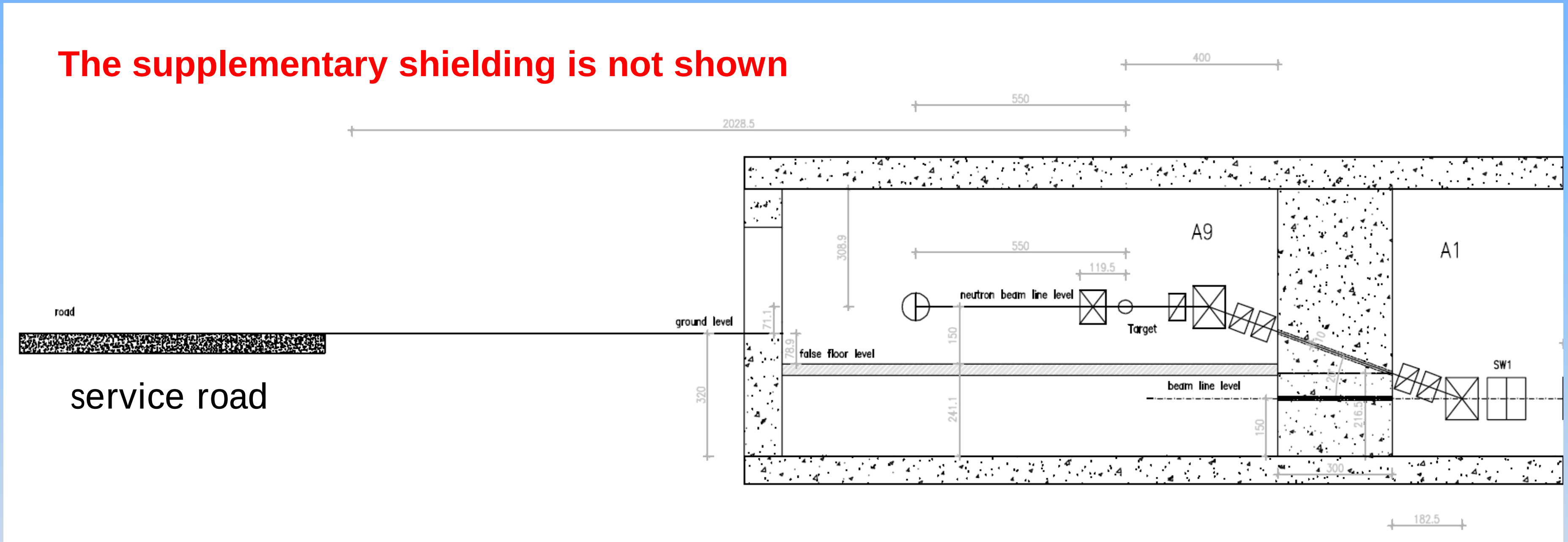
Idea of M. Maggiore (LNL)



At the test point, the neutron beam is 1.50 m from the false floor (3.91 m from the bottom cement floor). The optics: two dipole magnets, two quadrupole doublets, a single quadrupole, and a bending magnet for the spent proton beam. **The supplementary shielding is not shown.**

extendable (for time-of flight)

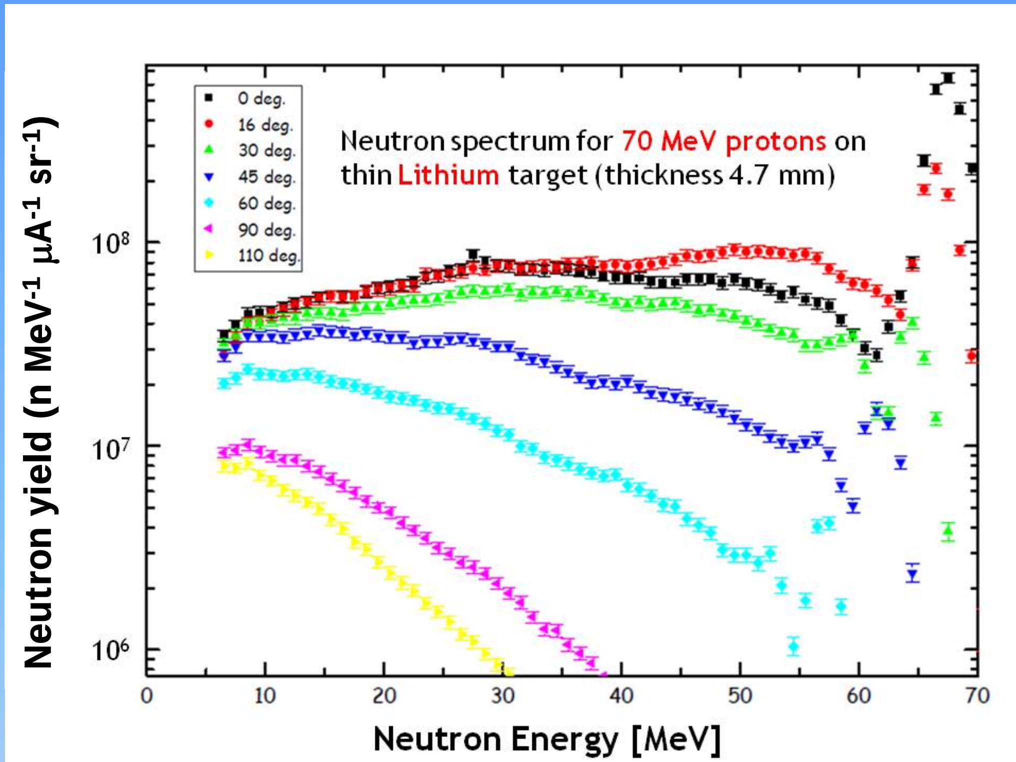
Up to ~ 20 m (maybe more by moving service road)



Angular dependence at E_{proton} = 70 MeV

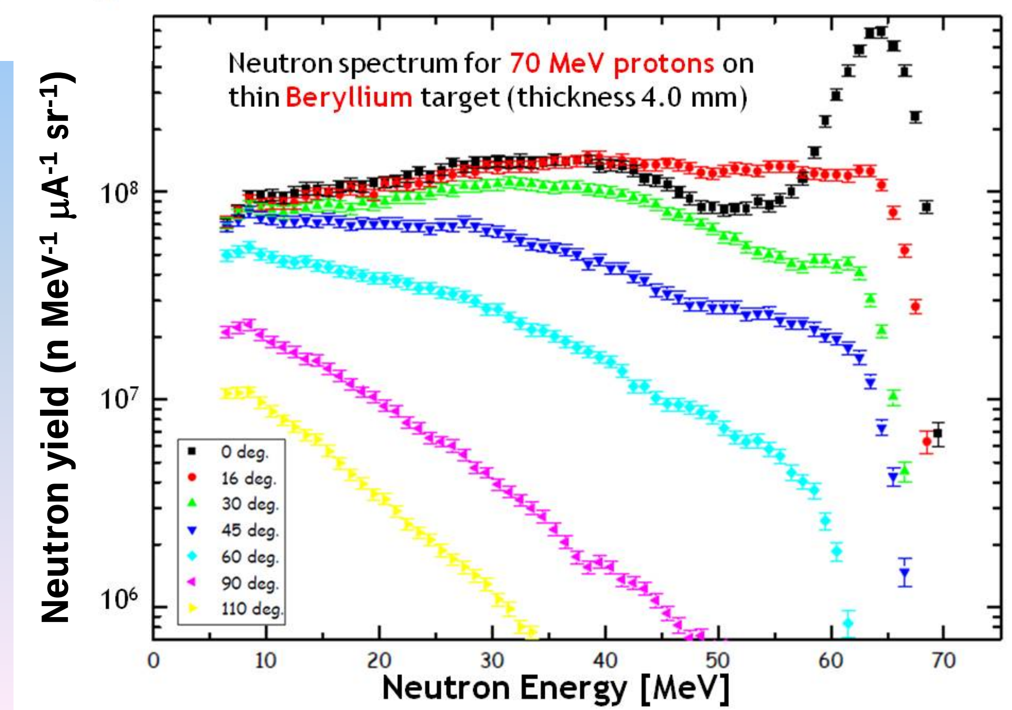
Kamata S., Itoga T., Unno Y., Baba M.
(CYRIC ANNUAL REPORT 2005)

Journal of the Korean Physical Society, Vol. 59, No. 2, August 2011, pp. 1676-1680



thin Lithium ⇑

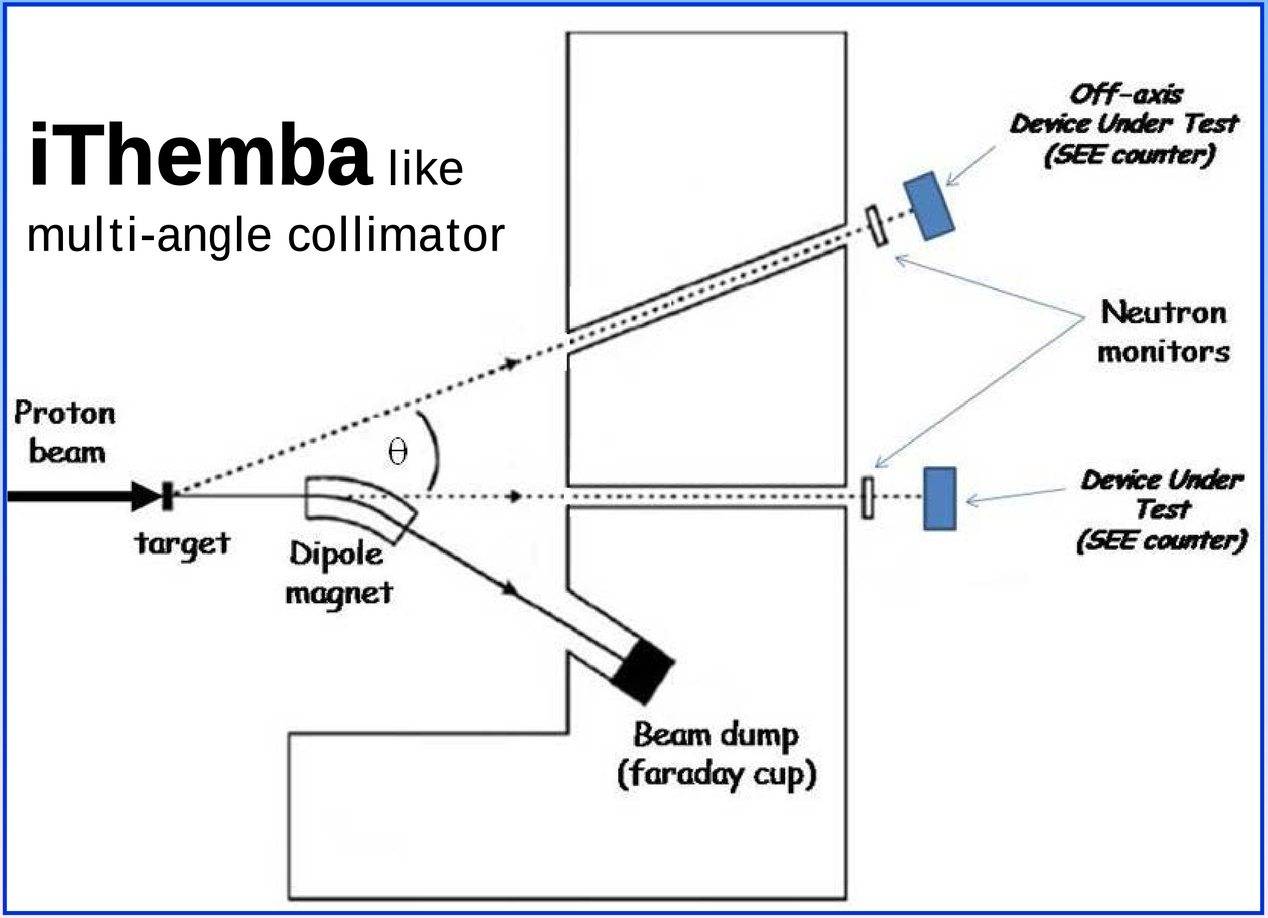
thin Beryillium ⇒



QMN: Forward (0º) neutron tail correction by measuring off-axis neutrons *(“wrong-energy tail correction technique”)*

The “good” mono-energetic neutrons are produced mainly in the direction of the proton beam (forward, $\theta = 0$);
wrong-energy neutrons are not as directional.

The neutron fluence of forward going mono-energetic neutrons can be corrected by subtracting the neutrons measured at angles (typically in the 15º-30º range).



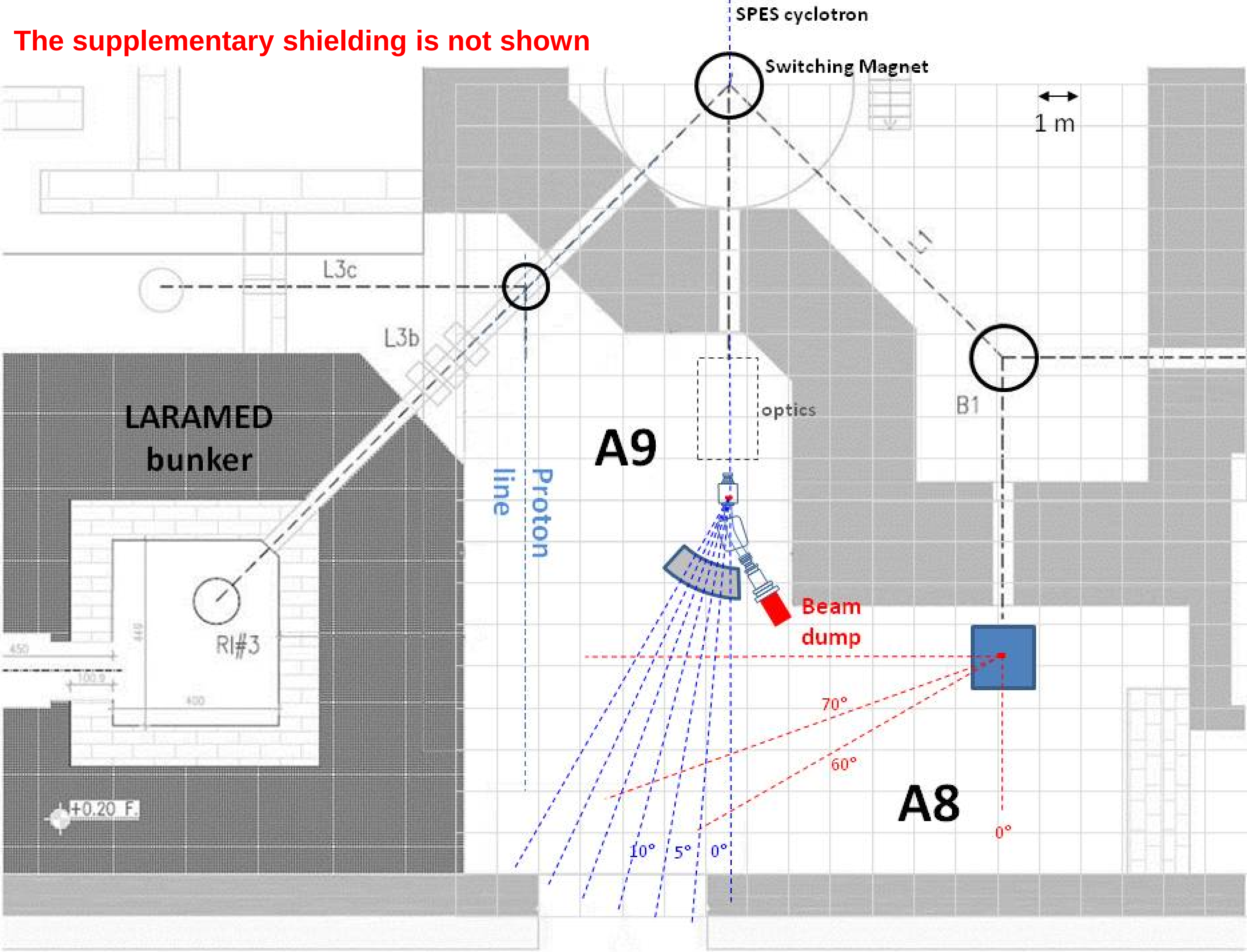
- both Li and Be QMN targets should be available

- 1-2mm Be will be used for high flux (> 3×10^5 n cm^{-2} s^{-1}) as the neutron yield can be kept high with more proton current (tens of microAmps) with test point few meters downstream of target

- the beam dump might be the one used for SPES test (full power) or scaled down similar design

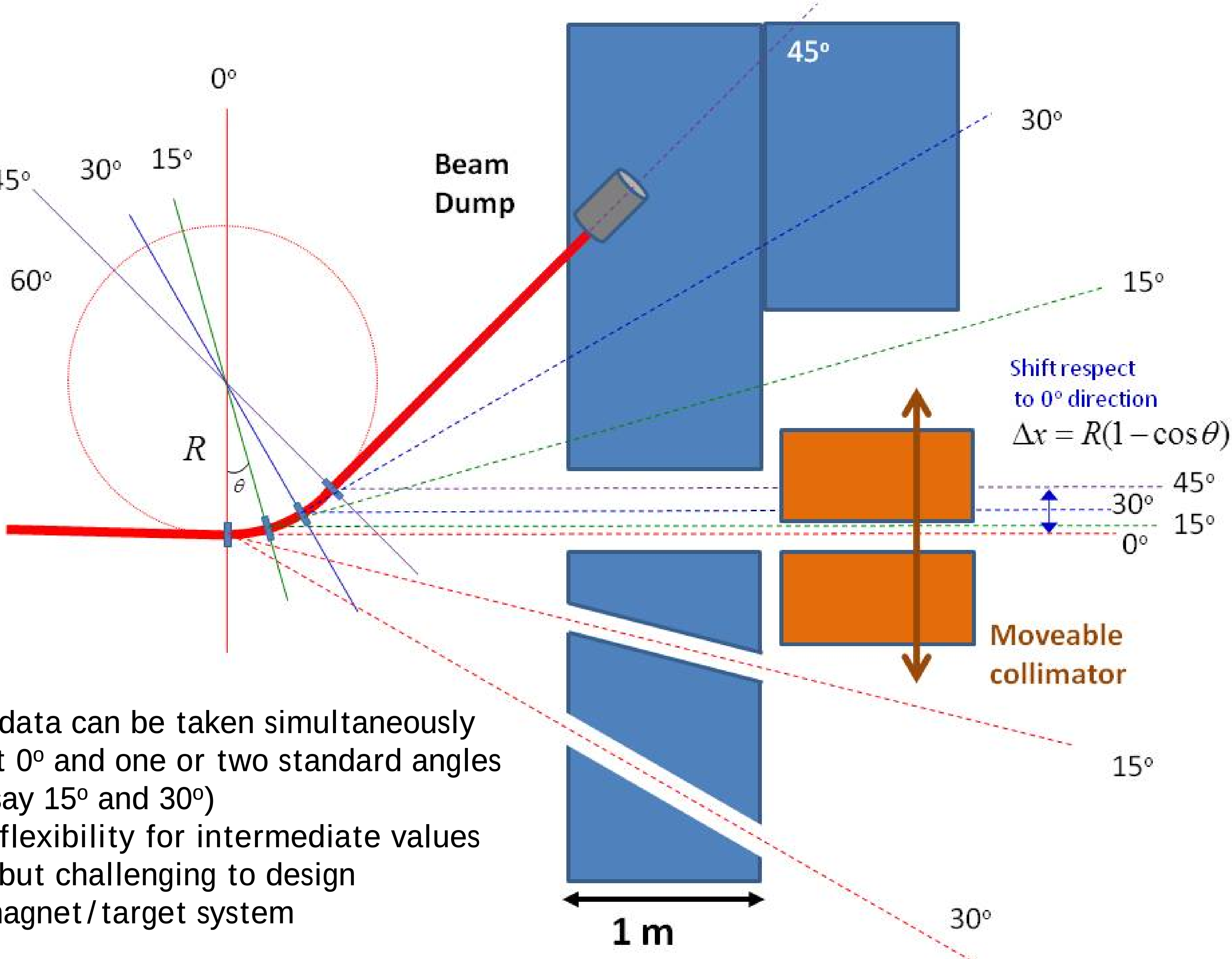
- A 30° collimator is likely to be the standard angle for correction, but this must be verified for the 20 $\leftarrow$35-70 MeV energy range

The supplementary shielding is not shown



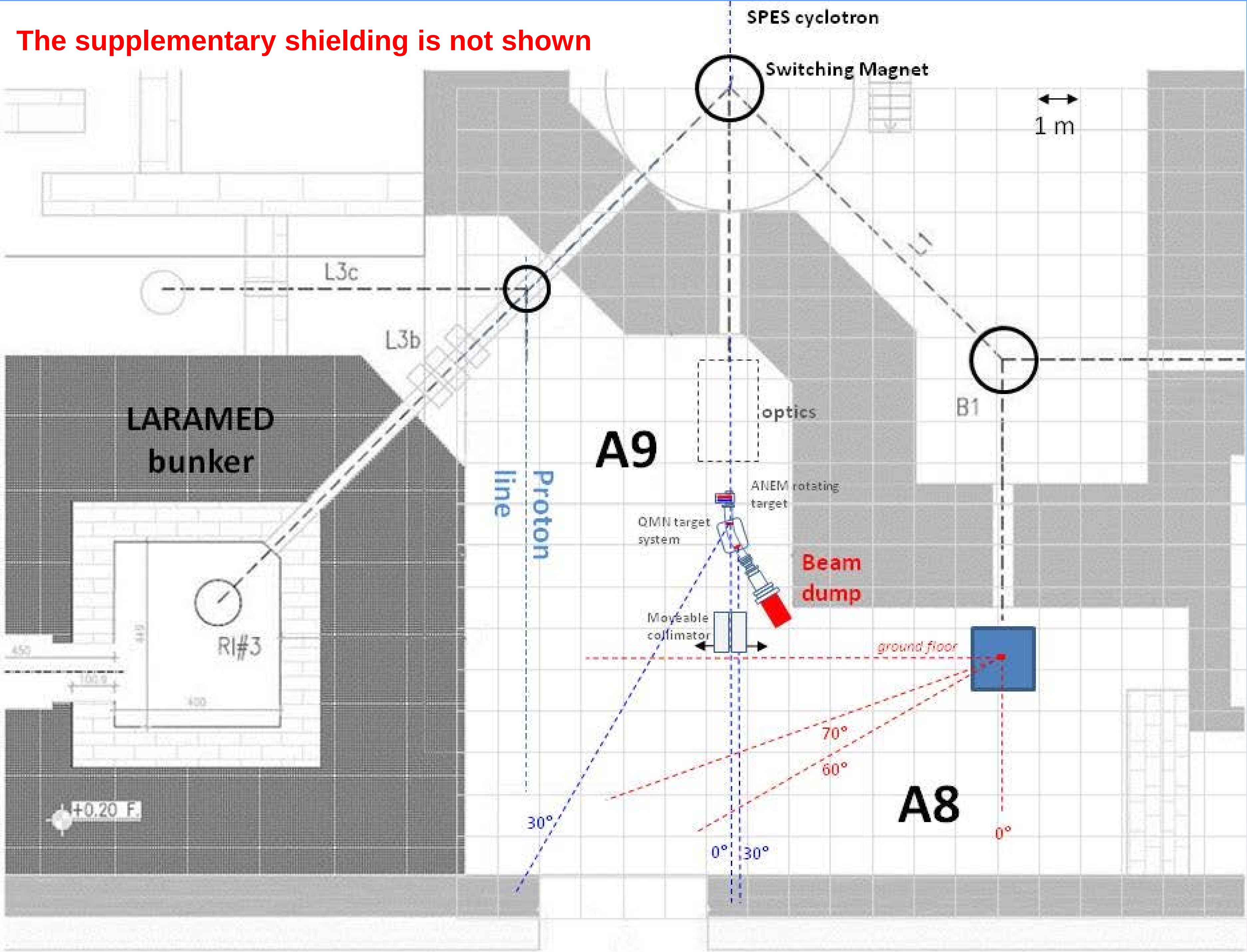


RIKEN-like



- data can be taken simultaneously at 0° and one or two standard angles (say 15° and 30°)
- flexibility for intermediate values
- but challenging to design magnet/target system

The supplementary shielding is not shown



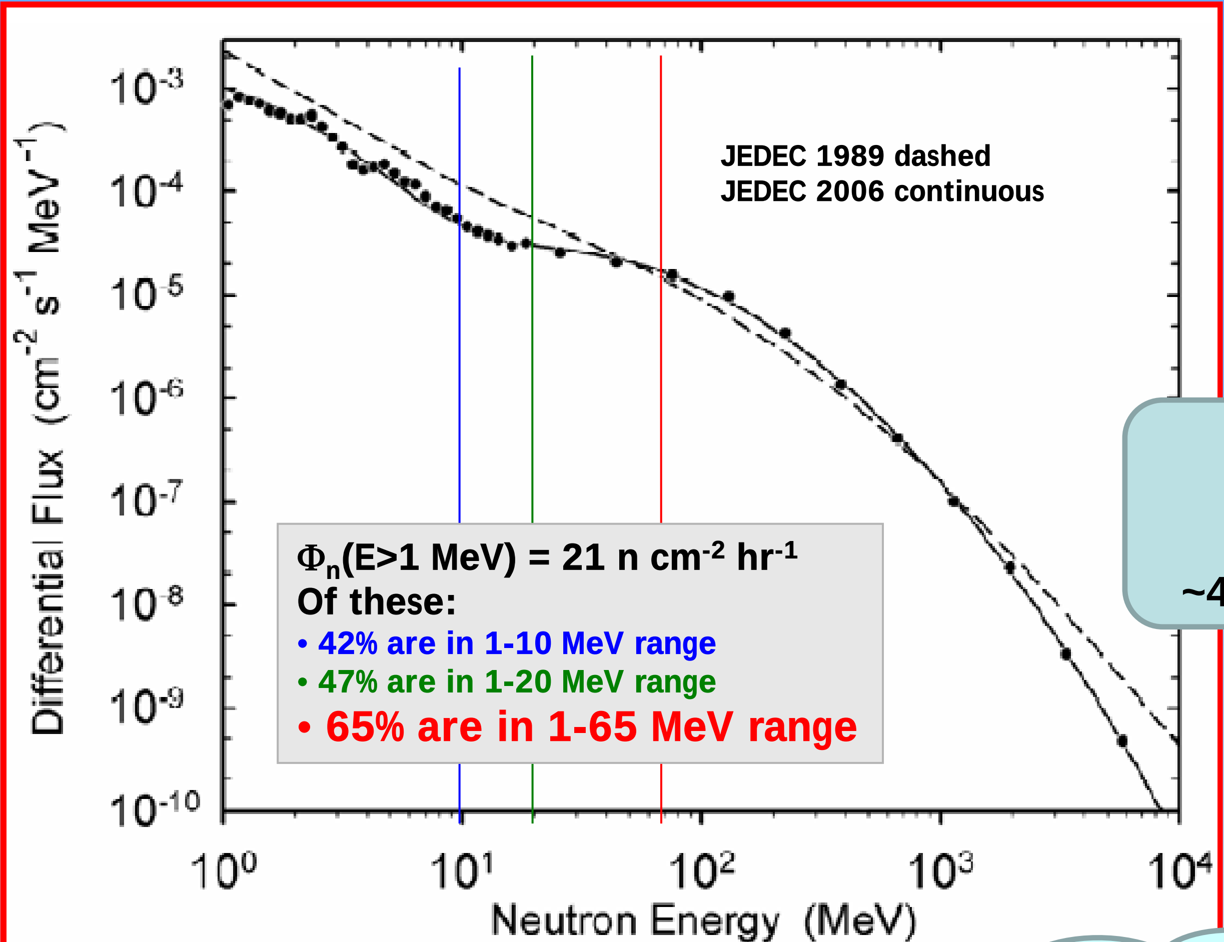
ANEM

A*tmospheric* ***N****eutron* ***EM****ulator*

- Interest
- Atmospheric neutron energy spectrum
- target development

SEE

Spectrum of fast (E>1MeV) atmospheric neutrons



Typical value for SEU
$\sigma_{Plateau}$ = 10^{-14} cm^2/bit
gives a low SEU rate
~4 SEU / (month · 8 GByte)

Boring! I need to speed these tests up...
I want an accelerator!

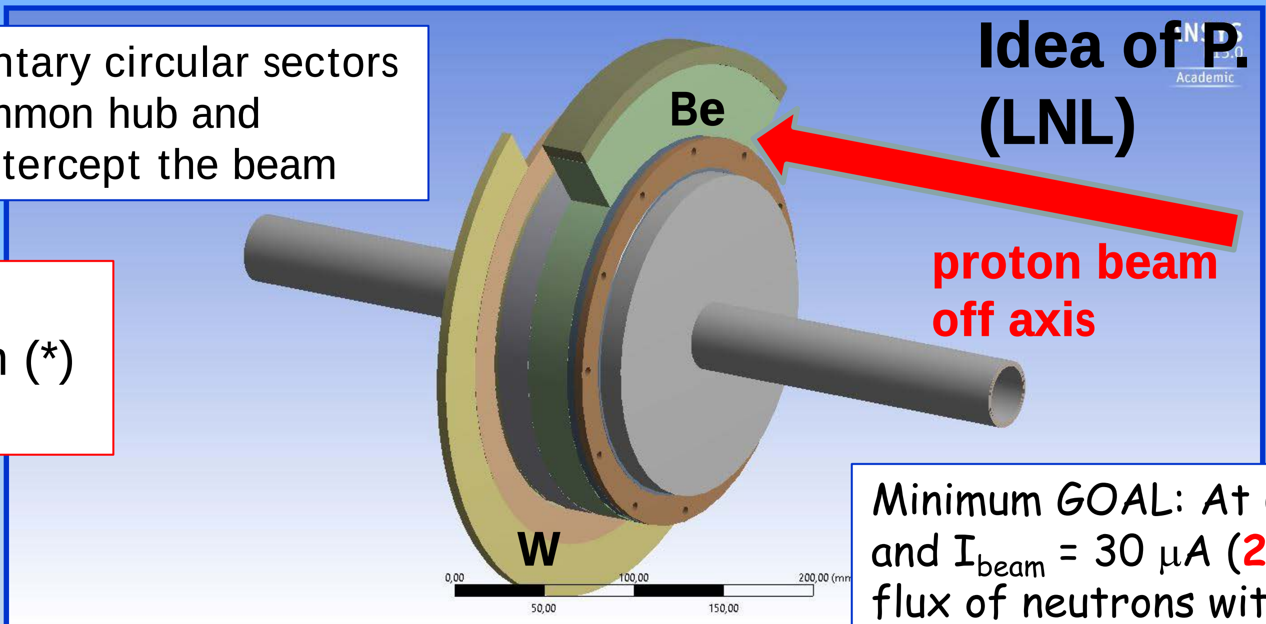
ANEM: a continuous energy neutron production target

A novel rotating composite target made of **thick** Be and W

An effective atmospheric-like neutron spectrum in the 1-65 MeV range is composed directly without the use of moderators.

Two complementary circular sectors rotate on a common hub and alternatively intercept the beam

Idea of P. Mastinu (LNL)



proton beam off axis

Thickness
Be: 24-26 mm (*)
W: 5 mm

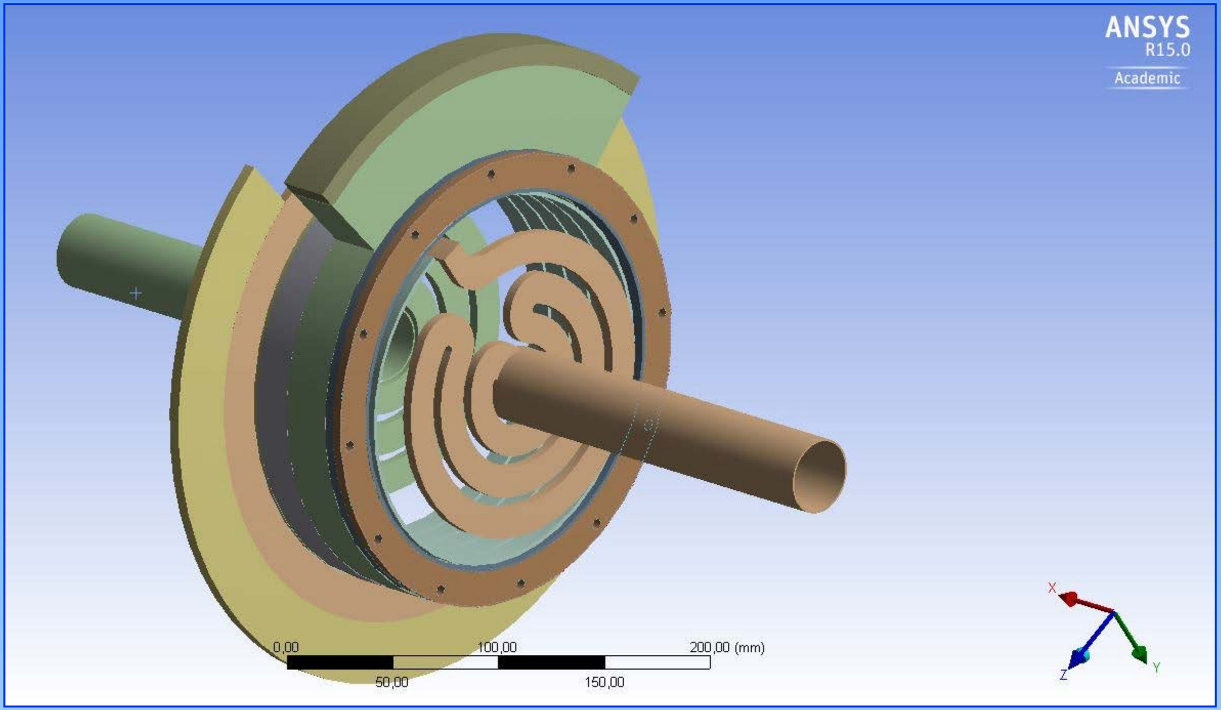
Minimum GOAL: At 6m distance and I_{beam} = 30 μA (**2.1 kW**) the flux of neutrons with E > 1 MeV is 3×10^9 times the natural one (comparable with factor expected at **ChipIR**).

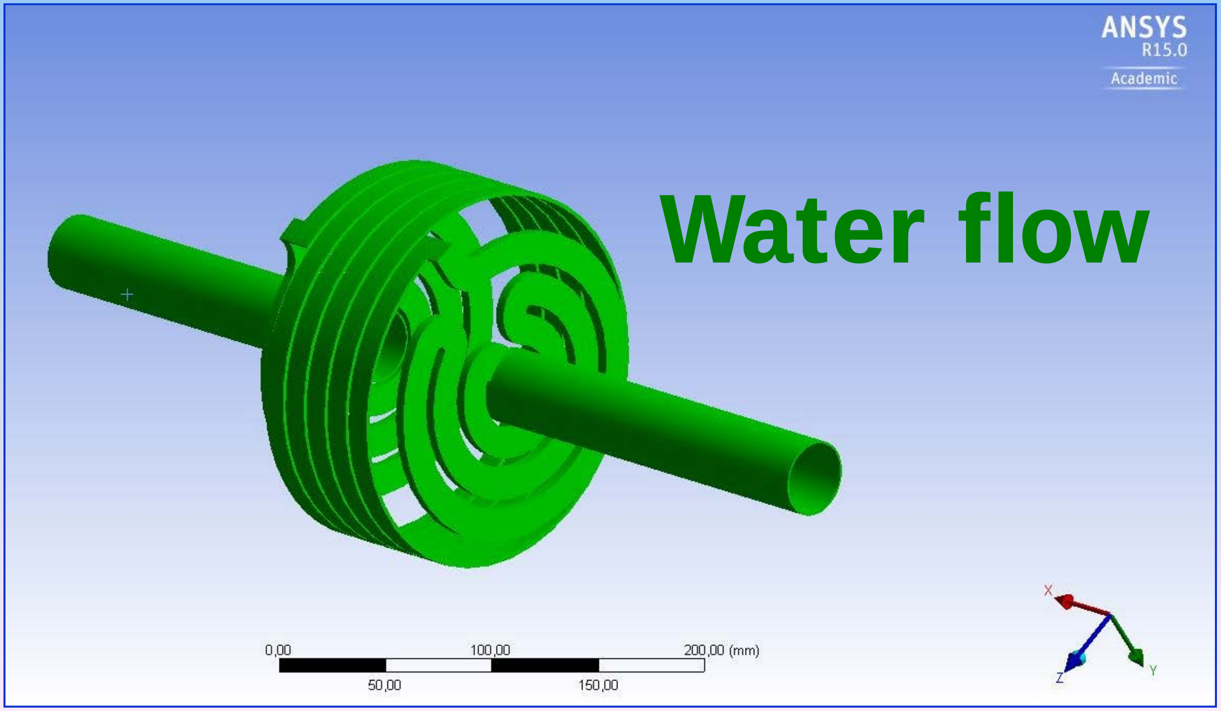
(*) The Be sector does not stop the protons (to avoid damage); most of the protons pass through without causing nuclear reactions. The emerging low energy protons are magnetically deflected towards a beam dump or **stopped in a thin copper slab**.

water cooling

P. Mastinu (LNL)

Detailed talk by Luca Silvestrin tomorrow





SLOWNE

- potential
- W-target
- Moderator, applications

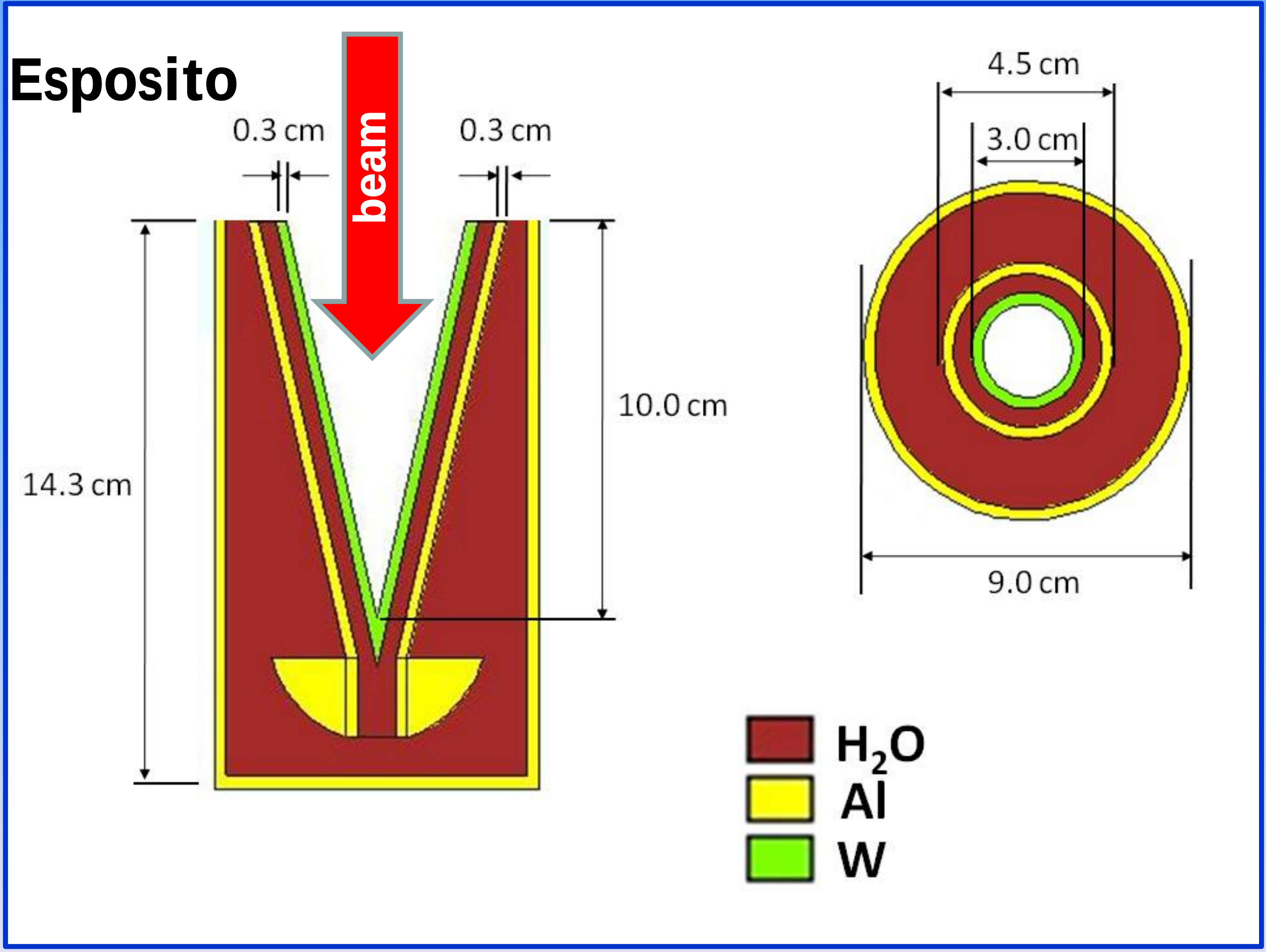
The **SLOWNE subsystem**

could be a used to **test novel ideas and techniques** for neutron science to be then used at ISIS (RAL) and the ESS. More in general this system would allow a new generation of European physicists and engineers to obtain precious (rare) first-hand experience in designing, constructing and performing neutron experiments .

SLOWNE thick W-target for various applications

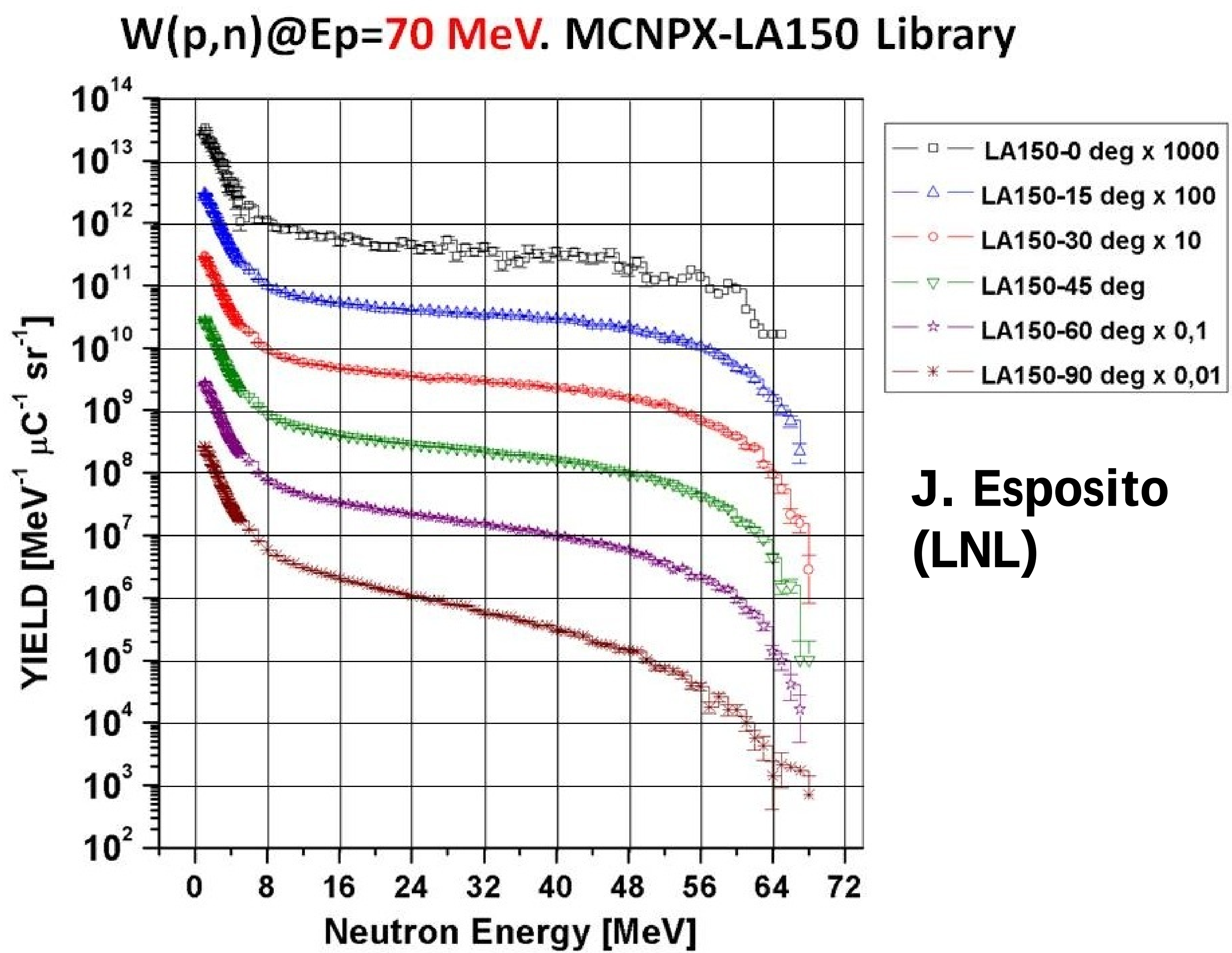
"thick" = the proton beam is stopped!

Idea of J. Esposito (LNL)



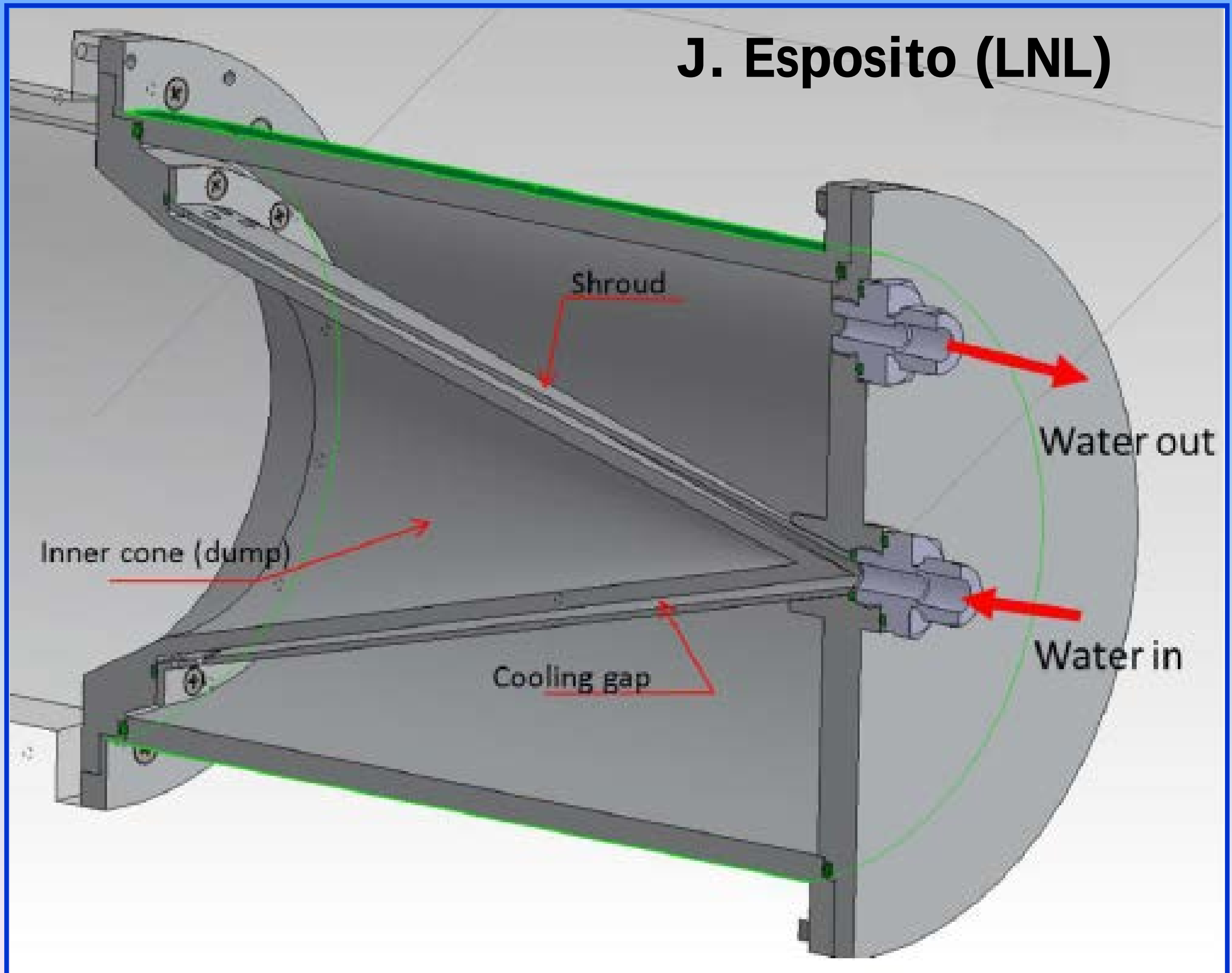
For high neutron intensity applications the target can handle full SPES power

A tungsten target is a ***wide angle source*** = the uniformity is good out to wide angles ⇒ can use a wide collimator and a short base line.



J. Esposito (LNL)

Variant for the “Low” Power Beam Dump of IFMIF



A moderator system

is then used to shift the energy of the neutrons and shape the energy spectrum to resemble the desired one for the application on the floor.

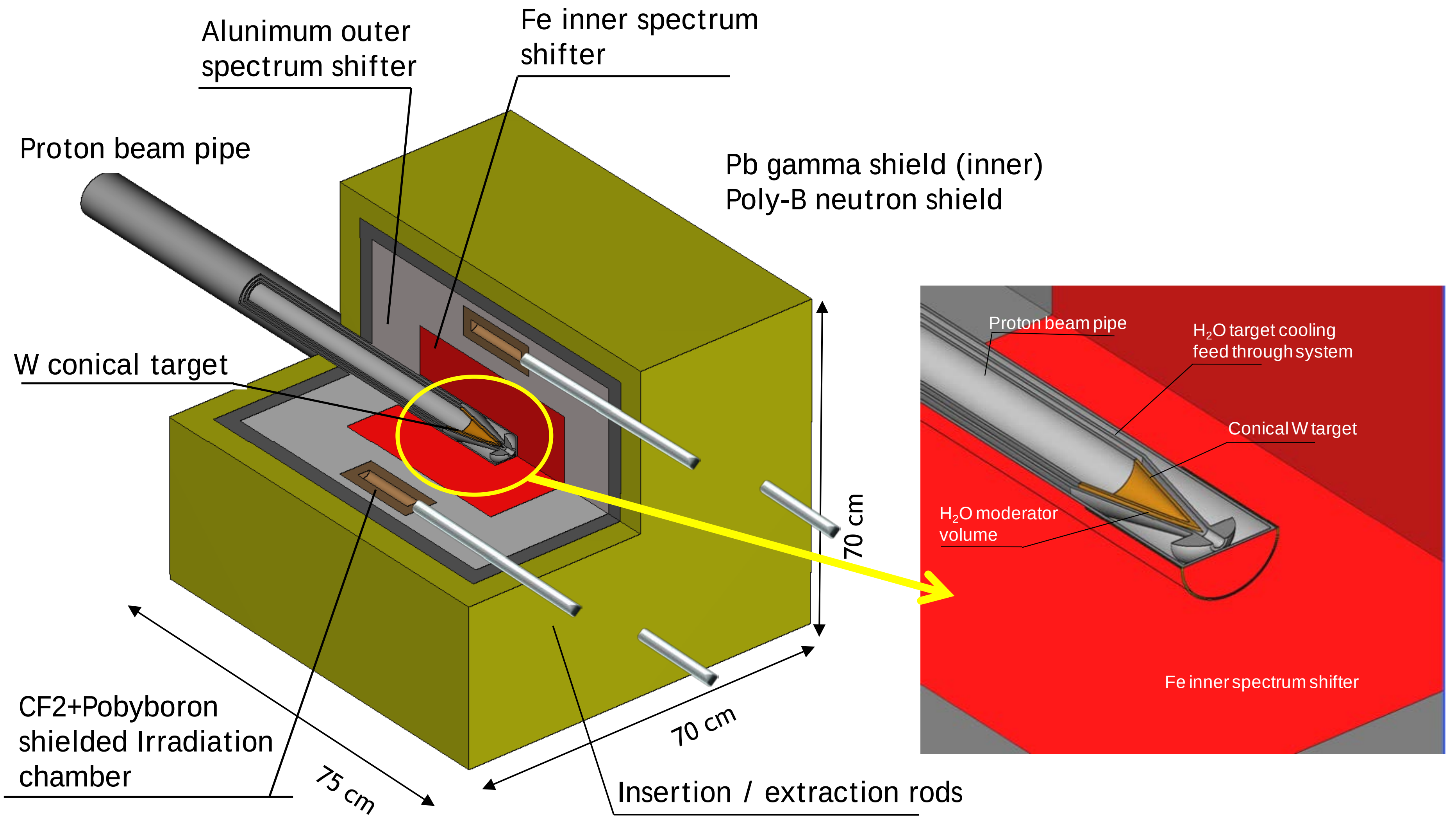
Examples of special applications:

1. Fast reactor simulator for transmutation studies (**FARETRA**)
2. Atmospheric neutrons

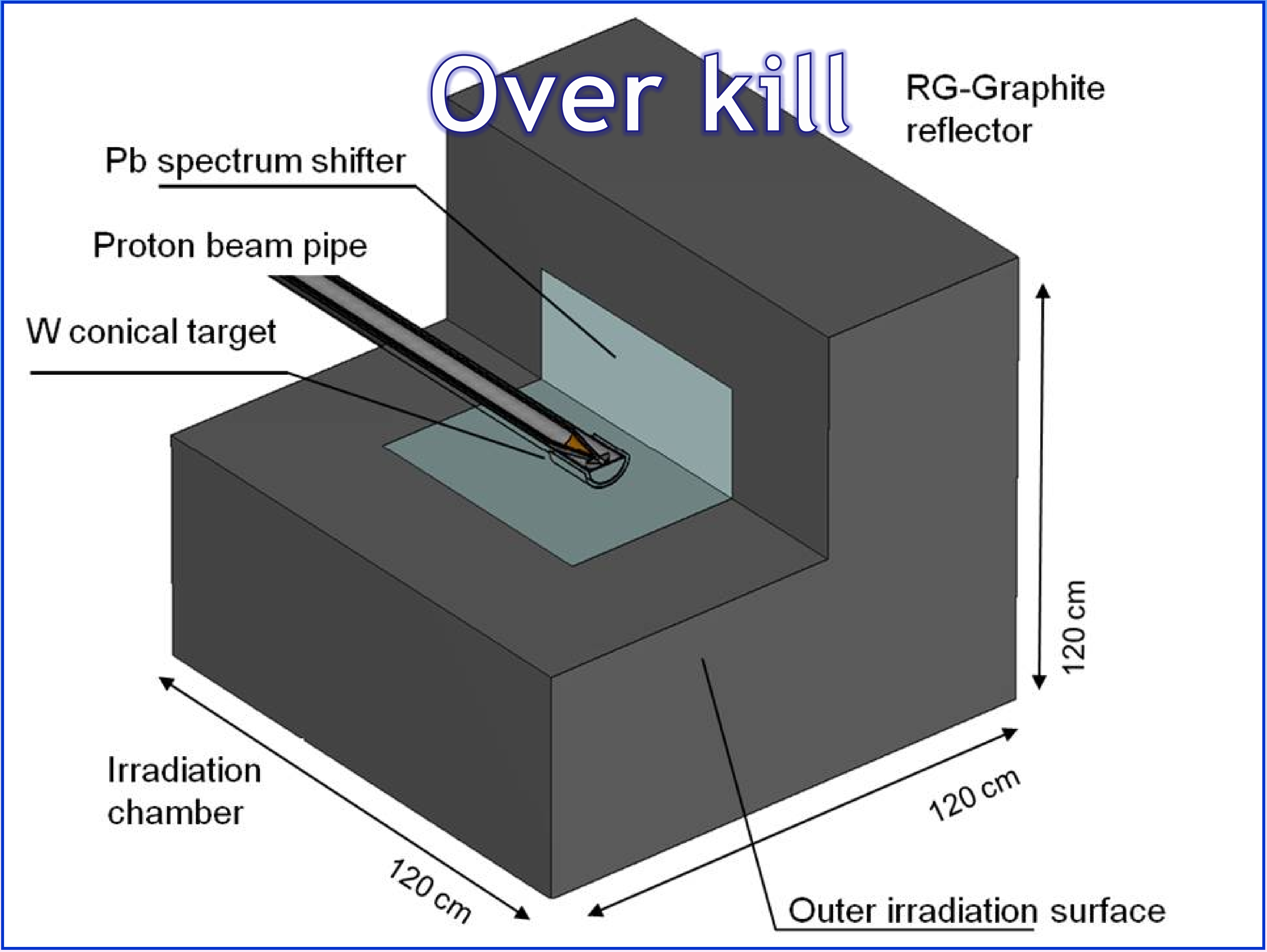
3. **neutron radiography**
4. **neutron scattering**
5. **Research on moderators**
6. **test novel ideas in neutron science techniques**

Preliminary system for FARETRA facility

original purpose of target



Preliminary system for atmospheric neutrons



situation

- Stalled
- looking for collaborators
- The present goal
- Work packages

- **At first** the LNL gave ***timid*** and fluctuating support,

- **but then** the work on the upcoming SPES facility absorbed all the human resources and **work on the project almost came to a halt!**

- **We did** manage continue to work on development of ANEM with INFN and University (Padova) funding.

- The SLOWNE target development is only indirect (IFMIF project)

At present, only feasibility studies and R&D of the ANEM, QMN and SLOWNE neutron production targets have been performed.

Our **present goal** is to complete a detailed conceptual and technical design study of the whole facility, a necessary step to obtain approval and funding for the final executive design and construction phase.

To this end, major progress requires significant human resources, beyond those presently available at LNL and Padova.

We are **searching for European partners**

- **universities;**
- **research institutions;**
- **private industries…**

to share the NEPIR project

An opportunity for Italy and Europe that SHOULD NOT be lost.

In particular

We are searching for partners to participate in **Horizon-2020 calls** such as **INFRADEV design study calls (expected in sept 2015)** for Research and Innovation Actions to **obtain funds for the international design team**.

The partners would sponsor their candidates to take part in the design study.

The completion of the study would then open a new phase for fund raising and construction.

Goal of design study

The goal of the NEPIR design-study is to address all major scientific and engineering issues of each of the subsystems, their integration, and the interaction with SPES and users. The objectives of the conceptual design study should:

- allow the realistic assessment of the four proposed subsystems of NEPIR;
- guide subsequent technical and executive designs;
- allow evaluation of construction costs;
- allow planning of a realistic construction time-table;
- address the interaction with the SPES complex (beam-time for NEPIR users);
- estimate running costs;
- address priorities to ensure an efficient exploitation of the new facility from start-up.


TO-DO LIST:
1.
2. EVERYTHING
3.

NEPIR work packages

Design issues (Work Packages)	status	Priority	work force
QMN and ANEM beam line optics	started	High	LNL
QMN target system	-	High	LNL
QMN beam dump	good	High	LNL
QMN magnet	soon to be started	High	
QMN collimator system	-	High	
Time-of-flight system	-	High	LNL
Rotating Be-W target (Atmospheric Neutron Emulator)	good	High	University & INFN Padova
Energy degrader system (to lower proton energy from 35 MeV to 20 MeV or less)	-	Medium	
neutron beam characterization, dosimetry	-	Medium	
Radioprotection (local shielding)	-	Medium	
High power W target for slow neutrons	-	Medium	
Slow neutron beam line	-	Medium	
Proton beam line	-	Low	

Some opinions for discussion

E-mails from:
Christopher Frost (Chip-IR, ISIS, RAL)
Roger Pynn (Indiana University)

Christopher Frost
ISIS, CHIP-IR

“The areas I think for collaborations [with LNL] are:

A QMN source is important as a complementary source to the broadband sources - ideally this would go to the same kind of energies as TSL 1(180MeV) but as the threshold energies are in the low MeV and rise up through to 100MeV, you would be able to provide key information even with a lower energy source; *if you could lower the QMN source down to 1MeV that would help.*

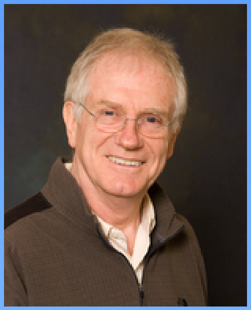
Calibrations and development of fast neutron detection techniques (which may eventually extend to on-board devices) also require QMN sources; colleagues have recently been to TSL with some of our diamond detectors to look at the QMN response.

The acceleration factor of 3**10^(8-9) in the 1-70MeV is useful for many devices.
I think it is the combination of QMN and atmospheric that should be pushed (i.e. like TSL) as this is not available at ISIS and is therefore very complementary.

The other area is tuneable flux - some problems require a lower flux than Chip-IR and our ability to vary is limited (as we are part of larger complex); the ability for user control of flux to lower levels is also complementary.”

Roger Pynn

Indiana University

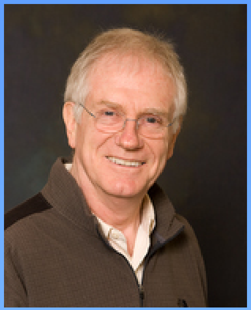


“Both proton and neutron irradiation activities using high energy particles are **obviously useful** and will allow you to **attract industrial customers**.
Research on neutron moderators and new ideas for neutron instrumentation are also obvious candidates as is training at the graduate level.
Radiography might also be an opportunity.

I doubt that such a facility can become a neutron scattering user center because there will be almost no users who are willing to spend their travel funds to come to a center where experiments, if they can be done at all, take 10 times longer than at a top flight neutron source. You might manage to attract a few local university faculty and perhaps there are some special neutron experiments that involve long set-up times that are also feasible.

My own opinion is that the **neutron scattering "ecology"** is becoming increasingly unbalanced in a way that cannot end well unless we begin to build some small sources for the **purposes referred to above**.”

Roger Pynn
Indiana University



Unbalanced neutron scattering "ecology"

“There will be no use for topnotch facilities like the ESS if no one knows how to exploit them except for a few instrument scientists at the facility.

And if only internal scientists do experiments at the forefront facilities it is hard to imagine where the political pressure to build further sources will come from.

Europe's success in neutron scattering relied on the presence of national **reactor sources**, many of which are now closed (with more to follow over the next decade).”

Thanks for your attention

Extra slides

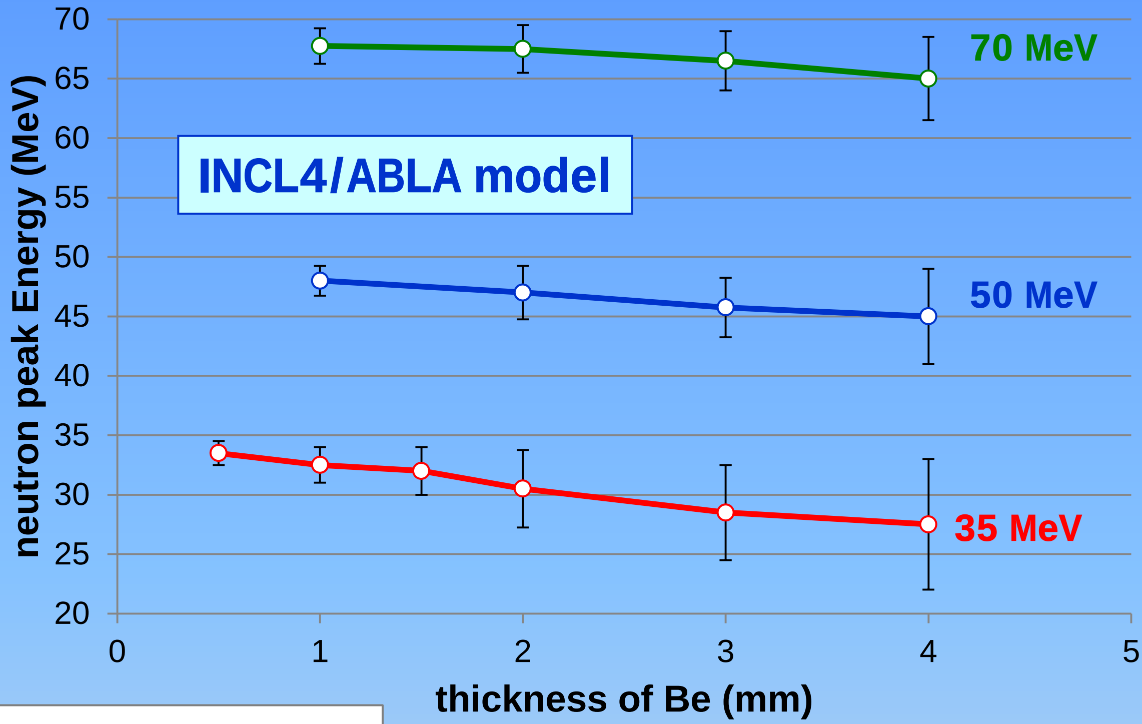
The estimated cost of the first phase of NEPIR (QMN and ANEM) is reported in the Table below. It is based on the optics reported in Figure 2. Although the table is for the moment not complete, we estimate that the total cost at about 2 MEuro.

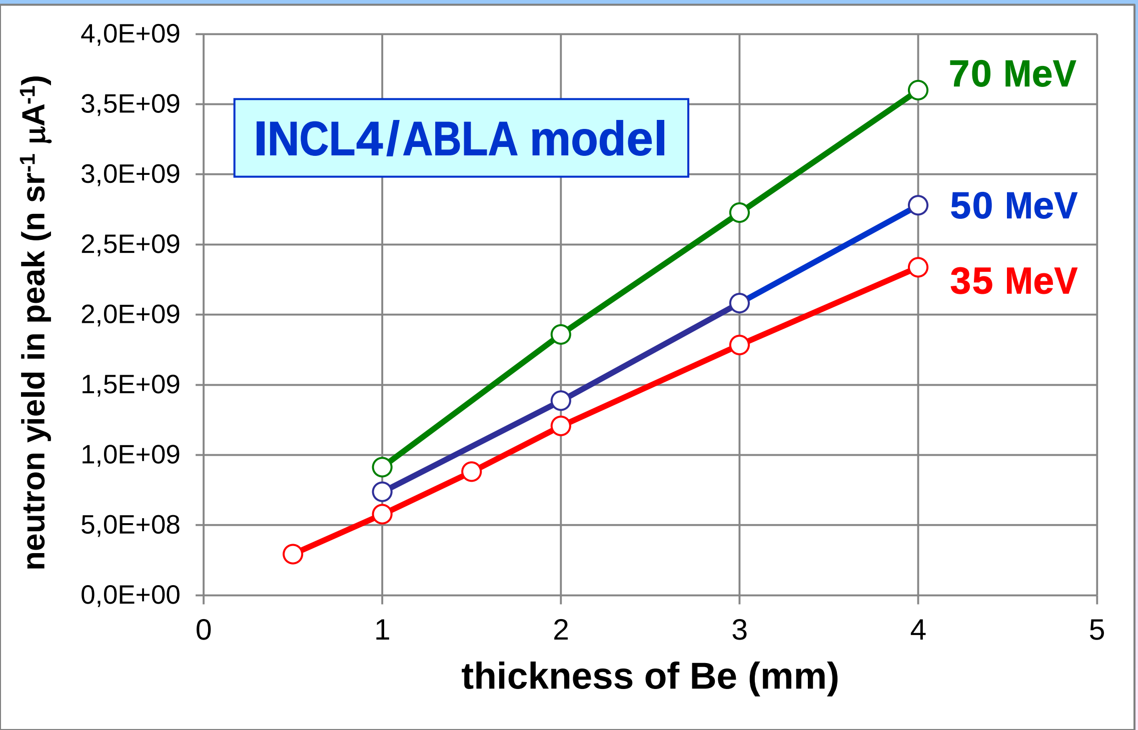
Item (description)	Cost (kEuro)	Incidence rate/item (%) Referred to total 2 MEuro
Two dipoles (magnet + supply)	500	25
5 quadrupoles (magnet + supply)	500	25
Bending magnet of spent protons	125	6.25
Two faraday cups (hardware + control)	10	0.5
Two pumping groups	20	1
Platform structure in Al (65 m^2)	150	7.5
Beam dump	50	2.5
Multi-angle collimator structure	?	?
Supplementary shielding	?	?
QMN target system	50	2.5
ANEM rotating target system	150	7.5
total	1555 + ?	-

Forward (0º) neutrons

The mean energy of the neutrons under the peak and the peak shape are degraded by the target.

Figure on the right: value of the neutron peak energy ± FWHM/2

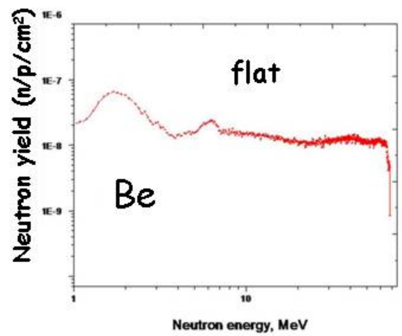




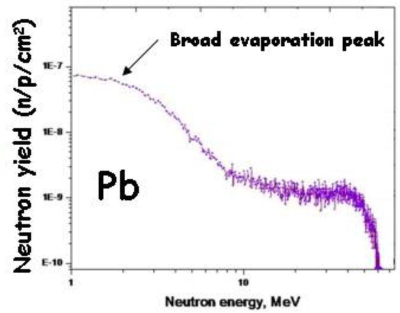
If the target is thin the neutron flux scales linearly with the thickness of the target (more nuclei).

Figure on the left: yield of neutrons in the energy peak (n sr^{-1} μA^{-1})

Energy spectrum of the Novel composite Target (PbBe variant)



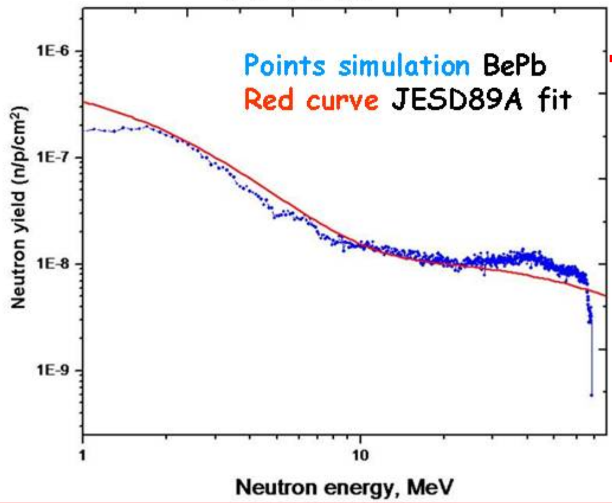
$E_p = 70$ MeV



Be 23%

Pb 77%

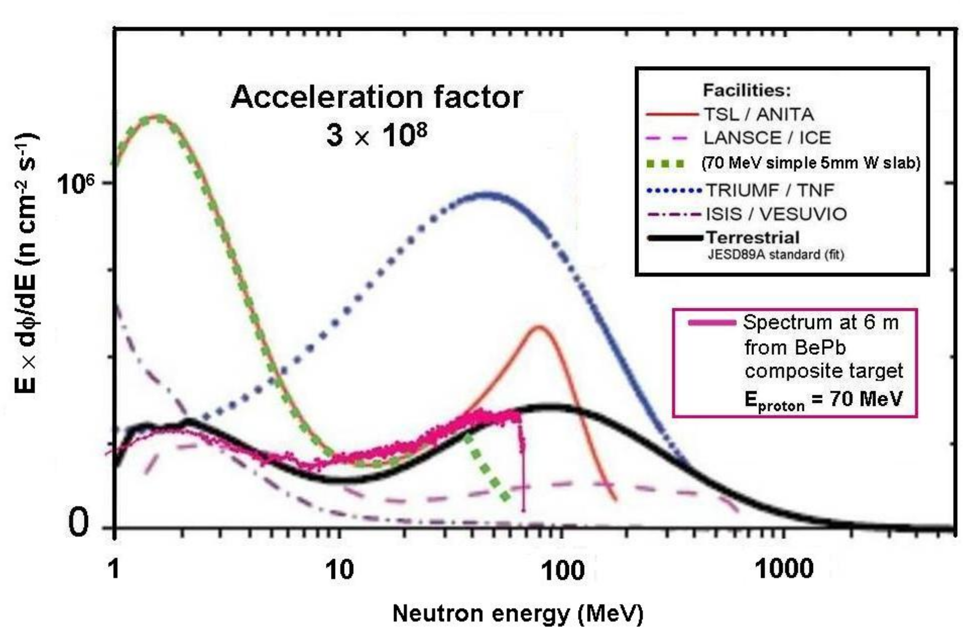
At 6m from target acceleration factor = 3×10^8 for $I_{protons} = 1\ \mu A$



Fast neutrons!
No moderators

Atmospheric neutrons at sea level New York integrated flux E > 1 MeV = 21 $cm^{-2}\ hr^{-1}$

Lethargy representation



Acceleration factors of few 10^9 can be achieved with few tens of μA

Forward (0º) neutrons

Current to have an integral flux $\Phi_{peak} = 3\times10^5$ n cm^{-2} s^{-1} (*) of neutrons in the energy peak at a distance of **3.50 m (*) from the thin target**			
Models	**Proton energy (MeV)**	**1 mm Be**	**2 mm Be**
INCL4-ABLA / CEM03	**70**	**40 / 41 μA**	**20 / 21 μA**
	50	**50 / 36 μA**	**27 / 18 μA**
	35	**64 / 42 μA**	**31 / 18 μA**

(*) TSL-like

$$\Phi_{peak} = \int_{peak} \frac{d\phi}{dE} dE = 3\times10^5 n\cdot cm^{-2}\cdot s^{-1}$$

The current scales with 1/distance^2

We conclude that by using thin Be targets there is ample margin at the SPES facility to reach $\Phi_{peak} = 10^6$ n cm^{-2} s^{-1} if the distance from the target is not too large.