A neutron facility at the INFN-LNL

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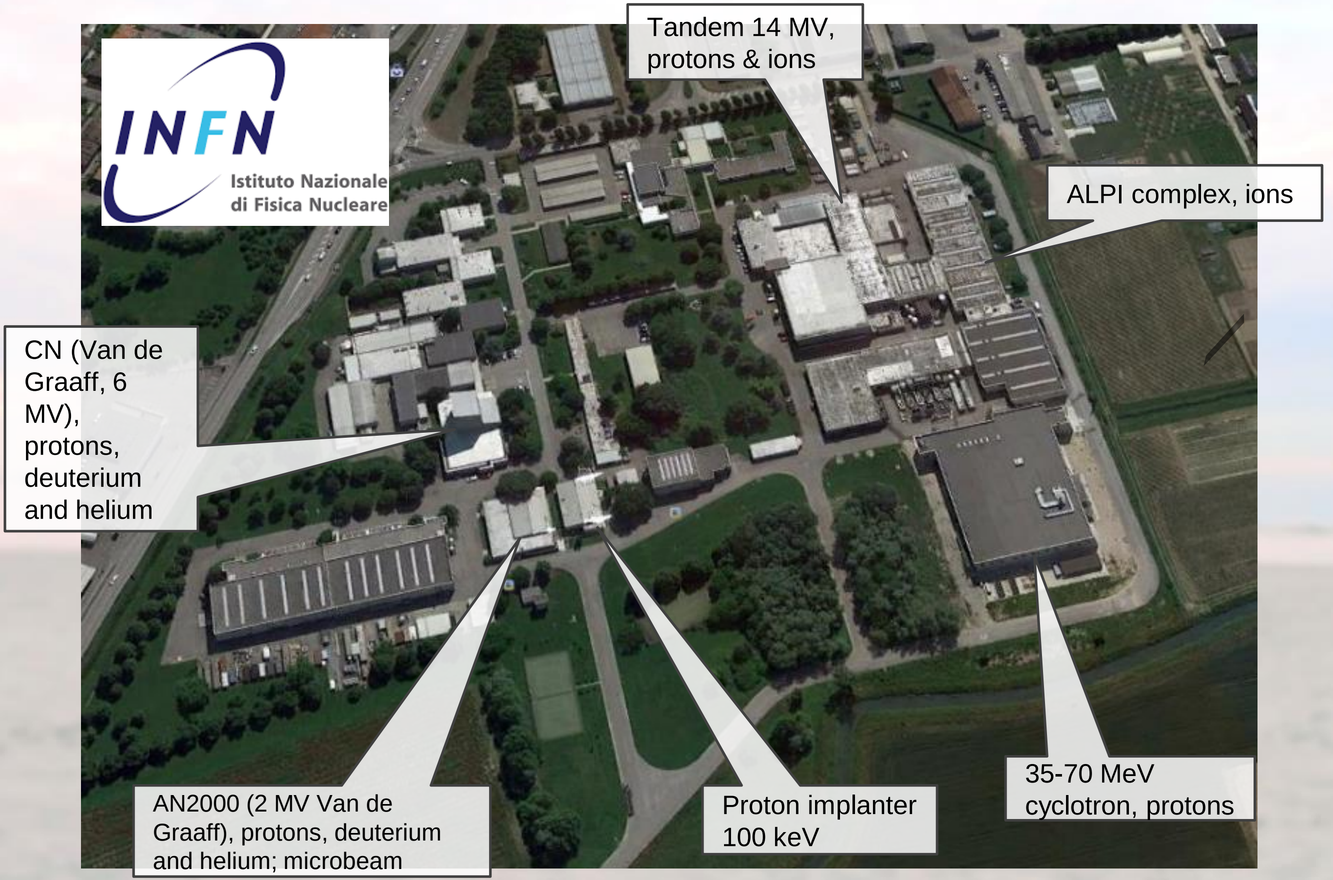
Outline

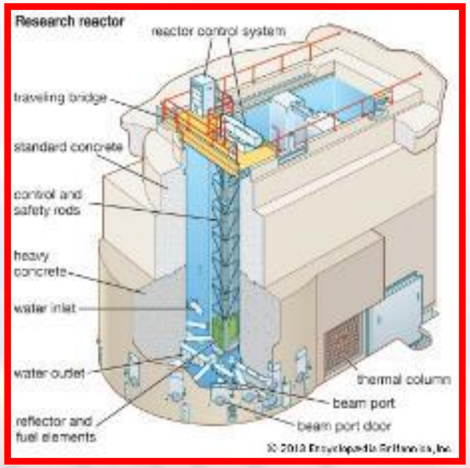
- Introduction
- NEPIR facility
  - Quasi-monoenergetc neutron facility
  - White spectrum neutron facility
- Atmospheric neutron emulator

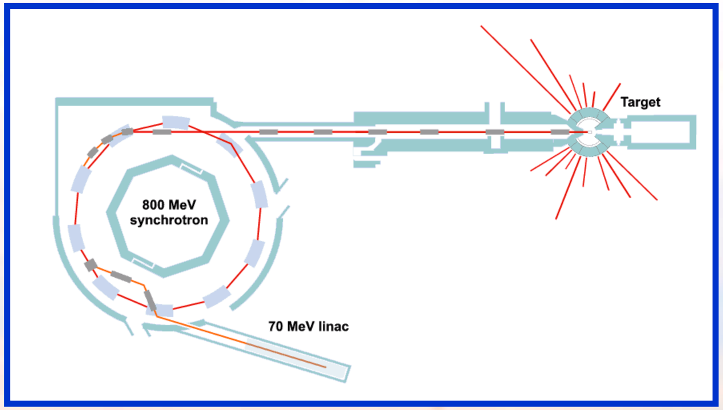


Background

Practical general-purpose neutron facilities are of two types:

1. **research reactors (fission reactions)**
2. **accelerator-driven sources** (non-fission nuclear reactions)
   - **Large High-energy accelerator spallation sources**
   - **Compact low energy accelerators (non-spallation sources)**





- Reactor sources play an essential role in materials characterization and other research purposes, **but some are going into closure** (Berlin; Orpheé;…). ☺ ⟶ ☹
- Present and future high-energy spallation sources (ISIS at RAL; ESS;…), in spite of their high neutron yields and sophisticated instrumentation **achievable at great costs (expensive)**, hey will **barely fulfill the demands** of the large neutron user community for materials research, let alone of other emerging important fields and disciplines. ☺ ⟶ 😐 ⟶ ☹

Neutrons at Legnaro

Compact Accelerator Driven Neutron Sources (CANS) have shown promising capabilities in bridging the **capacity insufficiency** and the **expanse of cross-disciplinary neutron applications.**

- **NEutron and Proton IRradiation (NEPIR) complex**. UNDER DEVELOPMENT

NEPIR is driven by the high power 30-70 MeV proton cyclotron (I_{max}=750 uA) of the SPES project and consists of 3 subsystems:

I. **QMN**: delivers quasi mono-energetic neutrons in the 20-70 MeV range

II. **ANEM**: delivers *atmospheric-like* neutrons in the 1-70 MeV range

III. **PROTON**: a direct proton (35-70 MeV) irradiation line (not this talk)

- **Legnaro Slow Neutron Source (LSNS)** FUTURE DEVELOPMENT

LSNS encompasses state-of-the-art **A**ccelerator-driven, **B**rilliant, and **C**ompact **N**eutron **S**ources (**ABC NS**) and cross-disciplinary R&D. It delivers cold, thermal, and epithermal neutrons.

NEPIR

Fast neutrons (E_n > 1 MeV)

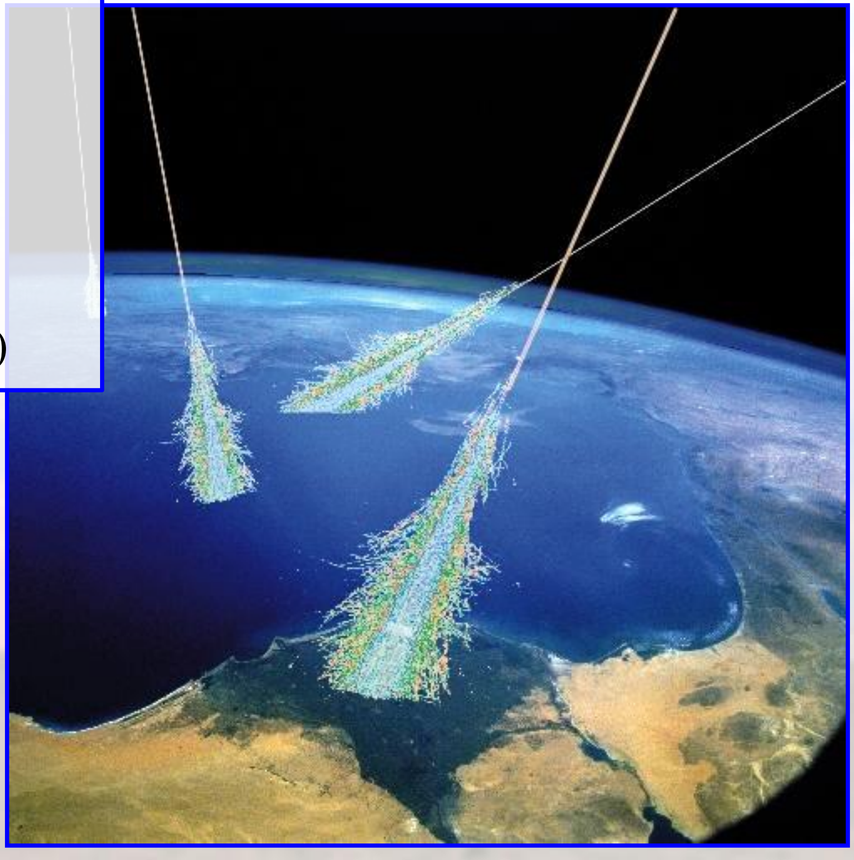
- Three subsystems: **QMN**, **ANEM** and **PROTON**
- Originally conceived to study of **radiation damage effects in electronic devices and systems** induced by:
  - flight-altitude and sea-level *atmospheric* **neutrons**
  - solar **protons**
- **They will be also used to perform:**
  - physics cross-section measurements,
  - biological samples irradiation,
  - shielding performance evaluation,
  - material degradation studies,
  - …

Radiation effects

Ionizing radiation can interfere with the proper operation of electronic devices, causing temporary unwanted effects (soft errors) or permanent failures (hard errors).

Neutrons in cosmic-ray air-showers are a widening problem for industry:

- Aviation
- Automotive
- Trains
- Information technolgy and Infrastructure
- Medical (e.g. pace makers,...)

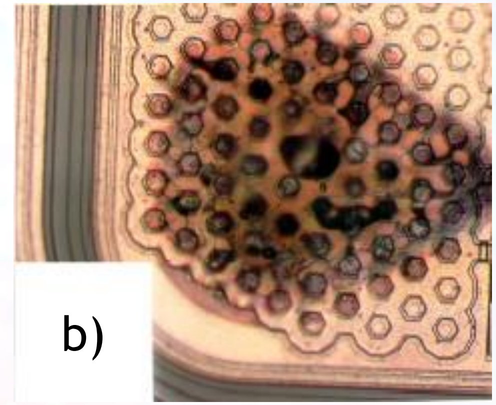


Soft error

Qantas Flight 72 (QF72) was a scheduled flight from Singapore […] to Perth […] on 7 October 2008 that made an emergency landing […] following an inflight accident featuring a pair of sudden **uncommanded pitch-down manoeuvres** that resulted in serious injuries to many of the occupants.
One of the aircraft's three air data inertial reference units (ADIRU 1) exhibited a **data-spike failure mode**, during which it transmitted a significant amount of incorrect data on air data parameters to other aircraft systems…

Australian Transport Safety Beureau
Aviation Occurrence Investigation Report
AO-2008-070

Hard error



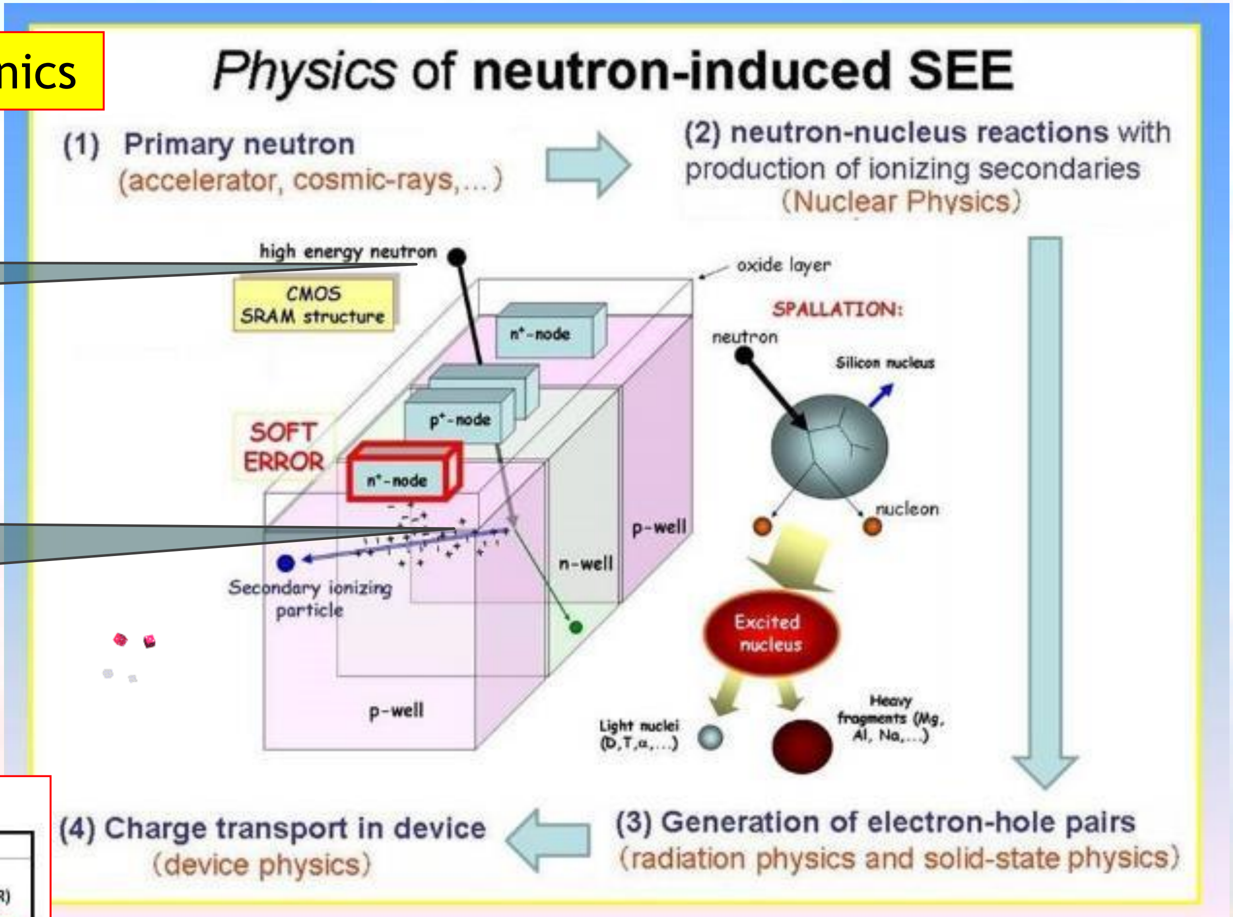
Destructive single event effect on a commercial 120 V power MOSFET in a DC-DC power supply.

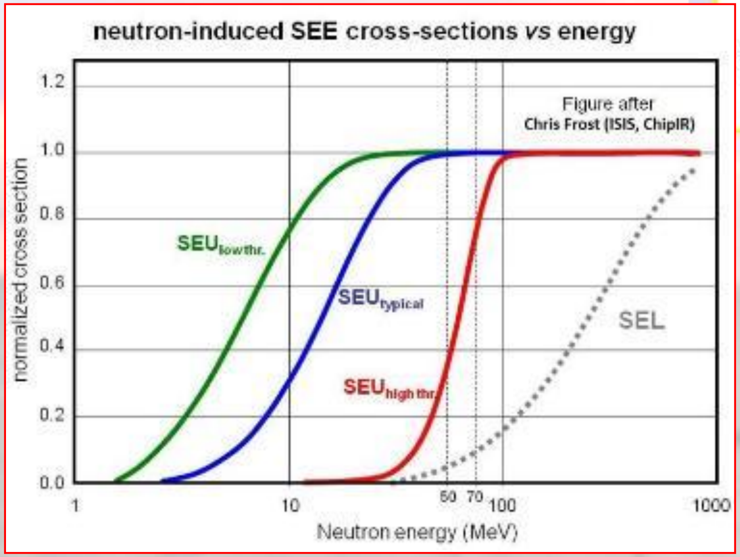
"Radiation induced single events could be happening on everyone's PC, but instead everybody curses Microsoft."
Paul Dodd, Sandia National Laboratories

Radiation effects on electronics

If a neutron (proton) is fast enough…

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





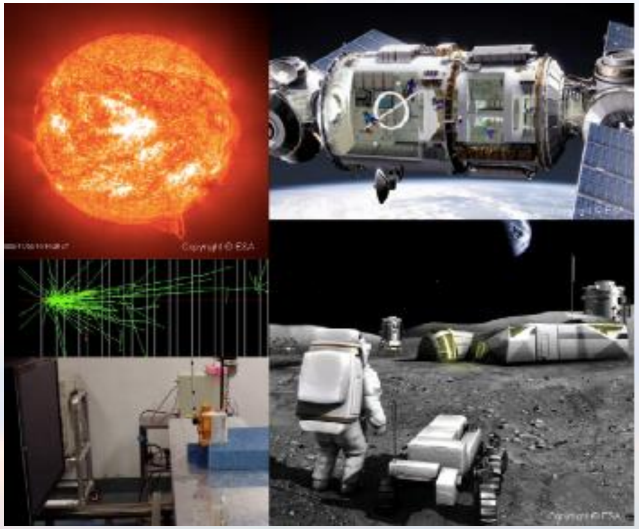
Reference cross-section for *"Soft Errors"* such as **SEUpset in digital electronics:**

$$\sigma_{SEU} = 10^{-14}\ \mathrm{cm^2/bit},$$

$$N_{bits}\ \text{per device} = 4 \times 10^6 \uparrow$$

The neutron facility is currently financed by SPARE (Space Radiation Shielding)

SPARE is a project involving ASI, INFN and Centro Fermi. The goal is to perform a test campaign to investigate the effectiveness of active and passive shielding materials for the human activity on Mars, using the proton beam facility at TIFPA (Trento Institute for Fundamental Physics Applications) with E_p = 70-228 MeV and fast neutron beams at the LNL-NEPIR facility (under development) E_p= 30-70 MeV.

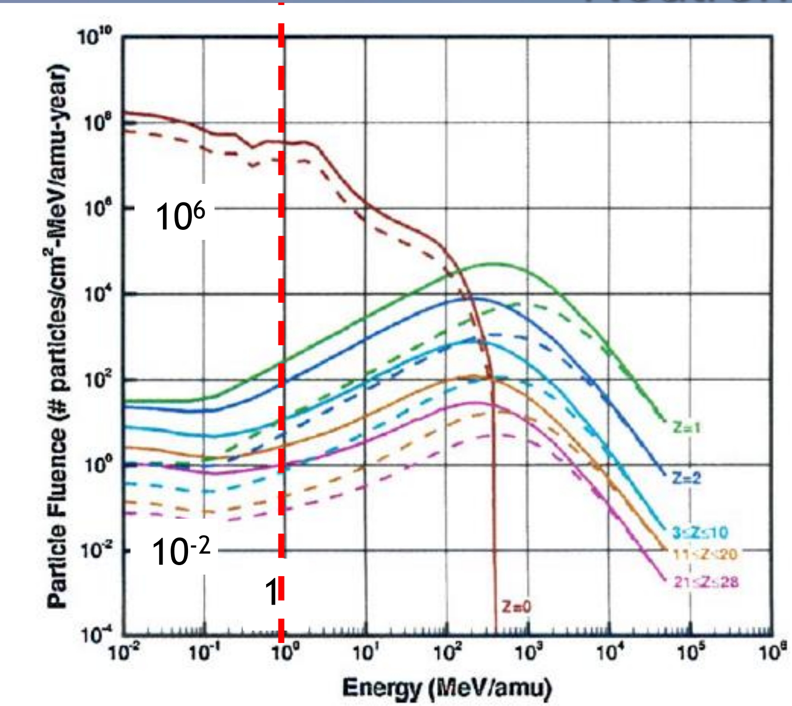


We have designed two versions:

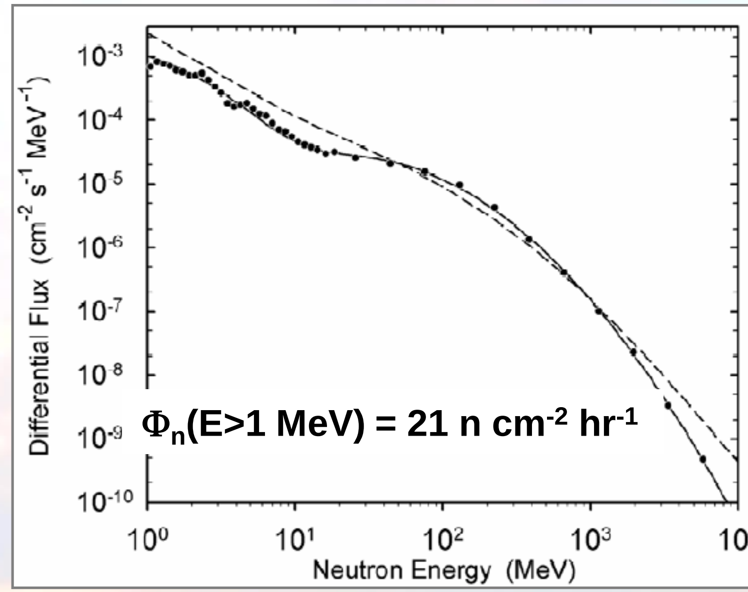
1) **true QMN**
2) **pseudo QMN**

The choice will depend on how the funds will be shared (under negotiation).
Additional funds will be necessary to provide QMN beams.

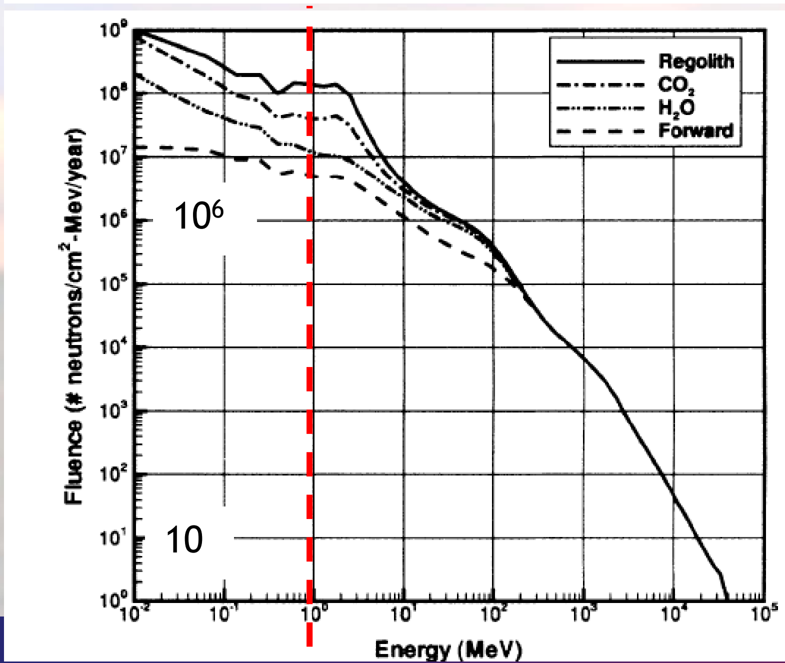
Neutrons on Mars and Moon



The galactic cosmic rays environment on the lunar surface is shown at solar minimum (dashed lines) and solar maximum (solid line). Z=0 corresponds to neutrons, which can be up to hundredths of MeV



The energetic (E > 1 MeV) neutron flux on earth is 21 N cm^{-2} s^{-1}; for comparison; on the surface of the Moon it's 3 orders or magnitude higher, as on the surface of the Moon where the spectrum is harder.



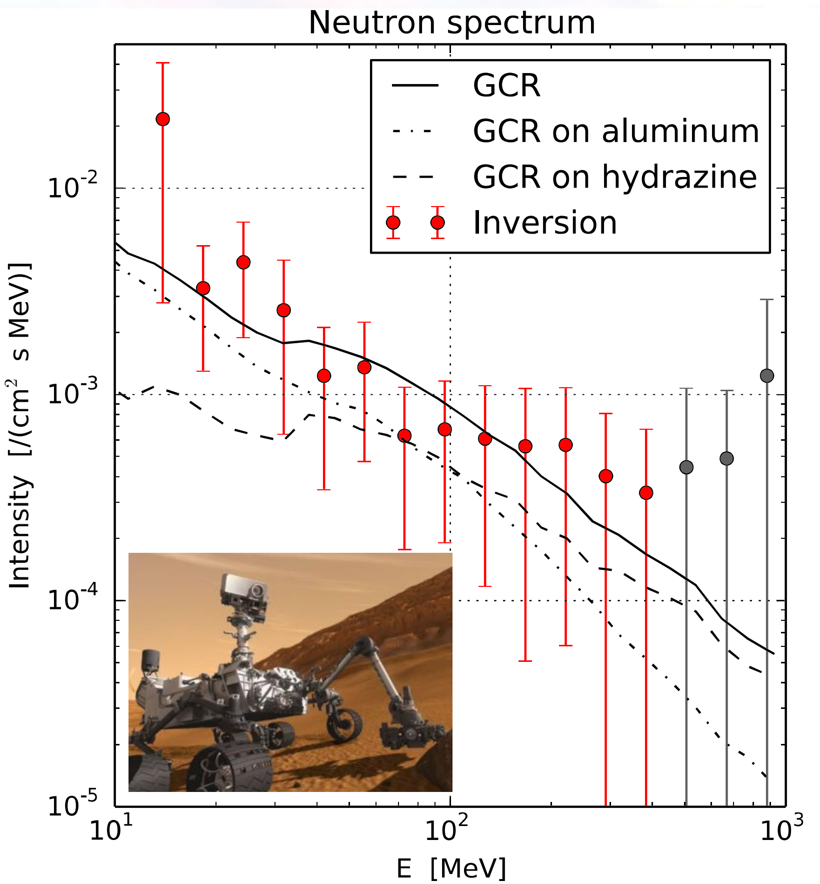
Mars surface neutron environment with 16 g/cm^2 CO_2 overhead and various surface material compositions.

Secondary particles from spacecraft material

Galactic cosmic rays are the dominant source of dose in a deep space mission, estimated to be around 1.8 mSv/day.

Mission	Altitude (km)	Neutron dose rate (μGy/day)	Charged particle dose rate (μGy/day)	Neutron equivalent dose rate (μSv/day)	Charged particle equivalent dose rate (μSv/day)
STS-55	302	5.9	57.2	52.0	120.1
STS-57	470	25.3	461.9	220.0	859.4
STS-65	306	11.0	75.2	95.0	157.8
STS-94	296	3.7	101.5	30.8	213.9

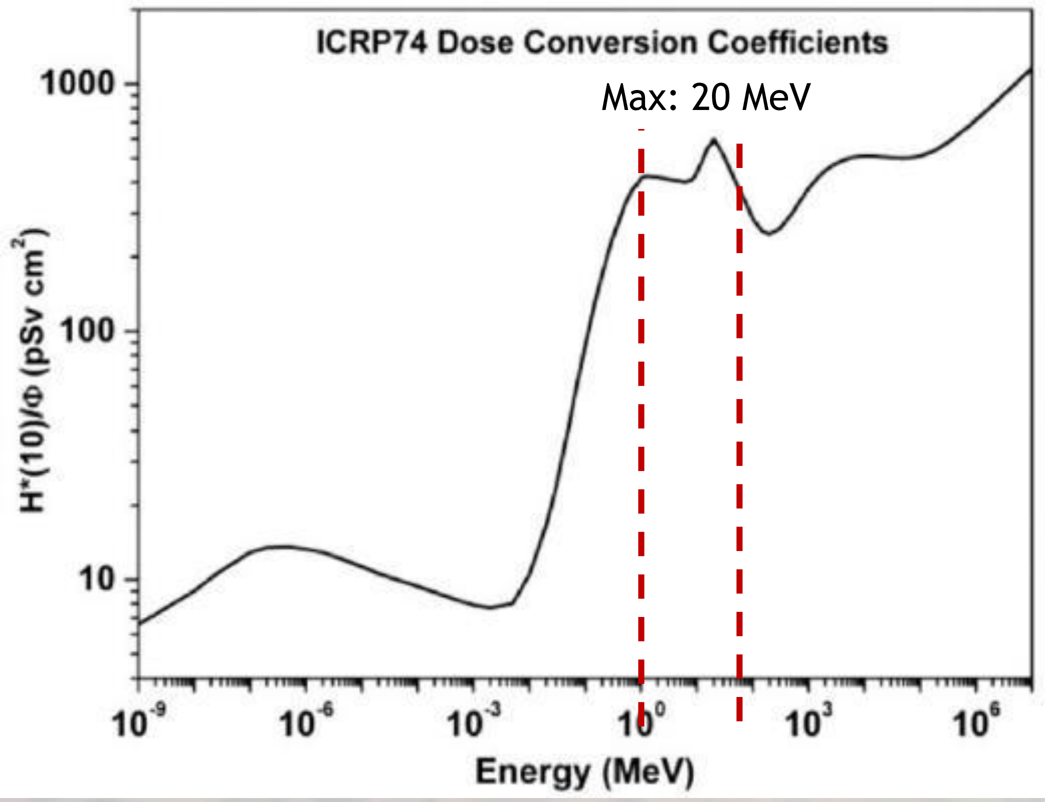
Comparison between dose and dose equivalents for neutrons and charged particles in four different Space Shuttle missions at 28.5° inclination in LEO.
Neutron dose (measured by nuclear emulsion) can account for 13-38% of the dose due to charged particles (measured by TLD-100 detectors).
Durante, M. & Cucinotta, F. A. Physical basis of radiation protection in space travel. Rev. Mod. Phys. 83, (2011)



Neutron energy spectrum measured by Mars Science Laboratory mission in deep space during the transit to Mars
Köhler, J. et al., Life Sci. Space Res. 5, 6–12 (2015)

Quasi Mono-energetic Neutron (QMN) reference fields allow one to study energy dependent neutron interaction mechanisms with matter, be it electronic, detector, dosimeter material, or living tissue…

In the context of SPARE,
the QMN beam to be developed at NEPIR (LNL, 30-70 MeV protons) will be used to perform bench mark shielding measurements for spacecraft and planetary bases.

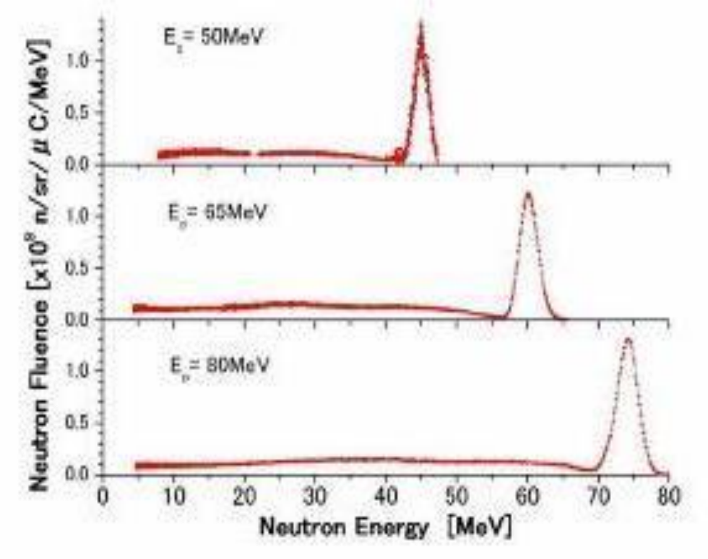


Log-log plot of the relationship between the neutron energy and the equivalent dose delivered by a neutron beam.

It is particularly complicated in the MeV to tens of MeV energy rage, where the local maximum is located.

This energy interval is accessible at the LNL neutron facility.

(Fast) Quasi Monoenergetic Neutrons



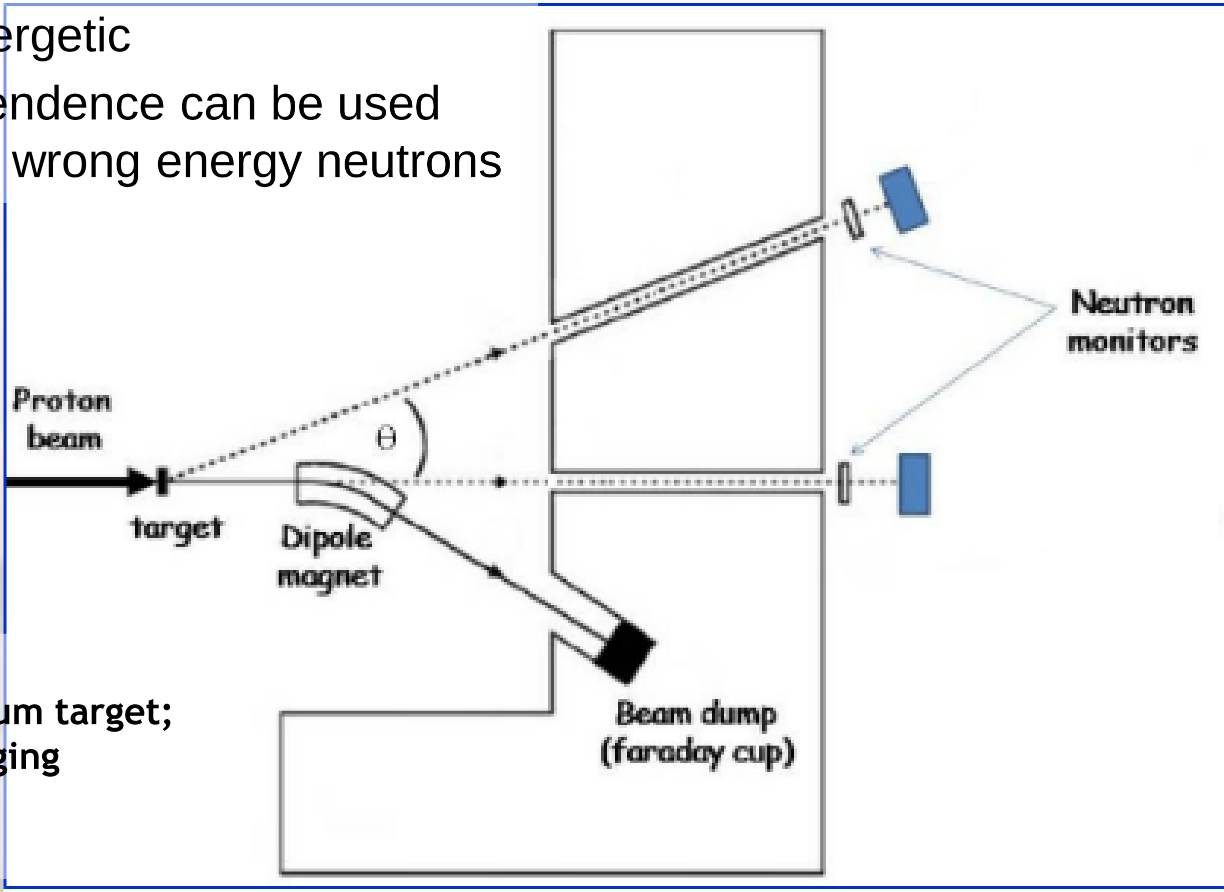
Forward (θ = 0°) QMN energy spectra beams for different proton beam energies on a thin (non beam-stopping) Lithium target

[TIARA facility, Japan].

Performance of different QMN sources (from Lithium) beams around the world.

LAB	Energy of the protons (MeV)	Distance (m) of target to the test point	Mono-energetic neutron (peak) flux at the test point
TIARA (Japan)	40-90	12.9	~3.5-5 $\times 10^3$ n cm^{-2} s^{-1} for max 1-3 μA
CYRIC (Japan)	14-80	1.2	10^6 n cm^{-2} for 3 μA
RCNP (Japan)	100-400	10	10^4 n cm^{-2} s^{-1} for 1 μA
ANITA (Sweden)	25-200	3.73	~ 3×10^5 n cm^{-2} s^{-1} for max 5-10 μA
NFS (France) *UNDER CONSTR.*	1-40	5	~ 8×10^7 n cm^{-2} s^{-1} for 50 μA, 40 MeV
iTHEMBA (South Africa)	25-200	8	1-1.5 $\times 10^4$ n cm^{-2} s^{-1} for typical 3 μA
QMN (LNL) ***PROPOSED***	**30-70**	**3**	**~ 2.6×10^5 n cm^{-2} s^{-1} for 10 μA, 70 MeV**

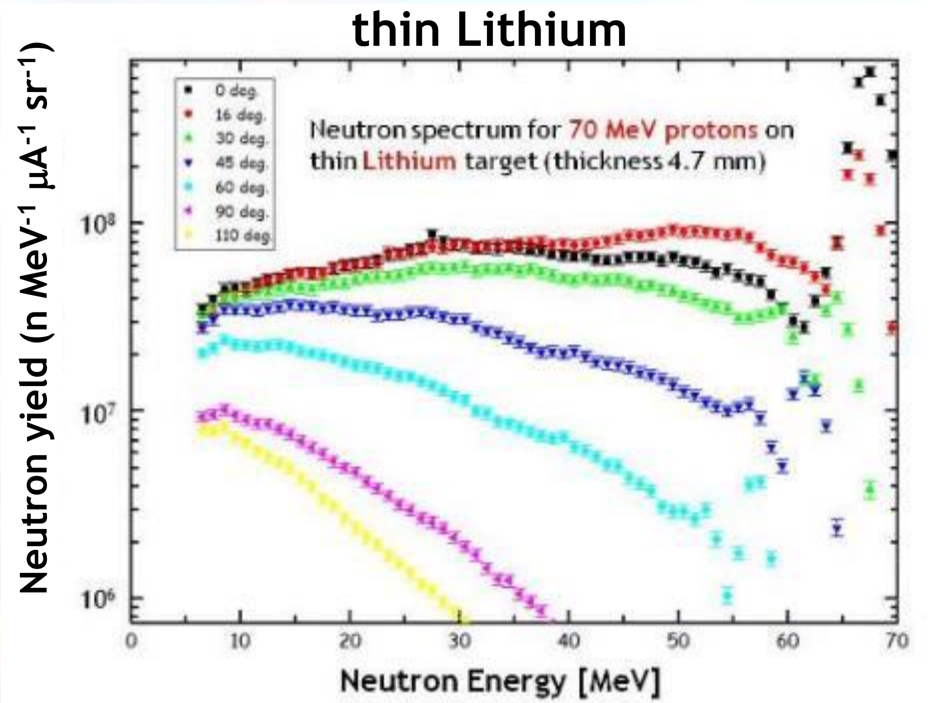
- ❑ Multi-disciplinary interest
- ❑ Energy dependent neutron-induced effects
  (e.g. measure the cross-section vs energy curve)
- ❑ Quasi ideal to study energy dependence
  - not 100% mono-energetic
  - strong angular dependence can be used to subract away the wrong energy neutrons



QMN concept:
- **Thin (few mm) lithium or beryllium target;**
- **Bending magnet to deflect emerging proton towards a beam dump;**
- **Collimator.**

QMN Neutron yield angular dependence

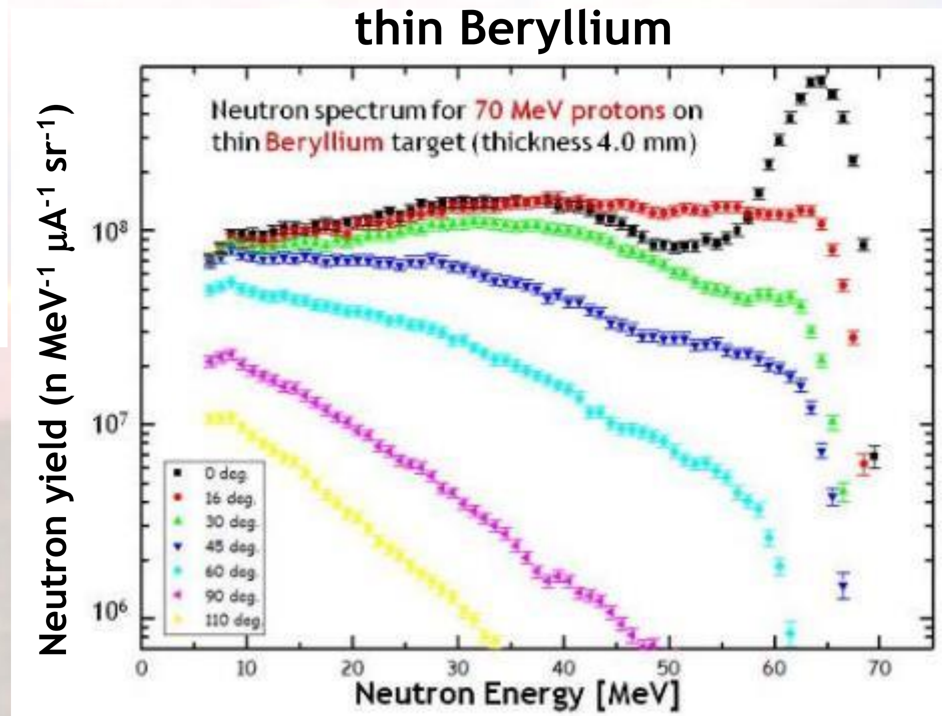
The “good” truly mono-energetic neutrons are produced mainly in the direction of the proton beam (forward, $\theta = 0$); wrong-energy neutrons are not as directional.



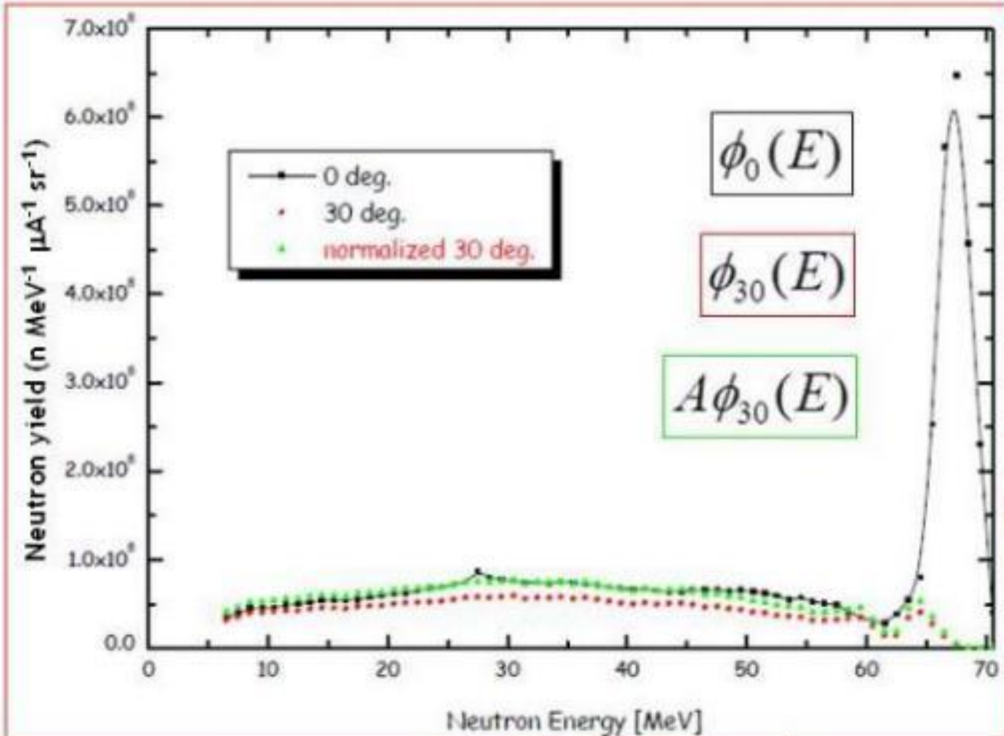
Angular dependence at $E_{proton} = 70$ MeV

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

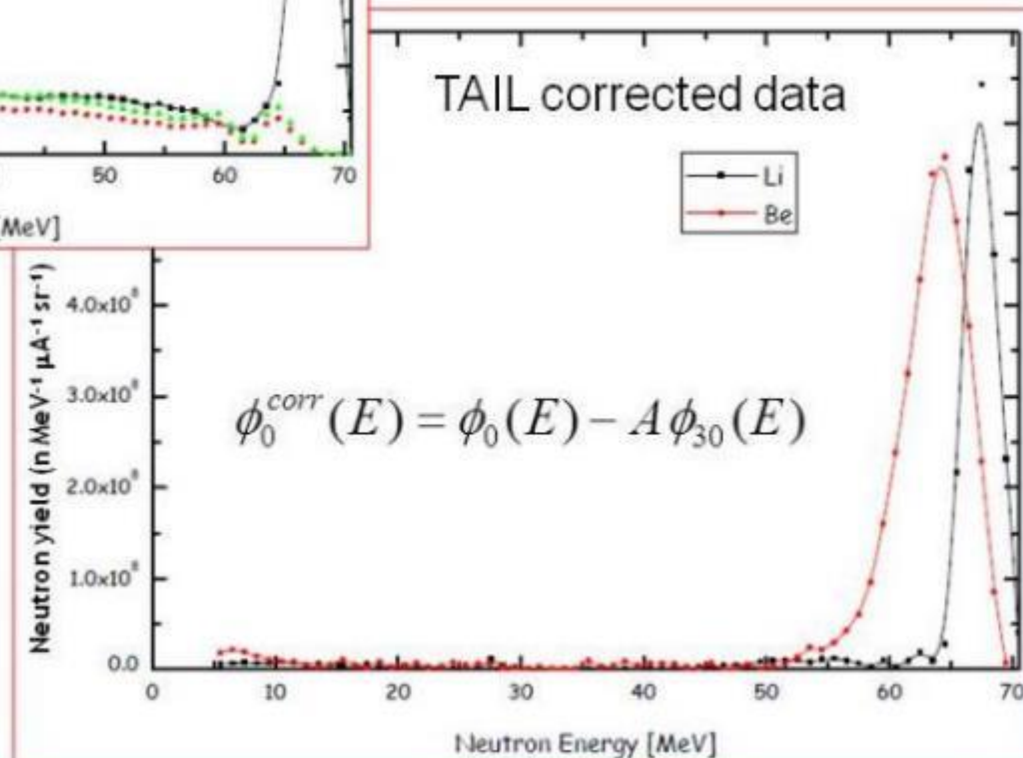


Wrong energy tail correction



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

E_{proton} = 70 MeV
Correction of 0° data
using 30° data.



- ❑ The corrected 0° peak with Li is sharper and closer to the proton beam energy.
- ❑ 30° subtraction works for both Li and Be with 70 MeV protons.

Low Z target

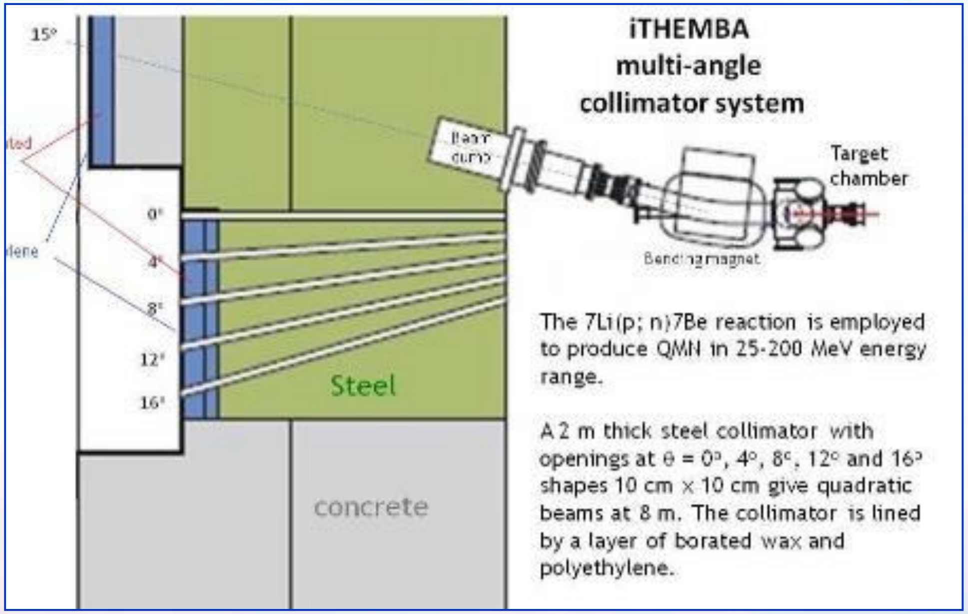
	Li	Be	
Melting point	180	**1287**	°C
Thermal conduct.	85	**190**	$W\ m^{-1}\ K^{-1}$
Machining	**easier**	difficult	
Reactivity to air	higher	**lower**	
Toxicity	**lower**	higher	
Cost	**lower**	higher	
Neutron yield	lower	**higher**	
Neutron energy distribution	**narrower**	larger	
Residual activity decay	**shorter**	longer	
Suffers swelling from implanted H	no	**yes**	

The favorite material as QMN target is Li, only if the heat generated by the energy deposited by the beam is efficiently evacuated.
When more than few tens of watts are deposited, a Be target is a simpler solution, at the price of a long cooling time of the activated material (also due to impurities).

Wrong-energy tail correction

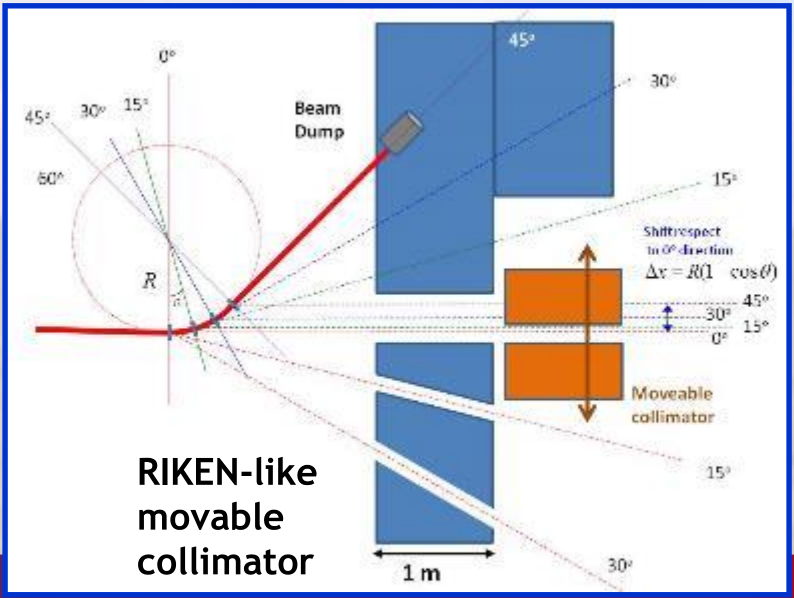
The number of neutron-induced effects due to forward going neutrons can be corrected by subtracting the number of effects at angles (typically in the 15º-30º range).

Fixed angles



Variable angle

- flexibility: adjustable angles
- but challenging to design magnet/target system

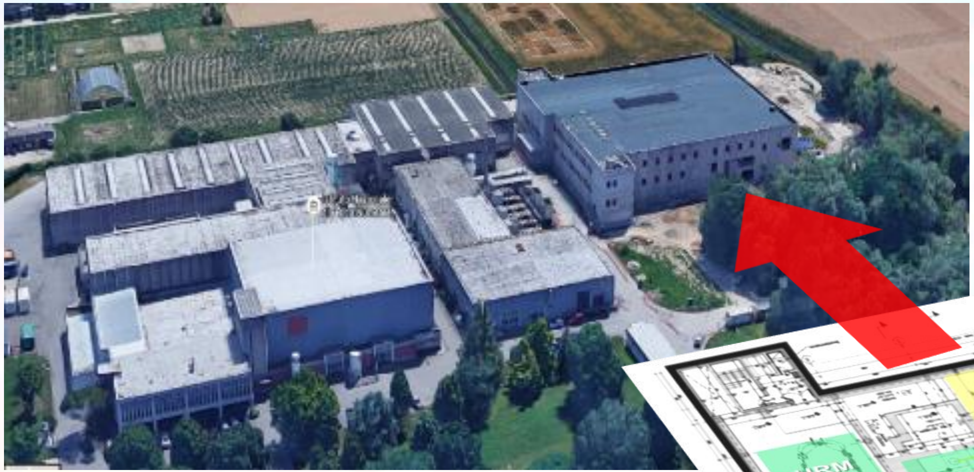


true QMN at NEPIR

- layout in SPES building
- layout detailed
- table of costs

NEPIR experimental hall

Completed SPES infrastructure



NEPIR

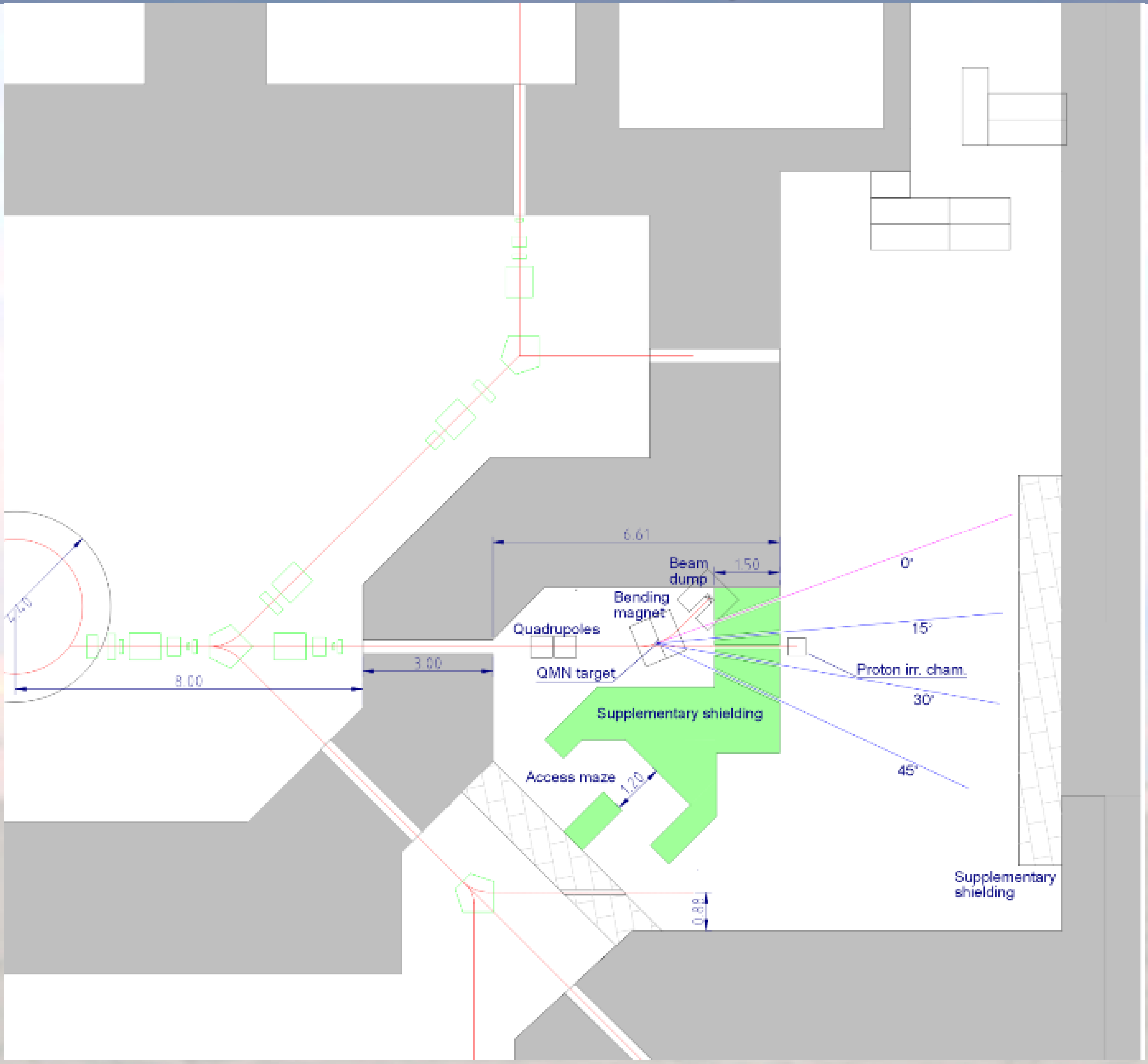
SPES lab underground level floor plan

SPES

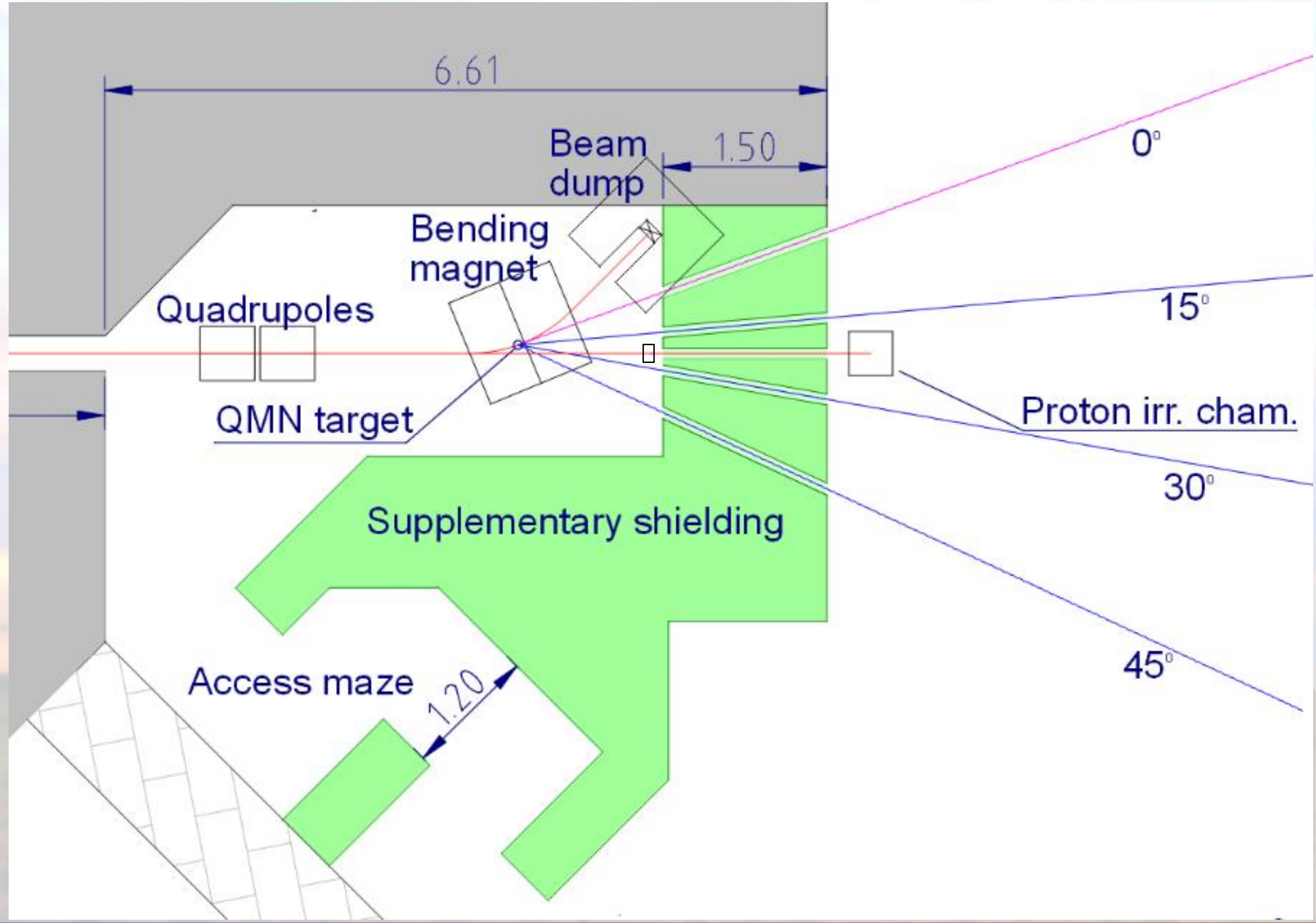
Radioisotope R&D and production

Existing (empty) NEPIR experimental hall

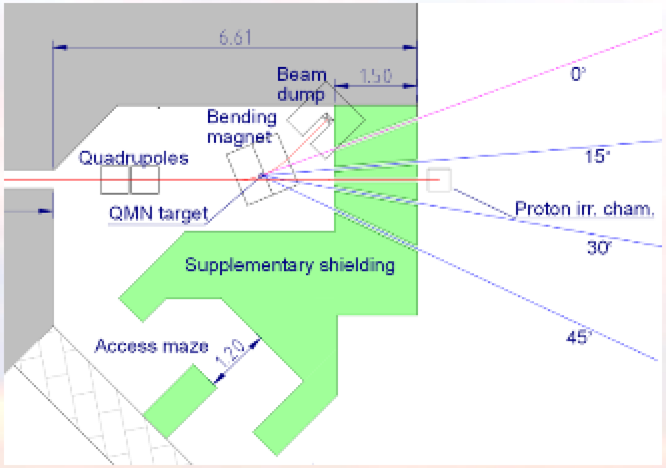
NEPIR: QMN layout



NEPIR: QMN layout (detail)



NEPIR: QMN system cost



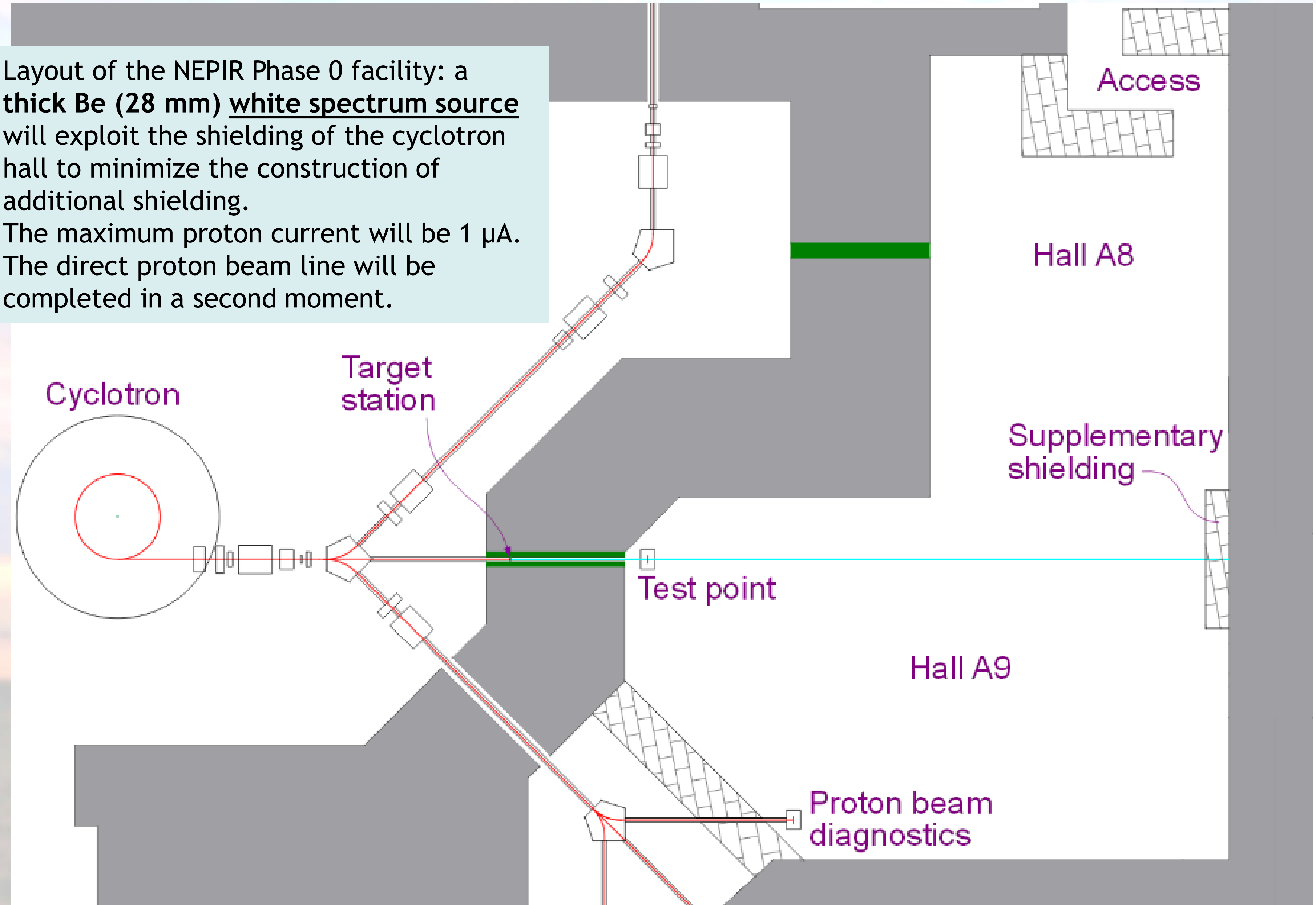
Fixed cost	k€
Services (electricity, water cooling, compr. air, conditioning…)	61
Access control system	18.3
QMN beam hardware	
Vacuum system and control	48.8
Concrete bunker	85.4
2 quadrupoles	195.2
QMN target system	61
QMN bending magnet (deflecting to beam dump)	152.5
QMN beam dump	18.3
Activated air management system (bunker depressuration)	61
Beam diagnosics for QMN (F.cup, wire monitor, control)	24.4
Total	725.9

Not included: manpower and proton energy degrader (30 -> 20 MeV)

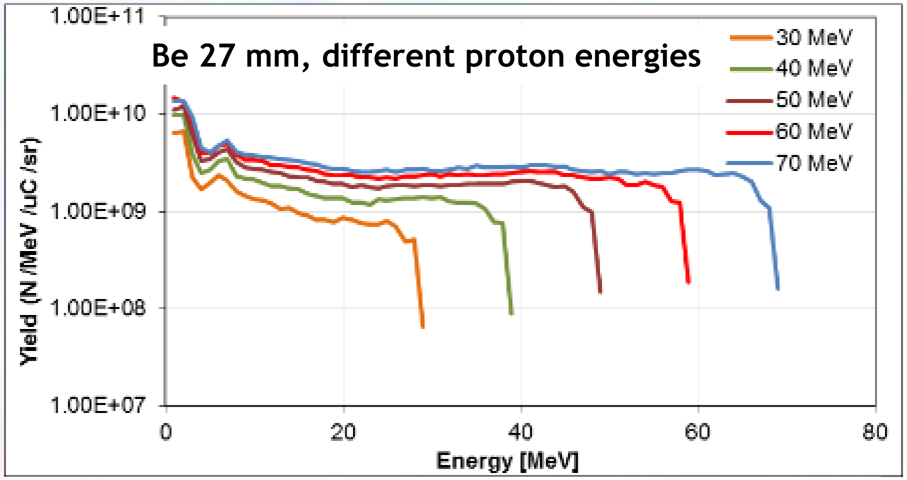
pseudo-QMN

- layout
- thick Be white neutron spectra
- pseudo-QMN spectra
- thermal mechanical details of thick target
- shielding calculations
- table of costs

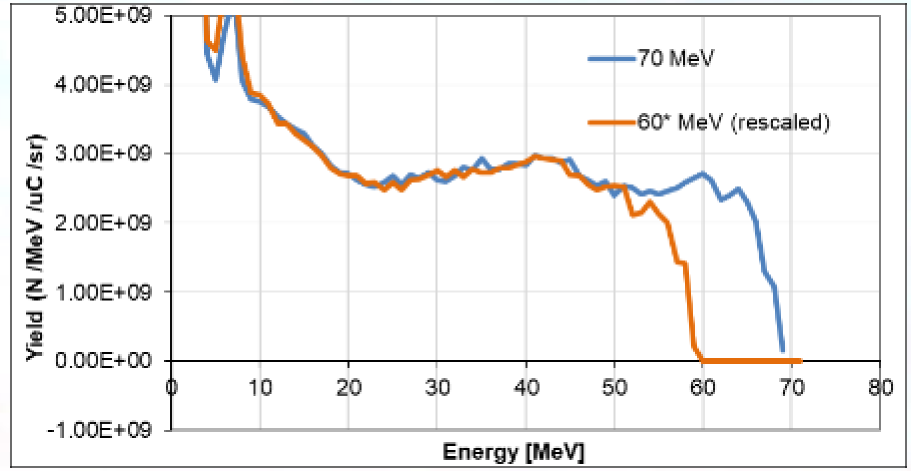
Layout of the NEPIR Phase 0 facility: a **thick Be (28 mm) <u>white spectrum source</u>** will exploit the shielding of the cyclotron hall to minimize the construction of additional shielding.
The maximum proton current will be 1 μA.
The direct proton beam line will be completed in a second moment.



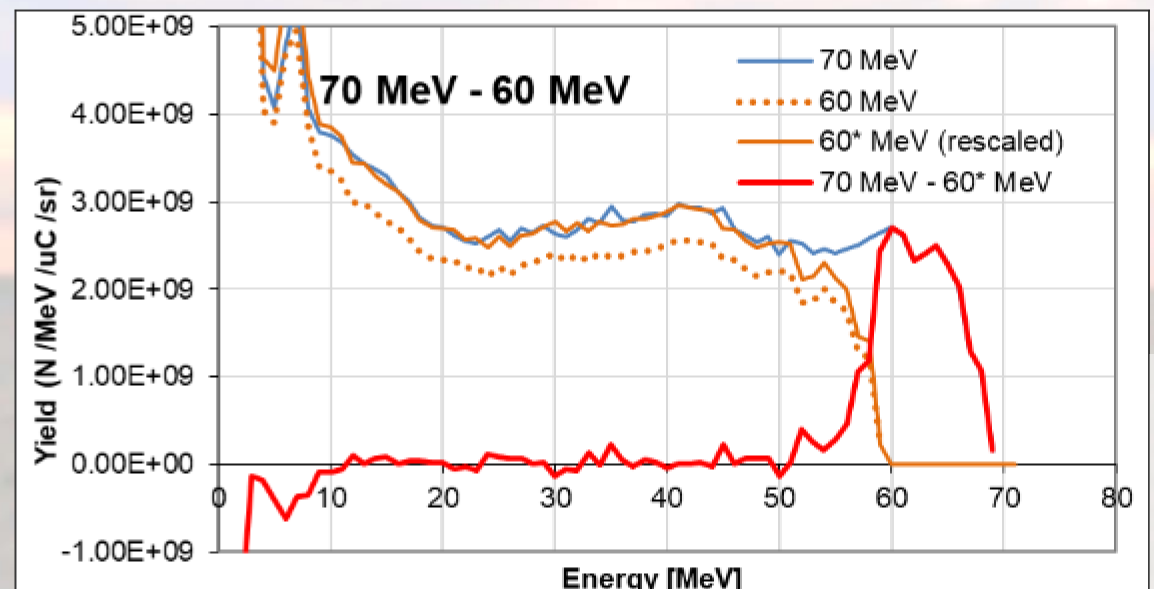
NEPIR: Thick Be white neutron spectra at different proton energies



Neutron spectra (simulated with MCNP) at test point for different energies of the impinging proton beam.



Comparison of the neutron spectra generated by 70 MeV protons and 60 MeV protons (rescaled by a factor 1.15).

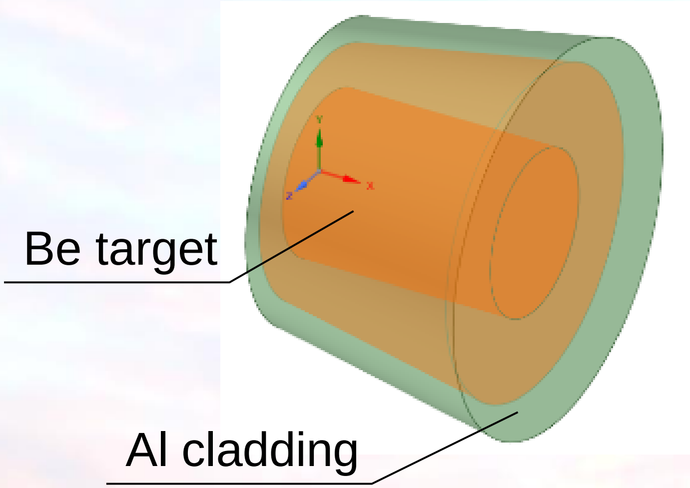


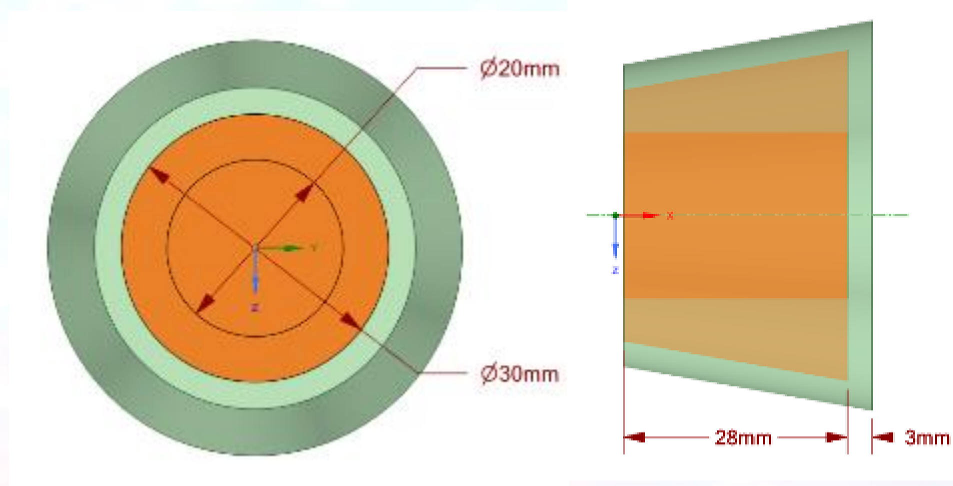
Maximum flux at closest test point: 3×10^6 N /cm^2 /s,

with 1 μA of 70 MeV protons

The difference between neutron spectra at different energies returns a quasi-rectangular neutron energy distribution with controllable width, down to few MeV.

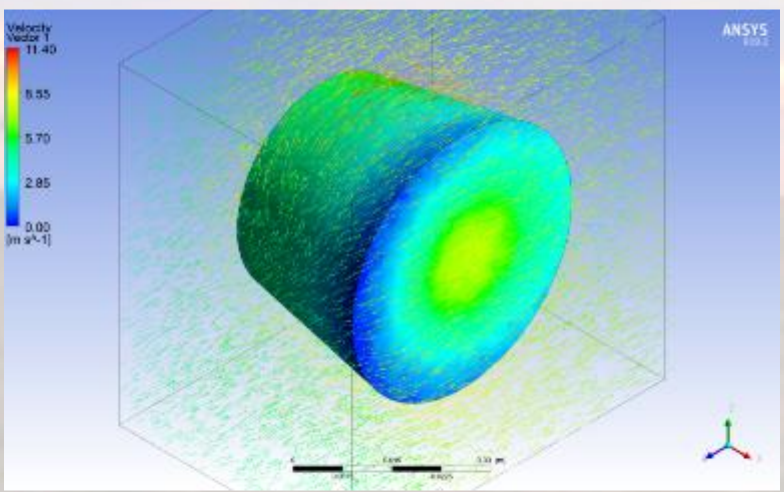
NEPIR: thick Be target ANSYS calculations

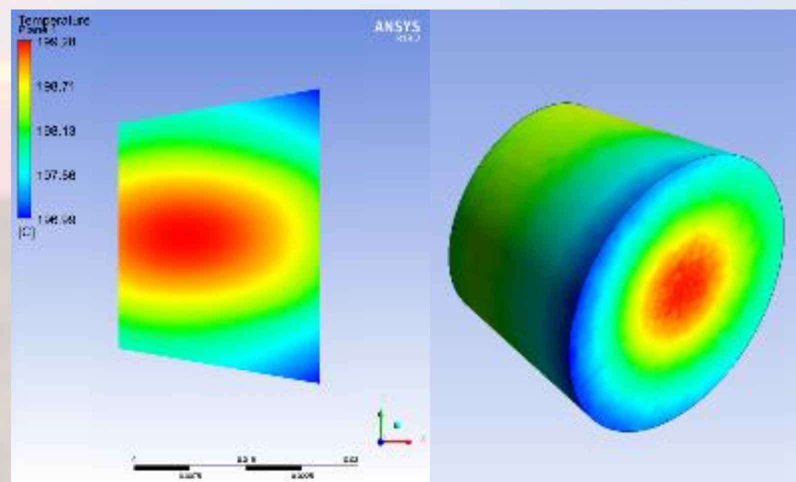




Power = 70W
Be T_{max} = 199°C
Be melting point: 1287°C.

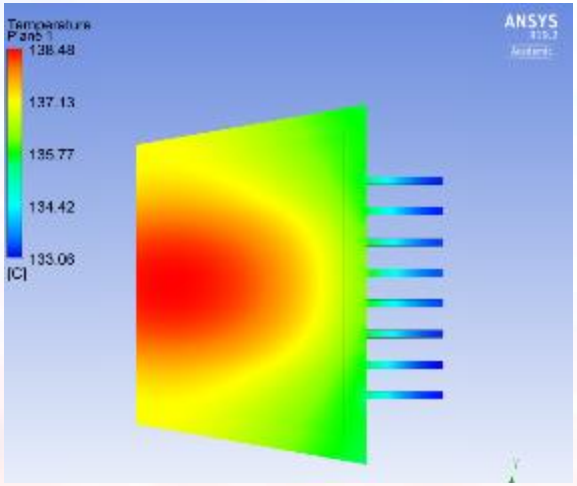
Air cooling:
v = 5m/s
T = 20°C



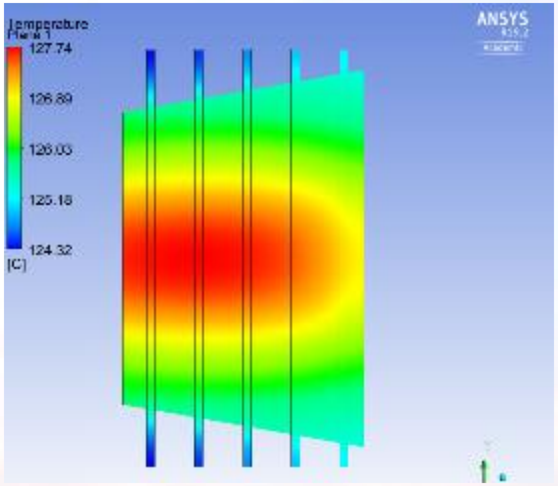


NEPIR: thick Be target cooling fins performance

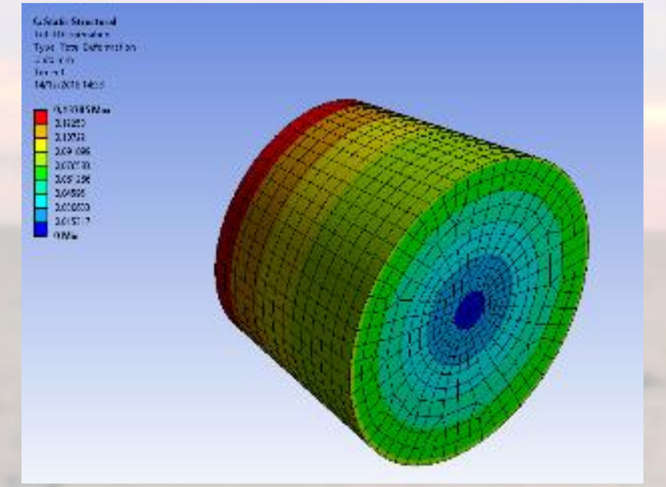
ANSYS CFX results for a target provided of cooling fins with different orientations.



Maximum Temperature = 138°C

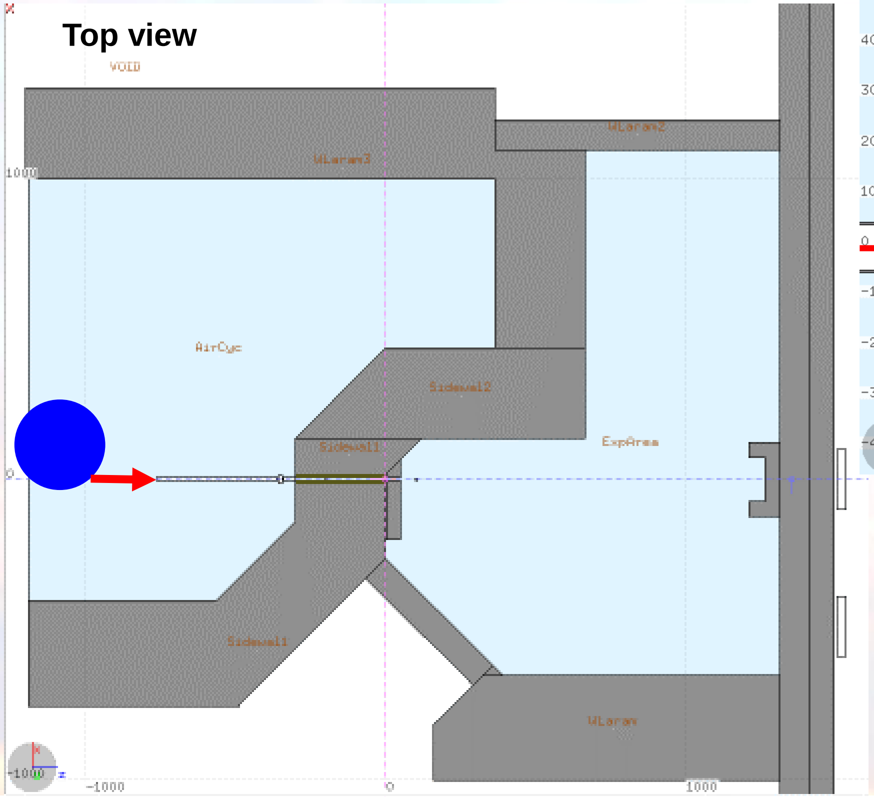


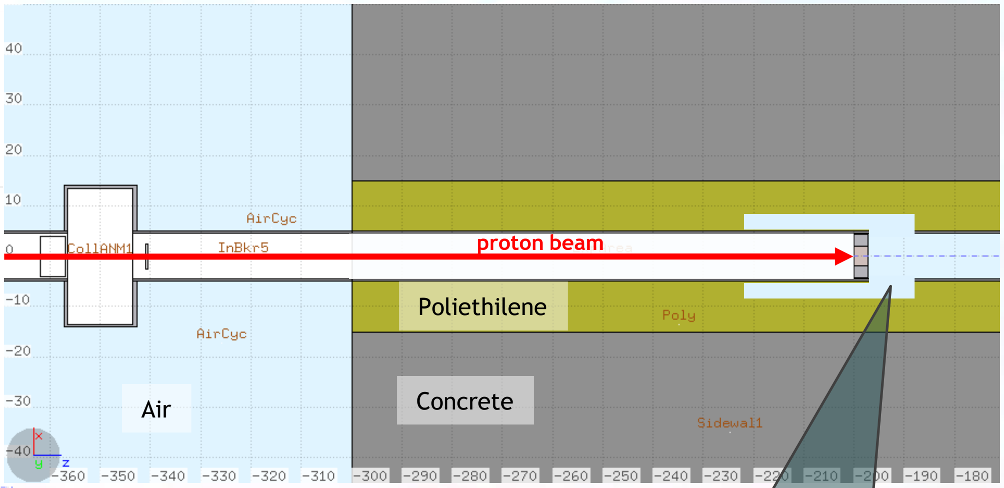
Maximum Temperature = 127°C

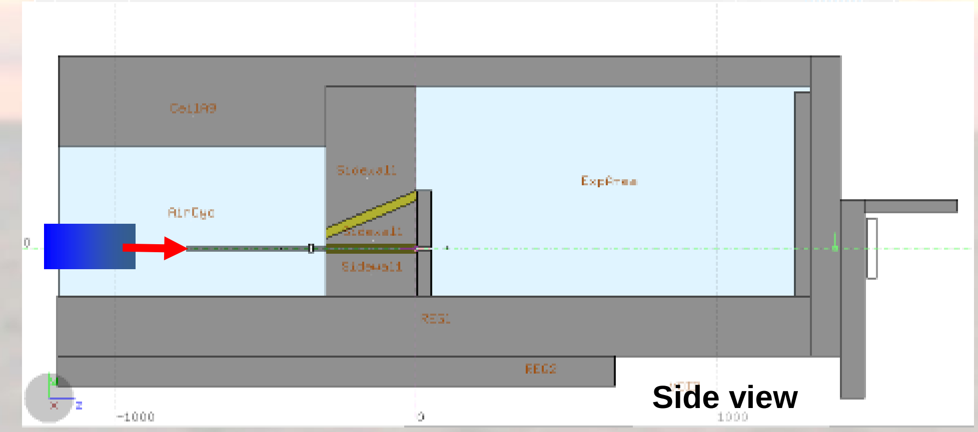


ANSYS static structural result:
total deformation due to thermal dilatiation: 0.14 mm

NEPIR: Phase-0 Fluka code geometry

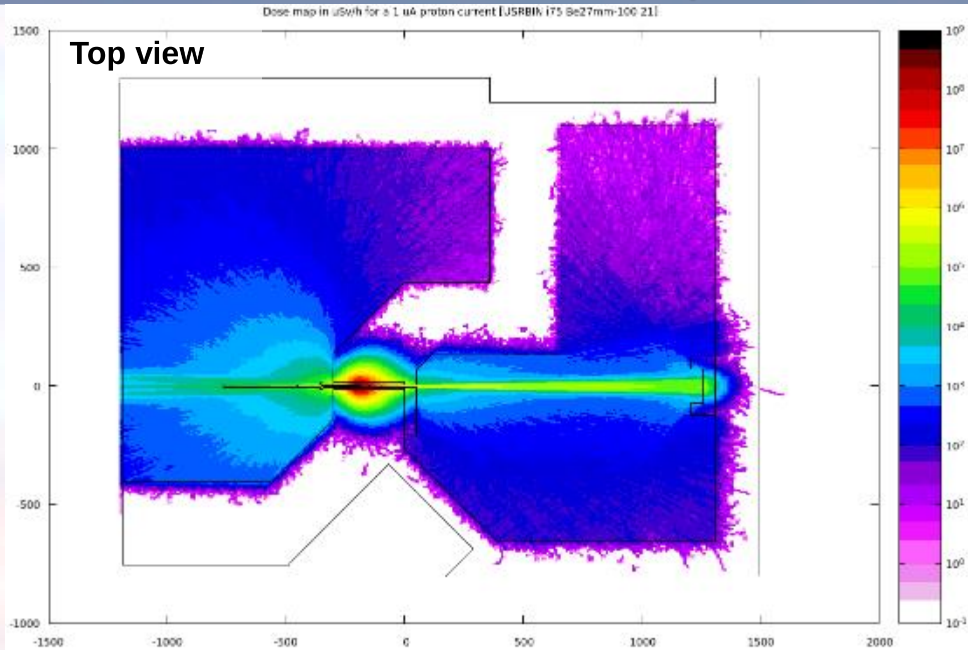


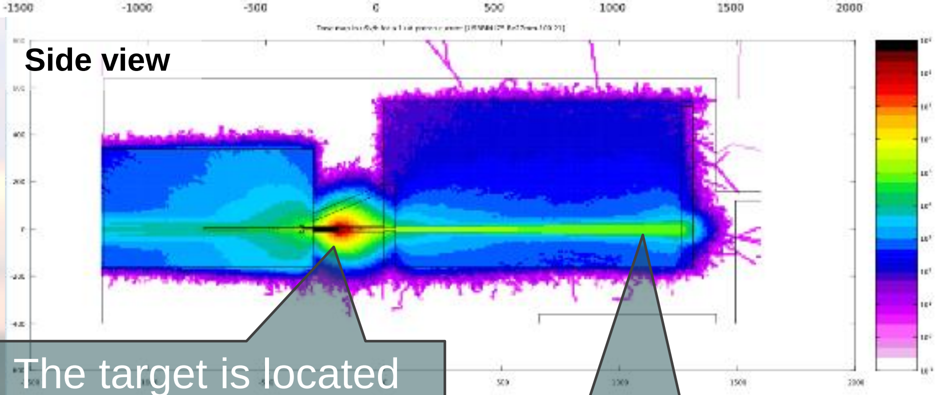




The beam-stopping target is a Be core, 28 mm thick, with an aluminum cladding, located inside the conduit between the cyclotron hall and hall A9. It is provided of a forced-air cooling system.

NEPIR phase-0 ambient dose rate





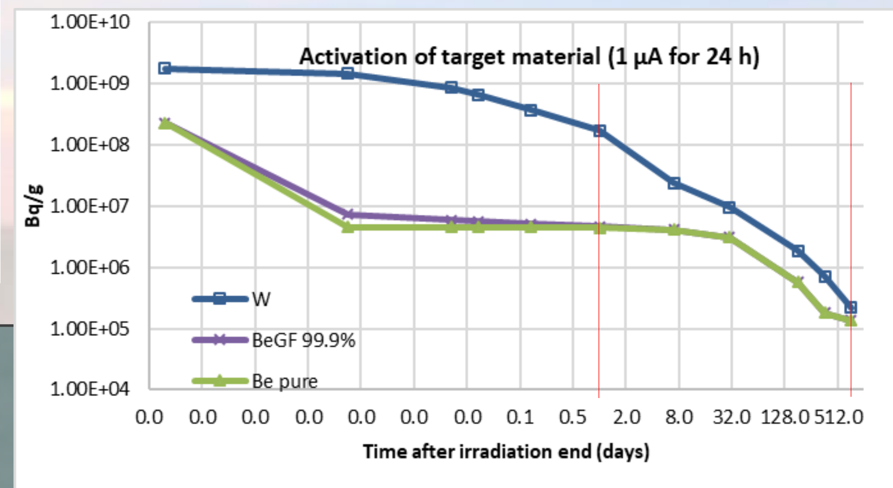
Prompt ambient equivalent dose rate [μSv/h] delivered by thick (28 mm) Be target with a proton beam current of 1 μA.

The dose delivered to the cyclotron hall is one of the factor driving the choice of the target position.

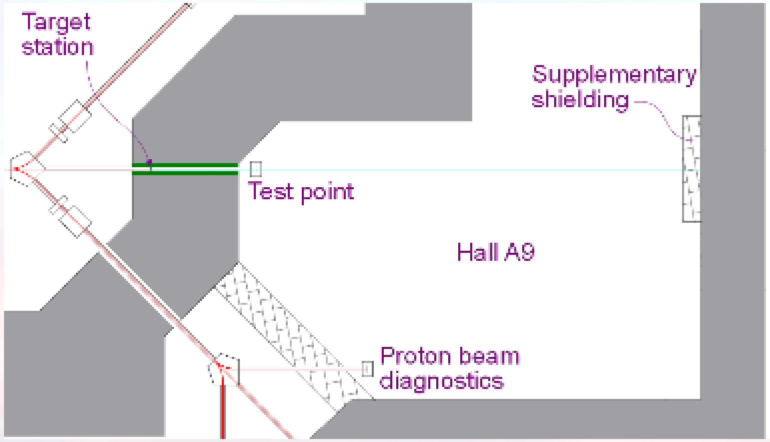
The air activation in hall A9 limits the proton beam current to 1.5 μA when the full length of the beam path is used.

The target is located inside the conduit between the cyclotron hall and hall A9 (exact position to be determined)

Equivalent dose:
in beam: ~10^5 μSv/h
far from beam: several μSv/h



NEPIR Phase-0 cost

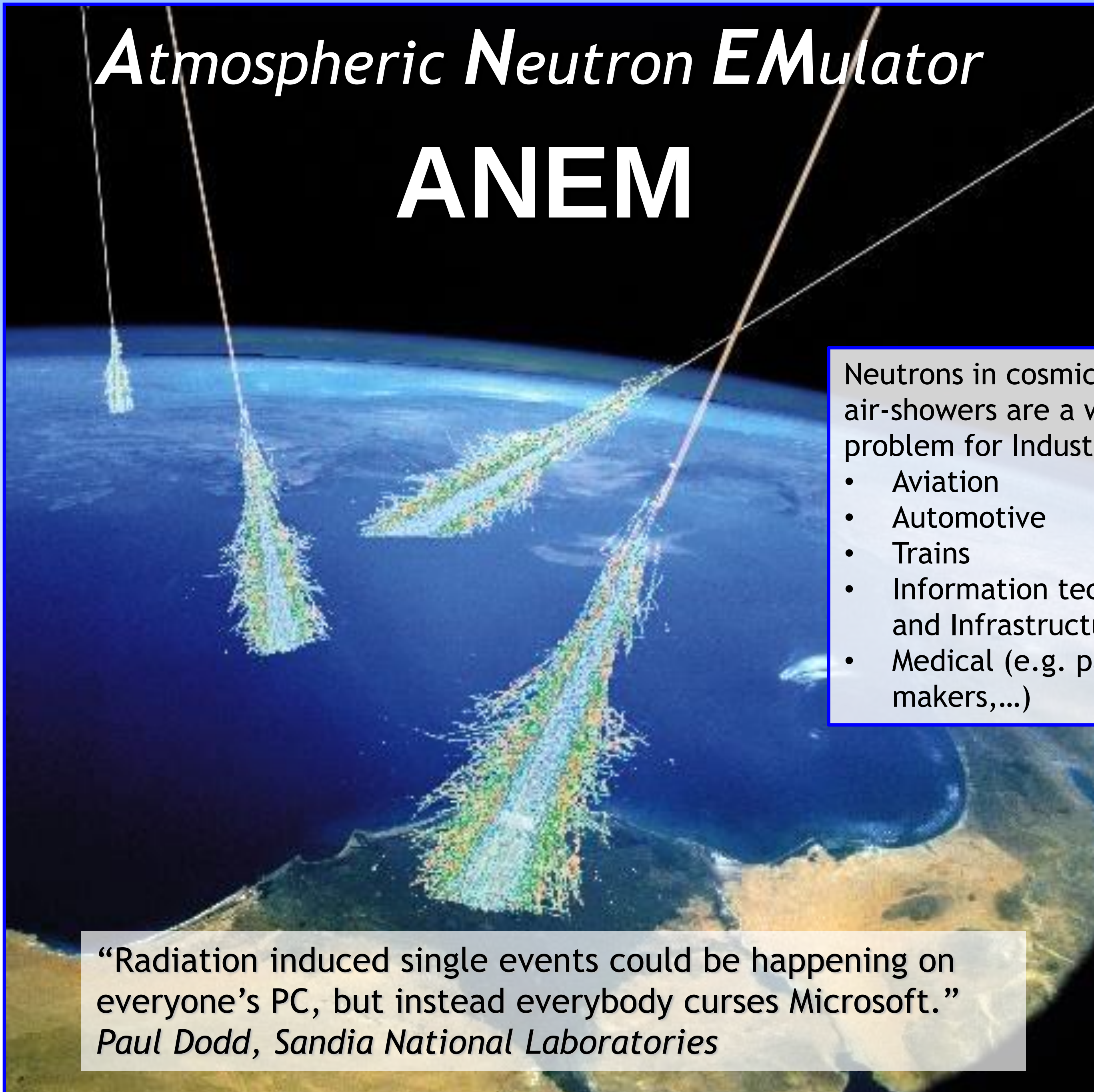


Fixed cost	**k€**
Services (electricity, water cooling, compr. air, conditioning…)	61
Access control system	18.3
White spectrum beam hardware	
Movable radiation plug	12.2
Safety target intelock (temp., cooling, vacuum…)	36.6
Be thick target	18.3
Vacuum system and control	48.8
Beam diagnosics for thick target (F.cup, wire monitor, control)	24.4
Total	219.6

The construction could start in 2019,
beam characterization could be completed by 2020,
first beam to users by the end of 2020 or in 2021.

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

ANEM



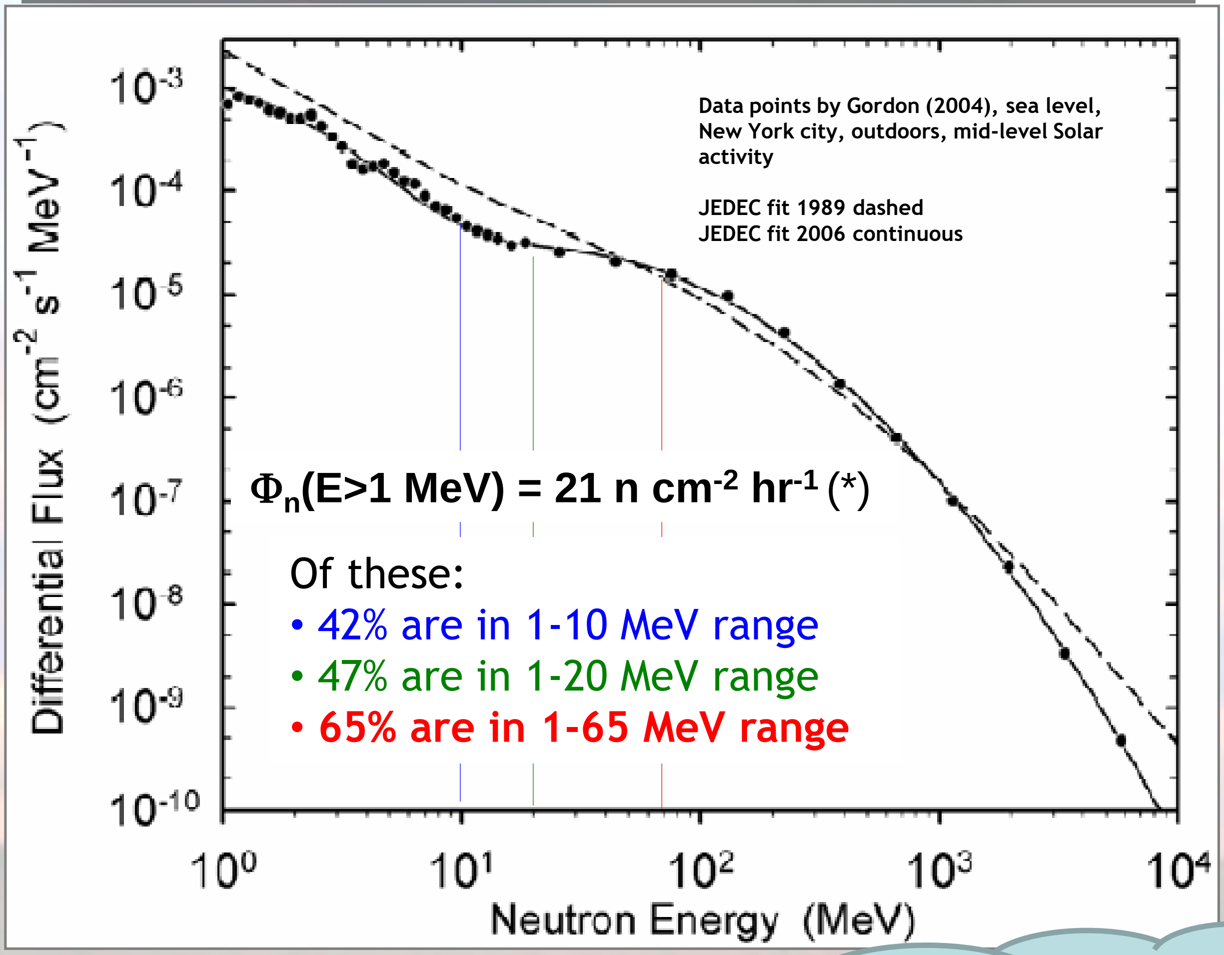
Neutrons in cosmic ray air-showers are a widening problem for Industry:

- Aviation
- Automotive
- Trains
- Information technolgy and Infrastructure
- Medical (e.g. pace makers,…)

"Radiation induced single events could be happening on everyone's PC, but instead everybody curses Microsoft."
Paul Dodd, Sandia National Laboratories

Atmospheric neutrons

Energy distribution of fast (E>1MeV) neutrons at sea level



Φ_n(E>1 MeV) = 21 n cm^{-2} hr^{-1} (*)

Of these:
- 42% are in 1-10 MeV range
- 47% are in 1-20 MeV range
- **65% are in 1-65 MeV range**

The standard reference spectrum used by the ***JEDEC Solid State Technology Association***, an independent semiconductor engineering trade organization and standardization body.

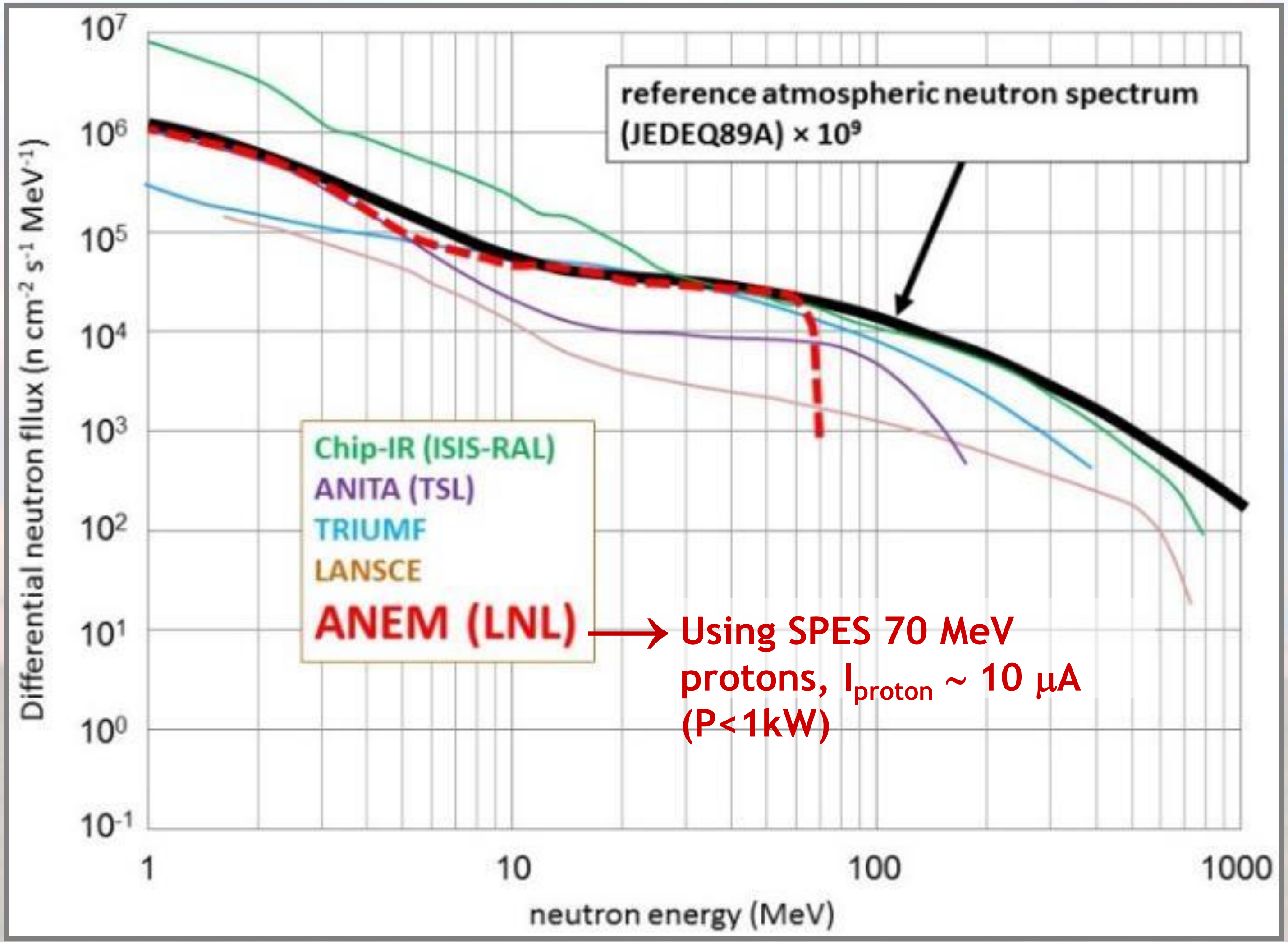
Typical value for SEU
$\sigma_{Plateau}$ = 10^{-14} cm^2/bit
gives a low SEU rate
~32 SEU / (month · 64 GByte)

(*) At flight altitudes the flux shape is similar, but~300 times more intense.

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

Atmospheric neutrons test facilities

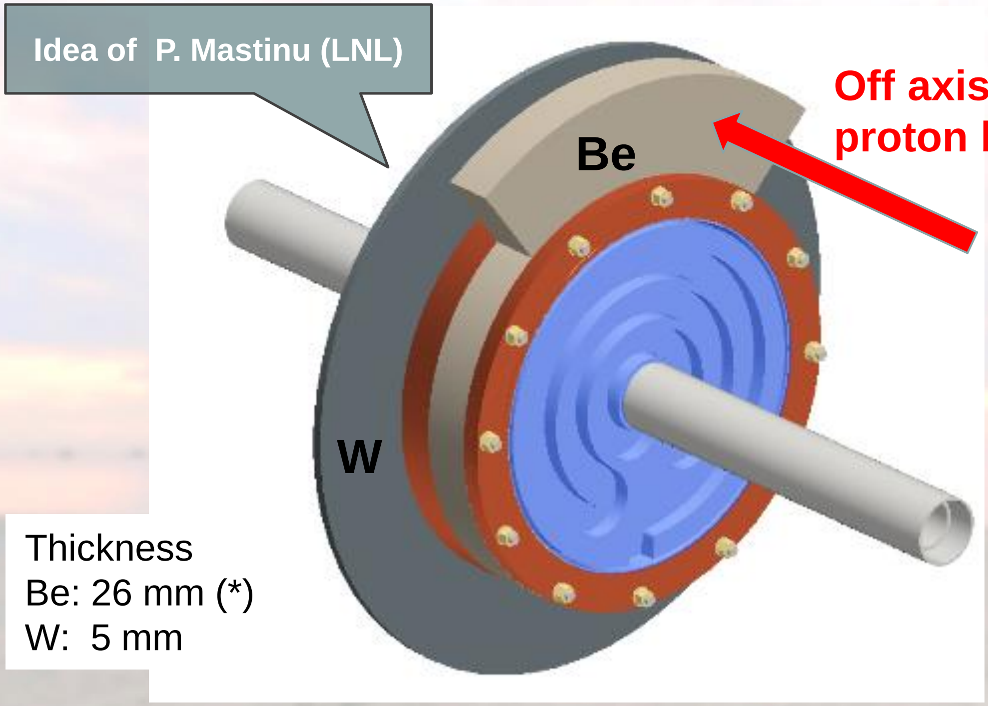
The neutron differential energy spectra at accelerator electronic test facilities used for accelerated neutron SEE testing. The **JEDEC reference spectrum** is the black curve multiplied by an *acceleration factor* F = 10^9.

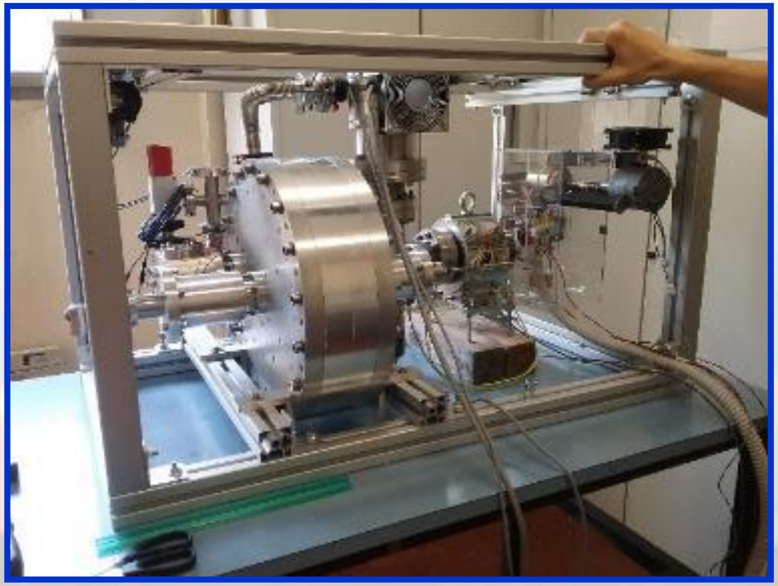


ANEM: a continuous energy neutron production target

A **novel** rotating, composite, **high power** target made of thick Be and W.
A W disk and a Be circular sector rotate on a common water cooled hub and alternatively intercept the beam. The effective atmospheric-like neutron spectrum in the 1-65 MeV range is composed directly, without the use of moderators.

The target is designed to tolerate a maximum current I_{beam} = 30 μA (**2.1 kW**), delivering at a distance of 6 m, a flux of neutrons (E = 1-65 MeV range) ~10^9 times the natural one, comparable with the highest factor to be used at **Chip-IR** facility.





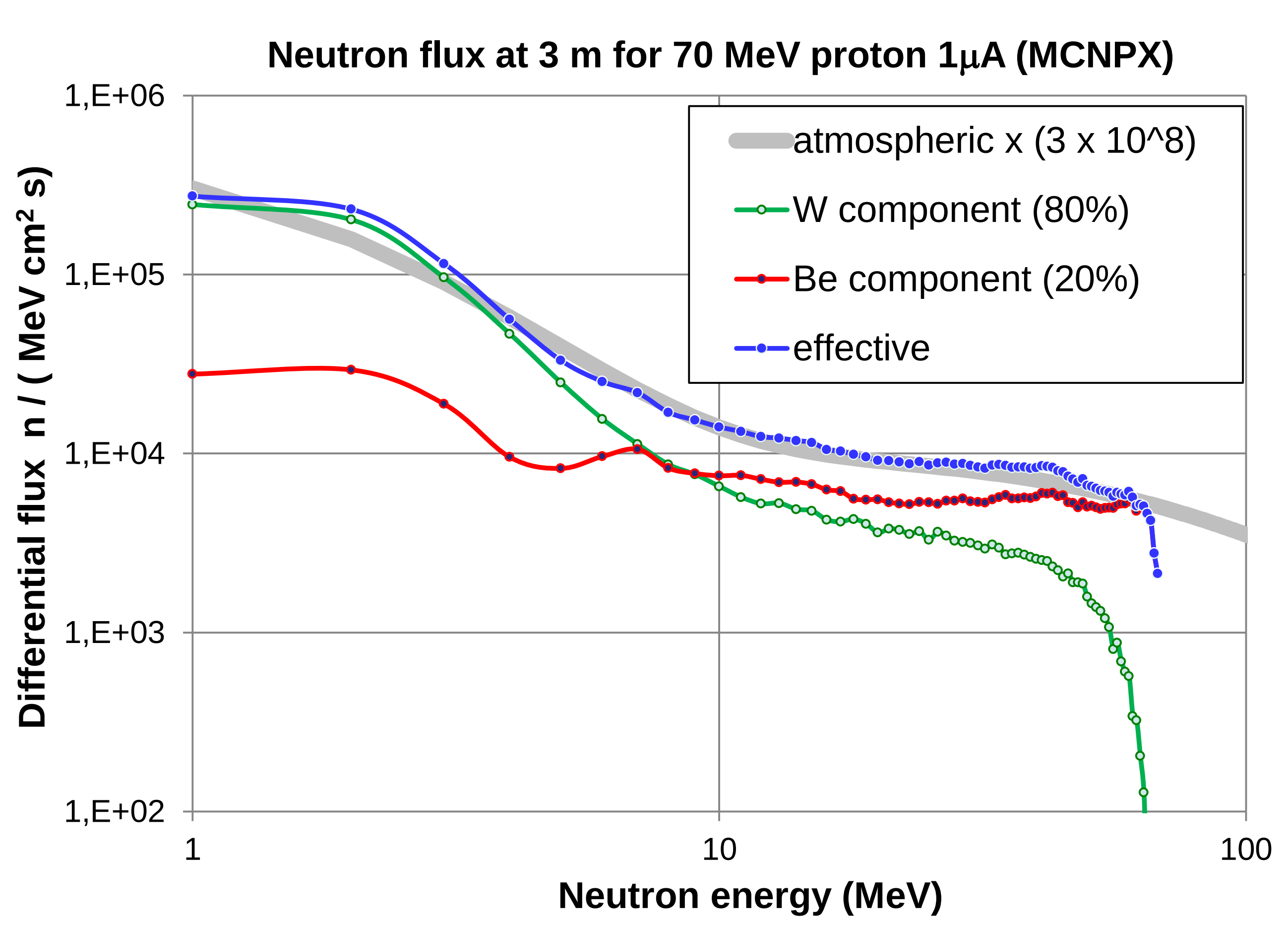
Target prototype almost ready for thermal test with electron-gun

(*) 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 stopped by the W disk.

Spectra combination

The combination of 20% Be spectrum and 80% W spectrum yields the best fit of the atmospheric spectrum, without use of moderation.

The delivered **neutron flux is 1.7×10^{6} cm^{-2} s^{-1}** (at 3 m for a 1 μA proton current), corresponding to an acceleration factor of 3 × 10^{8}



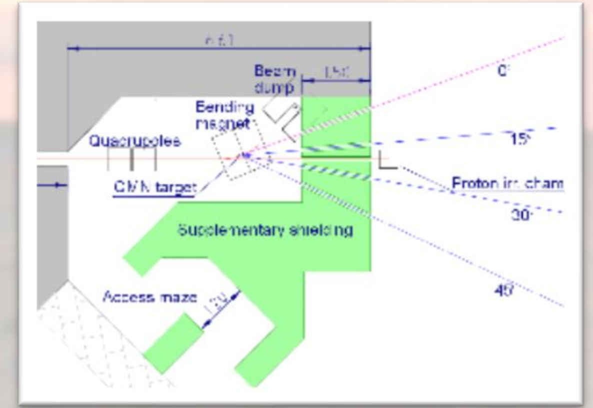
CONCLUSION

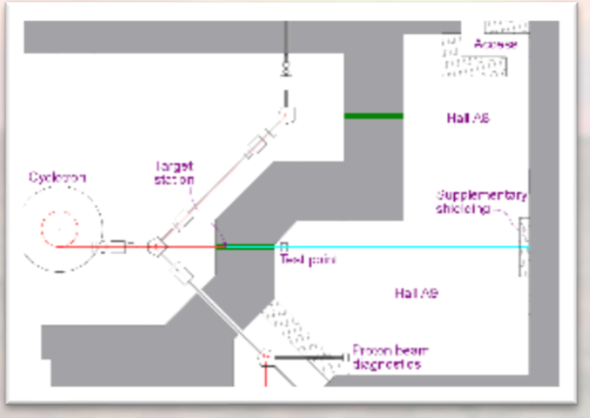
- The **basic design** of the NEPIR facility, its beam-optics, and different neutron production target systems are defined; shielding calculations are nearly completed;

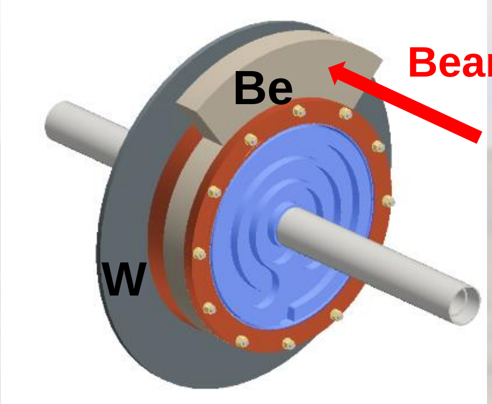
- A design of a **Phase-0 version** of the facility, with a white spectrum target that can be exploited for pseudo-QMN analysis was developed. The funding of the LNL work-package of the SPARE project is sufficient for this solution;

- The design of a more expensive **true-QMN** is in advanced stage, but present funds are not sufficient. Discussions within the SPARE collaboration are under way to evaluate benefit-cost ratio;

- An **ANEM prototype** exists, with an aluminum test disk and an electron gun system (under commissioning) for thermal tests to be completed in the next months.







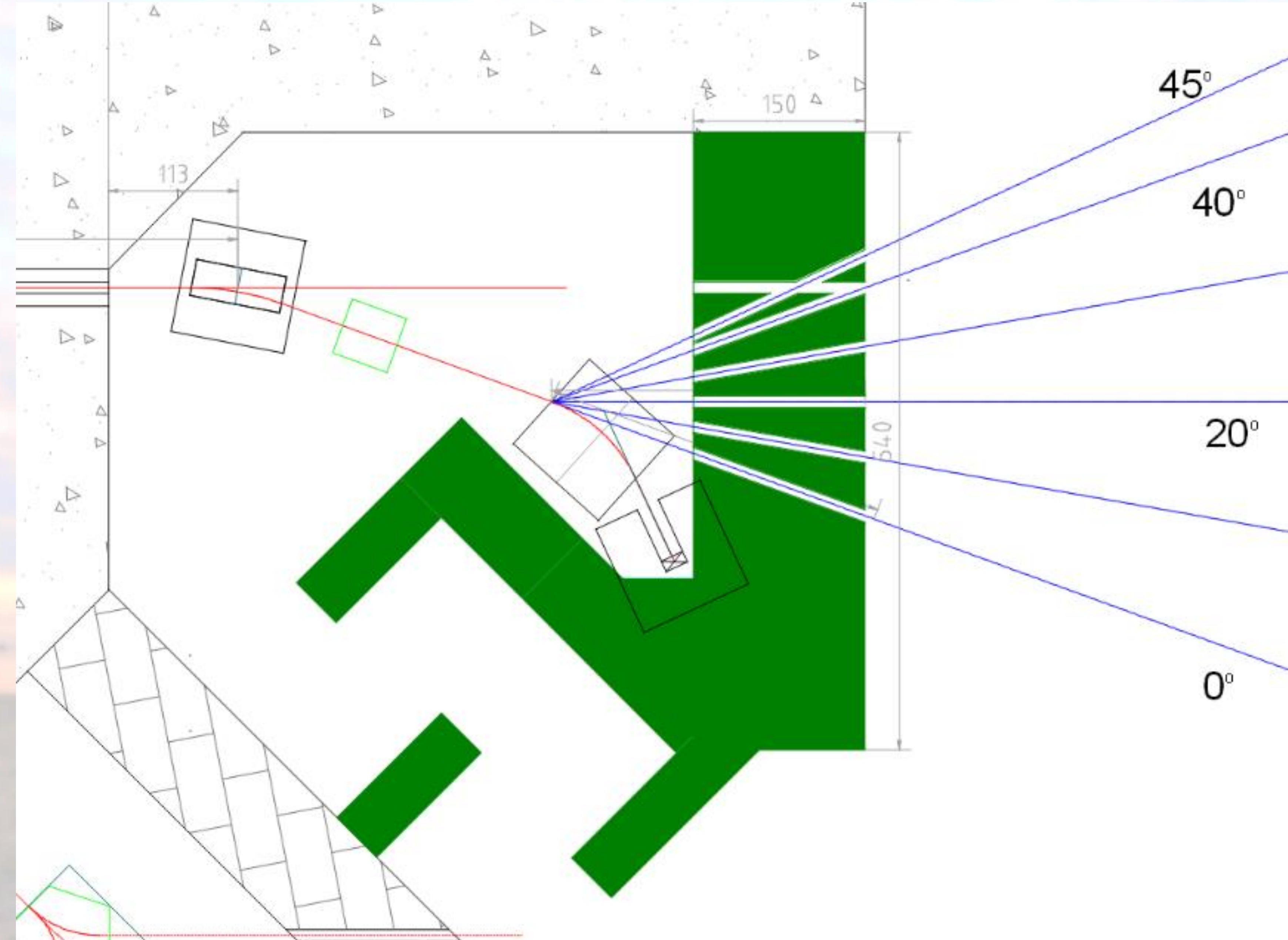
The end

Thank you for your attention

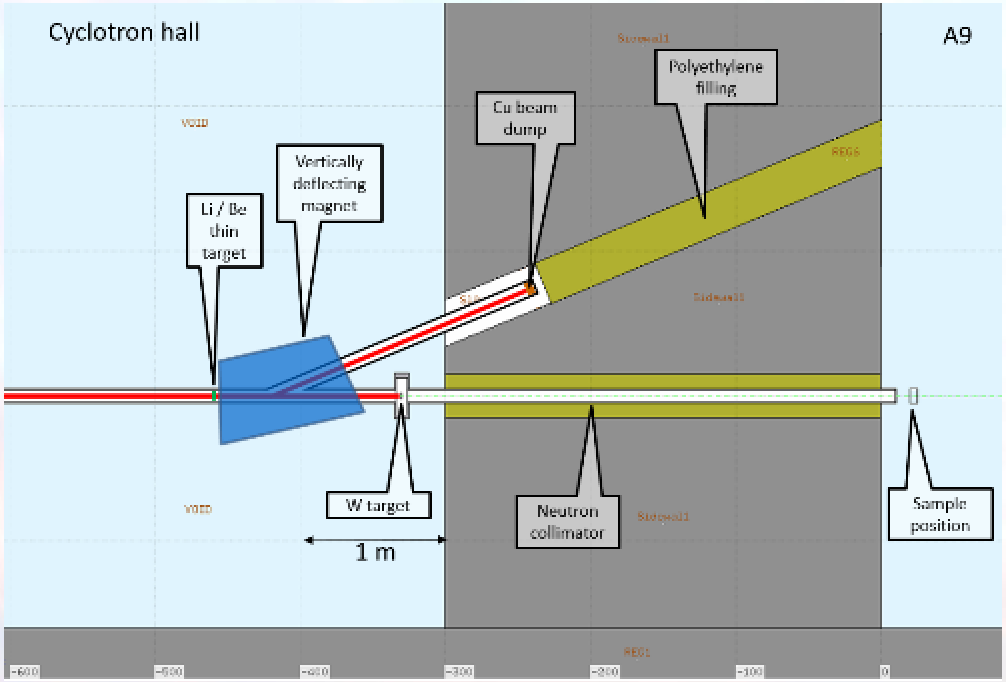
Extra slides follow

Extra slides

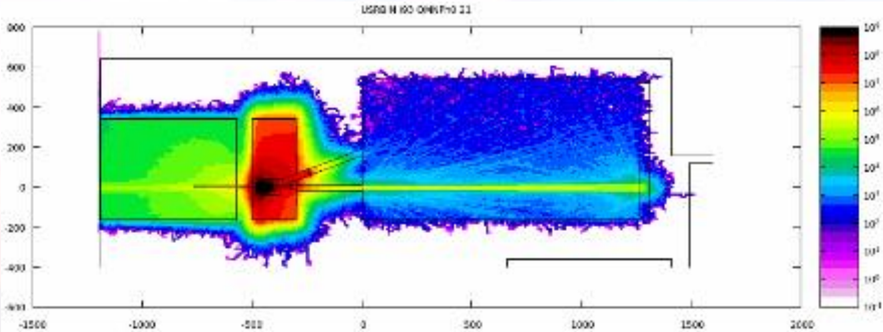
QMN alternative layout (detail)

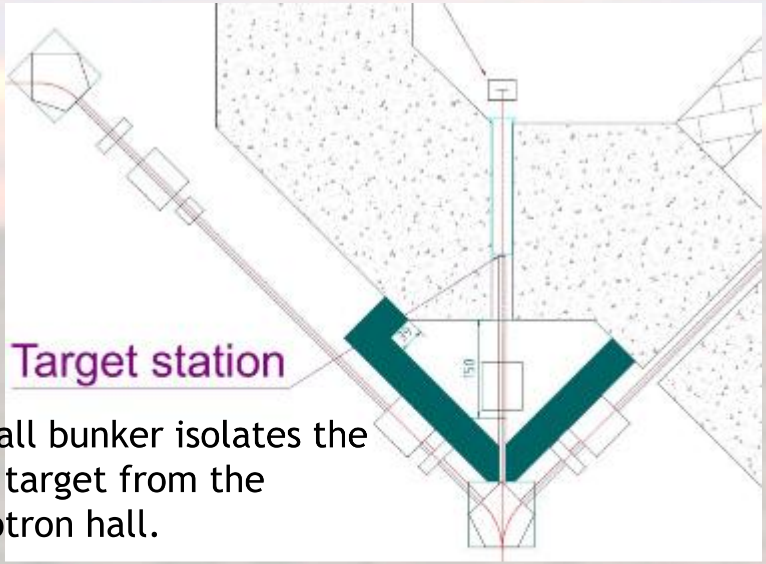


QMN Phase-0

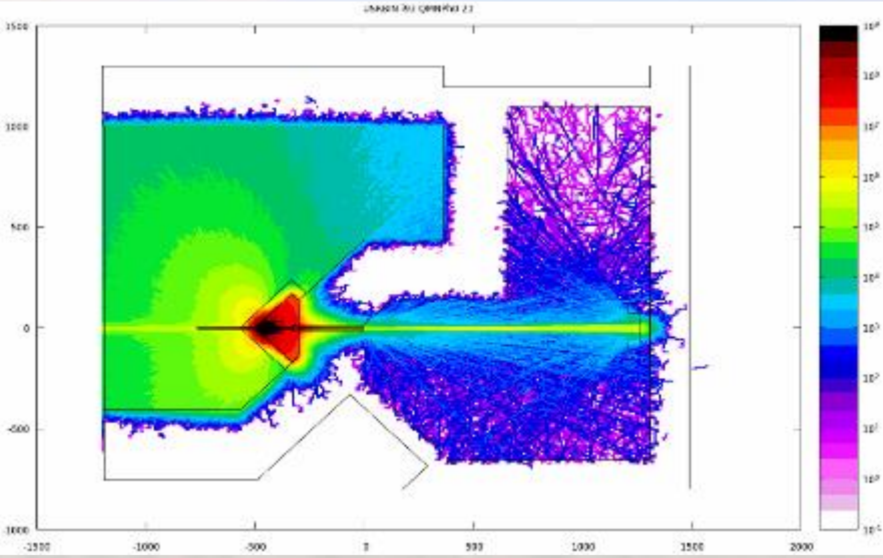


A vertical magnet is used to deflect the exiting proton beam towards a beam dump inside the slanted conduit.





A small bunker isolates the QMN target from the cyclotron hall.



High current QMN

Main limitaton comes from the power sustainable from the target. R6D needs to improve the cooling system

Avevo fatto dei calcoli ansys e dovresti avere qualche figura da mettere