International Collaboration on Advanced Neutron Sources (ICANS XXIII)

The Legnaro fast-neutron facility NePIR

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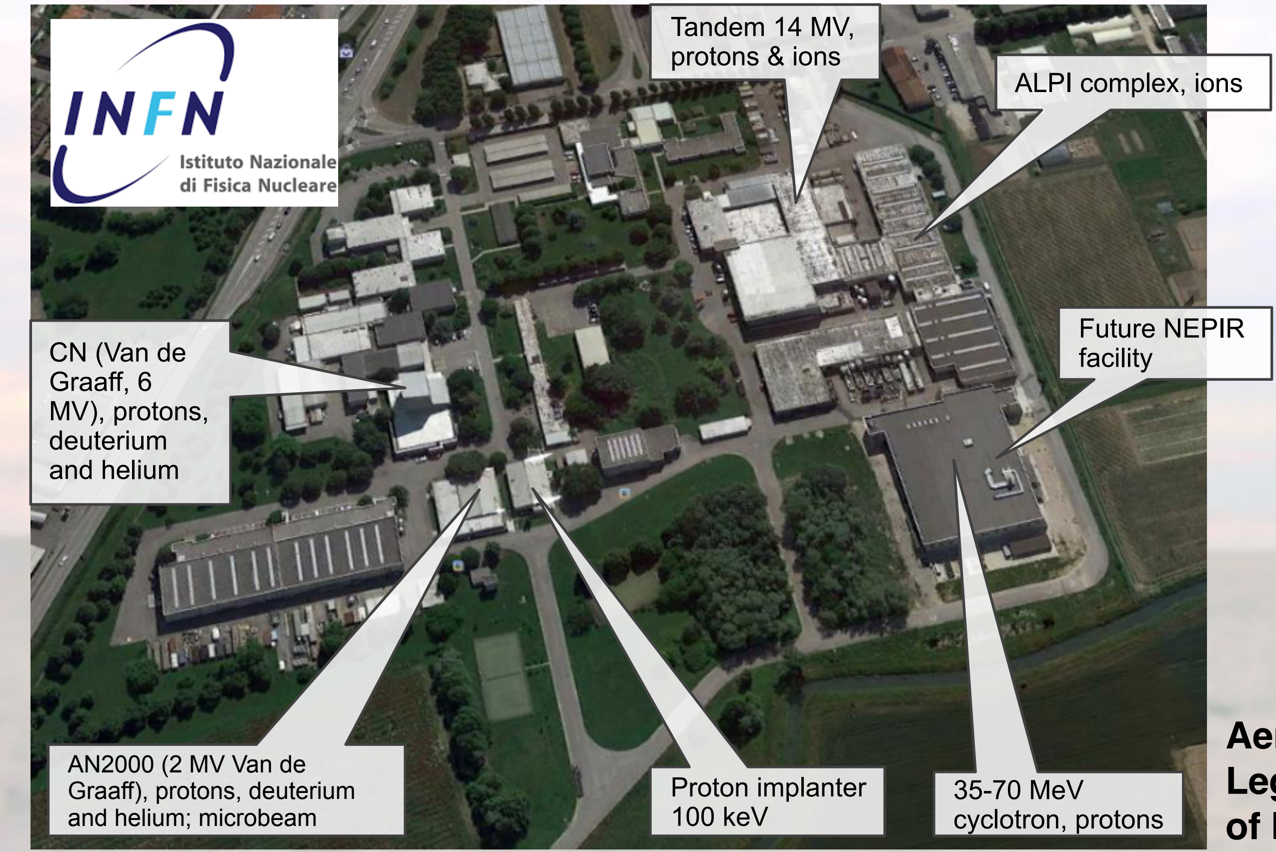
Outline

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



Tandem 14 MV, protons & ions

ALPI complex, ions

CN (Van de Graaff, 6 MV), protons, deuterium and helium

Future NEPIR facility

AN2000 (2 MV Van de Graaff), protons, deuterium and helium; microbeam

Proton implanter 100 keV

35-70 MeV cyclotron, protons

Aereal view of the Legnaro laboratories of INFN

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.**

I. NEutron and Proton IRradiation (NEPIR) complex.

UNDER DEVELOPMENT
this talk

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)

I. Legnaro Slow Neutron Source (LSNS)

FUTURE DEVELOPMENT

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

Single Event Effects (SEE)

In space applications electronic devices may receive **direct ionizing impacts** of galactic and extra-galactic heavy energetic ions (HZE) cosmic rays during operational lifetime of a spaceflight.

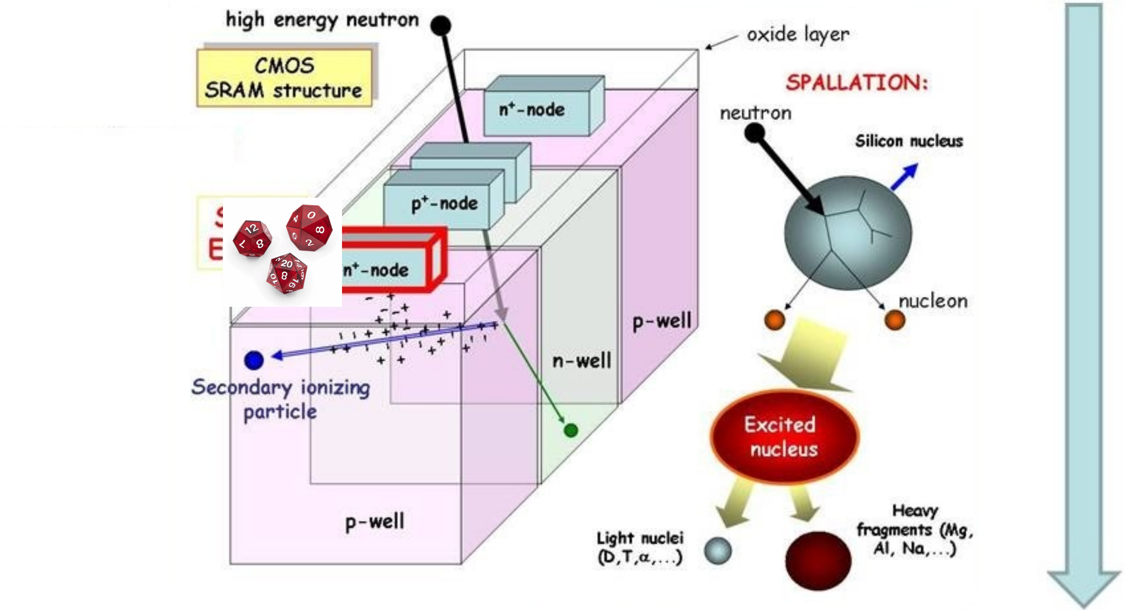
Neutrons induce SEE indirectly

by producing highly ionizing secondaries.

Physics of neutron-induced SEE

(1) **Primary neutron** (accelerator, cosmic-rays,…)

(2) **neutron-nucleus reactions** with production of ionizing secondaries (Nuclear Physics)

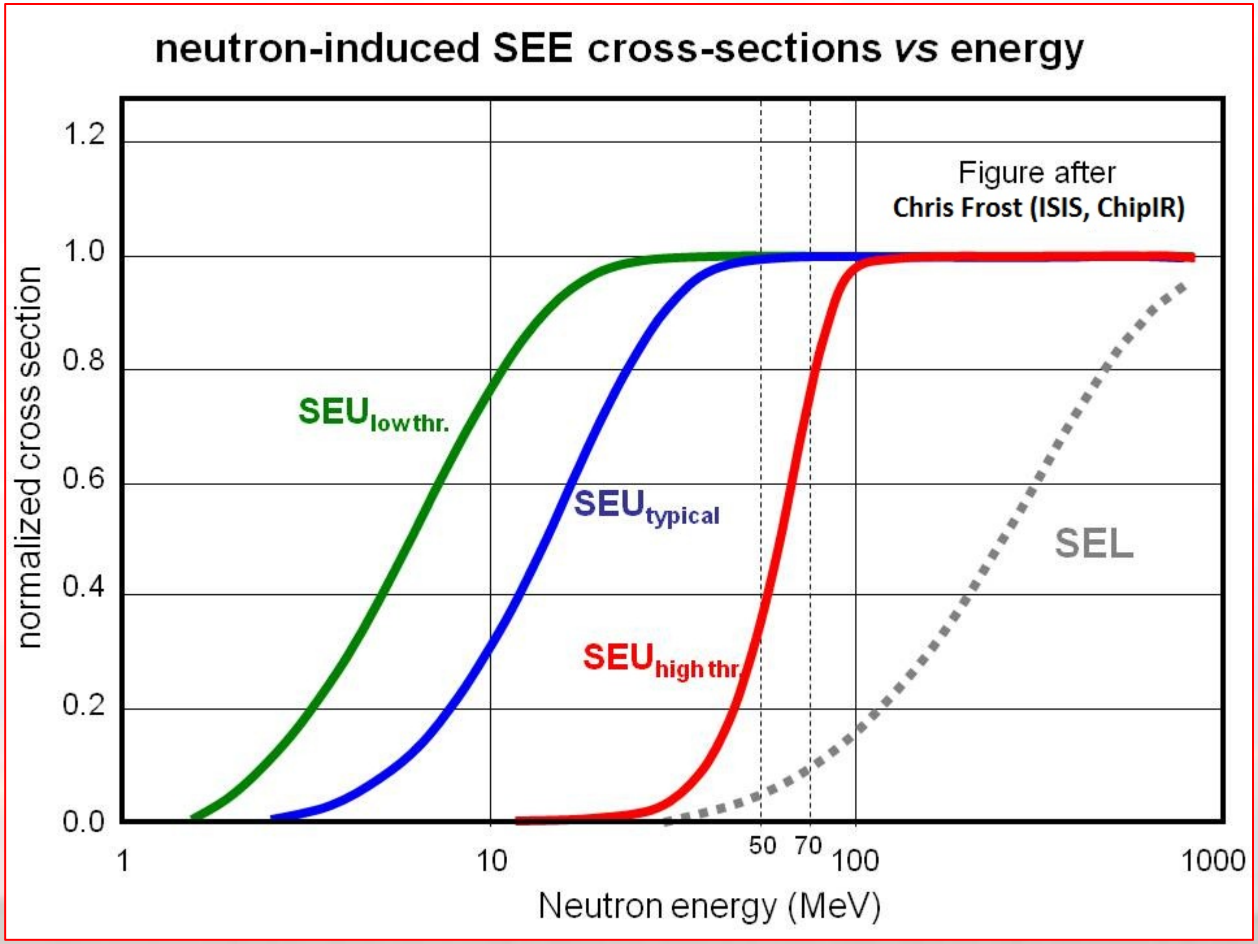


(3) **Generation of electron-hole pairs** (radiation physics and solid-state physics)

(4) **Charge transport in device** (device physics)

If neutron is fast enough, a SEE may occur

Typically neutron-induced may SEE occur when the energy of the impinging neutron is above some minimum **threshold value E_0** ; the probability of a SEE occurring, usually expressed as a **cross-section $\sigma(E)$**, increases with neutron energy until a **plateau value σ_P** is reached.



- E_0 threshold
- W width parameter
- S shape factor

Weibull function

$$\sigma(E) = \sigma_P \left(1 - e^{-\left[\frac{E-E_0}{W}\right]^S} \right)$$

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

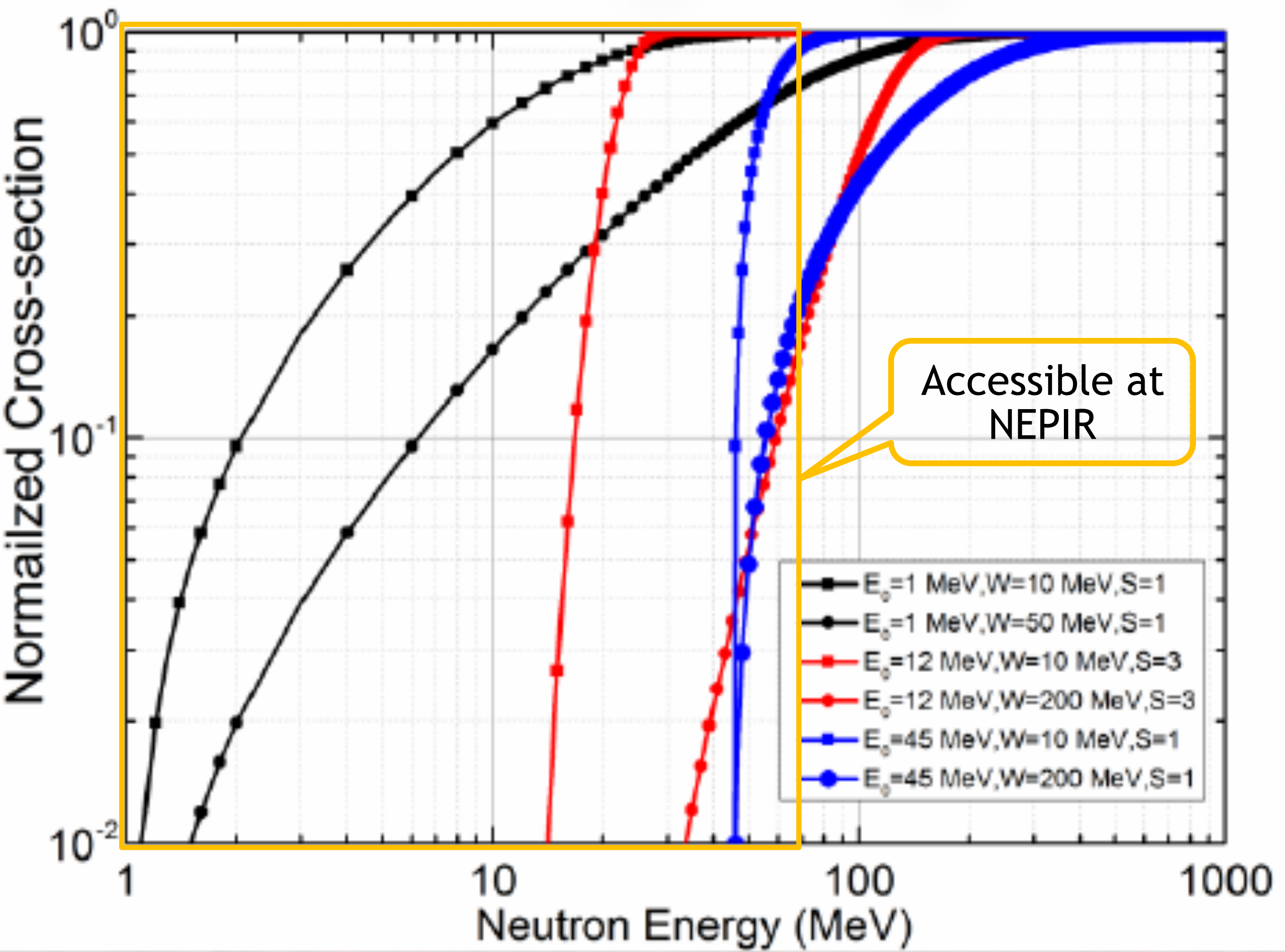
$$\sigma_{SEU} = 10^{-14}\ \mathrm{cm^2/bit},$$

N_{bits} **per device = 4 × 10^6** ↑

How the parameters change the shape of the Weibull fitting curve

$$\sigma(E) = \sigma_P \left(1 - e^{-\left[\frac{E-E_0}{W}\right]^S}\right)$$

4 parameters. In principle, four point at different energy fully determine the cross section. Best tool QMN

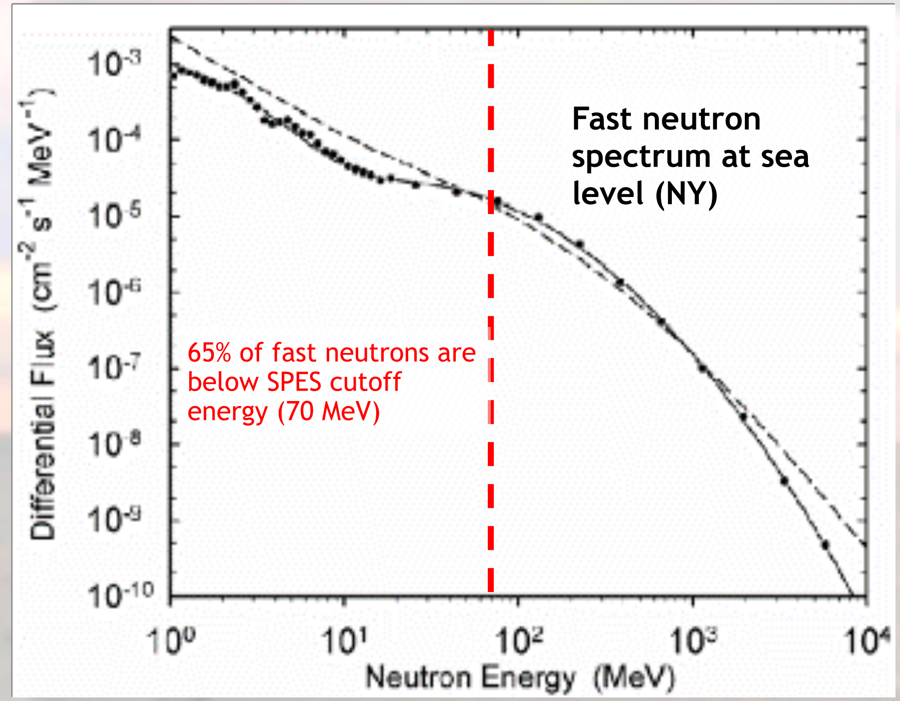


Accessible at NEPIR

Neutron effects in electronics

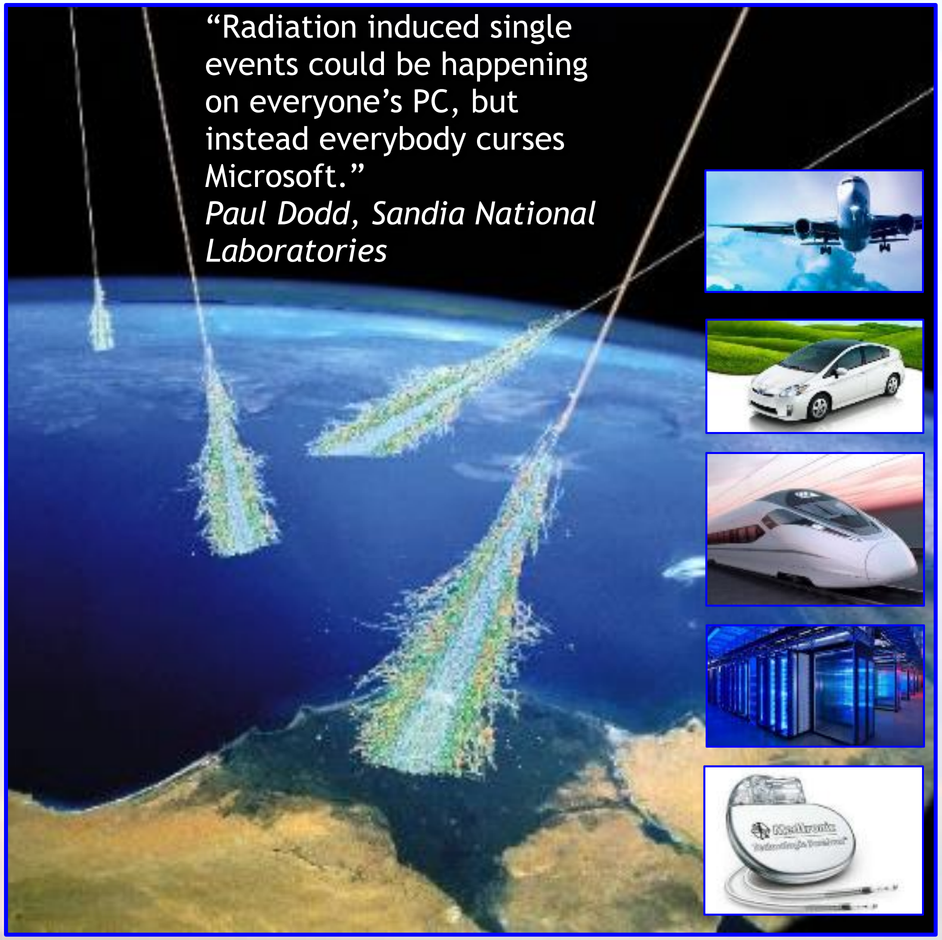
Neutrons in cosmic-ray air-showers are a widening problem for industry:

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



Fast neutron spectrum at sea level (NY)

65% of fast neutrons are below SPES cutoff energy (70 MeV)

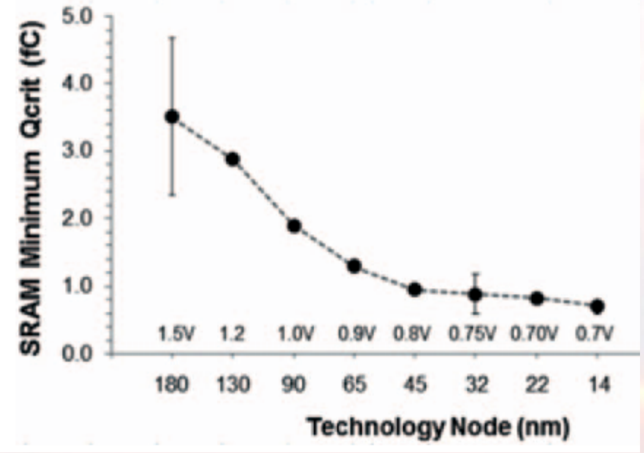


"Radiation induced single events could be happening on everyone's PC, but instead everybody curses Microsoft."
Paul Dodd, Sandia National Laboratories

The fast (E > 1 MeV) neutron flux at sea level is 21 n cm^{-2} hr^{-1}

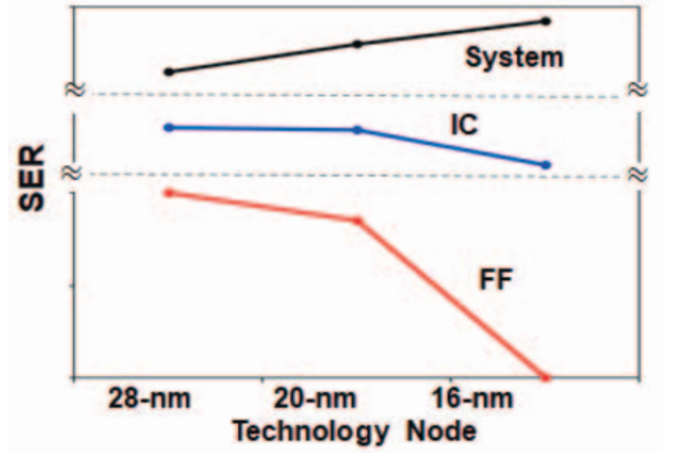
Sensitivity of Digital Electronics to Soft Errors (SE)

In the last decades, shrinking the transistor size as well as lowering the supply voltage resulted in a significant reduction of the electrical node charge, making integrated circuits more prone to ionizing radiation induced soft errors.



Critical charge required to cause an Soft Error (upset) for an SRAM cell as a function of technology node. This decrease brings a lower threshold.

At the transistor-level, this vulnerability stopped increasing in the most recent technology nodes; nevertheless the ever growing system complexity keeps high the failure rate at system-level, creating concern in the reliability of VLSI digital circuits for critical applications.



Soft Error Rate (arbitrary units) as a function of the technology node, at transistor, IC and system level. Soft Error Rate at Flip-Flop level decrease with technology, but remains constant at chip level and increases at the system level.

Neutron induced Soft Error Rate

While many electronic systems have an ***mean time between failure (errors)*** that exceeds the expected lifetime of the circuit, the neutron induced SE Rate (SER) may still be unacceptable to the manufacturer or customer.

•Many failures per million circuits due to SE can be expected in the field, if the system does not have adequate SE protection.

•The failure of even a few products in the field, particularly if catastrophic, can **tarnish the reputation of the product** and of the company that designed it.

•In **safety- or cost-critical applications** (the cost of system failure far outweighs the cost of the system itself), the risk of a 1% chance of SE failure per lifetime may be **unacceptable** to the customer.

It is advantageous to design for low SER when manufacturing a system in high-volume, or requiring extremely high reliability.

Test facilities are necessary.

Already established joint collaboration with Telecommunications Technology industries to test whole devices

Neutron SEE tests: field and “*accelerated*”

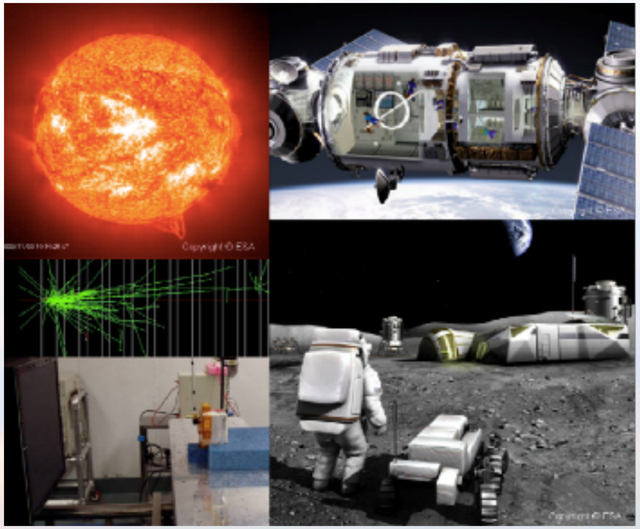
Boring! I need to speed these tests up… I want an accelerator!

Type	Experimental Method	Merit/demerit
Neutron Field Tests	Keep a large number of device under test (DUT) at a certain location for a long time.	• costly, time consuming • realistic ad reliable • few corrections necessary (related to altitude and location)
Monoenergetic Neutrons Thin light targets	Irradiate DUT with mono-energetic neutrons. Vary energy of the neutrons to study energy dependent effects	• facilities limited • versatile • actually neutrons are quasi-mono-energetic (QMN), hence corrections are necessary to account for significant fraction of neutrons with wrong energy.
Evaporation and Spallation Neutrons Thick targets	Irradiate DUT with neutrons of a broad energy range similar to atmospheric neutron spectrum.	• high fluxes • facilities limited • continuous (white) spectrum needs to be similar to atmospheric one • uncertain in selection of energy range
Thermal Neutrons	Irradiate DUT with thermal neutrons at experimental reactors or using targets with moderators	• facilities limited • using reactors the estimation of SEE rate in field is difficult due to great difference in neutron spectra
Proxy mono-energetic protons	*Irradiate DUT with mono-energetic protons. Vary the energy of the protons to study energy dependent effects.*	• *many facilities available* • *pseudo-equality with neutron nuclear cross-sections* • *ionization dose effects in DUT*

SPARE project

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

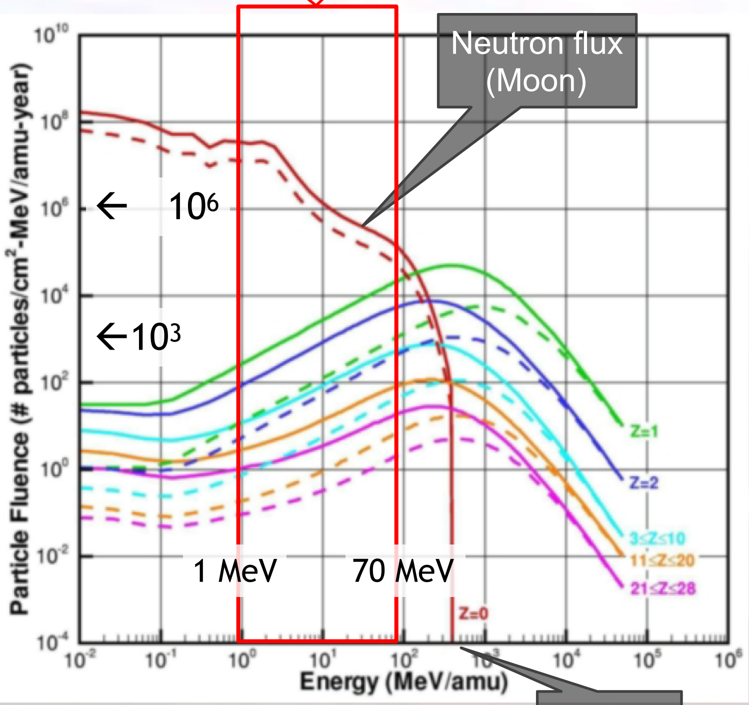
SPARE is a project involving ASI, INFN and Centro Fermi. The goal is to perform a test campaign to investigate the effectiveness of active and passive shielding materials for the human activity on Mars, using the proton beam facility at TIFPA (Trento Institute for Fundamental Physics Applications) with E_p = 70-228 MeV and fast neutron beams at the LNL-NEPIR facility (under development) E_p= (20)30-70 MeV.



Fast neutrons on Mars and Moon

The energetic (E > 1 MeV) neutron flux on earth is 21 n cm^{-2} hr^{-1}; for comparison; on the surface of the Moon it's 2 orders or magnitude higher, with a cutoff at 400 MeV. On the surface of Mars the spectrum is harder and the flux 3 orders of magnitude higher than on Earth surface.

Accessible at NEPIR



Neutron flux (Moon)

← 10^6

←10^3

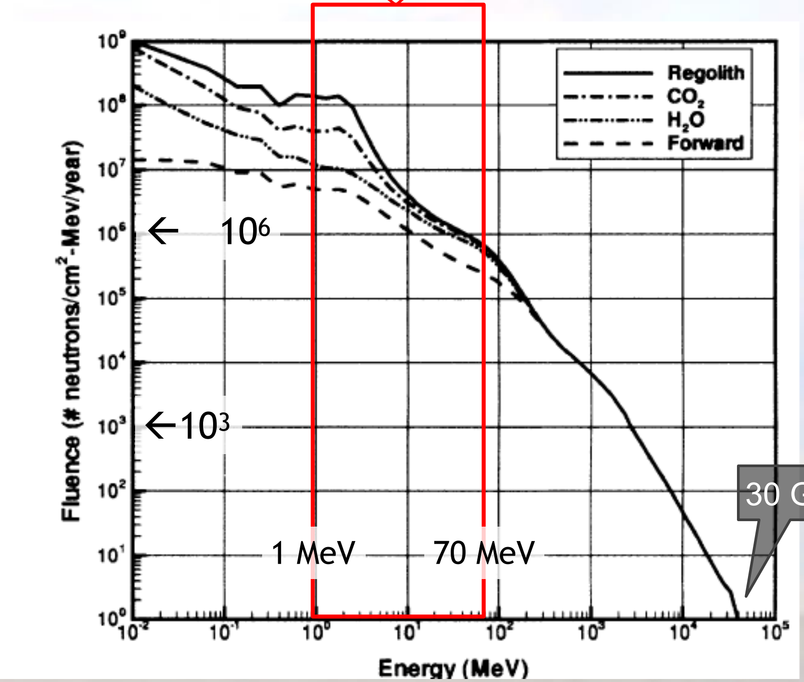
1 MeV

70 MeV

400 MeV

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

Accessible at NEPIR



← 10^6

←10^3

1 MeV

70 MeV

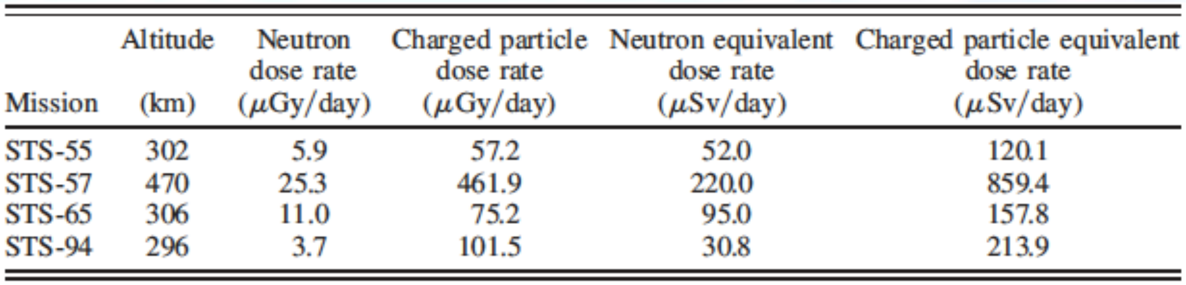
30 GeV

Mars surface neutron environment (with 16 g/cm² CO_2 overhead and various surface material compositions).

doi:10.1016/j.asr.2003.10.052

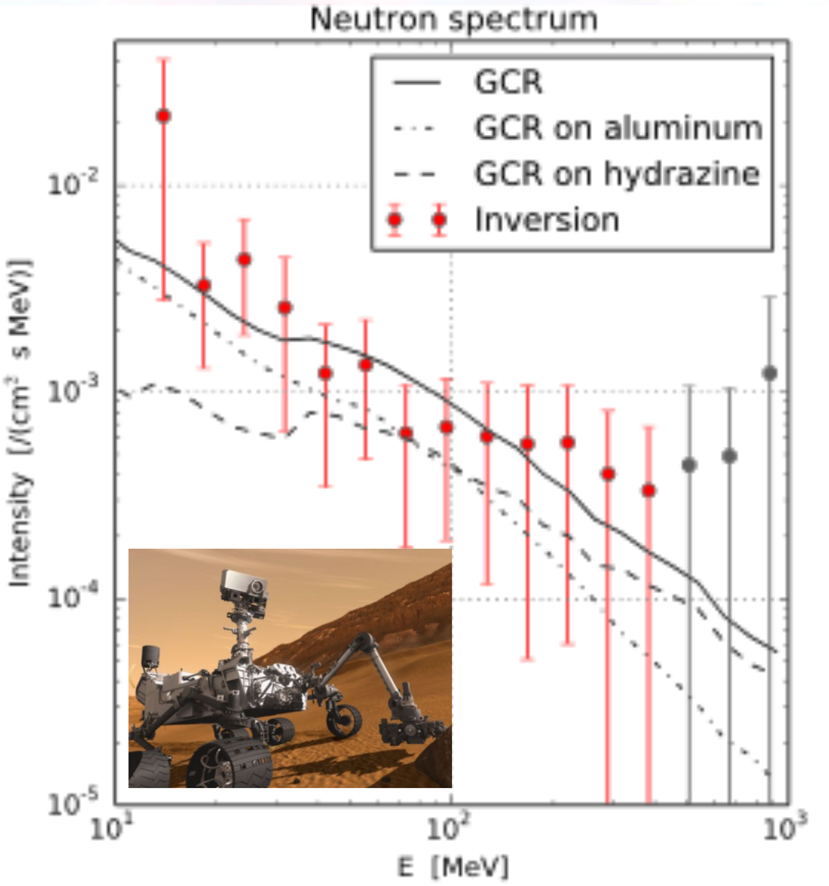
Secondary particles from spacecraft material

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)

Nuclear data measurements for energy and non energy applications

- Nuclear data are an essential quantity in wide applications. Energy and non energy applications require accurate cross section data, from thermal to several tents of MeV.

- Both excitation function and integral measurements are requested by the main important international agency, as IAEA or NEA. NEA collect the needs from different institutions, make analysis and produce a prioritized list of recomended measurements (HPRL- High Priority Request List).

- An example is the IAEA CRP for the new International Reactor Dosimetry and Fusion File (IRDFF): an update of a DATABASE OF USEFUL REACTION FOR FUSION AND FISSION REACTOR DOSIMETRY (https://www-nds.iaea.org/IRDFFtest/).

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Example of requested reaction cross section measurement:

^{nat}Fe(n,x)^{54}Mn, ^{51}Cr,
^{209}Bi(n,3-8n),
^{59}Co(n,3-5n),
^{175}Lu(n,2-4n),
^{93}Nb(n,3-4n),
^{139}La(n,4-10n),

^{nat}Ti(n,x)^{46}Sc, ^{47}Sc, ^{48}Sc
^{9}Y(n,2-4n)& (n,p)
^{197}Au(n,3-5n)
^{169}Tm(n,2-3n)
^{54}Fe(n,2n)
^{103}Rh(n,4-8n)

Cross section measurements for fusion and fission reactors

IFMIF-DONES and DEMO the Activation cross-section data

- The quality of activation cross-section data directly determines the accuracy of the predicted radiation sources and affects safety and licensing issues, decommissioning and waste management
- Latest version EAF-2010 included 816 different targets nuclides from ^{1}H to ^{257}Fm with 66,256 excitation functions up to the neutron energy of 60 MeV
- The strategy is to adopt the TENDL data library as source data library for activation cross-sections. It is mandatory to ensure that TENDL can actually preserve or increase the quality of EAF-2010 by including the variety of validated cross-sections and improving deficient data

credits: Javier Praena

List of raccomanded cross section data for IFMIF DONES

A set of 97 reaction cross-sections to be improved

^{23}Na(n,γ)^{24}Na, ^{24}Mg(n,γ)^{25}Mg, ^{50}Ti(n,γ)^{51}Ti, ^{51}V(n,γ)^{51}V,
^{54}Fe(n,γ)^{55}Fe, ^{58}Fe(n,γ)^{59}Fe, ^{54}Mn(n,γ)^{55}Mn, ^{55}Mn(n,γ)^{56}Mn,
^{58m}Co(n,γ)^{59}Co, ^{59}Co(n,γ)^{60}Co, ^{63}Cu(n,γ)^{64}Cu, ^{65}Cu(n,γ)^{66}Cu,
^{74}Ge(n,γ)^{75}Ge

^{27}Al(n,2n)^{26m}Al, ^{36}S(n,2n)^{35}S, ^{46}Ti(n,2n)^{45}Ti, ^{48}Ca(n,2n)^{47}Ca,
^{50}Cr(n,2n)^{49}Cr, ^{52}Cr(n,2n)^{51}Cr, ^{56}Fe(n,2n)^{55}Fe, ^{60}Ni(n,2n)^{59}Ni,
^{72}Ge(n,2n)^{71}Ge, ^{114}Sn(n,2n)^{113}Sn, ^{120}Sn(n2n)^{119}Sn, ^{140}Ce(n,2n)^{139}Ce

^{34}S(n,α)^{31}Si, ^{40}Ca(n,α)^{37}Ar, ^{48}Ca(n,α)^{45}Ar, ^{46}Ti(n,α)^{43}Ca,
^{50}Cr(n,α)^{47}Ti, ^{52}Cr(n,α)^{49}Ti

^{56}Fe(n,p)^{56}Mn, ^{67}Zn(n,p)^{67}Cu, ^{90}Zr(n,p)^{90g}Y, ^{94}Mo(n,p)^{94}Nb,
^{95}Mo(n,p)^{95}Nb, ^{116}Sn(n,p)^{116}In, ^{117}Sn(n,p)^{117}In, ^{183}W(n,2n)^{182}W,
^{187}Re(n,2n)^{186g}Re, ^{49}Ti(n,np)^{48}Sc, ^{28}Si(n,p)^{28}Al, ^{55}Mn(n,α)^{52}V,
^{60}Ni(n,p)^{60m}Co

credits: Javier Praena

NEPIR facility

Fast neutrons (E_n > 1 MeV)

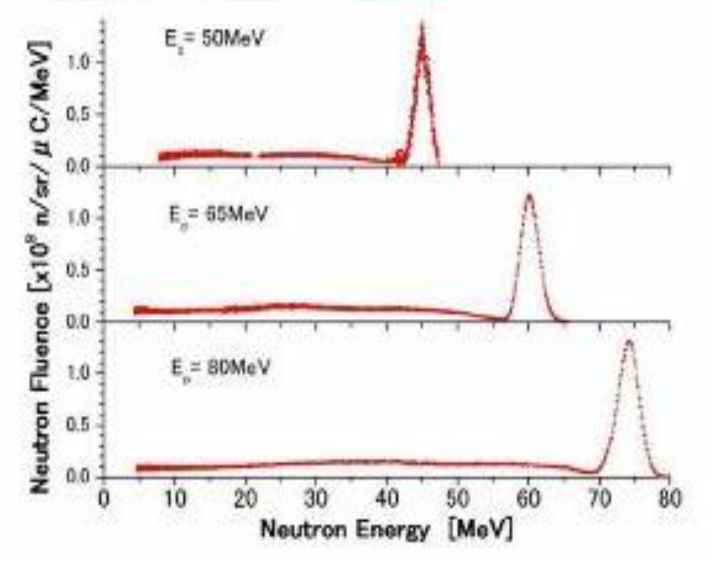
- Three subsystems: **QMN**, **ANEM** and **PROTON**
- Originally conceived to study of **radiation damage effects in electronic devices and systems** induced by:

  - flight-altitude and sea-level *atmospheric* **neutrons**

  - solar **protons** **(future: not discussed in this talk)**

- **They will be also used to perform:**
  - Nuclear physics: X(p,n+x) cross-sections, neutron yields,…
  - biological samples irradiation,
  - shielding performance evaluation,
  - material degradation studies,
  - …

(Fast) Quasi Monoenergetic Neutrons



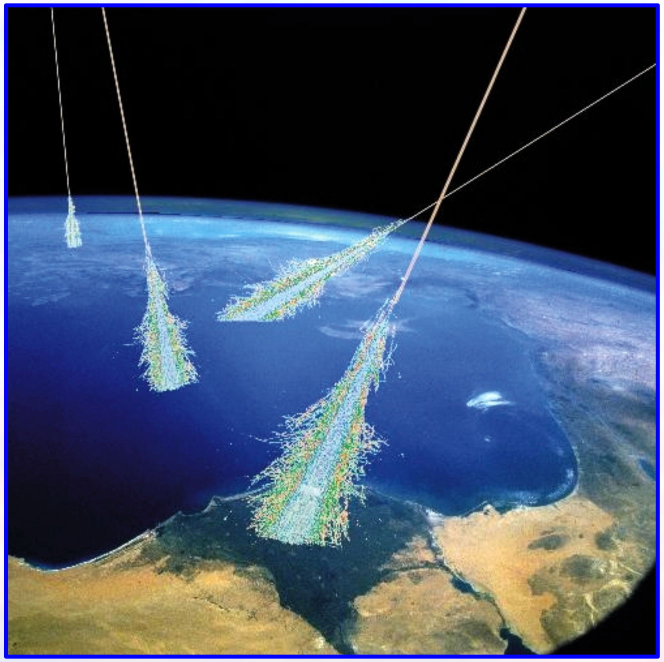
Forward (θ = 0°) QMN energy spectra beams for different proton beam energies on a thin (non beam-stopping) Lithium target

[TIARA facility, Japan].

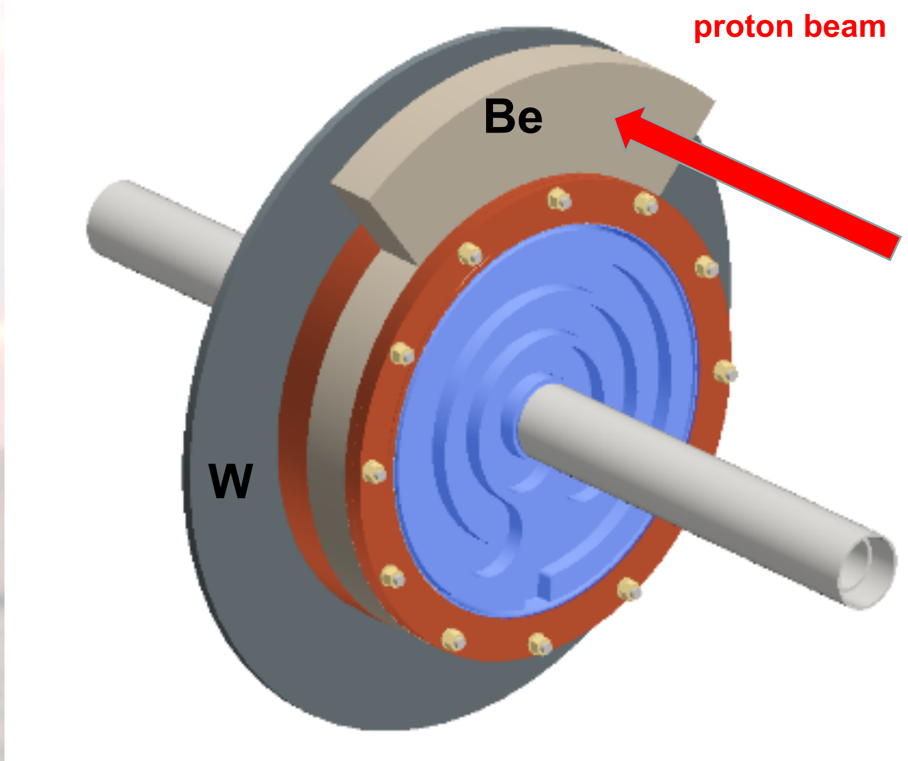
Performance of different QMN sources (from Lithium) beams around the world.

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**

Atmospheric Neutron Emulator (ANEM)



A **novel** 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 an off axis 70 MeV proton beam. The effective atmospheric-like neutron spectrum in the 1-65 MeV range is composed directly, without the use of moderators.

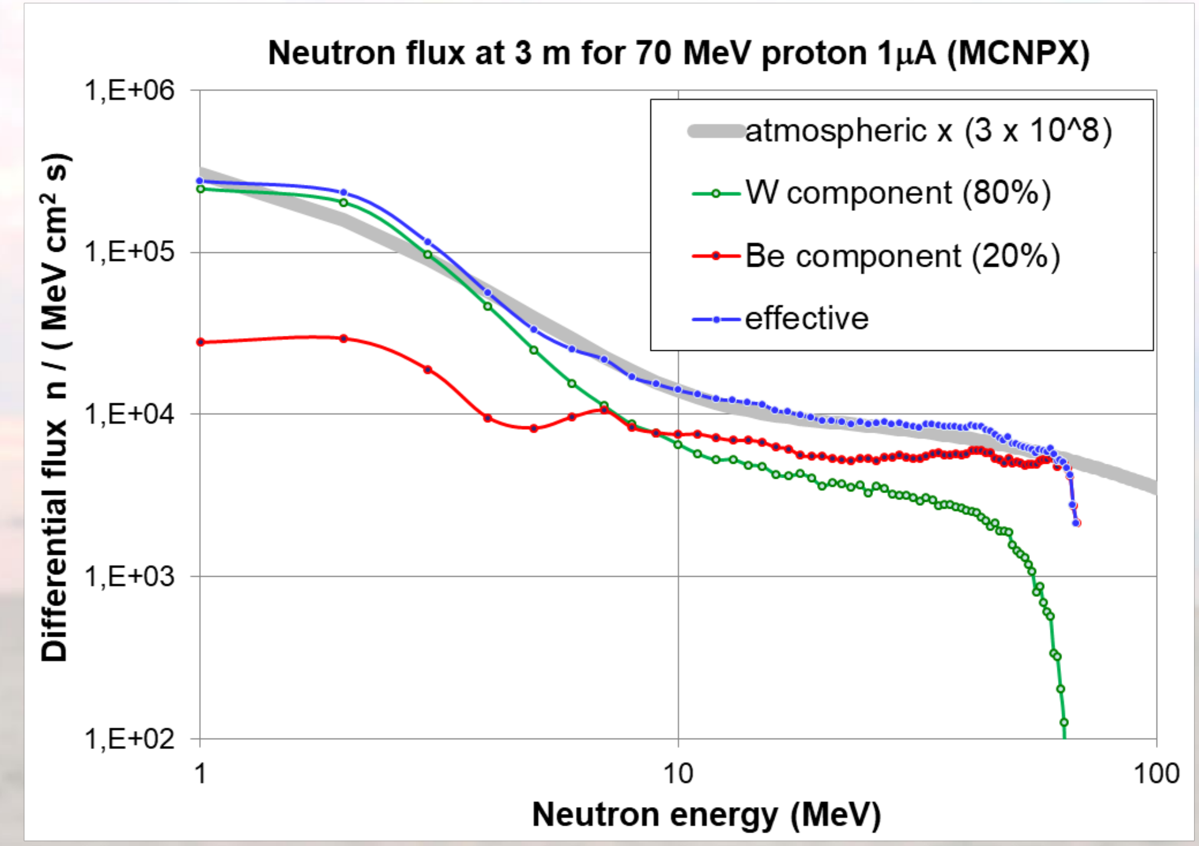


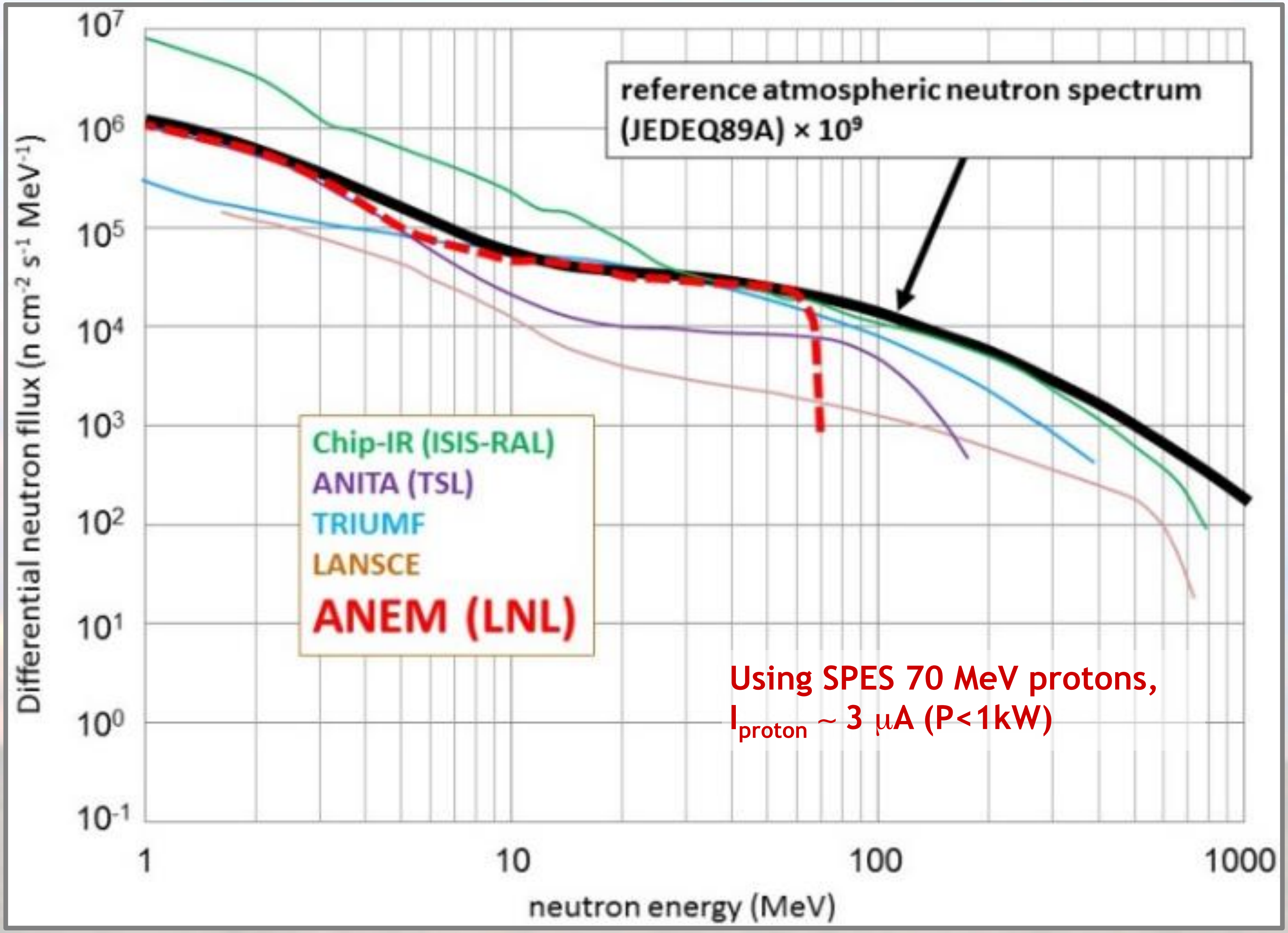
The target is designed to tolerate a maximum current I_{beam} = 30 μA (2.1 kW).

Spectra combination

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

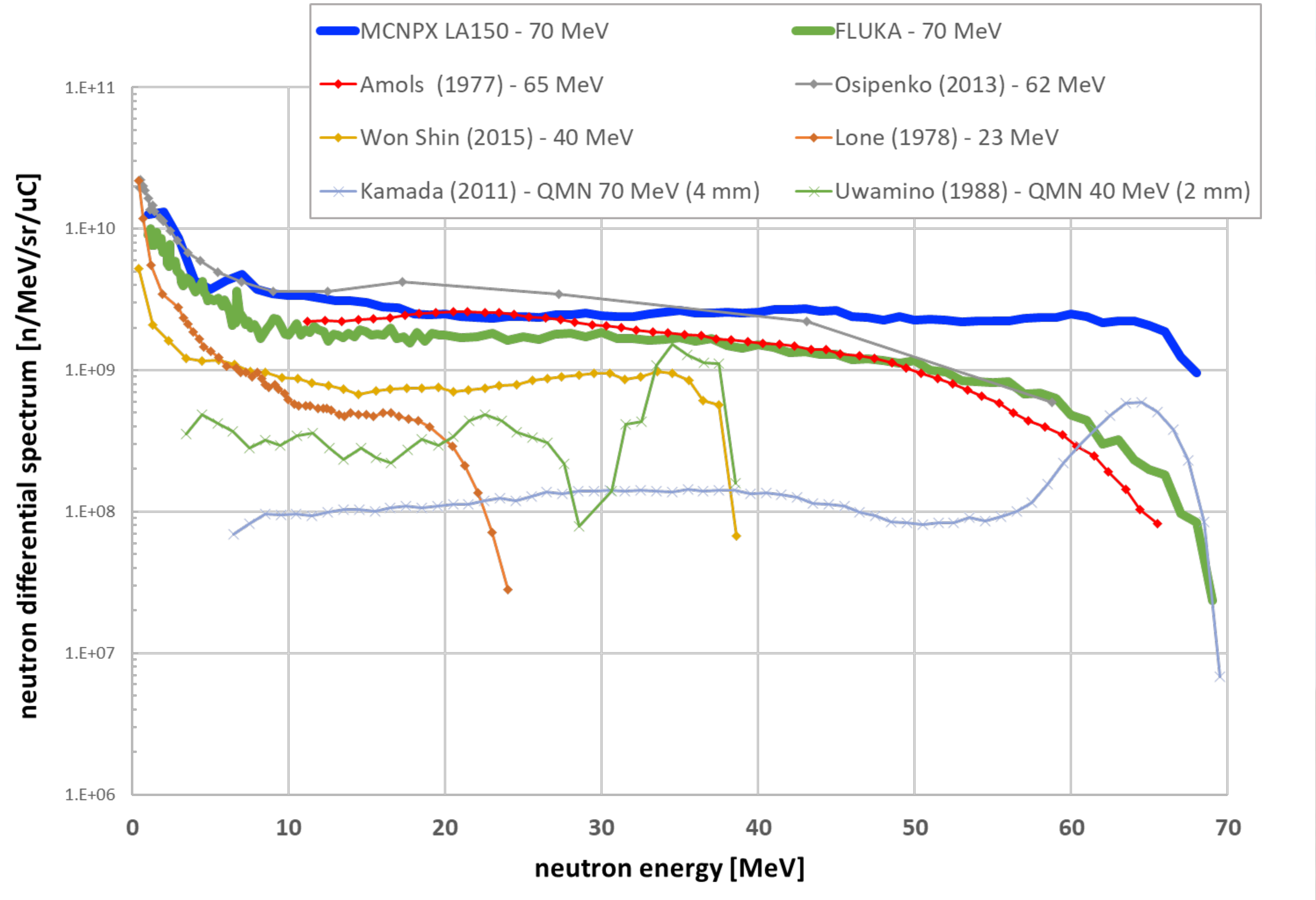
The delivered **neutron flux is 1.7×10⁶ cm⁻² s⁻¹** (at 3 m for a 1 μA proton current), corresponding to an acceleration factor of 3 × 10⁸



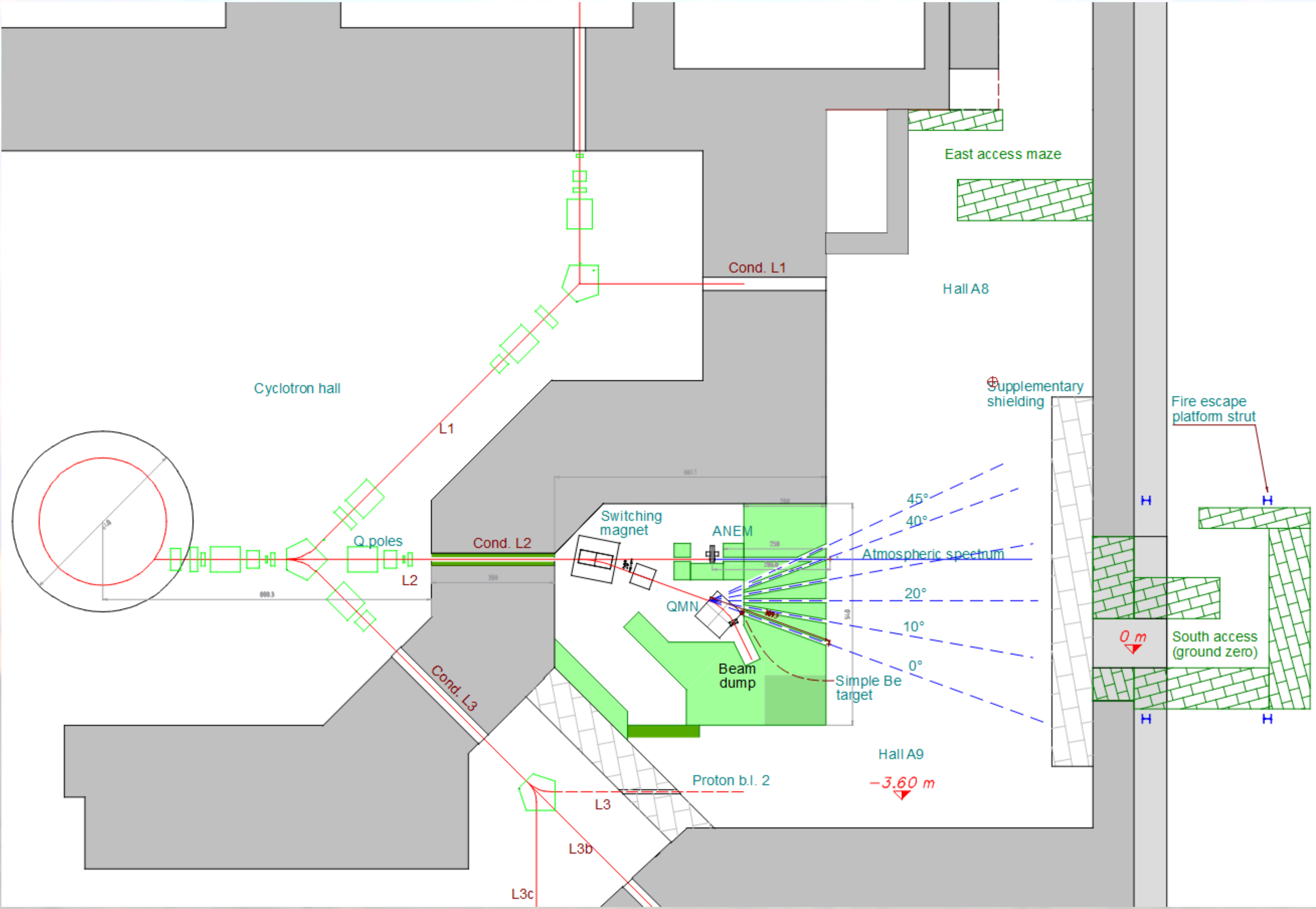


Using SPES 70 MeV protons, $I_{proton} \sim 3\ \mu A$ (P<1kW)

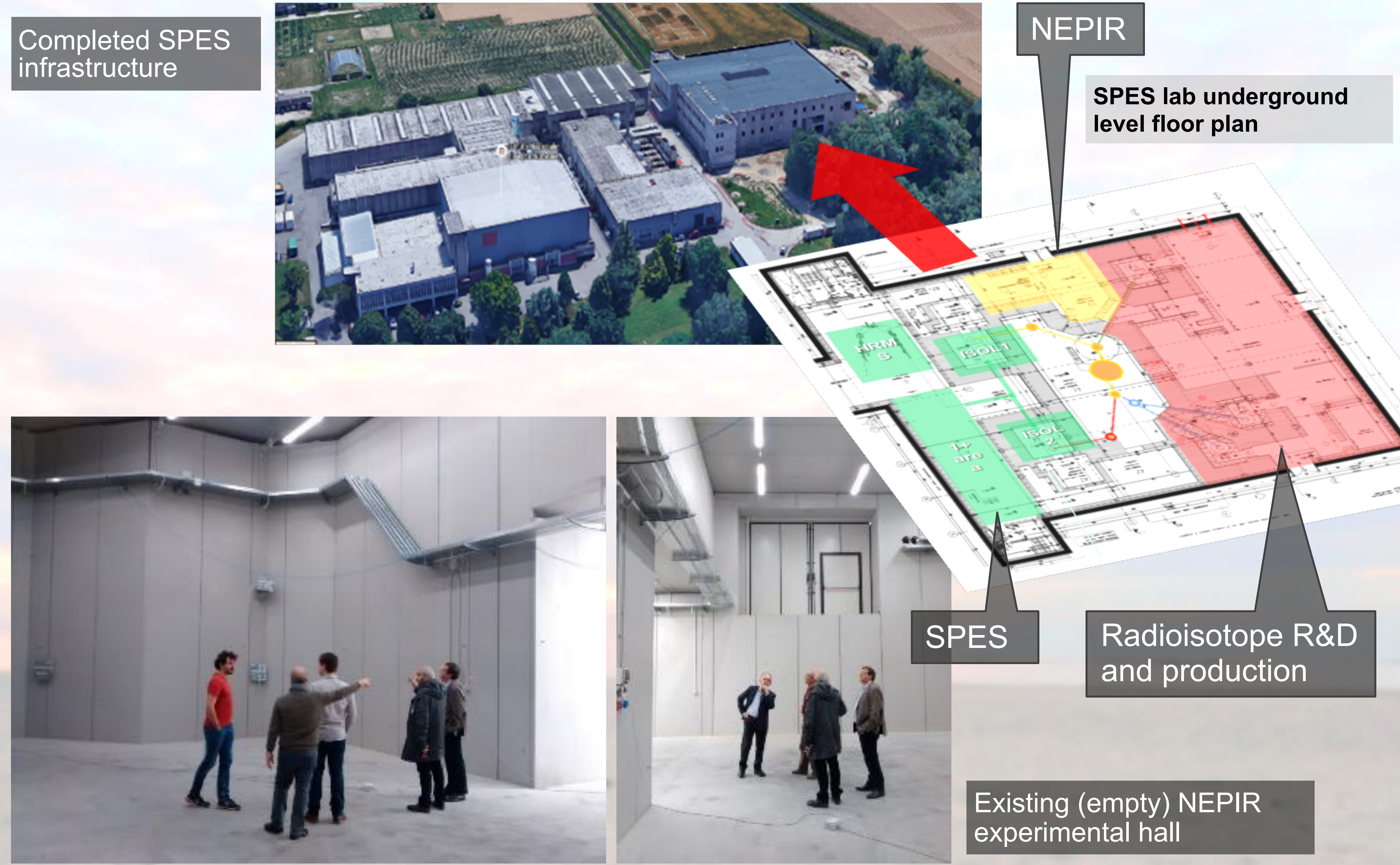
Proton on Be neutron energy spectra uncertainty (references in EXTRA SLIDES)



NEPIR Layout



Status of NEPIR facility construction



Completed SPES infrastructure

NEPIR

SPES lab underground level floor plan

SPES

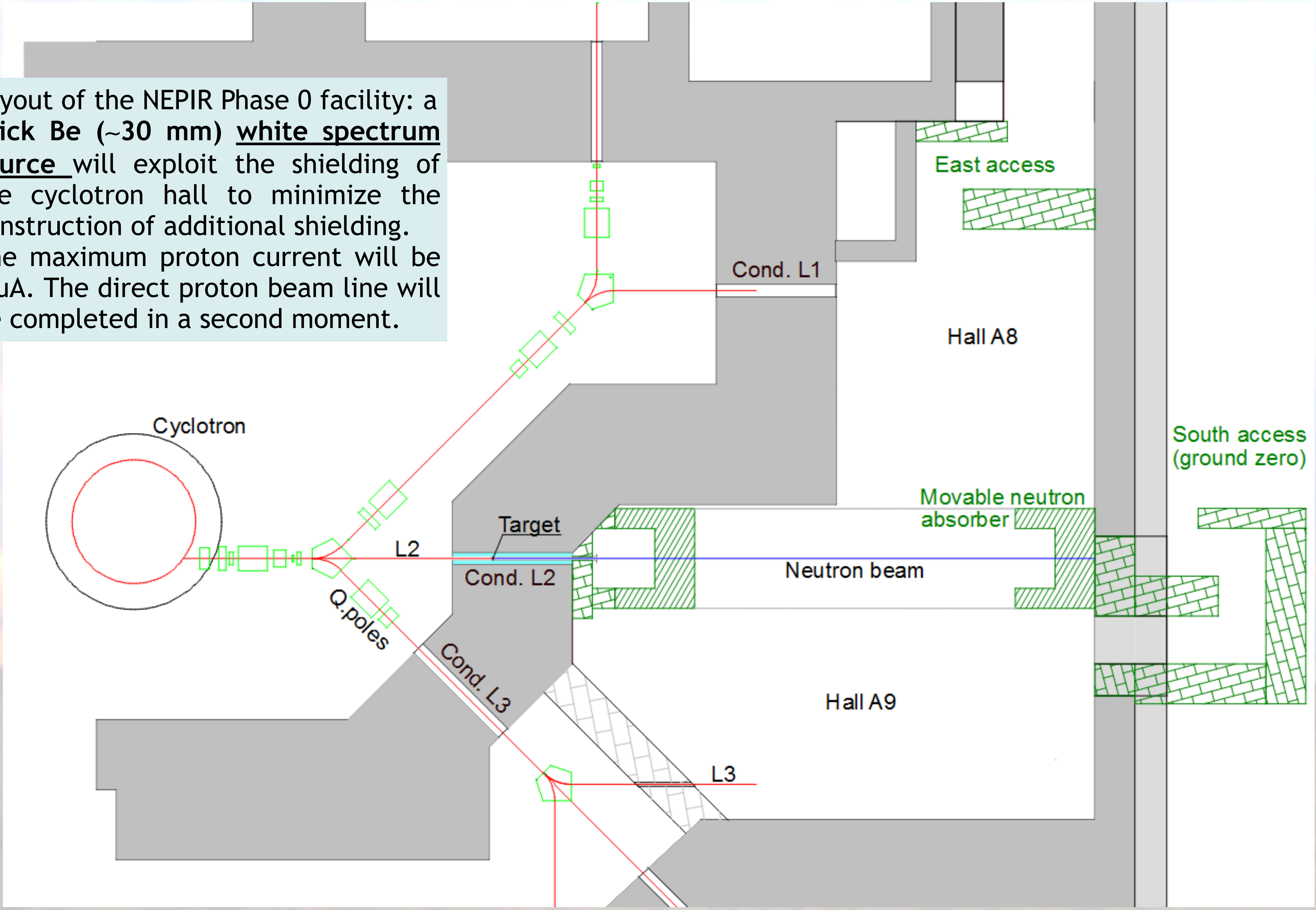
Radioisotope R&D and production

Existing (empty) NEPIR experimental hall

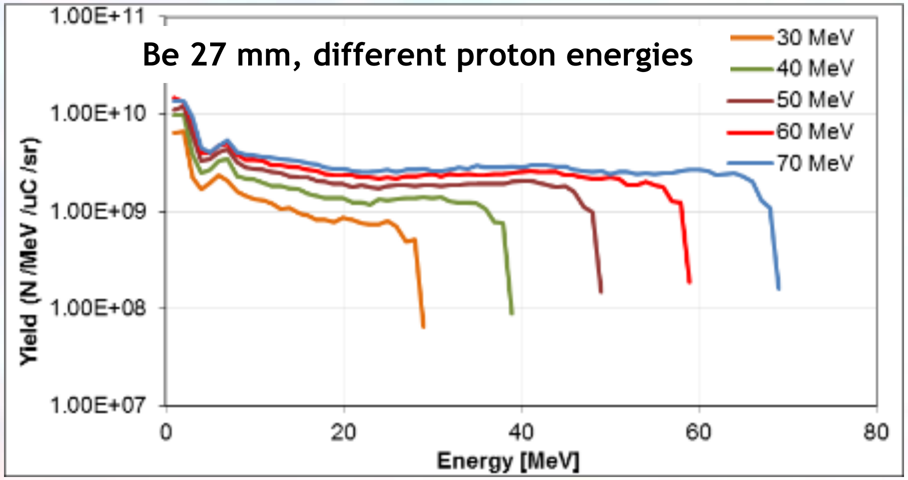
Limited SPARE funds
sufficient for a phase 0 facility
(NEPIR-0)
white spectra and pseudo-QMN

NEPIR: Phase-0 (thick white spectrum Be target); floorplan

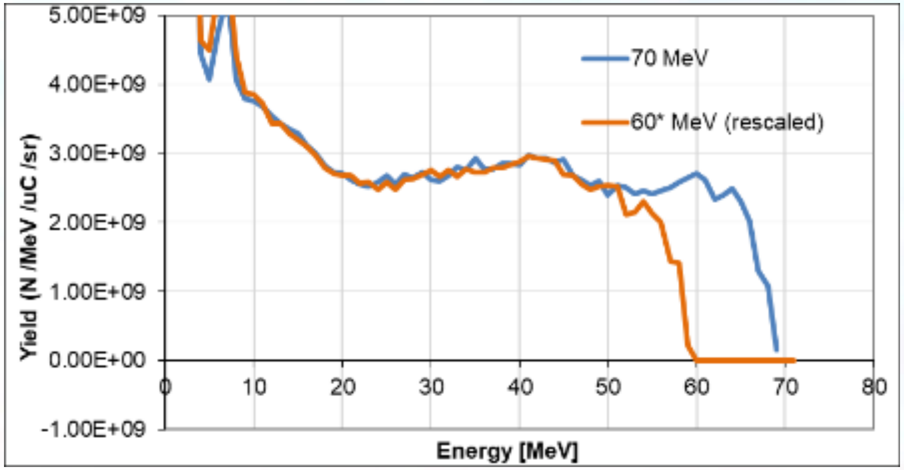
Layout of the NEPIR Phase 0 facility: a **thick Be (~30 mm)** **<u>white spectrum source</u>** will exploit the shielding of the cyclotron hall to minimize the construction of additional shielding. The maximum proton current will be 1 μA. The direct proton beam line will be completed in a second moment.



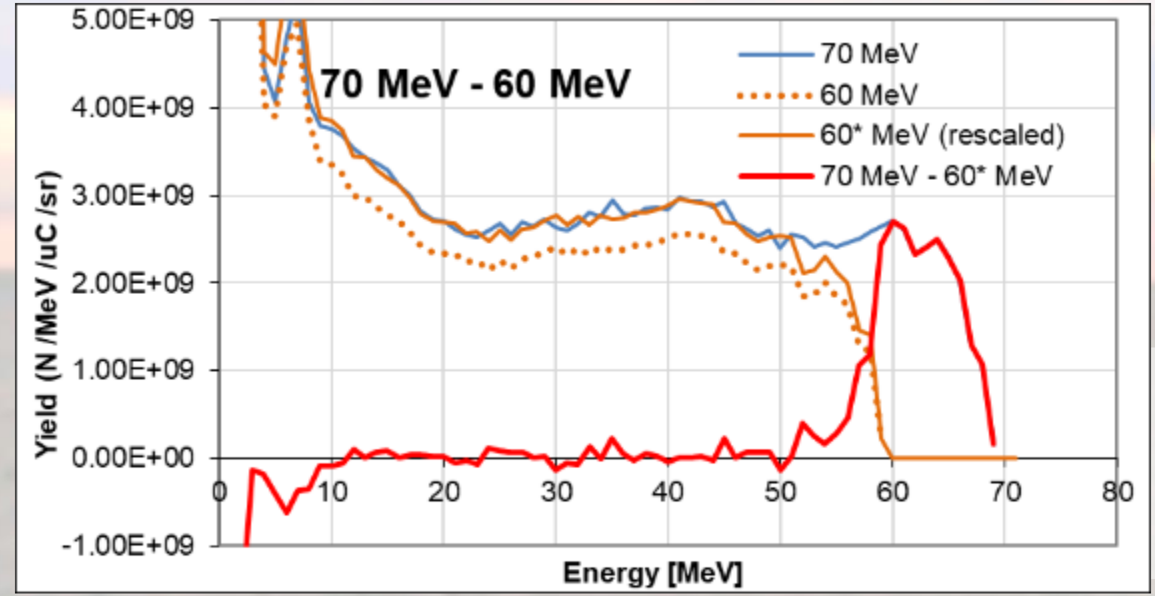
NEPIR-0: Thick Be white neutron MCNPX spectra at different proton energies



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,

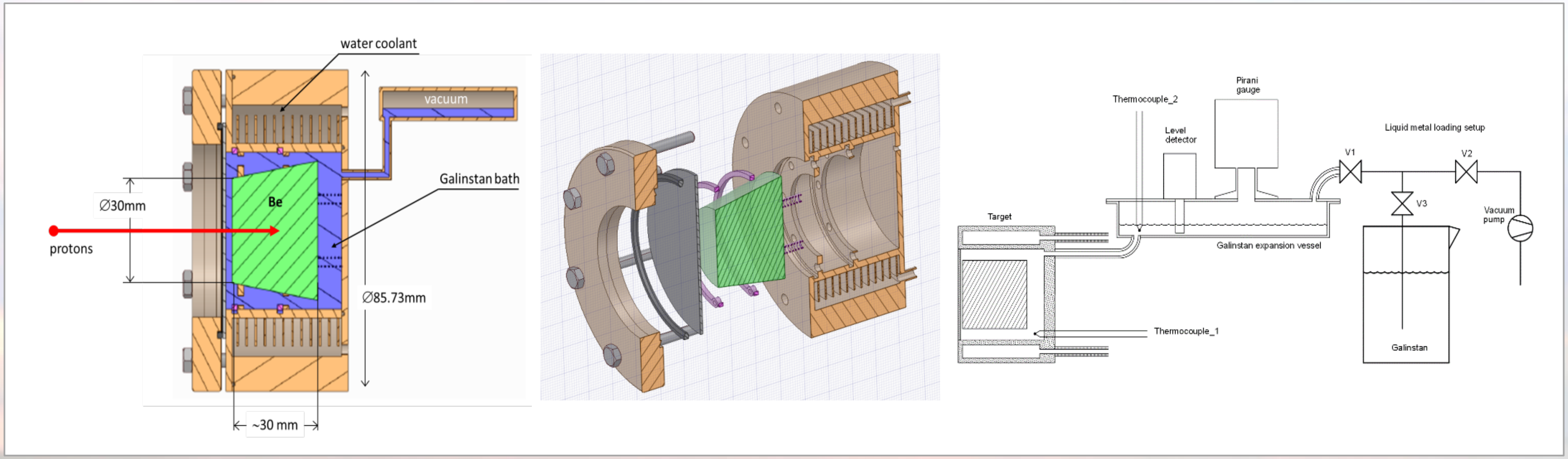
with 1 μA of 70 MeV protons

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

CoolGAL: a beryllium based target

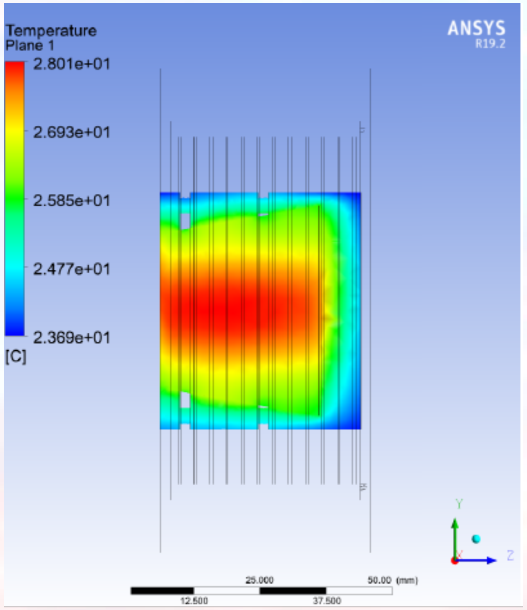
The beryllium target is in a bath of GALINSTAN (metal liquid alloy of SnInGa), incapsulated in a protected Copper cladding. For 70W air cooled is preferable.

The liquid metal alloy has a reservoir tank which works as expansion volume. The temperature of the liquid, the pressure of the reservoir and the level of the liquid is monitored and the data used to interlock the beam.

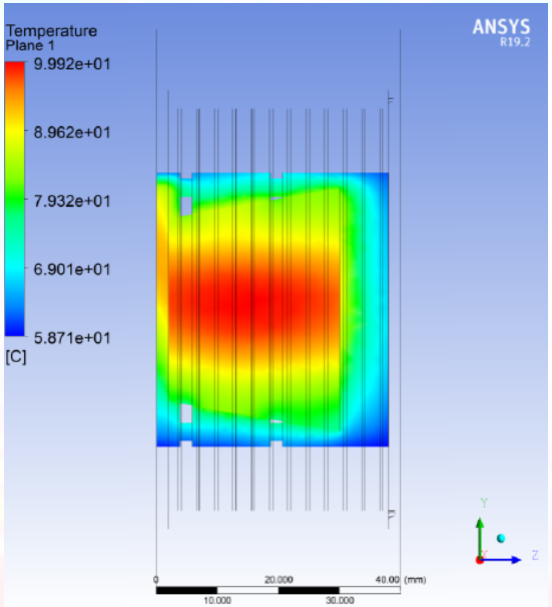


The liquid metal provide:
- To cool down the Havar window
- To ensure a good thermal contact and heat transfer to the cladding for conduction
- To keep the debris of beryllium if/when blistering occurs.
- Allow thermal dilatation of the beryllium
- Thanks to natural convection, distribute the heat on the whole surface of the cladding.

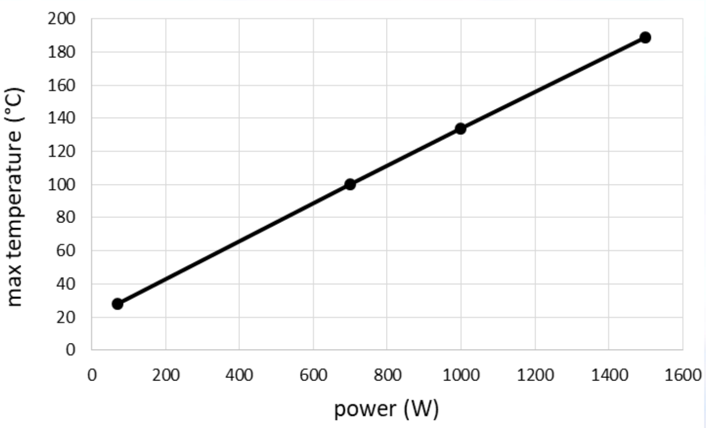
CoolGAL: ANSYS CFX simulations



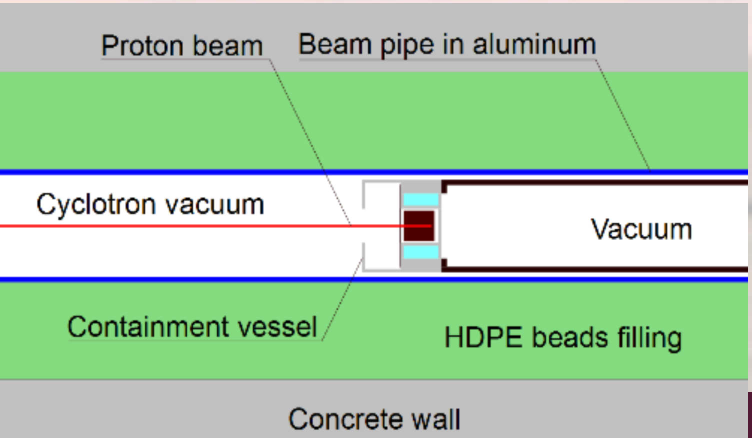
Temperature map of the Be and Galinstan of a preliminary ANSYS model of CoolGal with water coolant (v=2m/s) for a 1 uA current of 70 MeV protons (70 W). The maximum temperature of the Be component is 28°C.



Temperature map of the Be and Galinstan of a preliminary ANSYS model of CoolGal with water coolant (v=2m/s) for 700 W (10 uA current of 70 MeV protons). The maximum temperature of the Be component is 100°C.



Summary of the maximum temperature of the Be component versus beam power of the ANSYS model of CoolGAL using water coolant flowing at v = 2 m/s with an input temperature of 20°C.



Schematic representation of the target system inside the conduit through the cyclotron concrete shield wall (grey). In green, the polyethylene filling in the gap between the vacuum line and the wall. A composite material plug (in black) is used to insert the target system and then to hold it place.

CONCLUSIONS

- The **basic design** of the NEPIR facility, its beam-optics, and different neutron production target systems are defined; shielding calculations are essentially complete and have to be validated by radio protection service;
- A design of a **Phase-0 version** of the facility, with a white spectrum target (CoolGAL) is being developed; it can be exploited for pseudo-QMN analysis. The funding of the LNL work-package of the SPARE project is sufficient for this solution. Completion expected in about one year.
- The design of a more expensive **true-QMN** is in advanced stage, but present funds are not sufficient.
- An **ANEM prototype** exists, with an aluminum test disk and an electron gun system (under commissioning) for thermal tests.

The end

Thank you for your attention

Extra slides follow

Extra slides