NEPIR (NEutron and Proton Irradiation) facility at INFN-LNL

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Neutron sources @ LNL-INFN

Neutron Sources

From 2007

$^7Li(p,n)^7Be$

BELINA@**CN**

From 2022

$5<E_n<20$ MeV

Inverse reactions: $^{14}N(^7Li,n)$

FANNILI@**Tandem**

$5\cdot10^5$ n/cm^2/s/500 nA @ 10 cm

$35<E_n<70$ MeV

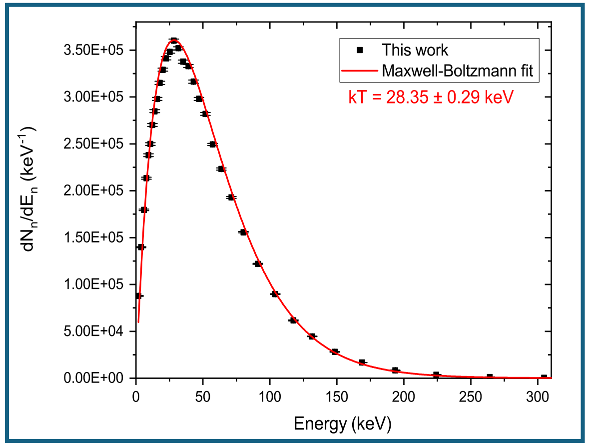
$2\cdot10^7$ n/cm^2/s/50 pnA @ 10 cm

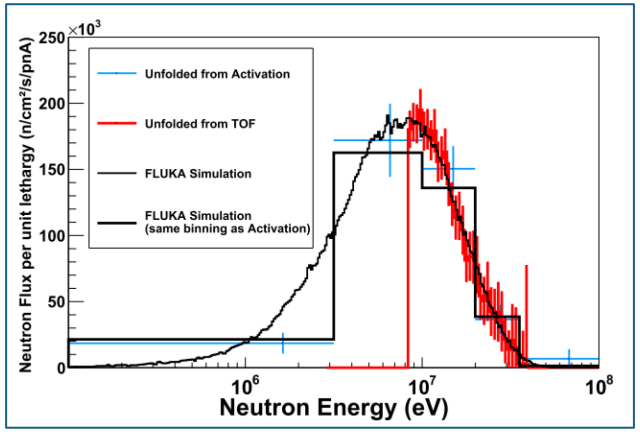
@ **SPES (P70)**

Nuclear astrophysics studies

Quasi-monoenergetic neutrons (QMN): neutrino scintillator development (JUNO), detector development. Radiation Damage in electronics

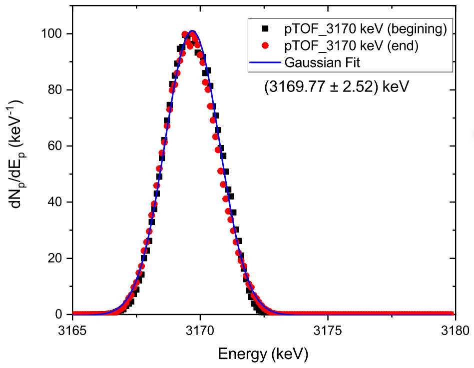
Scintillator and detector development, Radiation Damage in Electronics (SEE)





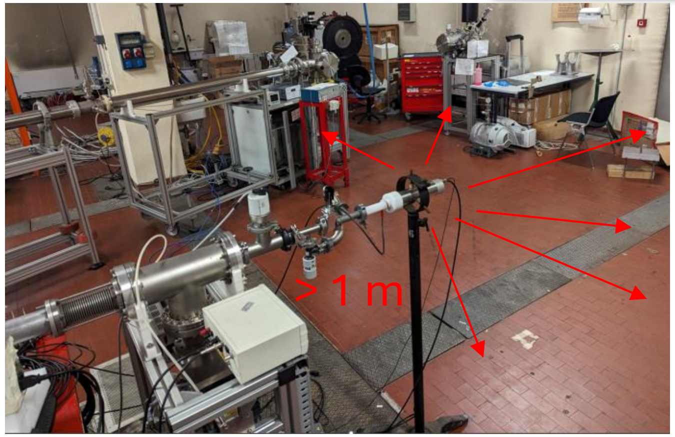
BELINA @ CN

Accelerated partcle	Min-Max HV (MV)	Time resolution (FWHM)	Rep Rate	Max I @3 MHz
p,d,He,h2+,d 2+,He+,He++	1-6	<2 ns	1Hz—3 MHz Δt=n 330 ns	300 nA



Proton TOF measurement

Li metallic target + Cu backing

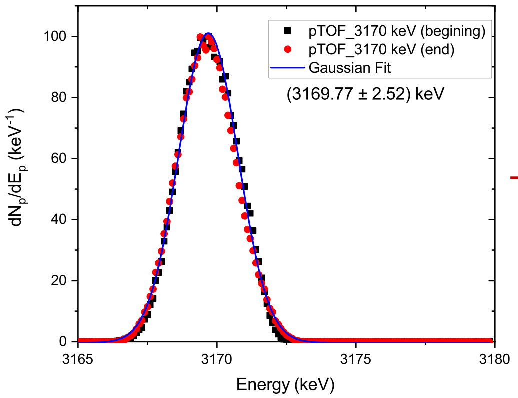


Target assembly

Low mass movable goniometer

Nucleosynthesis @ LNL

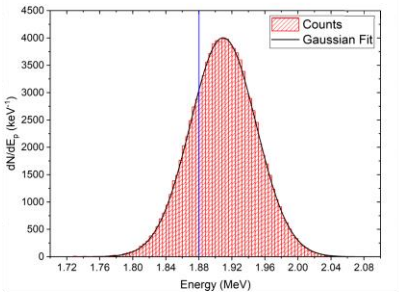
PROTON BEAM



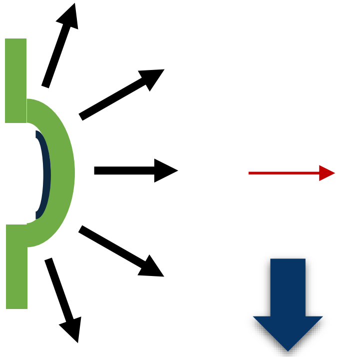
$E_p = 3.17$ MeV

51 μm Al foil

Shaped proton distribution

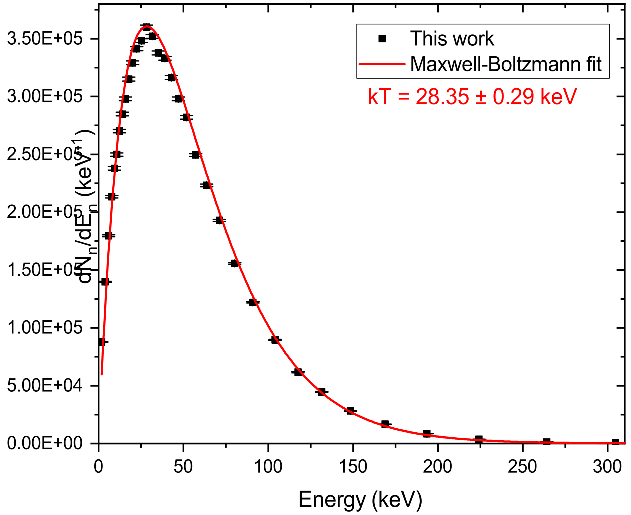


Li target



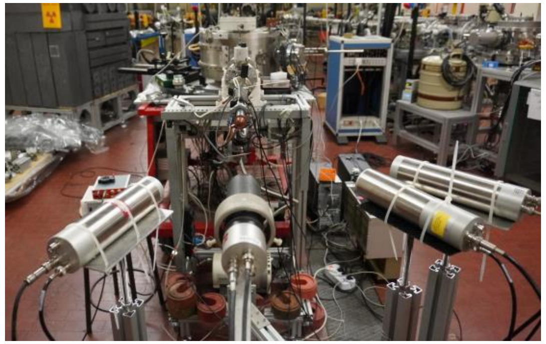
Neutron Time-of-Flight

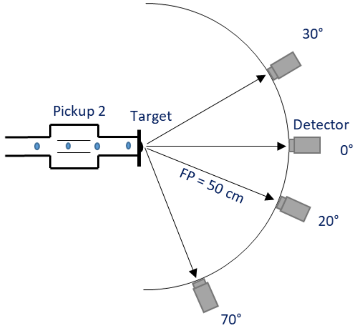
0°-90° INTEGRAL NEUTRON SPECTRUM



$R^2 = 0.992$

Well reproduce Maxwell-Boltzmann spectrum





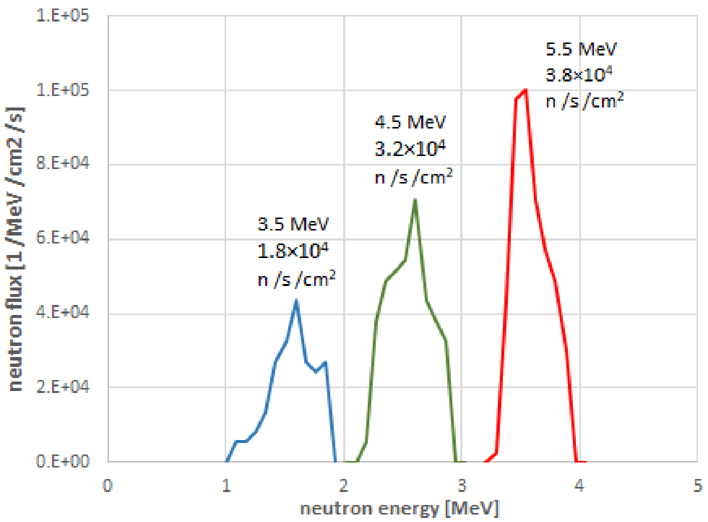
E. Musacchio-Gonzalez et al., NIMA, 1063, 169255 (2024)
https://doi.org/10.1016/j.nima.2024.169255

QMN @ BELINA

0° beam line

The 0° beam line of the old 6 MV CN can deliver protons on a thin (>20 μm) lithium target to produce QMN neutron beams with gaussian-like energy distributions.

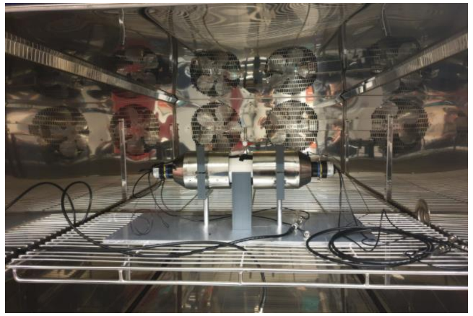
Figure below: simulated neutron spectra for different proton beam energies with 3 μA currents.



With the present radioprotection limits of the CN, the maximum current is 9 μA. At a proton energy of 5 MeV and at 40 cm, the simulated peak neutron energy is 3.5 MeV and integral flux under the peak is **1.1×10^5 n cm^{-2} s^{-1}**. Measurement already scheduled.

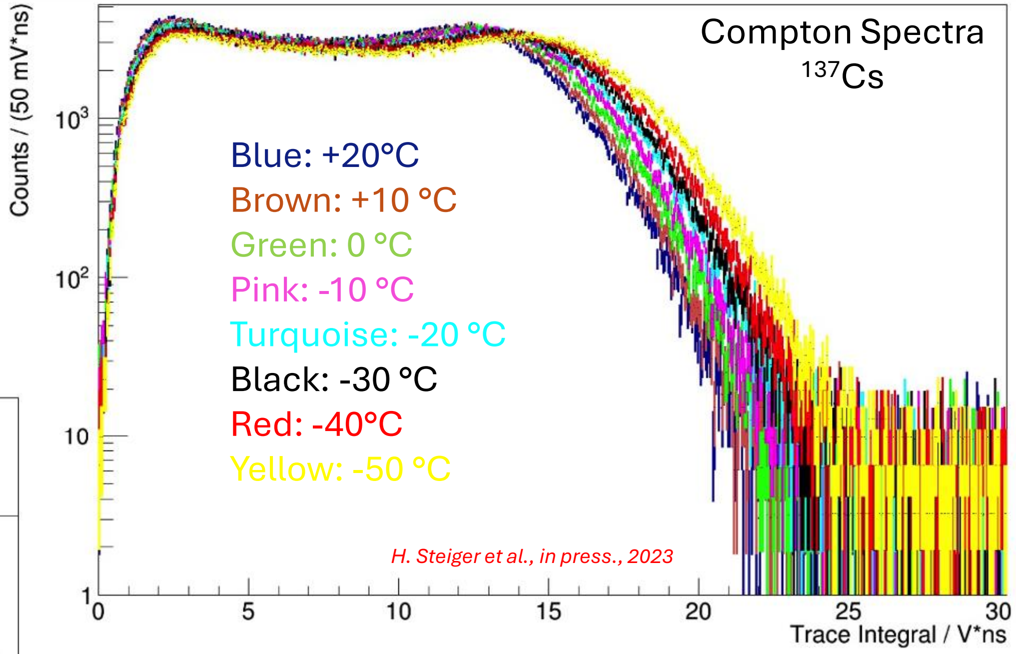
Overview: A Fridge for the TAO Measurements

BINDER MKT 115
Climate Chamber
(with air dryer and thir window)

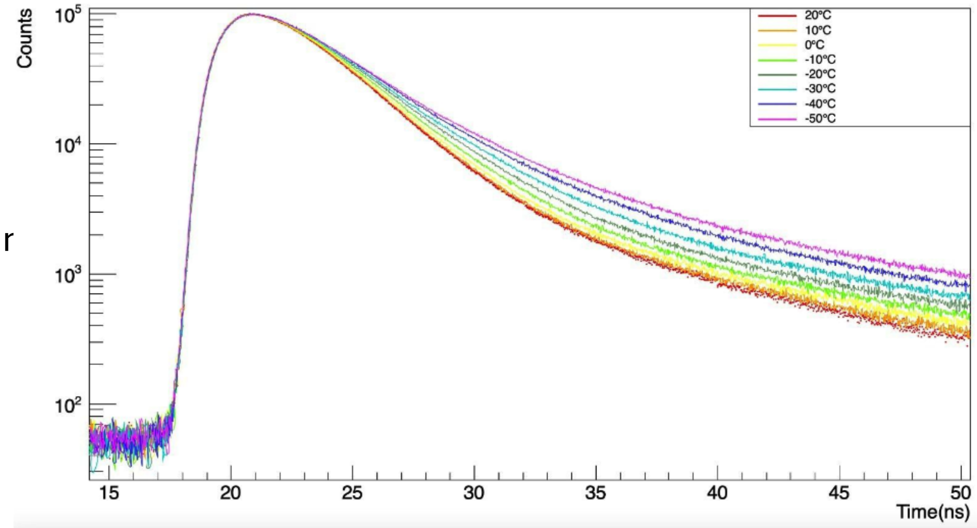


Modified QF Setup in the climate chamber

Detector Response from +20 °C down to -50 °C



Light yield went up during the cool down
→ approx. ~ 12% from +20°C to -50°C



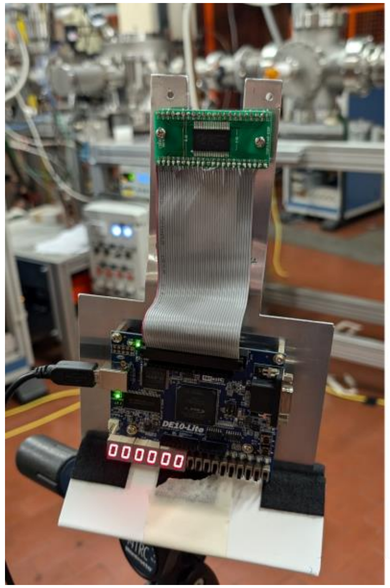
Scintillation Time Profile (UV excitation): Slower with lower T! *H. Steiger et al., in press., 2023*

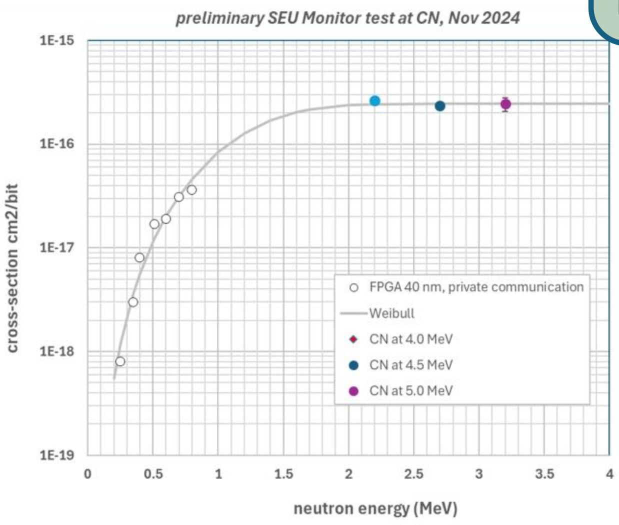
Electronics: Neutron induced SEE

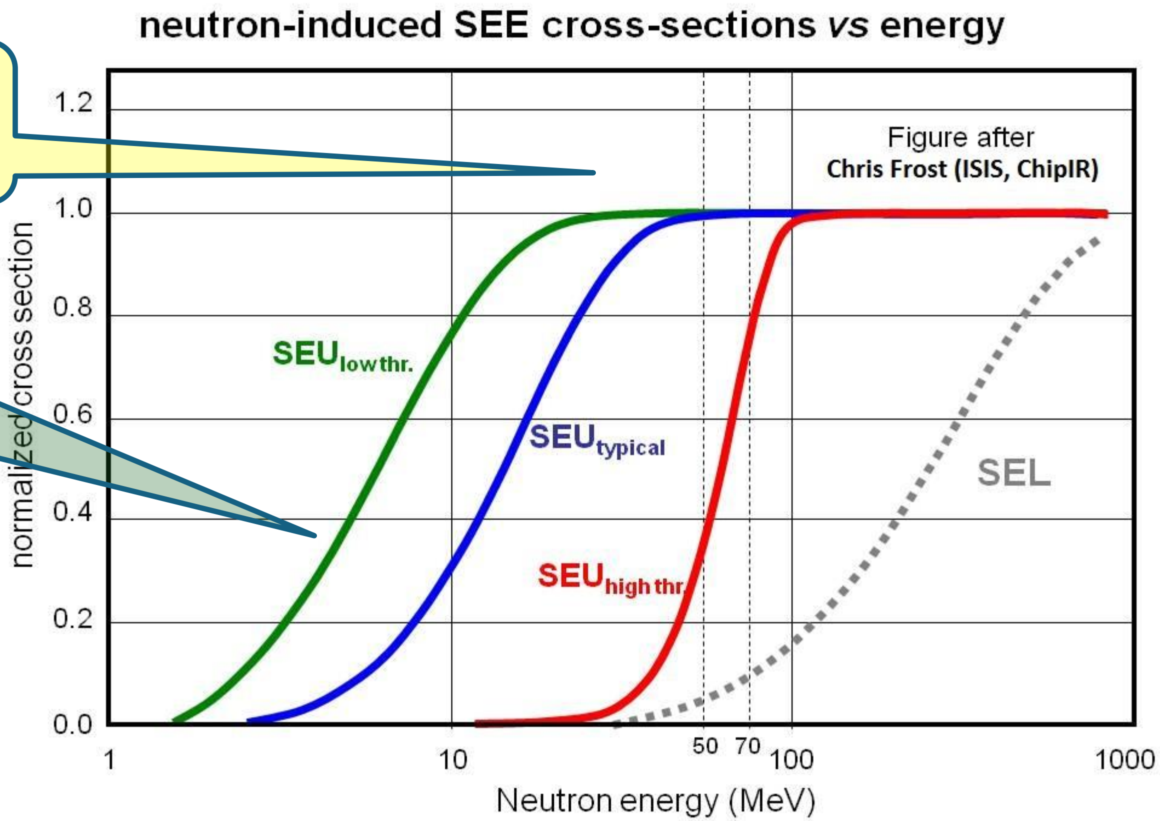
Now available @BELINA, soon at C70.

Range accessible by QMN at NEPIR.

Can probe below 20 MeV by using CN and Tandem.





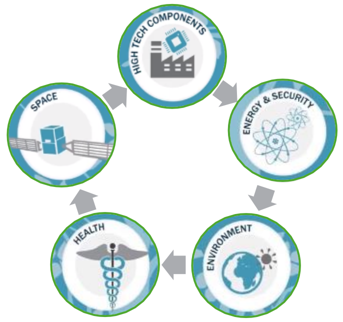


Because of the shape of tyhe cross section (Weyll-bull function) it is of paramount importance to Characterize the treshold

Neutrons @ SPES facility

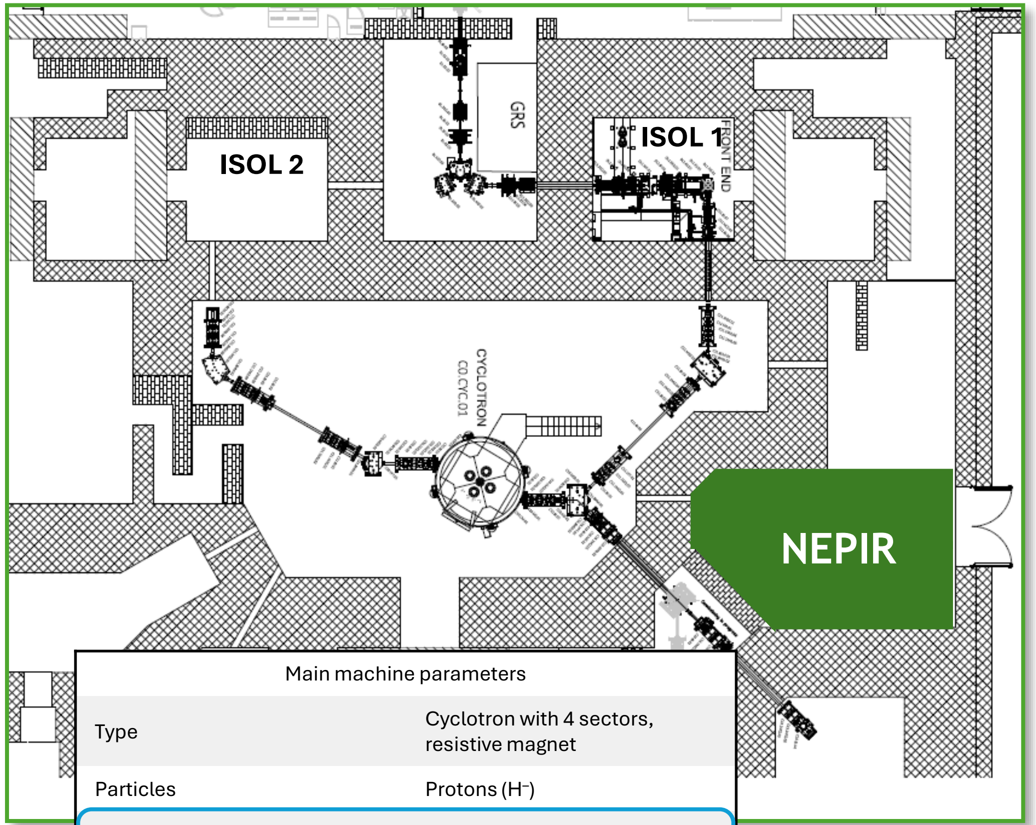
NEutron and Proton IRradiation facility
(multidisciplinary project)

Fast neutron irradiation facility



Neutrons @ SPES

- **NEPIR-0** — White neutron spectrum
- **NEPIR-1**
  - Atmospheric Neutron Emulator **(ANEM)**
  - Quasi Mono-energetic Neutron **(QMN)**



Main machine parameters	
Type	Cyclotron with 4 sectors, resistive magnet
Particles	Protons (H^-)
Energy	35 - 70 MeV
Maximum current intensity	750 μA
Extraction	Double
Maximum magnetic field	1.6 T (Bo = 1 T)

SPARE project

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

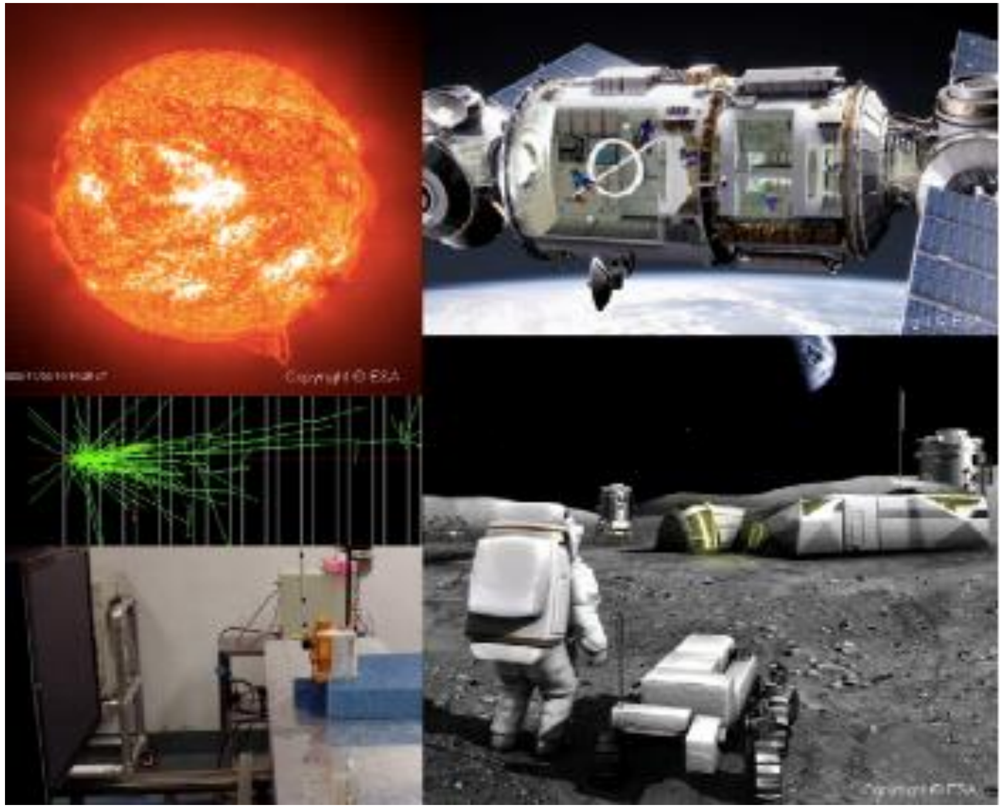
INFN Istituto Nazionale di Fisica Nucleare

agenzia spaziale italiana

CENTRO FERMI Museo Storico della Fisica e Centro Studi e Ricerche Enrico Fermi

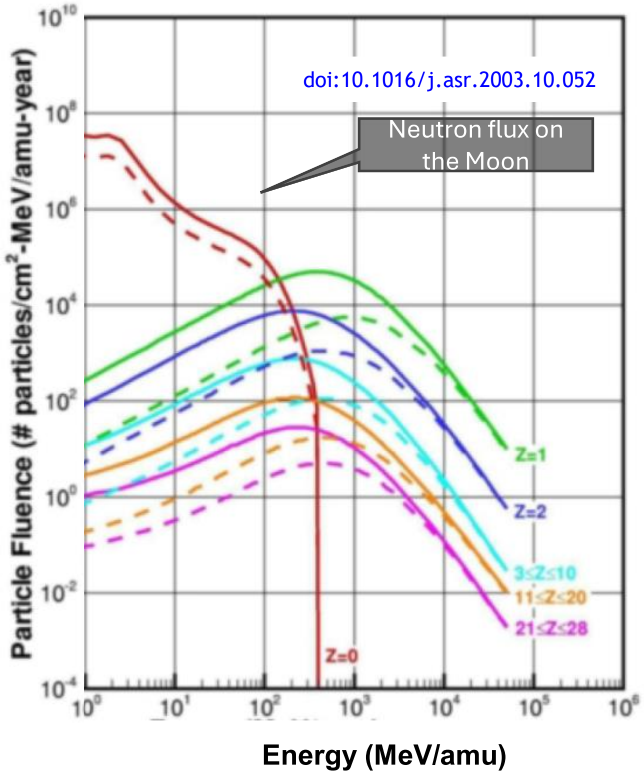
SPARE is a project involving ASI, INFN and Centro Fermi.

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 with E_n= 20-70 MeV.

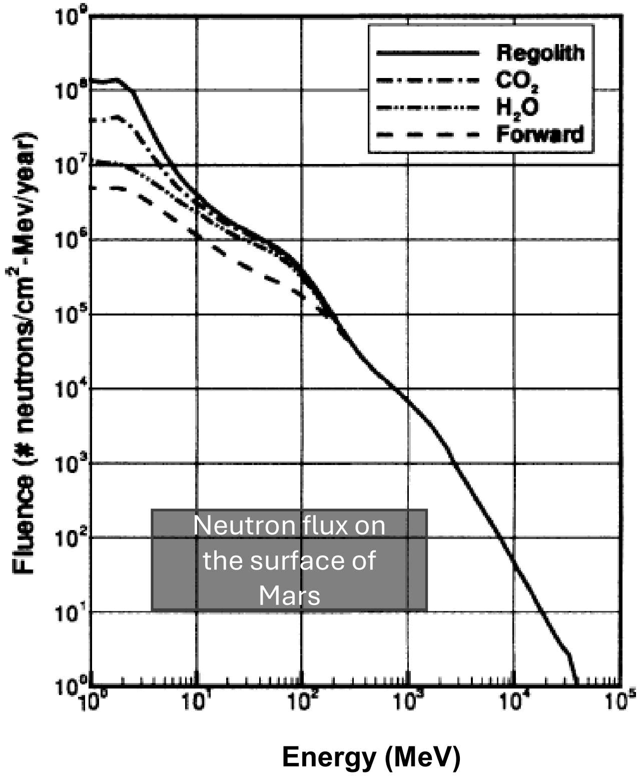


Fast neutrons on Mars and Moon

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

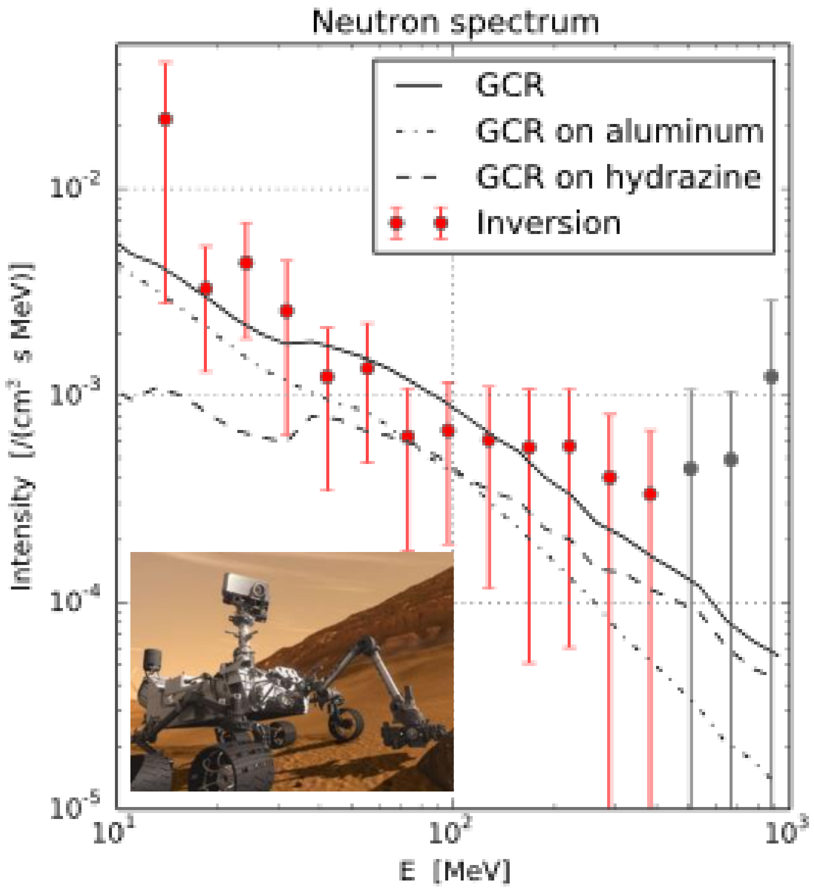


The galactic cosmic ray's environment on the lunar surface is shown at solar maximum (dashed lines) and solar minimum (solid line). **Z=0 corresponds to neutrons.**



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

Secondary particles from spacecraft material



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)

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

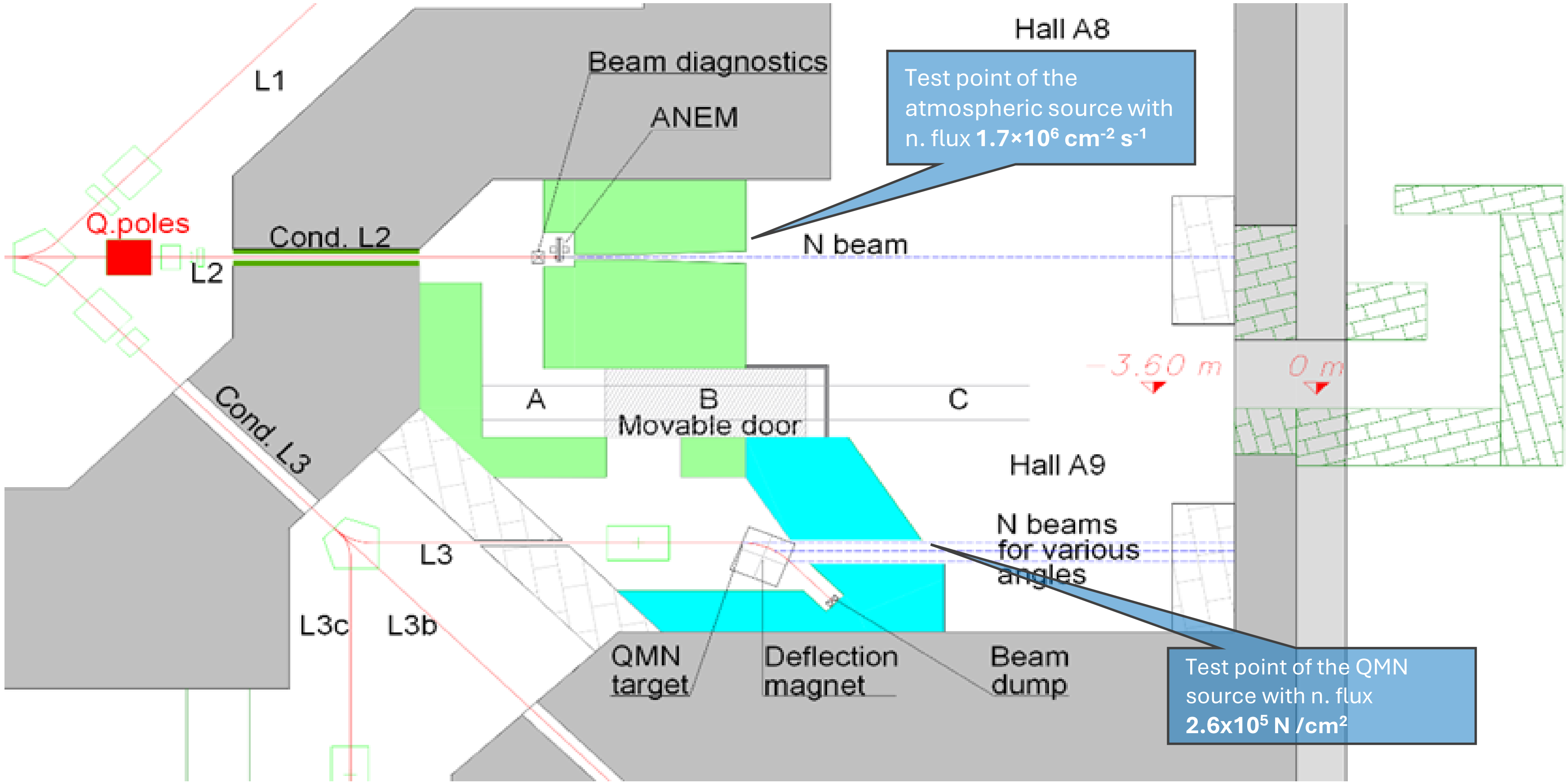
Mission	Altitude (km)	Neutron dose rate (μGy/day)	Charged particle dose rate (μGy/day)	Neutron equivalent dose rate (μSv/day)	Charged particle equivalent dose rate (μSv/day)
STS-55	302	5.9	57.2	52.0	120.1
STS-57	470	25.3	461.9	220.0	859.4
STS-65	306	11.0	75.2	95.0	157.8
STS-94	296	3.7	101.5	30.8	213.9

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)

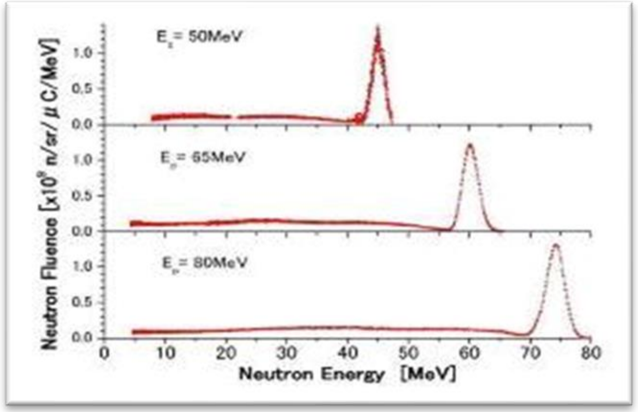
Final NEPIR Layout (phase 1)

The delivered **neutron flux is 1.7×10^6 cm^{-2} s^{-1}** (at 3 m for a 1 μA proton current)



Existing (empty) NEPIR experimental hall, 140 m^2

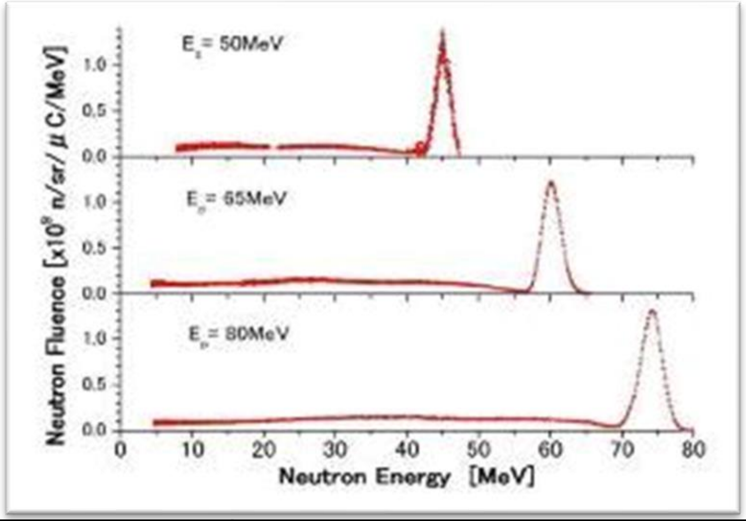
Maximum QMN flux at closest test point is: **2.6x10^5 N /cm^2 /s**, for 10 μA of 70 MeV protons



QMN spectra for different energy values of the primary proton beam.

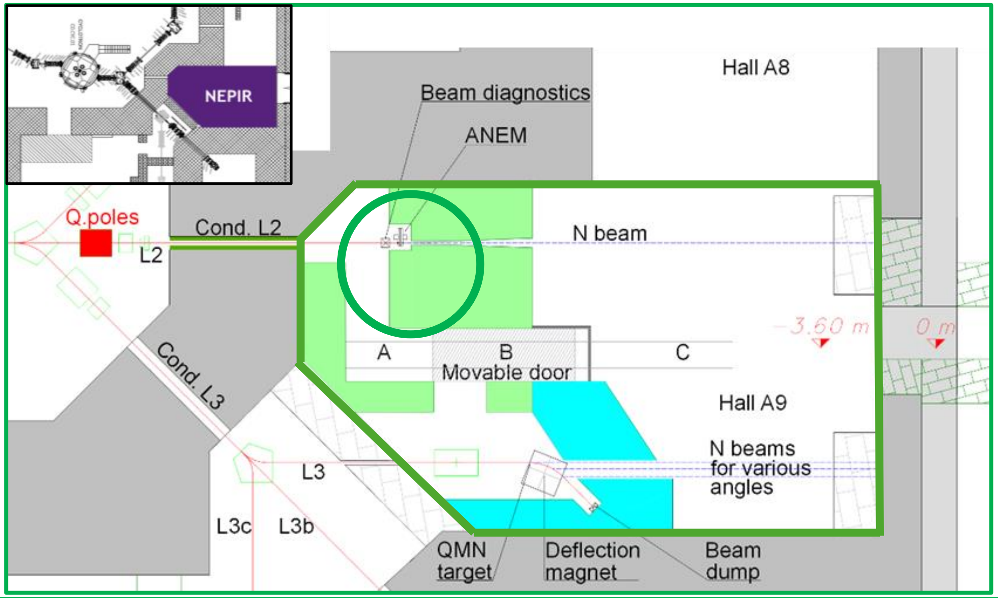
QMN beams (thin Li target)

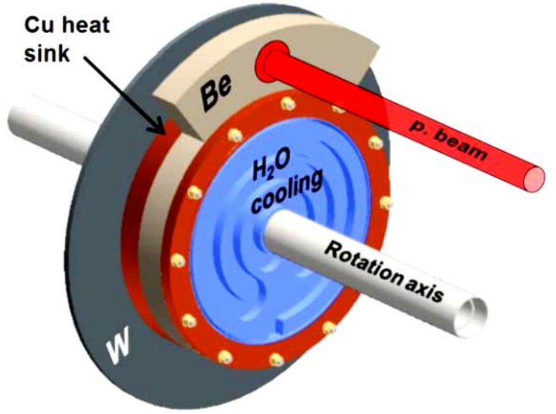
Suitable for excitation function measurements on electronics and nuclear data
Best option for detector and dosimeter response studies as well as calibrations.
Available from **35 to 70 MeV in NEPIR 1**



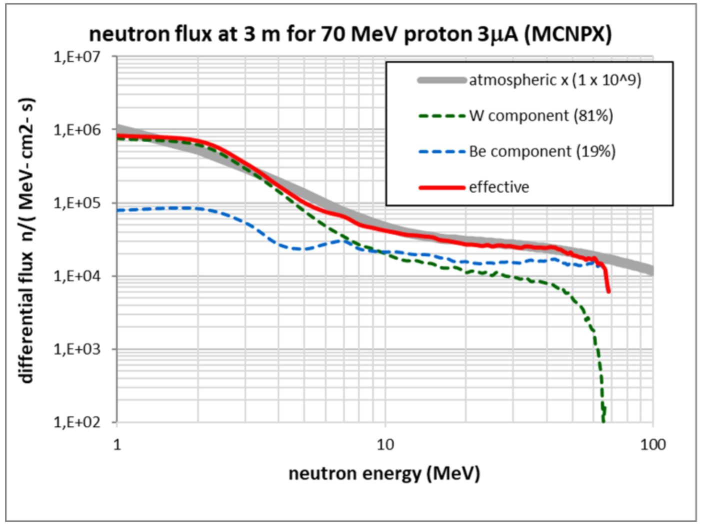
TIARA (Japan)	40-90	12.9	~3.5-5 $\cdot 10^{3}$ n cm^{-2} s^{-1} for max 1-3 μA
CYRIC (Japan)	14-80	1.2	10^{6} n cm^{-2} for 3 μA
RCNP (Japan)	100-400	10	10^{4} n cm^{-2} s^{-1} for 1 μA
ANITA (Sweden)	25-200	3.73	~ $3 \cdot 10^{5}$ n cm^{-2} s^{-1} for max 5-10 μA
NFS (France) *UNDER CONSTR.*	1-40	5	~ $8 \cdot 10^{7}$ n cm^{-2} s^{-1} for 50 μA, 40 MeV
iTHEMBA (South Africa)	25-200	8	1-1.5 $\cdot 10^{4}$ n cm^{-2} s^{-1} for typical 3 μA
QMN (LNL) ***PROPOSED***	**30-70**	**3**	**~ $2.6 \cdot 10^{5}$ n cm^{-2} s^{-1} for 10 μA, 70 MeV**

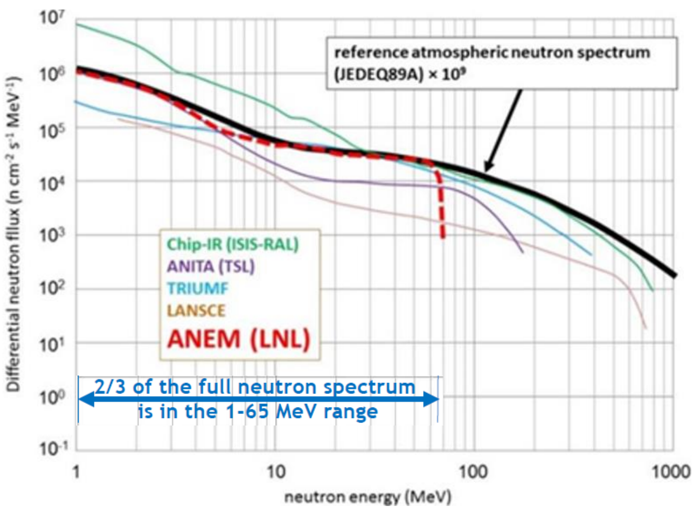
Atmospheric Neutron Emulator (ANEM)





Thickness
W: 5 mm (beam stopping)
Be: 24 mm





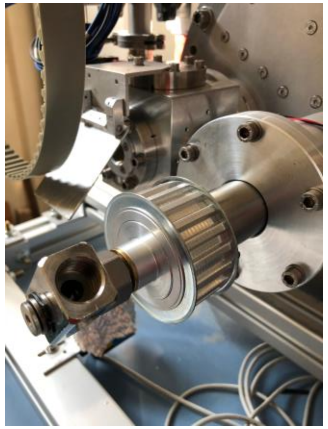
- A **coaxial rotating Be sector and W disk** intercept the off-axis proton beam; a stainless-steel rotating drum houses a helicoidal water cooling circuit.
- An intense source of fast neutrons (E > 1 MeV) with a continuous energy distribution.
- Atmospheric-like energy distribution in the 1-65 MeV energy range, found at flight-altitudes and at sea-level.
- Designed to handle 2.1 kW (30 μA @ 70 MeV). The maximum 10 μA proton current is set by radioprotection constraints, A < 1 Bq/g.

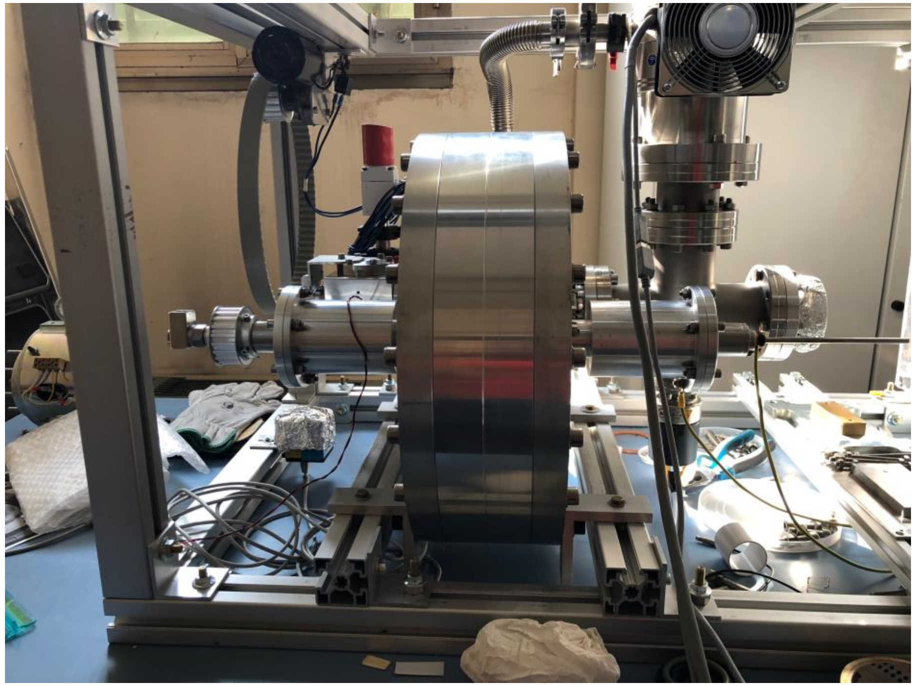
ANEM applications

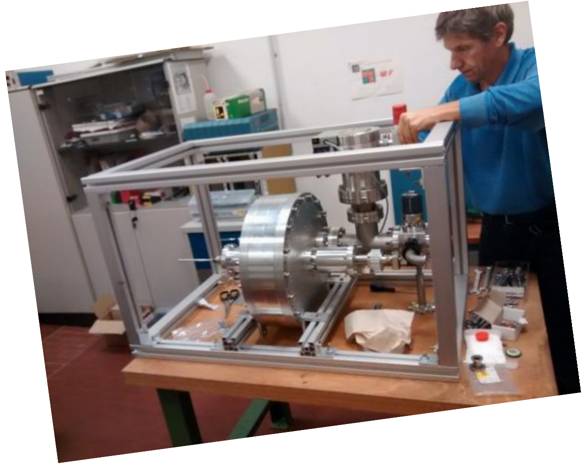
Study **radiation damage effects** of atmospheric neutrons on material, in particular electronic devices and systems at sea level, but also at flight altitudes (avionics) where the neutron flux is 300–450 times higher.

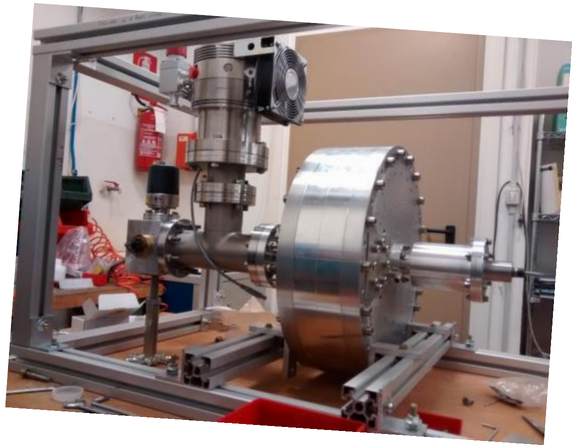
Mockup realized

- Water inlet temperature : 18°C;
- Water inlet velocity 1m/s
- W disk
- **Gaussian beam spot FWHM = 1 cm**
- **Beam Power 5 kW**
- Rotating beam (10 rev/sec)

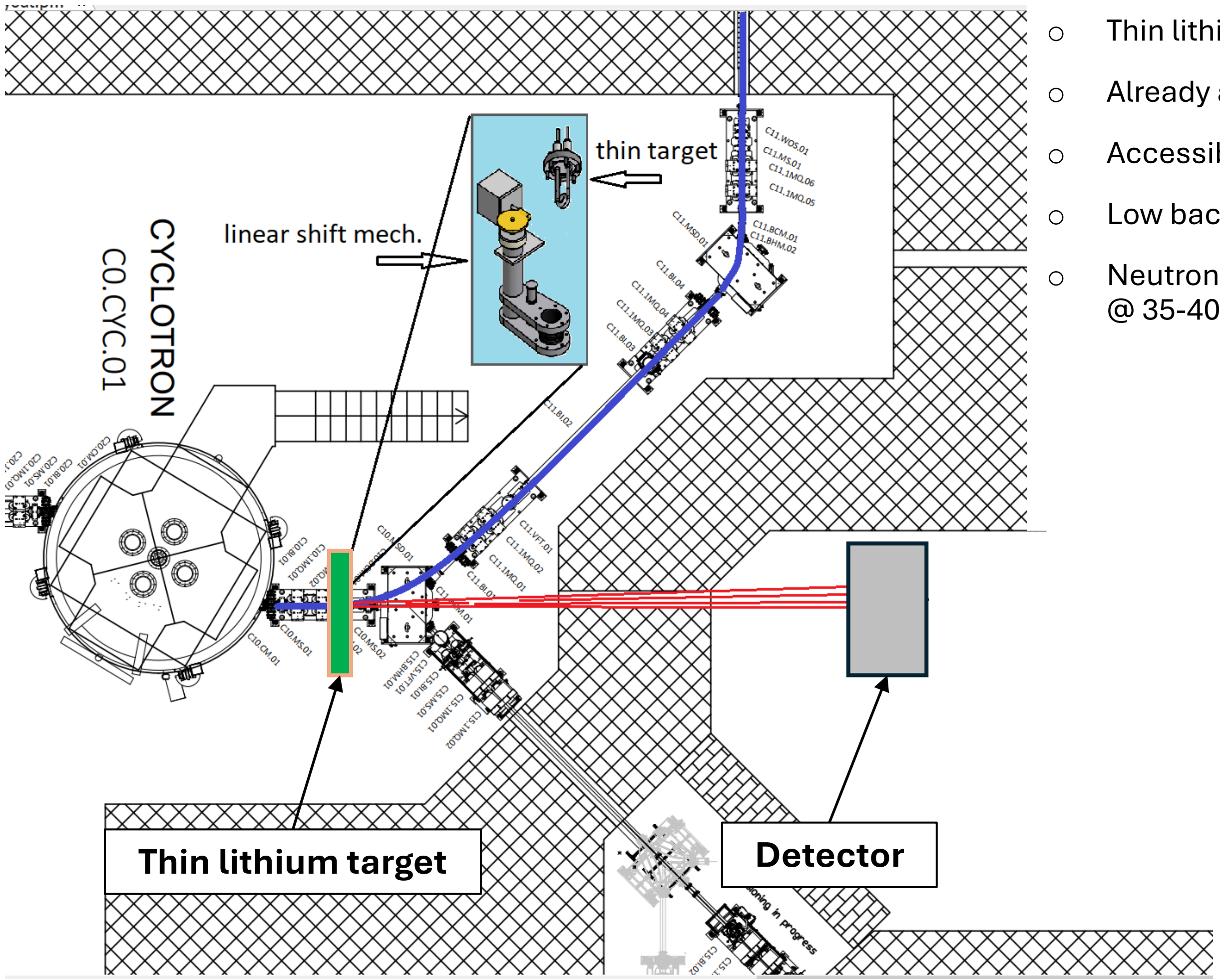




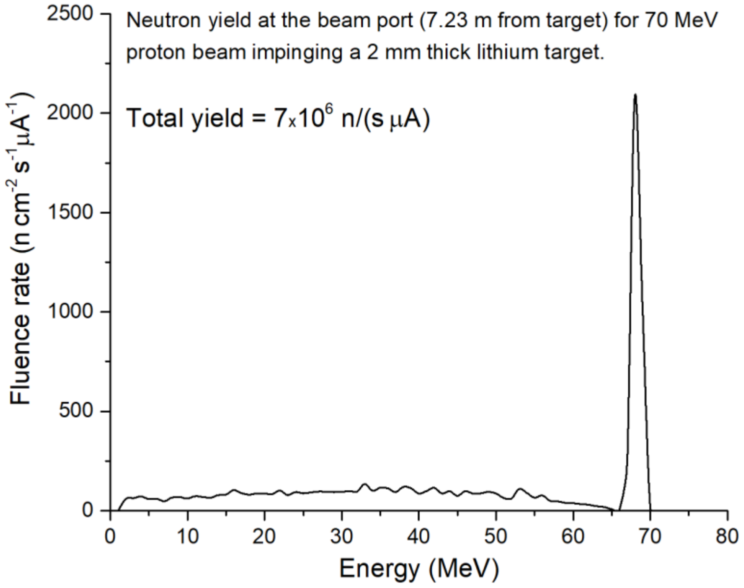




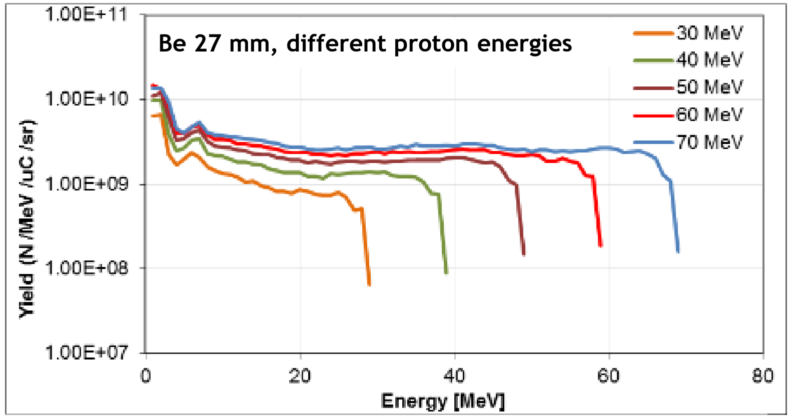
Phase Zero: white spectrum and -QMN beam - setup



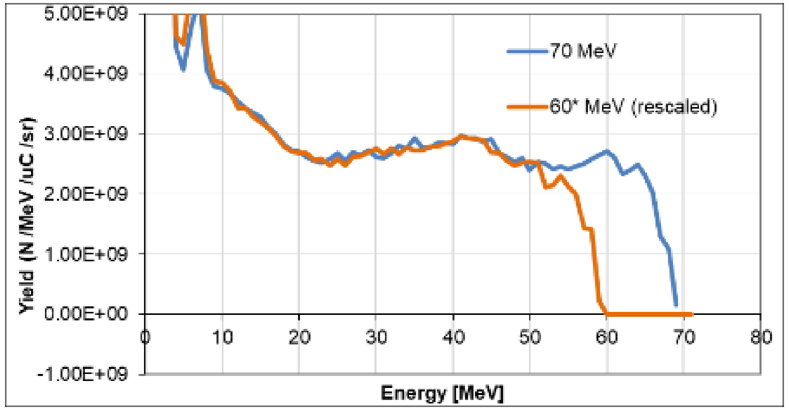
- Thin lithium target (0.5-2 mm) along proton beam line
- Already available hole along the concrete wall
- Accessible area
- Low background
- Neutron fluxes: ≈ 10^5 n cm^{-2} μA^{-1} @ 7.23 m @ 35-40-50-60-70 MeV



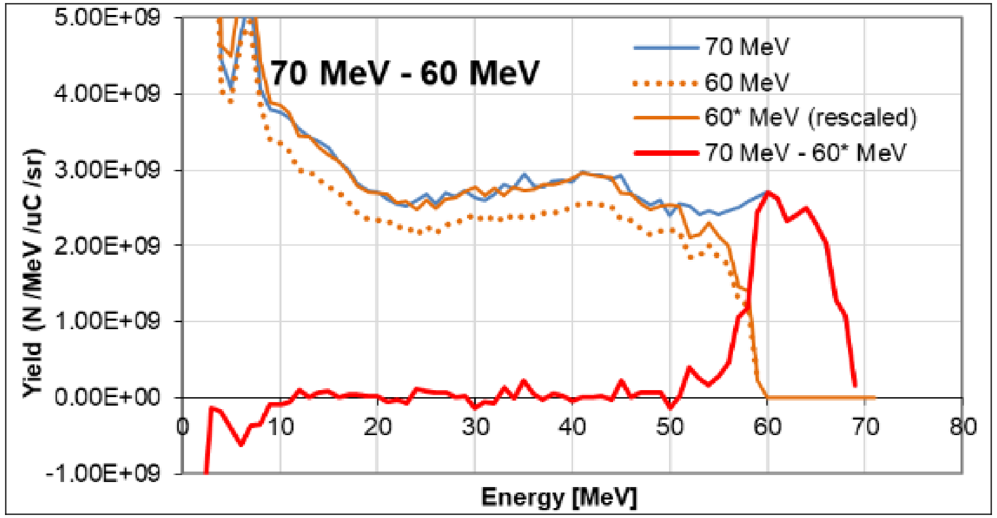
NEPIR-O: Thick Be white neutron MCNPX spectra : Pseudo-Monochromatic neutron beams



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



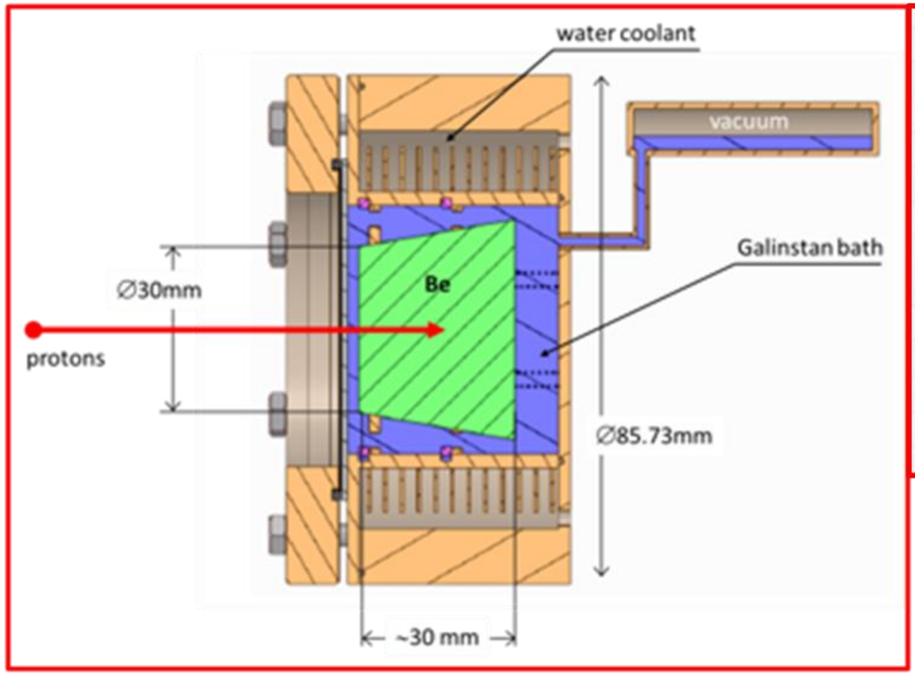
Comparison of the neutron spectra generated by 70 MeV protons and 60 MeV protons (rescaled by a factor 1.15).

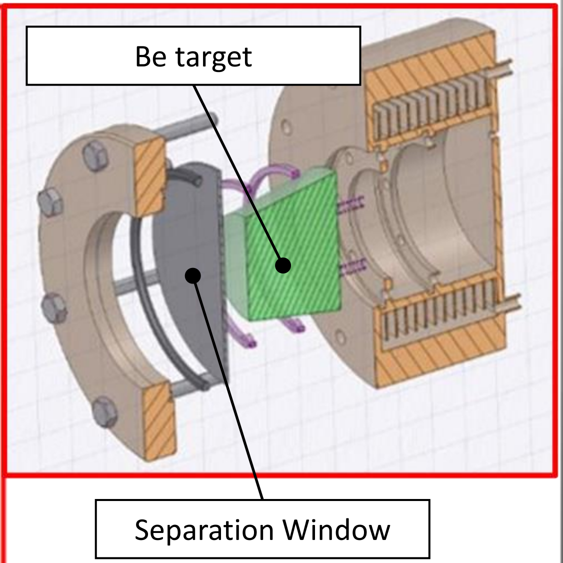


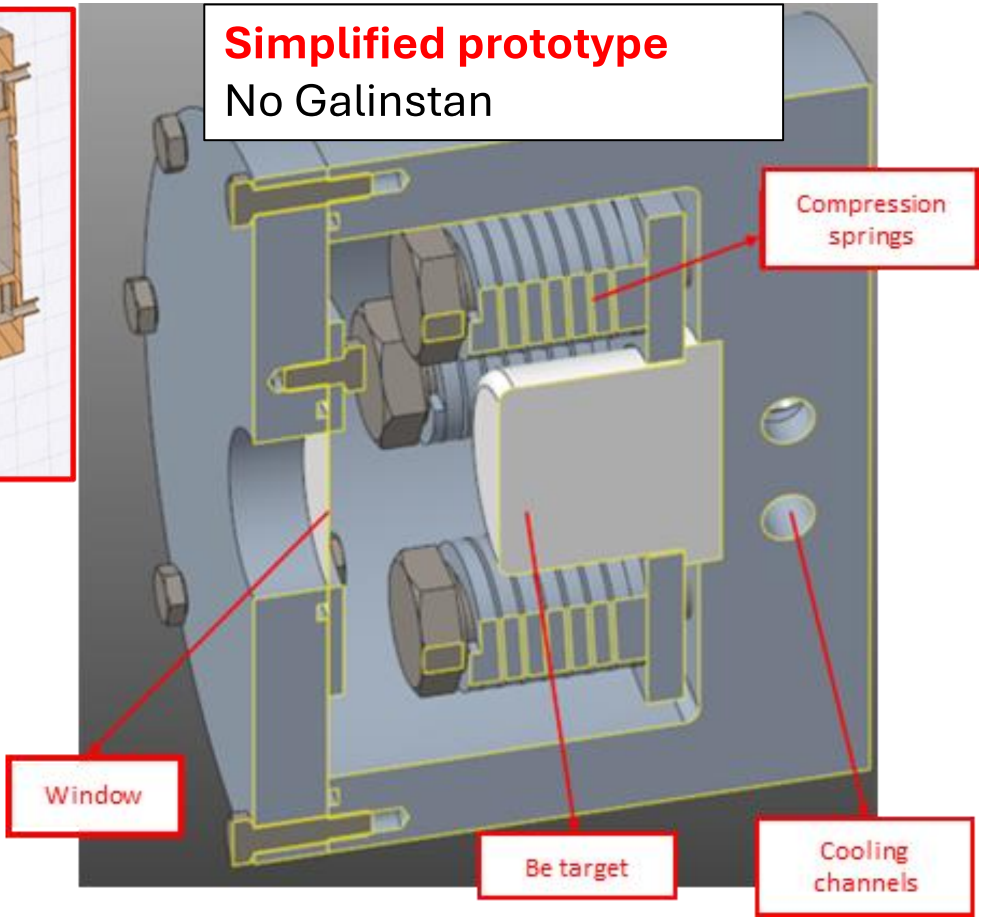
Maximum flux at closest test point:
3×10^6 N /cm^2 /s,
with 1 μA of 70 MeV protons

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

CoolGal concept: a GALinstan COOLed Be target





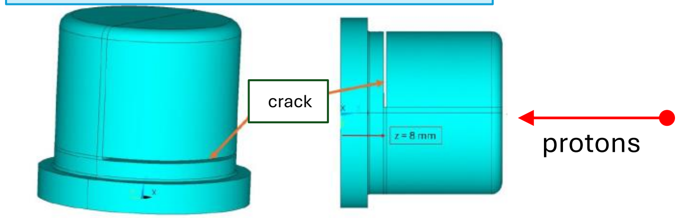


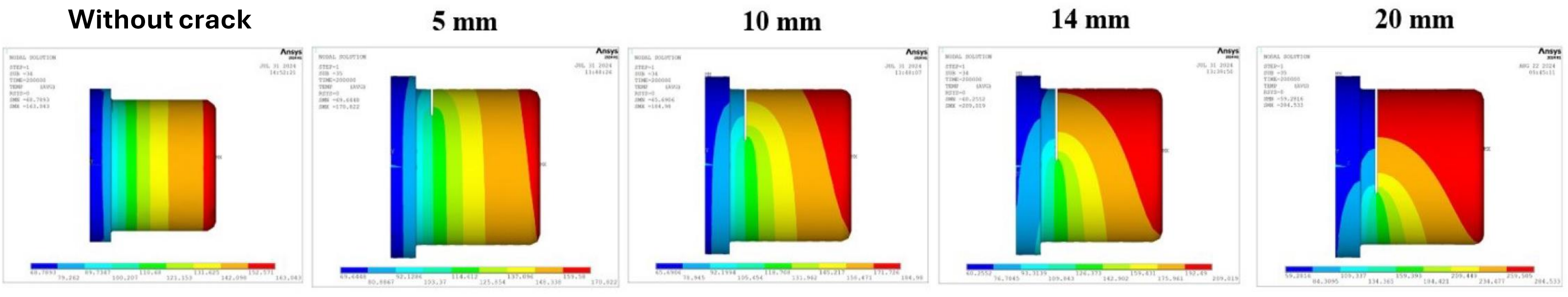
Goal:
- measure the Be spectrum
- test the separation window
- verify thermal and activation calculations

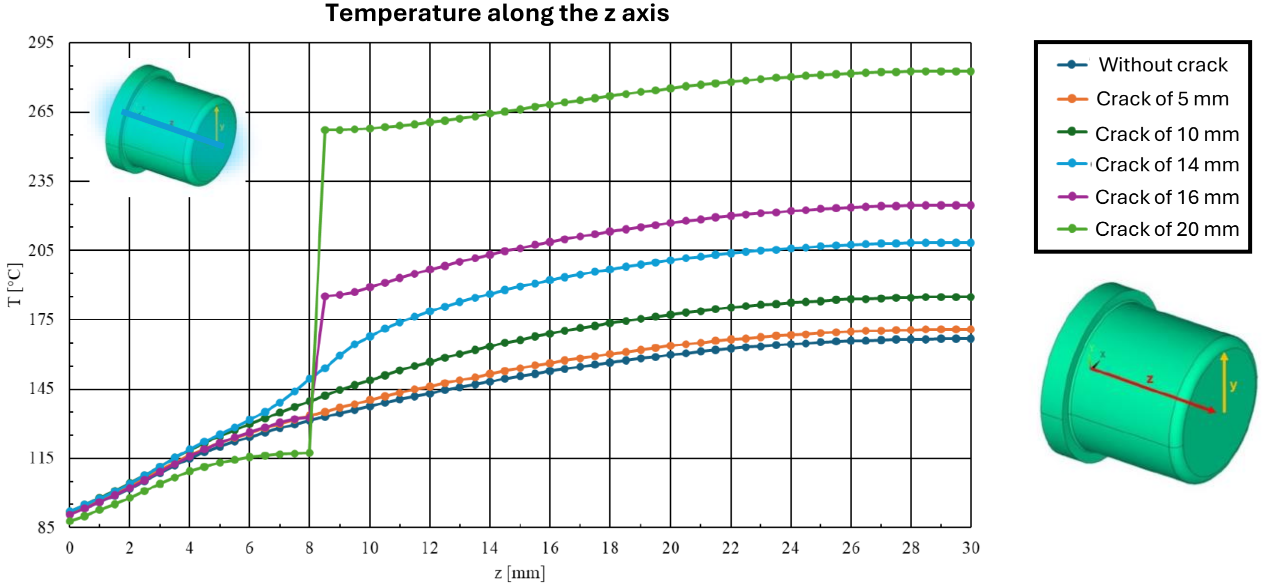
CoolGal: simplified version air/water cooled

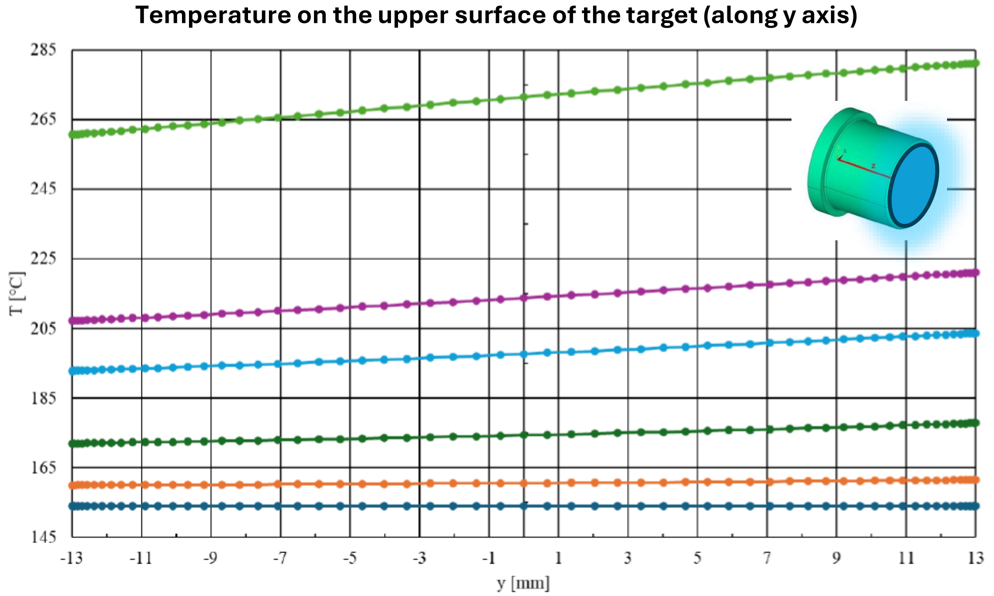
The crack made on the target under consideration is a lateral fissure, 0.5 mm thick, with increasing length.

P = 700 W





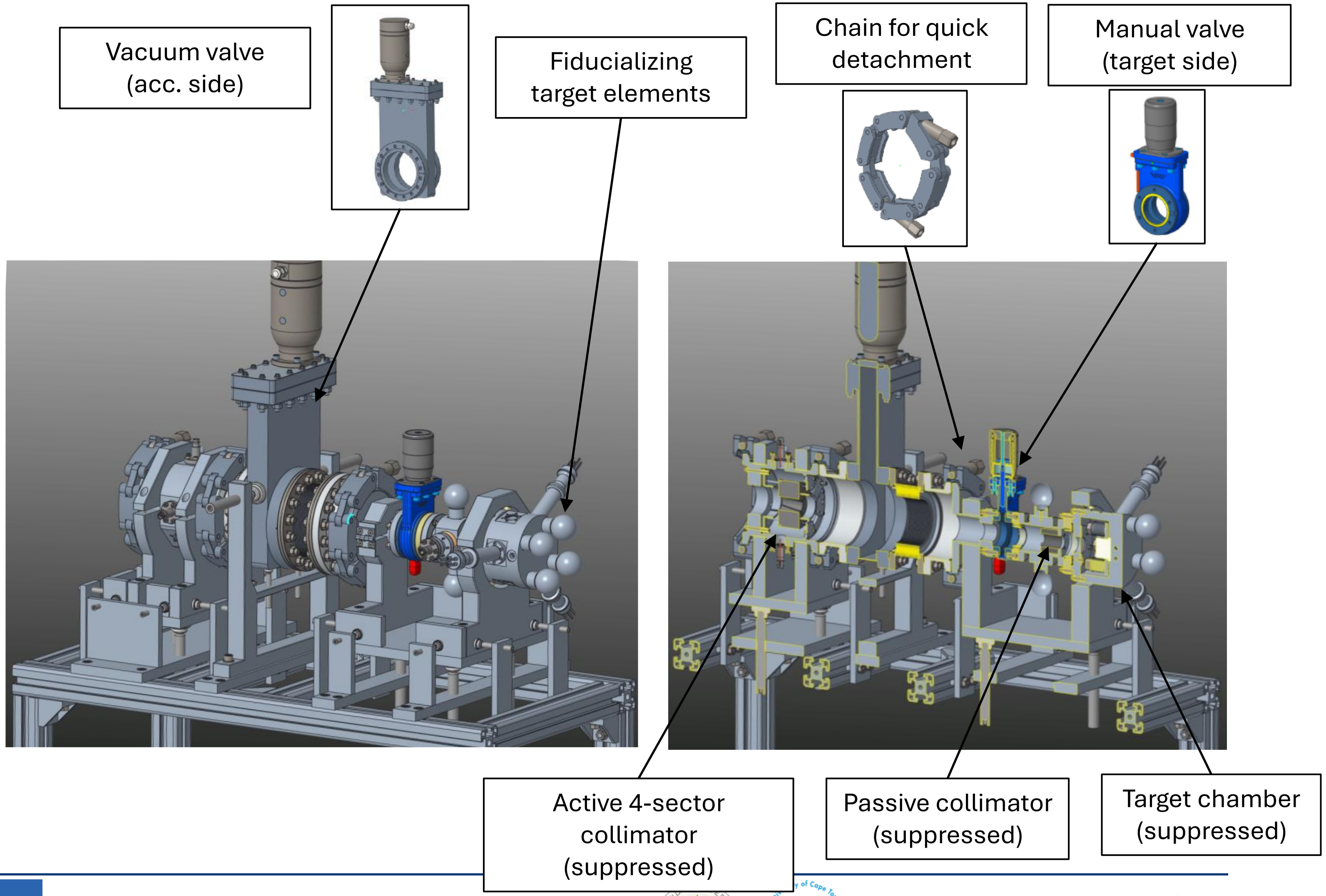




Layout of the Beamline

Fully designed: window, diagnostic, temperature map, mechanical stress, blistering

Under construction
Tests planned end of the year



Conclusions

- At INFN-LNL we can provide high quality neutron beams from few keV up to 70 MeV.
- The facilities uses 7 MV Van Der Graaf, 14 MV Tandem and 35-70 MeV C70 cyclotron (just re-commissioned).
- The cyclotron facility has been designed in 2 phases:
  - Phase 0:
    - QMN beams
    - White Be neutron spectra
  - Phase 1
    - QMN beams
    - White neutron spectra
    - Atmospheric neutron spectra up to 70 MeV.
- Phase zero almost financed by PRIN and Progetto Premiale: to be completed before half of next year
  - Be neutron spectra measurement
  - QMN neutron spectra measurement
  - Simplified CoolGal target beam tests.

Thank you for your attention

More spectra comparison