40th European Cyclotron Progress Meeting

Status of NEPIR,
the NEutron and Proton Irradiation facility
at SPES cyclotron

Luca Silvestrin et al.

Univesity of Padova and INFN

luca.silvestrin@pd.infn.it

Bisello D., Esposito J., Fagotti E., Loong C.K., Maggiore M., Mastinu P., Prete G., Wyss. J.

The original purpose of NEPIR:

study of **radiation damage effects in electronic devices and systems**, induced by **flight-altitude and sea-level atmospheric neutrons** and **solar protons.**

TOOLS

QMN: a source of quasi mono-energetic neutrons (QMN) with a controllable energy peak in the (20)35-70 MeV energy range.

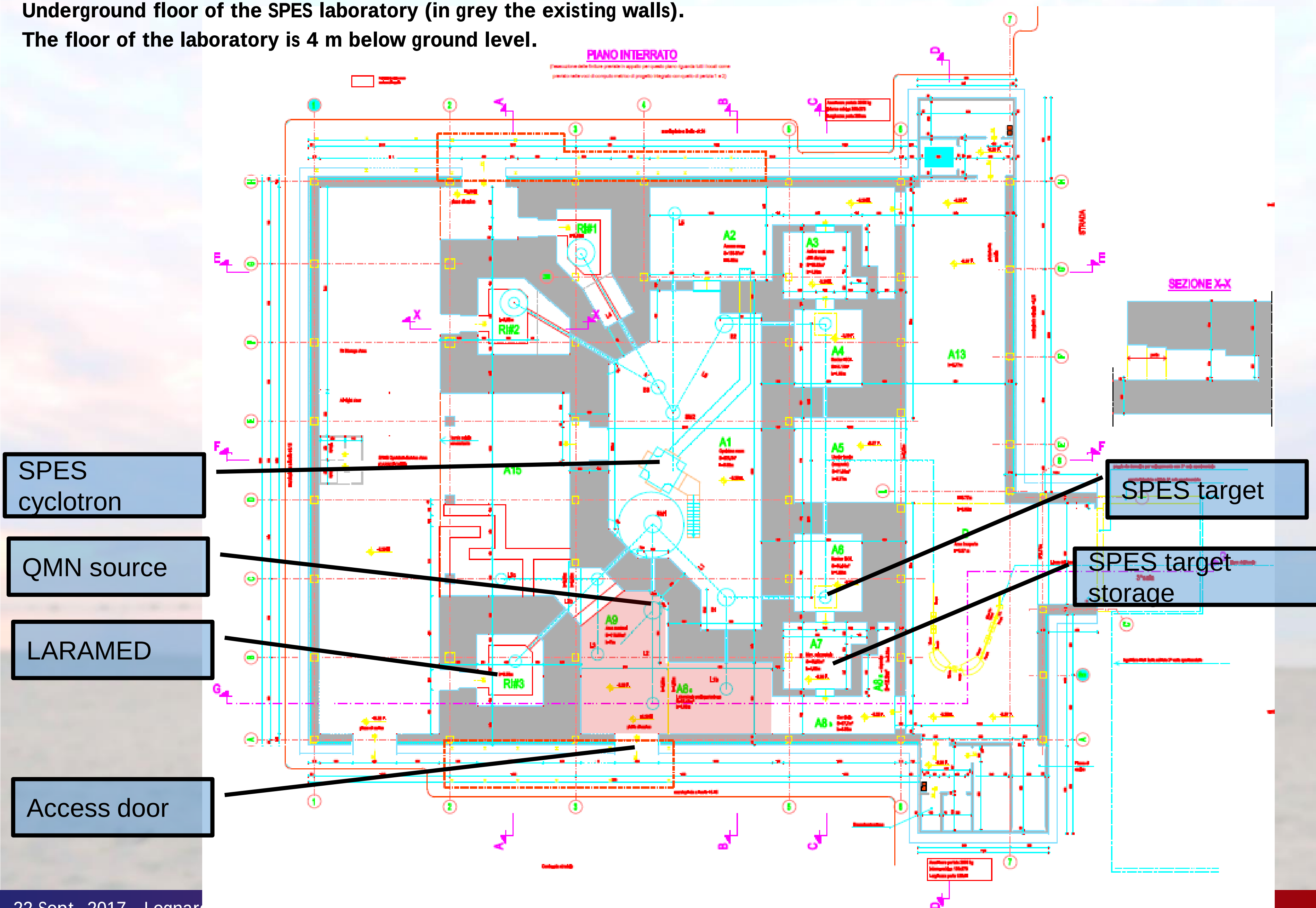
ANEM: (*Atmospheric Neutron Emulator*) an intense source of ***fast* neutrons (E > 1 MeV)** with a continuous energy distribution similar to that of atmospheric neutrons found at flight-altitudes and at sea-level in the 1-65 MeV energy range.

PROTON: a general purpose low intensity beam of direct protons with variable energy in the (20)35-70 MeV range.

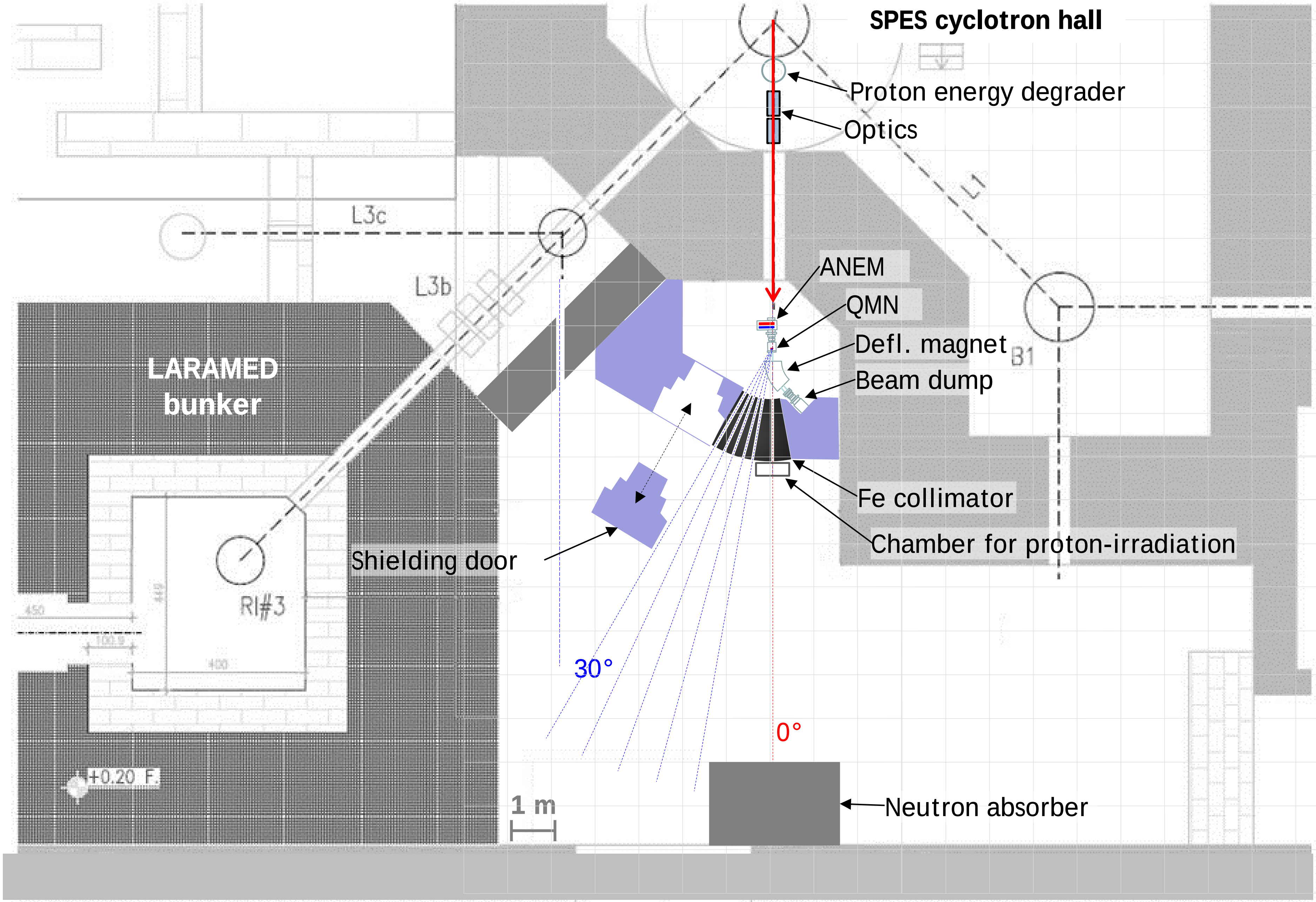
Neutrons for electronics				
QMN discrete	Energy range 20-70 MeV 😐	Essential to study energy dependencies (cross-section vs energy curves) ☺	Neutron flux at test point is user controlled, up to 10^5 n cm^{-2} s^{-1} ☺	Angle correction ☺!
ANEM continuous	Energy cut-off 70 MeV ☹	Before full energy tests 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 $\phi \sim 10^7$ n cm^{-2} s^{-1} ☺	

SPES laboratory layout

Underground floor of the SPES laboratory (in grey the existing walls).
The floor of the laboratory is 4 m below ground level.



Layout of NEPIR



Floor plan of the NEPIR facility (4 m below ground level).

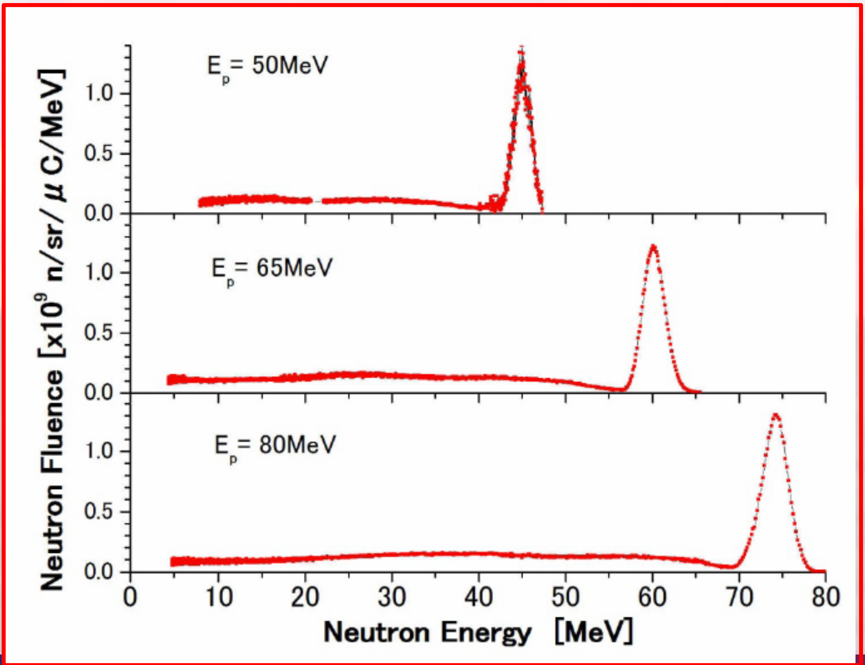
QMN

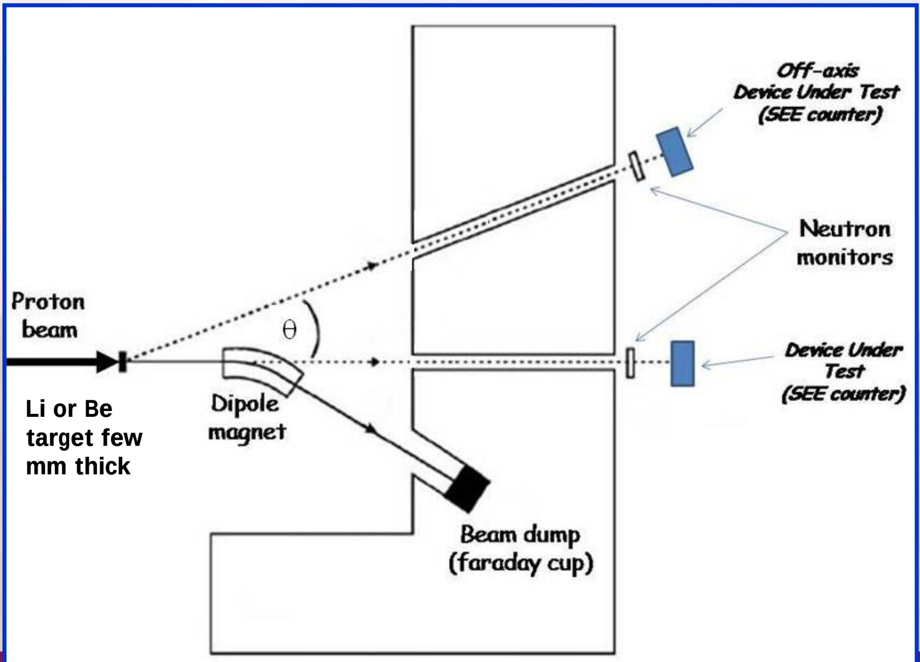
Quasi Mono-energetic Neutrons

- Study energy dependent neutron-induced effects

  (e.g. measure the SEE cross-section vs energy curve)

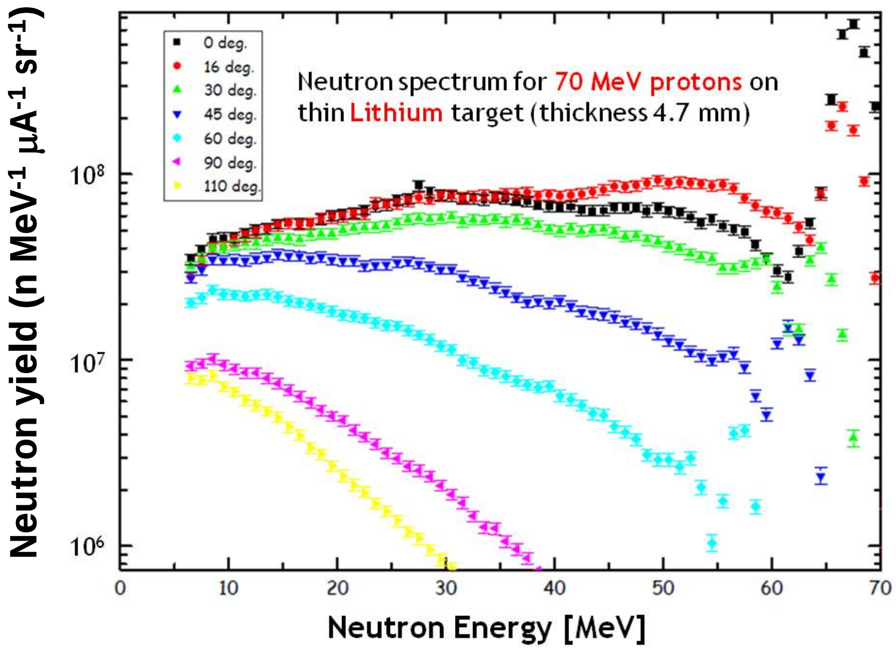
- Multi-disciplinary interest





Neutron yield angular dependence

thin Lithium

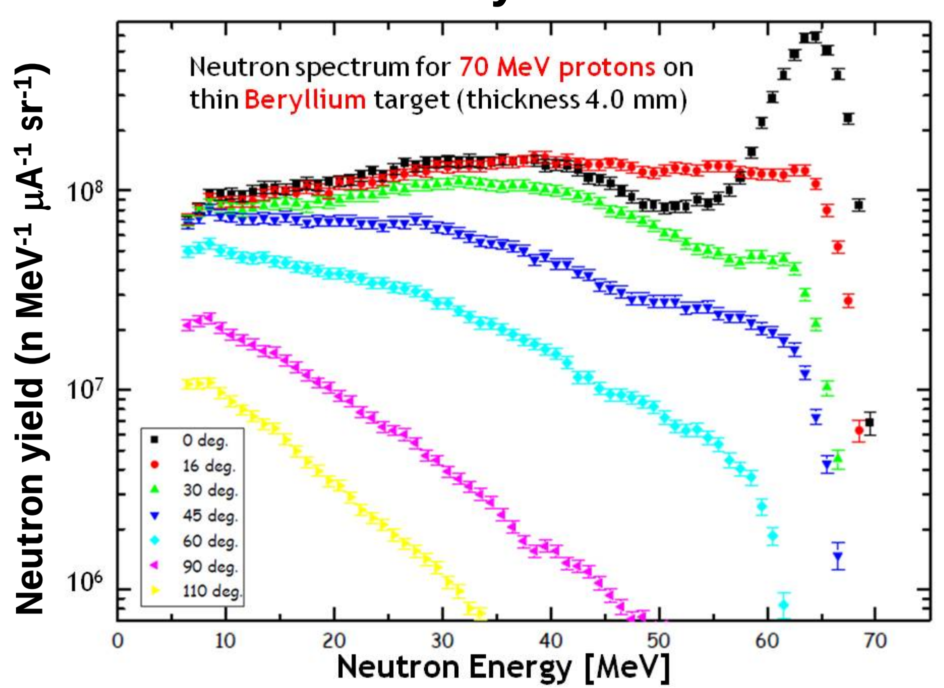


Angular dependence at E_{proton} = 70 MeV

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

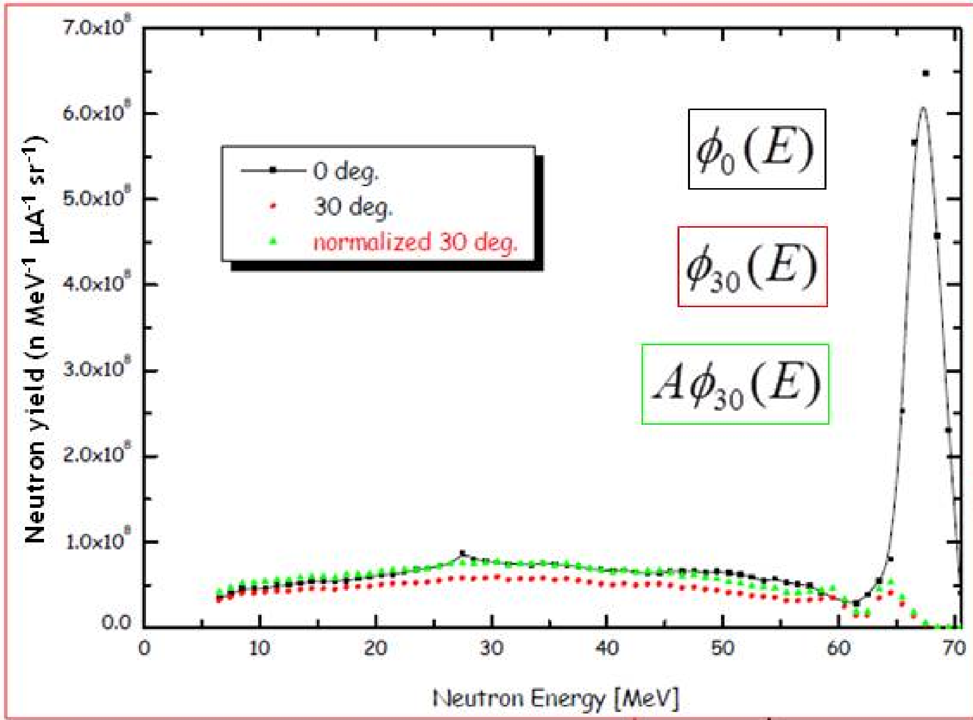
Journal of the Korean Physical Society, Vol. 59, No. 2, August 2011, pp. 1676-1680

thin Beryllium



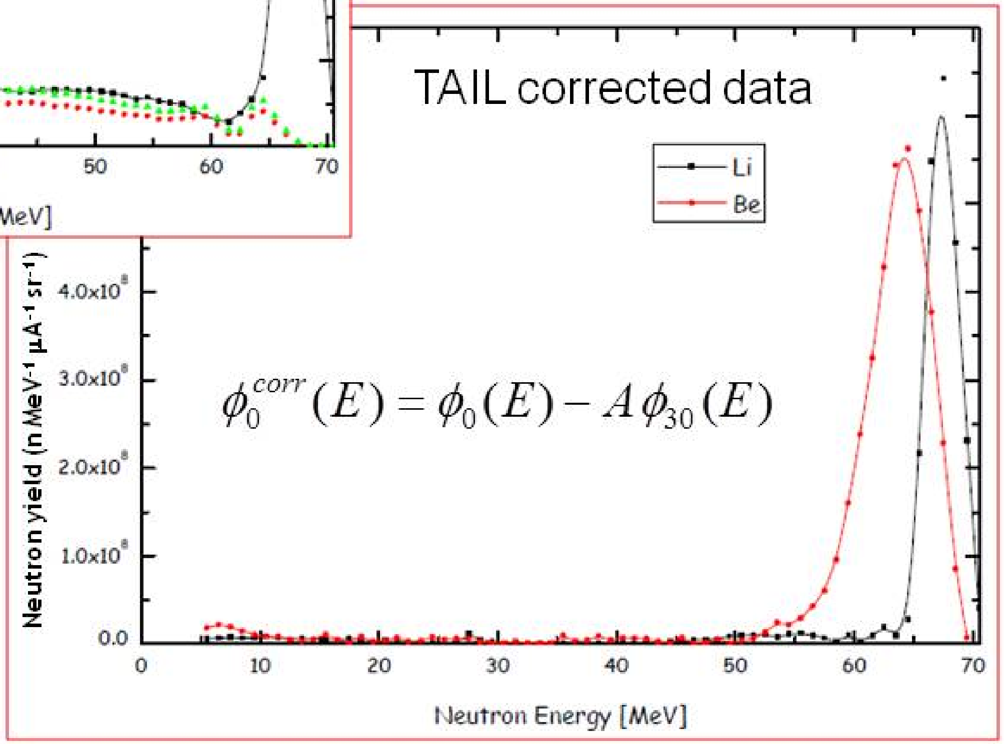
The “good” truly mono-energetic neutrons are produced mainly in the direction of the proton beam (forward, θ = 0); wrong-energy neutrons are not as directional.

"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.

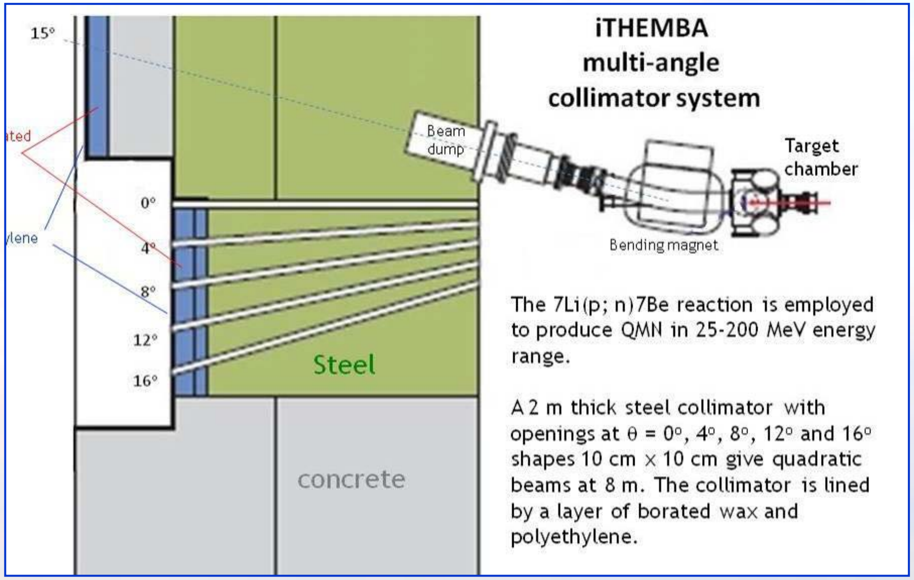


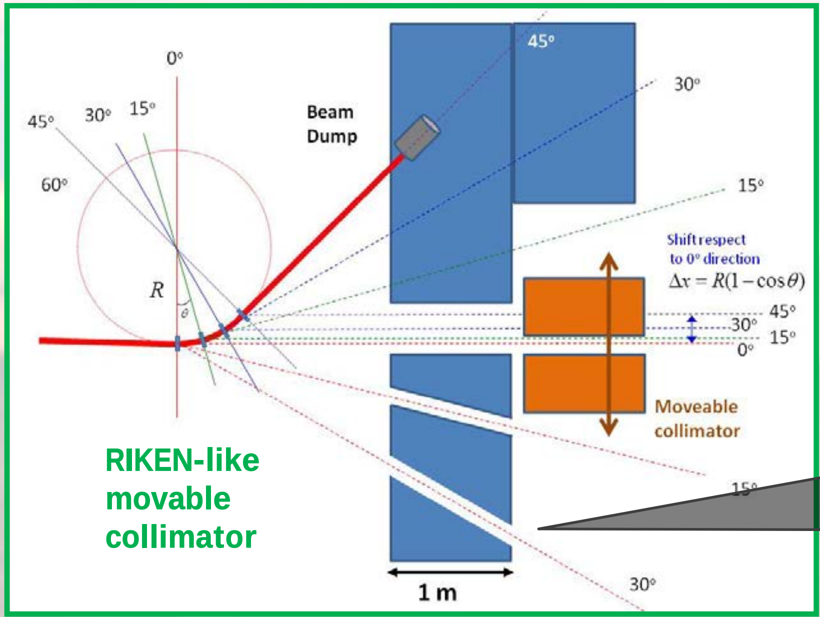
- ❑ The corrected 0° peak with Li is sharper and closer to the proton beam energy.
- ❑ 30° subtraction works for both Li and Be with 70 MeV protons.

Multi-angle collimators

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).

i-Themba multi-angle collimator





RIKEN-like movable collimator

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

QMN comparison

Comparison of NEPIR QMN with existing QMN 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
CRYIC (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
iTHEMBA (South Africa)	25-200	8	1-1.5 $\times$ 10^4 n cm^{-2} s^{-1} for typical 3 μA
ANITA (Sweden)	25-200	3.73	~ 3×10^5 n cm^{-2} s^{-1} for max 5-10 μA
NFS (France) <u>UNDER CONSTR.</u>	1-30	5	~ $1{,}2\times10^5$ n cm^{-2} s^{-1} for 30 μA, 30 MeV (calc.)
NEPIR Li target, 4.7 mm thick	30-70	3	~ 5×10^4 n cm^{-2} s^{-1} for 1 μA, 70 MeV
NEPIR Be target, 4.0 mm thick	30-70	3	~ 4.5×10^4 n cm^{-2} s^{-1} for 1 μA, 70 MeV

Target current for LNL QMN to be comparable with ANITA (TSL, Sweden): 10 μA

Foreseen flux: ~ 5×10^5 n cm^{-2} s^{-1} for 70 MeV protons, using a Li target 4.7 mm thick

After the shutdown of the ANITA facility (TSL - Uppsala, Sweden) the i-Themba facilty (South Africa) is the new, de-facto reference QMN source, with a flux of ~1×10^4 n cm^{-2} s^{-1} (1 order of magnitude smaller than ANITA). In this case, the target current for LNL QMN is 1 μA

Luca Silvestrin luca.silvestrin@unipd.it

Interest

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

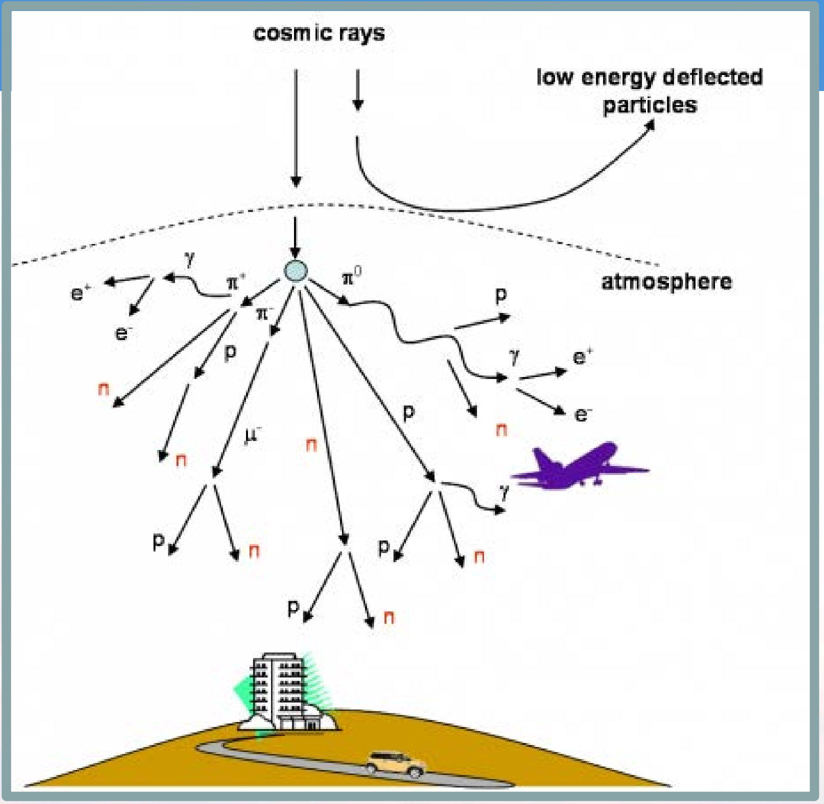
Used to study energy dependent neutron interaction mechanisms with matter

- high-energy and nuclear physicists (data; 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***).

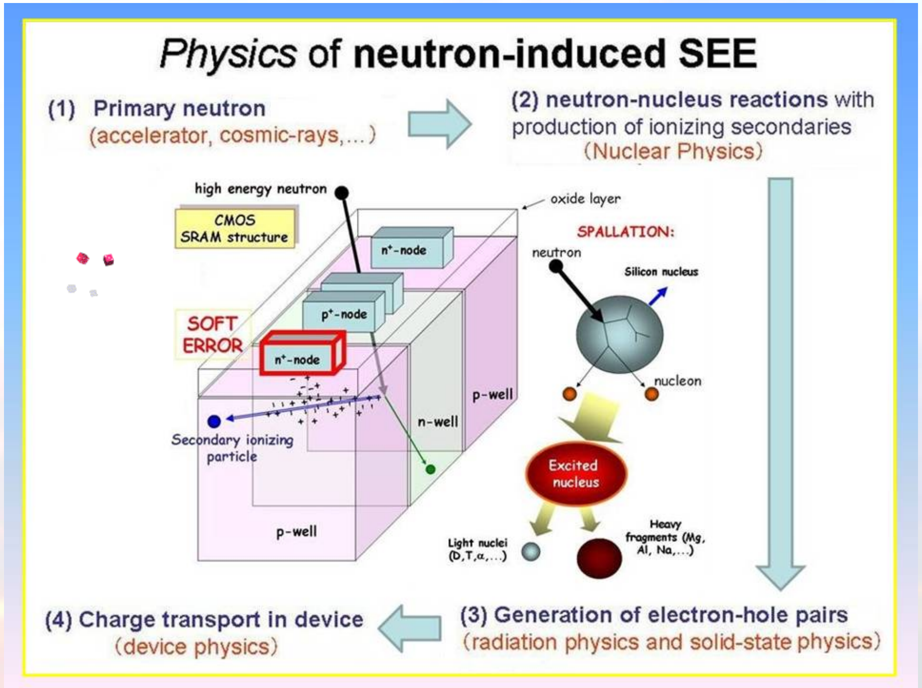
USERS:

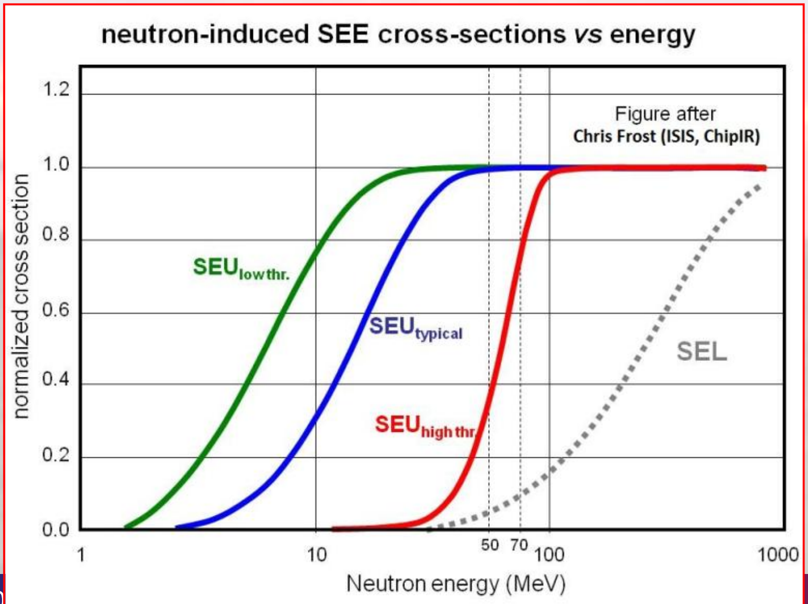
- *electronics industry for critical applications in hostile neutron fields (sensitive electronics anywhere, airlines, accelerator halls in hospitals and industry, space ...);*
- *electronics (ASICs) for HEP and nuclear physics experiments and space applications;*

ANEM



Study radiation damage effects in electronics induced by flight-altitude and sea-level *atmospheric* neutrons and solar protons.





Reference cross-section for *"Soft Errors"*

such as **SEUpset in digital electronics**:

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

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

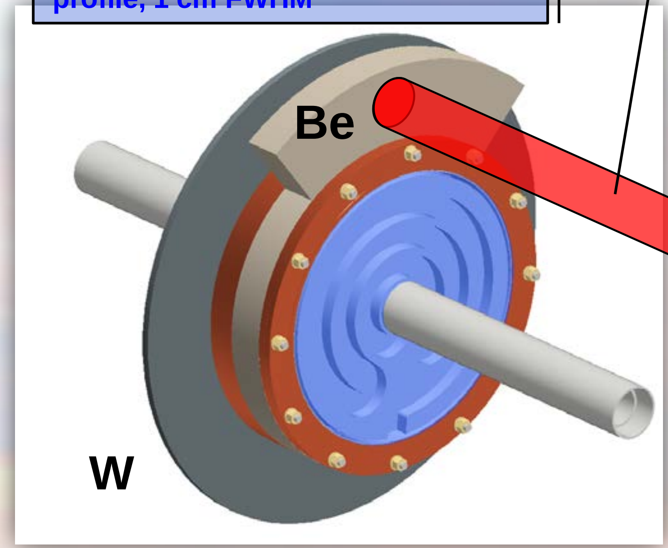
ANEM: a continuous energy neutron source

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

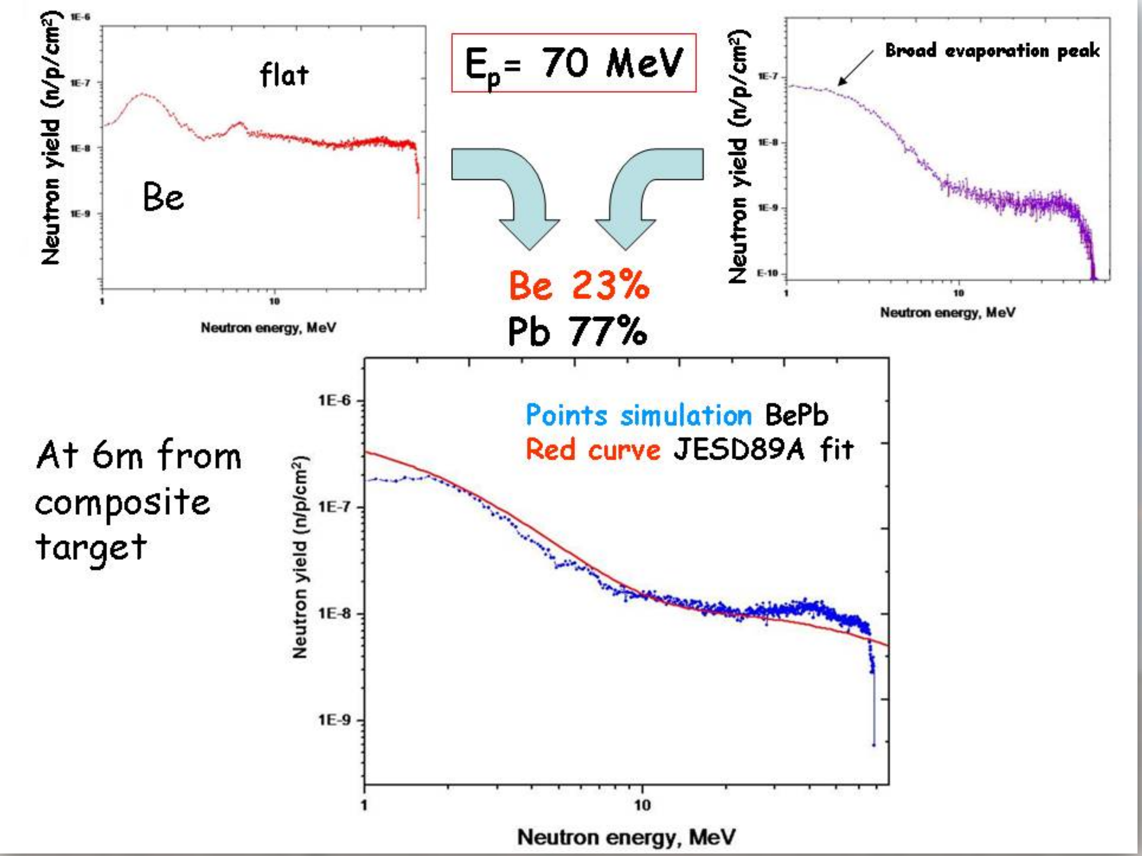
A W disk and a Be circular sector rotate on a common water cooled hub and alternatively intercept the beam. The effective atmospheric-like neutron spectrum in the 1-65 MeV range is composed directly without the use of moderators.

Idea of P. Mastinu (LNL)

Off axis proton beam, gaussian profile, 1 cm FWHM



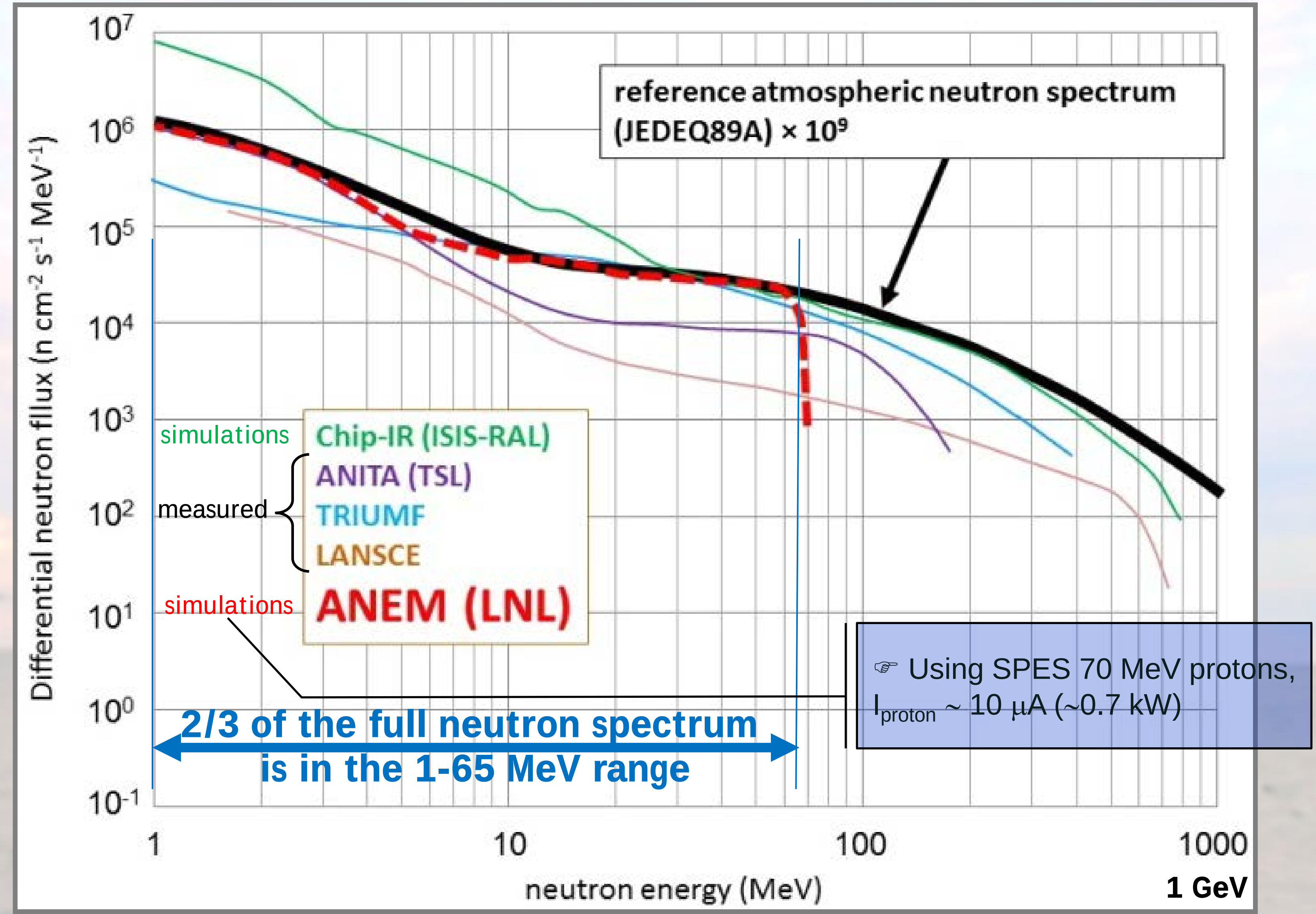
Thickness
W: 5 mm (beam stopping)
Be: 24 mm



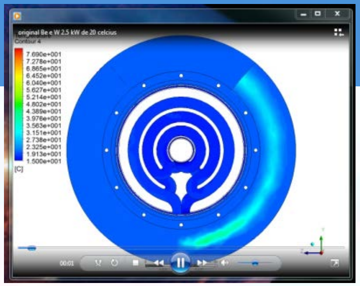
The Be sector does not stop the protons (to avoid blistering induced by hydrogen implantation); most of the protons pass through without causing nuclear reactions. The emerging low energy protons are stopped by the W disk.

ANEM white spectrum

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



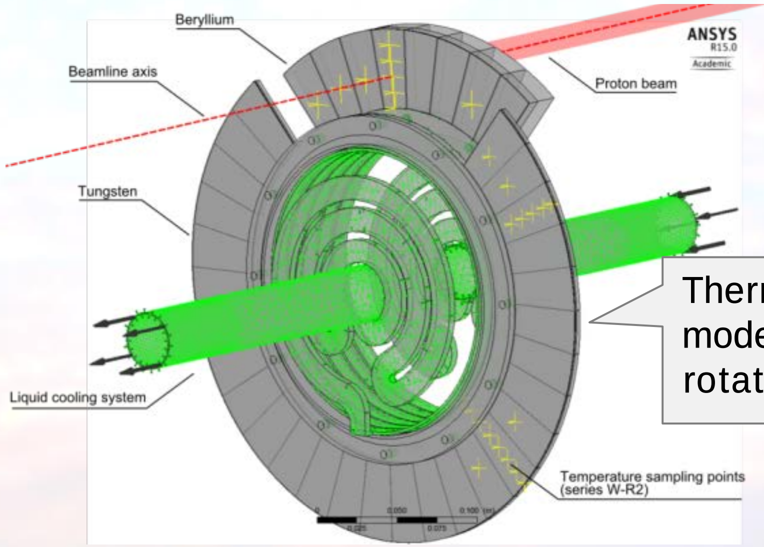
ANEM performance



Movie clip of the temperature distribution during warm-up.

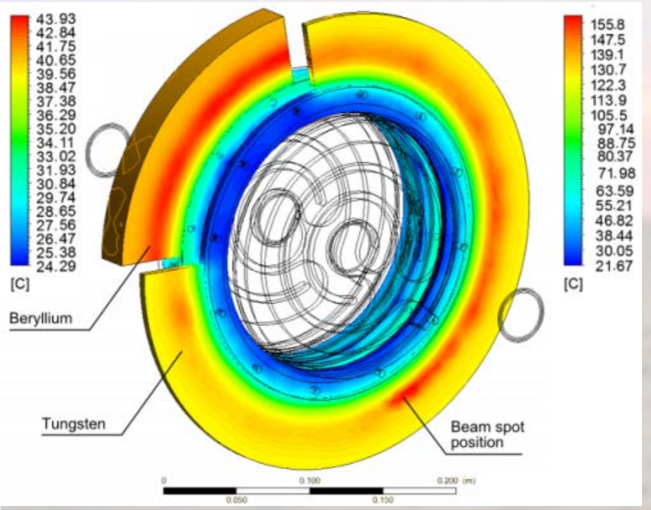
The desing of the ANEM target was modeled with ANSYS to calculate the maximum tolerable thermo-mechanical stress.

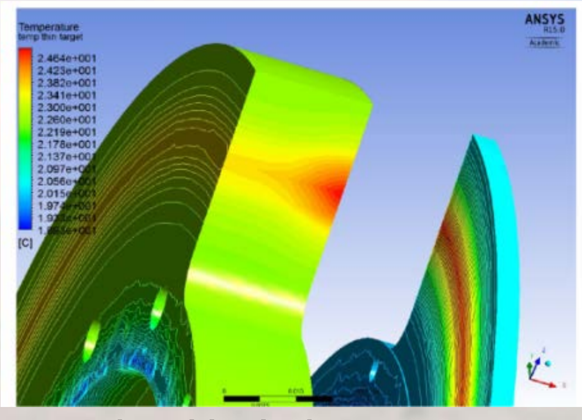
The calculations indicate that ANEM can conservatively handle a 70 MeV proton beam (gaussian distribution, 1cm FWHM) with a <u>current up to 30 µA</u> (2.1 kW) with a rotating speed of 120 rpm.



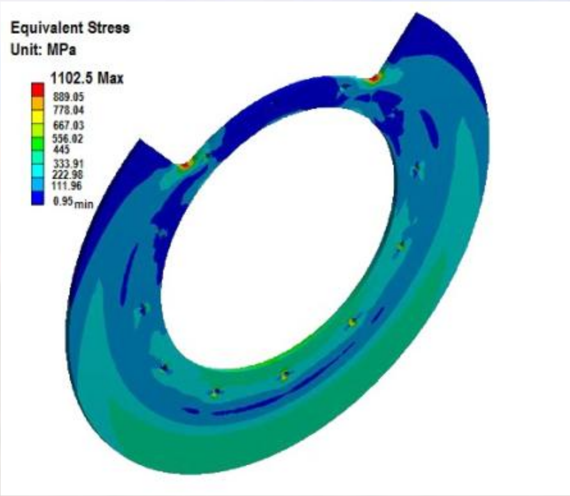
Thermo-mechanical model intercepting the rotating proton beam

Thermal performance modeling





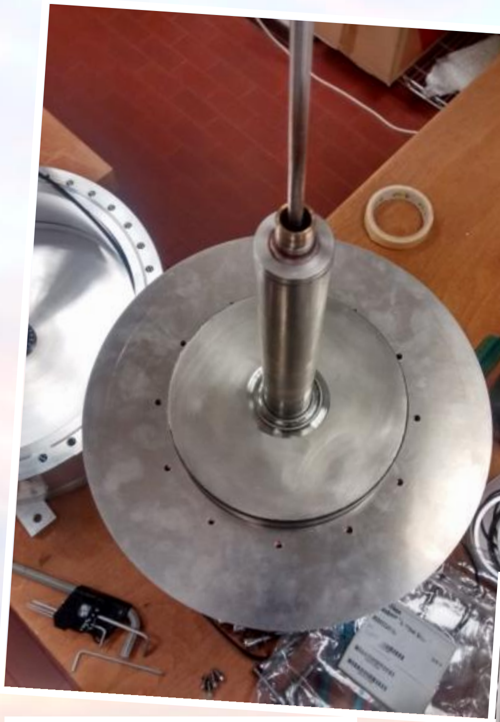
Power deposition in the Be sector, the bragg peak is visible

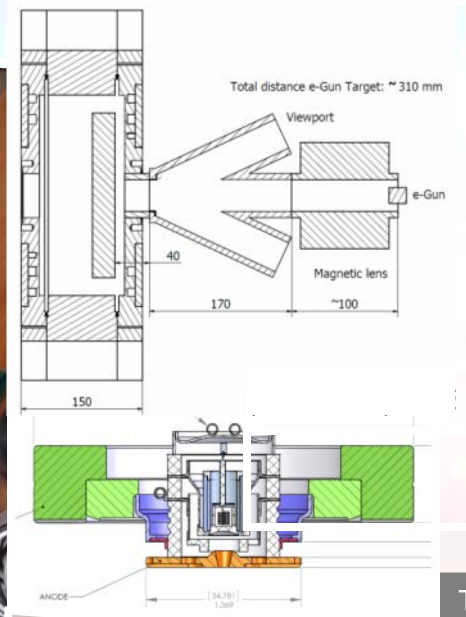


A dynamic model of the stress induced by the thermal expansion is being developed.

ANEM prototype

The ANEM prototype will undergo thermal tests in the next months

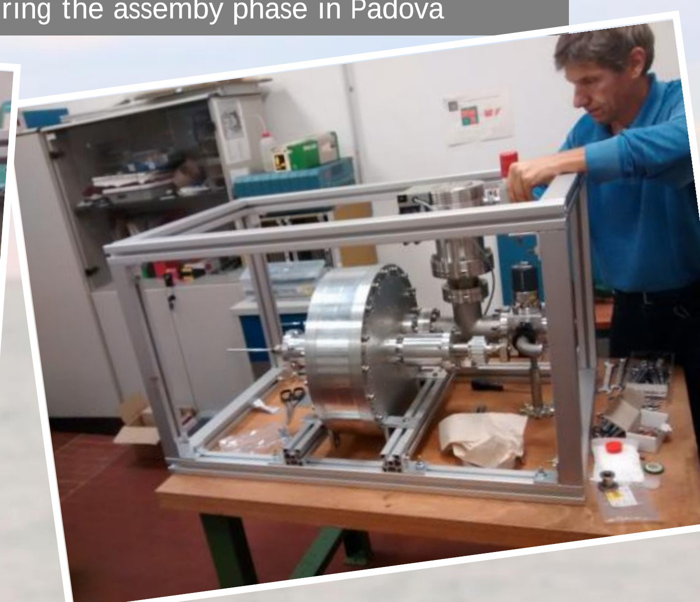




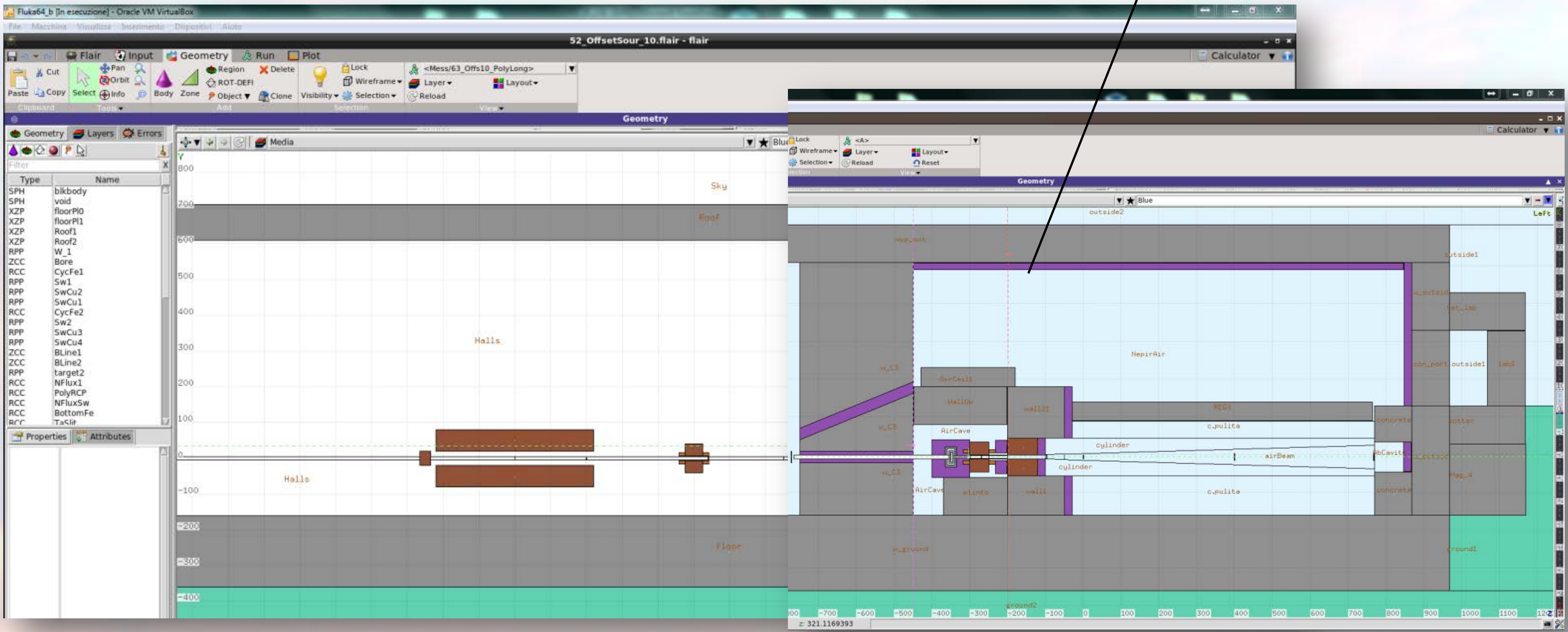
The thermal tests will use a 10 kV electron beam,
- Maximum current 1 A
- Beam current controlled by varying cathode voltage;
- Electron emitter shaped to give and initial rough focusing
- Flange mounted (CF 3 3/8) gun assembly;
- Independent magnetic focusing coil (by Danfysik): minimum beam spot 1 cm^2 (gaussian);

Altair electron gun

The prototype during the assemby phase in Padova



Dose calculation geometry



Borated polyethylene

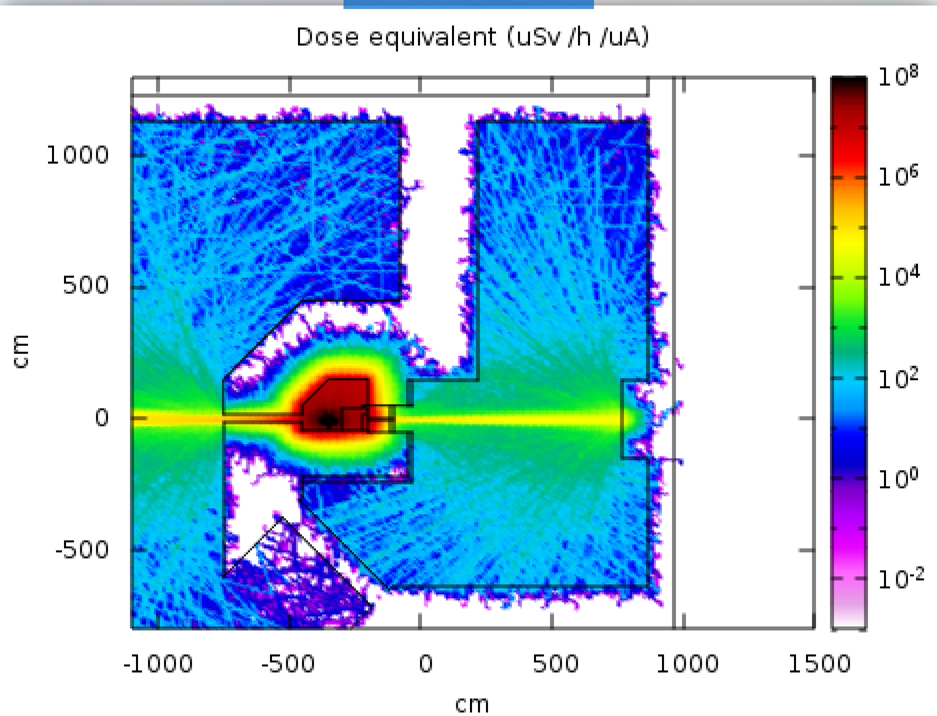
Fluka simulation geometry for the calculation of the backstreaming neutrons form the QMN target to the cyclotron hall.

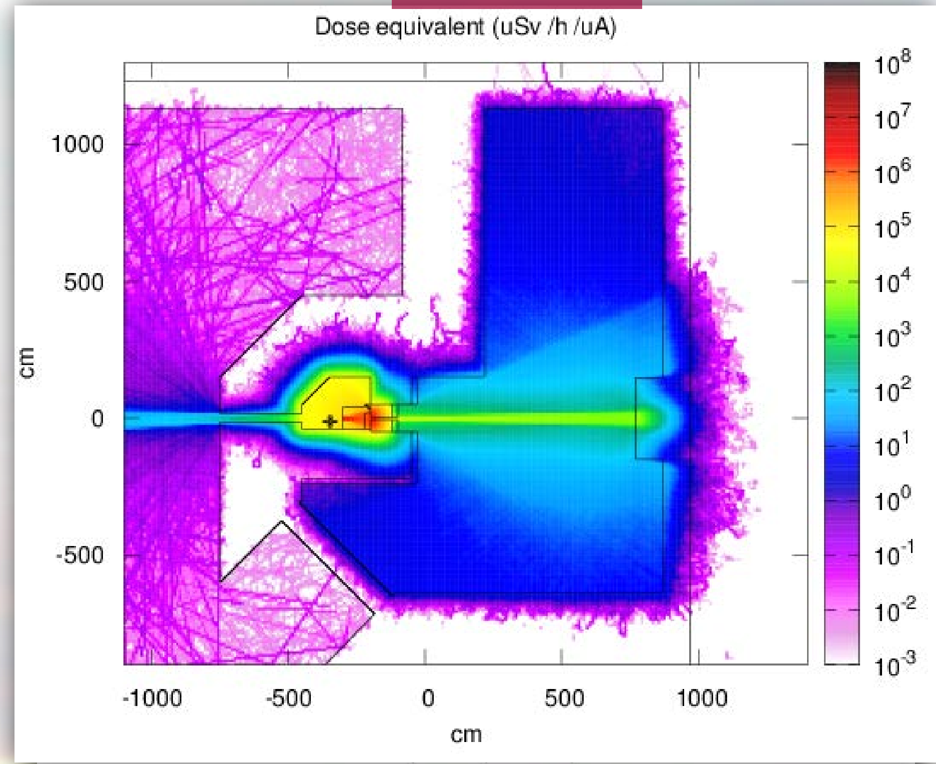
Fluka simulation geometry of the NEPIR bunker and irradiation hall (vertical section through the beam axis).

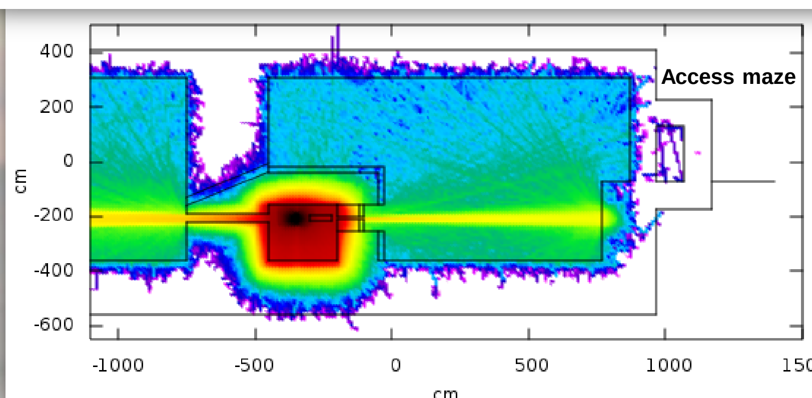
Dose rate in the experimental hall

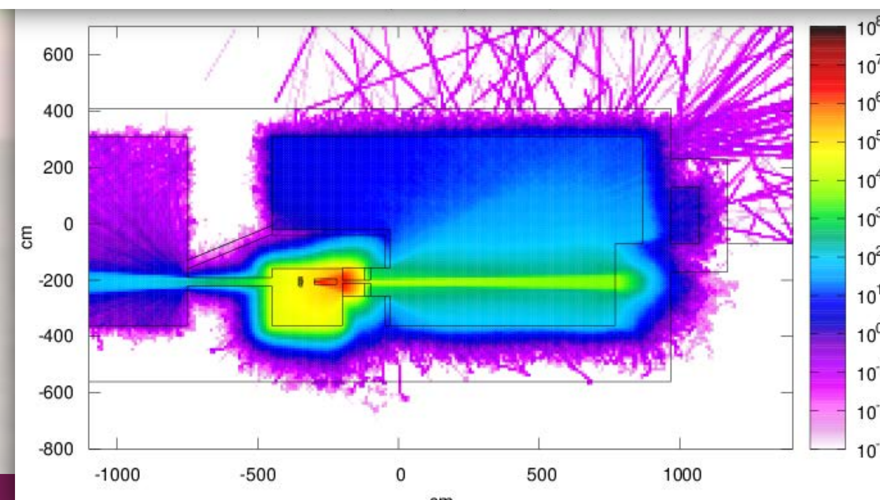
ANEM

QMN









Prompt ambient equivalent dose rate delivered by the QMN target with a proton beam current of 1 uA.

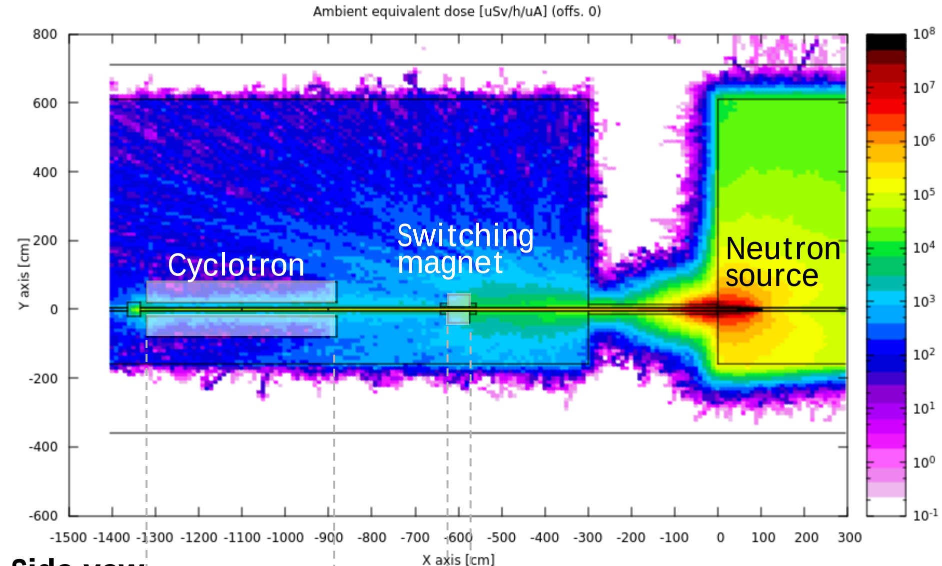
Backstreaming neutrons: prompt dose rate

Prompt ambient equivalent dose delivered by the ANEM target in the cyclotron experimental hall was assessed for different conditions.

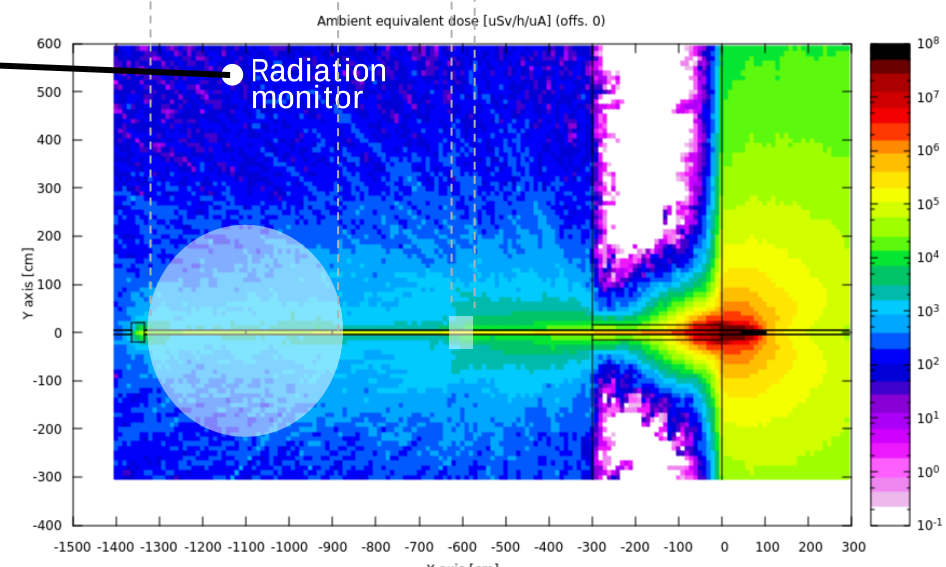
A worst case calculation was performed, using “forward” neutron yield from 70 MeV protons on 5 mm W (ANEM) (“forward” = as if protons coming from the right)

NB: At the radioprotection monitors, the worst case contribution from ANEM is 1/10 of the dose rate of Cyclotron itself.

Dose at monitor position ~ 100 µSv/h (MAX), with 1 µAmp proton current on the target

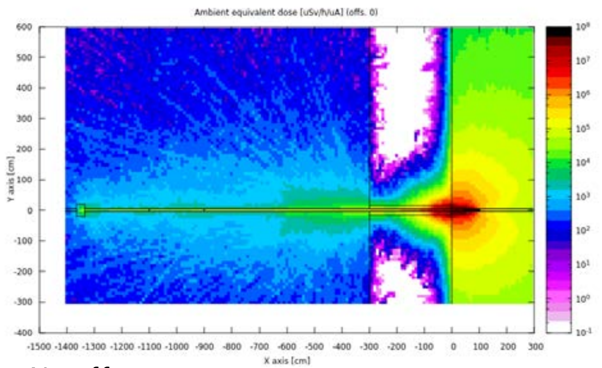


Side vew

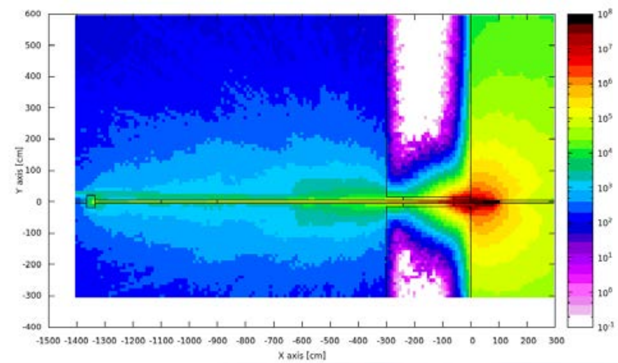


Top vew

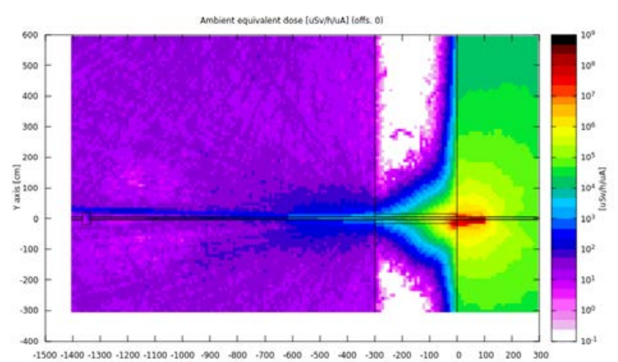
Backstreaming neutrons dose: source offset



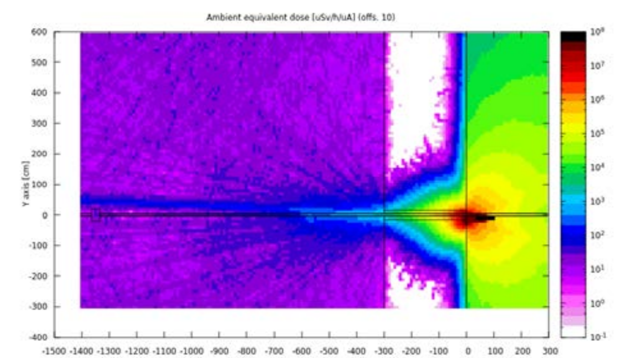
No offset



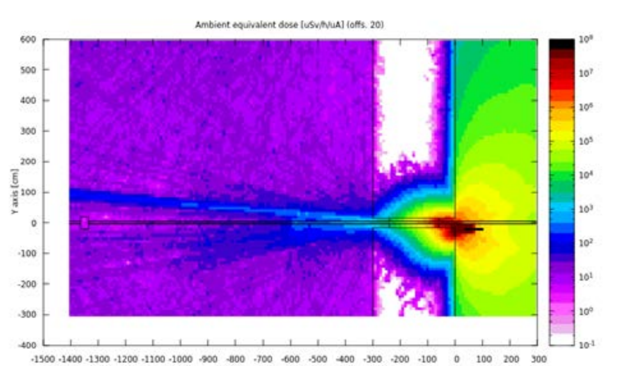
Offset: 3 cm



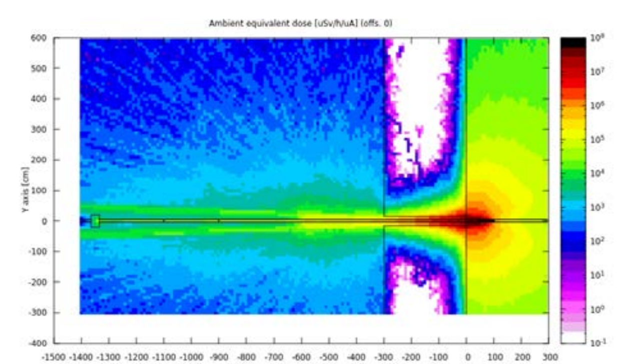
Offset: 5 cm



Offset: 10 cm



Offset: 20 cm



No offset, no Poly

Air activation

Calculations for QMN target:

Proton beam condition: current: 1 uA, energy: 70 MeV, irradiation time: 24 h.

Experimental hall air activation (the considered air is the one filling the whole experimental hall).

Time after end of beam		Air activation	
0	min	0.02	Bq/g
15	min	<0.01	Bq/g
60	min	<0.01	Bq/g

Bunker air activation (the one filling the targets bunker).

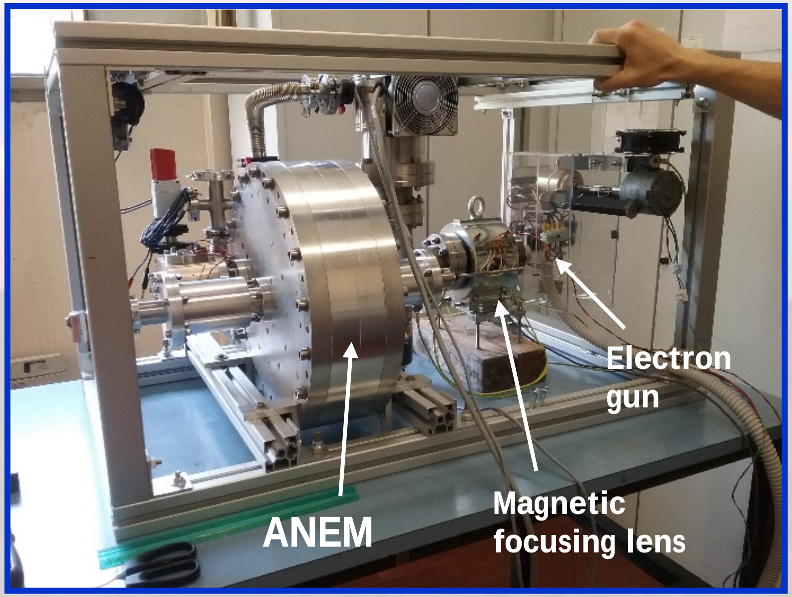
Time after end of beam		Air activation	
0	min	2000	Bq/g
2	days	5	Bq/g
3	days	<1	Bq/g

NOTE: the values reported in this table do not take into consideration the contributions of the beam dump for the deflected proton beam.

Conclusions

NEPIR current status

- Funds required to MIUR (Italian ministry of university and research) to build the QMN (20-70 MeV) line of NEPIR (will also host ANEM) and the QMN (70-230 MeV) target for TIFPA (Trento proto-therapy center).
- an ANEM prototype system exists, with aluminum test disk, that will be used in the next moths to assess the thermo-mechanical performance of the device
- the basic design of the beam-transport for QMN/ANEM completed
- detailed TDR (shielding, radioprotection issues) work in progress



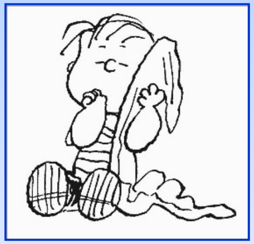
Prototype of the ANEM target in LNL, ready for thermal dissipation test

The end

(Extra slides follow)

Extra slides

LINUS: The Legnaro Integrated NeUtron Sources facility



A ***suite*** of sources of multipurpose neutrons, **from cold to fast**

Luca Silvestrin et al.
University of Padova and
INFN Padova (ITALY)
luca.silvestrin@unipd.it

Bisello D., Fagotti E., Esposito J., Loong C.K., Maggiore M., Mastinu P., Prete G., Wyss J.

The Legnaro Nuclear Laboratories

The Legnaro Nuclear Laboratories are located in Legnaro (Italy), at 10 km from Padova.

INFN
Istituto Nazionale di Fisica Nucleare

Van Der Graaf 6 MV

Tandem 14 MV

S-conductive RFQ

Microbeam 2 MV

Cyclotron 70 MeV

Aereal view of the Legnaro Laboratories

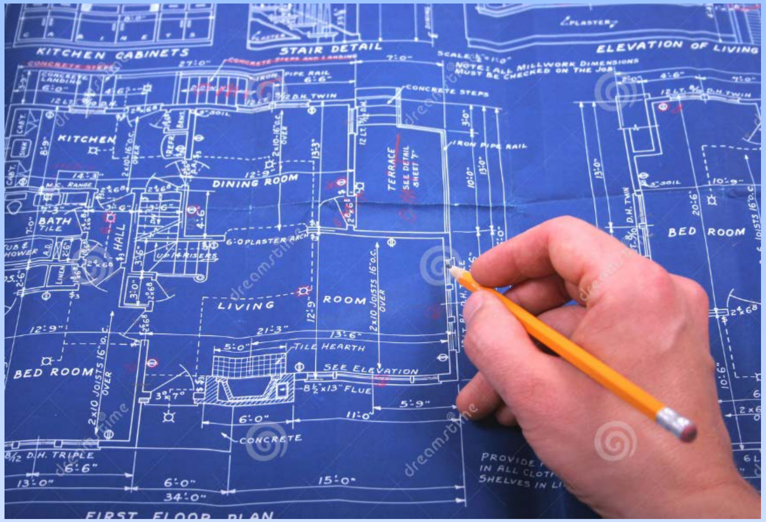
Outline

Introduction

LINUS A project of an Integrated Neutron Sources facility for the INFN Legnaro laboratory

INFN Istituto Nazionale di Fisica Nucleare

Italian National Institute of Nuclear Physiscs



- LSNS: Legnaro Slow Neutron Surces

  and its subsystems

- NEPIR: **NEutron and Proton IRradiation** facility

  and its subsystems (QMN, ANEM,…)

Extra slides

LINUS Facility

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

LINUS consists of:

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

RFQ

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.

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

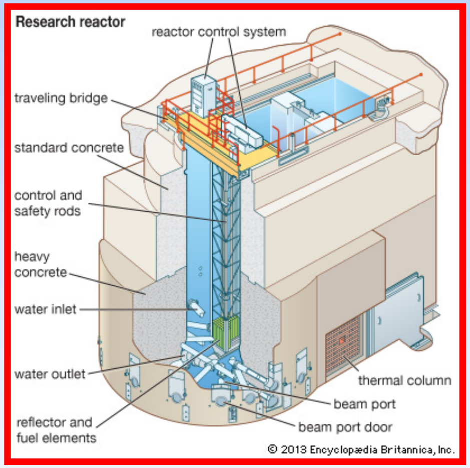
NEPIR is driven by the high power 35-70 MeV proton cyclotron of the SPES project and consists of four subsystems:

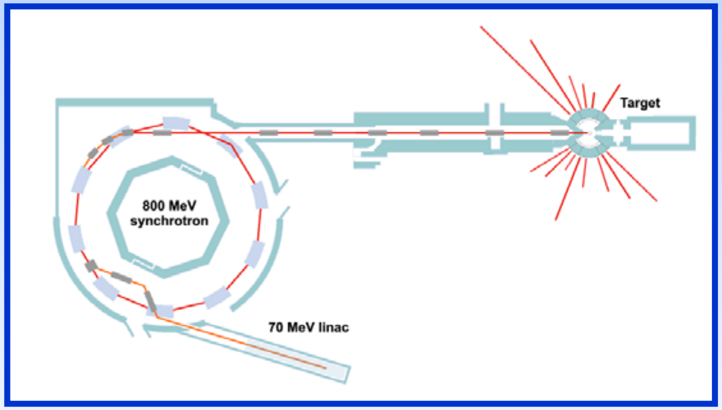
I. **QMN**: delivers quasi mono-energetic neutrons in the 20-70 MeV range
II. **ANEM**: delivers *atmospheric-like* neutrons in the 1-70 MeV range
III. **SLOWNE**: a special applications “slow/medium/fast” neutron source
IV. **PROTON**: a direct proton (35-70 MeV) irradiation line (not this talk)

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 retirement** (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)**, they will **barely fulfill the demands** of the large neutron user community for materials research, let alone of other emerging important fields and disciplines. ☺ ⟶ 😐 ⟶ ☹

Luca Silvestrin luca.silvestrin@unipd.it

LSNS is a green-field (no constraints) project

GOAL: ensure an expansive neutron R&D landscape and a thriving community of neutron users.

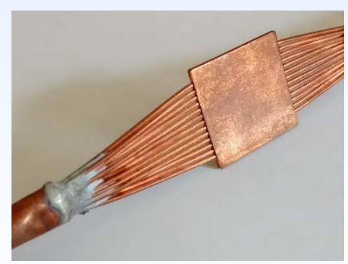
It will combine:

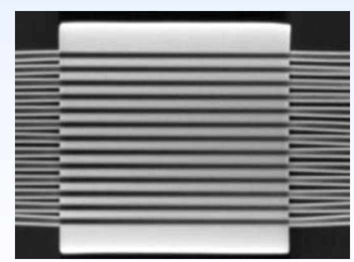
- ❑ **cutting-edge technologies** achieved at LNL
  - high-power, high-current proton **RFQ** proton accelerators;
  - neutronics technologies;
  - High power Li and **Be** production targets (eg. MUNES).

Trasco accelerator:
RFQ, 5 MeV 40 mA

Be target for BNCT
(MUNES project)

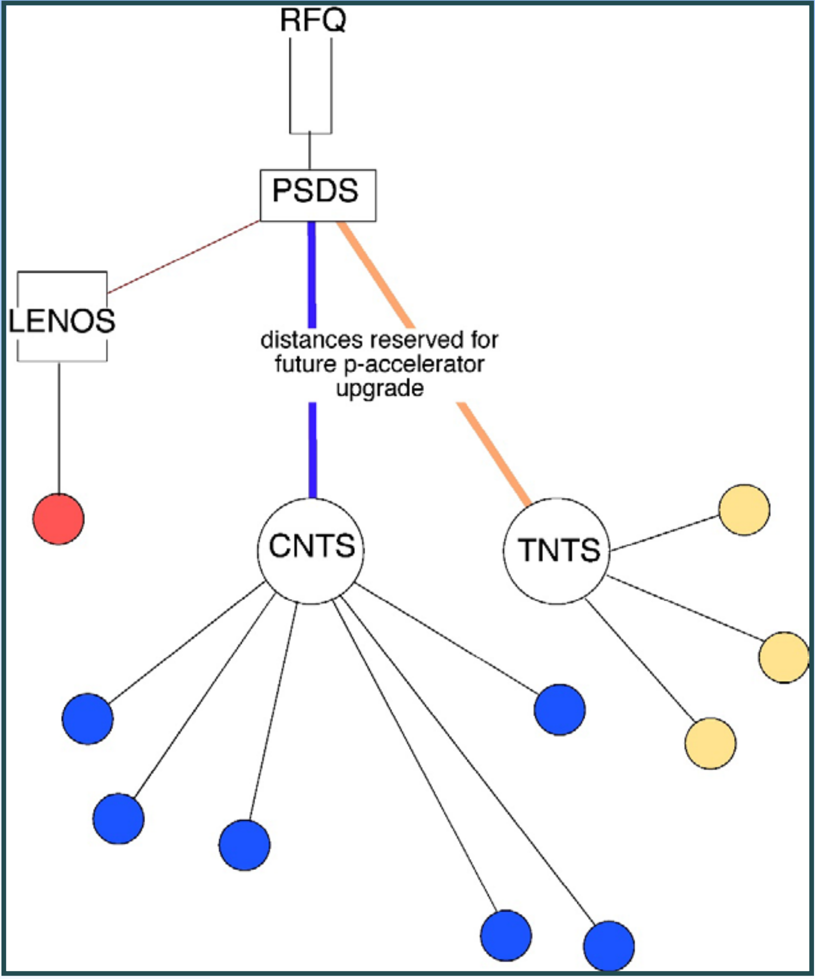
Microchannel cooled thin target. Performance better than 3.5 kW/cm2





- ❑ **optimizable infrastructure** of various neutron beamlines and end-stations for a suite of R&D user facilities using cold, thermal and epithermal neutrons.

Modular facility structure



Proton beam PSDS
(**Pulse Selection** and **Distribution Station**)

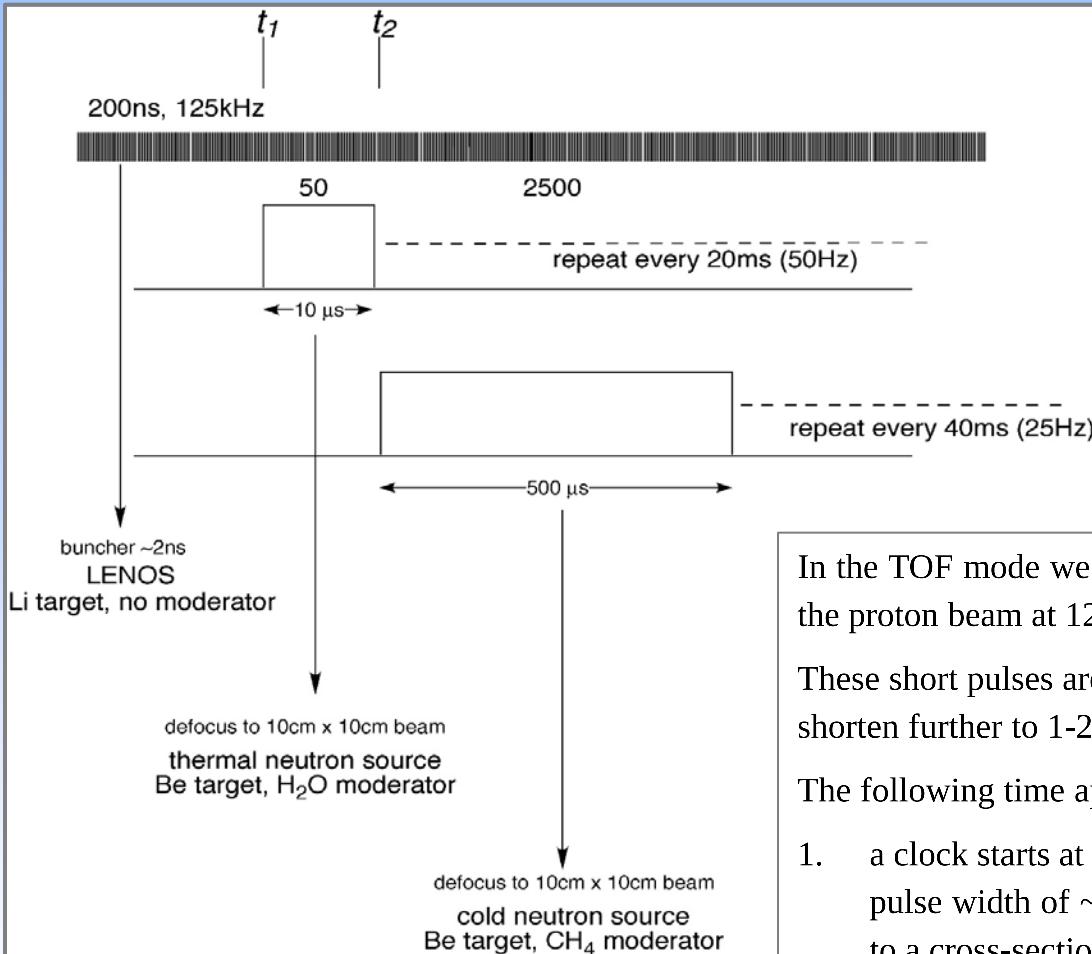
- CNTS (**Cold Neutron Target Station**)
  - Be target
  - Cryogenic moderator of solid methane
  - Reflector (graphite or water)
  - Up to 6 ports to expermental halls
- TNTS (**Thermal Neutron Target Station**)
  - Identical design to CNTS but with water (abient temperature) moderator
  - Initially three ports
- LENOS (astrophysics)

- **Modular** structure
- **Mild radioactivity** by low-energy protons ($\leq$ 5 MeV)
- Both **Short Pulse** (SP) and **Long Pulse** (LP) options
- Cryogenic and gas handling systems for hydrogenous moderator

CNTS and TNTS are ideal for experimental validation of novel moderator systems

Luca Silvestrin luca.silvestrin@unipd.it

Time structure



A conceptual scheme of distribution of proton pulses of different time structures to the epithermal-, thermal- and old neutron applications. The time axes are not in scale, numbers are ballpark figures.

Proton beam
Pulse and Selection
Distribution Station

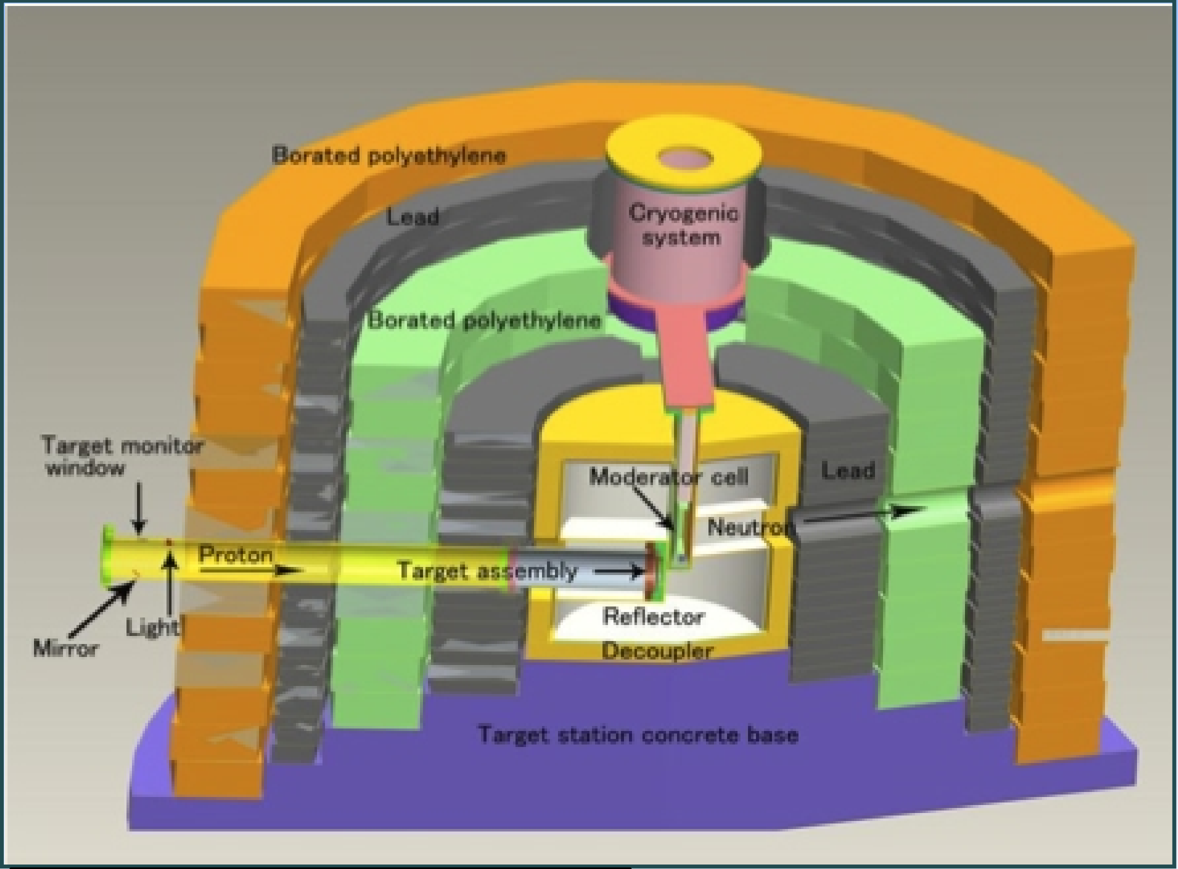
In the TOF mode we assume a **chopper, upstream of the RFQ**, will pulse the proton beam at 125 kHz with a pulse width (FWHM) of ~200 ns.

These short pulses are nominally delivered to the LENOS target station and shorten further to 1-2 ns by a **buncher**.

The following time appropriation takes place:

1. a clock starts at t_1 for the accumulation of the short pulses to achieve a pulse width of ~10 µs in conjunction with the defocusing of the beam to a cross-section of 10cm x 10cm.
2. Afterward this proton pulse is delivered to TNTS. This process is to repeat every 20 ms so as to enable a short pulse (SP) neutron source running at 50 Hz.
3. After each SP the clock starts at t_2 to accumulate a long pulse (LP) of ~500 µs width, defocused, then to feed the CNTS. This process repeats every 40 ms for a LP cold neutron source running at 25 Hz.

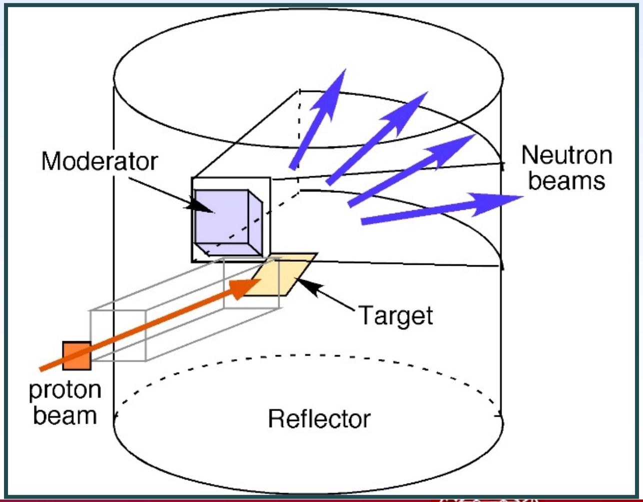
Schematic structure of the target stations



Cold neutrons target station layout

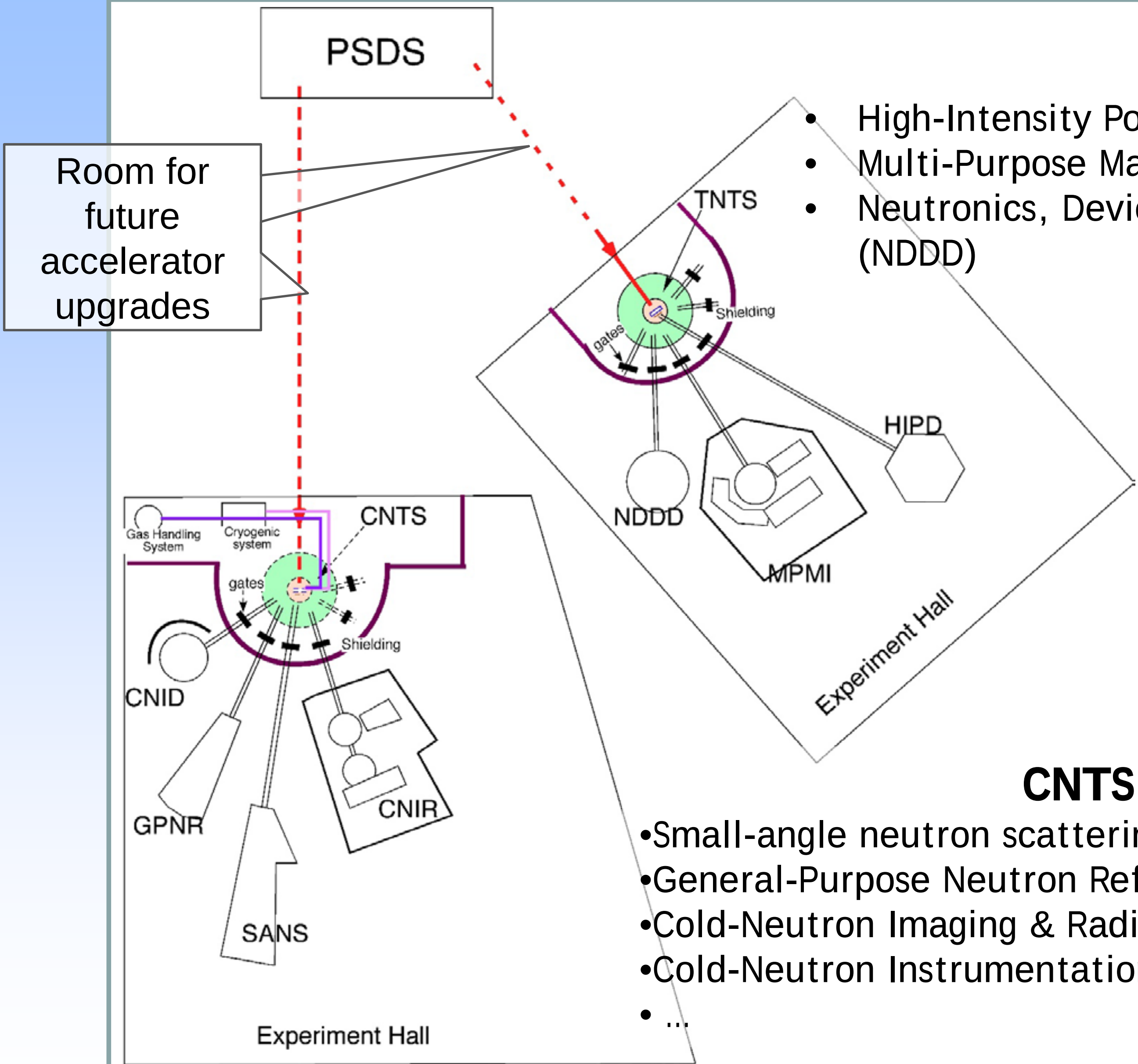
In the case of the CNTS, a cryogenic system and a gas handling system (not shown) will cool the moderator medium (e.g. solid methane) to ~10 K.

Target station core



A schematic layout of the target station's inner core, showing a defocused proton beam incident on a thin target (Be) and a moderator above for generation of cold neutrons which exit through the beam ports.

Schematic layout of the LSNS facility



TNTS

- High-Intensity Powder Diffractometer (HIPD)
- Multi-Purpose Materials Interrogation (MPMI)
- Neutronics, Device and Detector Development (NDDD)

CNTS

- Small-angle neutron scattering (SANS)
- General-Purpose Neutron Reflectometer (GPNR)
- Cold-Neutron Imaging & Radiology (CNIR)
- Cold-Neutron Instrumentation Development (CNID)
- ...

LSNS numbers

Legnaro Slow-Neutron Source (LSNS) driver

proton RFQ (E_{proton} = 0.08-5 MeV, 30-50 mA, 150-250 kW, CW or Pulsed)

Cold neutrons

Be-target,

25 Hz 0.5 ms LP

duty cycle ~1/800

- Imaging & radiography
- Small-angle scattering
- Neutron reflectmetry
- Instrumentation R&D (neutronics, polarization ...)

Thermal neutrons

Be-target,

50 Hz 0.01 ms SP

duty cycle ~1/2000

- Diffraction
- Neutron interrogation
- Instrumentatio n R&D

LENOS

Li-target,

125 kHz 200ns

bunched to 2 ns SP

duty cycle ~1/40

- Nuclear astrophysics TOF
- Nuclear astrophysics Activation

Medical therapy

Be-target

CW

duty cycle = 1

- BNCT (thermal)
- BNCT (epithermal)

NEPIR

NEutron and Proton IRradiation facility

QMN: A source of **Quasi Mono-energetic Neurons** 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): An intense source of ***fast* neutrons (E > 1 MeV)** with a continuous (*white*) energy distribution similar to that of atmospheric neutrons found at flight-altitudes and at sea-level in the 1-65 MeV energy range.

SLOWNE: A high intensity slow/fast neutron source (4π-flux > 10^{14} n/s) for special ***slow* $\rightarrow$ *fast* 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.

NOT DISCUSSED in this talk

The original purpose:

The **QMN**, **ANEM** and **PROTON** subsystems will be used for the study of

radiation damage effects in electronic devices and systems

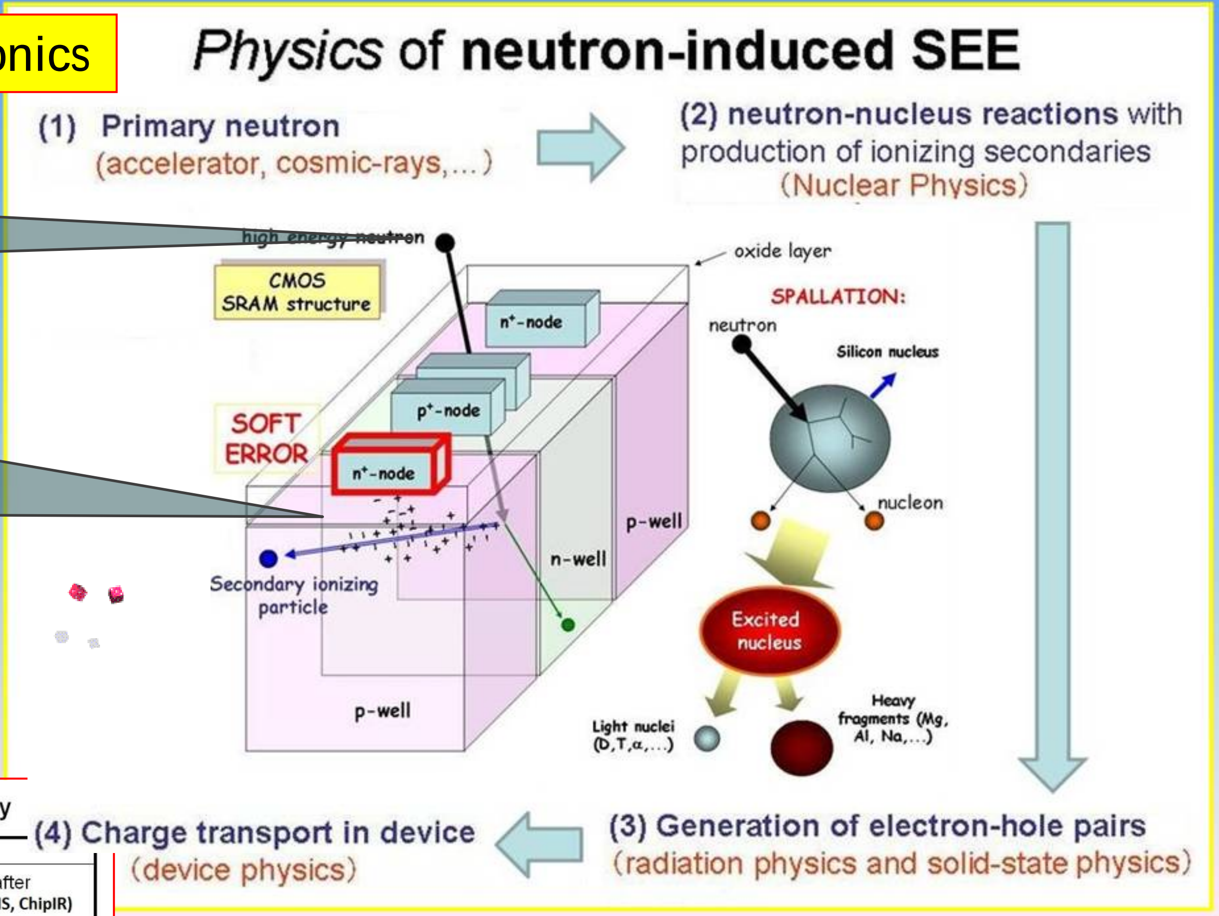
induced by:

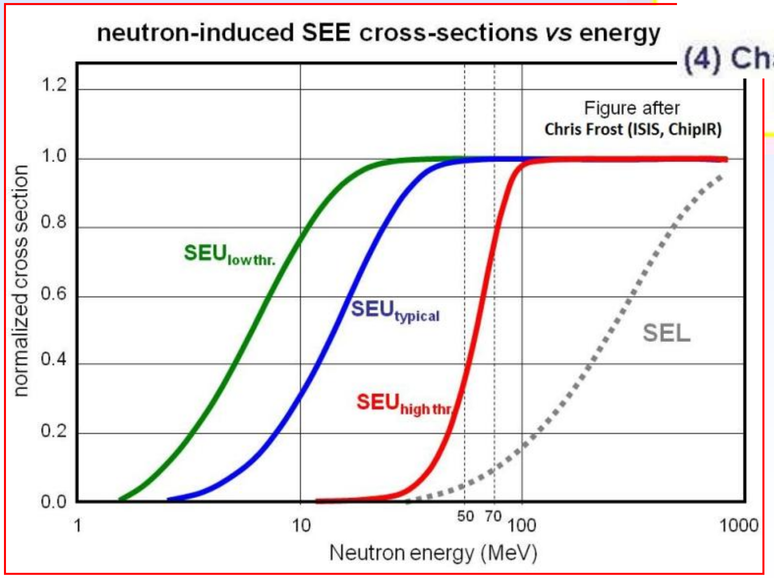
- **flight-altitude and sea-level *atmospheric* neutrons (especially)**
- **solar protons**

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

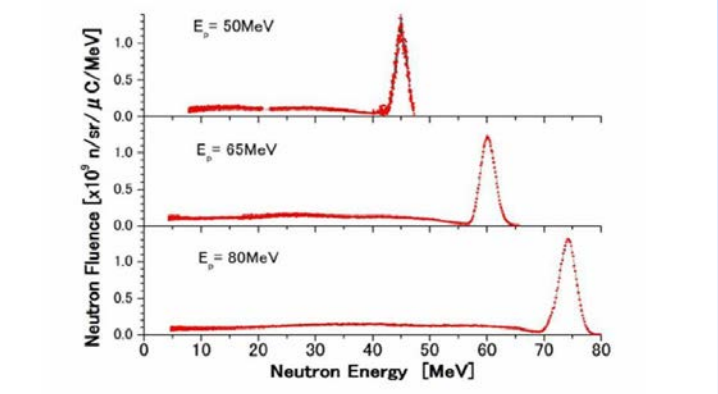
"Soft Errors" such as **SEUpset in digital electronics**:

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

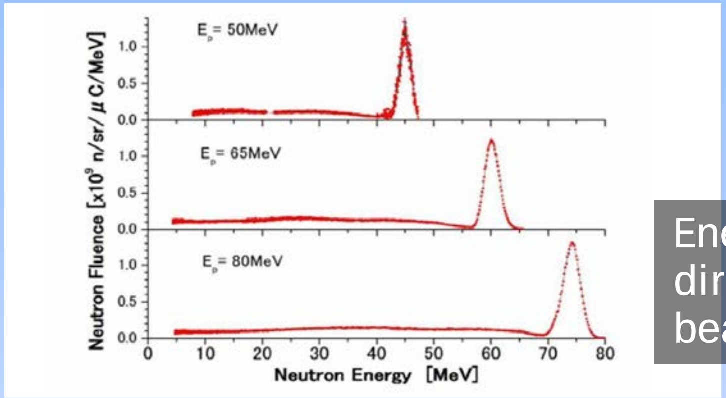
$$N_{bits}\ \text{per device} = 4 \times 10^6\ \uparrow$$

QMN

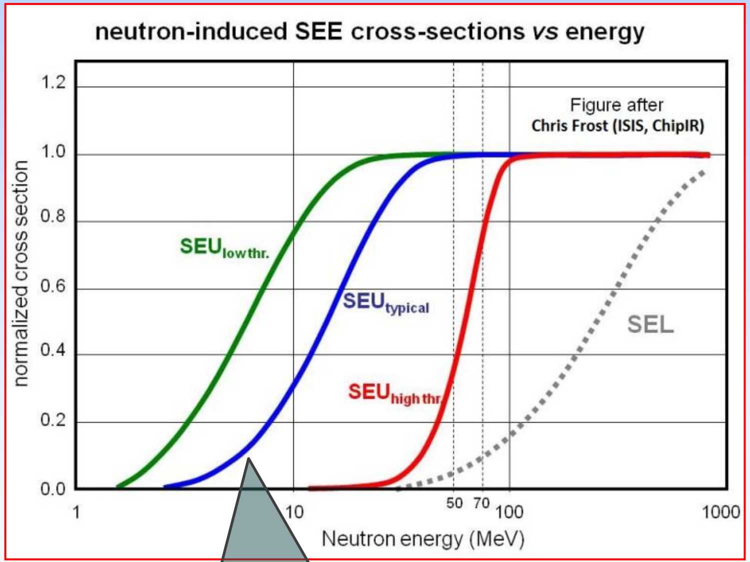
the Quasi Mono-energetic Neutron source



QMN



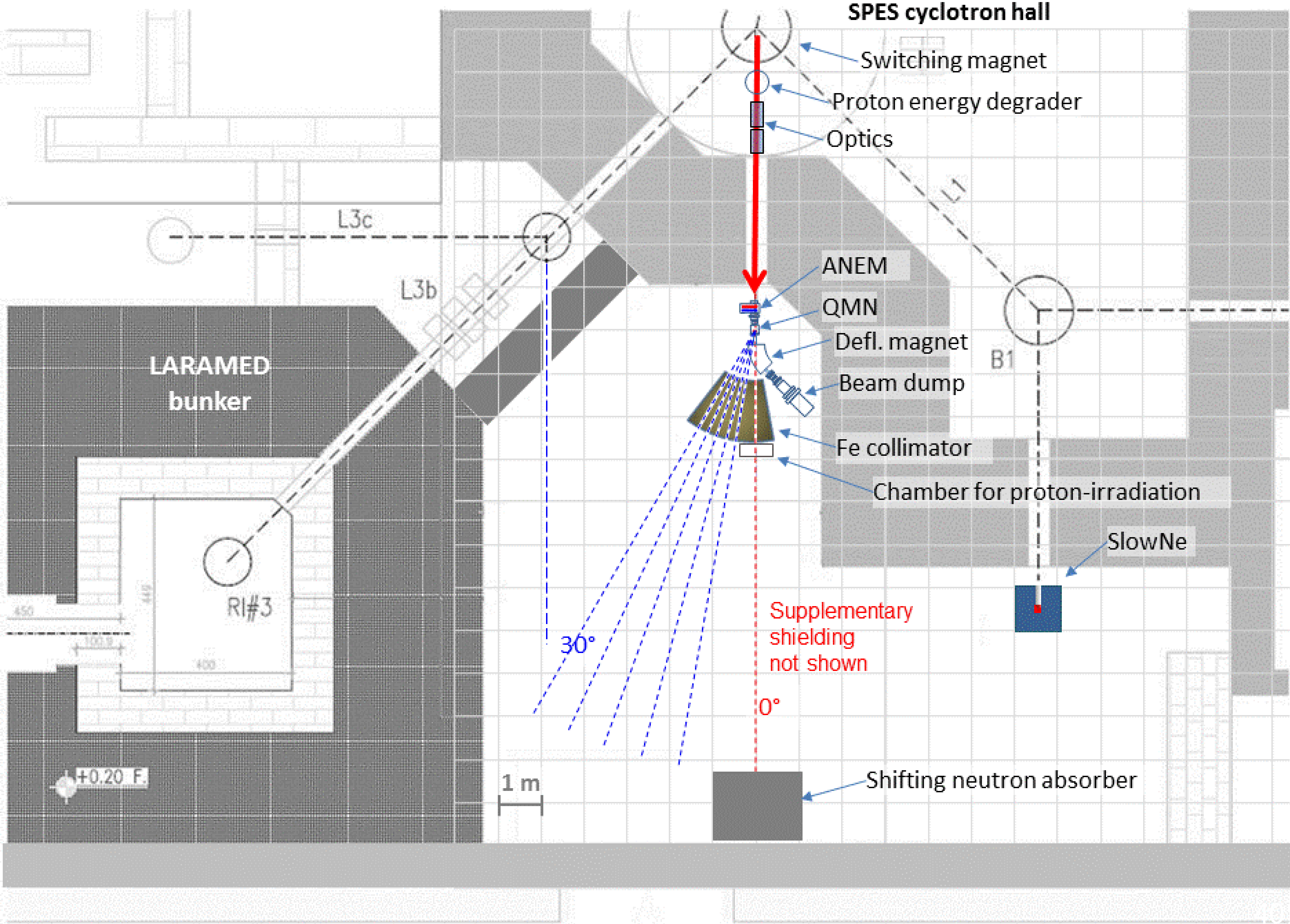
Energy spectra of QMN neutrons in the forward direction at the TIARA facility for three proton beam energies.

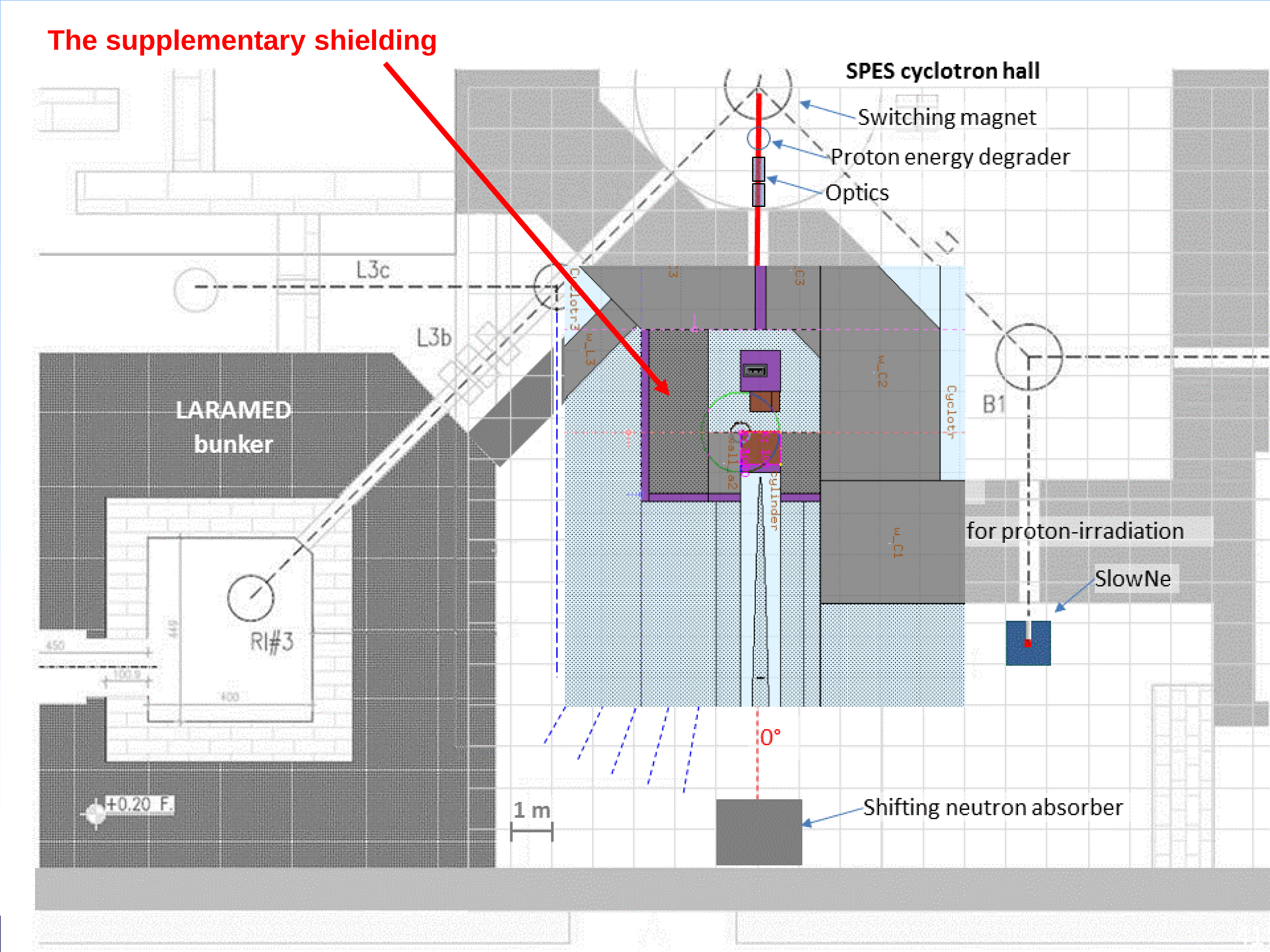


- Multi-disciplinary interest
- Energy dependent neutron-induced effects
  (e.g. measure the cross-section vs energy curve)
- Angular dependence
  - iTHEMBA-like (fixed angle collimator)
  - RIKEN-like (variable angle collimator)

Quasi-ideal tool to sample components sensitivity

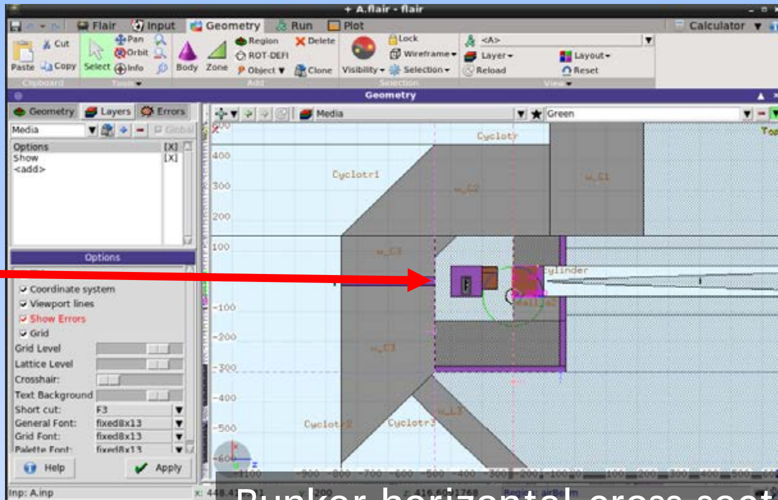
The supplementary shielding is not shown



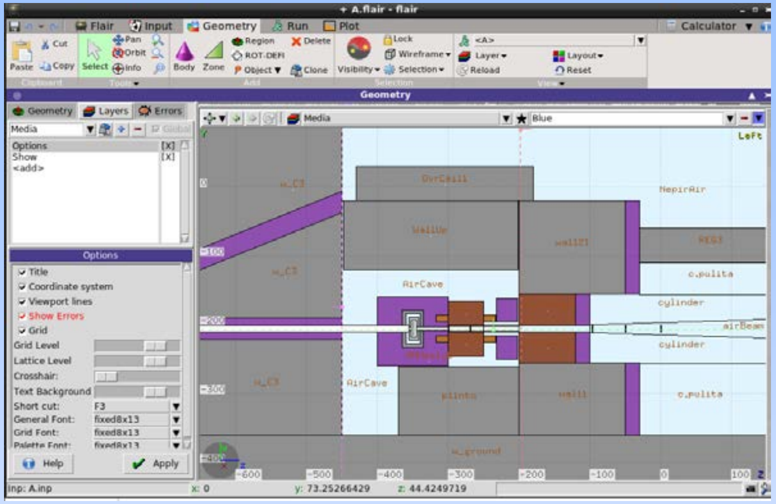


The supplementary shielding
SPES cyclotron hall
Switching magnet
Proton energy degrader
Optics
L3c
L3b
L1
B1
LARAMED
bunker
RI#3
for proton-irradiation
SlowNe
0°
1 m
Shifting neutron absorber
+0.20 F.

(ongoing) **Shielding calculations**

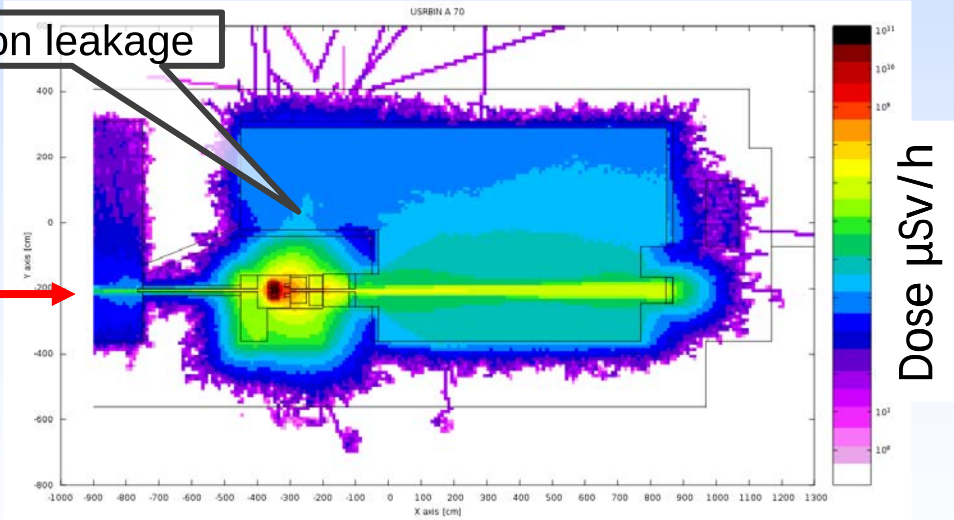


Bunker horizontal cross section



Bunker vertical cross section through the beamline

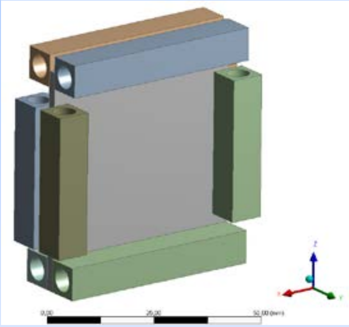
Neutron leakage

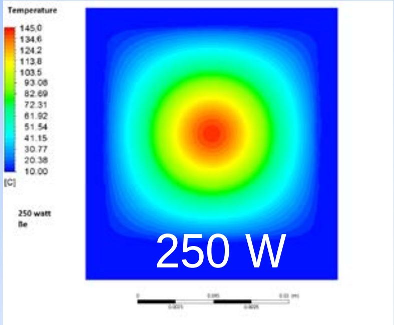


Fluka simulation: dose map, vertical cross section through the beamline

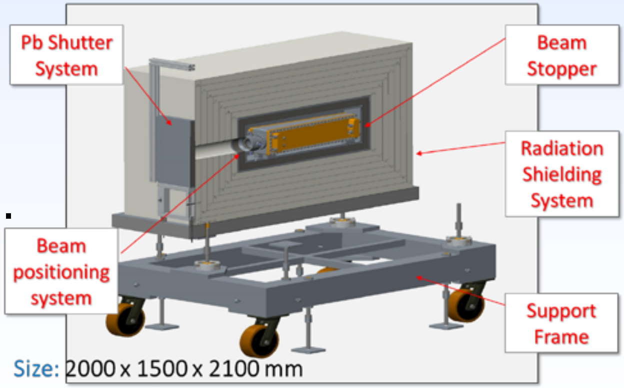
- A 30° collimator is likely to be the standard angle for correction, but this must be verified for the 20 ←35-70 MeV energy range. **MC are not at all reliable in this energy range.**
- both thin Li and Be (few mm) targets will be available (energy deposition in target ~ 3 MeV → power ~100 W)

Simple Be design can safely handle 200 W





- **1-2mm Be (similar FHWM as Li)** will be used for high flux (> 3×10^5 n cm^{-2} s^{-1}). The neutron yield can be kept high with more proton current (up to 30 microAmps) with test point at 3 m downstream of target
- the beam dump will be like the one used for SPES tests (for full 700 kW power), or a scaled down version.



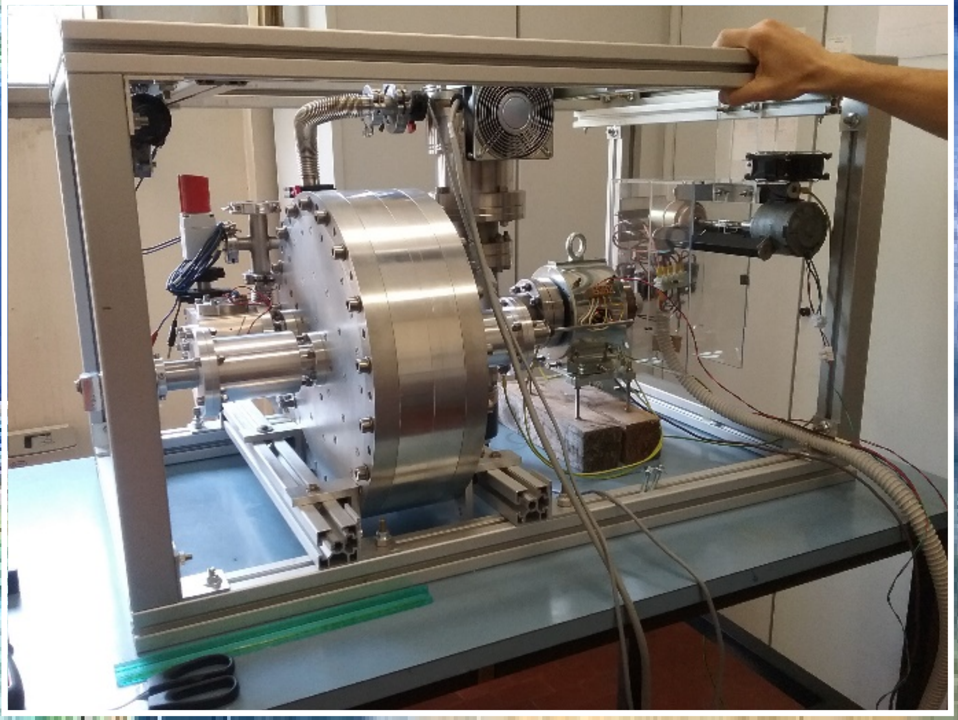
NEPIR experimental hall

Completed SPES infrastructure

Existing (empty) NEPIR experimental hall

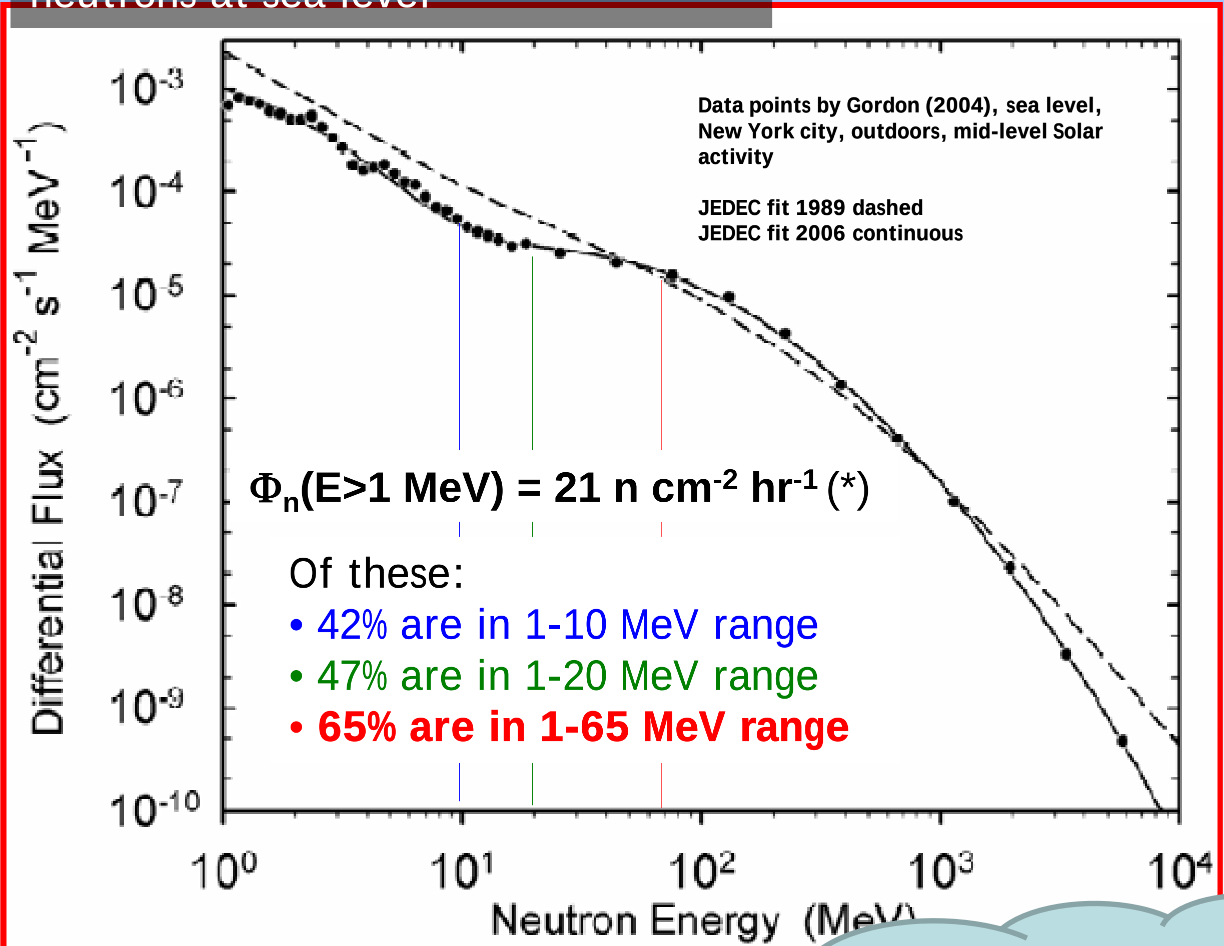
ANEM

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



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**

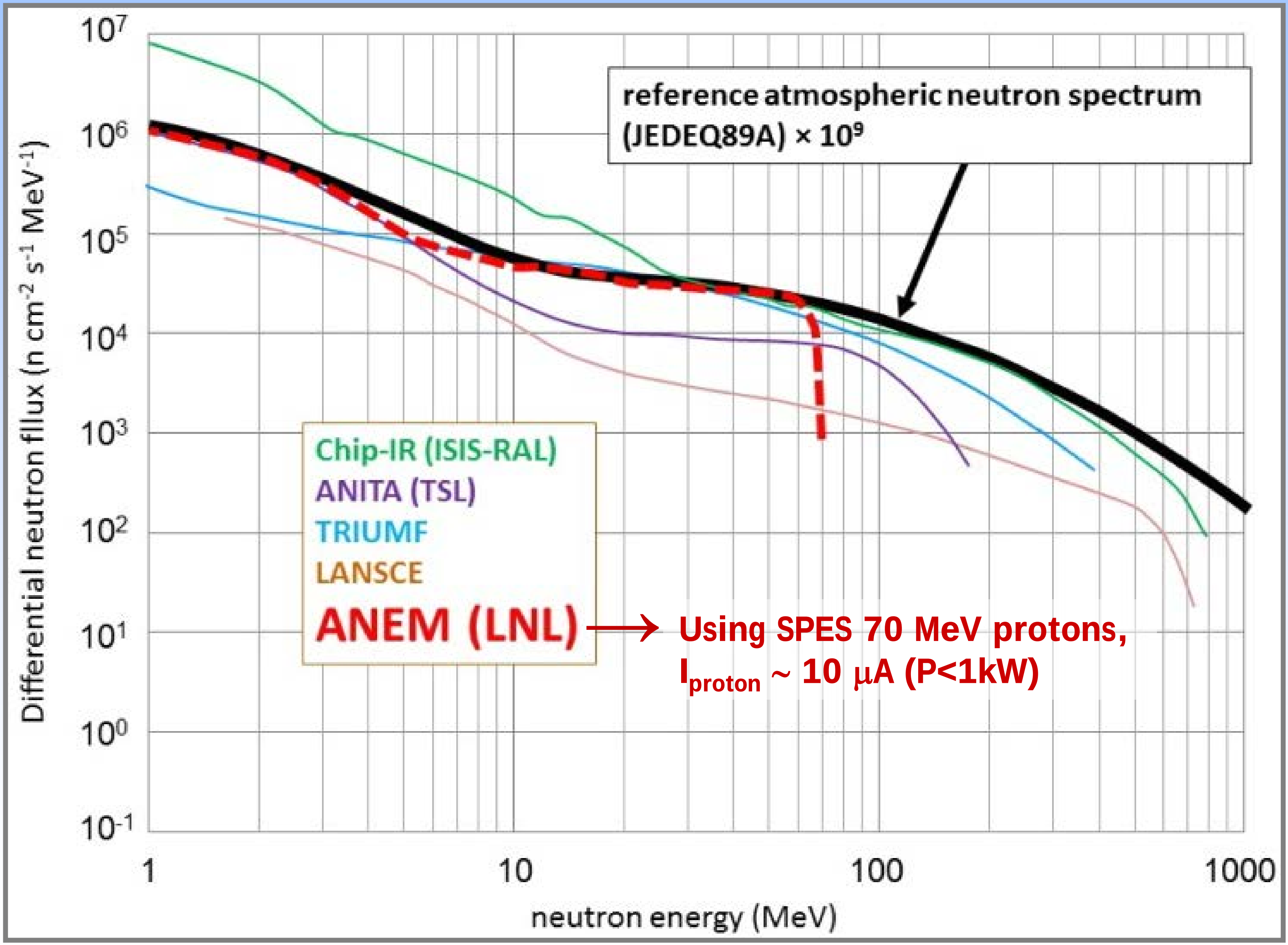
The standard reference spectrum used by the ***JEDEC Solid State Technology Association***, an independent semiconductor engineering trade organization and standardization body.

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

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

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

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.



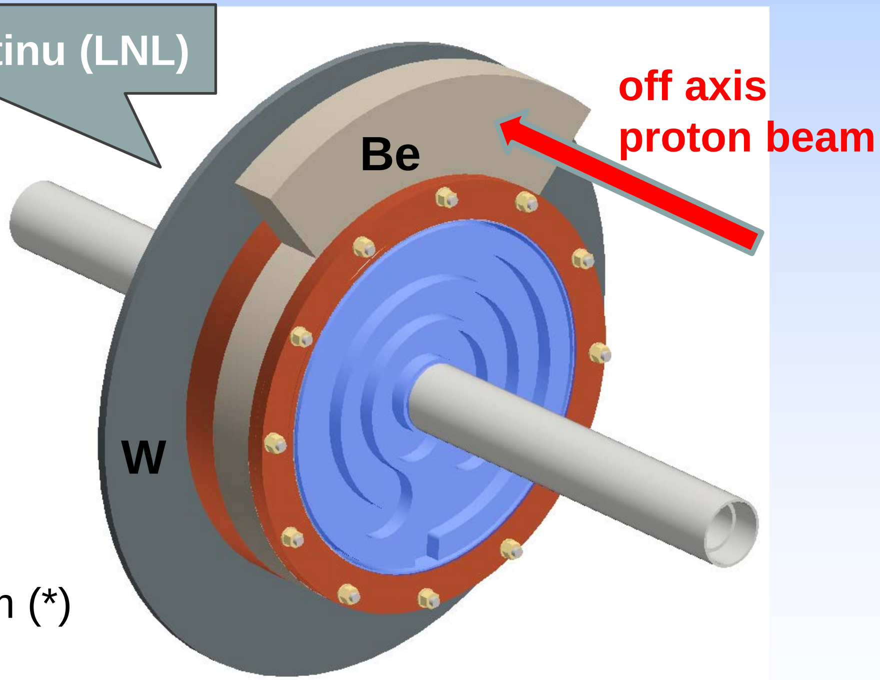
ANEM: a continuous energy neutron production target

Minimum Design GOAL: At 6m distance and I_{beam} = 30 μA (**2.1 kW**) the flux of neutrons with E > 1 MeV is ~10^9 times the natural one in the 1-65 MeV range, comparable with the highest factor to be used at **Chip-IR** facility.

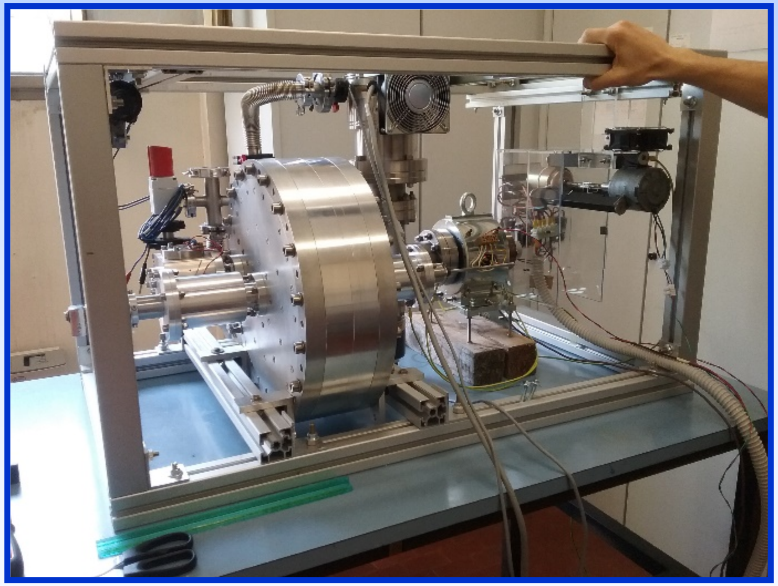
A **novel** rotating composite target made of **thick** Be and W.

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.

a of P. Mastinu (LNL)



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



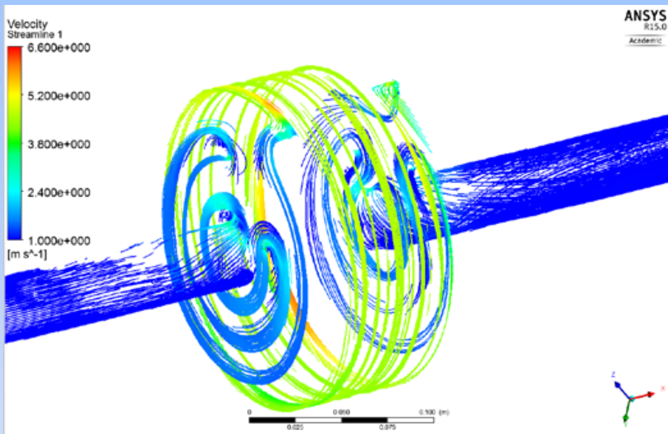
Target prototype almost ready for thermal test with electron-gun

(*) 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.

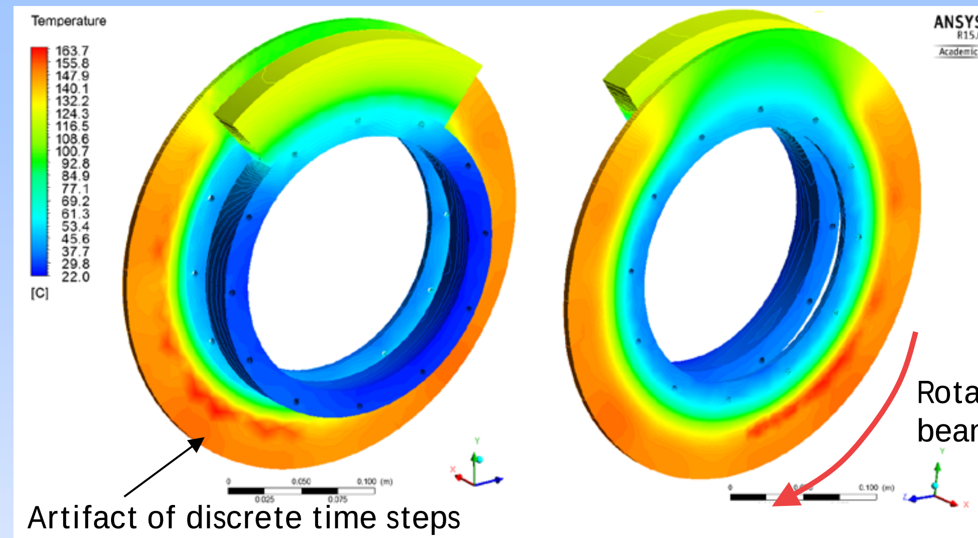
Thermal simulations

W full disk, 5 mm thick , beam power 3.5 kW, rotation 1 Hz

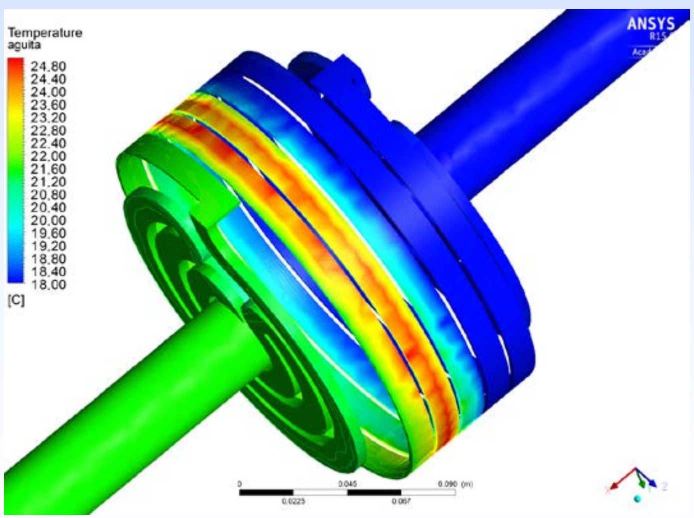
Bragg peak energy deposition included



Water flaw lines in the cooling circuit



Thermal map, snap-shot at regime with 2Hz rotating beam



Water temperature distribution in the lliquid cooling system

- Water inlet temperature : 18°C;
- Water inlet velocity 1m/s

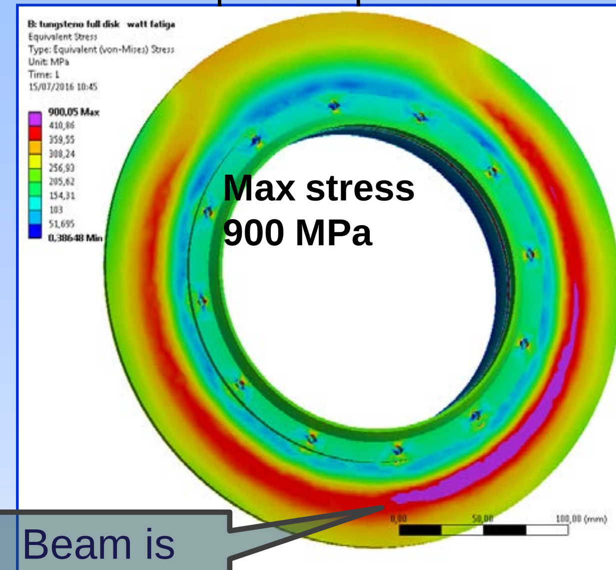
- W disk
- **gaussian beam spot FWHM = 1 cm**
- **beam Power 5 kW**

- rotating beam (10 rev/sec)

Stress simulation

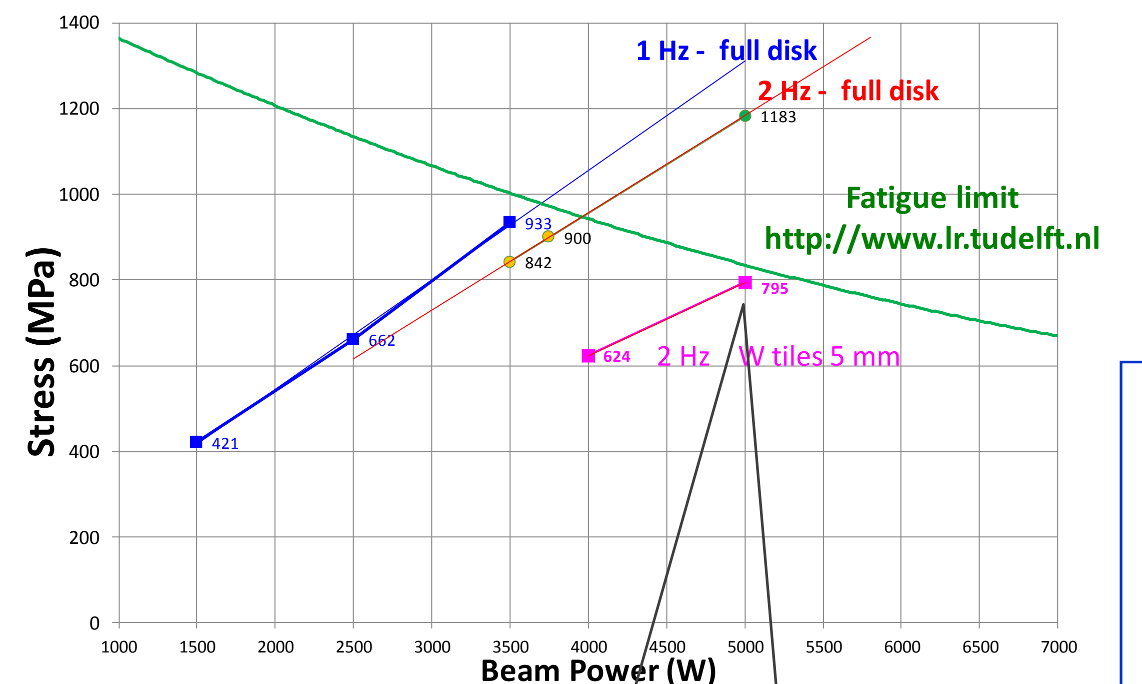
Snap-shot at regime with rotating beam

Tungsten full disk, 5 mm thick
Rotation frequency 2 Hz
Deposited power: 3.75 kW

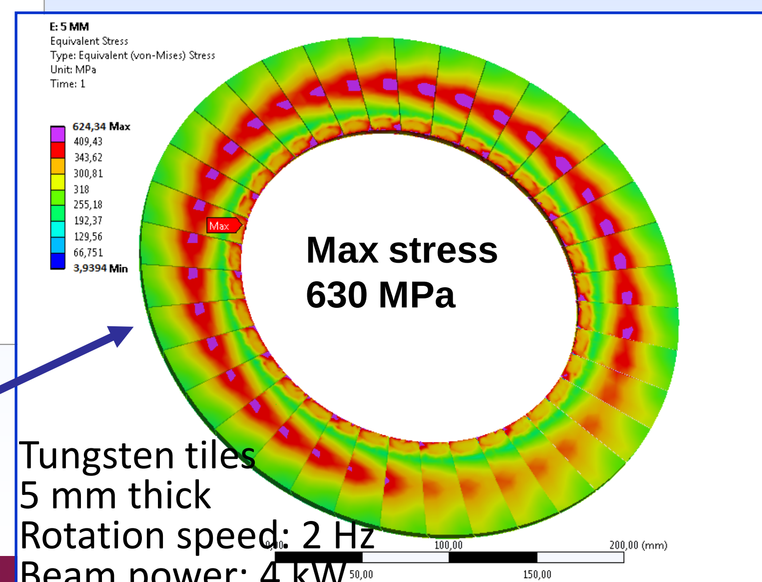


Beam is hitting here

Max stress for different power, compared to fatigue limit (for «infinite» cycles)



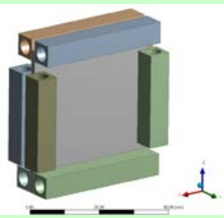
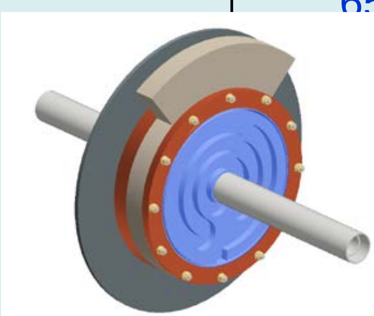
Maximum deliverable power with tiles configuration **5 kW**



Tungsten tiles
5 mm thick
Rotation speed: 2 Hz
Beam power: 4 kW

QMN and ANEM numbers

To study neutron effects on electronics

QMN discrete 	Energy range 20 ← 35-70 MeV 😐 ☞ ☺ Complementary with Trento for QMN in 70-235 MeV	Essential to study energy dependencies (cross-section vs energy curves) 😐 ☞ ☺	Neutron flux at test point is **user controlled**, up to **~ 5×10^{5} n cm^{-2} s^{-1}** ☺	Angle correction ☺
ANEM continuous 	Energy cut-off 65 MeV	Useful to make flexible studies/checks for unexpected sensitivity to lower energy neutrons, before performing full energy tests at high-energy facilities like Chip-IR (RAL). 😐 ☞ ☺	Neutron flux at test point is **user controlled**, flux (E_n > 1 MeV) at test point up to **ϕ ~ 10^{7} n cm^{-2} s^{-1}** ☺ ~ 10^{9} higher than the natural flux at sea level in the 1-65 MeV energy range	

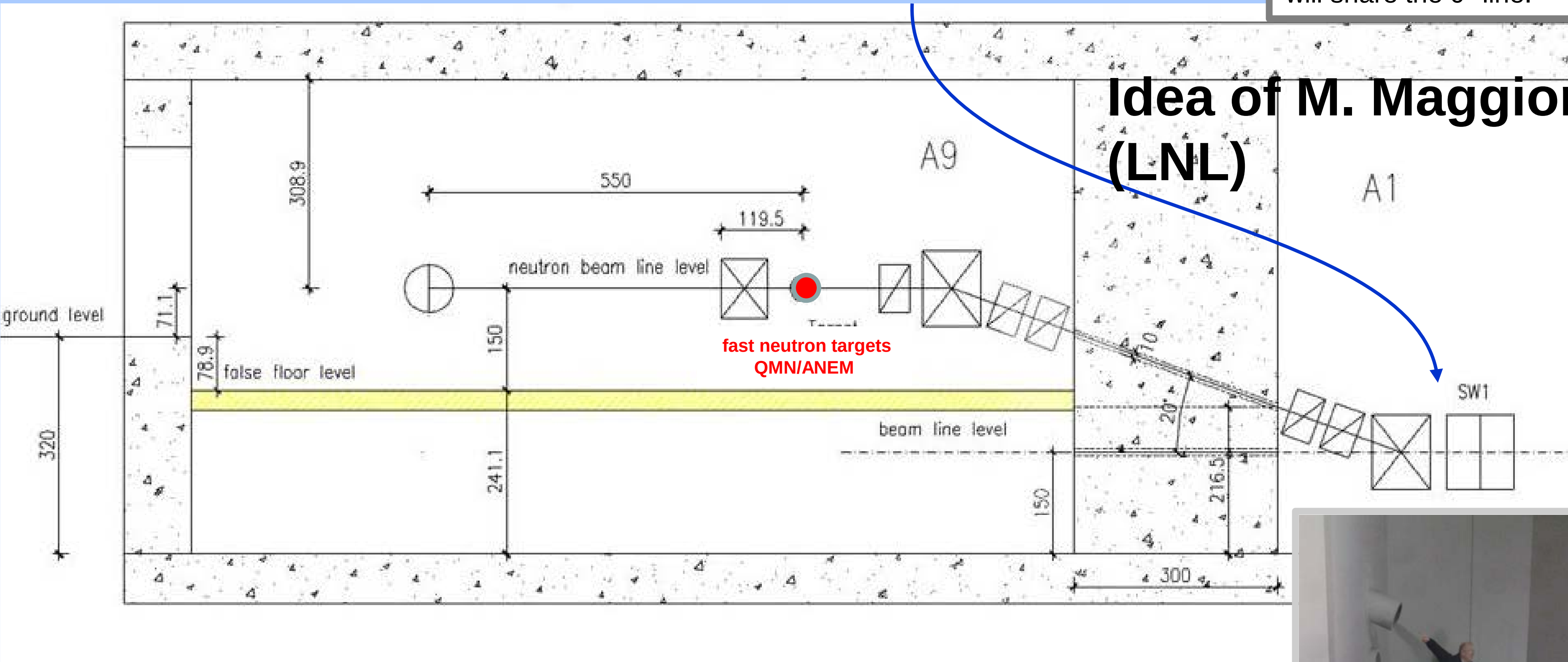
NEPIR fast neutron line UPGRADE

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.

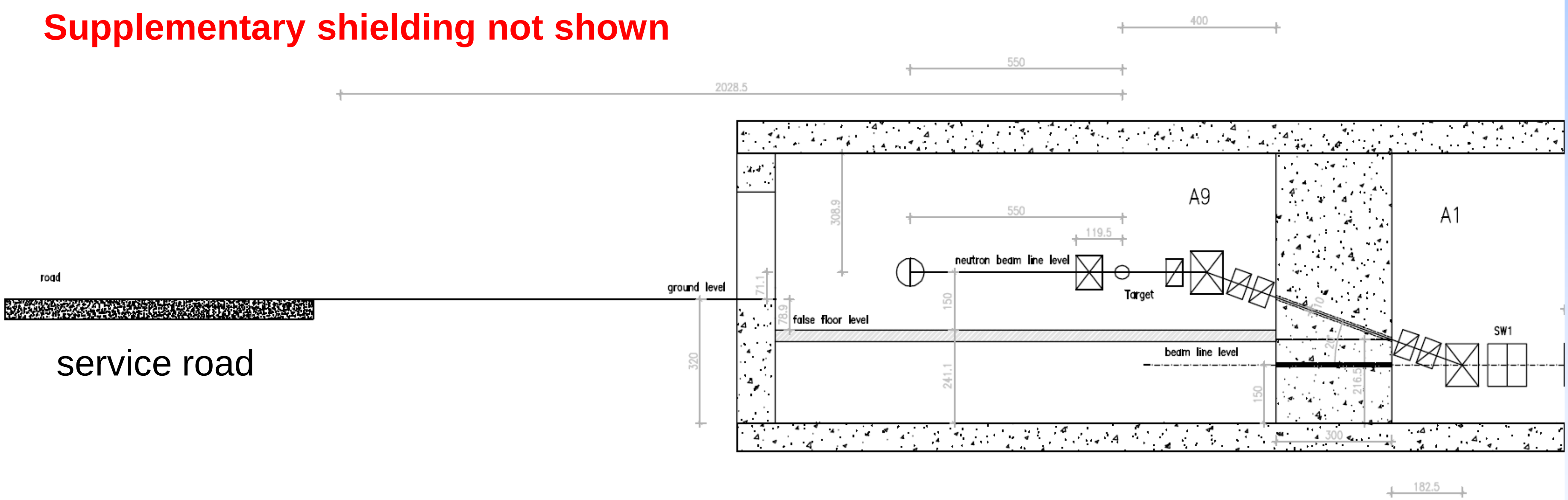
Idea of M. Maggiore (LNL)



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.

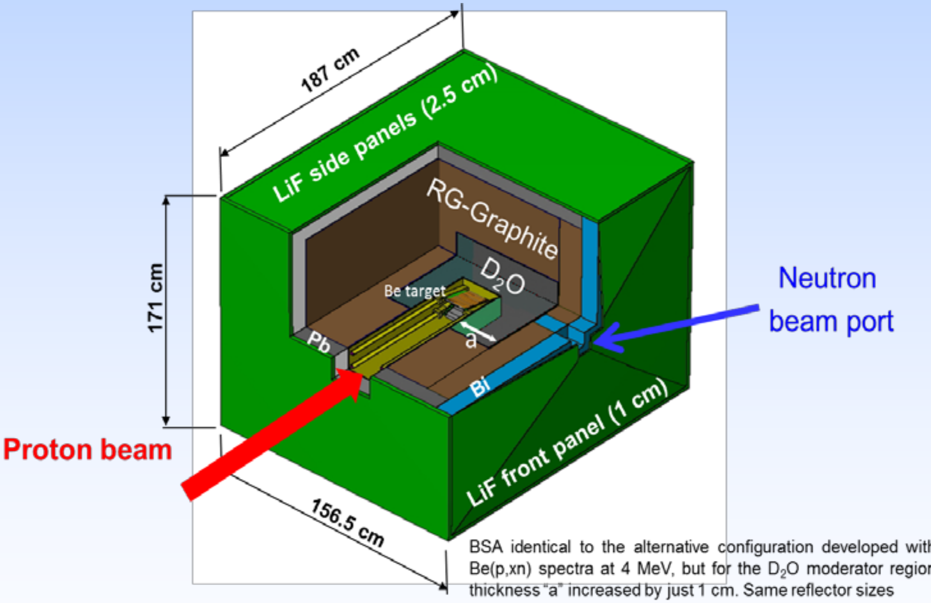
UPGRADE 2: flight path extension

An extension of the Time of Flight path up to ~ 20 m (maybe more by moving service road) outside of the laboratory is possible.



SLOWNE

the slow neutron source

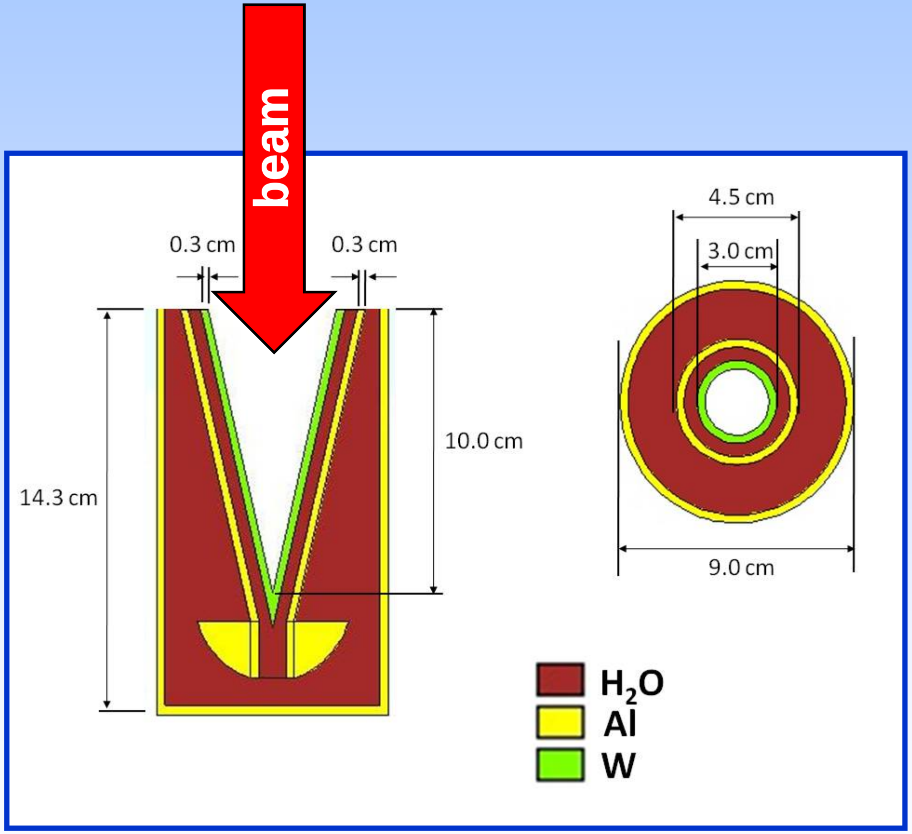


BSA identical to the alternative configuration developed with Be(p,xn) spectra at 4 MeV, but for the D_2O moderator region thickness "a" increased by just 1 cm. Same reflector sizes

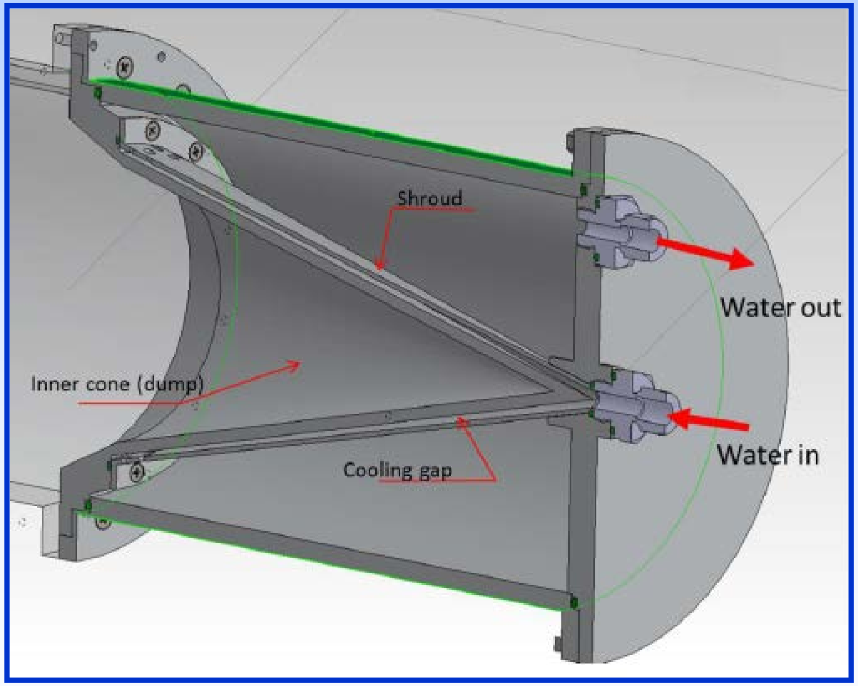
SLOWNE

Thick (beam stopping) W-target for high neutron intensity applications.
The target is designed to handle full SPES power (50 kW).

Idea of J. Esposito (LNL)



FARETRA W neutron converter cross sections

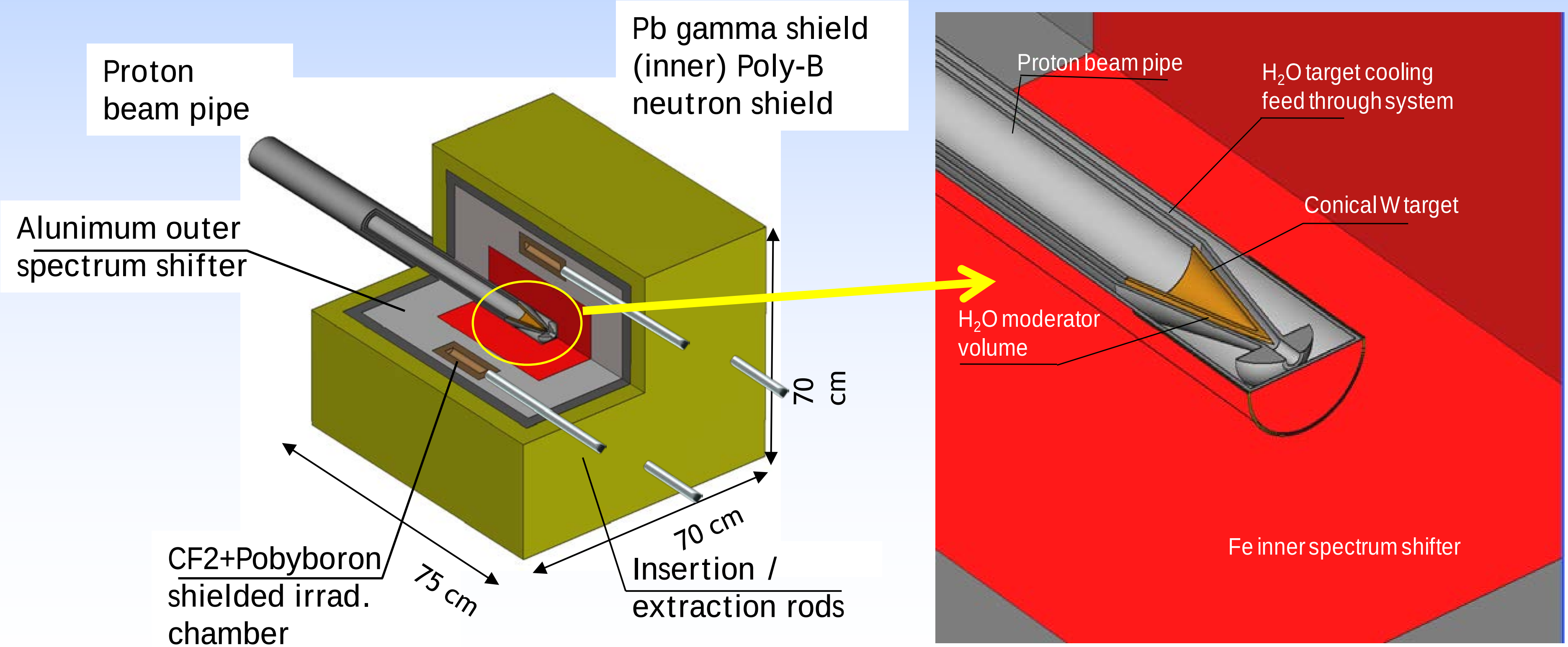


Based on the "Low" Power Beam Dump of IFMIF project

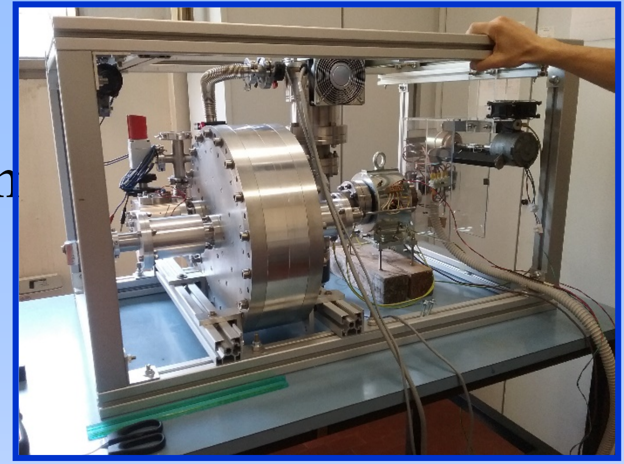
A moderator system is then used to shift the energy of the neutrons and shape the energy spectrum to resemble the desired one.

Examples of special applications:

1. **FA**st **RE**actor simulator for **TR**ansmutation studies (**FARETRA**)
2. Atmospheric neutrons effects (not only terrestrial atmosphere)
3. **research on moderators**
4. test novel ideas in neutron science techniques



CONCLUSION



- an **ANEM prototype** exists with an aluminum test disk and an **electron gun** system (under commissioning) for thermal tests ;

- the basic design of the **beam-optics** of ANEM and QMN are completed;

- SLOWNE on hold. Only feasibility studies the SLOWNE neutron production targets has been performed

- PROTON is on hold.

Our **present goal** is to **complete a technical design study** of the **whole LINUS facility (LSNS and NEPIR),** a necessary step to obtain approval and funding for the final executive design, before construction phase.

The end

Thank you for your attention

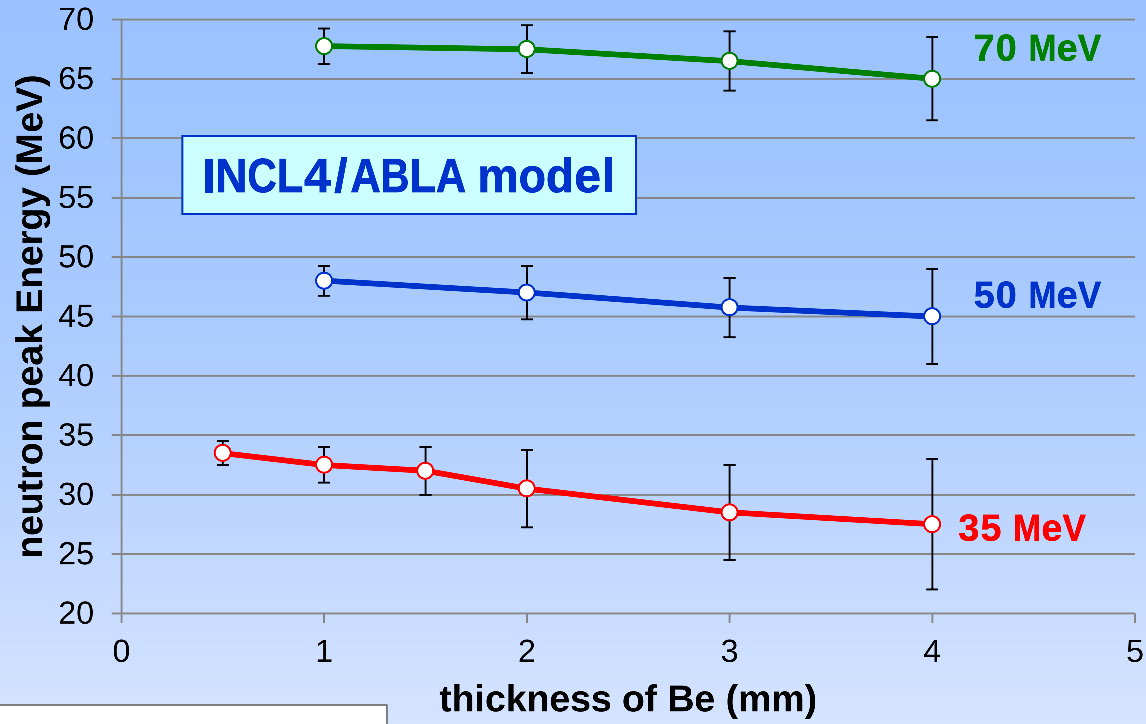
Extra slides follow

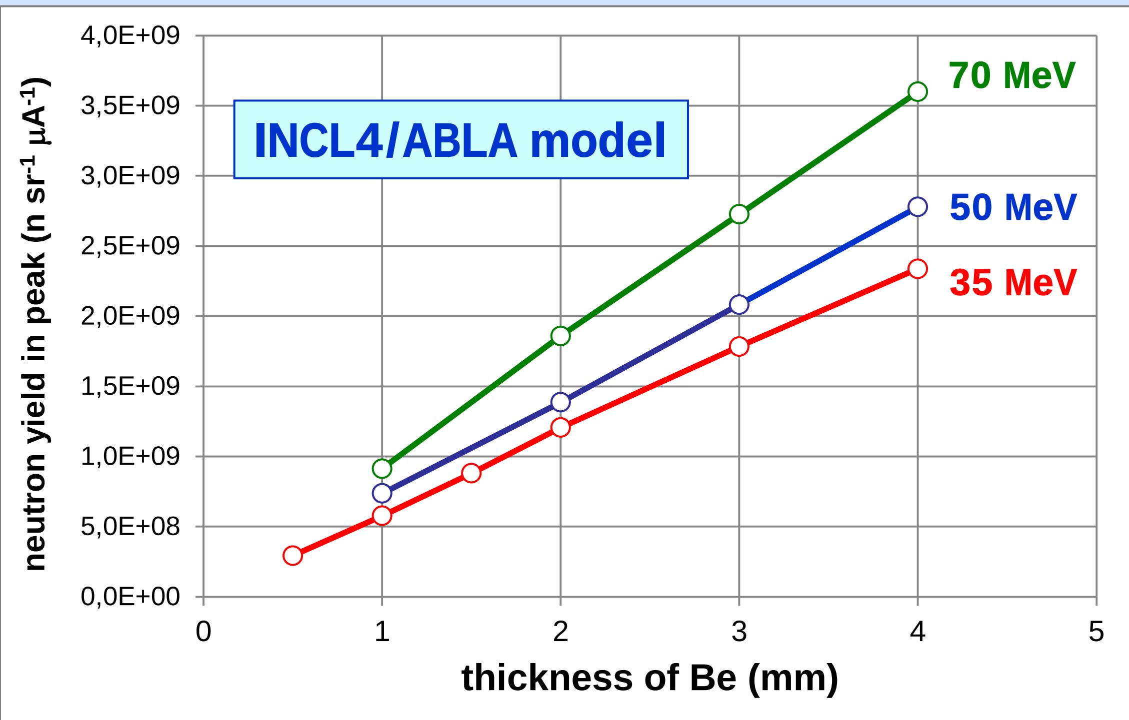
Extra slides

Forward (0^o) 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 $\pm$ FWHM/2

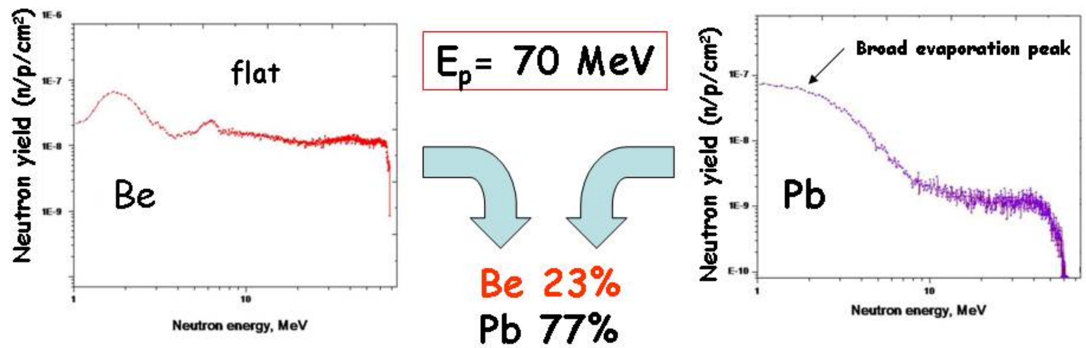




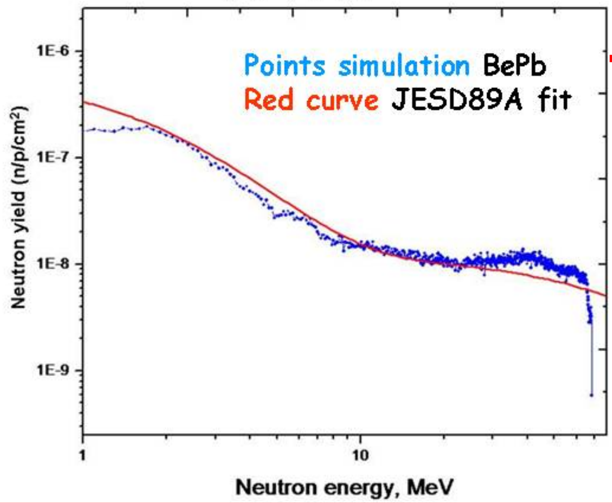
If the target is thin the neutron flux scales linearly with the thickness of the target (more nuclei).

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)

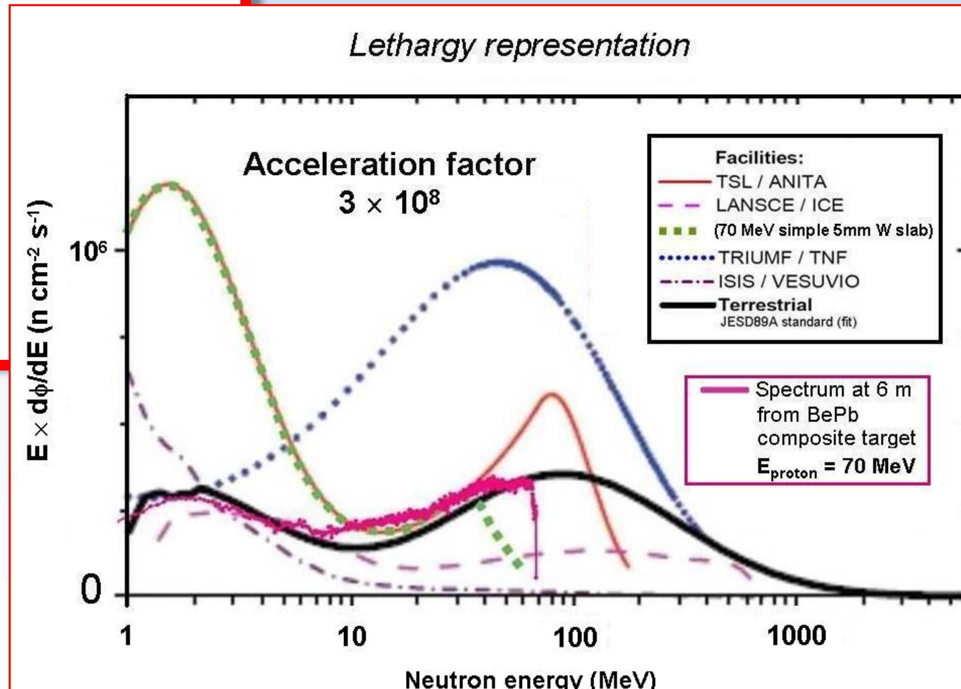


At 6m from target acceleration factor = 3×10^8 for $I_{protons}$ = 1 μA



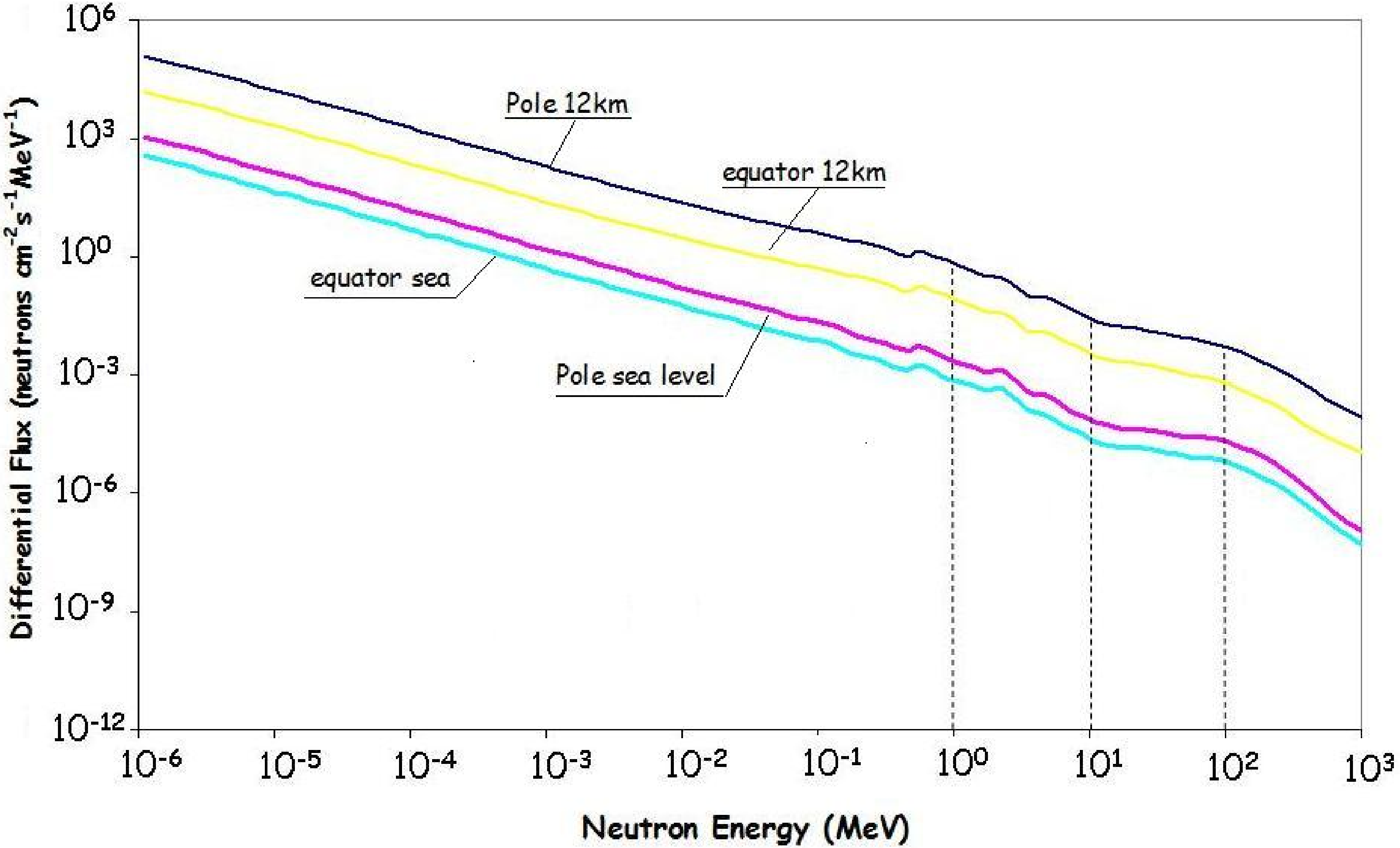
Fast neutrons!
No moderators

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

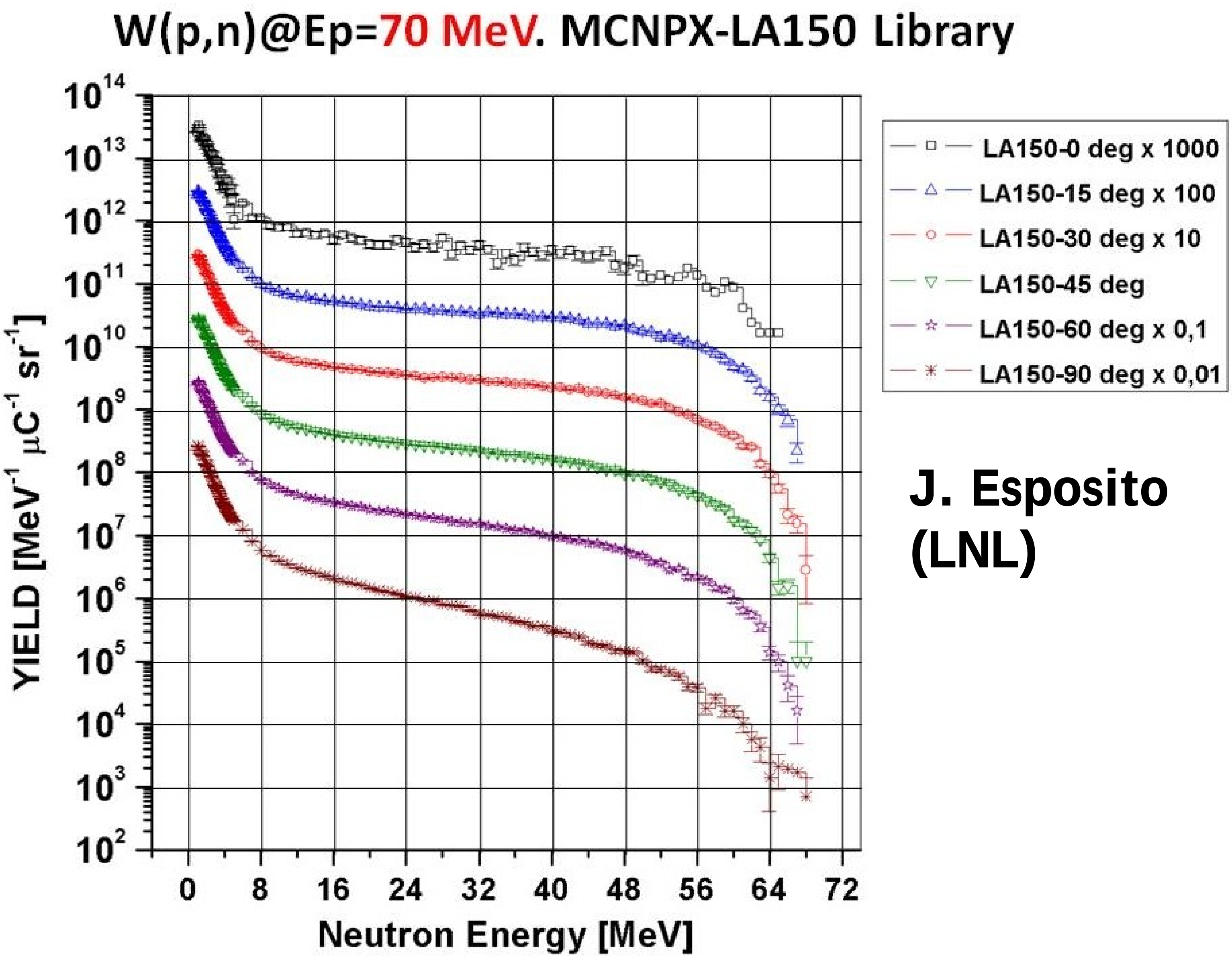


Acceleration factors of few 10^9 can be achieved with few tens of μA

Neutrons produced in the atmosphere



The SLOWNE 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.

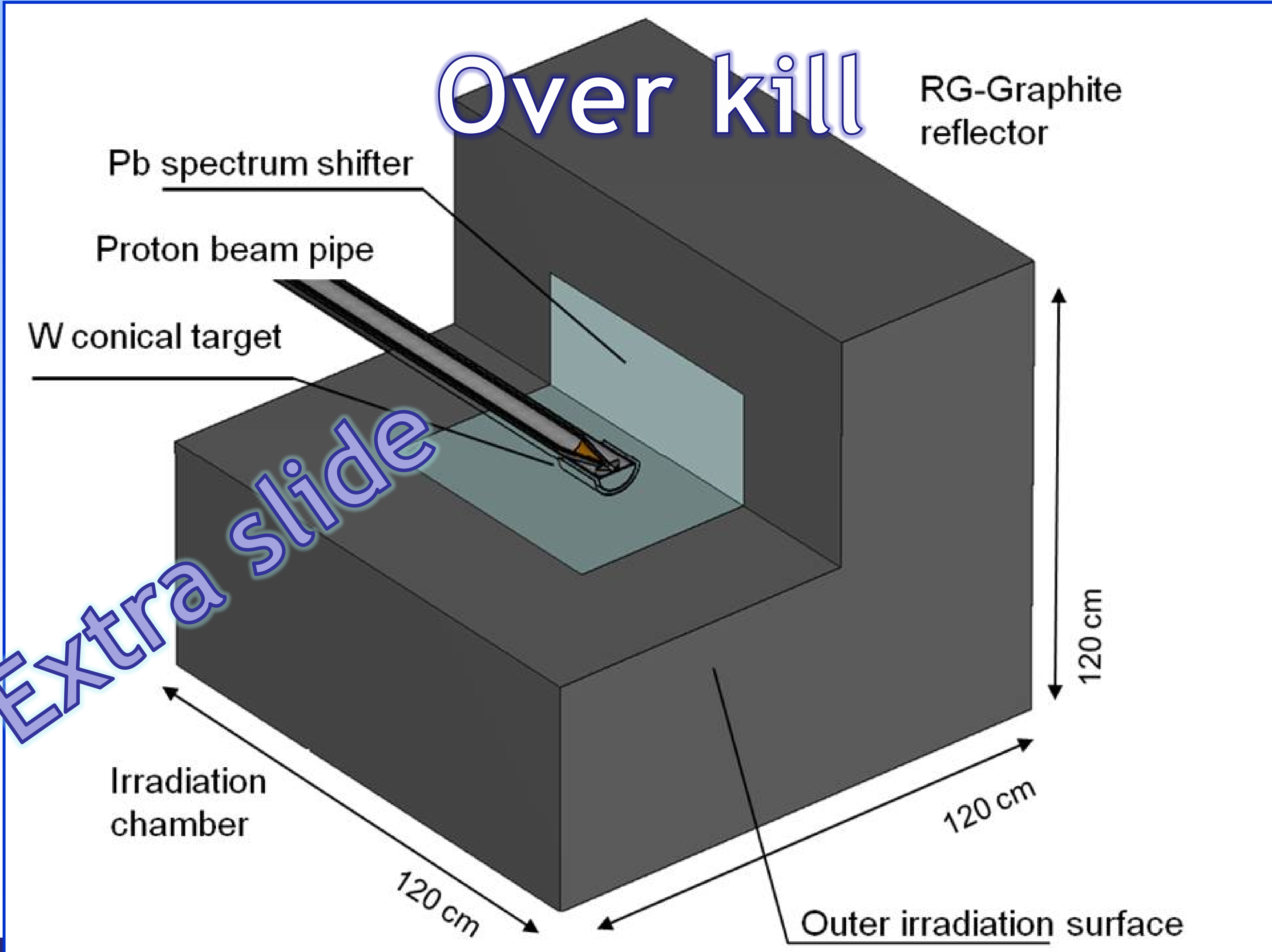


J. Esposito (LNL)

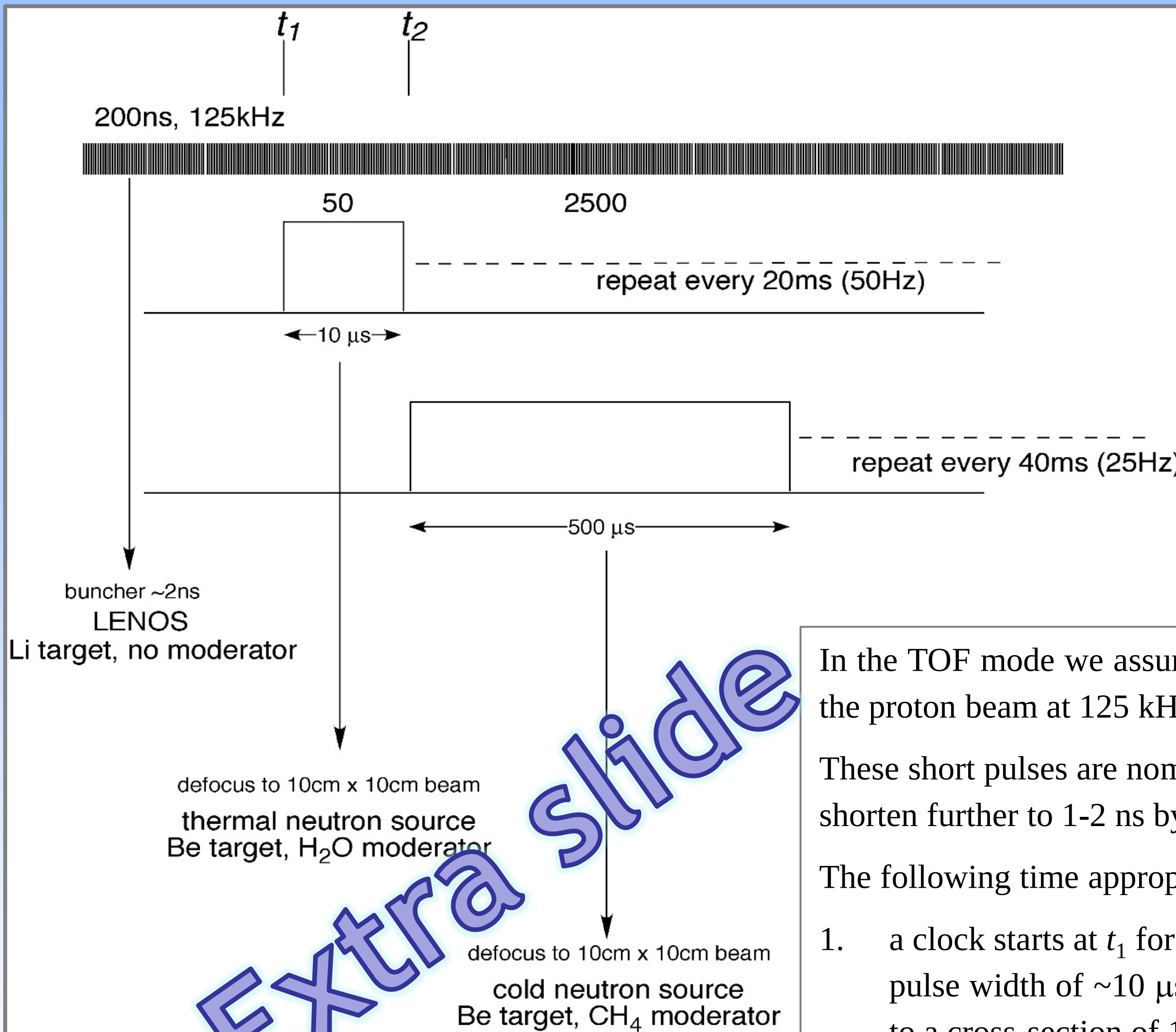
Preliminary system for atmospheric neutrons

Over kill

Extra slide



Proton beam Pulse and Selection Distribution Station



A conceptual scheme of distribution of proton pulses of different time structures to the epithermal-, thermal- and old neutron applications. The time axes are not in scale, numbers are ballpark figures.

In the TOF mode we assume a **chopper, upstream of the RFQ**, will pulse the proton beam at 125 kHz with a pulse width (FWHM) of ~200 ns.

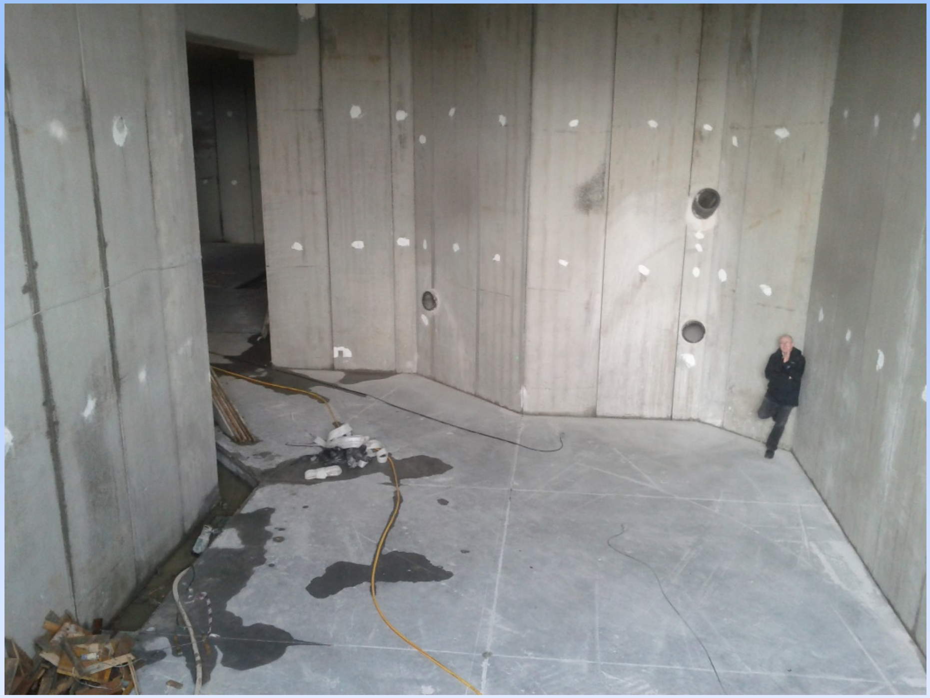
These short pulses are nominally delivered to the LENOS target station and shorten further to 1-2 ns by a **buncher**.

The following time appropriation takes place:

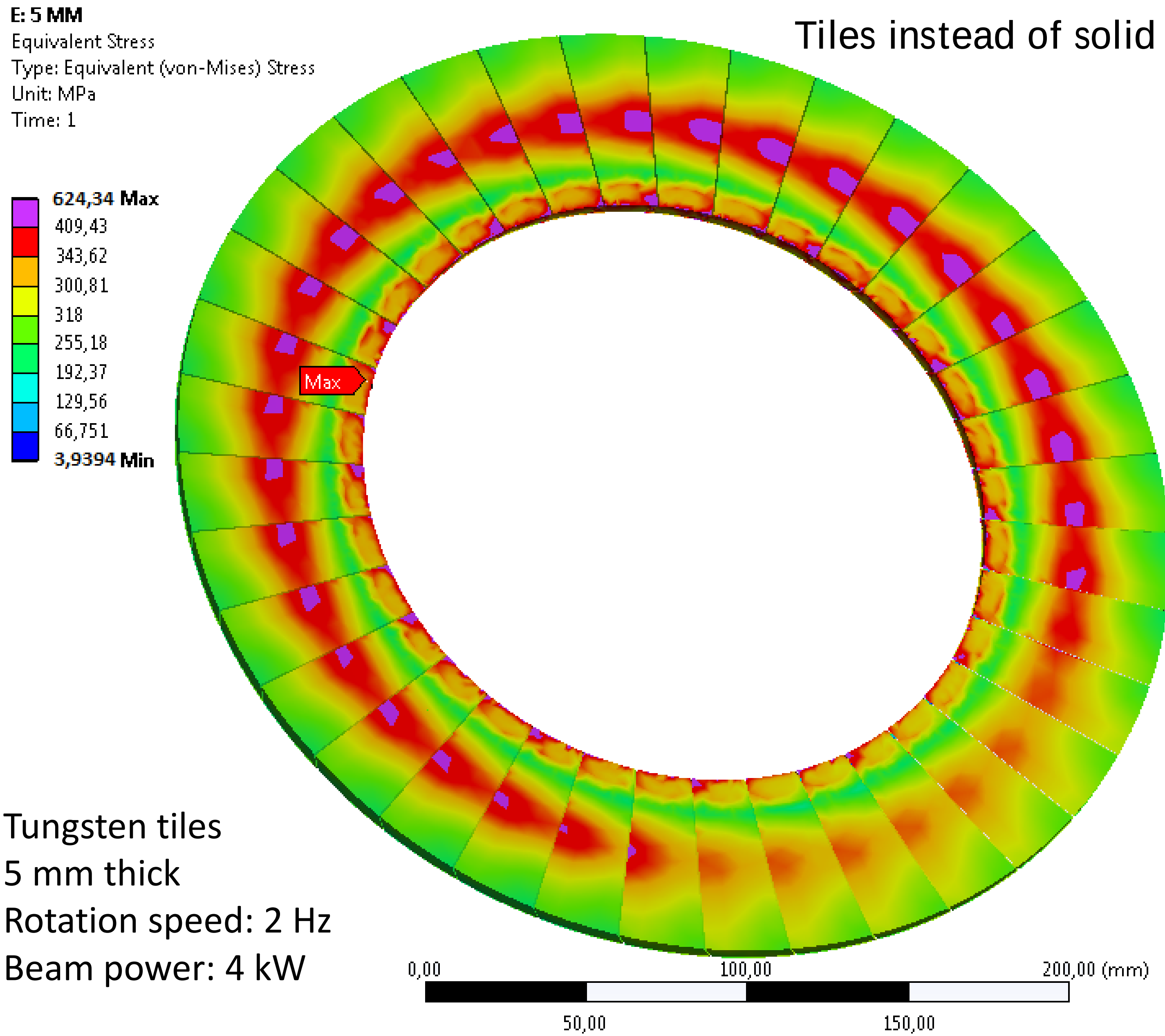
1. a clock starts at t_1 for the accumulation of the short pulses to achieve a pulse width of ~10 μs in conjunction with the defocusing of the beam to a cross-section of 10cm x 10cm.
2. Afterward this proton pulse is delivered to TNTS. This process is to repeat every 20 ms so as to enable a short pulse (SP) neutron source running at 50 Hz.
3. After each SP the clock starts at t_2 to accumulate a long pulse (LP) of ~500 μs width, defocused, then to feed the CNTS. This process repeats every 40 ms for a LP cold neutron source running at 25 Hz.

The **LSNS suite** will be useful for the widest scientific community possible, making it unique in Italy and very useful for European research, both applied, industrial and basic.

It will lead a class of ABC **Neutron Sources** to replenish the neutron capacity surrendered by the retired reactor sources.



Tiles instead of solid disk



Tungsten tiles
5 mm thick
Rotation speed: 2 Hz
Beam power: 4 kW

LSNS is a green-field (no constraints) project

GOAL: ensure an expansive neutron R&D landscape and a thriving community of neutron users.

By optimizing key elements:

- High brilliance and compactness;
- beam-line and user station layout;
- synergy in conjunction with
  - **user engagement (involved in design, construction, management,…)**
  - **international collaborations**
  - **attendant by assets at LNL and Italian Universities (Padova**,…)

…. LSNS can quickly become the world's first cost-effective ABC NS to serve users across different fields and disciplines:

- nuclear science,
- experimental nuclear astrophysics,
- materials research,
- life sciences,
- medical therapy,
- nuclear instrumentation,
- cultural heritage
- Education (e.g. training new generations).

Interest

QMN fields with E_n > 20 MeV (maybe lower) 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, industry and research facilities, 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);

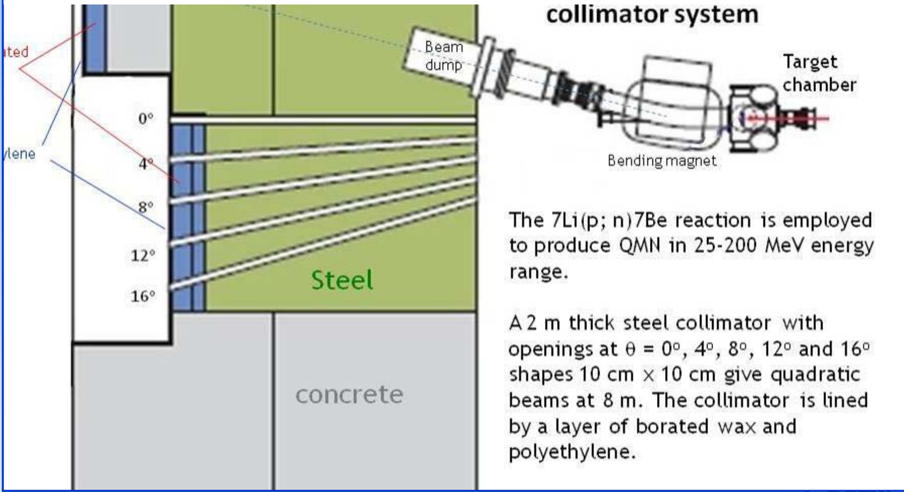
• radiation physicists (studies for: fast neutron treatments; modeling of exposure of patients to secondary neutrons at proton accelerators; bench-mark shielding experiments).

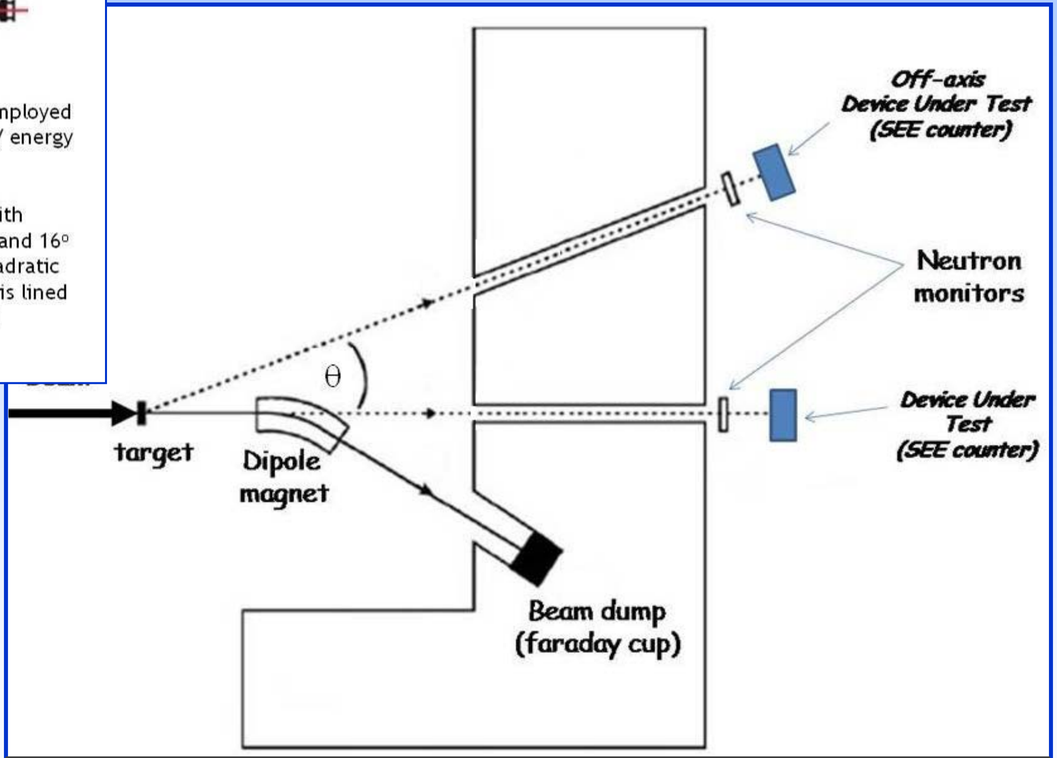
Luca Silvestrin luca.silvestrin@unipd.it

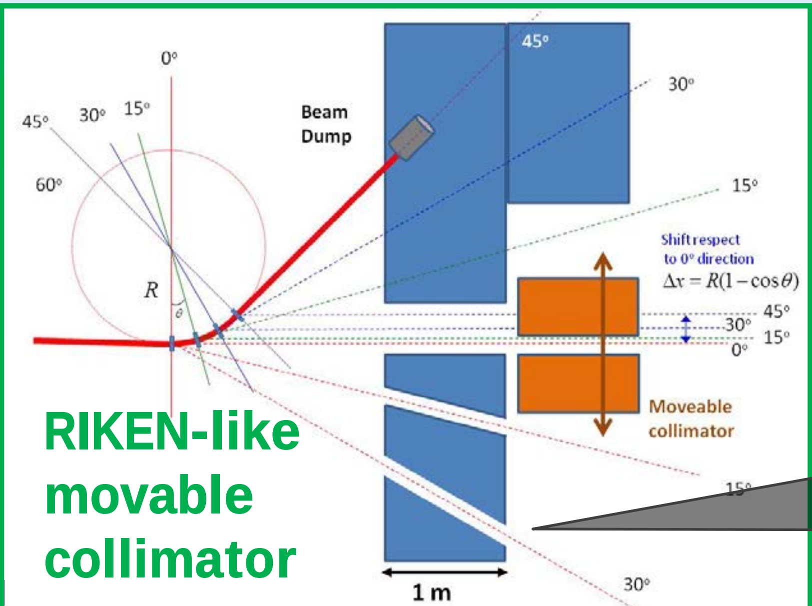
"Wrong-energy tail" **correction**

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).

i-Themba multi-angle collimator







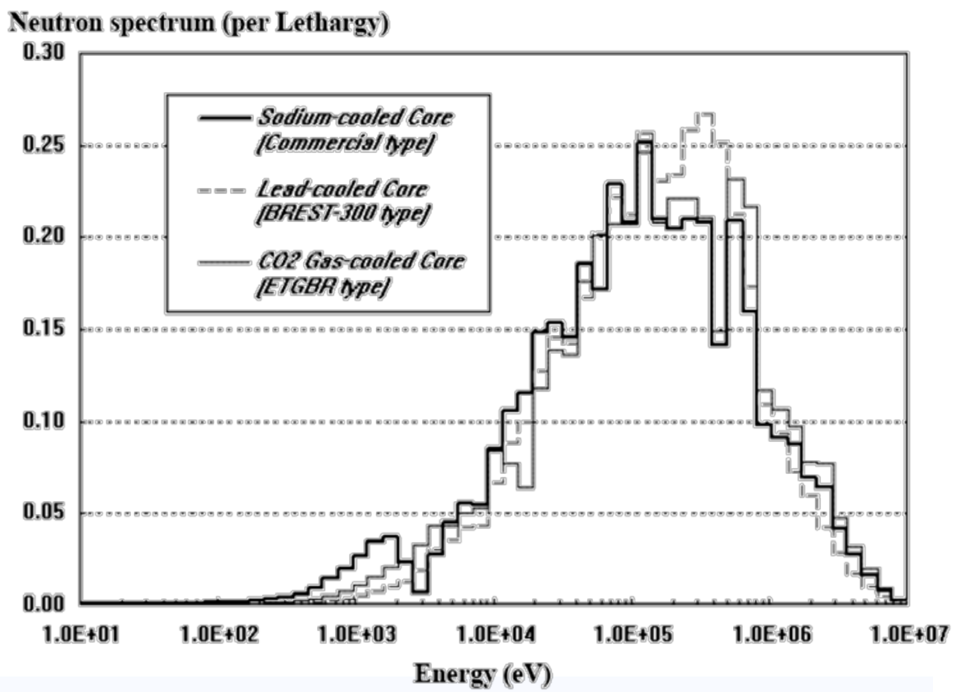
RIKEN-like movable collimator

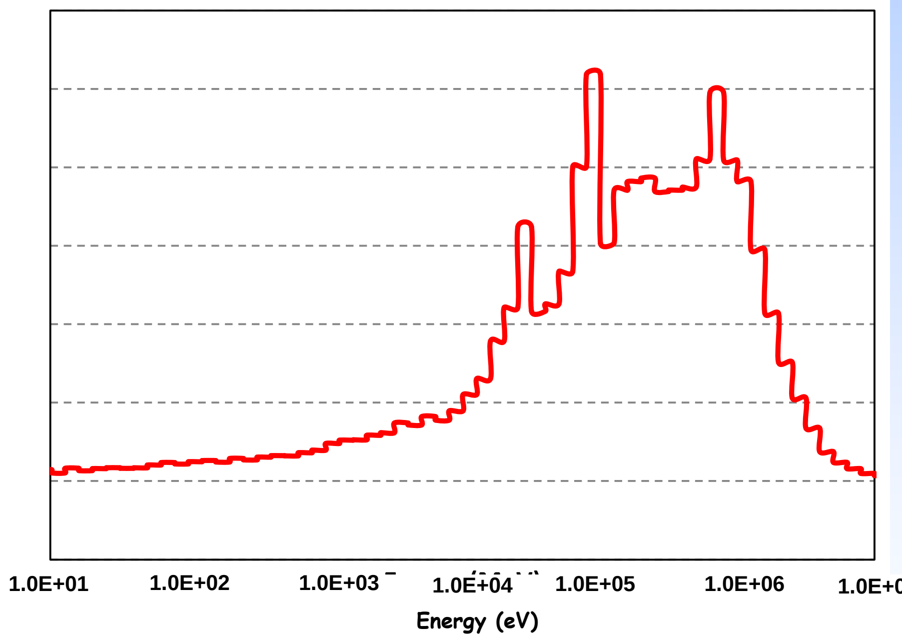
- data can be taken simultaneously at 0º and one or two standard angles (say 15º and 30º)
- flexibility for intermediate values
- but challenging to design magnet/target system

Neutron spectrum inside irradiation chamber MCNPX calculation results

"Accelerator-driven Systems (ADS) and Fast Reactors (FR) in Advanced Nuclear Fuel Cycles: A comparative study" NEA-OEDC, 2002

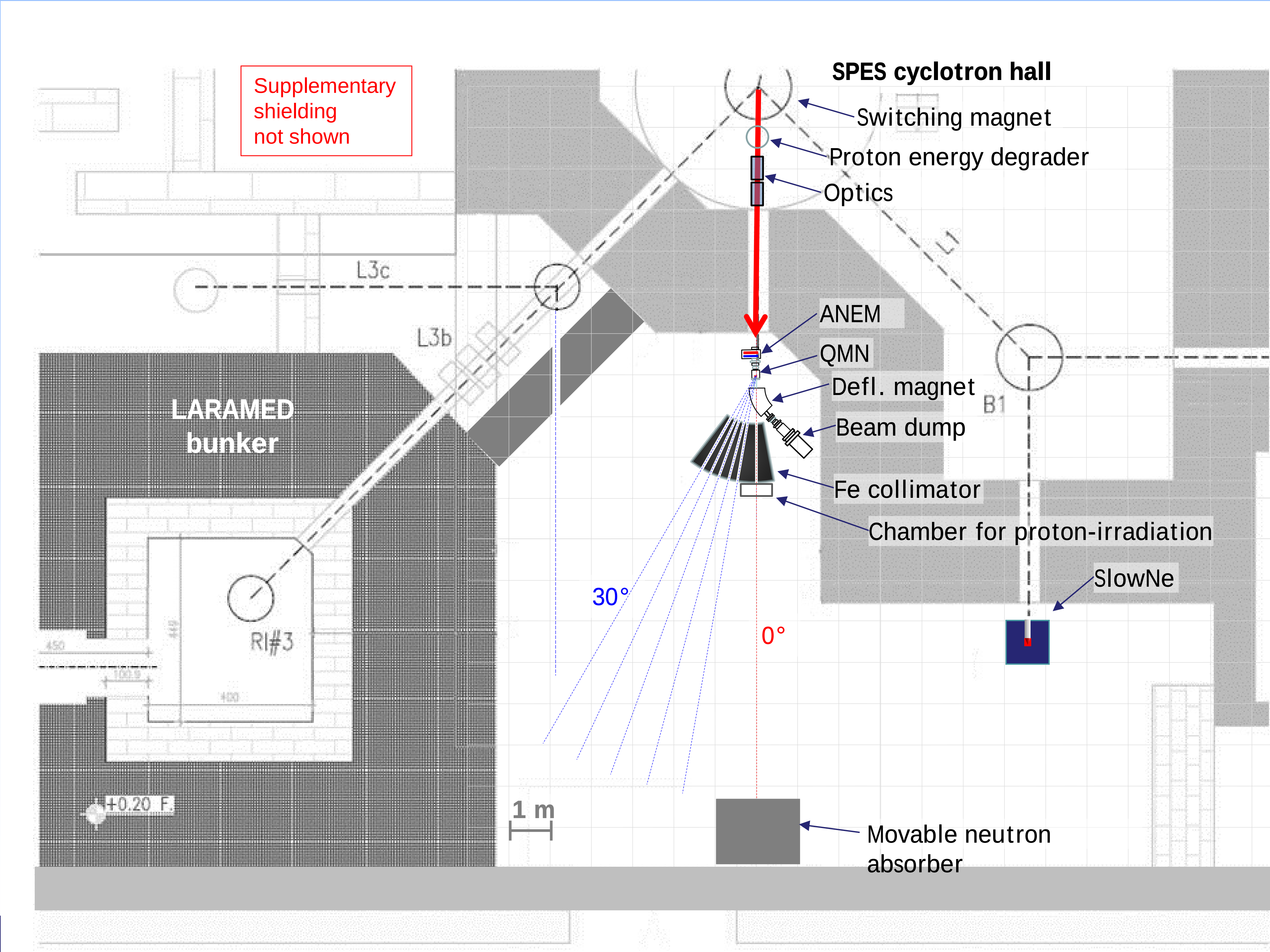
FARETRA facility, MCNPX simulated spectrum





Results of simulation: Moderation Efficiency (10 eV−10 MeV) : ~ $5 \cdot 10^{-4}$

Integral neutron flux: Φ_n= ~ $1.0 \cdot 10^{11}$ cm^{-2} s^{-1}

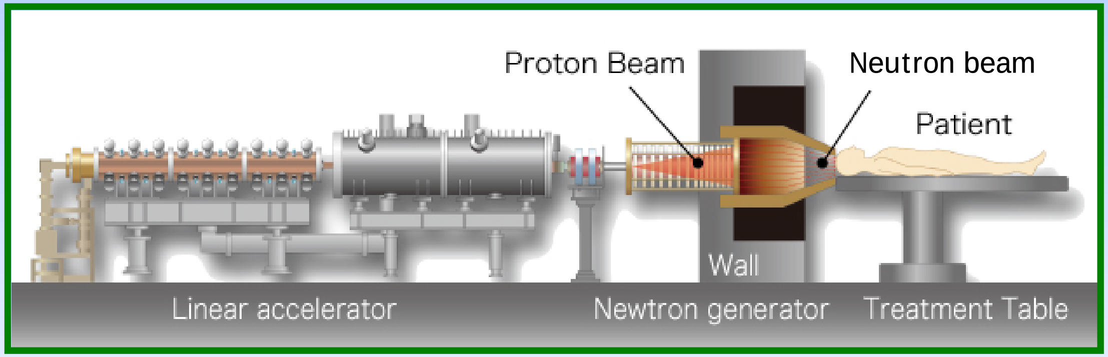


Supplementary shielding not shown
SPES cyclotron hall
Switching magnet
Proton energy degrader
Optics
L1
L3c
L3b
ANEM
QMN
Defl. magnet
B1
Beam dump
LARAMED bunker
Fe collimator
Chamber for proton-irradiation
SlowNe
30°
0°
RI#3
+0.20 F.
1 m
Movable neutron absorber

"Compact" Accelerator-driven Neutron Sources (CANS)

Non-spallation-based

- CANS have shown promising capabilities in bridging the **capacity insufficiency** and the **expanse of cross-disciplinary neutron applications**. ☺



Typical BNCT system

LNL SPES 70 MeV proton cyclotron

- NOTE! However, the majority of CANS are **not new**.

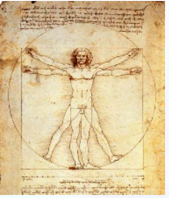
  In addition many originated as proof-of-principle demos at existing accelerator systems where **the infrastructure for a broad and growing range of applications under variant configurations was never anticipated**. 😐 ⟶ ☹

LINUS and its two parts:

1) Legnaro Slow Neutron Source (LSNS): a *state-of-the-art* **A**ccelerator driven, **B**rilliant, and **C**ompact **N**eutron **S**ource (**ABC NS**). It will deliver **cold**, **thermal,** and **epithermal** neutrons.

2) NEutron and Proton Irradiation facility (NEPIR): driven by the high power SPES 35-70 MeV proton cyclotron, it will consist of four subsystems:

I. **QMN**: quasi mono-energetic neutrons in the (20)35-70 MeV range
II. **ANEM**: *atmospheric-like* neutrons in the 1-70 MeV range
III. **SLOWNE**: special applications “slow/medium/fast” neutron beam line
IV. **PROTON**: direct protons (20)35-70 MeV)

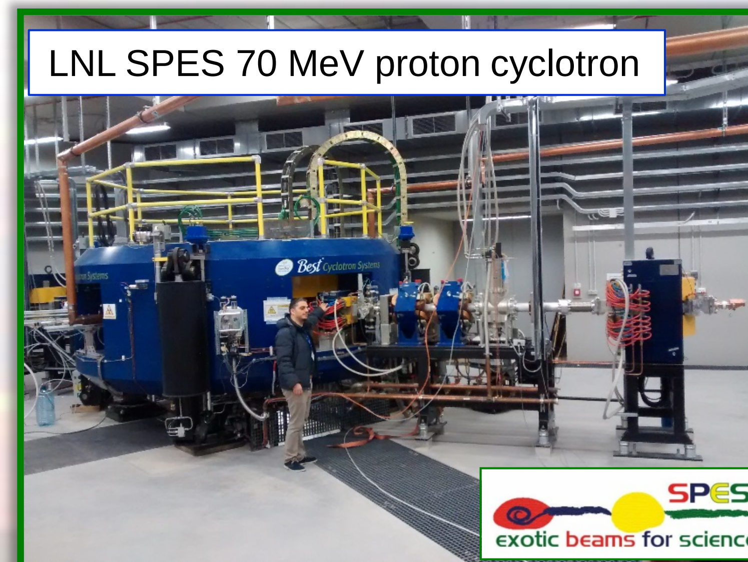


Practical **general-purpose neutron facilities** are of two types:

1. **research reactors** (fission reactions)
2. **accelerator-driven sources** (non-fission nuclear reactions)
   a. **Large High-energy accelerator spallation sources**
   b. **Compact low energy accelerators (non-spallation sources: CANS "Compact" Accelerator-driven Neutron Sources)**

LNL 5 MeV, 30 mA proton RFQ

LNL SPES 70 MeV proton cyclotron



- LINUS program foresees a low energy non-spallation source and a higher energy mixed source.

LSNS is a green-field (no constraints) CANS project

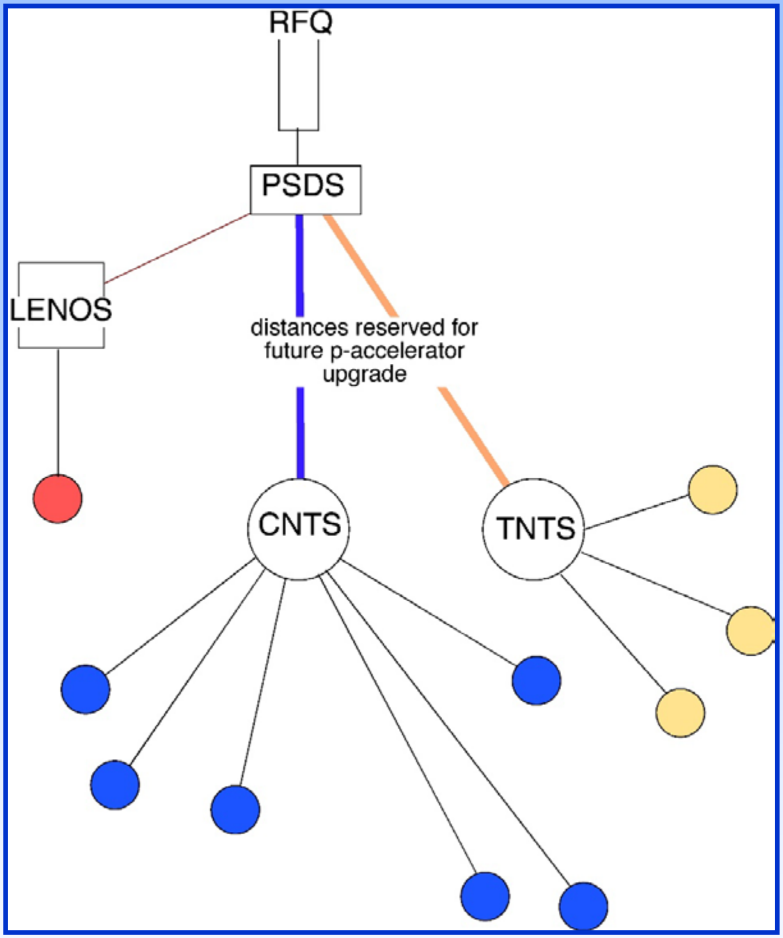
GOAL: ensure a healthy expanding neutron R&D landscape and a thriving community of neutron users.

By optimizing key elements LSNS can quickly become the world's first <u>cost-effective</u> ABC NS to serve users across different fields and disciplines:

- ❑ Compactness and high brilliance;
- ❑ Smart beam-line and user stations layout;
- ❑ Synergy in conjunction with
  - **present assets at LNL, INFN labs and Italian Universities**
  - **international collaborations**
  - **user engagement (concept, design, construction, management,…)**

- nuclear science,
- experimental nuclear astrophysics,
- materials research,
- life sciences,
- medical therapy,
- nuclear instrumentation,
- neutron instruments for spectrometric and dosimetric characterization of neutron fields,
- cultural heritage,
- Education (e.g. training new generations),
- fundamental physics (ultracold neutrons).

Conceptual layout of LSNS



- **Proton beam PSDS**
  (Pulse and Selection Distribution Station)

- **CNTS** (Cold Neutron Target Station)
  - Be target
  - Cryogenic moderator solid methane
  - Reflector (graphite or water)
  - Up to 6 ports to experimental halls

- **TNTS** (Thermal Neutron Target Station)
  - Identical design to CNTS but with water at ambient temperature
  - Initially three ports

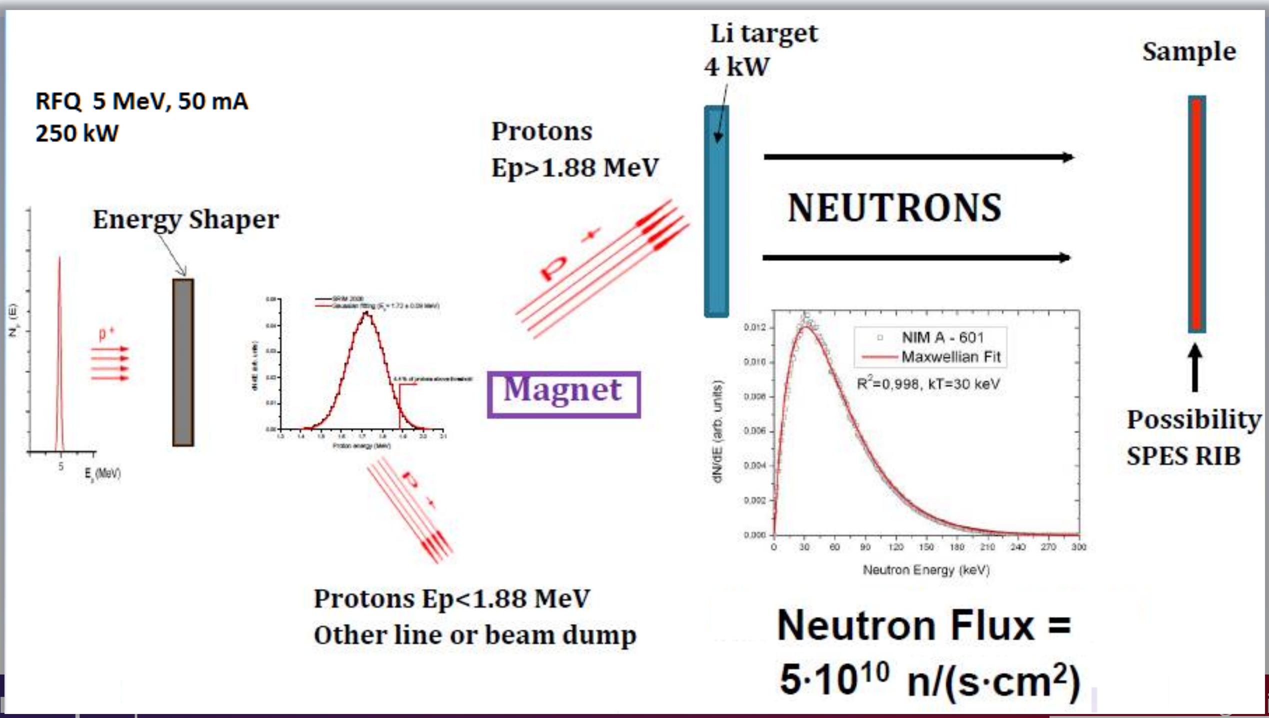
- LENOS (astrophysics)
- BNCT (oncologic research)

- Mild radioactivity by low-energy protons ($\leq$ 5 MeV)
- Modular structure
- **CW**, and both **Short Pulse (SP)** and **Long Pulse (LP)** options
- Cryogenic and gas handling systems for hydrogenous moderators

CNTS and TNTS are ideal for experimental validation of novel moderator systems

Maxwell-Boltzmann
Legnaro NeutrOn Source (LENOS)

- A neutron irradiation facility for nuclear astrophysics studies and data validation for energy and non-energy applications.
- Based on **pulsed** low energy high current 5 MeV, 50 mA proton beam of RFQ of LNL
- **Goal**: produce an unprecedented neutron flux, precisely shaped to a **Maxwell-Boltzmann energy distribution**.



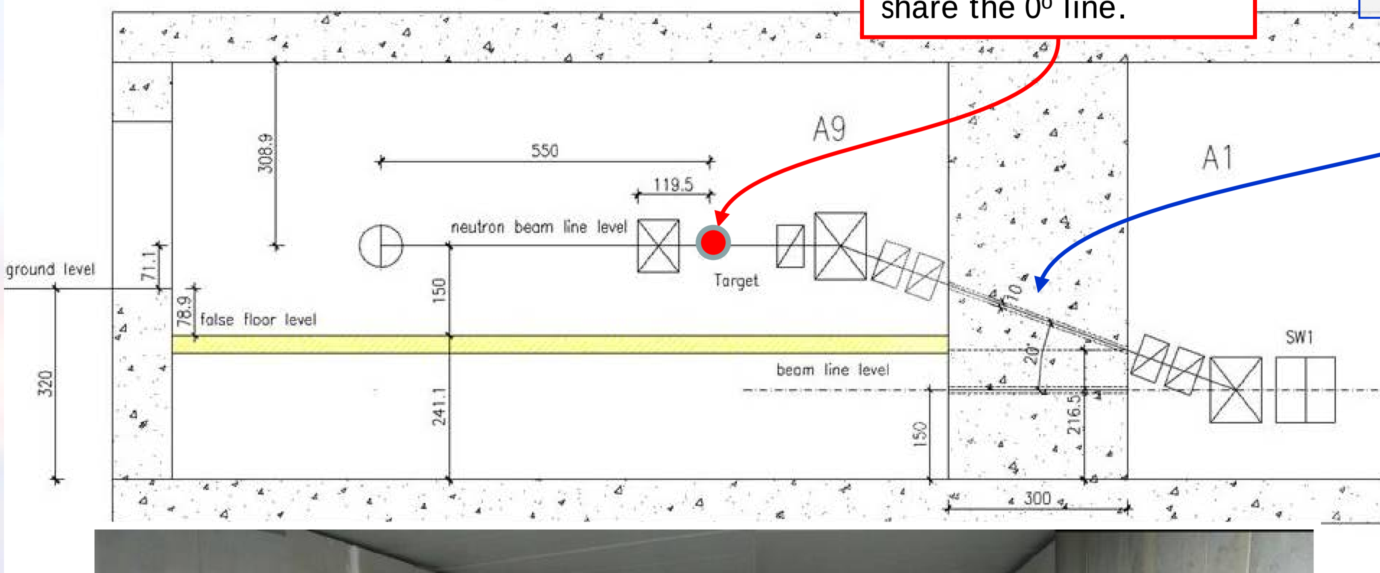
Courtesy:
P. Mastinu
(LNL)

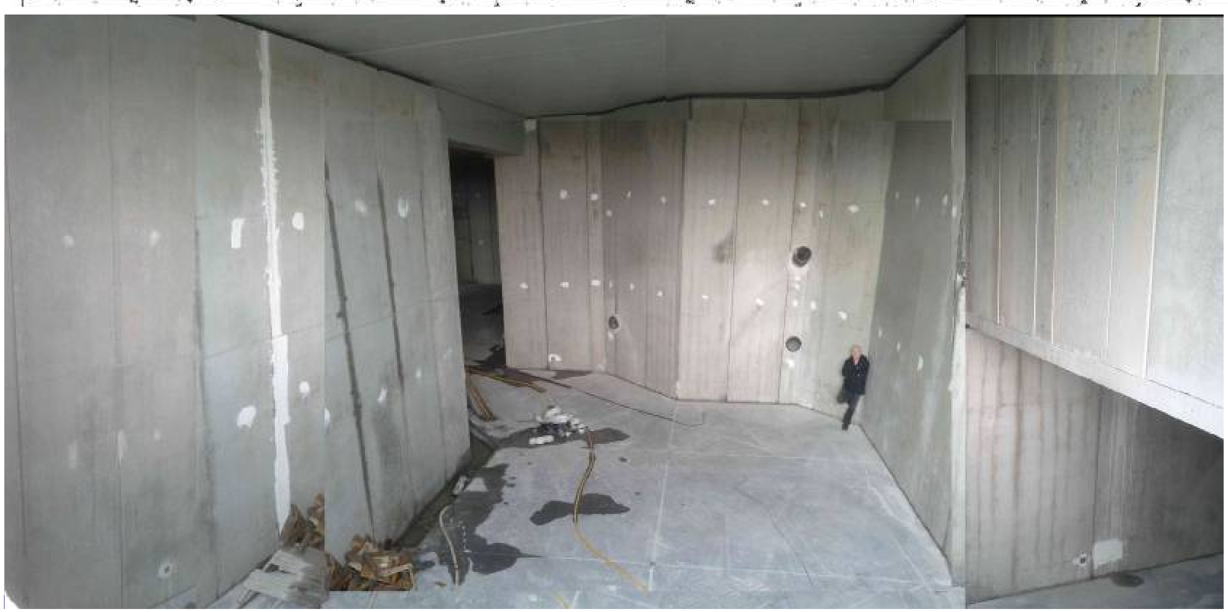
NEPIR chicane option

SPES hall A9, side view of the Fast Neutron Line (QMN+ANEM)

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

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





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.

SiRAD

SiRAD

SiRAD

SiRAD

SiRAD

SiRAD

SiRAD

SiRAD

SiRAD

SiRAD

SiRAD