SNRI

Seminario Nazionale Rivelatori Innovativi

Neutron Detectors, Status and Applications
part 2

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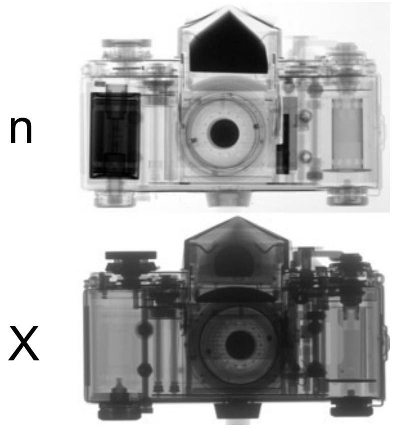
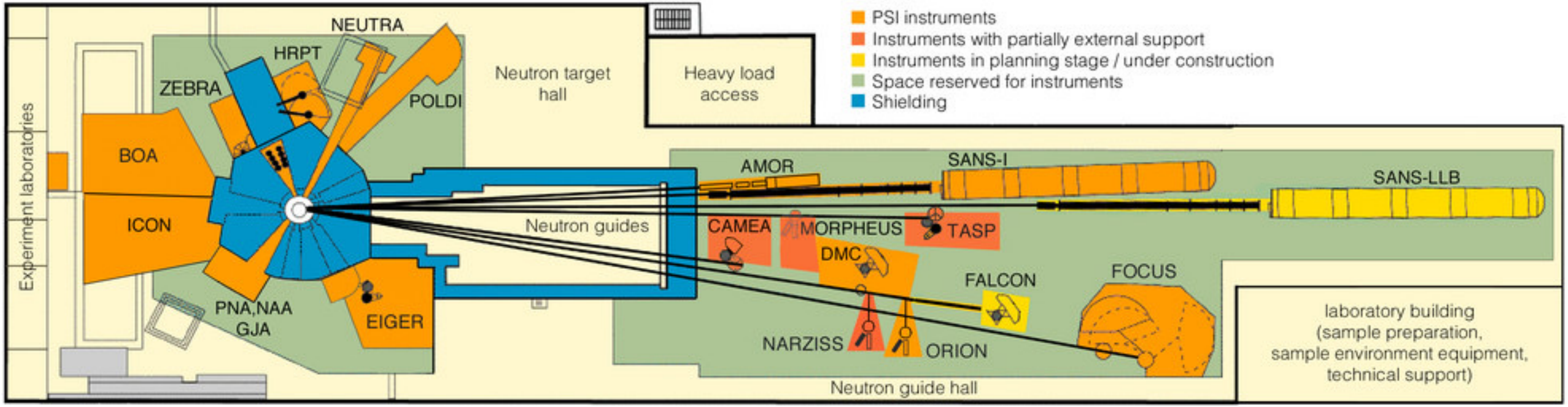


Absolutely non-exhaustive list of topics

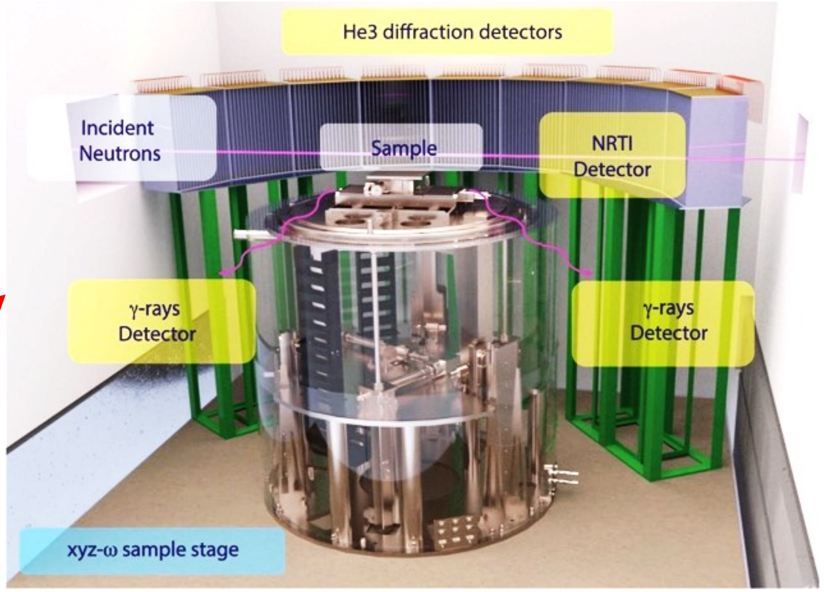
- Main neutron production facilities and instruments in Europe
- Application examples
- Boron and Lithium based detector examples

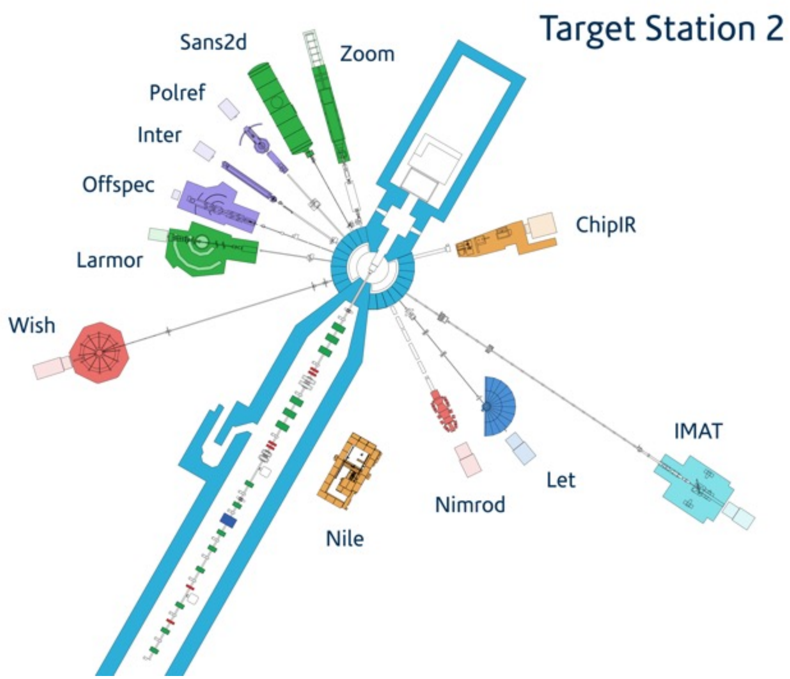
SINQ at PSI, Villigen, CH



Spallation Neutron Source

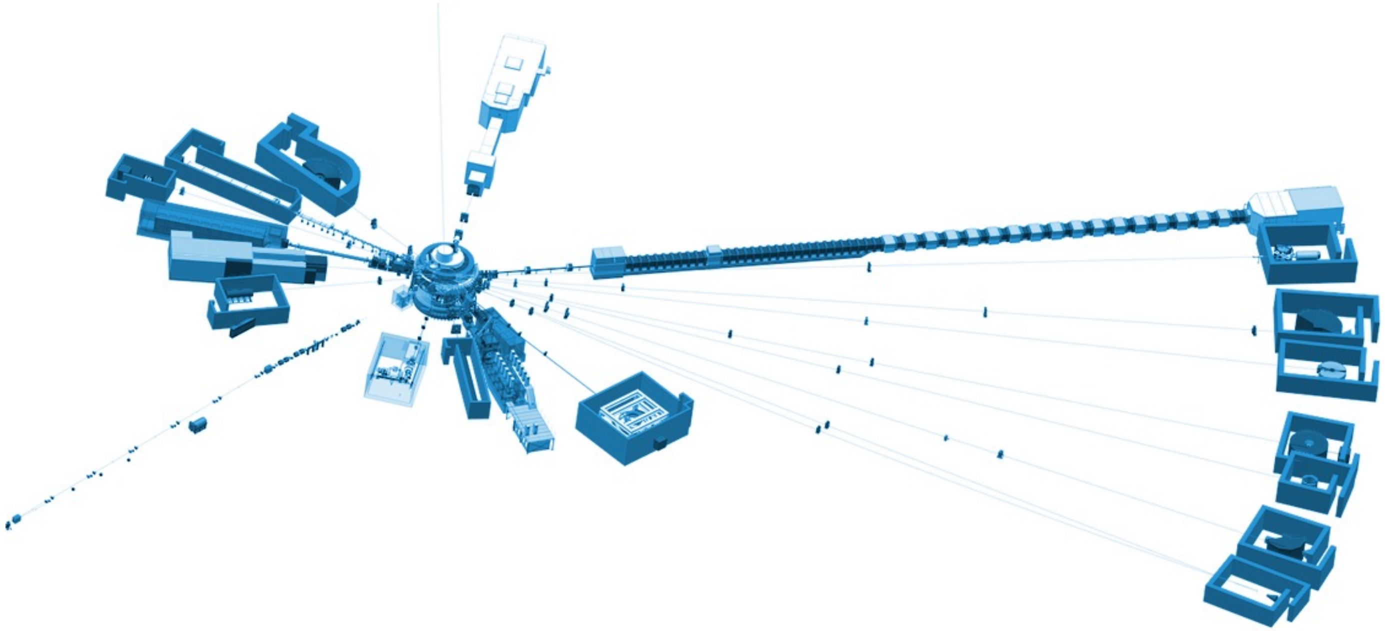
ISIS at DIAMOND, Didcot, UK

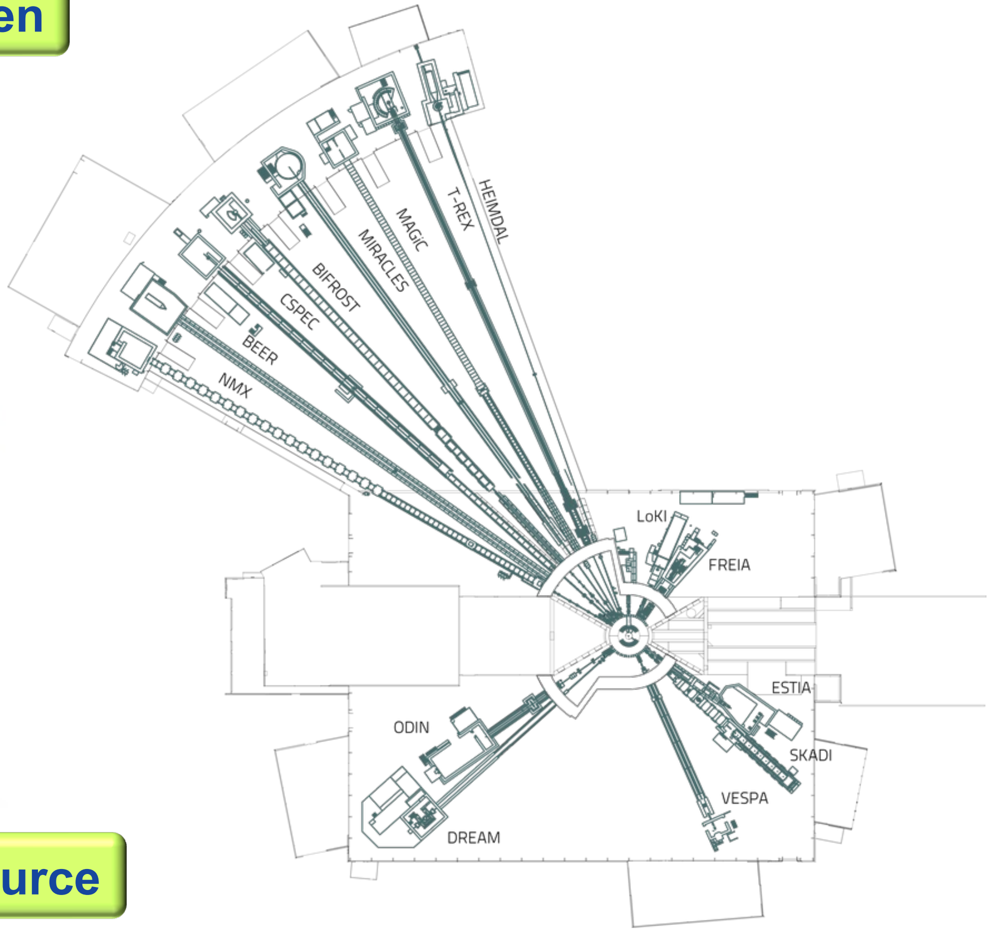




Spallation Neutron Source

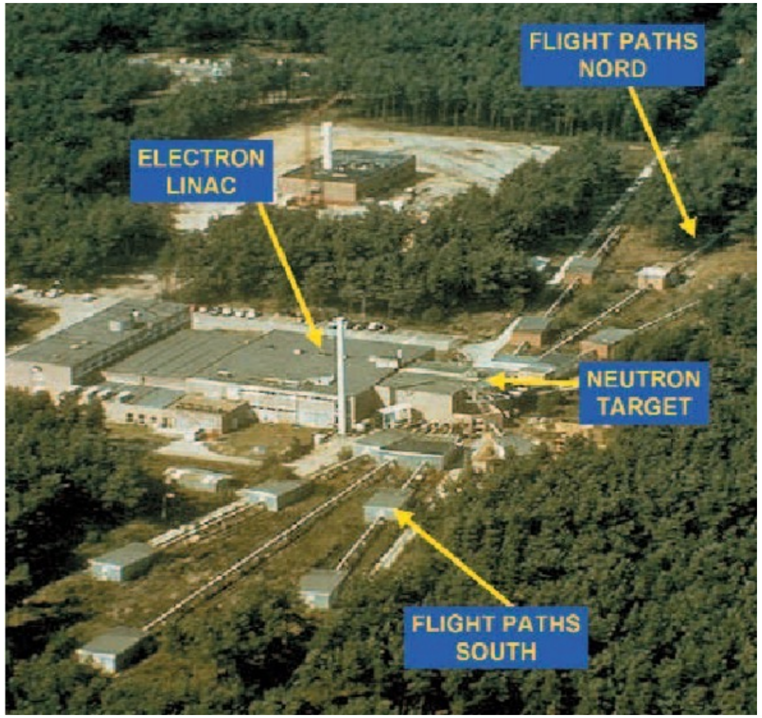
ESS at Lund, Sweden





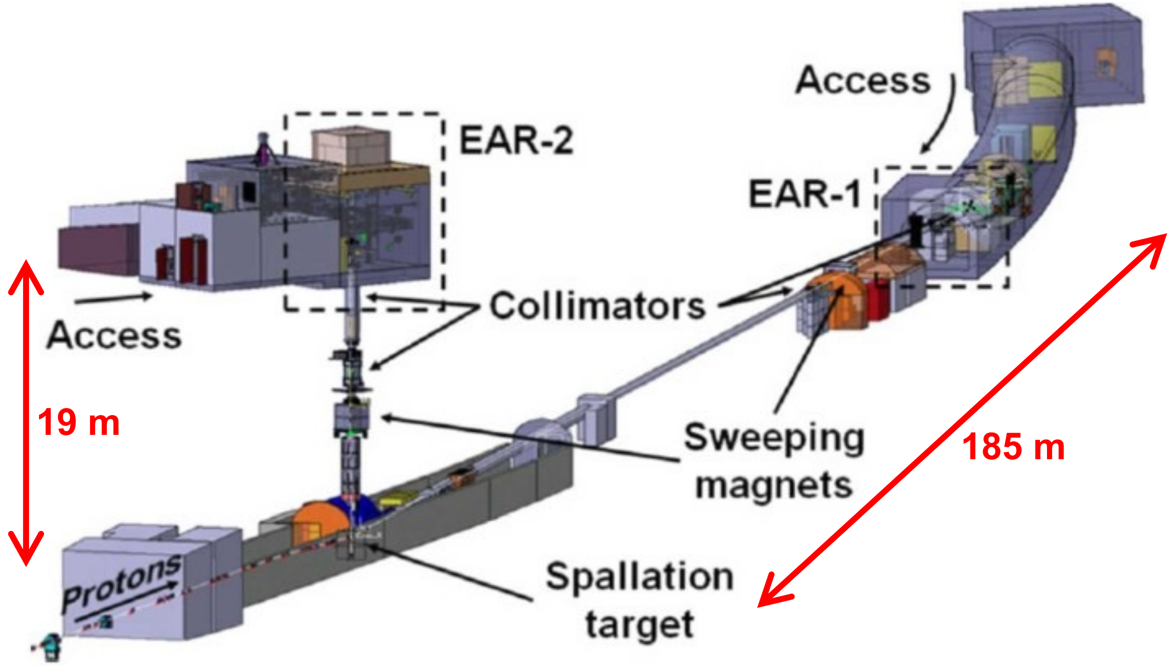
Spallation Neutron Source

GELINA at JRC Geel, Belgium



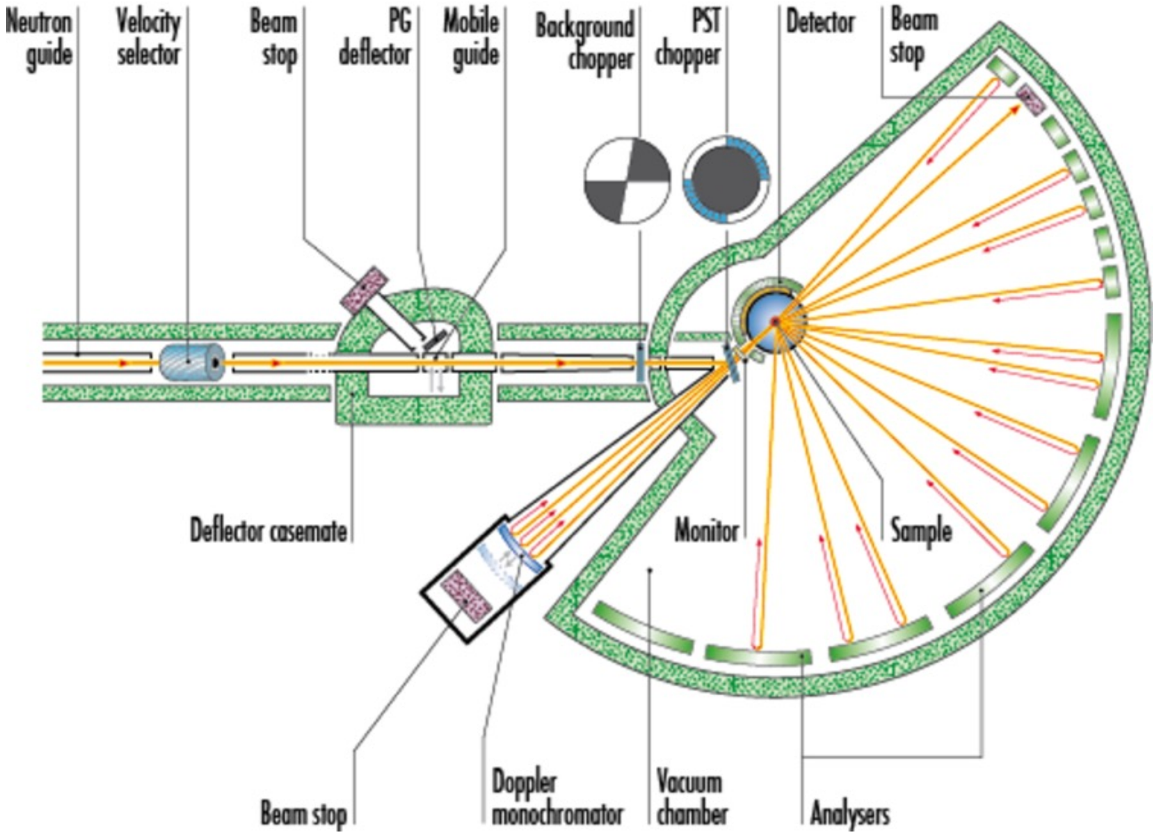
Photonuclear Neutron Production

n_TOF at CERN
almost totally devoted to nuclear physics



Spallation Neutron Source

ILL at Grenoble, France



Neutrons from fission reactors

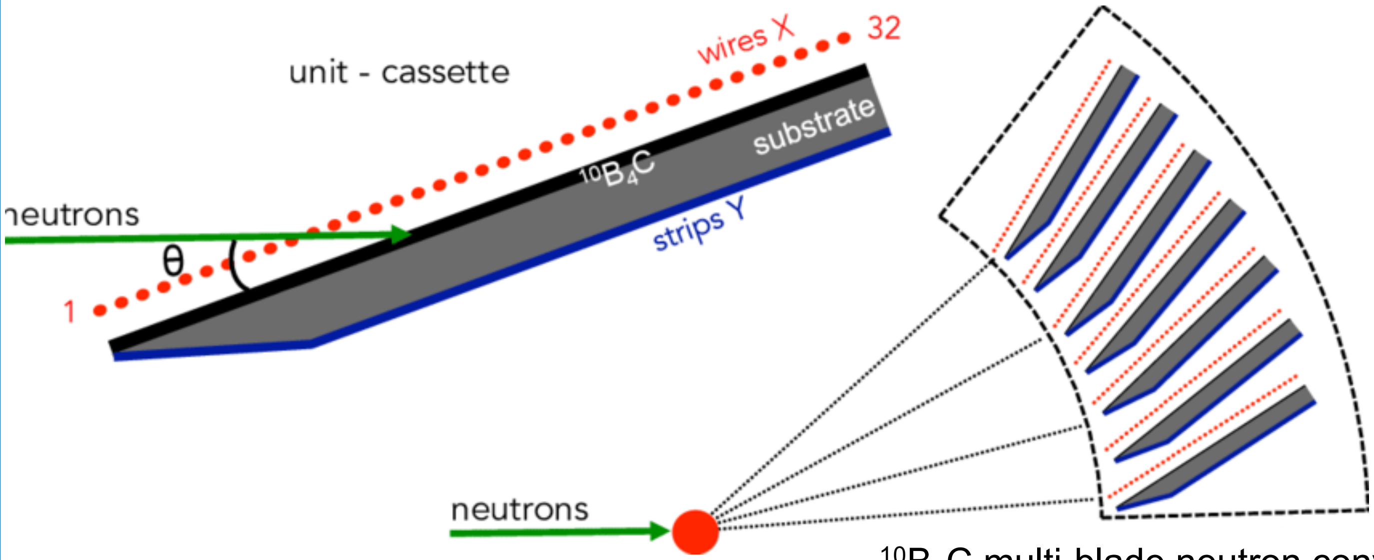
Instruments at neutron facilities

mostly large area gas detectors
multiwire gas chambers
based on ^3He and ^{10}B
in many different configurations

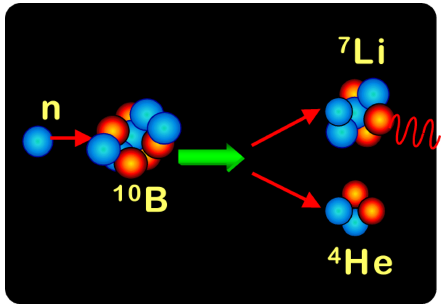
BF_3 gas forbidden almost everywhere
toxic
dangerous for the environment

^3He crisis: converter to be replaced

mostly ^{10}B or $^{10}B_4C$ solid converters
inside "standard" gas chambers



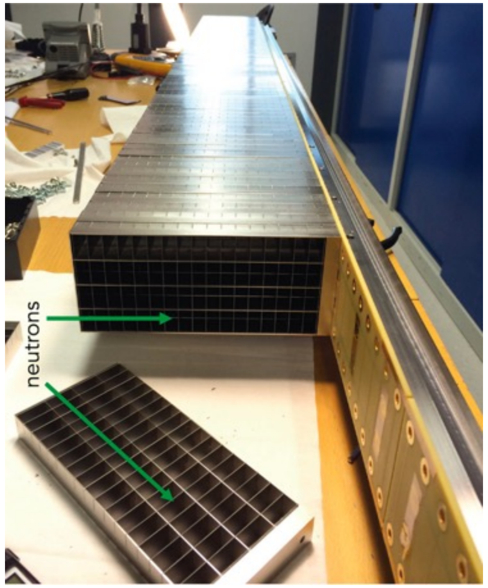
$^{10}B_4C$ multi-blade neutron converters

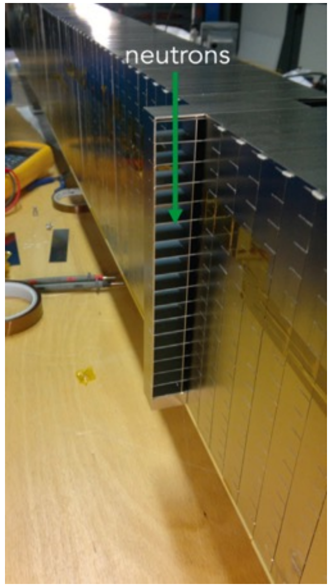


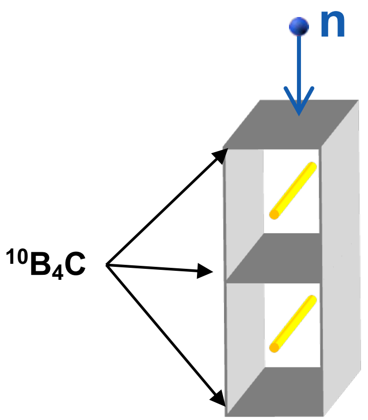
^{10}B lined straw tubes

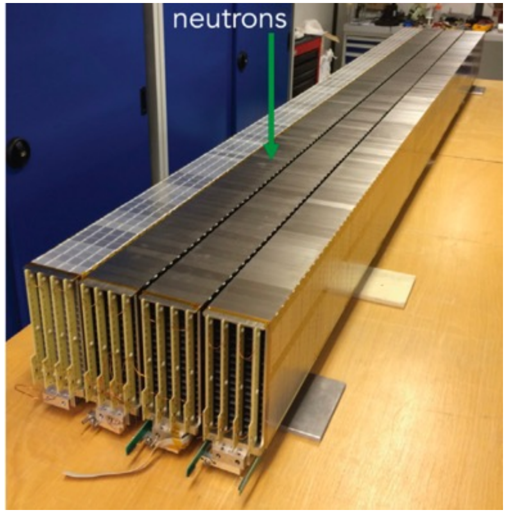
Instruments at neutron facilities

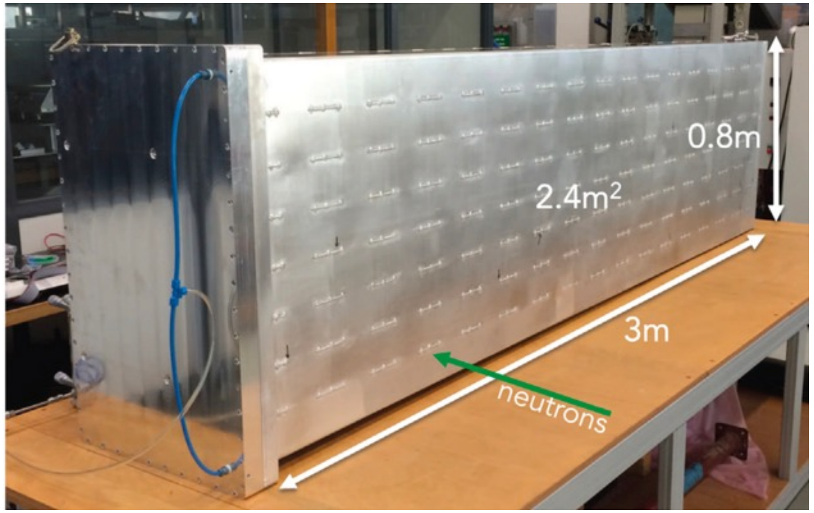
Multi-grid neutron gas chamber at ESS
stacks of blades lined with $^{10}B_4C$
inside rectangular cavities
with anode wires



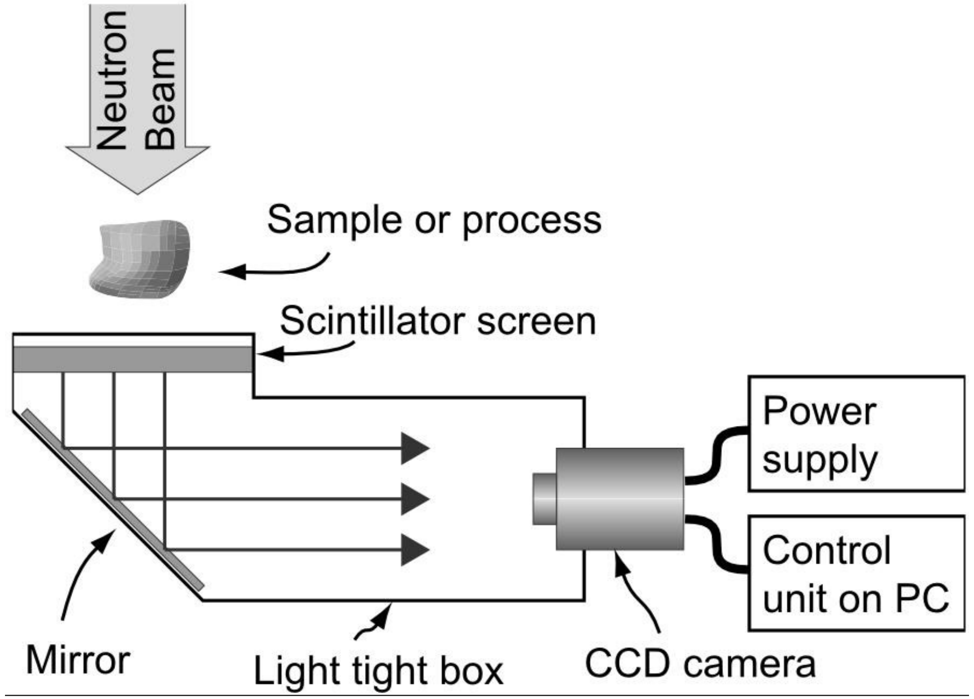


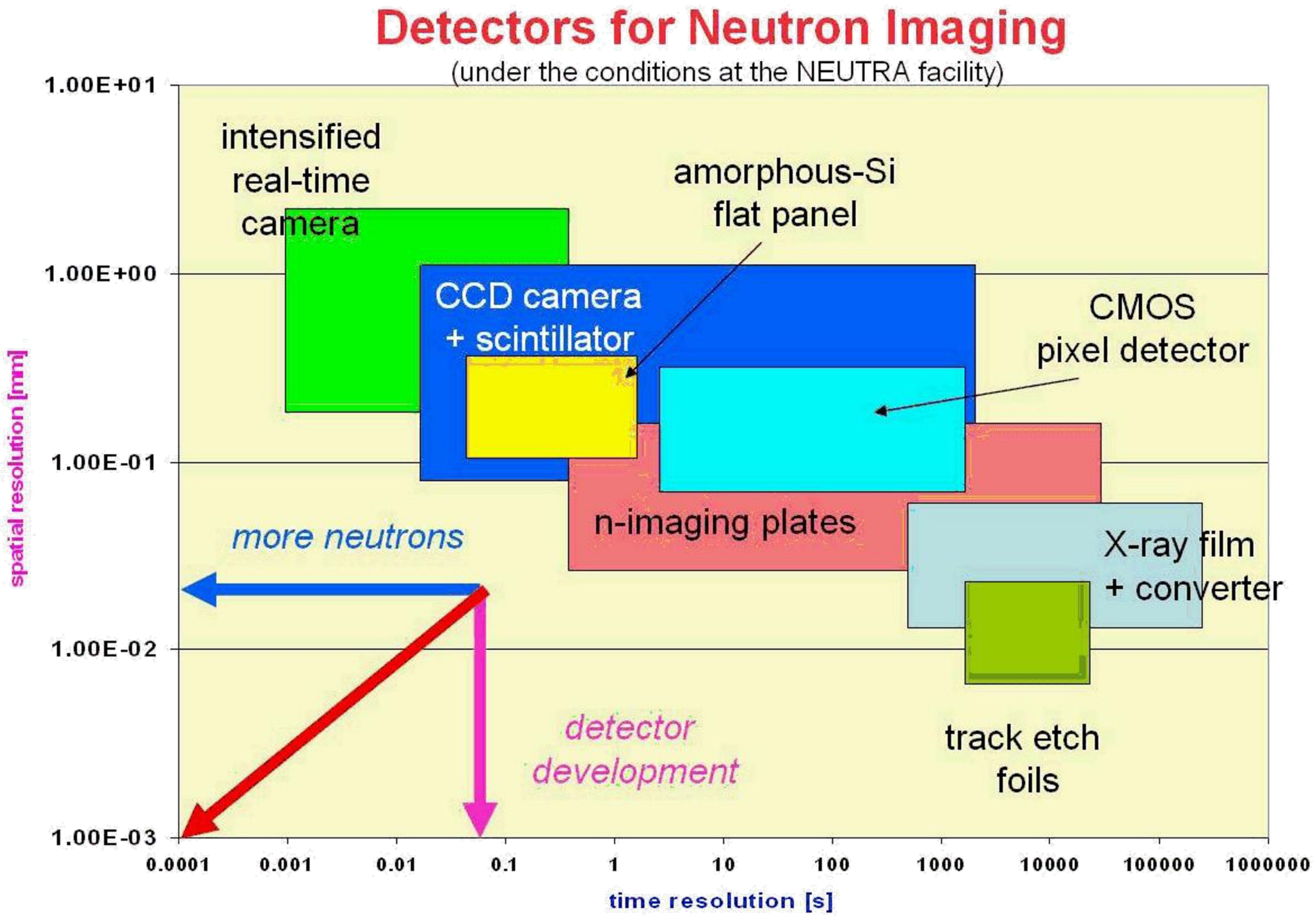






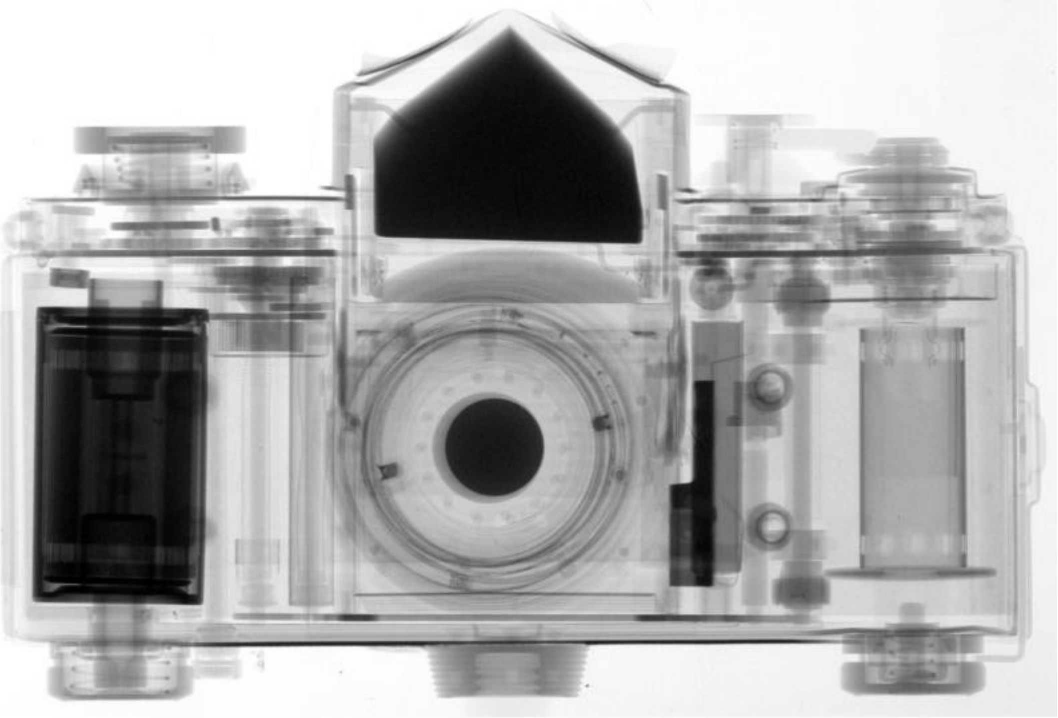
Application: neutron imaging





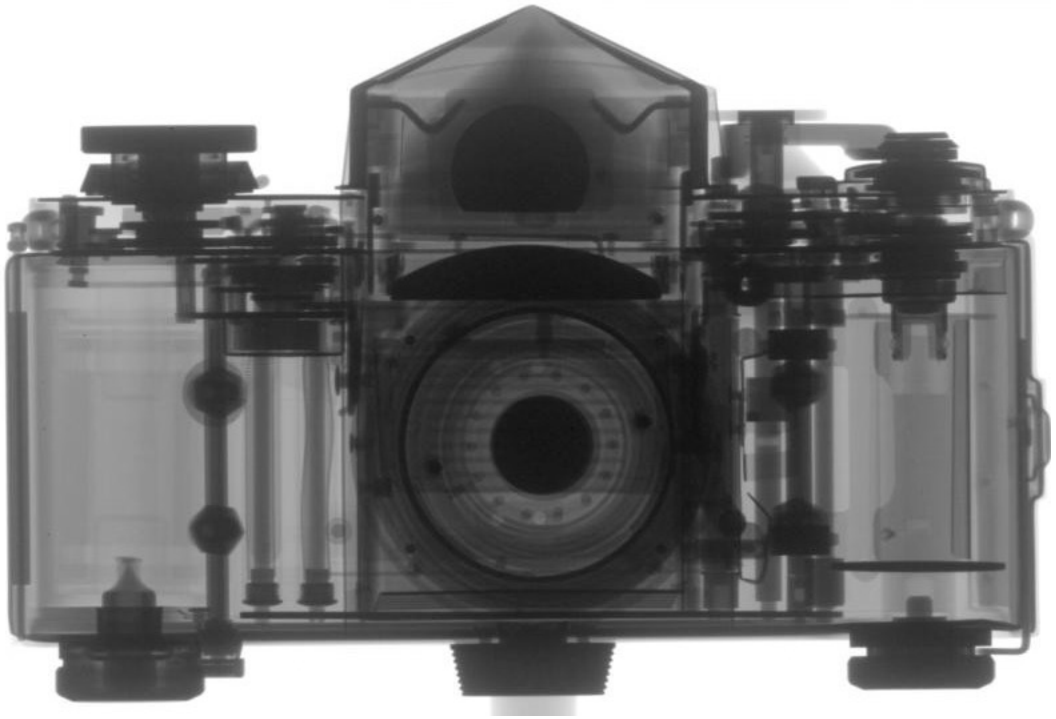
Application: neutron imaging

neutron radiography



most sensitive to
hydrogenous materials

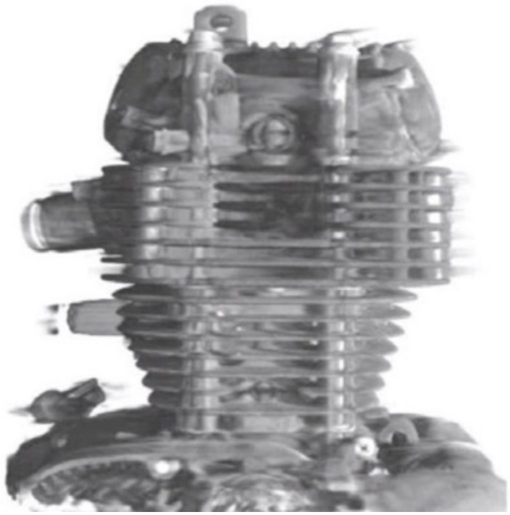
X-ray radiography



density profile info

Application: neutron imaging

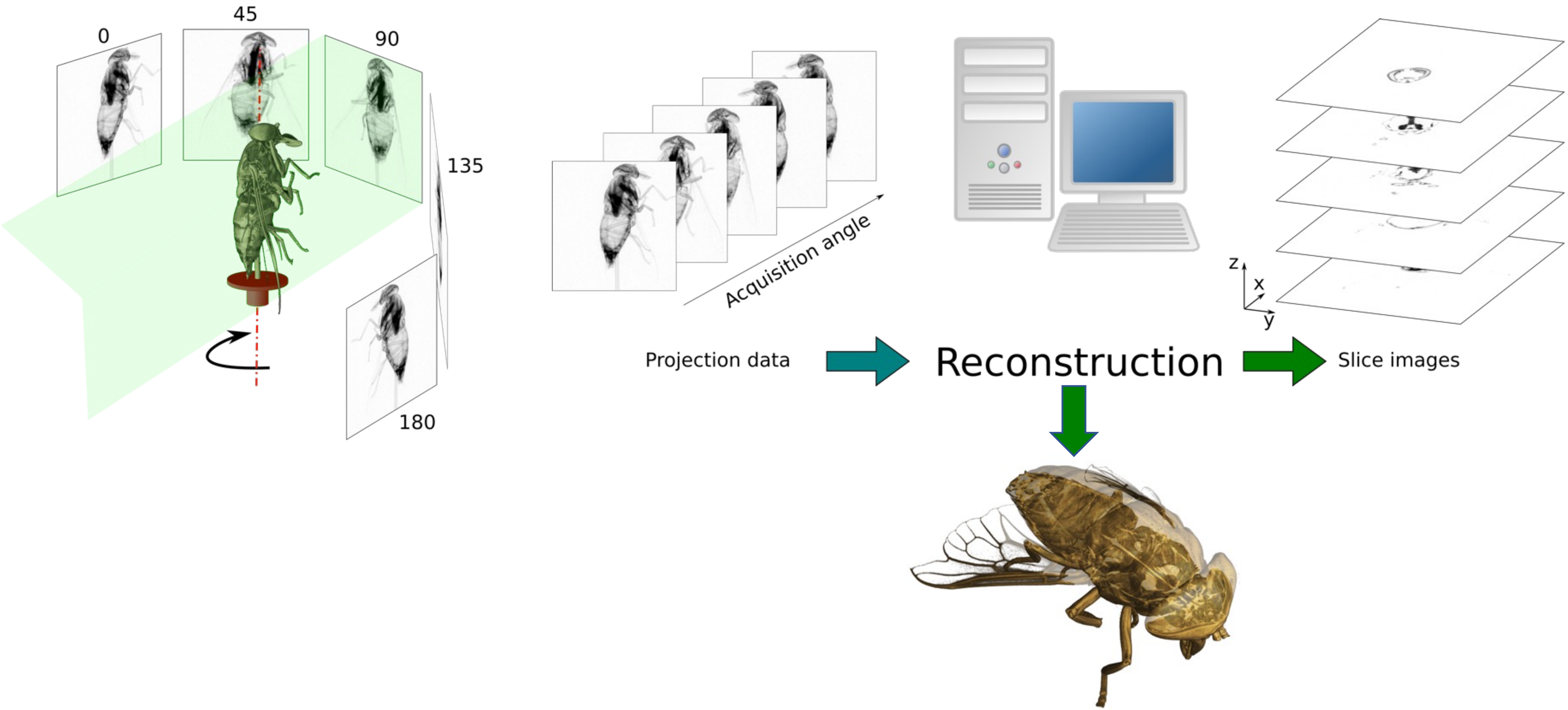
visible light



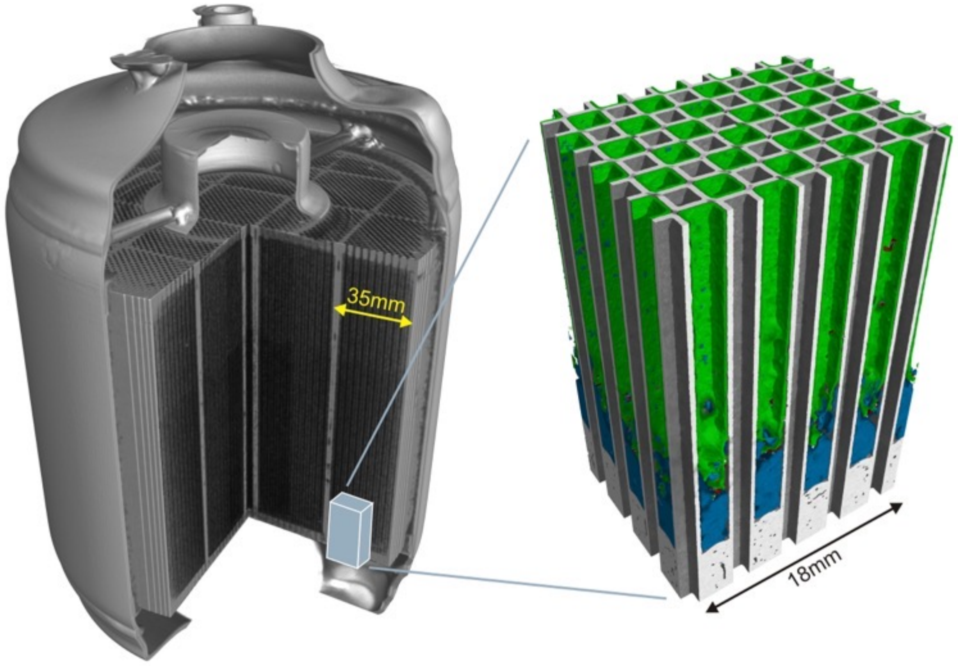
3D neutron tomography

non-destructive insight

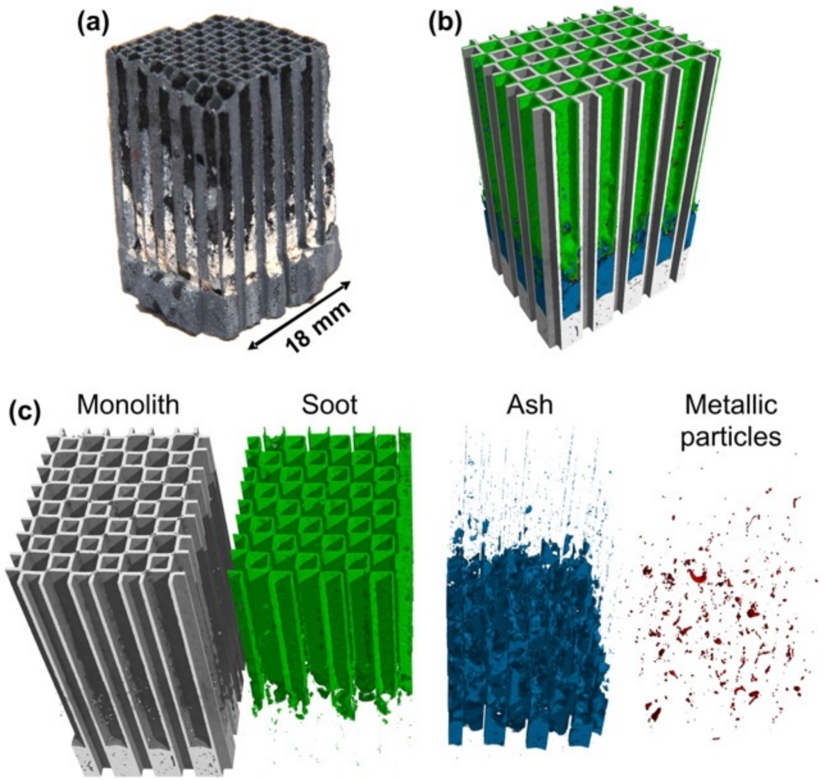
Application: neutron tomography



Application: neutron tomography



Neutron tomography data of a loaded diesel particulate filter

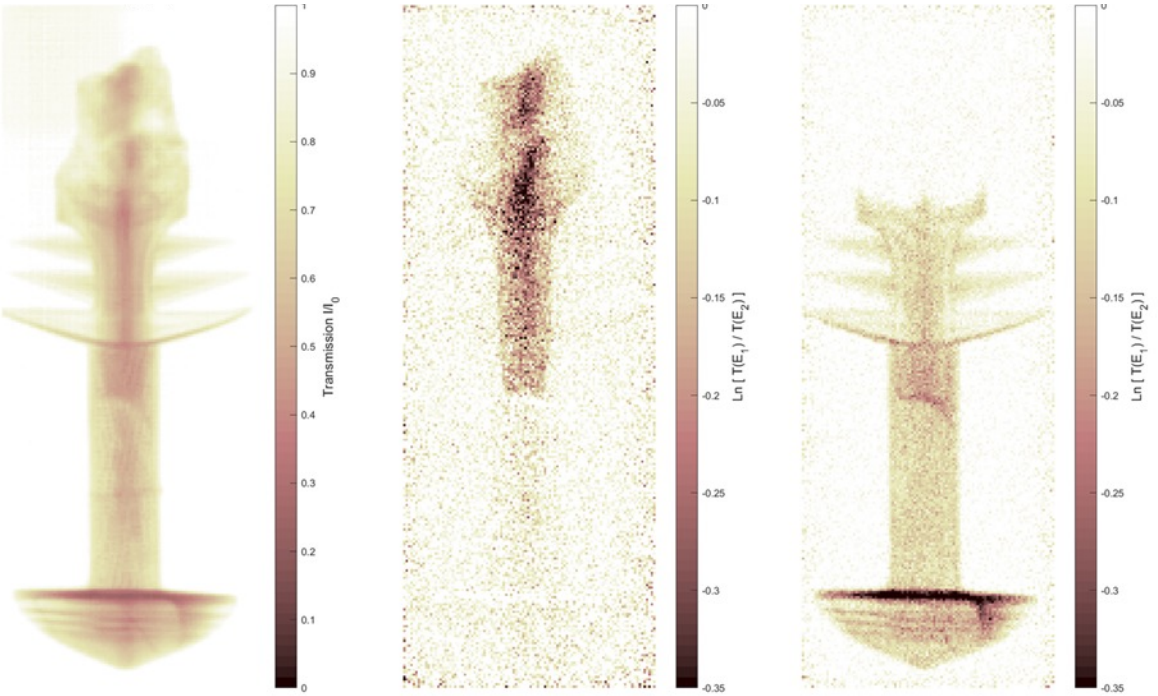


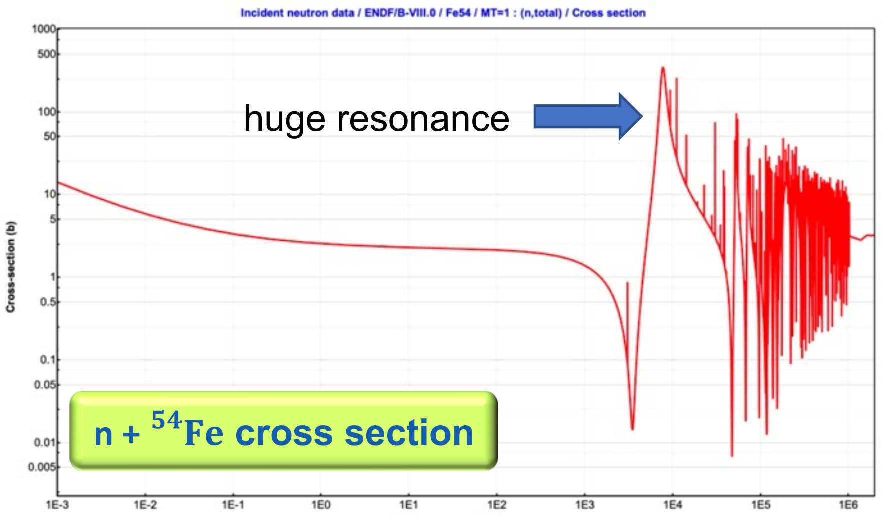
The steel jacket is no barrier for neutrons and allows an insight into the loaded monolith

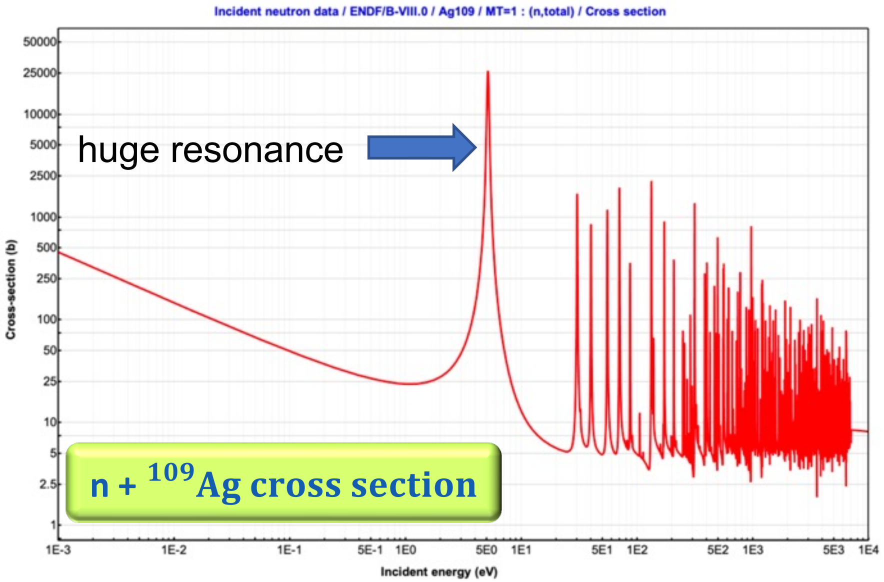
Application: selective neutron radiography

Neutron Resonance Transmission Imaging

n radiography | ^{54}Fe | ^{109}Ag



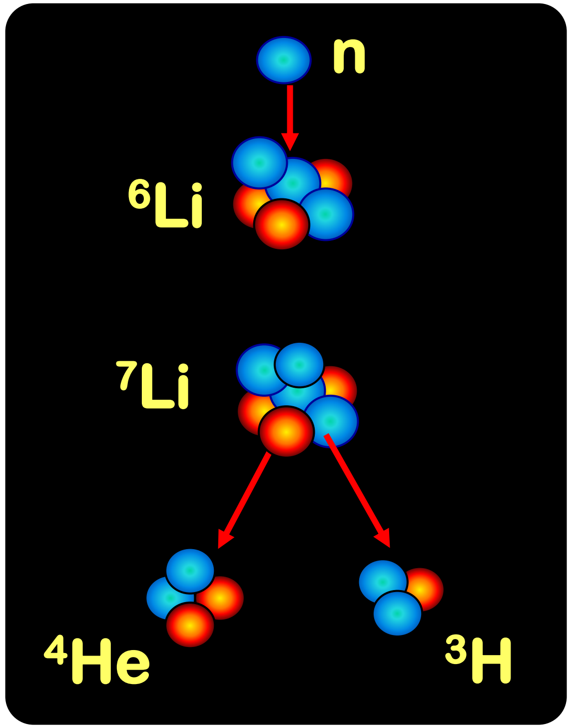




Boron and Lithium based detector examples

^{6}Li – natural abundance: 7.6%

a ^{6}LiF converter
captures a neutron...



2.05 MeV   2.73 MeV

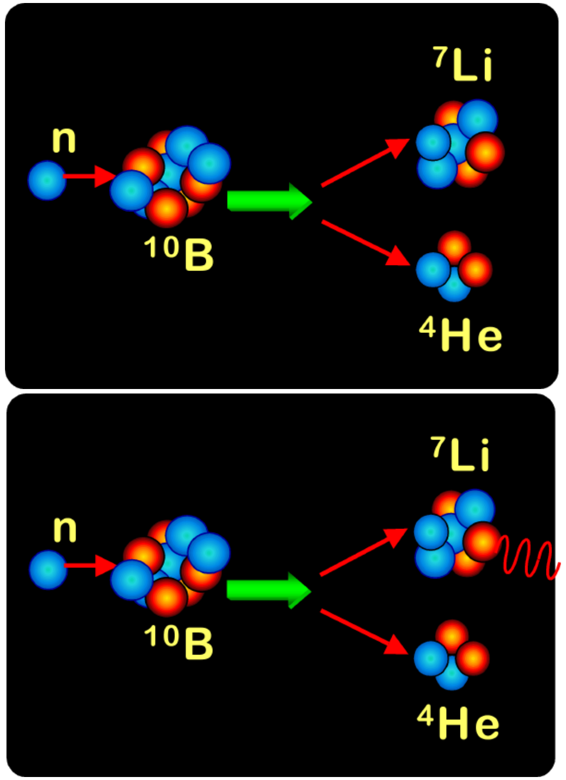
...and produces ^{4}He and ^{3}H
which can be detected

^{10}B – natural abundance: 19.9%

a ^{10}B converter
captures a neutron...

6%

94%



1.01 MeV

1.78 MeV

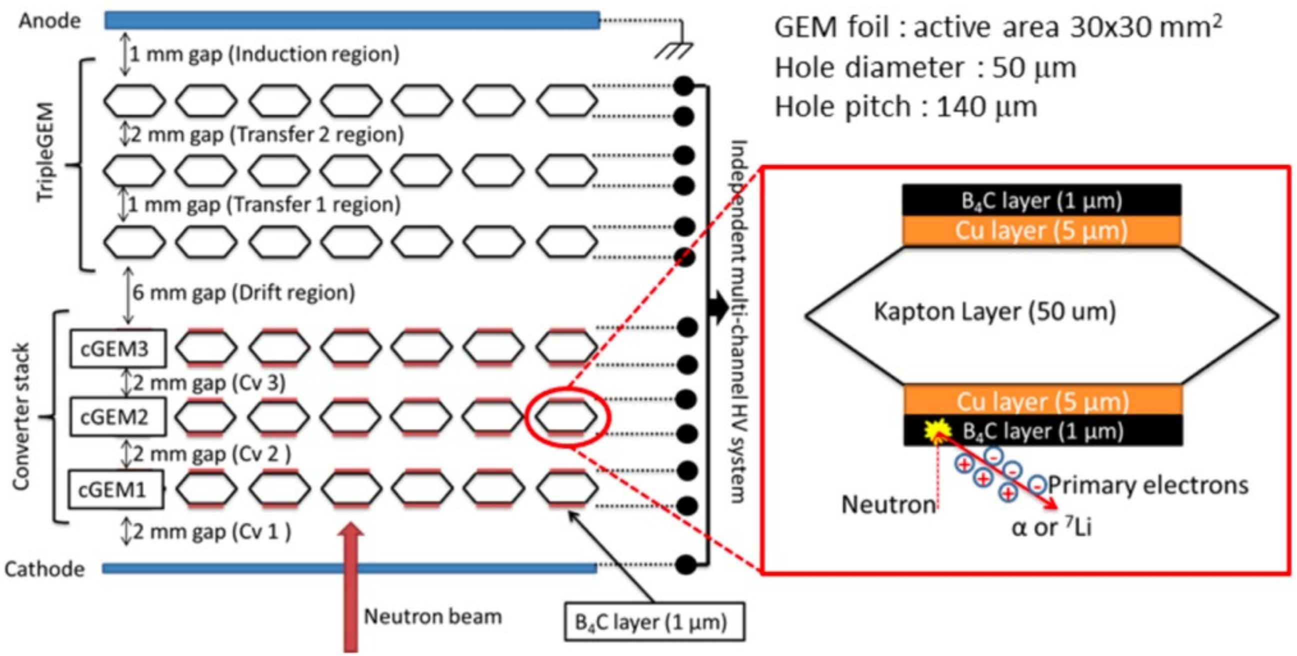
0.84 MeV

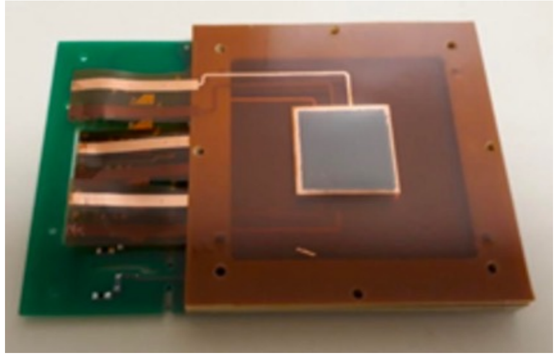
1.47 MeV

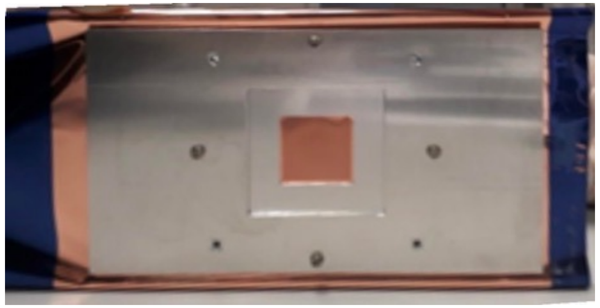
...and produces (^{7}Li and) ^{4}He
which can be detected

Multi Boron Gas Electron Multiplier (MBGEM)

idea and development by the late Fabrizio Murtas and his collaborators (INFN-LNF and ENEA)







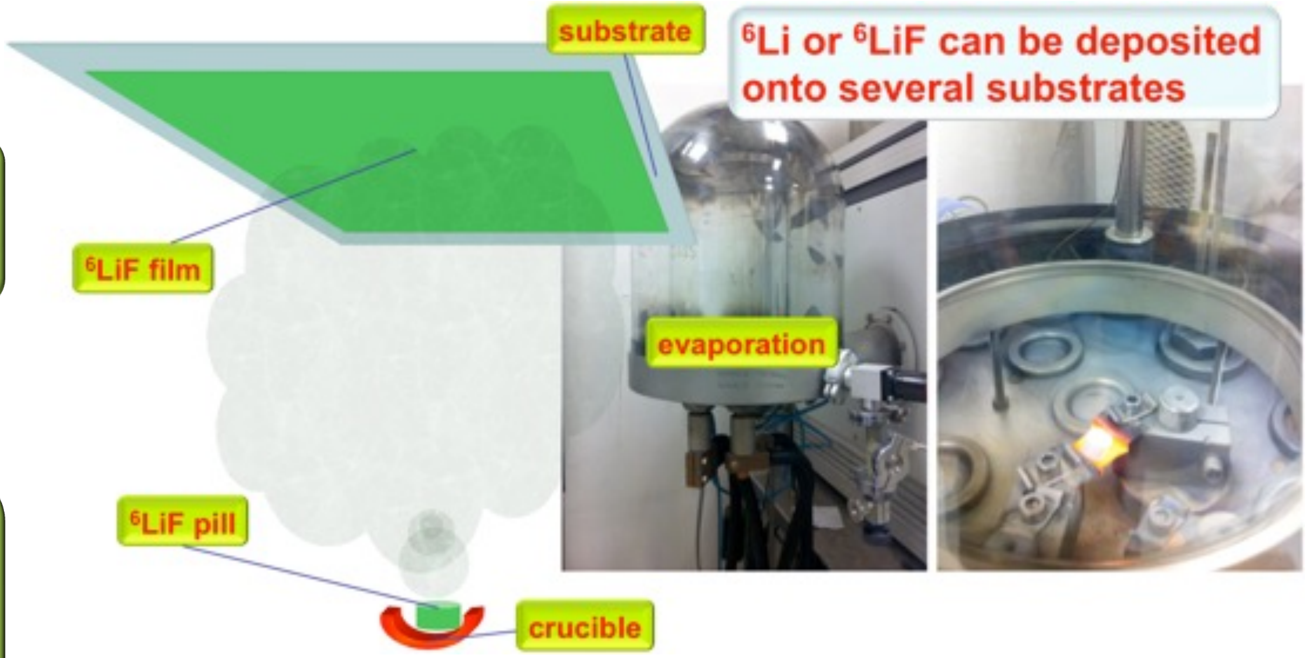
Boron and Lithium based solid state detectors

^{6}Li converter production by evaporation (INFN-LNS)

^{6}Li converter production

^{6}Li is easily flammable
strongly hydrophilic
easily oxidated

^{6}LiF is preferred
very stable salt
melts at 845 ºC
boils at 1646 ºC
can be deposited
chemically



^{6}LiF (enriched at @95%)
on carbon fiber

Boron and Lithium based solid state detectors

^{6}Li converter production

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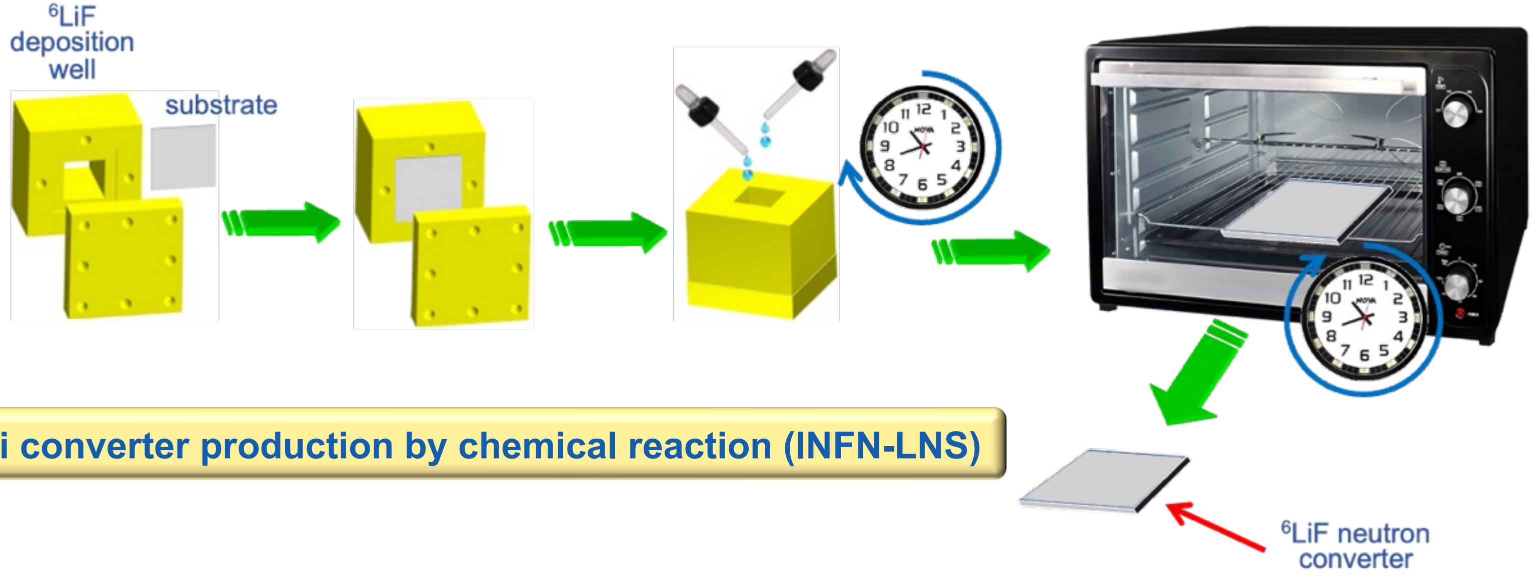
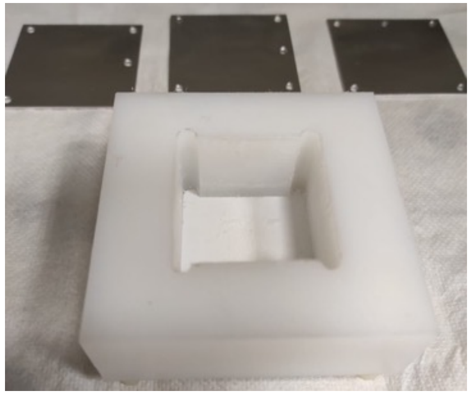
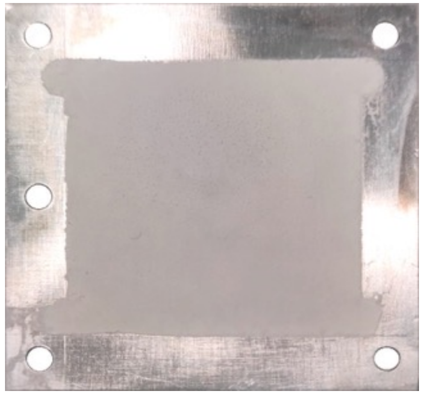


^{6}Li converter production by chemical reaction (INFN-LNS)





^{6}LiF (enriched at @95%) on aluminum

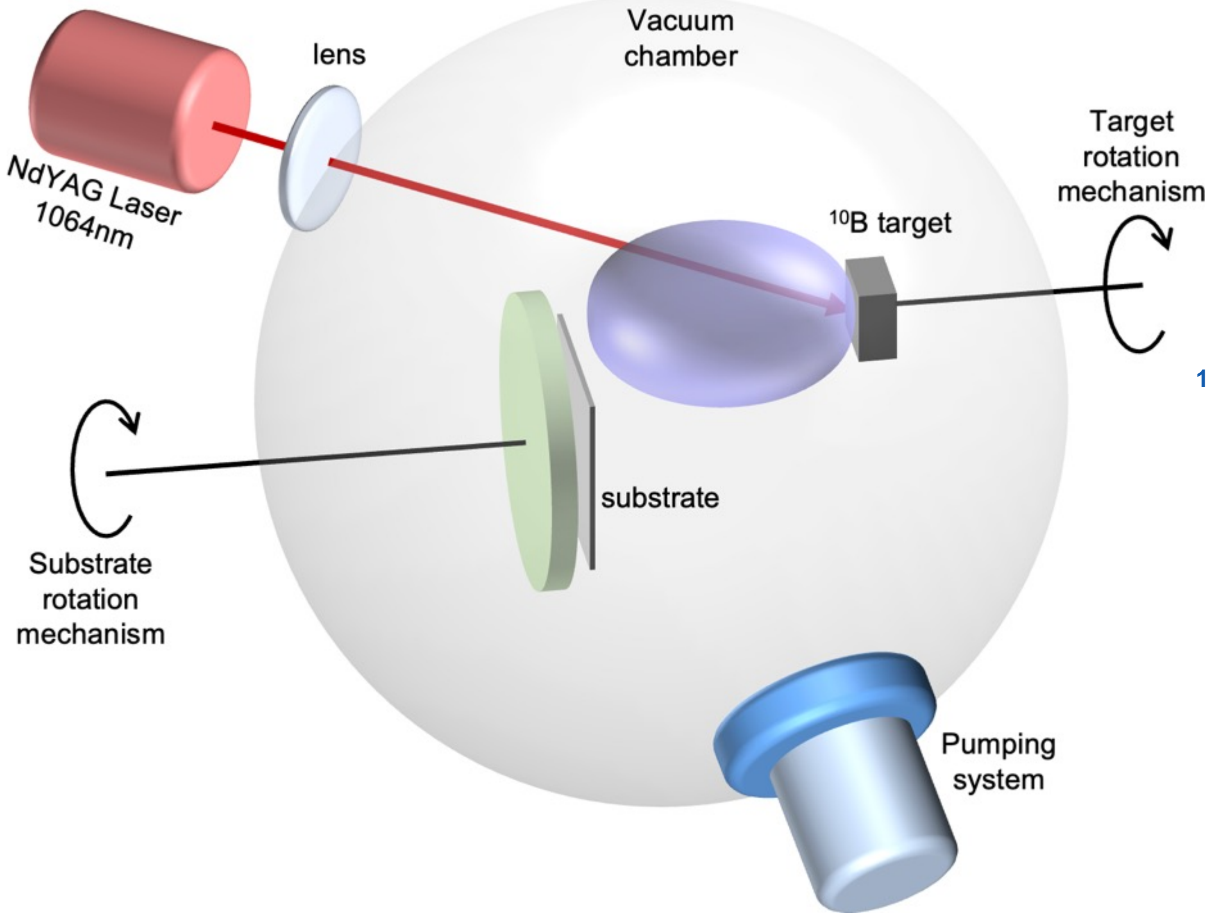
Boron and Lithium based solid state detectors

^{10}B converter production

B is quite stable
melts at 2077 ºC
boils at 4000 ºC
cannot be evaporated

can be deposited by
electron gun,
sputtering, laser

^{10}B converter production by
Pulsed Laser Deposition (INFN-LE)

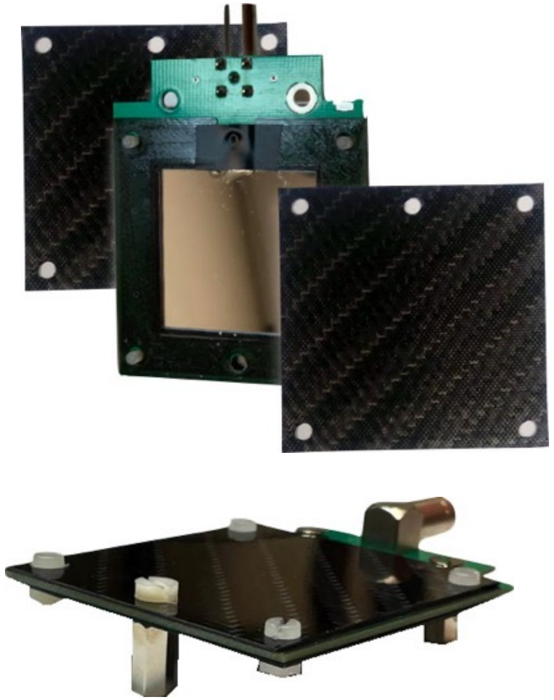


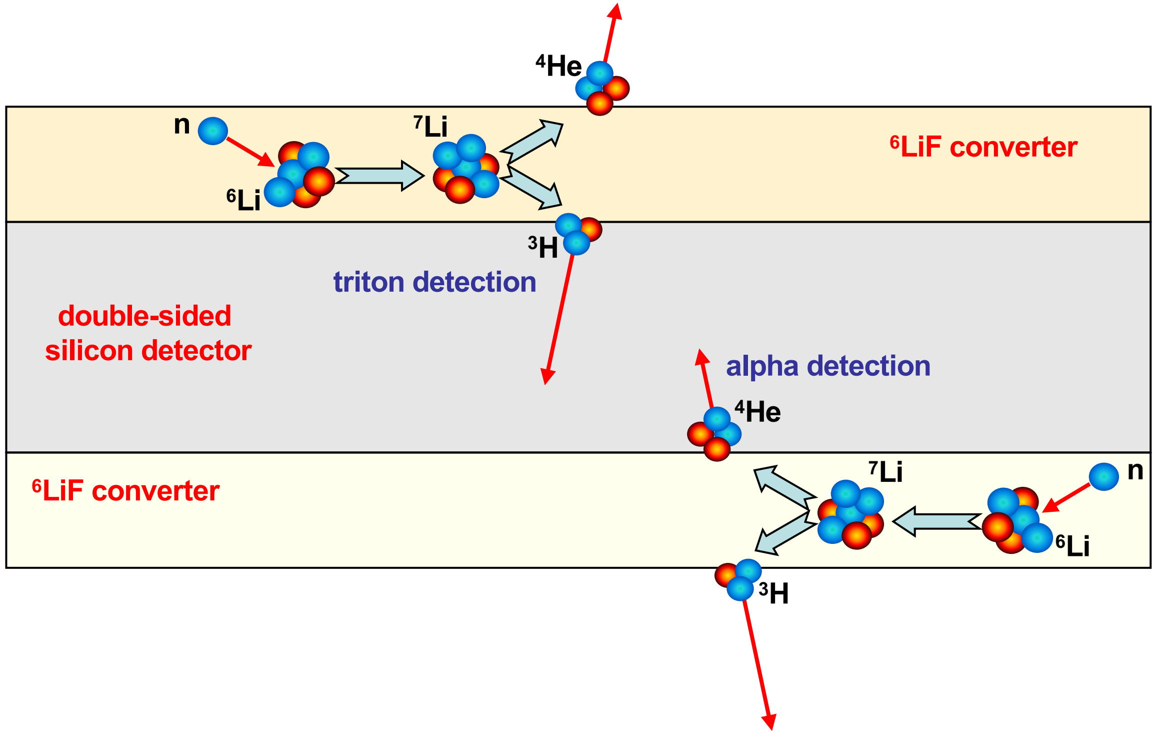
^{10}B (enriched at @95%)
on carbon fiber

SiLiF and SiB neutron detectors

single/double ^{10}B or ^{6}LiF converter

coupled to Si detector
(single or double sided)





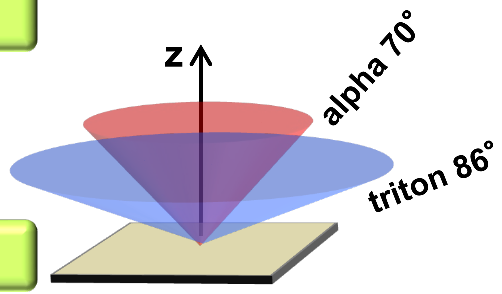
SiLiF: exit angle limit

the emission from the ^{6}LiF converter was simulated

GEANT4
A SIMULATION TOOLKIT

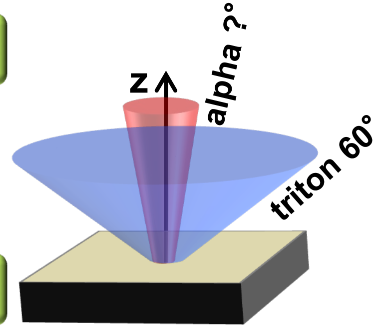
thin

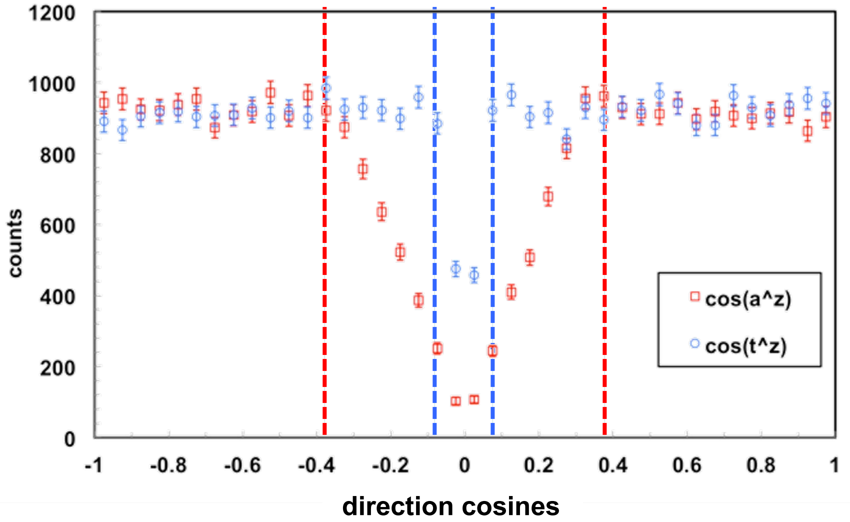
1.6µm

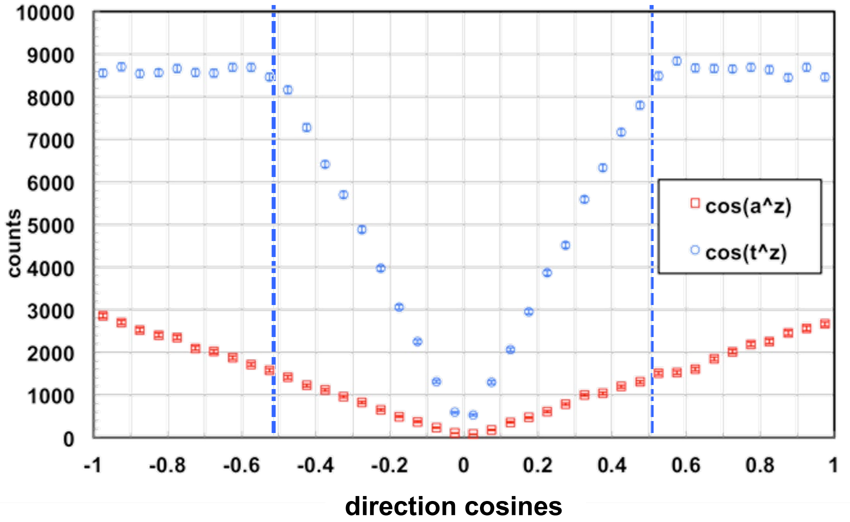


thick

16µm







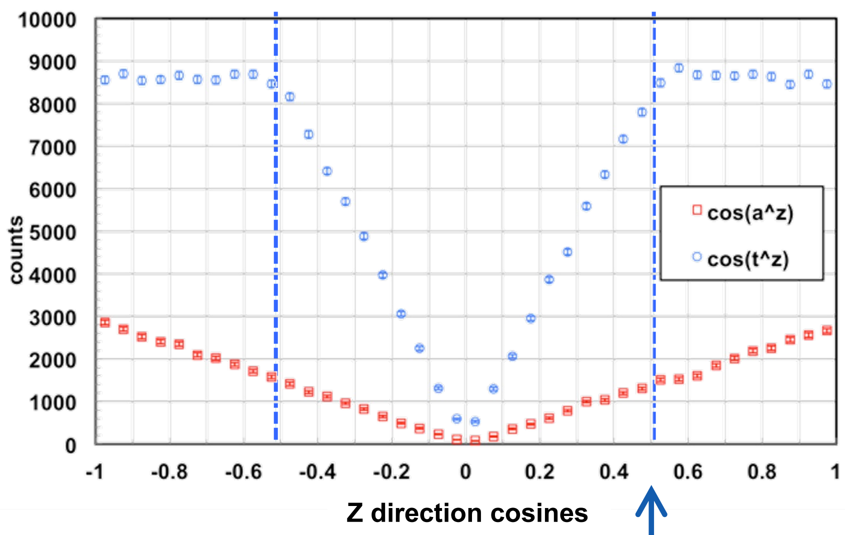
^{10}B: lower Q and heavier products

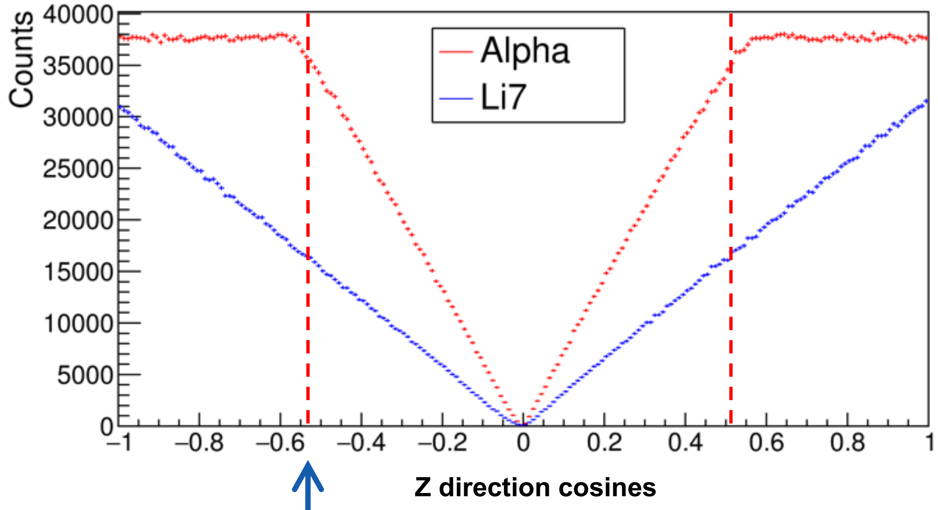
SiLiF 16 µm

cross section 940 b

SiB 2 µm

cross section 3500 b





≈ 60º

similar exit angle limit for triton (SiLiF) and SiB (alpha)

similar density (2.5 vs 2.3)

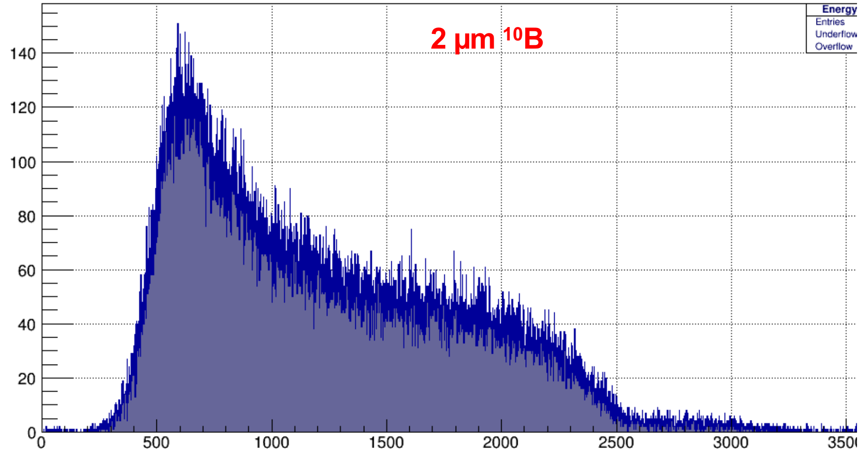
yield ∝ 16 · 940 ≈ 15000

det. efficiency ≈ 5%

yield ∝ 2 · 3500 ≈ 7000

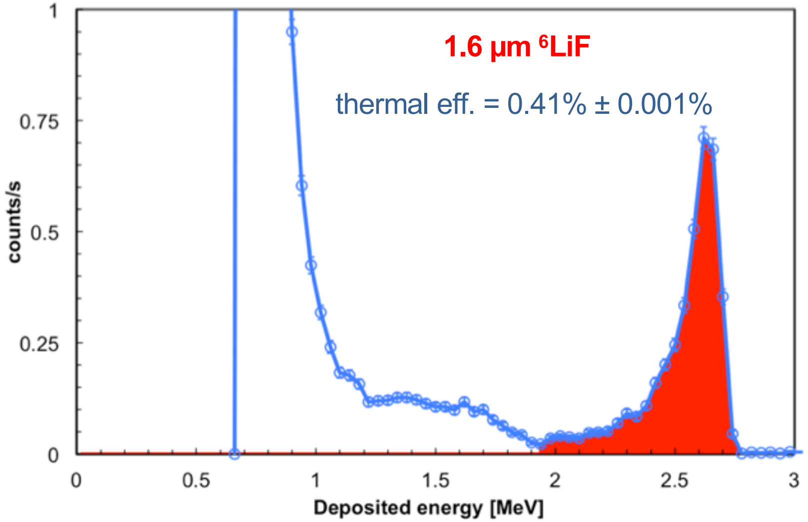
det. efficiency ≈ 2.5%

important feature required to n detectors: gamma/neutron rejection



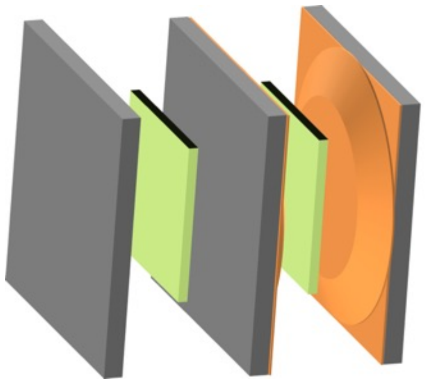
^{10}B: lower Q and heavier products

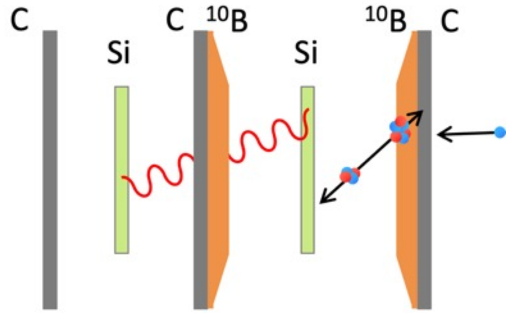
SiB requires gamma subtraction

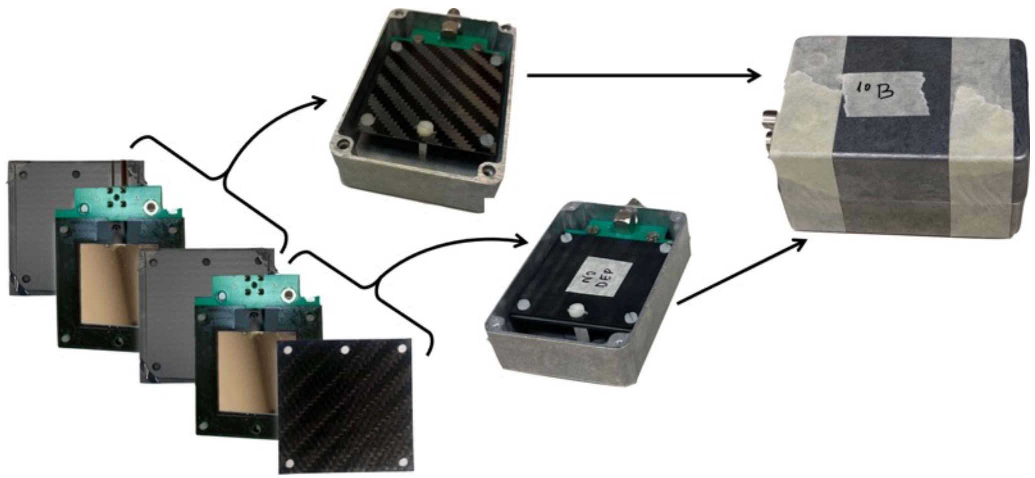


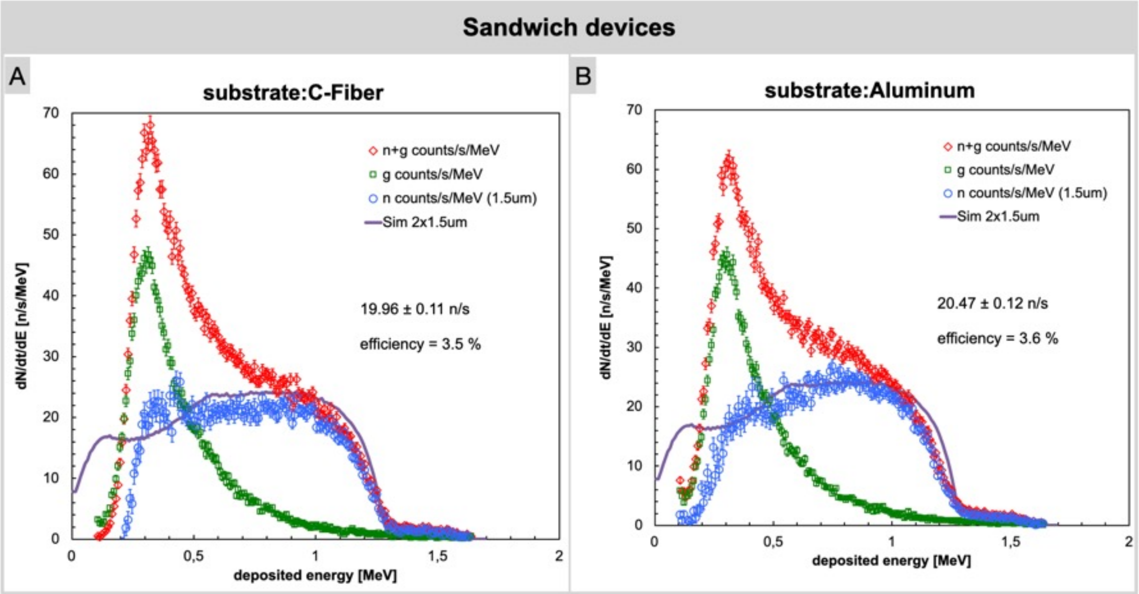
SiLiF just needs a threshold

gamma subtraction with SiB double sandwich (BOLAS experiment INFN LNS and LE)





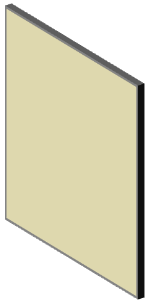


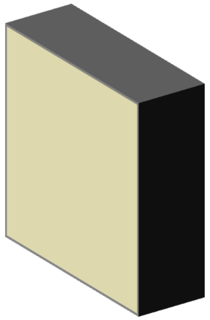


converter thickness plays a dominant role

thin:
better discrimination
poor efficiency

thick:
worse discrimination
better efficiency

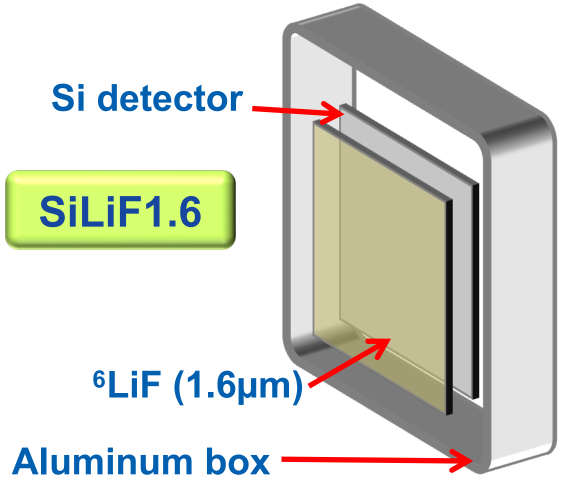




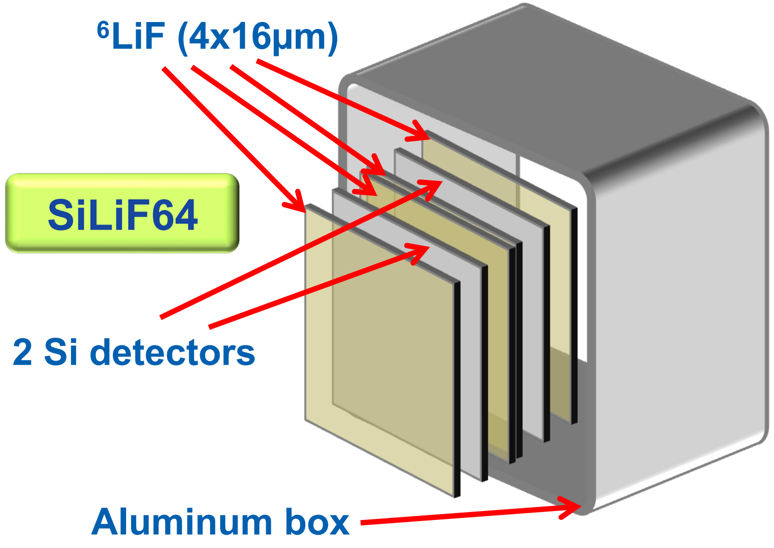
a trade-off is needed

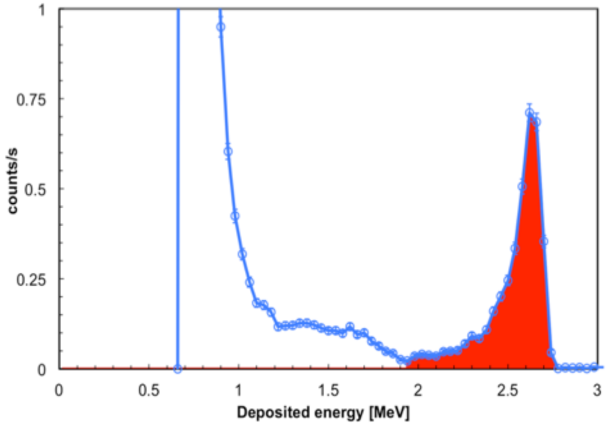
SiLiF: thin vs thick converter

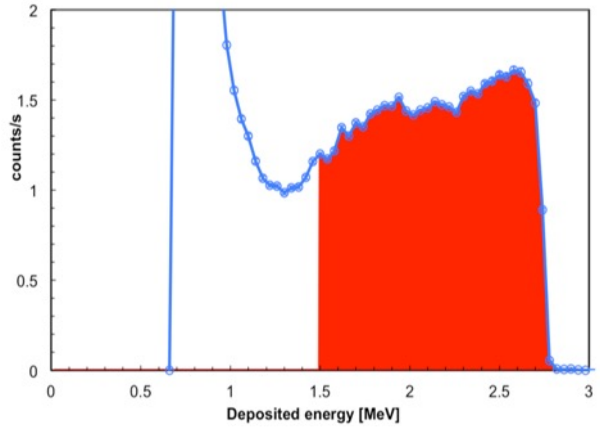
SiLiF1.6



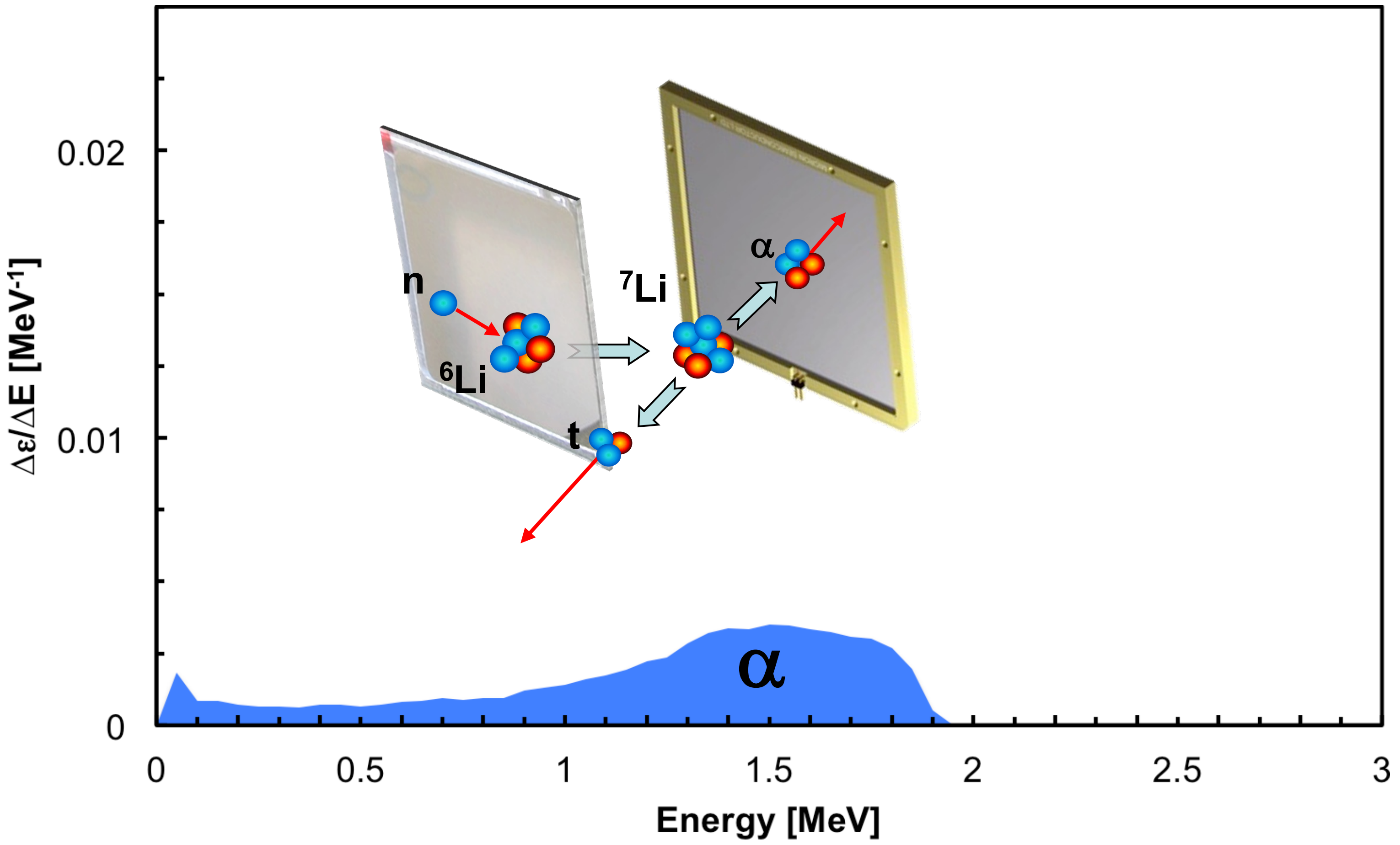
SiLiF64



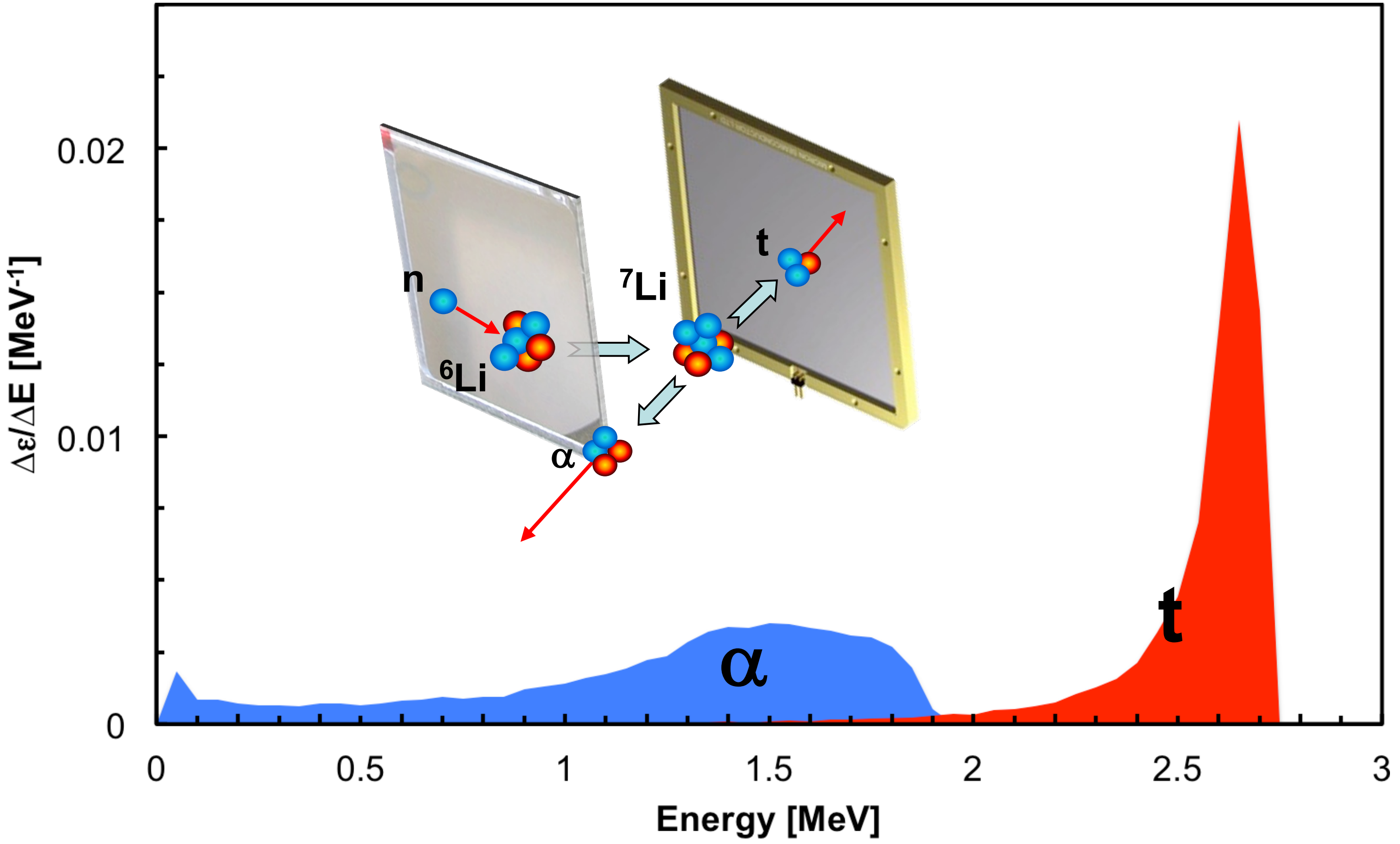




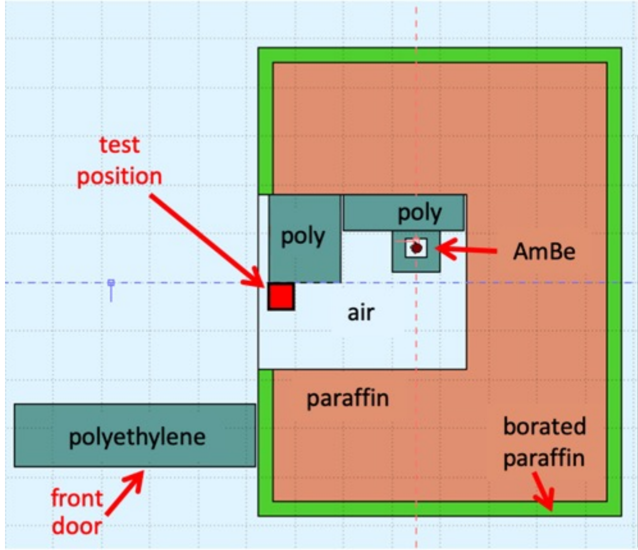
SiLiF1.6 - simulation with 25.3 meV monochromatic n-beam

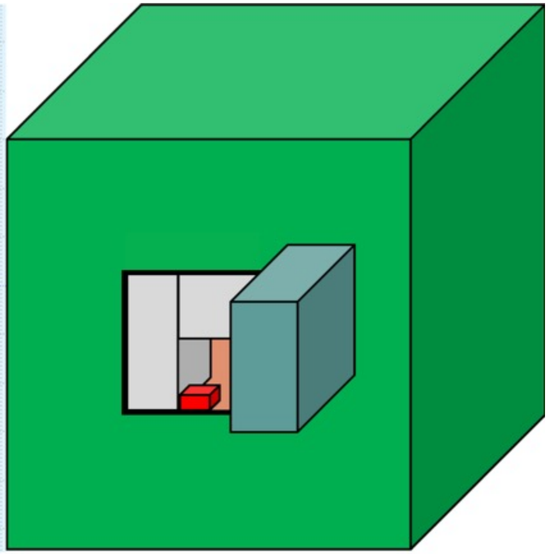


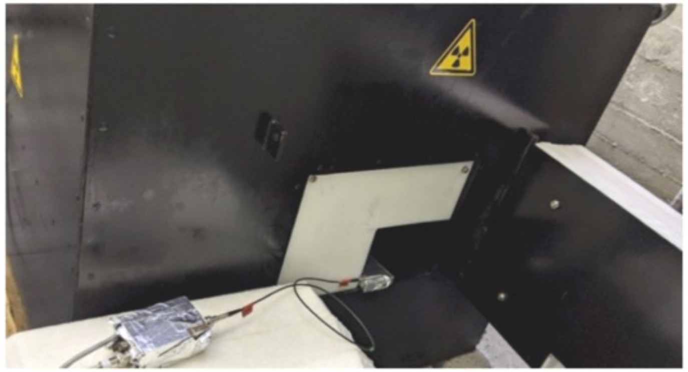
SiLiF1.6 - simulation with 25.3 meV monochromatic n-beam



neutron source: AmBe







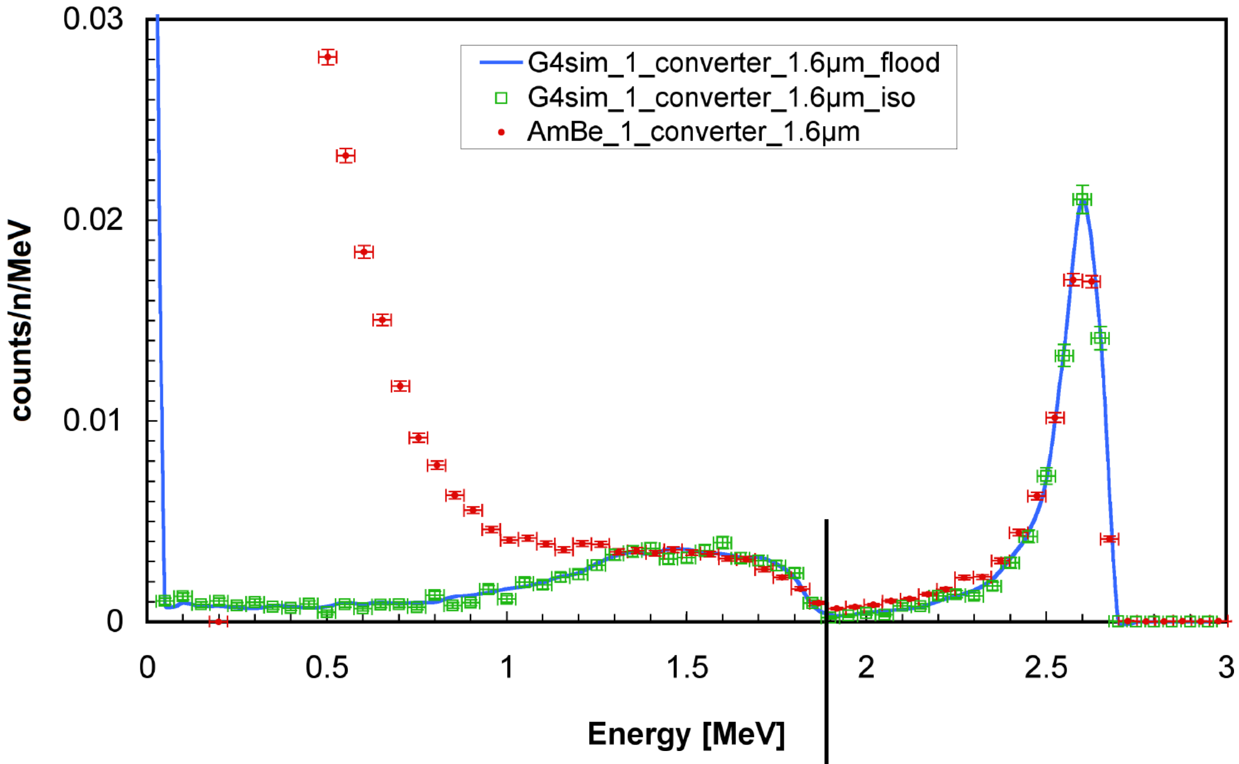
exploits the ^{241}Am alpha decay for a reaction on Beryllium

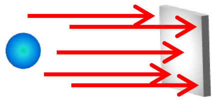
$^{9}Be + \alpha \rightarrow n + ^{12}C^{*}$

^{241}Am also emits 59 keV gamma rays

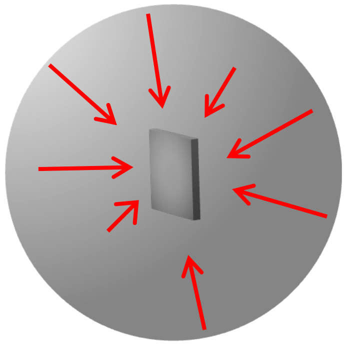
20 GBq of ^{241}Am to get 10^{6} n/s

Geant4 simulations reproduce the experimental spectrum shape both in flood and isotropic irradiation scheme





flood (beam)



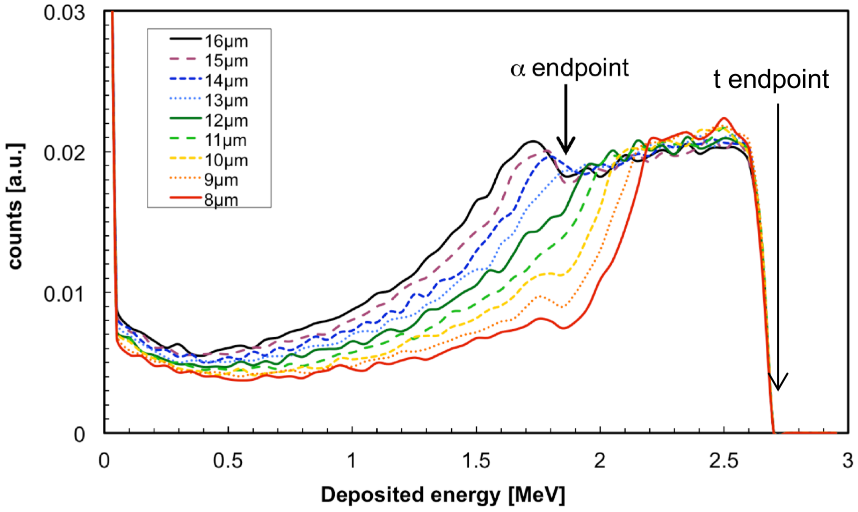
isotropic (AmBe source)

only 3.1% tritons below alpha endpoint

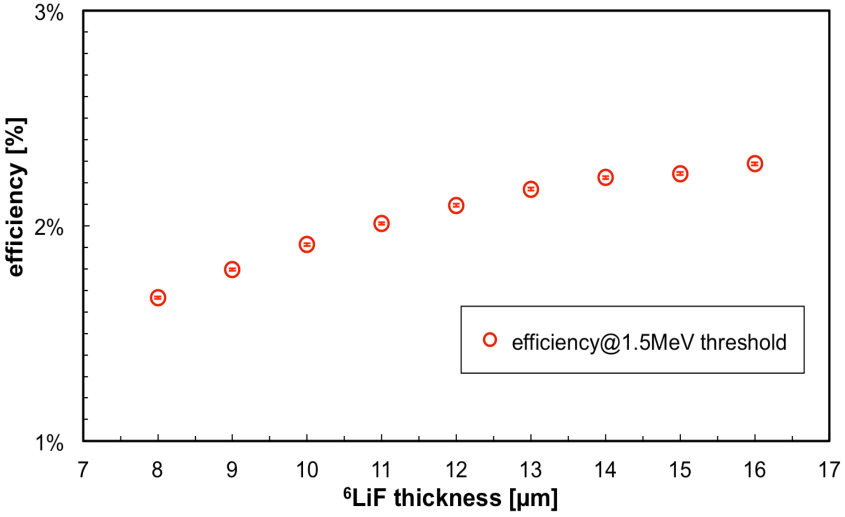
SiLiF1.6 can be exploited as reference neutron counter

SiLiF

why 16μm as "thick" layer?

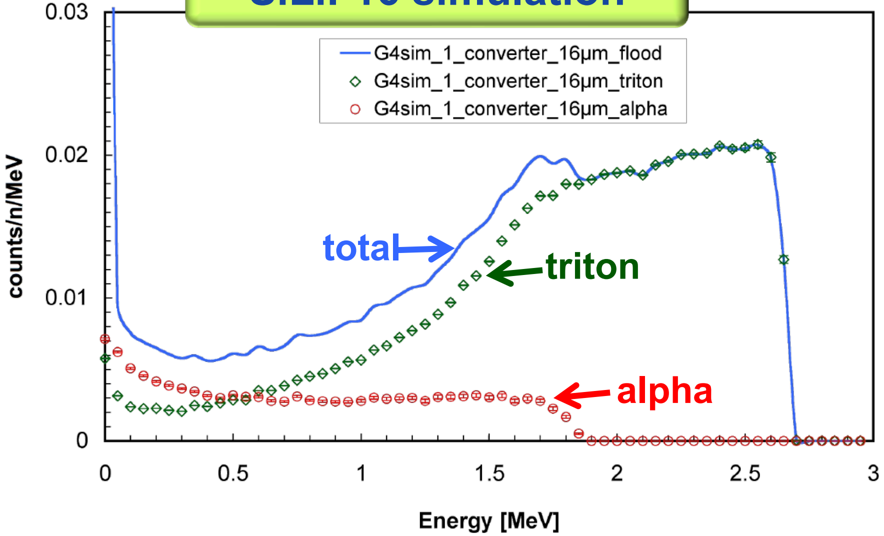


- neutron contribution rather flat
- alpha endpoint is clear
- allows simple energy calibration
- triton range ≈ 32μm (16μm = half range)
- > 16μm: layer delicate and tends to detach

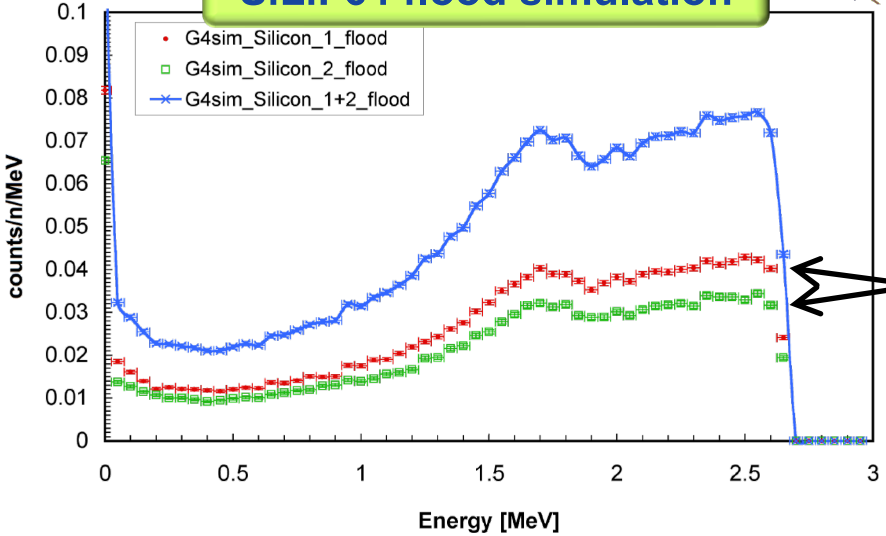


- efficiency saturation at ≈ 16μm
- gain in tritons loss in alphas
- the acceptance cone shrinks

SiLiF16 simulation

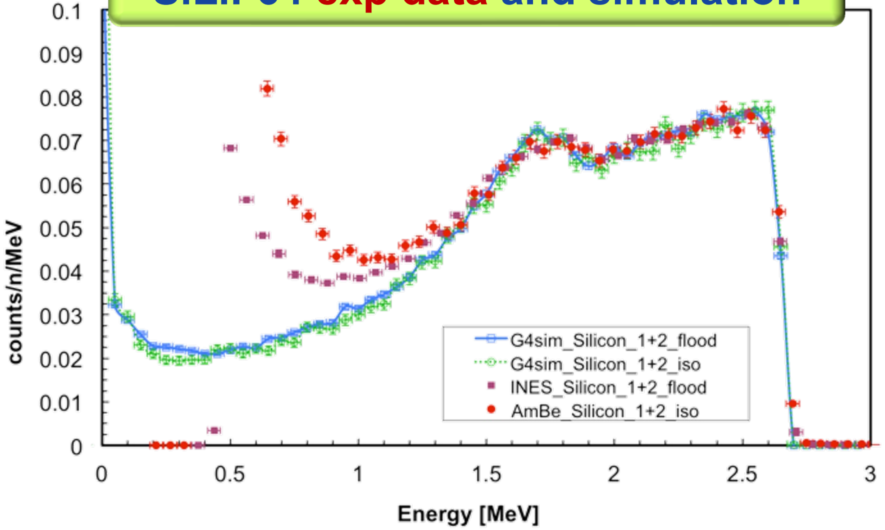


SiLiF64 flood simulation

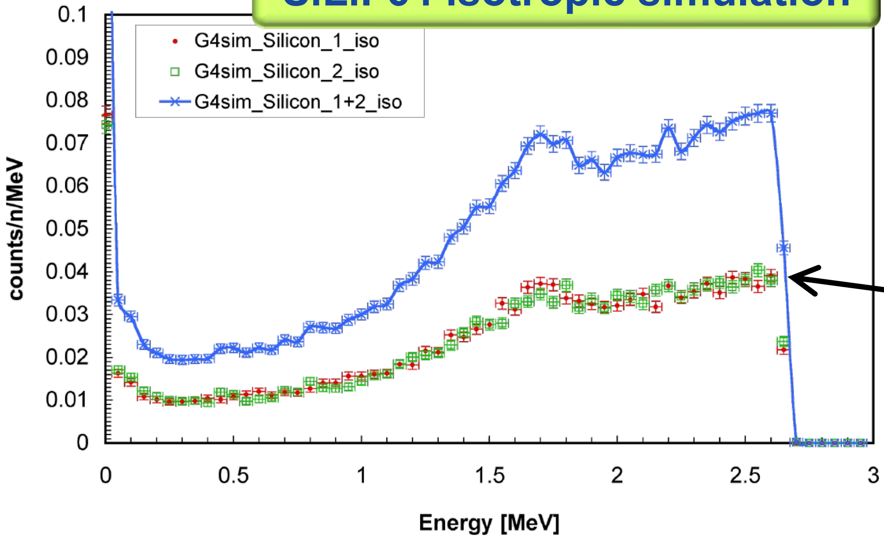


absorption in the first detector

SiLiF64 exp data and simulation

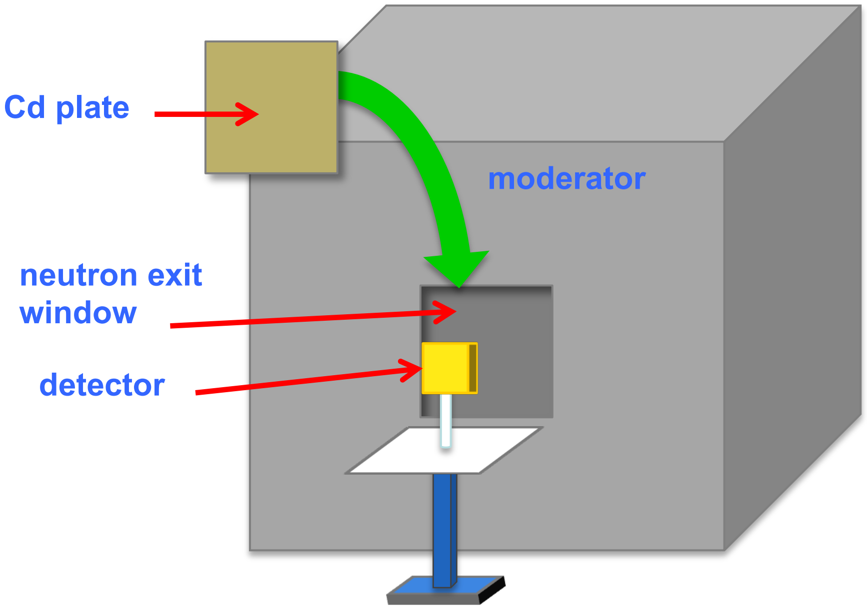


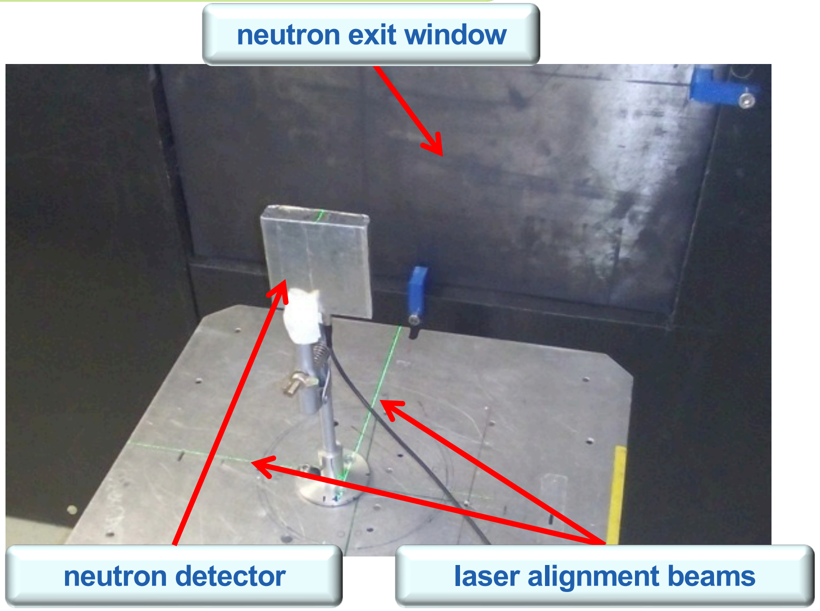
SiLiF64 isotropic simulation



not in the isotropic case

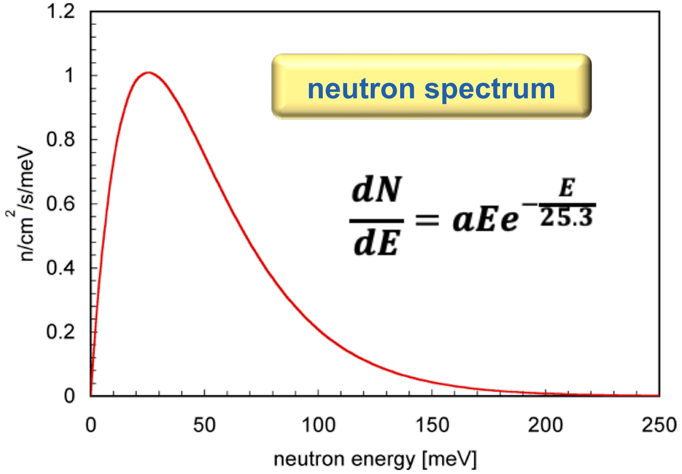
SiLiF absolute efficiency calibration at PTB with the Certified Thermal Neutron Calibration Facility



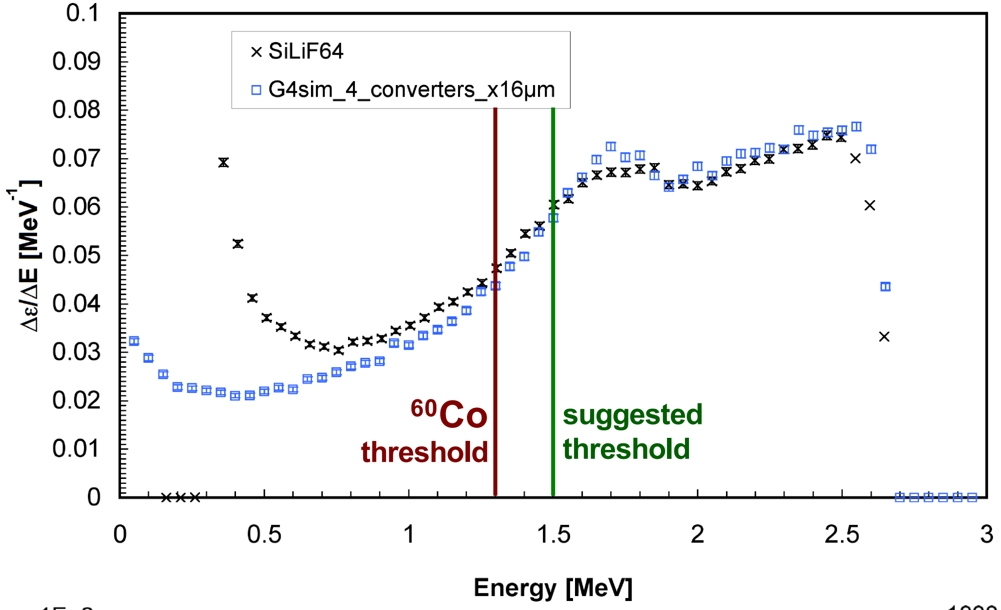


neutron flux: 68.3 n/s/cm²
uniform over > 10cm x 10cm

with Cd plate: < 1 n/s/cm²



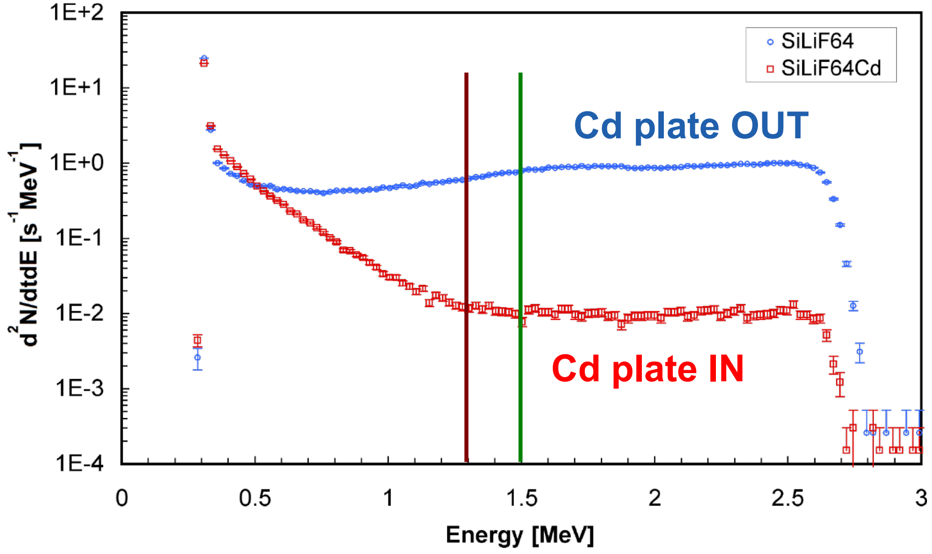
SiLiF64

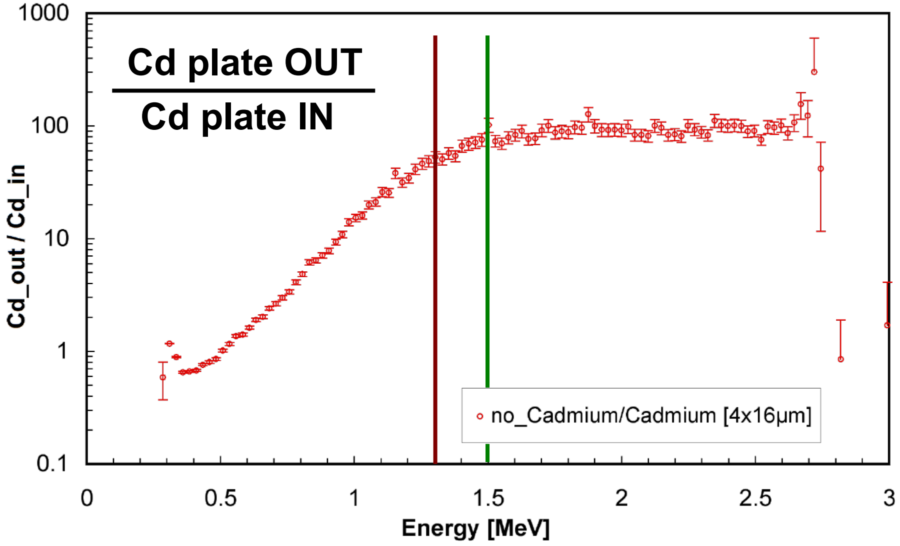


neutron detection efficiency: 8%
with threshold at ^{60}Co: 10%

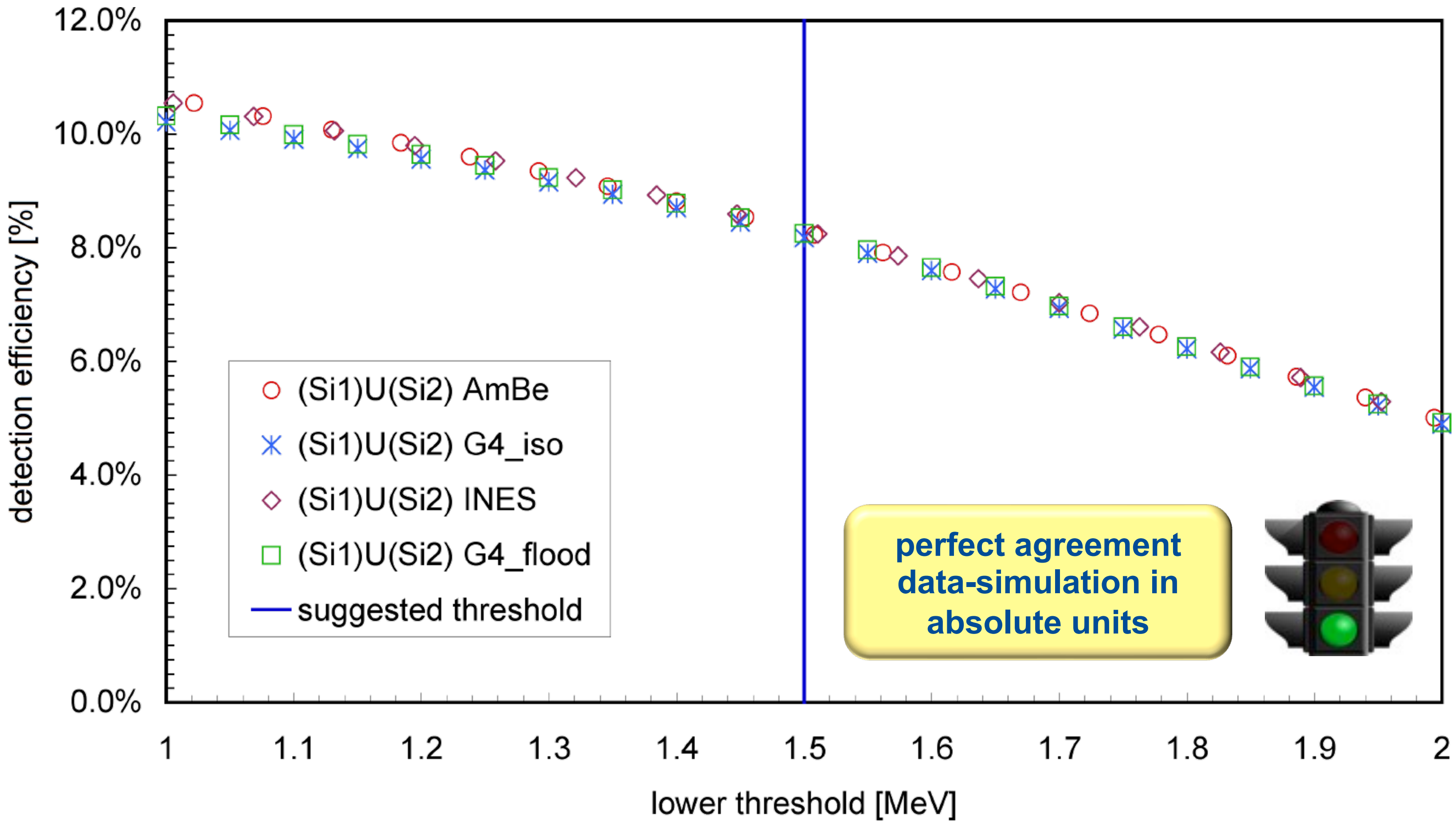
agreement between data and simulation better than 4% (mainly systematic uncertainty)

ratio Cd_OUT to Cd_IN flat above 1.5 MeV





SiLiF64 neutron efficiency vs discrimination threshold



perfect agreement data-simulation in absolute units

this sample 3cm x 3cm
also available 5cm x 5cm

solid state (Silicon + ^{6}LiF)

low cost technology, cheaper than ^{3}He

low voltage (25 V)

compact, robust, manageable

good detection efficiency (5 ÷ 10%)

optimum gamma discrimination ($<10^{-8}$)

tested and in use at neutron beam facilities nTOF at CERN and ISIS at RAL

^{6}LiF material: benefits vs drawbacks

- detection of ^{4}He and/or ^{3}H
- 4.78 MeV available energy
- enrichment @95%   € 7 / g
- stable salt, easily evaporated
- substrate: C-fiber, Al, glass, ...
- substrate thickness up to 20 μm

- not very high cross section
- natural abundance: 7%

detector mechanical structure

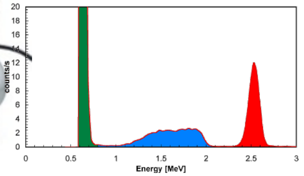
rugged, manageable

little non-detector material

stackable

large area = many detectors

operating features & summary



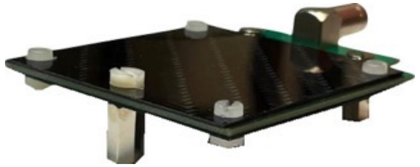
vacuum compatible

low voltage operation

quite stable

easily handled (simple box)

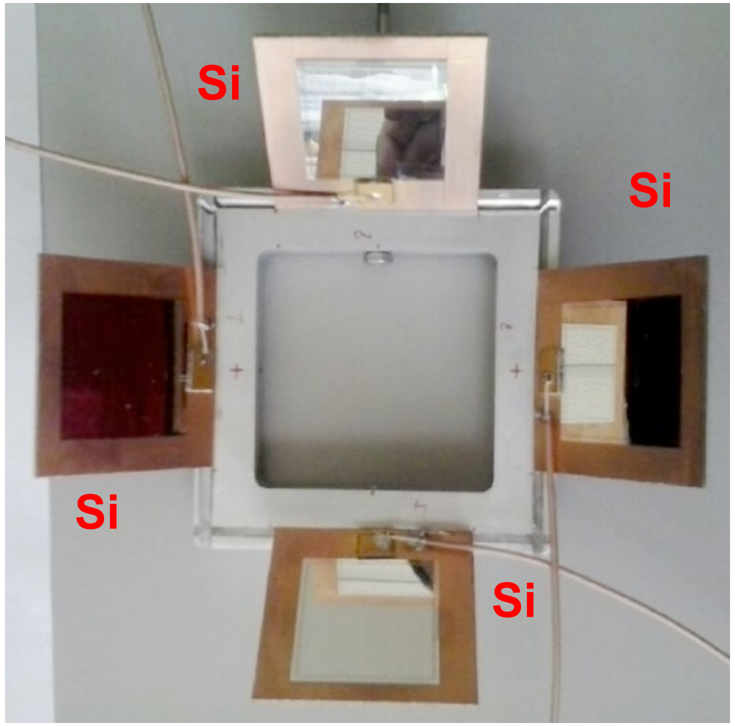
easily assembled/disassembled

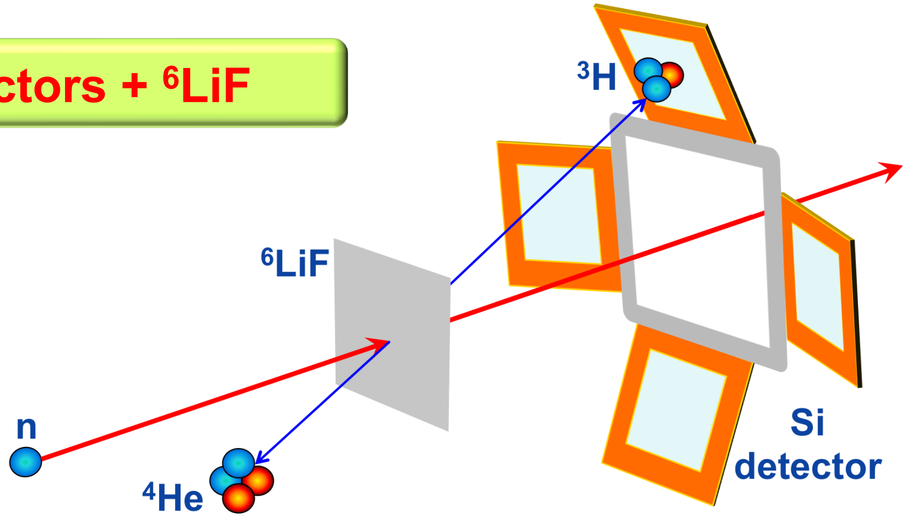


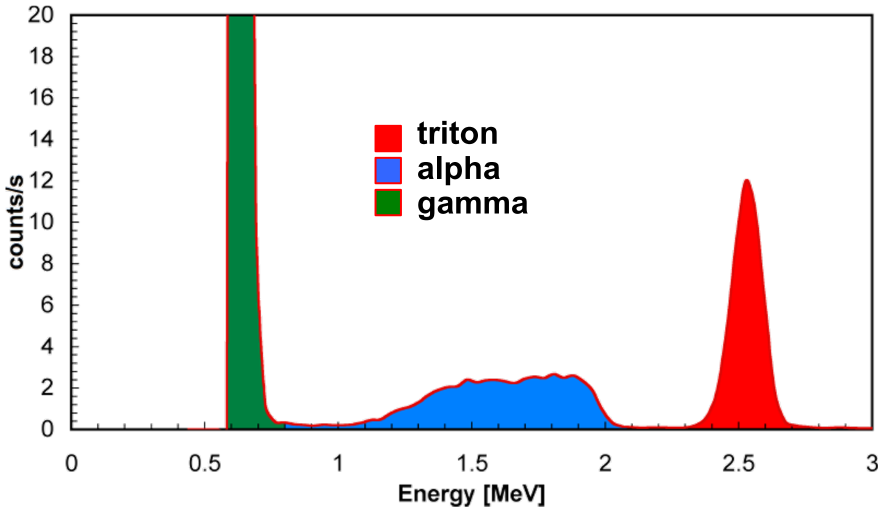
no physical/chemical agents on the converter (gas, high electric field,...)

SiMon @ n_TOF neutron beam monitor

Si detectors + ^{6}LiF



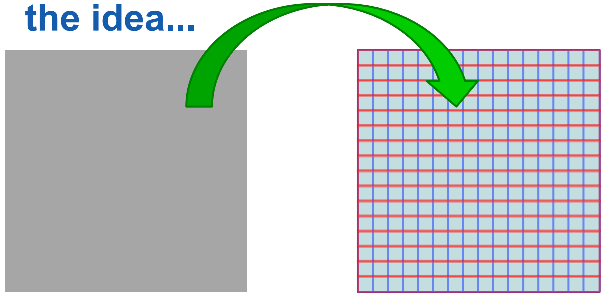




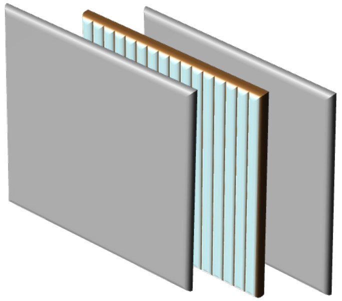
SiMon2D: neutron beam characterization

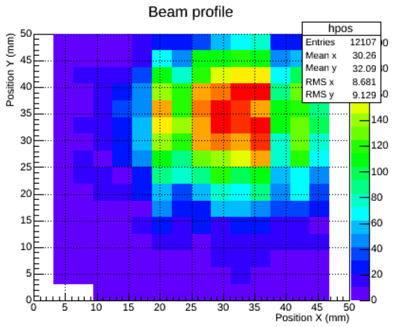
Si detector + ^{6}LiF

the idea...



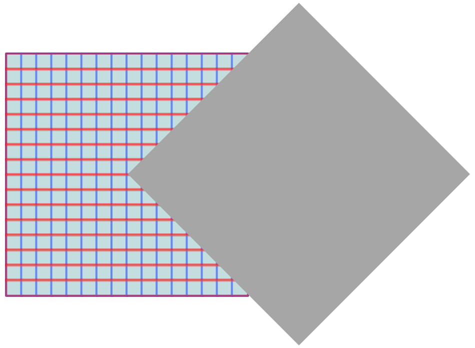
^{6}LiF foil   16+16 strip Si

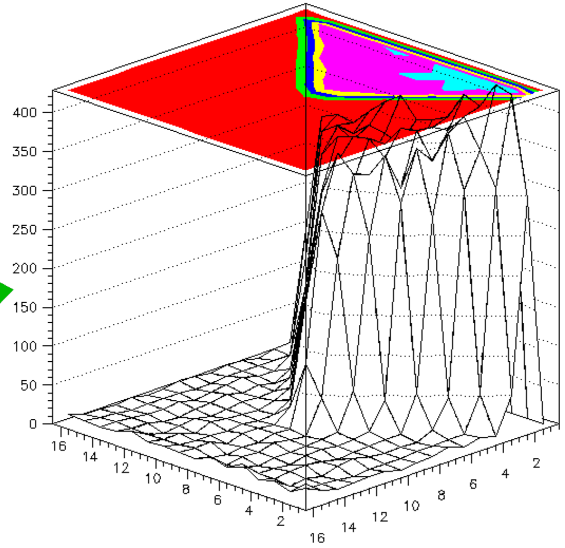




XY distribution

the test with AmBe source

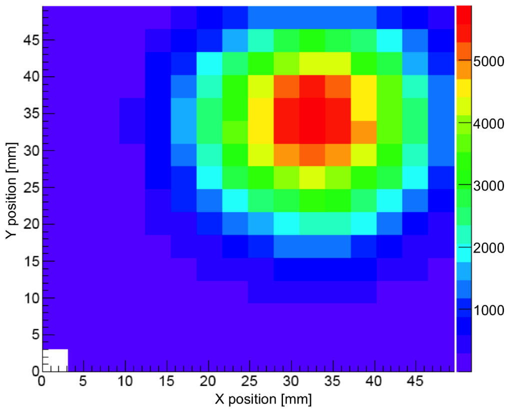


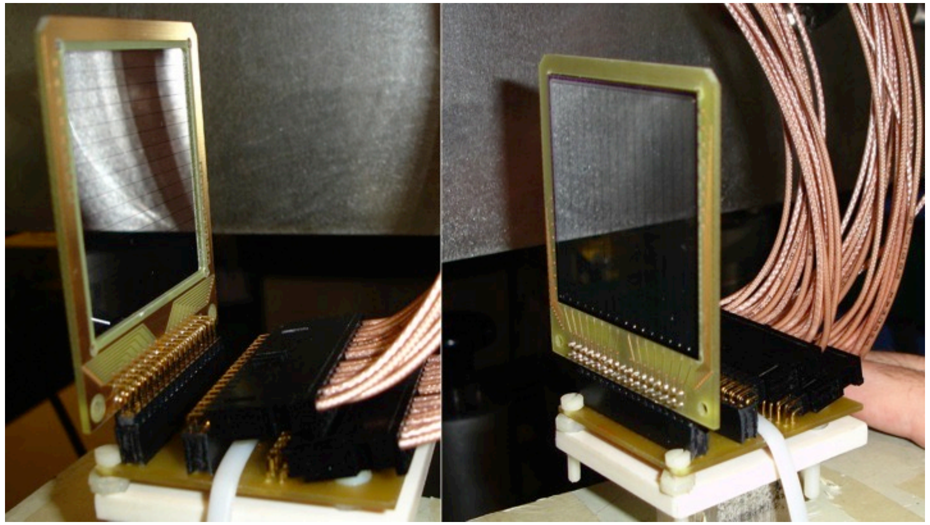


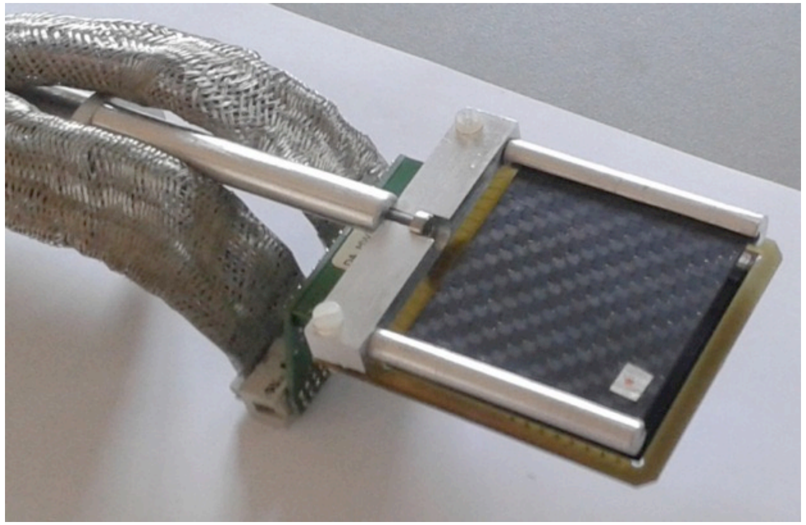
SiMon2D @ n_TOF: neutron beam profiler

5cm x 5cm double-sided strip SiLiF detector
25 strips, 2mm x 5cm

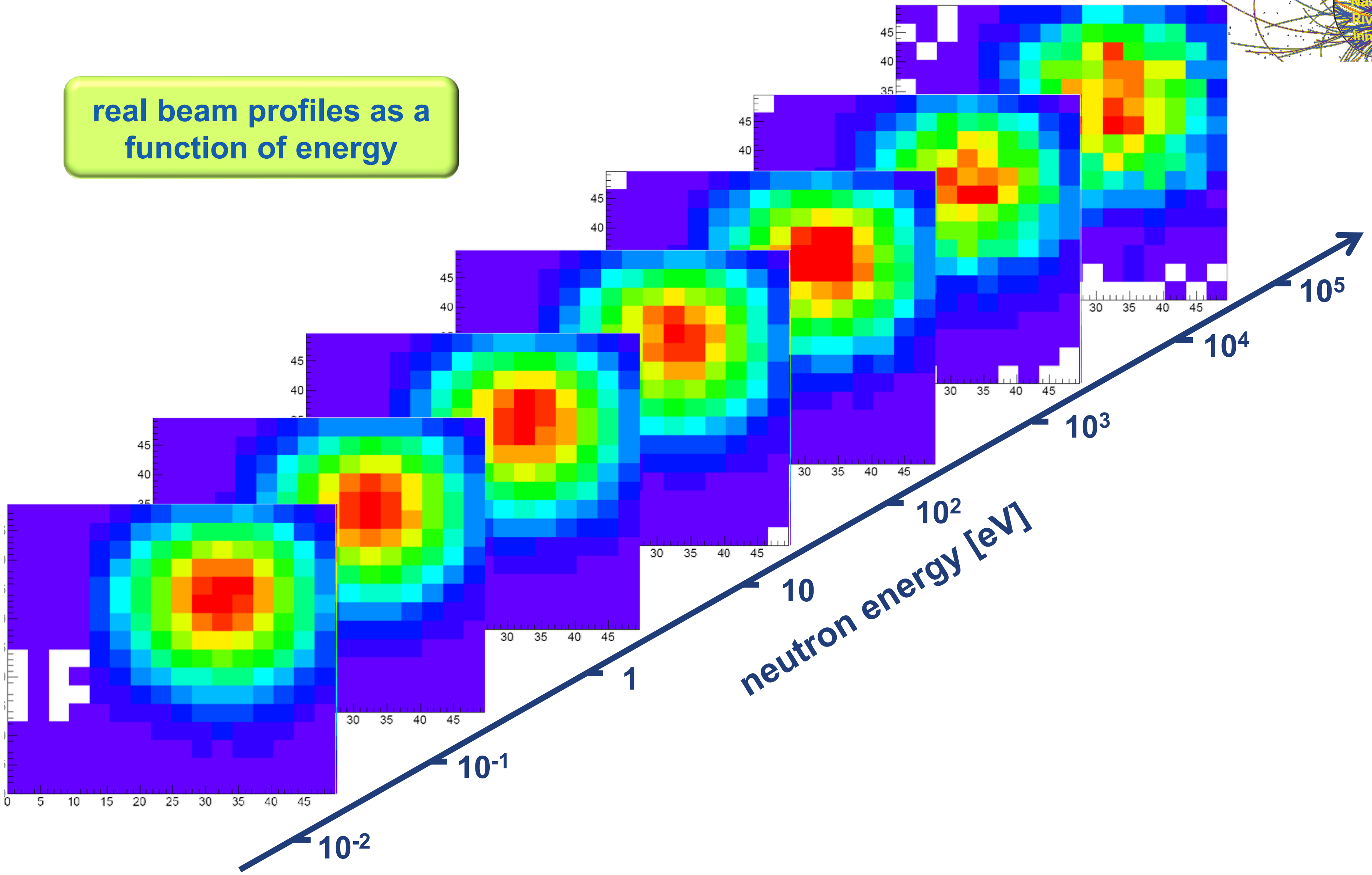
real beam profile





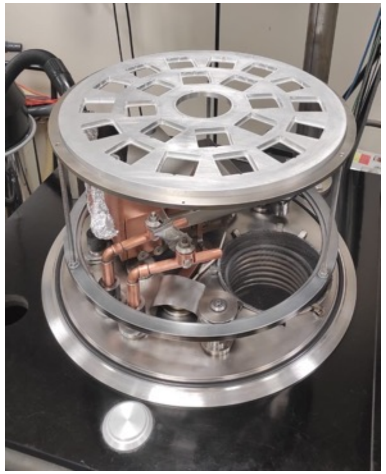


real beam profiles as a function of energy

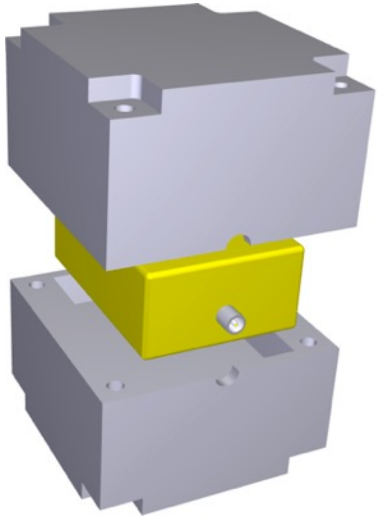


32 SiLiF detectors built for MICADO EU project to monitor emission from radioactive waste

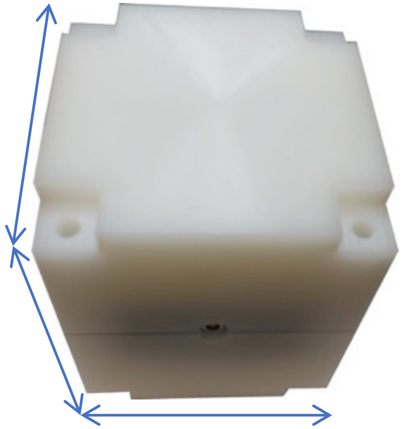
multiple ^{6}LiF evaporation on C-fiber



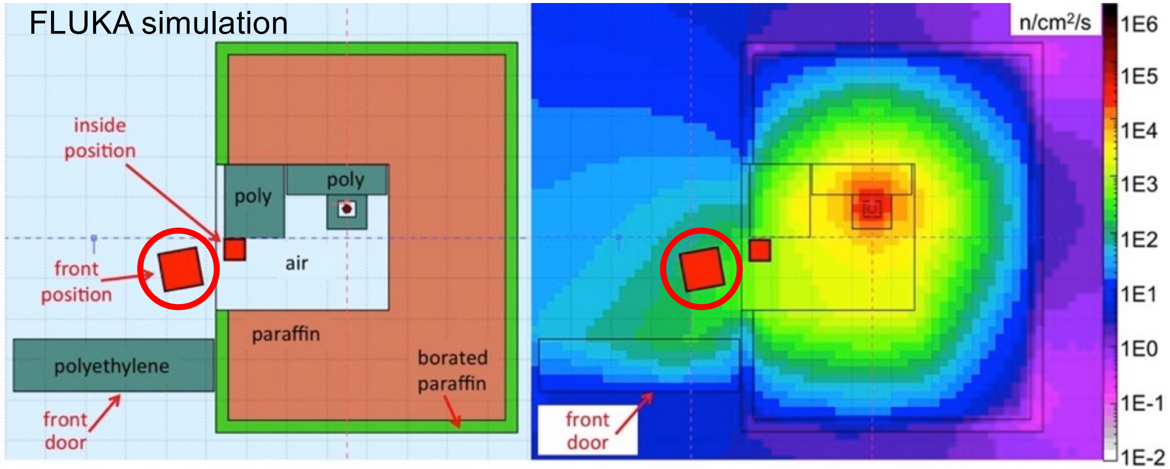
detector assembling

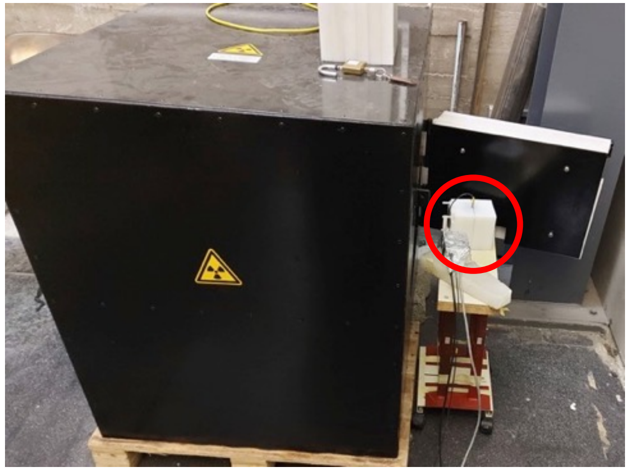


10 x 10 x 10 cm^3
PET moderators to
slow down neutrons

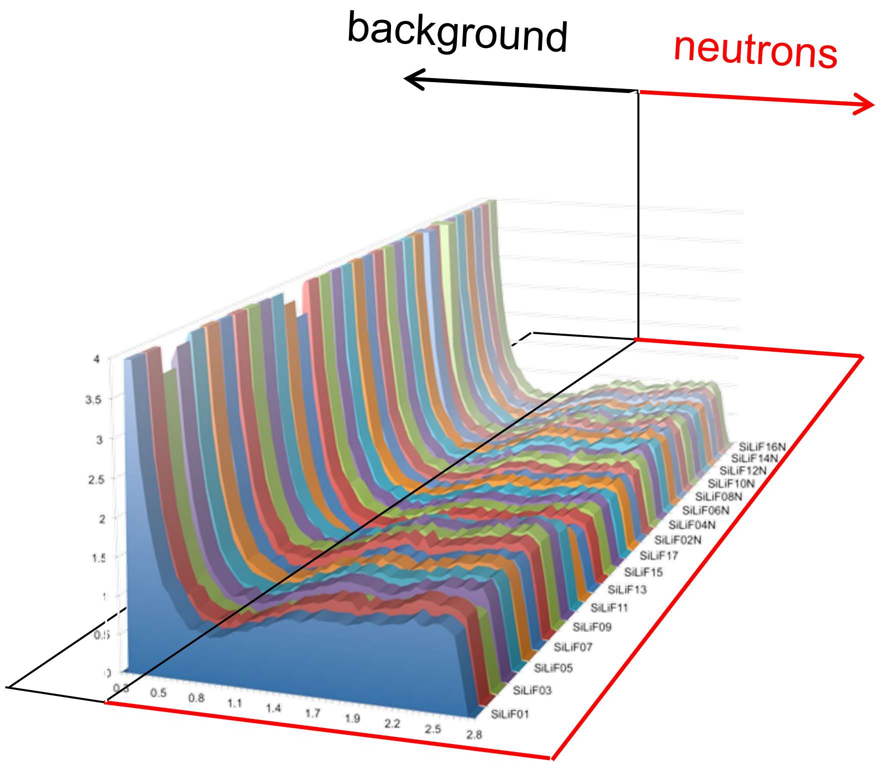


32 SiLiF detectors tested for MICADO EU project

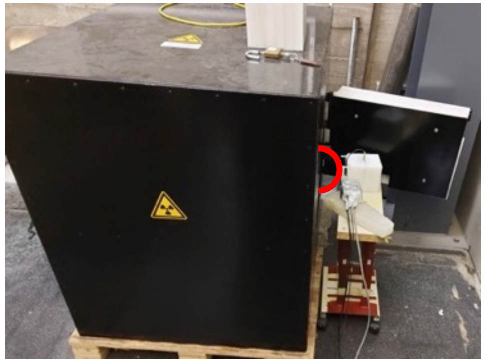




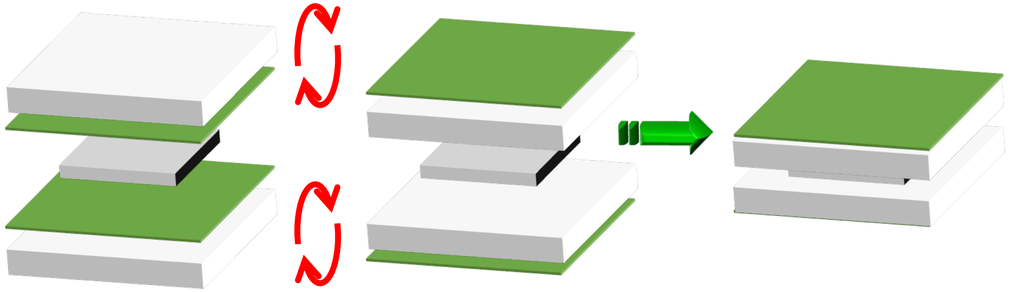
AmBe neutron source

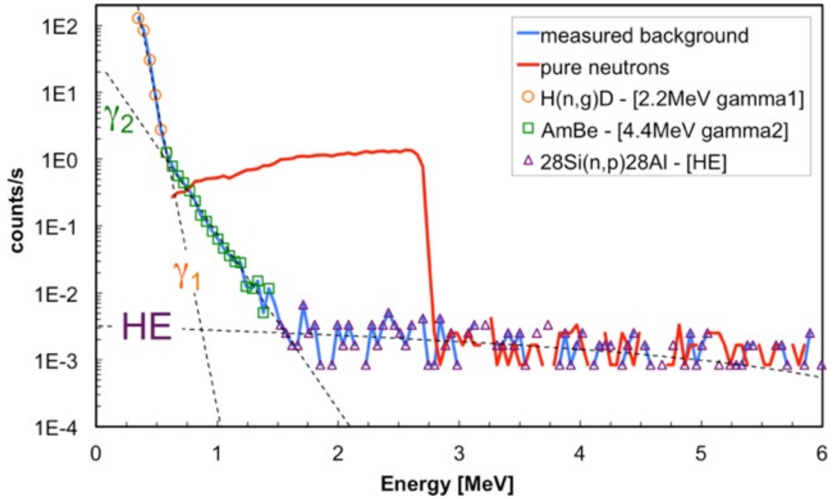


evaluation of gamma rejection

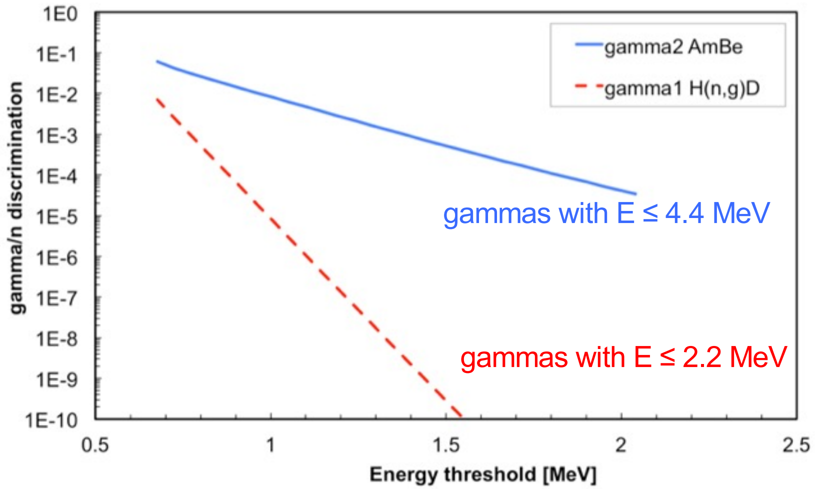


measurement of background with upside-down converters



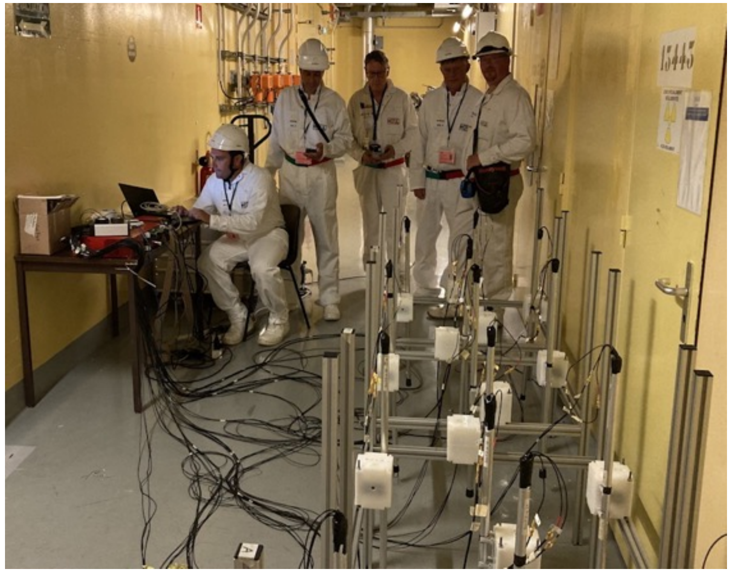


knowledge of pure neutron and pure background to calculate gamma/neutron discrimination power



target: 10^{-5} with Eγ ≤ 1.3 MeV (“optimal” according to IAEA)

obtained: ≤ 10^{-9} with Eγ ≤ 2.2 MeV (SiLiF with threshold at 1.5 MeV)

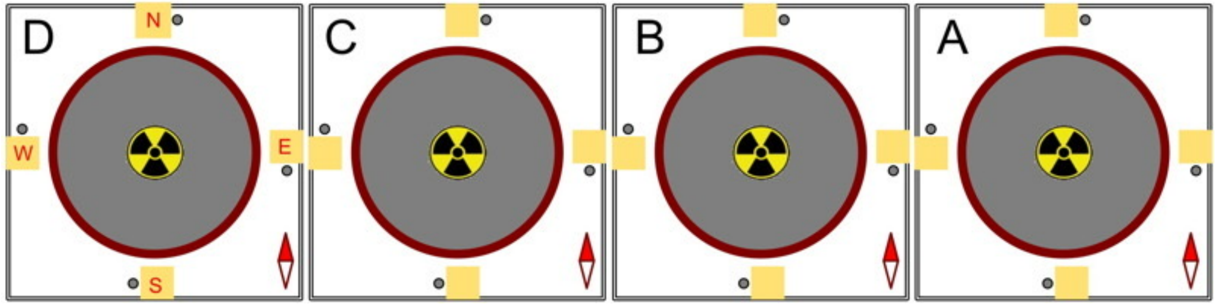


MICADO test at ORANO
La Hague on four drums (with Pu)
25-28 Jul 2022

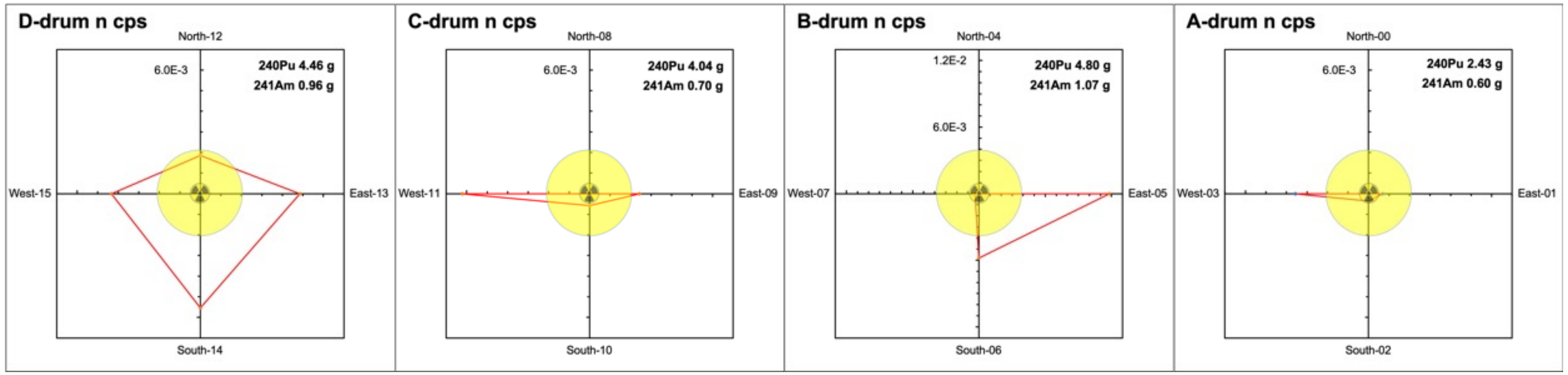
MICADO test at Nucleco
Casaccia on four drums
14 Dec 2022 to 26 Jan 2023

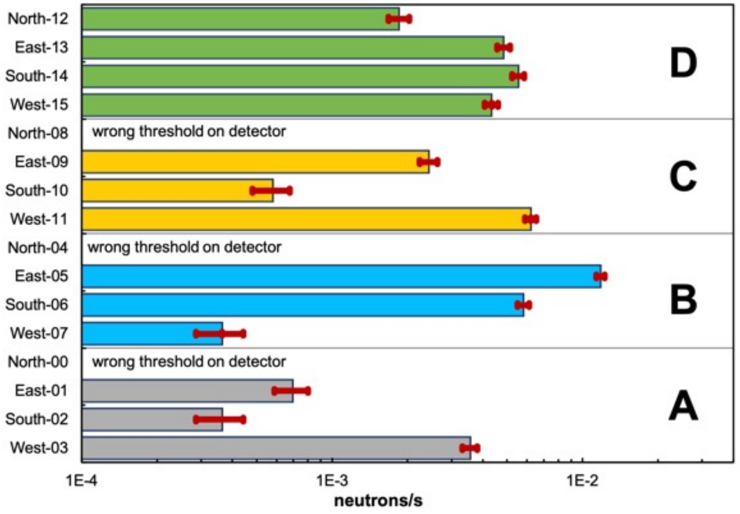
Test at ORANO La Hague on four drums (with Pu)

SiLiF neutron detectors



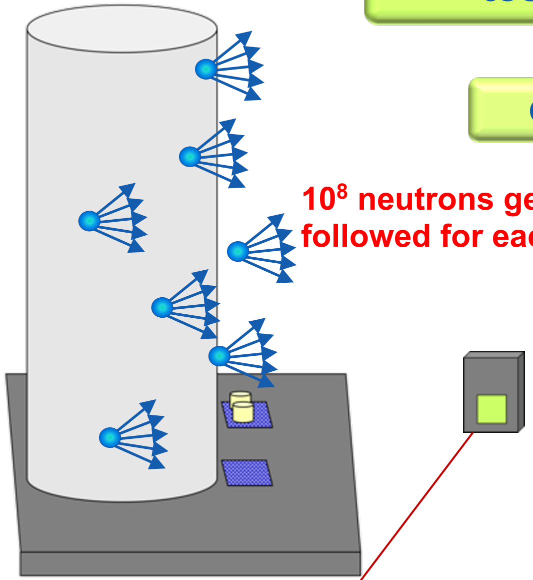
RP people measured and declared << 1 n/s (basically zero)



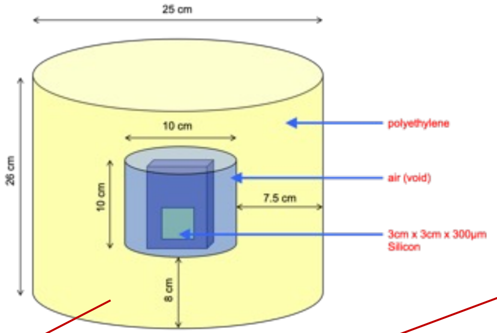


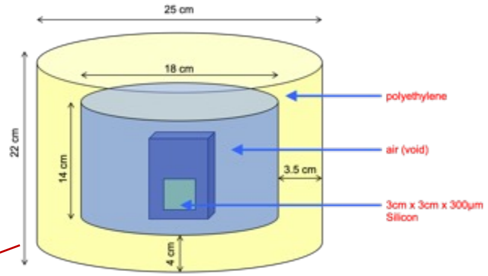
test with spent fuel casks at ZWILAG (CH)

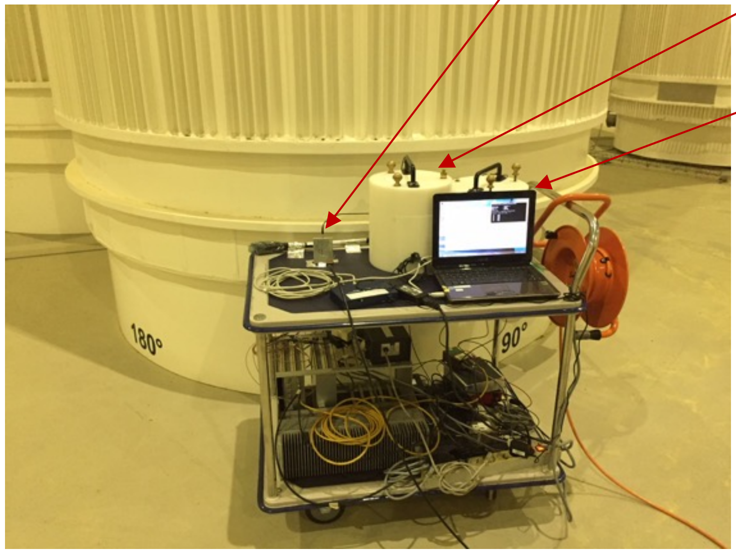
Geant4 simulation and validation of a test setup for spent fuel monitoring

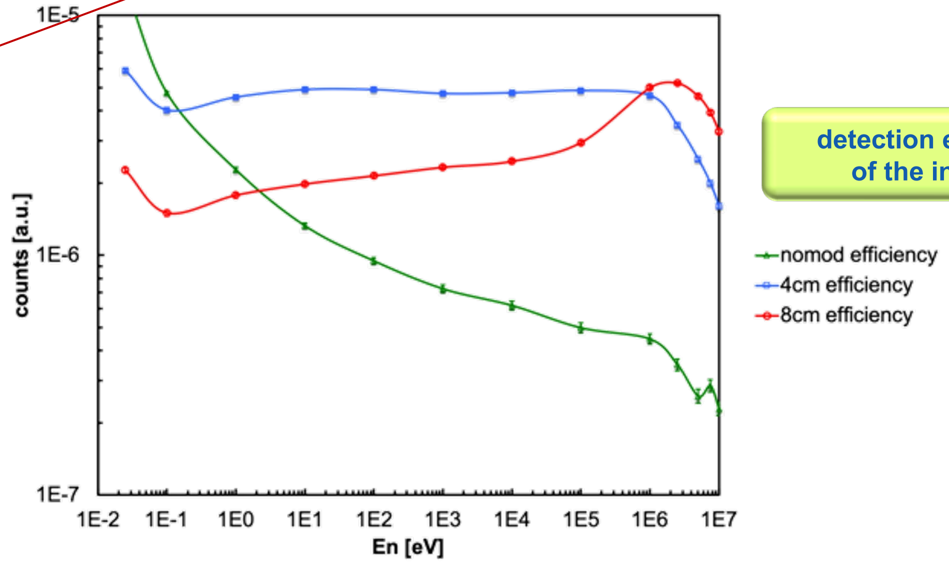


10^8 neutrons generated and followed for each energy







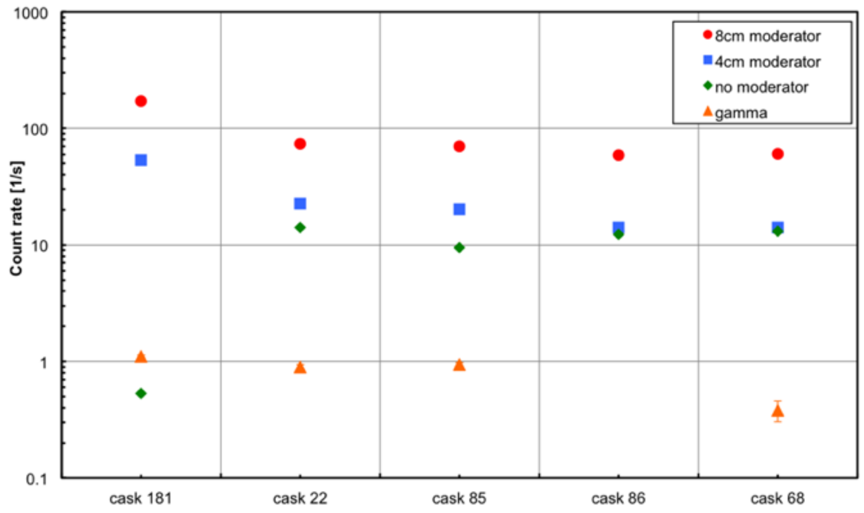


detection efficiency as a function of the initial neutron energy

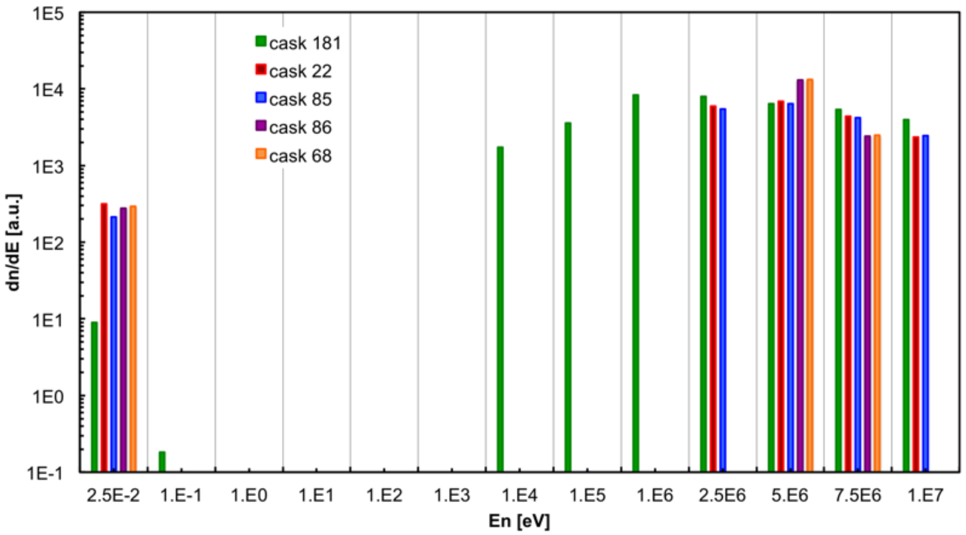
test with spent fuel casks at ZWILAG (CH)

test in collaboration with ZWILAG

ZWILAG



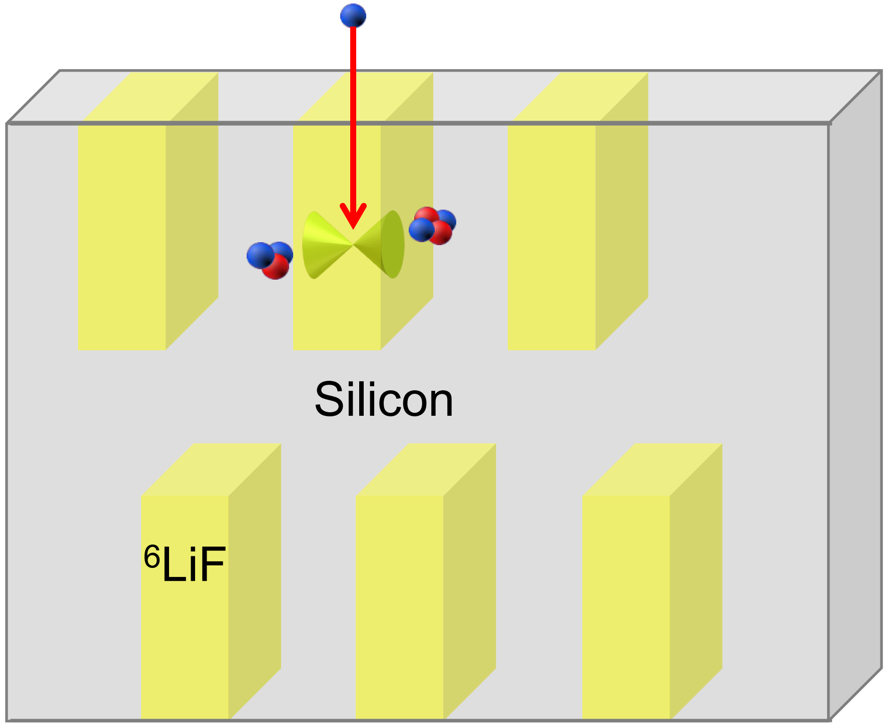
neutron counting rates
5 casks tested

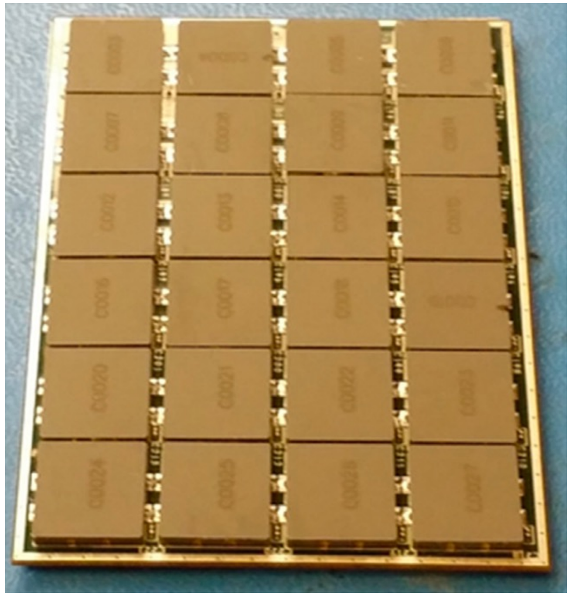


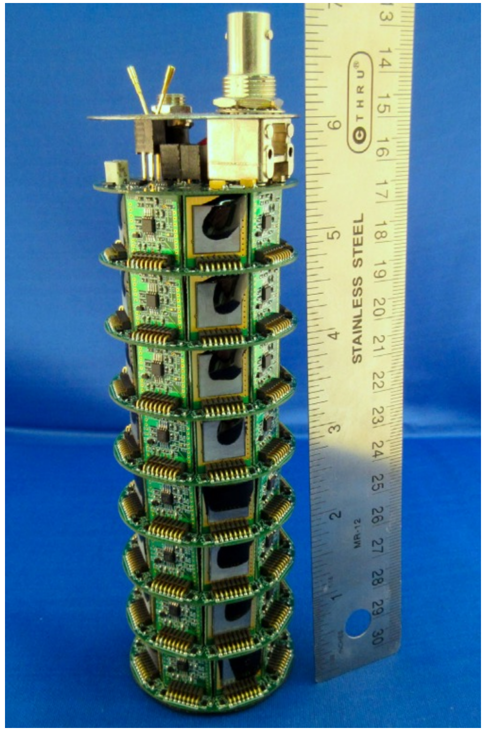
rough reconstructed neutron energy spectrum

Double Sided Multi Structured Neutron Detector

up to >30% detection efficiency, gamma/n ~ 10^{-5}







developed by D. McGregor and collaborators

a few papers about neutron detection

...but by googling you can also find quite interesting presentations...

- A. Pietropaolo, M. Angelone, et al. Neutron detection techniques from µeV to GeV, https://doi.org/10.1016/j.physrep.2020.06.003
- I. Liu, et al., Sci. China-Phys. Mech. Astron. 66, 232001 (2023), https://doi.org/10.1007/s11433-022-2021-6
- Jun-Kai Yang, et al., Nuclear Science and Techniques (2022) 33:164
- T.R. Ochs, et al., Nuclear Inst. and Methods in Physics Research, A 954 (2020) 161696
- T.R. Ochs, et al., Radiation Physics and Chemistry 155 (2019) 164–172
- P. Finocchiaro et al., Nucl. Instr. Meth. A885 (2018) 86–90
- S. Lo Meo et al., Nucl. Instr. Meth. A866 (2017) 48–57
- A.Pappalardo et al., Results in Physics 6 (2016) 12–13
- A.Pappalardo et al., Nucl. Instr. Meth. A810 (2016) 6-13
- L.Cosentino et al., Rev. Sci. Instr. 86 (2015) 073509
- D.Henzlova et al., "Current Status of 3He Alternative Technologies for Nuclear Safeguards", prepared for NNSA-DOE and Euratom
- P.Kavrigin et al., Nucl. Instr. Meth. A795 (2015) 88–91
- I.A. Pawełczak, et al., Nuclear Instruments and Methods in Physics Research A 751 (2014) 62–69
- S.M.Carturan et al., EPJPlus 129 (2014) 212
- P.Finocchiaro, Nuclear Physics News, 2014, v24, n3, (2014) 34
- A.Pappalardo et al., Optical Engineering 53(4)047102, April 2014
- M.Barbagallo et al., Rev. Sci. Instrum 84 (2013) 033503
- P.Finocchiaro, in “Radioactive Waste: Sources, Types and Management”, Nova Science Publishers, 2012

Thank you