# Radwaste monitoring: detectors and system developments

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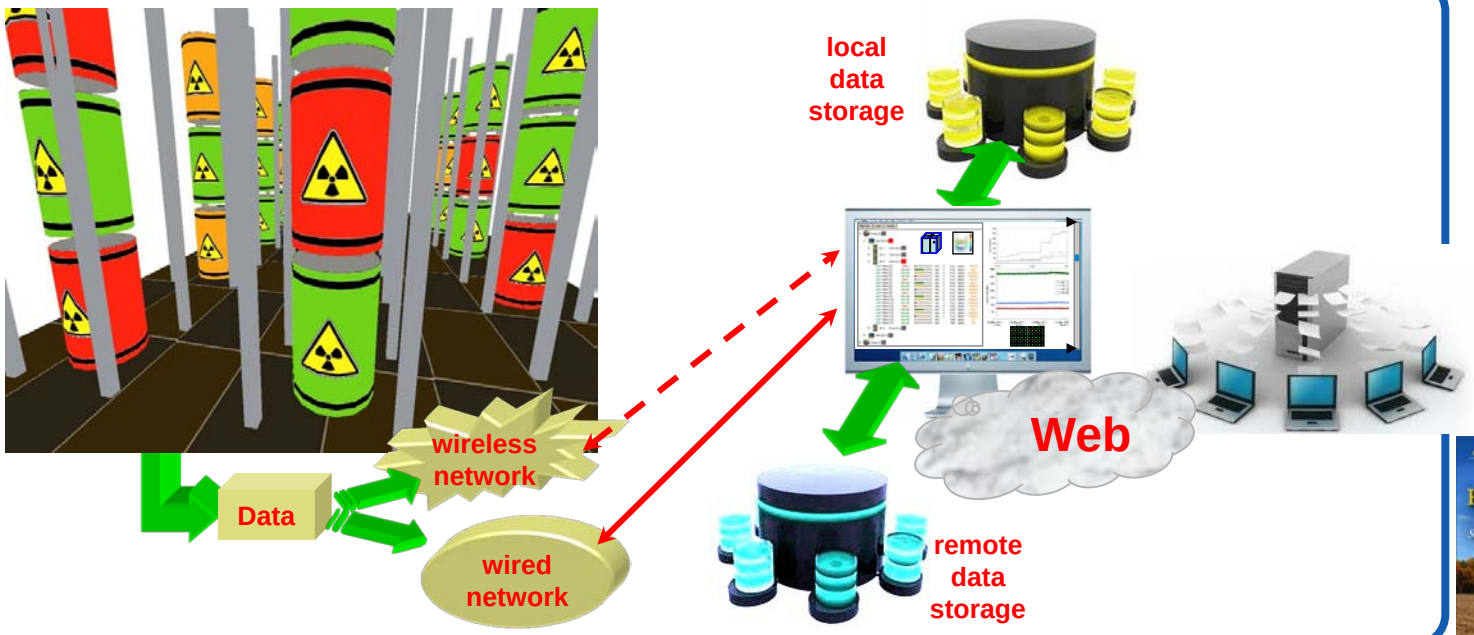
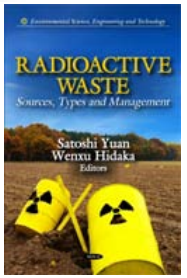
**Real-time online monitoring of radioactive waste**




**DMNR** Detector Mesh for Nuclear Repositories

# the problem

radwaste produced worldwide
usually packed into special drums

the storage site should be monitored for leaks or breaks, to prevent possible contamination of the environment and/or people

**online monitoring can minimize the need of human intervention inside (ALARA)**

**No repository with online real-time monitoring (to our knowledge)**

radwaste confined into "*long lasting*" drums?


**DMNR: the system**

- On-line monitoring of short/medium term radioactive waste storage
- Application of non-conventional detectors for decommissioning

**DMNR: goals**

- real-time continuous activity monitoring & recording
- on-line availability of data to control authorities, fire departments, local and national governments, etc.
- radwaste handling by means of advanced tools and procedures suitable for reducing the risks to the local workers and to the population

# What comes out of a waste drum?

***basic radioactivity coming out is gamma rays***

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*They know, they know, but...*
*I'll tell them anyhow!!!*

*beta particles are mostly stopped inside the material and in air*

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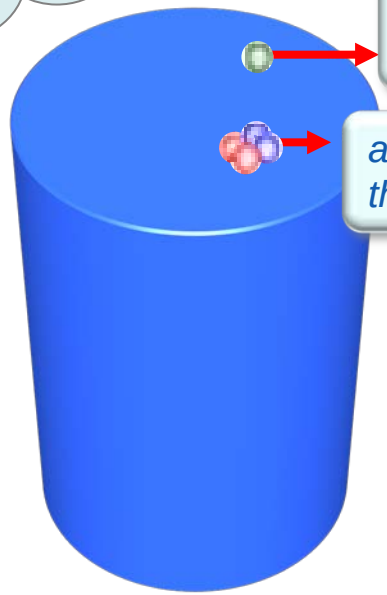

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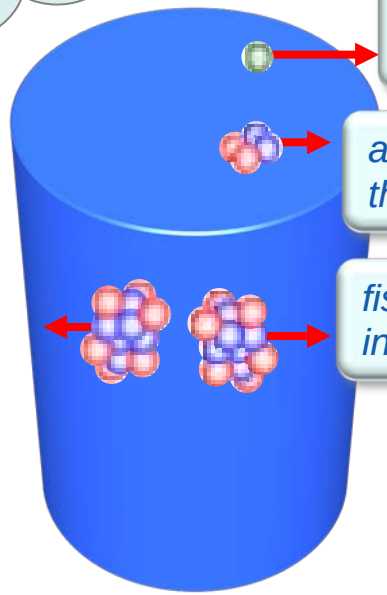

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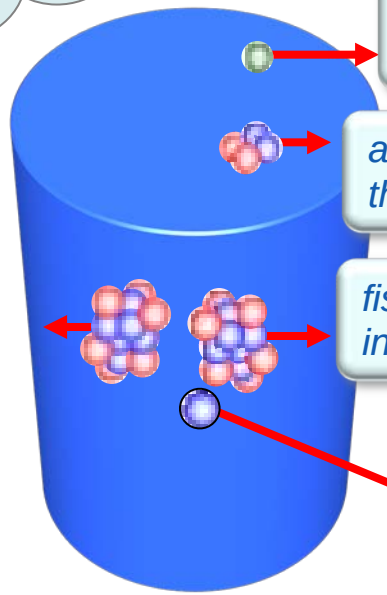

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*neutrons (from fission) come out very easily but at very small dose. The amount of fissile material in the drums is small: it is removed before packing the drums (not so for spent fuel rods)*

*I love fuel rods*

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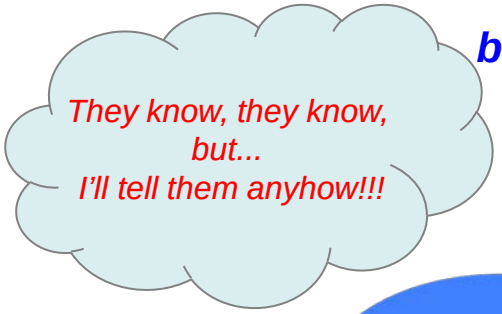



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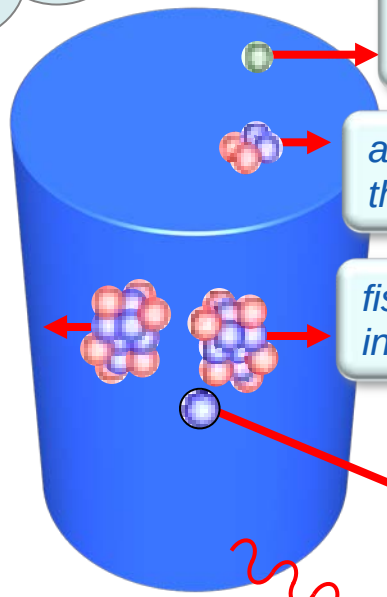

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*gamma rays are penetrating, therefore they come out easily and abundantly*

**the detector:**
**scintillating fiber + 2 SiPM**

*the SiPM can detect the very short scintillation light pulse produced by gamma interaction*

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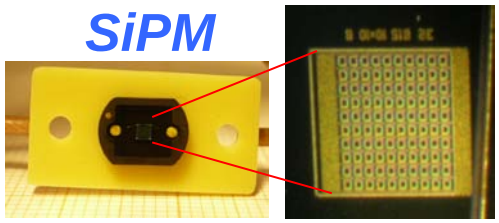
**scintillating fiber + 2 SiPM**

## SiPM

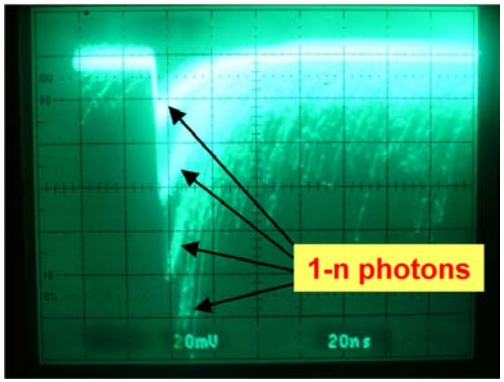


the SiPM can detect the very short scintillation light pulse produced by gamma interaction

1-cell ⇒ charge = k
n-cells ⇒ charge = nk

*low bias voltage (30V)*
*high gain*

*1 photon gives rise to a signal of about 10^6 electrons*



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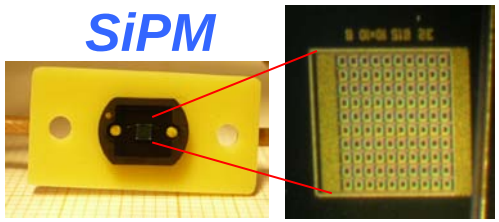

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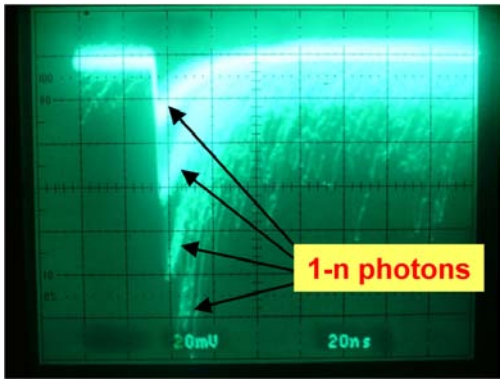
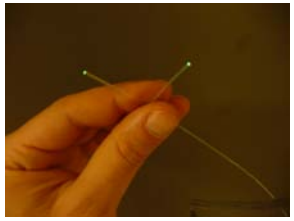
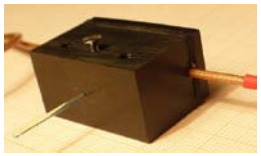



*SiPM*



*fiber*



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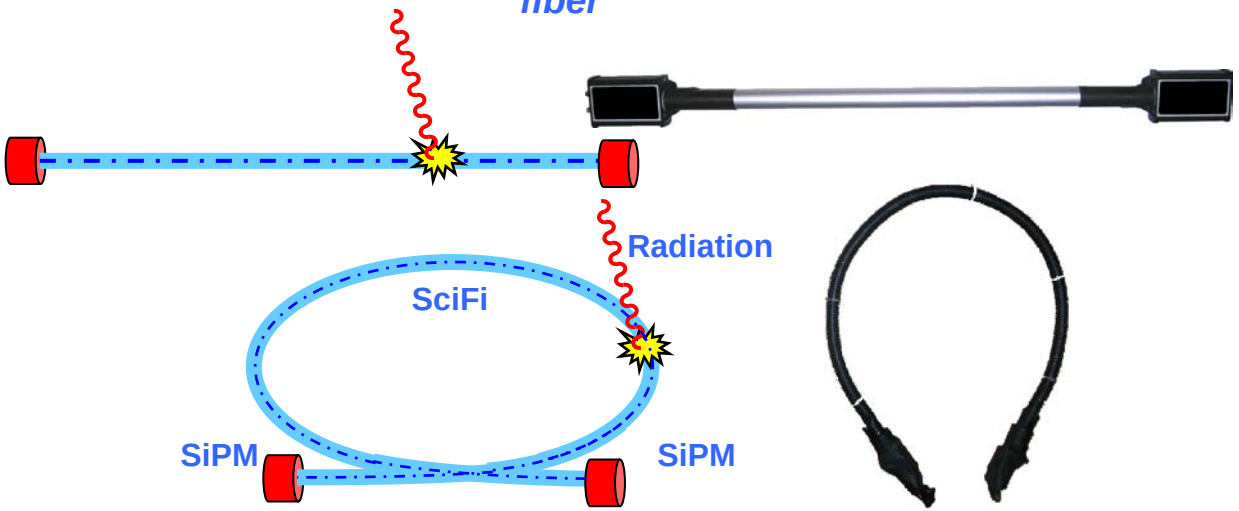

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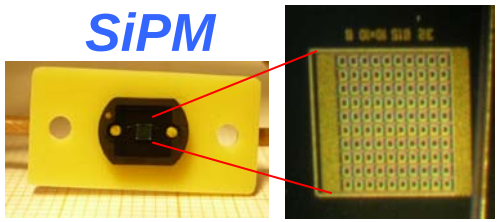

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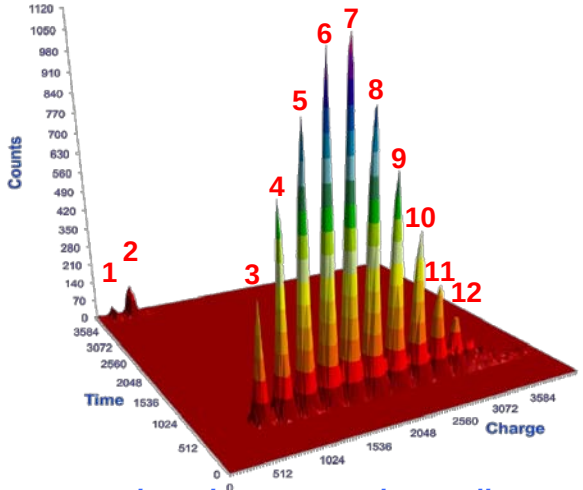


*each peak corresponds to a discrete number of detected photons*

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*high gain*

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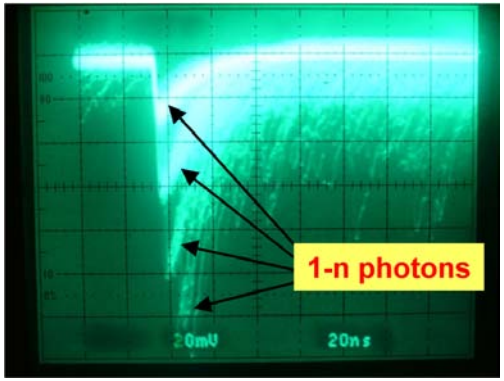


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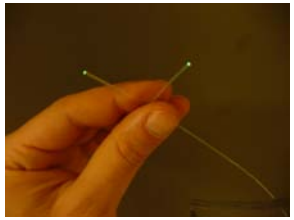

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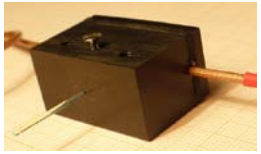

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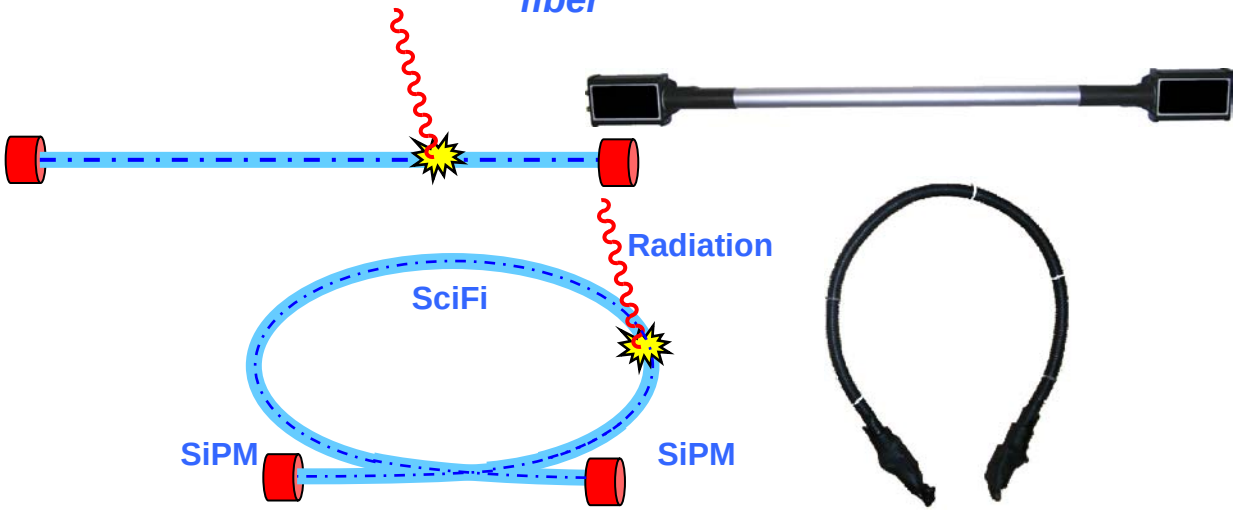


# Sensor features

radiation hardness ≈100-1000 years close to a drum with 10-100 mGy/h

robustness yes, plastic scintillators; SiPM not damaged by ambient light exposure

low efficiency ≈0.1%

high sensitivity: few photons

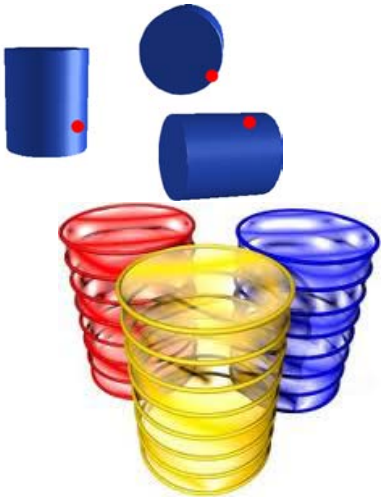
reliability yes

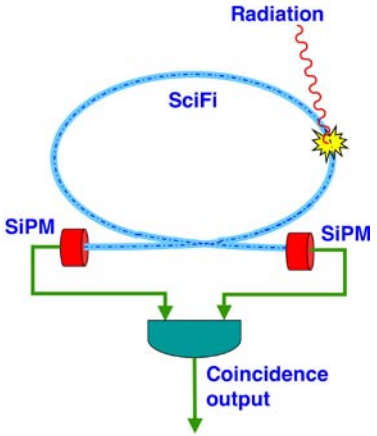
(possible position sensitivity) yes

ease of handling yes

low cost yes

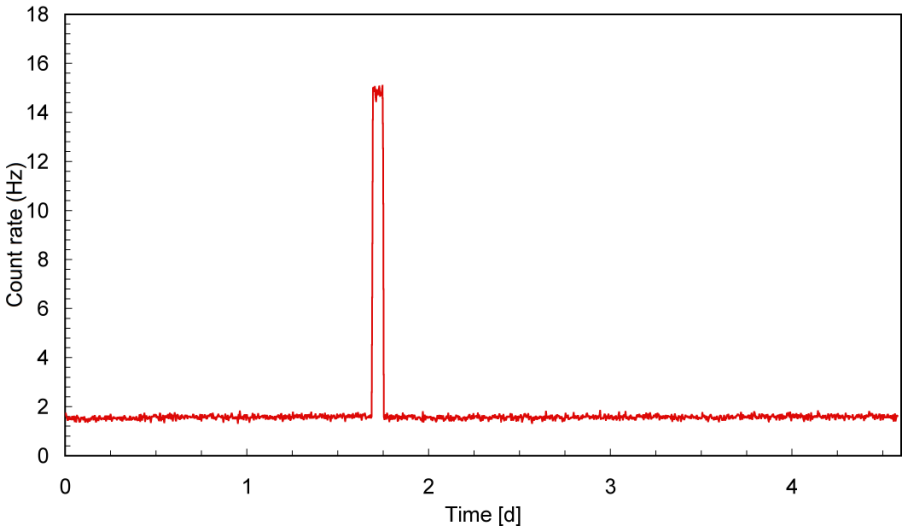
***the left-right coincidence suppresses spurious counts***




***a mesh of scintillating fibers read-out at both ends by means of Silicon PhotoMultipliers (SiPM)***

# bench tests



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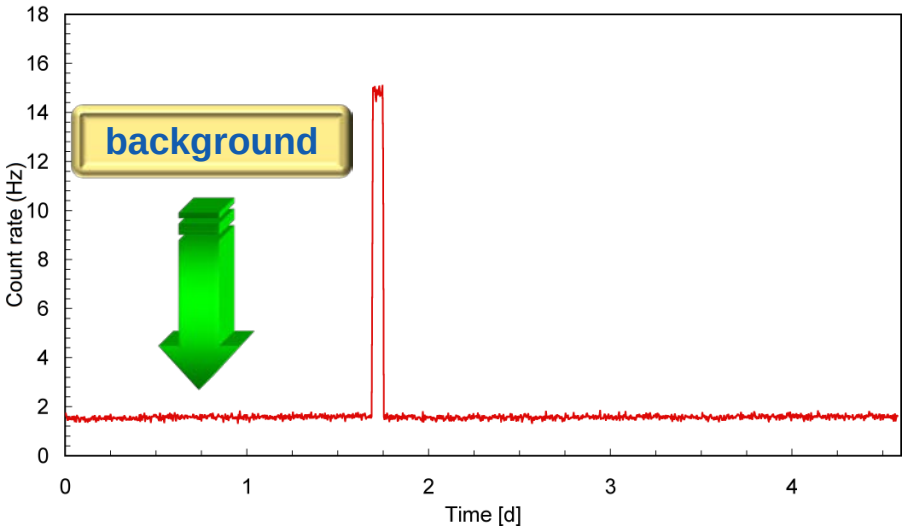
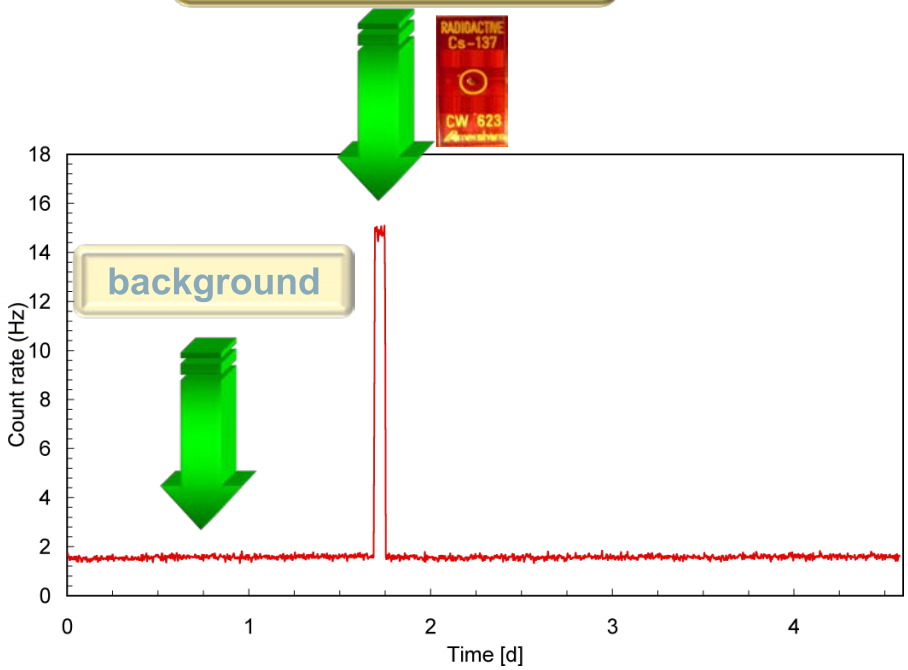


# bench tests

gamma source
2.7MBq at 10cm



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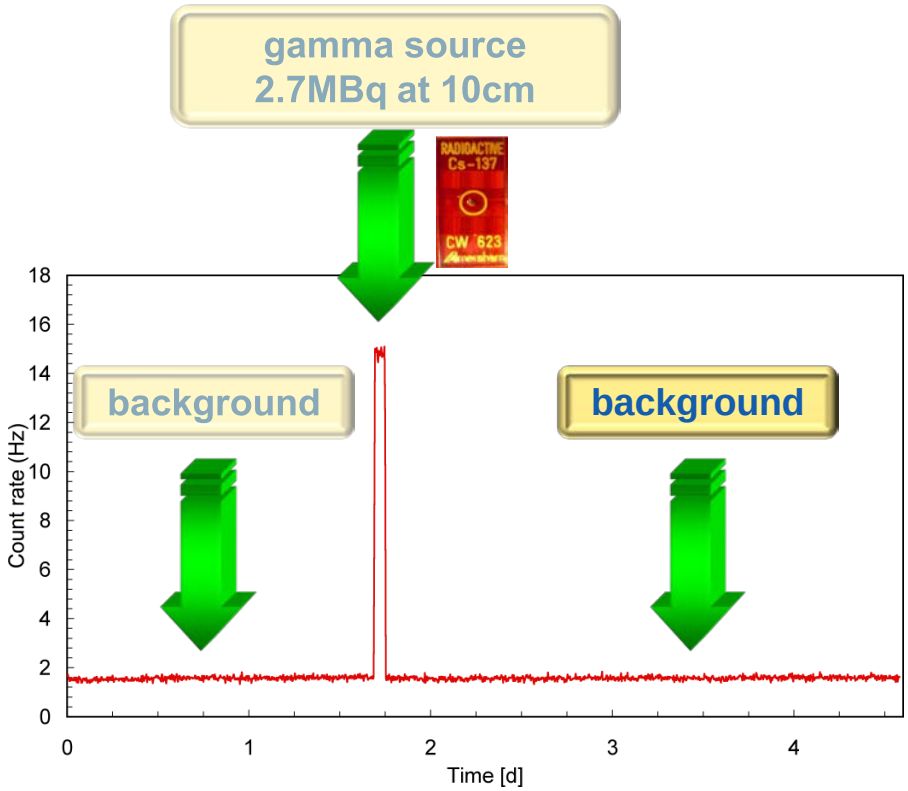
gamma source
2.7MBq at 10cm
RADIOACTIVE
Cs-137
CW 623
background
background
Count rate (Hz)
Time [d]
0
2
4
6
8
10
12
14
16
18
0
1
2
3
4

# bench tests

gamma source
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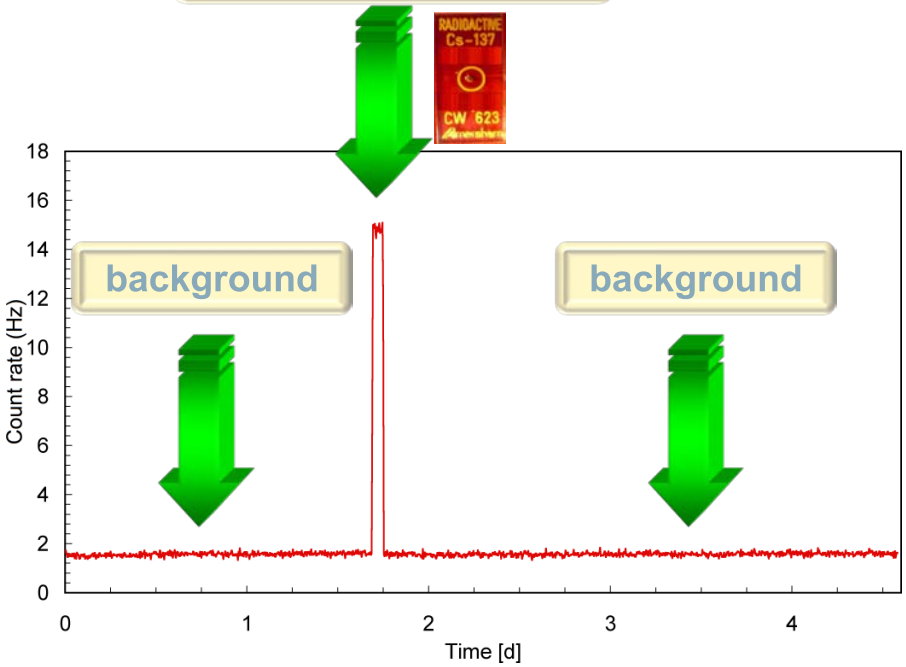


3D reconstruction by
crossed fibers

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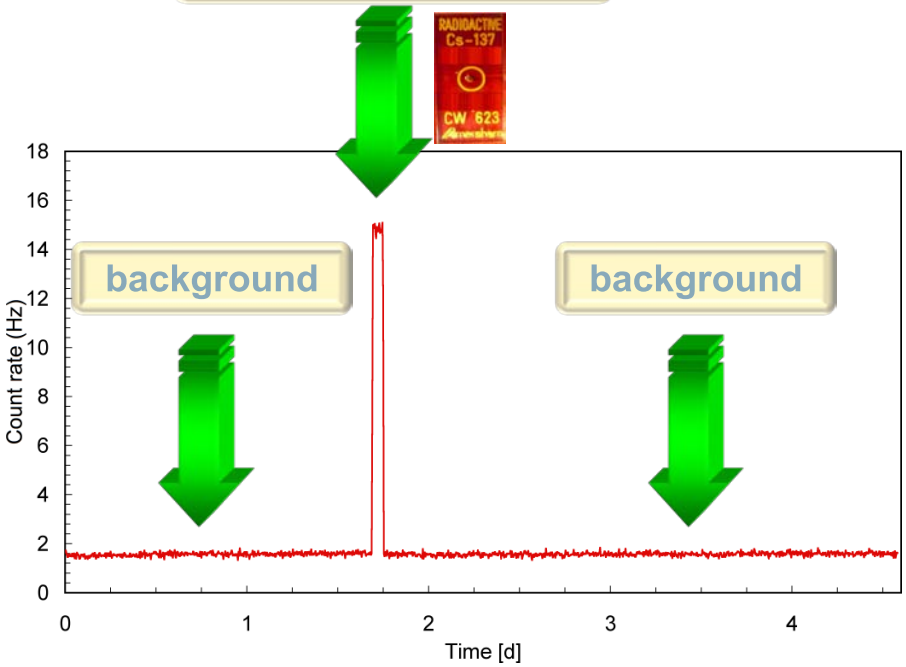


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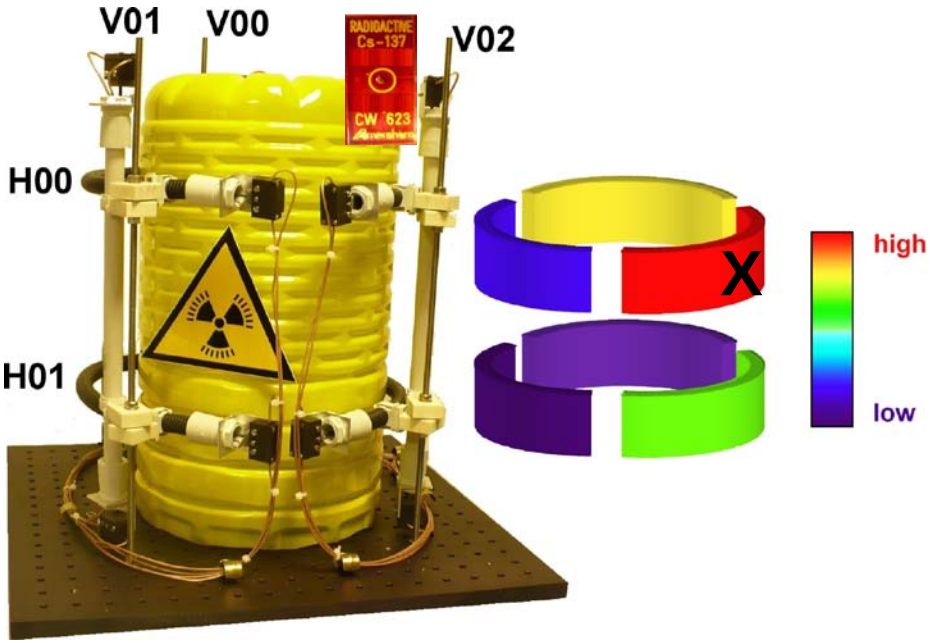
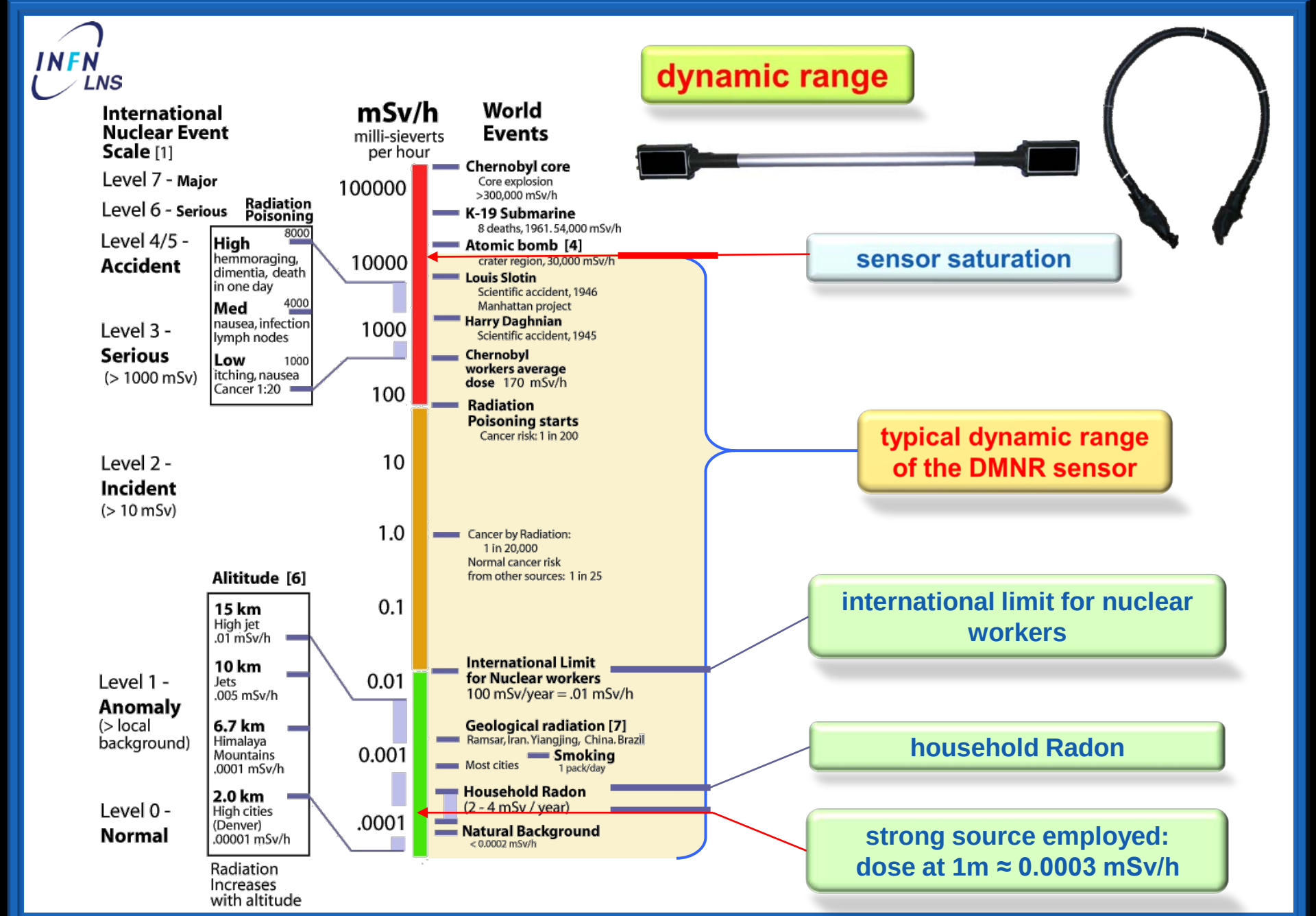



dynamic range
International Nuclear Event Scale [1]
Level 7 - Major
Level 6 - Serious
Level 4/5 - Accident
Level 3 - Serious (> 1000 mSv)
Level 2 - Incident (> 10 mSv)
Level 1 - Anomaly (> local background)
Level 0 - Normal
Radiation Poisoning
8000 High hemmoraging, dimentia, death in one day
4000 Med nausea, infection lymph nodes
1000 Low itching, nausea Cancer 1:20
Alititude [6]
15 km High jet .01 mSv/h
10 km Jets .005 mSv/h
6.7 km Himalaya Mountains .0001 mSv/h
2.0 km High cities (Denver) .00001 mSv/h
Radiation Increases with altitude
mSv/h
milli-sieverts per hour
100000
10000
1000
100
10
1.0
0.1
0.01
0.001
.0001
World Events
Chernobyl core
Core explosion >300,000 mSv/h
K-19 Submarine
8 deaths, 1961. 54,000 mSv/h
Atomic bomb [4]
crater region, 30,000 mSv/h
Louis Slotin
Scientific accident, 1946 Manhattan project
Harry Daghnian
Scientific accident, 1945
Chernobyl workers average dose 170 mSv/h
Radiation Poisoning starts
Cancer risk: 1 in 200
Cancer by Radiation: 1 in 20,000
Normal cancer risk from other sources: 1 in 25
International Limit for Nuclear workers
100 mSv/year = .01 mSv/h
Geological radiation [7]
Ramsar, Iran. Yiangjing, China. Brazil
Most cities
Smoking 1 pack/day
Household Radon
(2 - 4 mSv / year)
Natural Background
< 0.0002 mSv/h
sensor saturation
typical dynamic range of the DMNR sensor
international limit for nuclear workers
household Radon
strong source employed: dose at 1m ≈ 0.0003 mSv/h

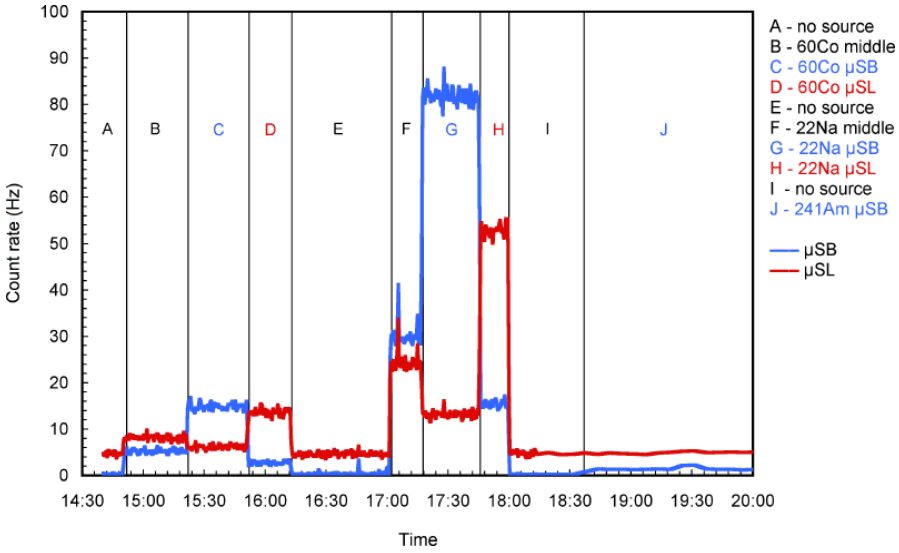
## new low-noise μSB sensors

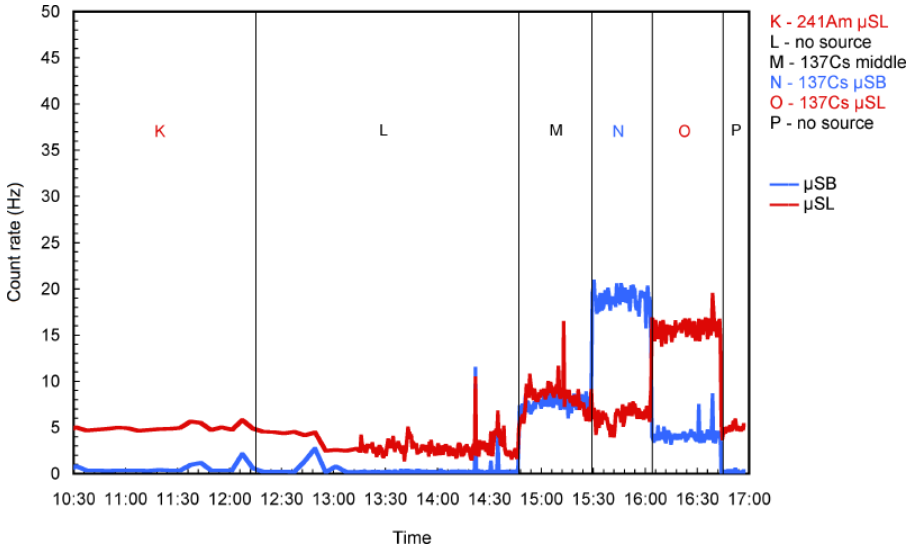
tests with $^{241}$Am, $^{22}$Na, $^{137}$Cs, $^{60}$Co sources

μSL

μSB

intrinsic efficiency: between $10^{-2}$ and $10^{-6}$



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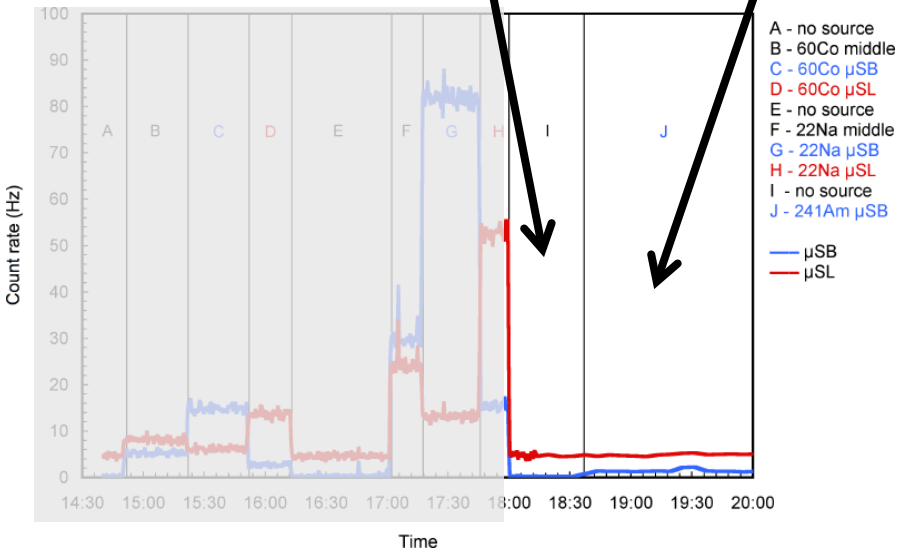
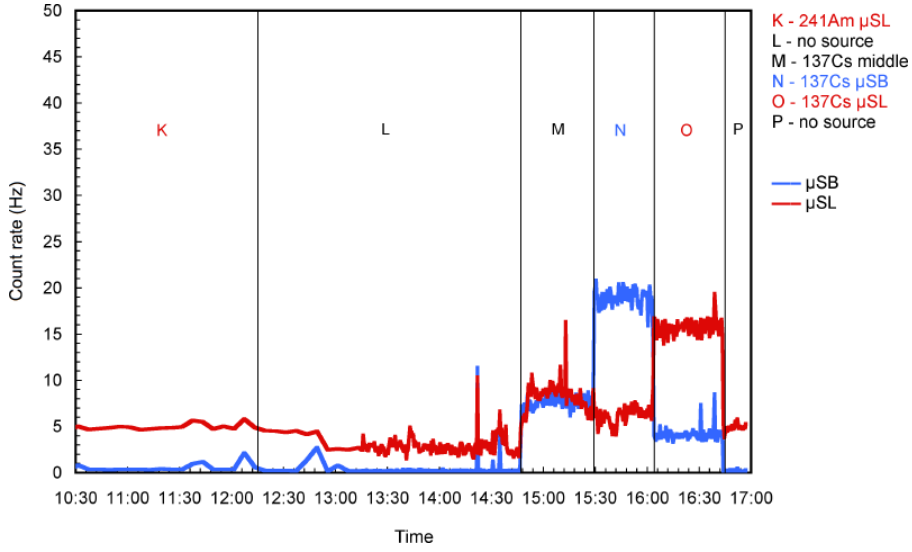
no source

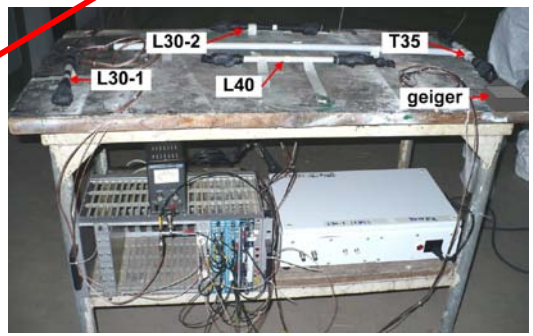
$^{241}$Am

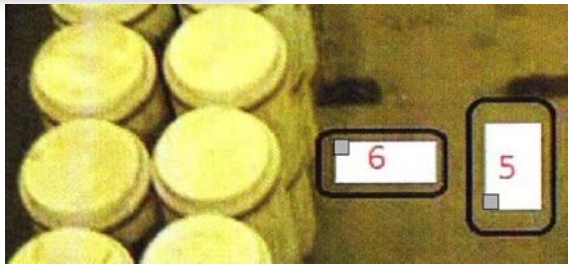


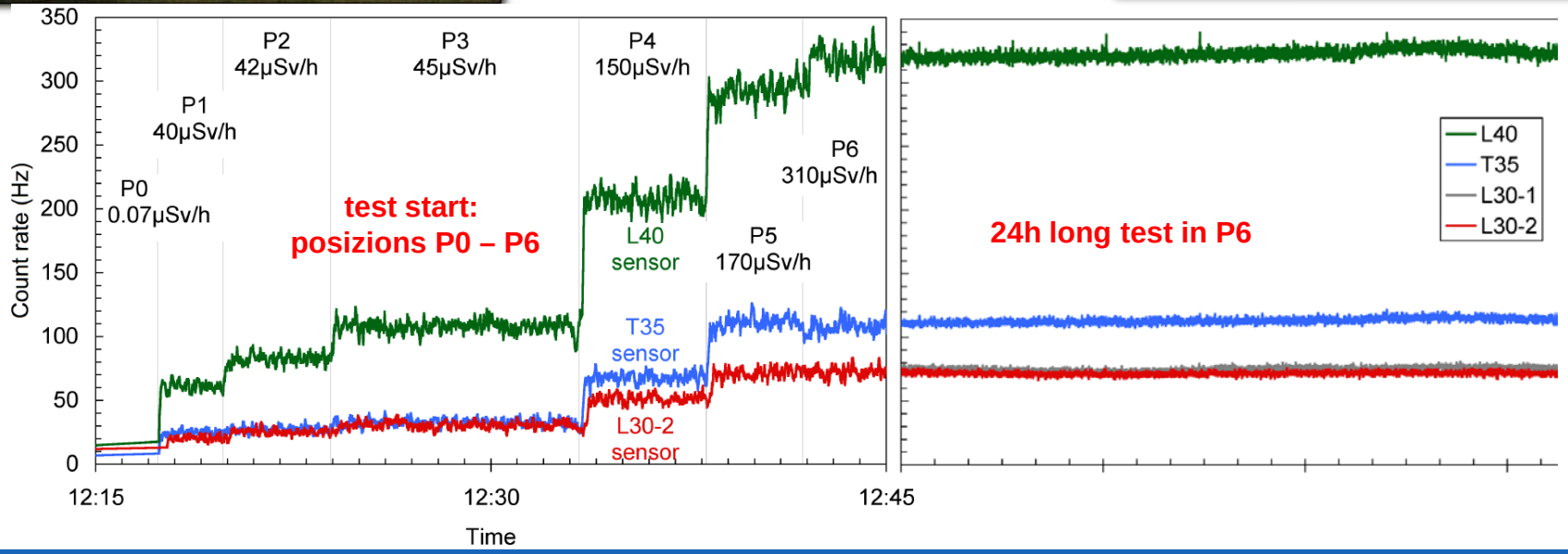
# test with real radwaste drums

temporary storage inside the former power plant of Garigliano at Sessa Aurunca (SOGIN S.p.a.)



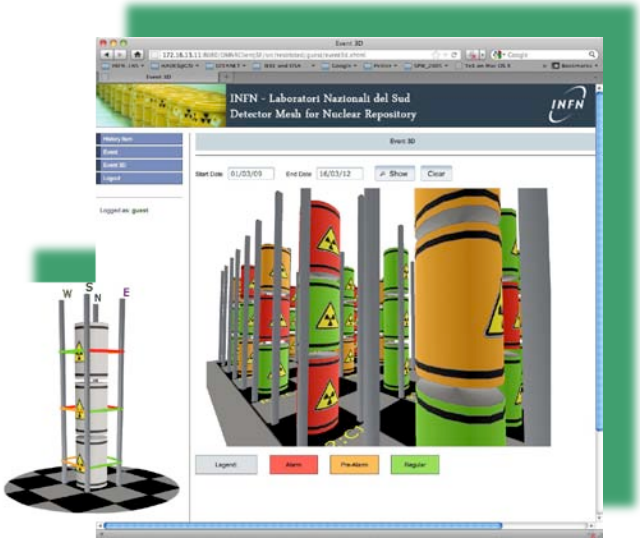




4 sensors (+geiger) on a pushcart placed at 7 positions (P0-P6) with increasing dose rates



**Technology transfer**

**collaboration agreement**
**INFN - SOGIN**
**signed on 8-Nov-2012**
**duration: 2 years**

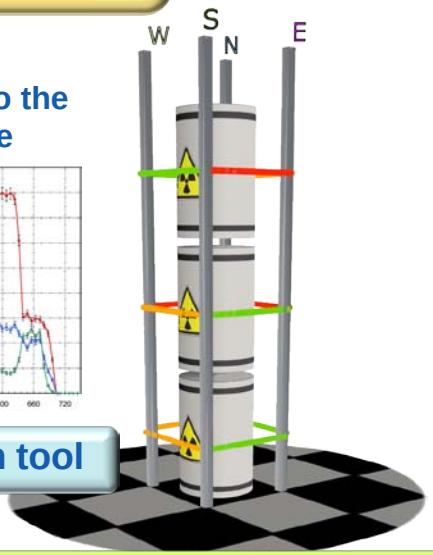



**implementation of a prototype DMNR monitoring system in a new radwaste repository (Garigliano former power plant)**

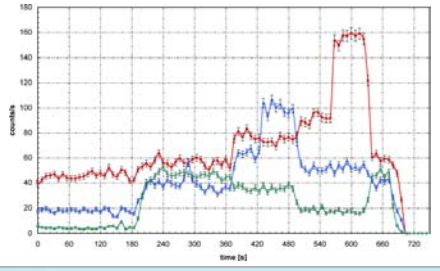
# user interface

- *online display and data check*
- *counting rate channel by channel*
- *programmable alarm levels*

***details available in real time down to the single drum and to the single fiber around a drum***




**direct connection to the sensor database**



**3D virtual navigation tool**



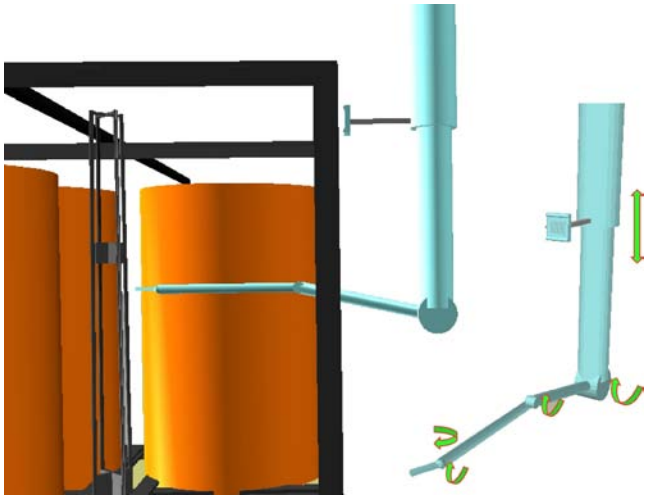

**electronics and computing entirely developed at LNS**

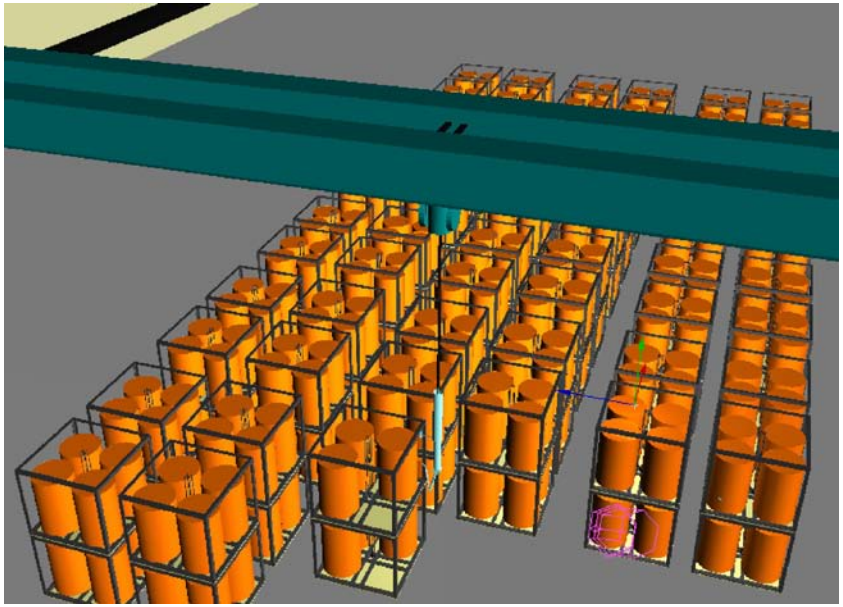
## drum inspection: new remotely controlled robotic arm

**5 degrees of freedom**

**payload:**

**inspection video camera**
**gamma detector**



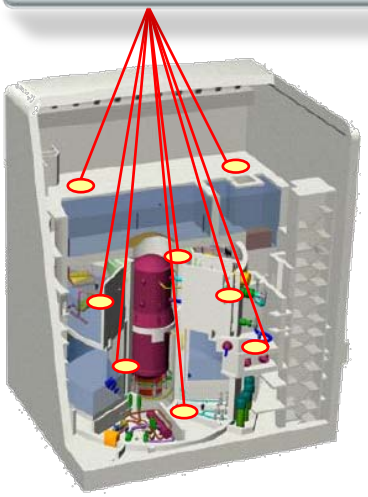


**young student L.Russo**
**winner of a SIF award to participate in E2C 2013 conference in Budapest**

# Collaboration with JRC & Euratom: neutron detection

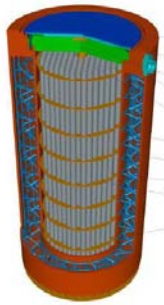
(INFN patent pending RM2013A000254)

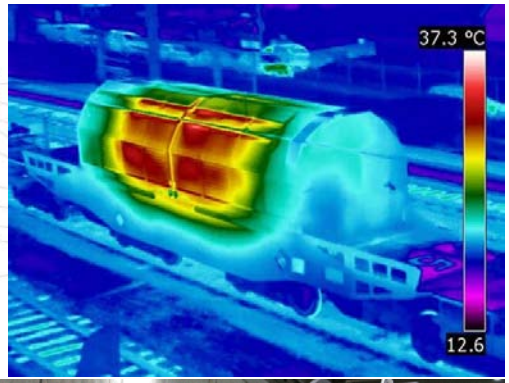
out-of-core monitoring in NPP

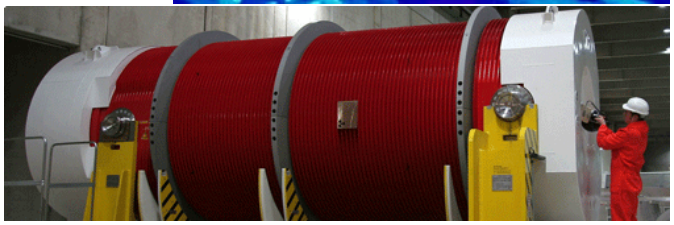


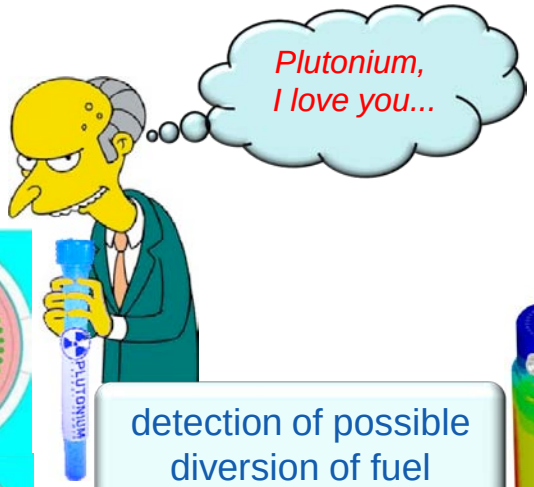
## why neutrons?

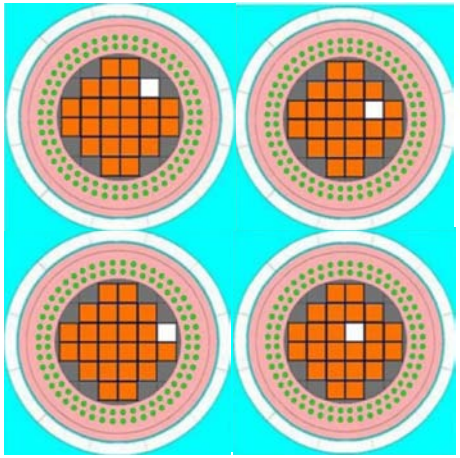
spent fuel monitoring in place and/or during transportation



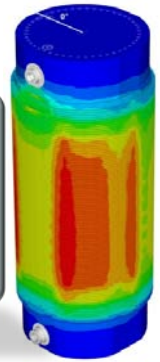




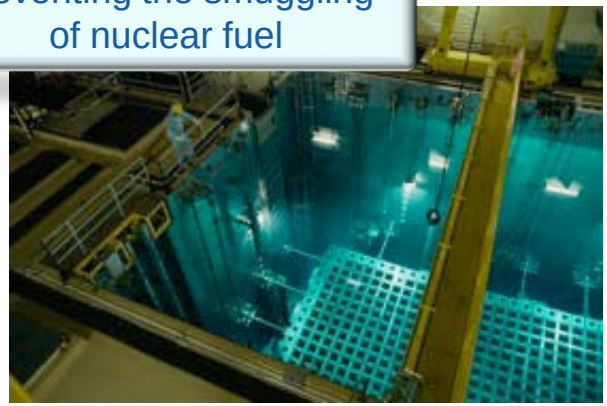



detection of possible diversion of fuel elements from Castor containers

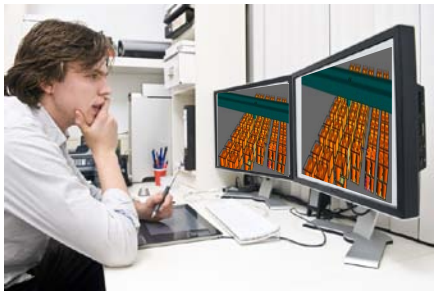


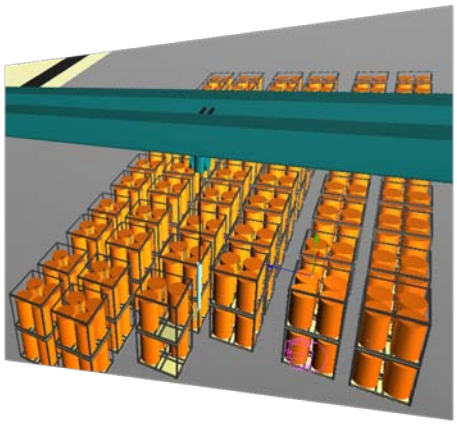
(P.Peerani, M.Galletta, Nuclear Engineering and Design 237 (2007) 94-99)

preventing the smuggling of nuclear fuel

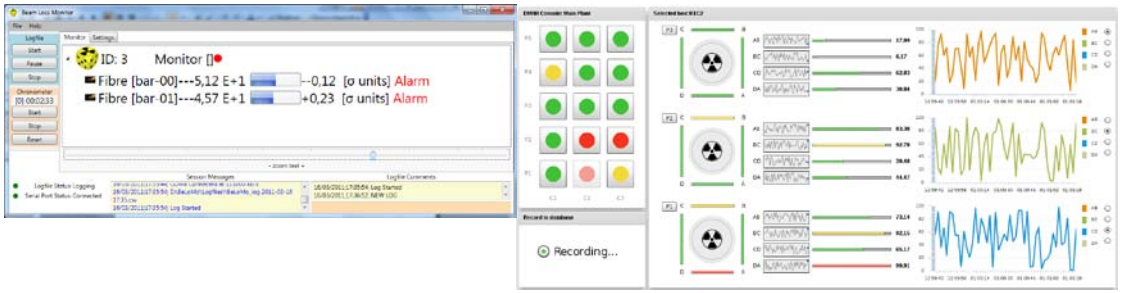


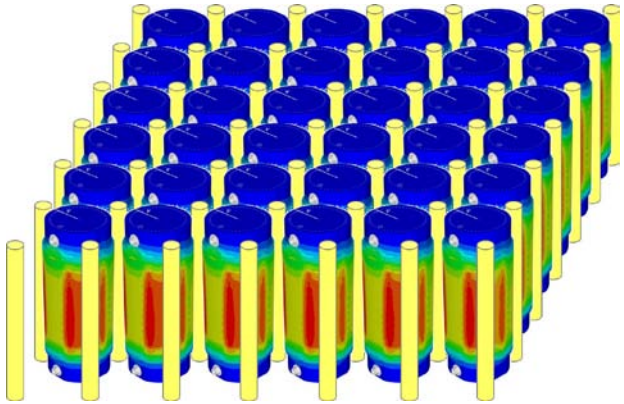
# ensuring continuity of knowledge





## current monitoring method: video camera

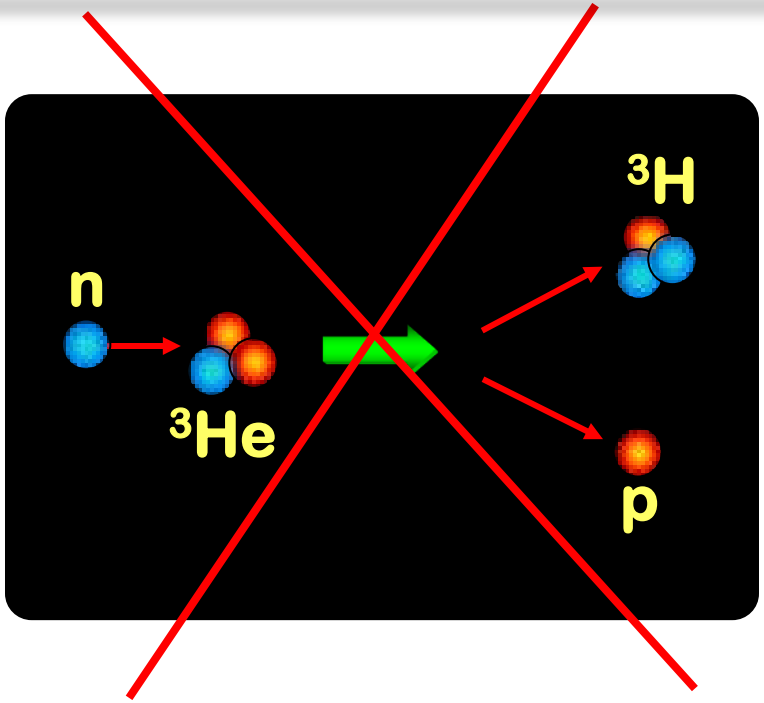


## our idea: granular, real time, automatic

# How?

materials for thermal neutron conversion: $^3$He



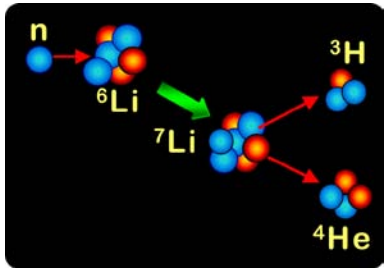

$\sigma(0.025)$
$\approx$ 5330 b

available energy
0.76 MeV
no gamma rays

perfect gas detector but... worldwide lack of $^3$He

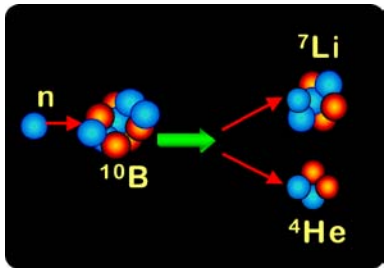
# materials for thermal neutron conversion: which one?

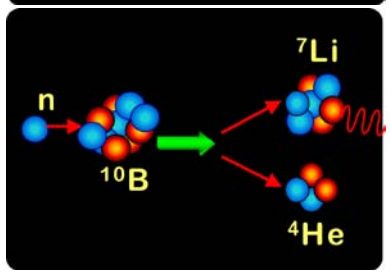
$^{6}$Li




σ(0.025)
≈ 940 b
available E
4.78 MeV

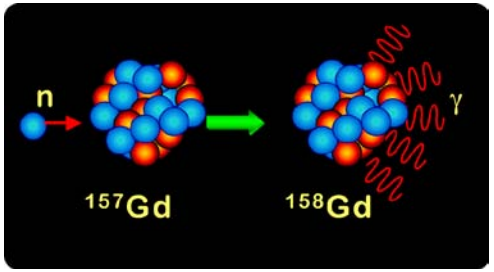
$^{10}$B



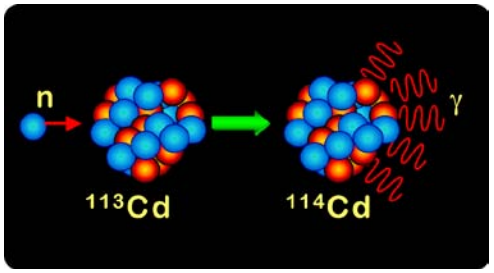

σ(0.025)
≈ 3840 b
available E
2.79 MeV
(and gamma rays)

$^{157}$Gd




σ(0.025)
≈ 240 kb

$^{113}$Cd

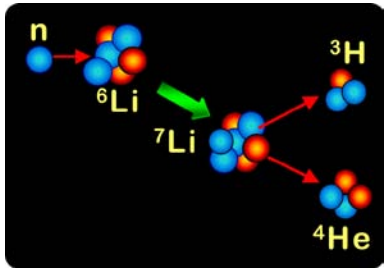



σ(0.025)
≈ 20 kb

large available E
but in form of gamma rays:
difficult neutron identification

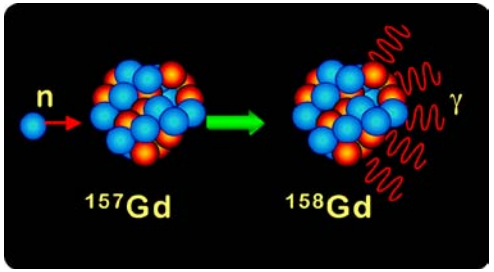
# materials for thermal neutron conversion: which one?


$^{6}Li$



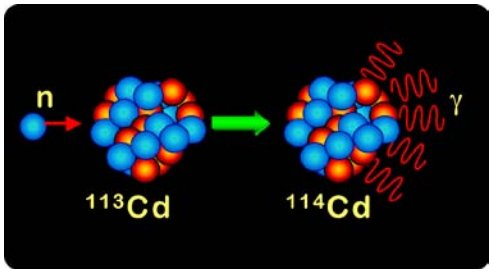

σ(0.025)
≈ 940 b
available E
4.78 MeV

$^{157}Gd$




σ(0.025)
≈ 240 kb

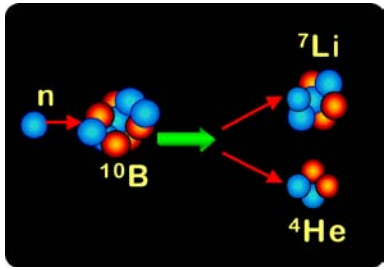
$^{113}Cd$

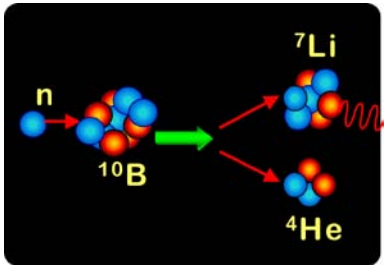



σ(0.025)
≈ 20 kb

large available E
but in form of gamma rays:
difficult neutron identification

$^{10}B$



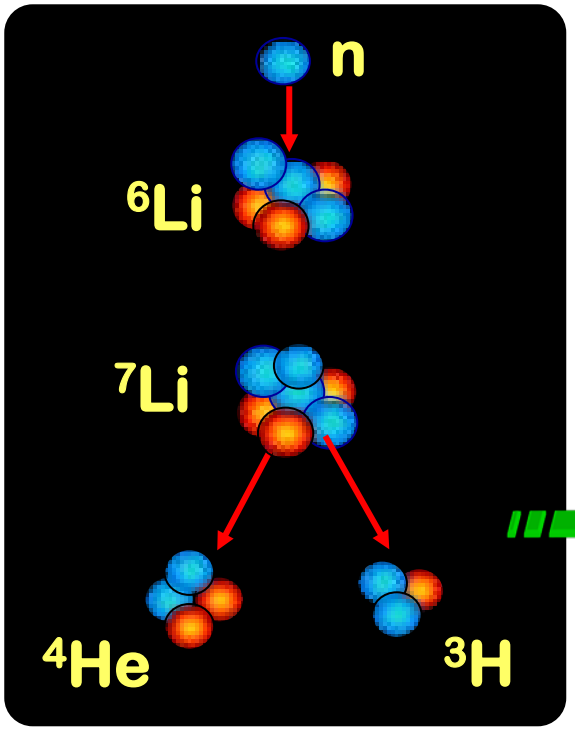




σ(0.025)
≈ 3840 b
available E
2.79 MeV
(and gamma rays)

# physical process

**$^6$Li – natural abundance: 7%**

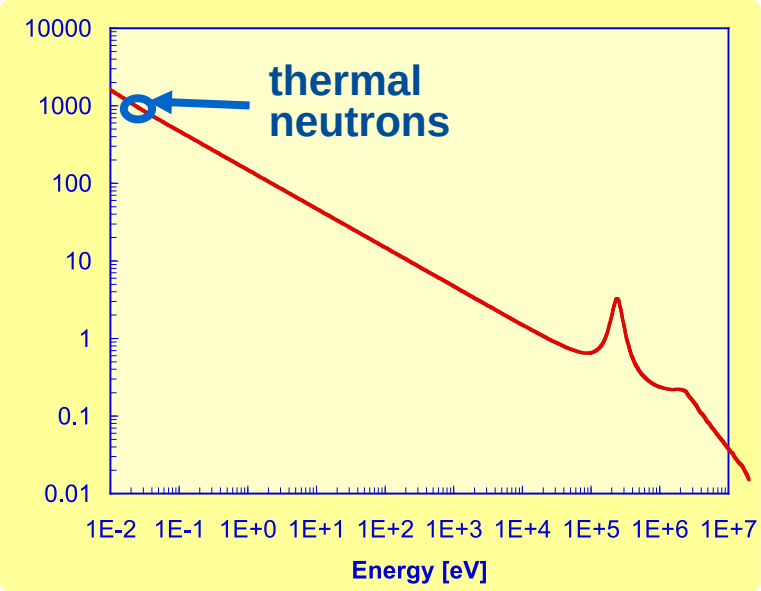
a $^6$LiF converter
captures a neutron...




**2.05 MeV** **2.73 MeV**

...and produces $^4$He ed $^3$H
which can be detected

**Cross section ≈ 940 b**

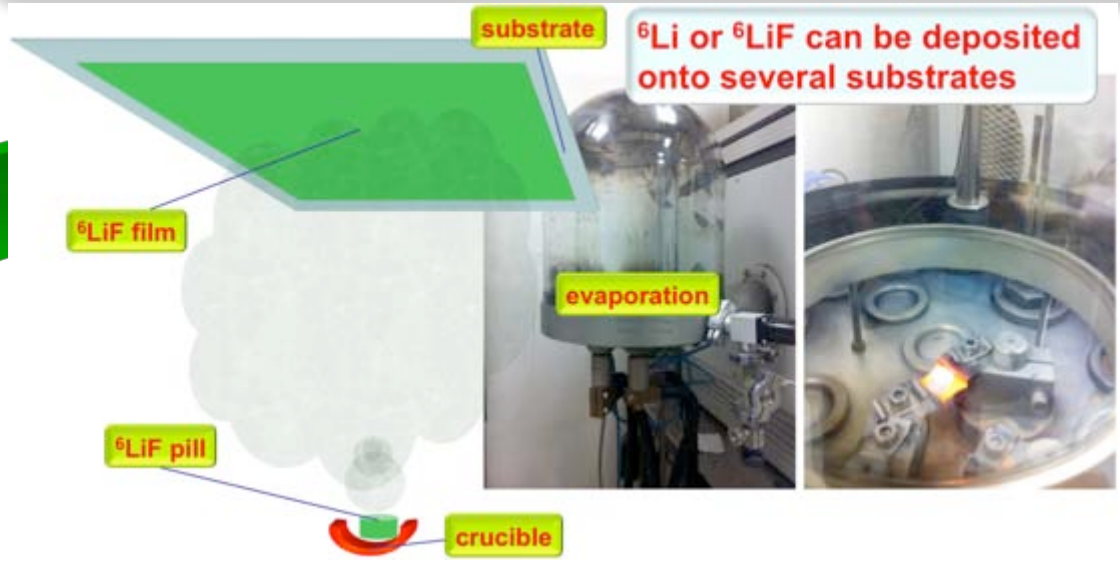


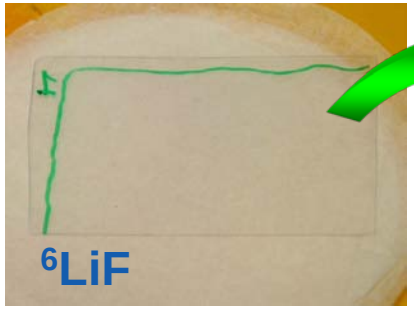

**detection of $^3$H and/or $^4$He**

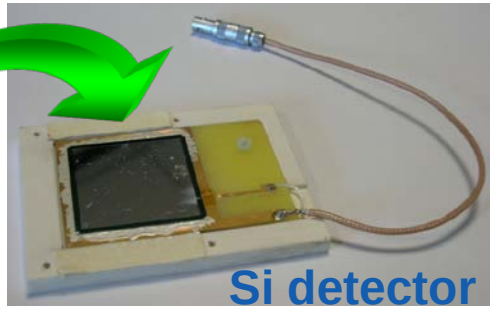
**how?**

# $^{3}$He-free Lithium-based NEutron Monitors

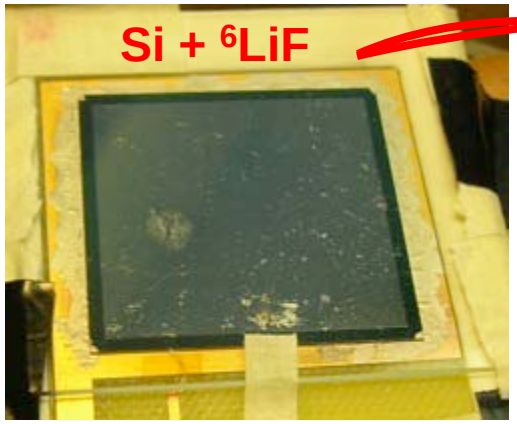
## with removable converter

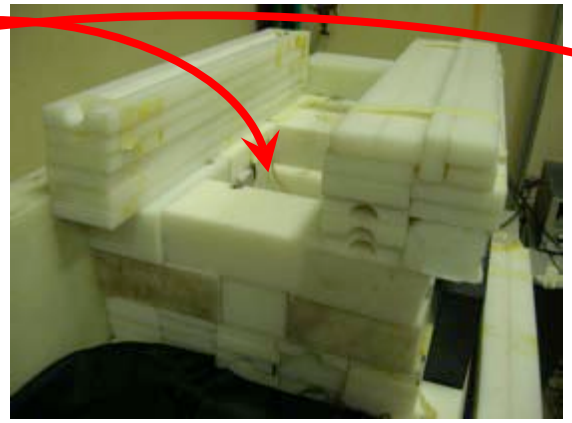


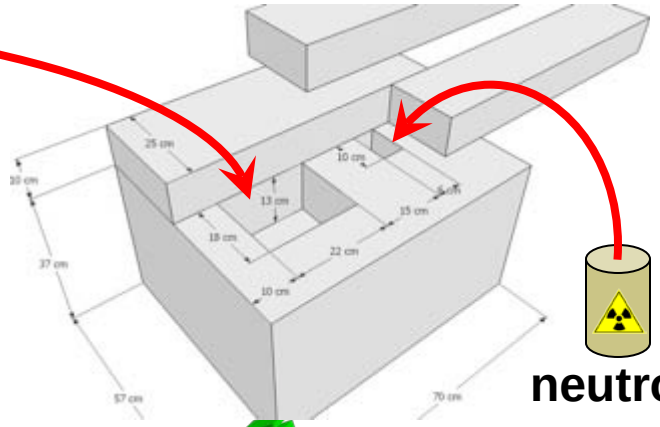



AmBe neutron source 1.6E6 n/s thermal flux ≈ 150 n/s/cm²

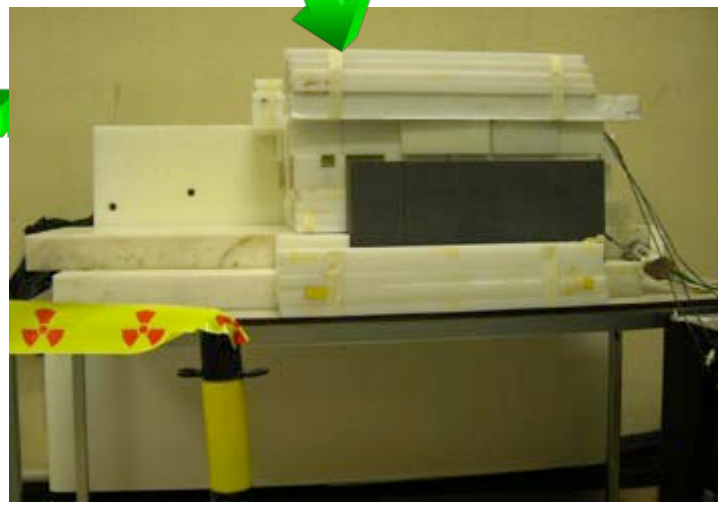


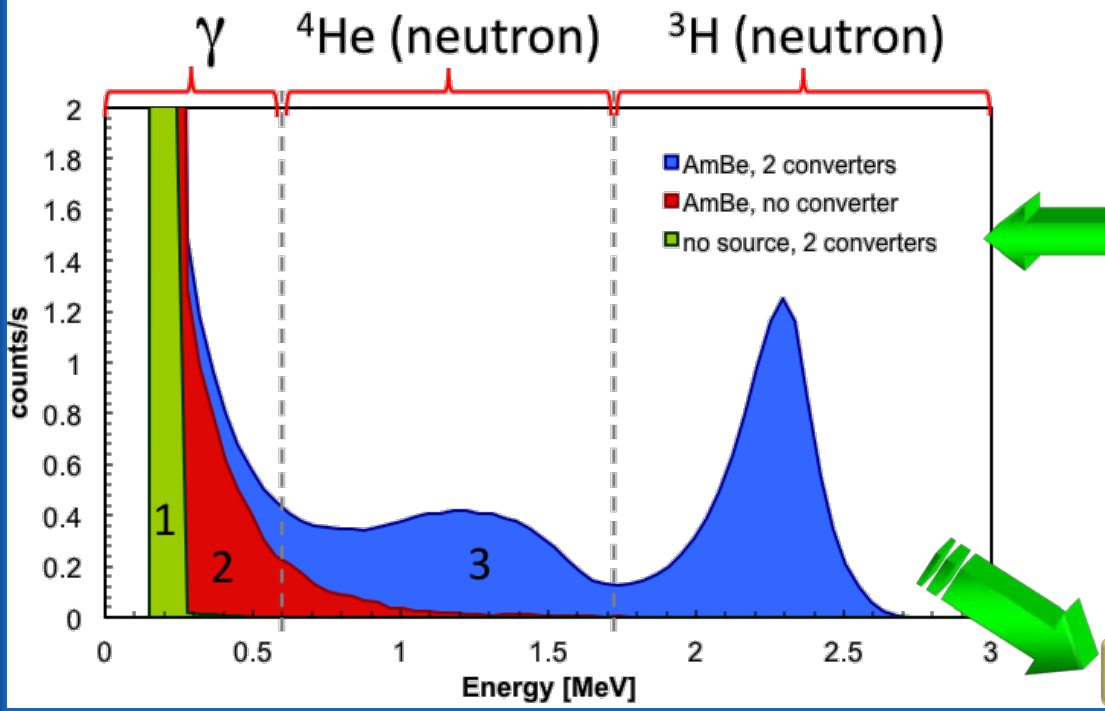





neutron source

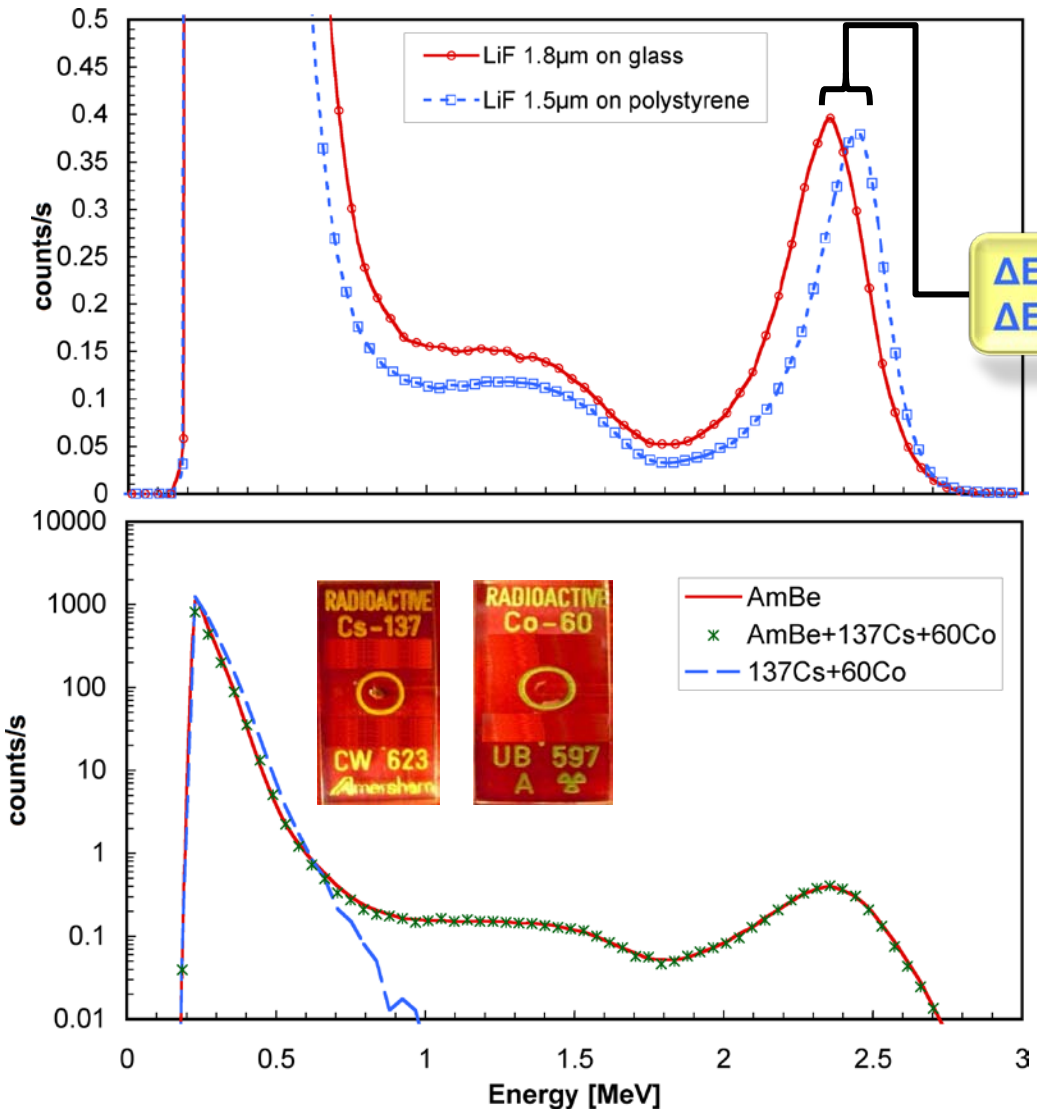
PET moderator






expected ≈ 4 cps measured 3.3

# Si detector + $^6$LiF



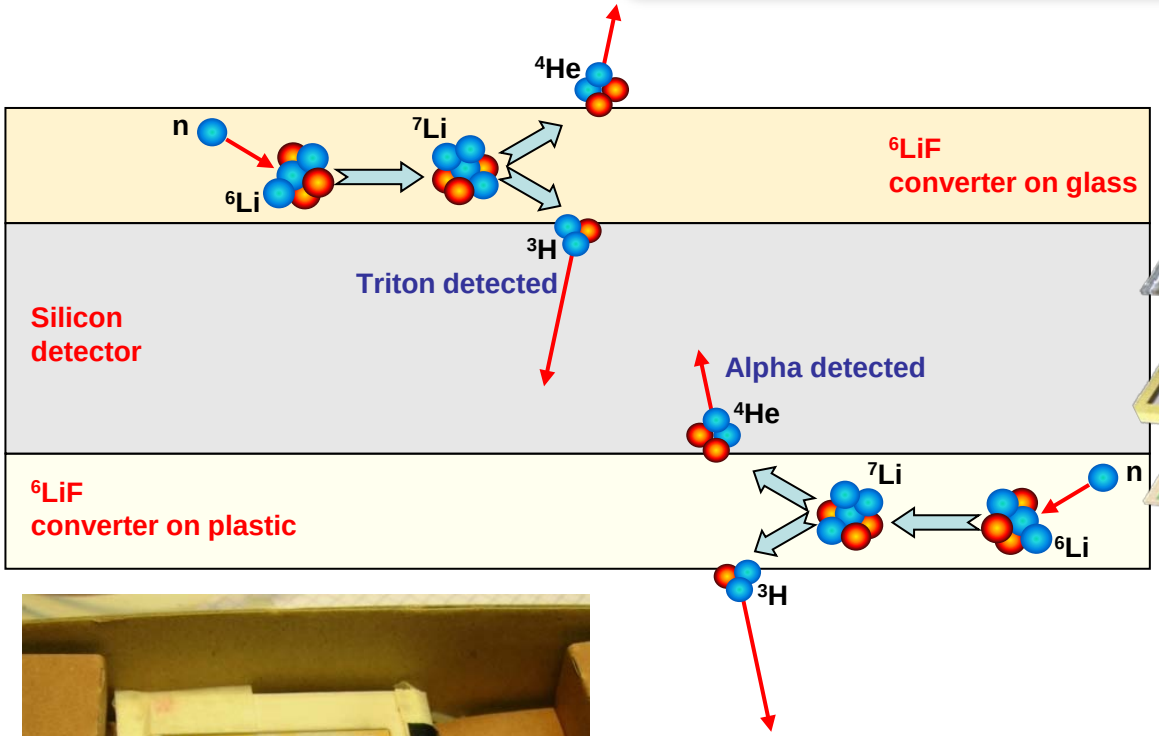

thickness: 1.8μm vs 1.5μm
20% more efficient

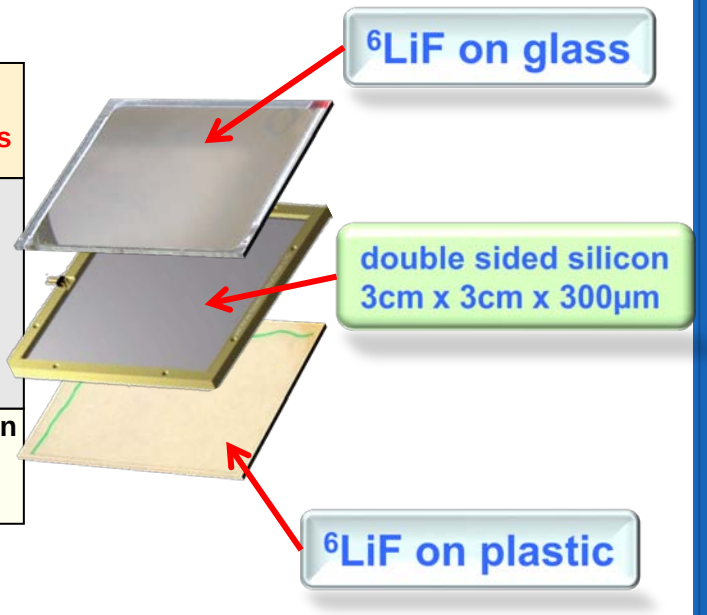
ΔE calculated: 195 keV
ΔE measured: 200 keV

optimal $^6$LiF thickness 1.8μm

added 2 gamma sources
to test rejection (740 MBq)

# Si detector + $^{6}$LiF




**2 converters: double efficiency**

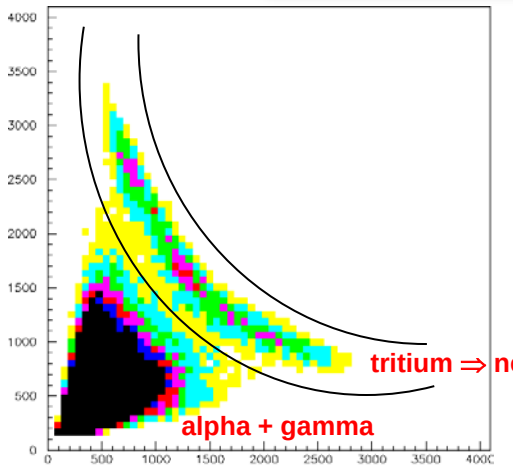
## features

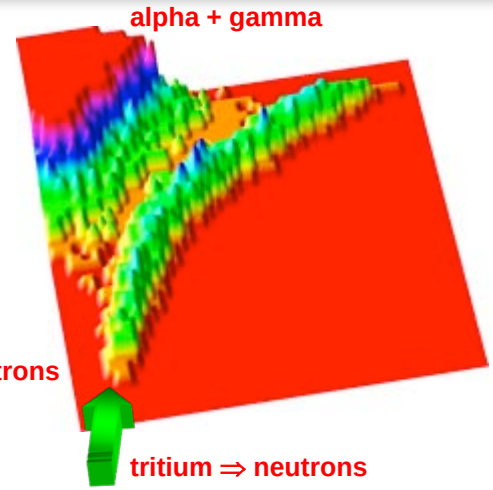
- mechanically simple and robust
- reasonably cheap
- commercial solid state detectors
- strips for position measurements
- simple use (no spectrum analysis or subtraction for gamma rejection)

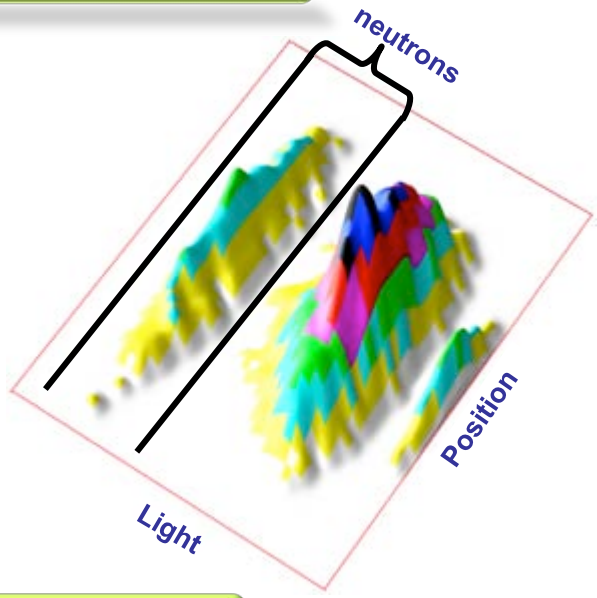
## next steps

- $^{6}$Li deposits over large area (A4?)
- better efficiency (up to 50%?)
- scintillators... → patent? YES

# test with AmBe source: Scintillators + $^6$LiF

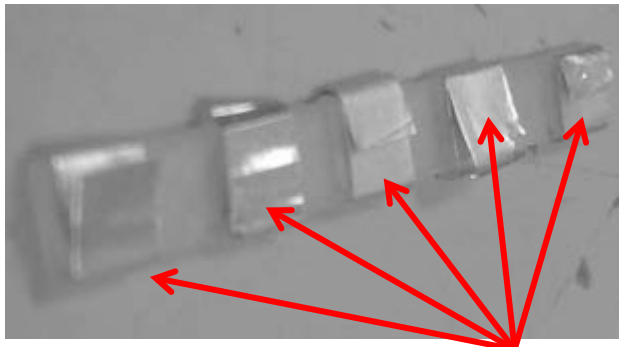


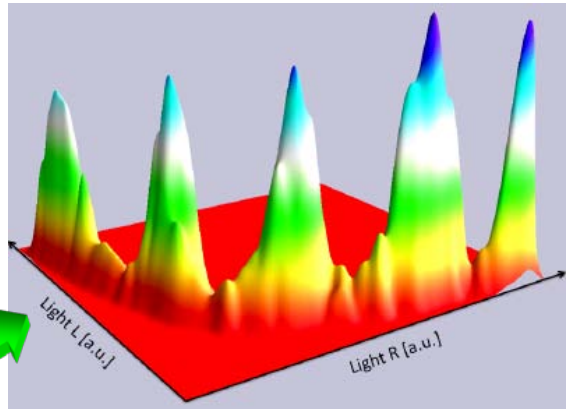




- good intrinsic efficiency
- position sensitive (Δx ≈ 1-2 mm)
- low cost
- many possible geometries and schemes

**...and more to come**



$^6$LiF converter



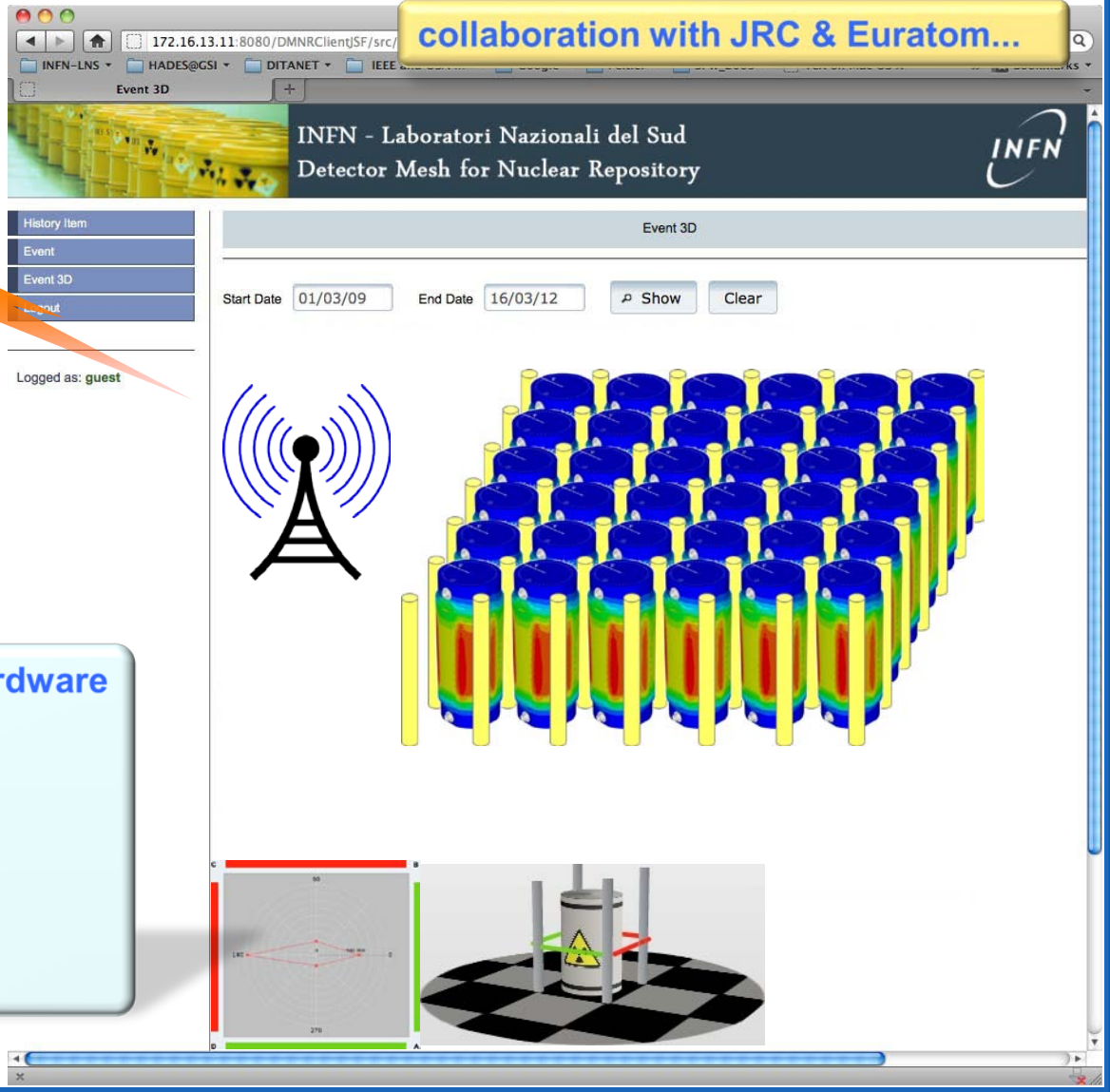


RM2013A000254

# real-time castor storage monitoring

wireless transmission

collaboration with JRC & Euratom...




easily integrated into the existing hardware and software architecture of DMNR:

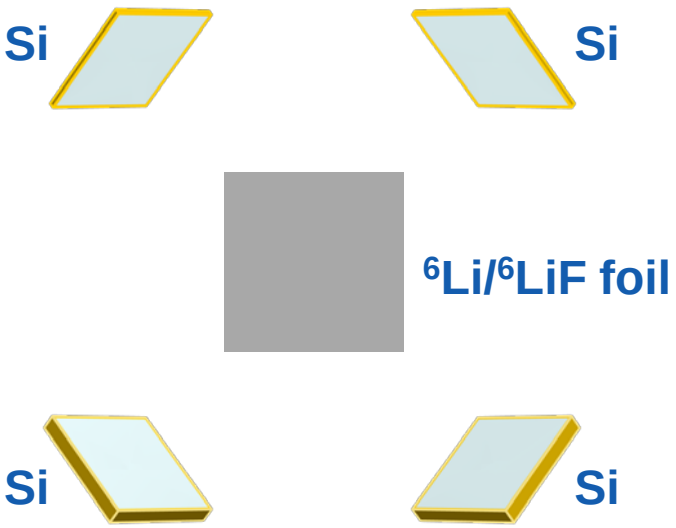
- electronics
- data acquisition
- system control
- data logging
- database handling
- Graphical User Interface

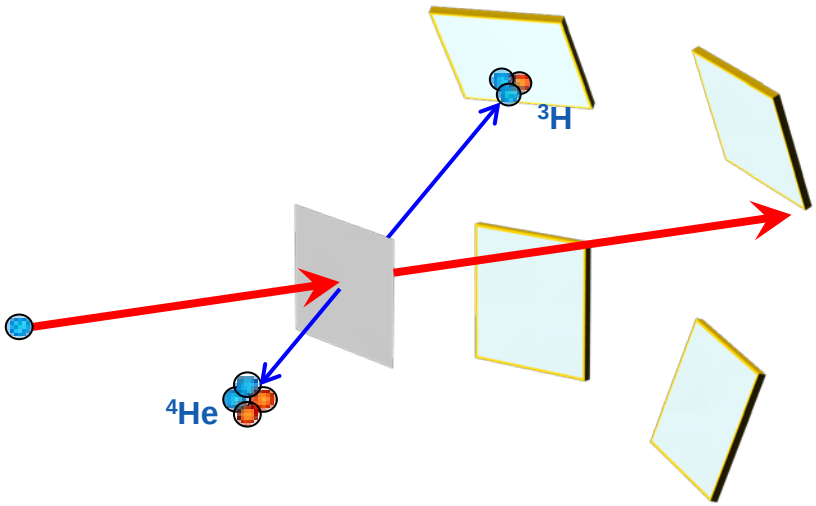
# possible applications

- Nuclear physics research
- Homeland security (nuclear material smuggling)
- Dosimetry
- Radwaste monitoring
- Spent fuel handling and storage monitoring
- Search for nuclear material accidentally lost among scrap metal
- Material structure (with neutron beams)
- other...

# SiMon2: neutron beam monitor for flux normalization

**Si detector + $^{6}Li/^{6}LiF$**

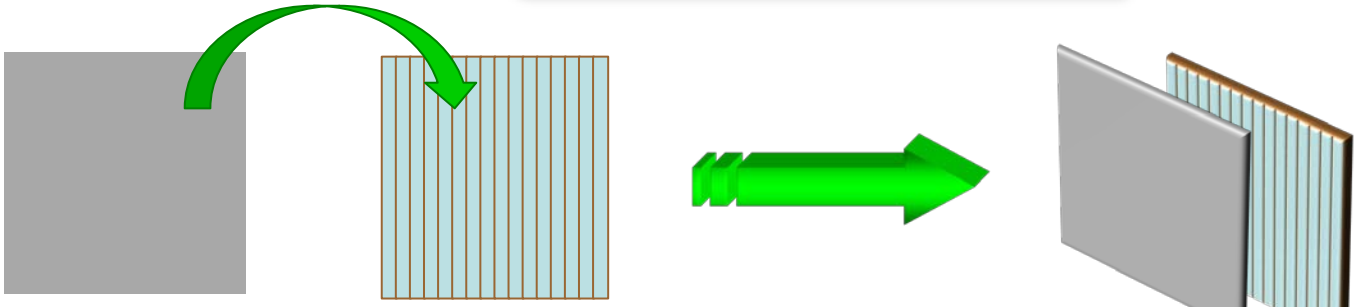



**n-TOF collaboration @ CERN**

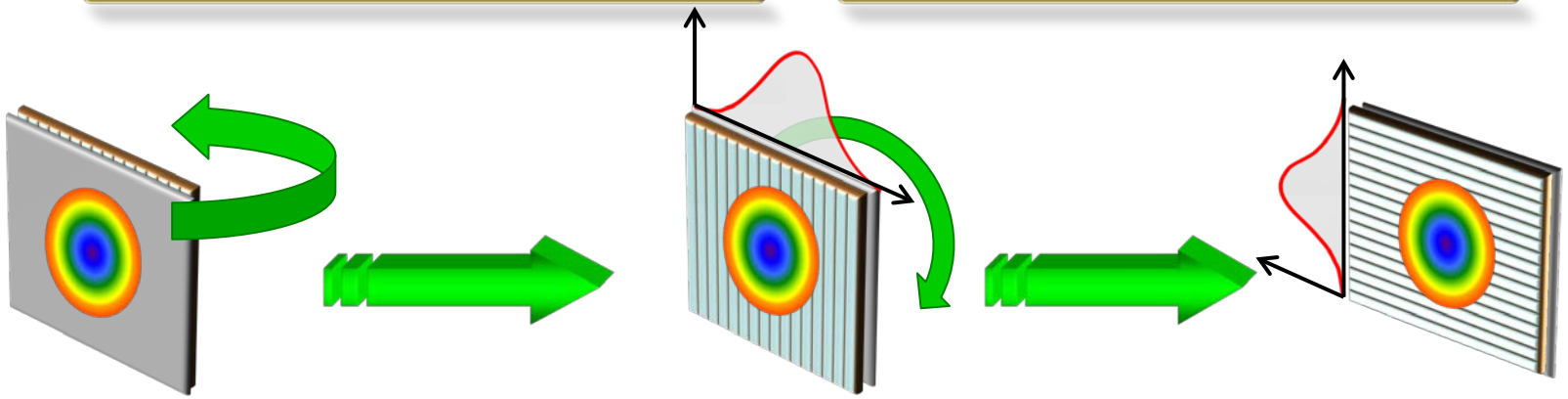
# BeaMon: neutron beam characterization

## Si detector + $^{6}$Li/$^{6}$LiF




α-t forward-backward asymmetry

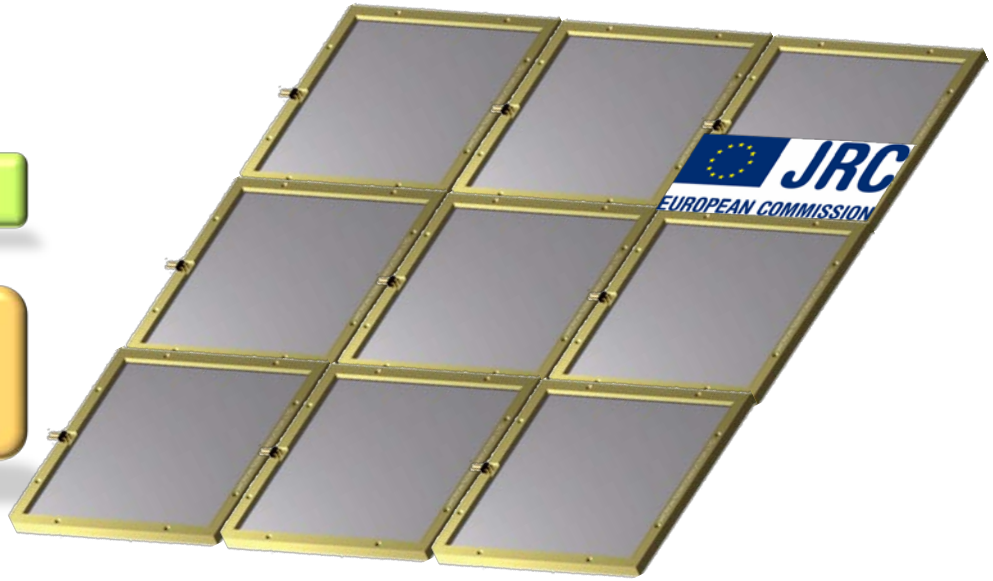
XY distribution



n-TOF collaboration @ CERN

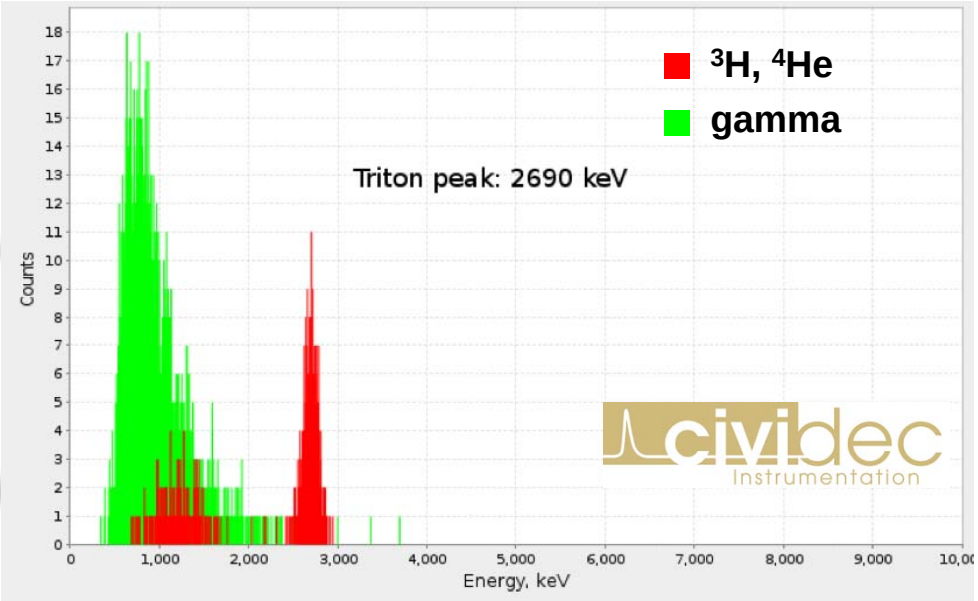
**Ongoing ollaboration with JRC & Euratom:**

**large panels for neutron coincidence measurements as possible $^{3}$He panels replacement**




**Last week's result from collaboration with CIVIDEC (Austria):**

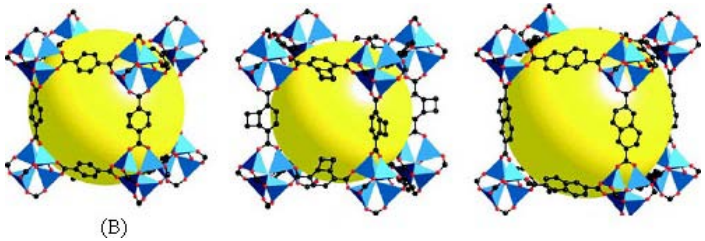
**diamond detectors for thermal neutrons outstanding results with the first test at a reactor**



# applications with neutron beams?

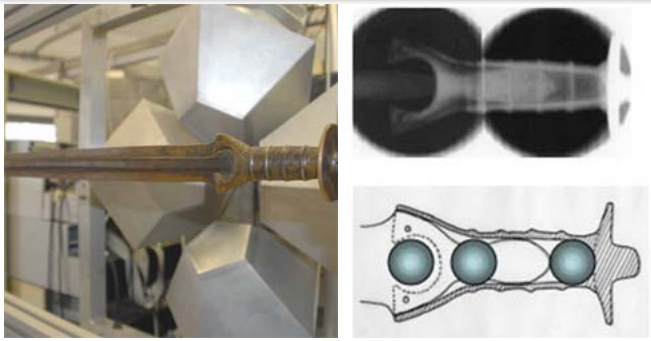
## Time-of-Flight Neutron Diffraction (ToF- ND)

**e.g.: University of Milan, inorganic stereochemistry**



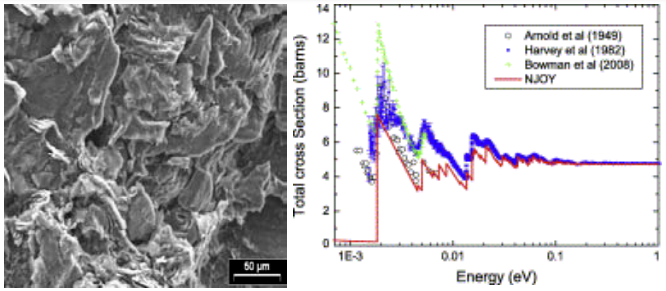

## Neutron Resonance Capture Analysis

**e.g.: Ancient Charm EU project**
**secrets of Bronze Age sword unveiled**



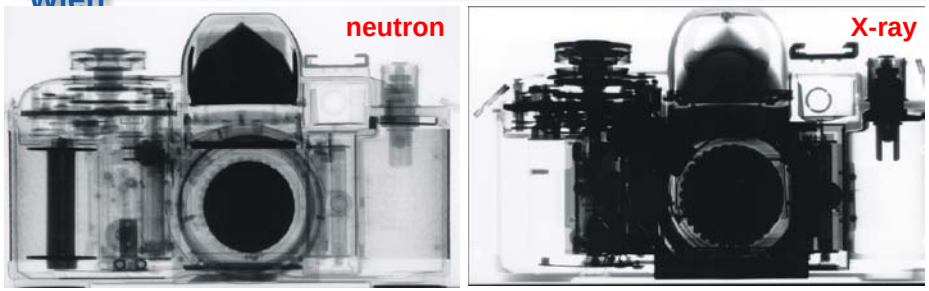
## Bragg Edge Transmission

**e.g.: S.Petriw, J.Dawidowski, J.Santisteban,**
**Porosity effects on the neutron total cross section of graphite**
**Journal of Nuclear Materials 396 (2010)181-188**




## Neutron Radiography

**e.g.: Institute of Atomic and Subatomic Physics - TU Wien**



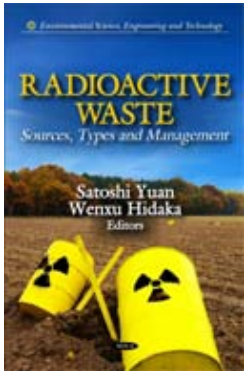

## material analysis: composition and structure

# compact neutron monitors?




# scientific production

- P.Finocchiaro, talk given at the Helium-3 Replacement in Italy meeting, 2-3 december 2013
- A.Pappalardo, talk given at the 3rd European Energy Conference, Budapest, 27-30 October 2013
- P.Finocchiaro, talk given at the 3rd European Energy Conference, Budapest, 27-30 October 2013
- L.Russo, presented at the 3rd European Energy Conference, Budapest, 27-30 October 2013
- P.Finocchiaro, invited talk to be given at XCIX Congress of Italian Physics Society, 2013, Trieste
- P.Finocchiaro et al., presented at the 1st SCINTILLA public workshop, Budapest, 12-Sep-2013
- P.Finocchiaro, et al., Invited seminar at University of Milan 2013
- M.Barbagallo et al., Rev. Sci. Instrum 84 (2013) 033503
- G.Vecchio et al., International Journal of Nuclear Energy Science and Engineering, 10089, vol.3, issue 3, (2013)64
- G.Vecchio, P.Finocchiaro, Global Journal of Computer Science and Technology Graphics & Vision, v12, n12 (2012) 1-5
- P.Finocchiaro et al., IEEE Trans. Nucl. Sci., v59, n4 (2012) 1426-1431
- P.Finocchiaro, in “Radioactive Waste: Sources, Types and Management”, Nova Science Publishers, 2012
- A.Pappalardo et al., Nucl. Phys. B 215 (2011) 41-43
- P.Finocchiaro, invited talk given at the Low Carbon Earth Summit (LCES) 2011, Dalian
- L.Cosentino, talk given at the XXXV International Symposium "Scientific Basis for Nuclear Waste Management", 2011, Buenos Aires
- P.Finocchiaro, invited talk at XCVII Congress of Italian Physics Society, 2011, L'Aquila
- P.Finocchiaro et al., talk given at the 3rd International Nuclear Chemistry Congress, Terrasini 2011
- P.Finocchiaro et al., talk given at ANIMMA 2011, Ghent
- A.Pappalardo, presented at the 49th International Winter Meeting on Nuclear Physics, Bormio 2011
- P.Finocchiaro, invited talk at the Round Table on "Science and Technology for the solution of the Energy Supply Problems", Ekaterinburg 2010
- P.Finocchiaro, invited talk at SSEM 2010, Royal Society of Chemistry, London
- P.Finocchiaro et al., talk given at SSD16 2010, Sydney
- M.Barbagallo et al., Rev. Sci. Instr. 81 (2010) 093503
- P.Finocchiaro et al., NIM A652 (2011) 143-145
- M.Barbagallo et al., NIM A652 (2011) 355-358
- P.Finocchiaro, invited seminar at University of California Los Angeles 2010
- A.Pappalardo et al., presented at IPRD 2010
- P.Finocchiaro et al., presented at SORMA 2010
- P.Finocchiaro et al., presented at DNDO workshop 2010
- A.Pappalardo et al., presented at E2C European Energy Conference 2010
- V.Bellini, M.Capogni, V.Febbraro, and P.Finocchiaro, Appl. Rad. and Isot. 68 (2010) 1320
- P.Finocchiaro et al., Nucl. Phys. B197 (2009) 35 Proc. Supp.
- M.Capogni, presented at ICRM 2009, Bratislava, Slovak Republic, September 2009
- A.Pappalardo et al., presented at ANIMMA 2009
- L.Cosentino et al., presented at ICENES 2009
- L.Cosentino et al., presented at IPRD 2008

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## *theses*

- L.Russo, upper level (master) Thesis (2013)
- F.Oliveri, first level Thesis (2013)
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- C.Greco, first level Thesis (2011)
- S.Grillo, first level Thesis (2011)
- C.Scirè, upper level (master) Thesis (2011)
- V.Finocchiaro, first level Thesis (2011)
- G.Guardo, upper level (master) Thesis (2011)
- V.Febbraro, upper level (master) Thesis (2009)
- S.Scirè, LNS Stage final report (2009)
- G.Greco, upper level (master) Thesis (2009)
- M.Barbagallo, upper level (master) Thesis (2009)

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