Setup and test of a system for radiography with fast neutrons

April 2014 | Manuel Schumann, R. Engels, J. Furletova, S. Furletov, G. Kemmerling, E. Mauerhofer

NISRA Project
Forschungszentrum Jülich GmbH, RWTH Aachen University and Siemens AG

Outline

Introduction

NISRA
NEUTRON
IMAGING
SYSTEM FOR
RADIOACTIVE-WASTE
ANALYSIS

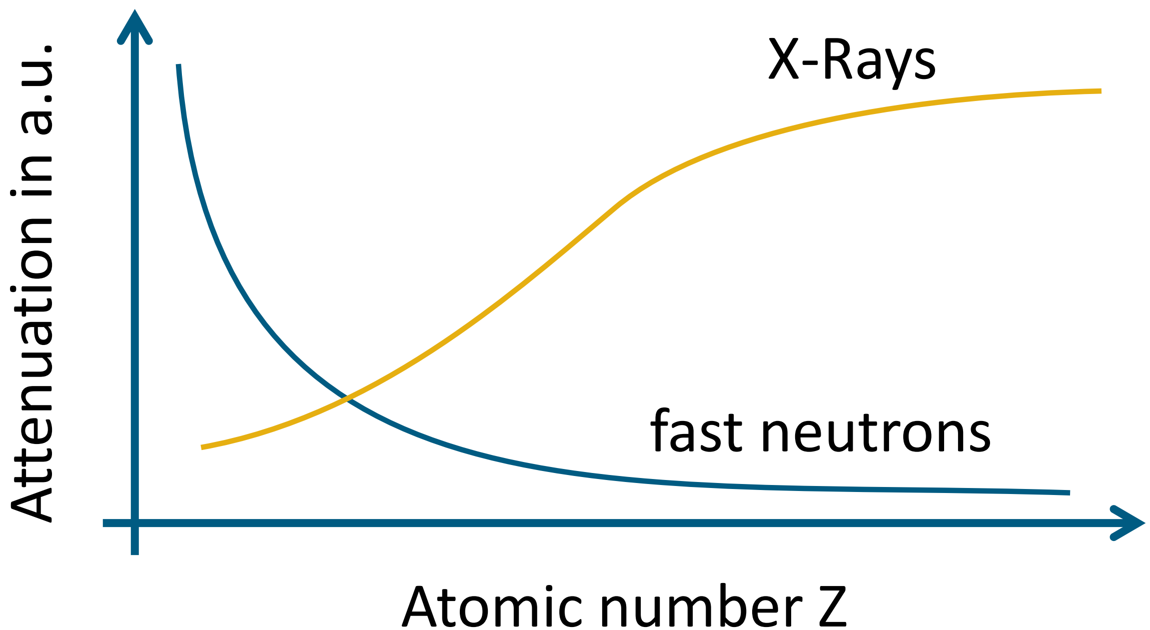
Funded by

Federal Ministry of Education and Research

JÜLICH FORSCHUNGSZENTRUM	**IEK-6:** Dr. E. Mauerhofer, M. Schumann	Experimental Setup, simulations
	ZEA-2: Dr. R. Engels, Dr. J. Furletova, Dr. S. Furletov, Dr. G. Kemmerling	Detector and scintillator development, simulations
RWTH AACHEN UNIVERSITY	**MathCCES:** Prof. Dr. M. Frank, Dr. R. Vasques	Image reconstruction
	NET: A. Havenith, Dr. J. Kettler, D. Voss	Simulations
SIEMENS	Dr. O. Schitthelm	Interface between raw data and reconstruction

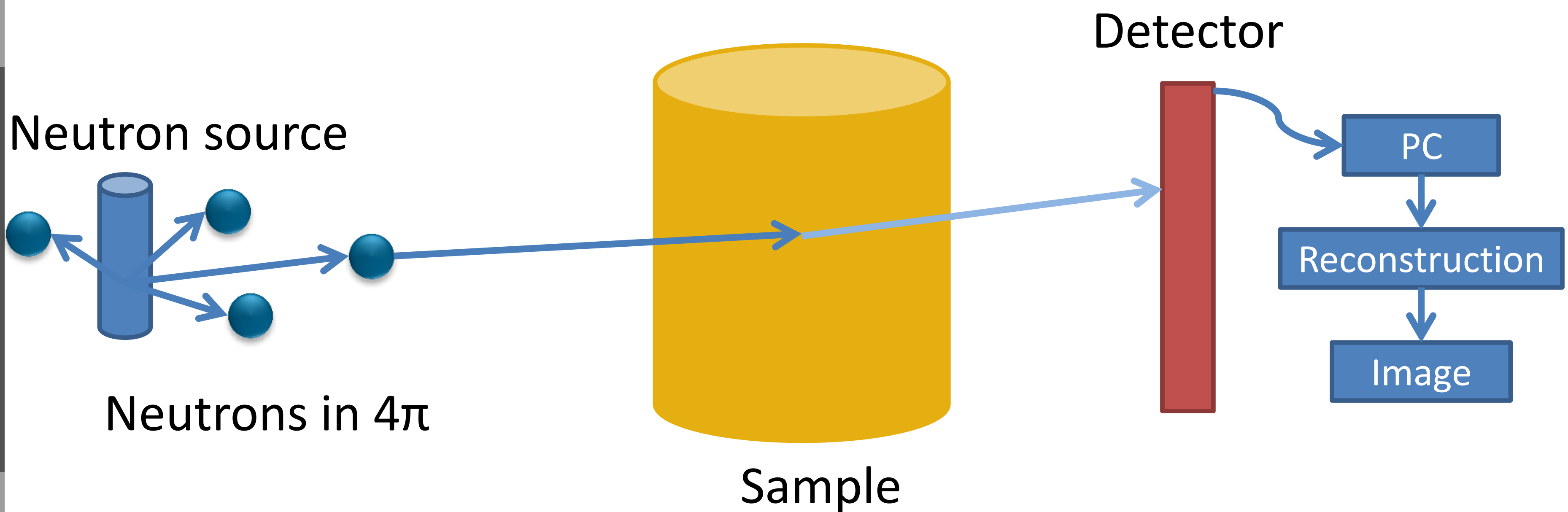
Introduction

- Historical waste (mixed waste) is still a challenging issue
- The packages are huge (200 l drums) and heterogeneous
- Massive and dense structural components
- ➢ Need detailed information from radiography to improve radiological and chemo-toxic characterisation
- ➢ Neutron radiography is complementary to X-Ray radiography



Neutron Radiography

How does neutron radiography work?



For neutrons: $I = I_0 e^{-\Sigma_{mac} d}$ similar to γ-rays $I = I_0 e^{-\mu d}$

Challenges

Build a compact fast neutron radiography system

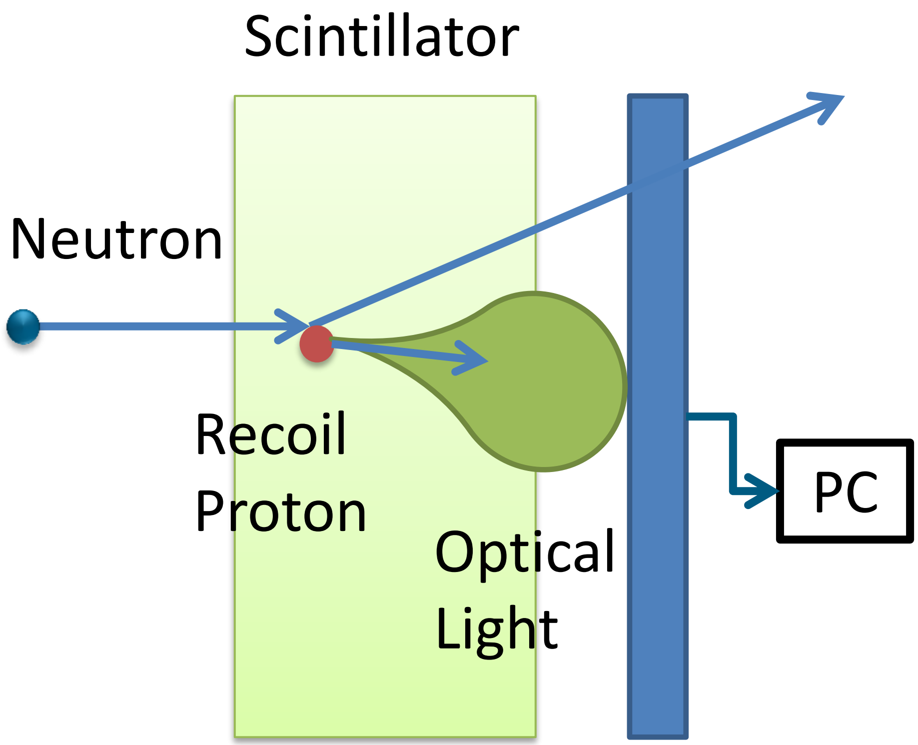
What is state of the art for neutron imaging?

- CCD camera
  - Camera is neutron sensitive
  - Need a mirror

Requirements:

- Fast Neutrons
- High efficiency for neutron detection
- Sufficient resolution
- Sufficient contrast
- Neutron to gamma discrimination
- Image reconstruction due to divergent beam

Detection Principle



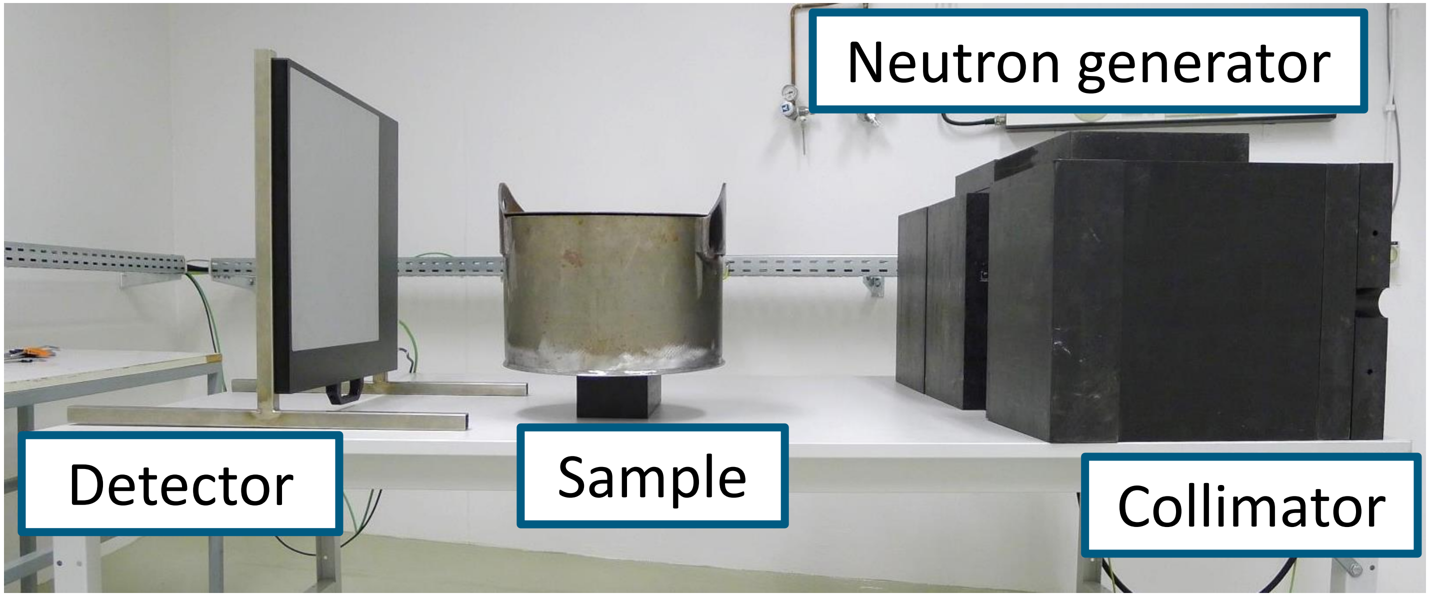
Spatial resolution detector for optical light

Scintillator is most important for all detectors:

- Neutron absorption
  - Hydrogen inside (plastic)
  - Thick
- Light output
  - Thin (self-absorption)
- Sufficient resolution and contrast

Setup

- Commercial neutron generator from Sodern (GENIE16GT)
- D-T reaction for 14 MeV neutron production
- Up to 10^8 neutrons per second
- Pulsed and continuous mode
- Experimental setup in irradiation room



Neutron Flux Determination

Determine the neutron flux in the irradiation room to scale numerical simulations

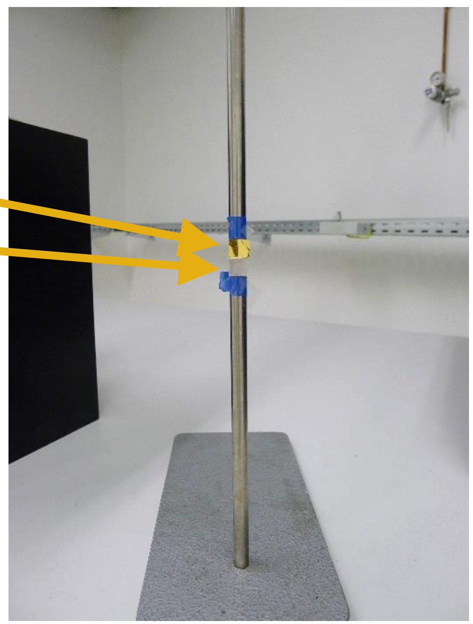
- Distance 30 cm, irradiation 2 h and 24 h γ counting

Au

Al

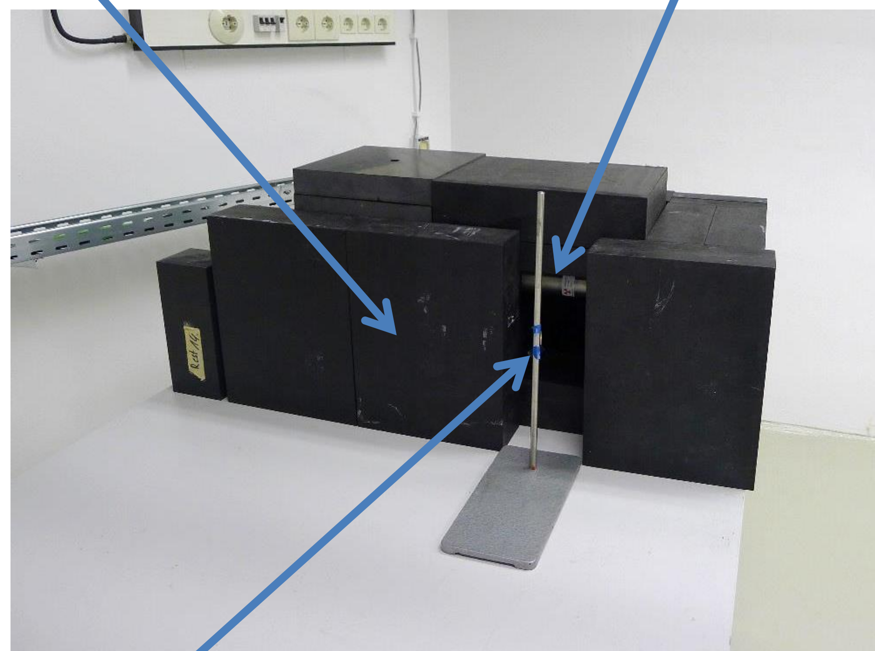
1.6 cm^2

~0.1 g



Collimator

Neutron generator



Flux monitor

Neutron Flux Determination

reaction	$t_{1/2}$	$E(\sigma_{max})$	σ_{max}	E range
$^{197}Au(n,2n)\,^{196}Au$	6 d	14 MeV	2.17 barn	10-20 MeV
$^{197}Au(n,\gamma)\,^{198}Au$	3 d	epi/thermal	1571 barn	$1\cdot10^{-5}$ -1 MeV
$^{27}Al(n,\alpha)\,^{24}Na$	15 h	13 MeV	0.11 barn	3-14 MeV

$$A = \frac{m}{M_{mol}} \cdot N_a \cdot h \cdot \sigma \cdot \phi \left(1 - e^{-\lambda \cdot t_b}\right)$$

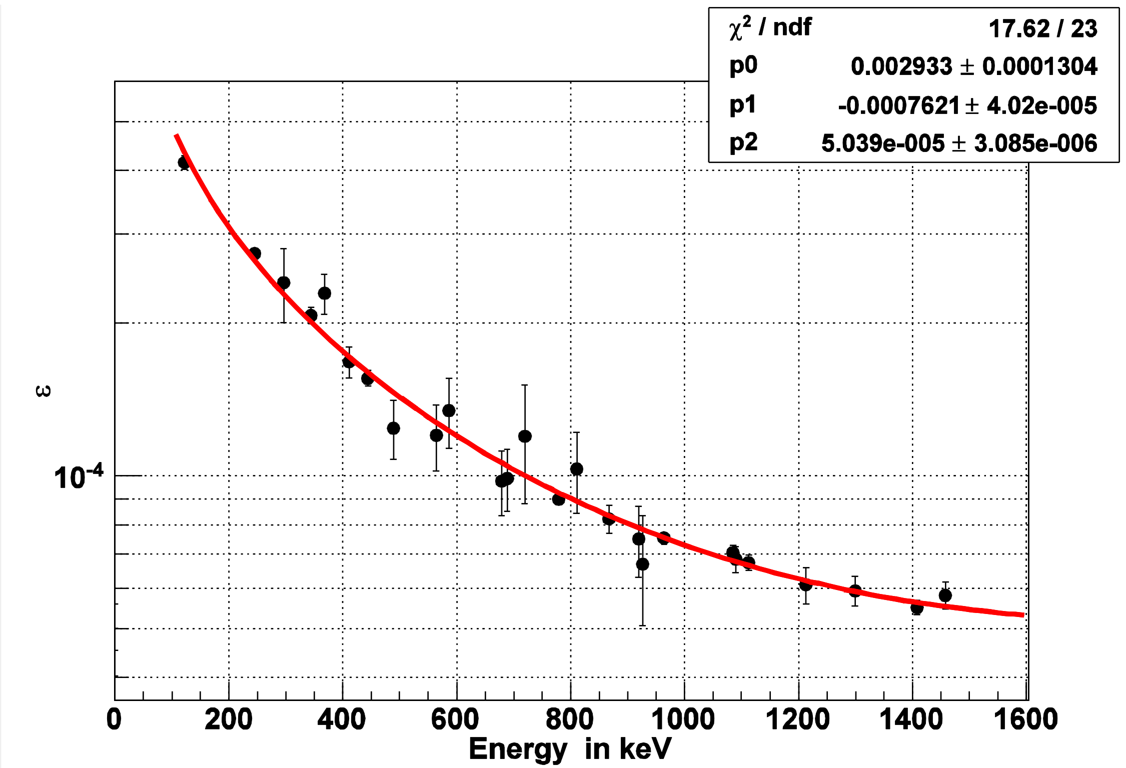
Selfabsorption of neutrons within the sample $A = A_0 \cdot \frac{1 - e^{-\Sigma d}}{\Sigma d}$

Neutron Flux Determination

Analysis

- Low-Level gamma detector (HPGe in lead-castle)
- $P = A \cdot I_\gamma \cdot \varepsilon_{E_\gamma} \frac{1}{\lambda}\left(1 - e^{-\lambda t_{meas}}\right) e^{-\lambda t_{decay}}$
- determination of ε_{E_γ} with Eu-152 reference on filter

$$\varepsilon = \frac{P}{A\, I_\gamma\, t} = \sum_{i=0}^{2} p_i \ln(E)^i$$



Results

Sample	*E* in keV	Reaction	Counts	Efficiency 10^{-5}	Activity in Bq
Au-1	412	n,γ	2471 ± 180	17.12 ± 0.03	3.09 ± 0.23
Au-1	356	n,2n	132 ± 29	19.50 ± 0.08	0.13 ± 0.03
Al-5	1368	n,α	98 ± 16	5.72 ± 0.11	0.32 ± 0.05

Sample	Reaction	Selfabsorption	ϕ in n/s/cm^2	Q in n/s	
Au-1	n,γ	0,80	281 ± 21	(3.2 ± 0.2) 10^6	slow n
Au-1	n,2n	1,00	15600 ± 3600	(1.8 ± 0.4) 10^8	fast n
Al-5	n,α	1,00	13100 ± 2100	(1.5 ± 0.2) 10^8	

$$Q = \phi 4\pi (30\text{cm})^2$$

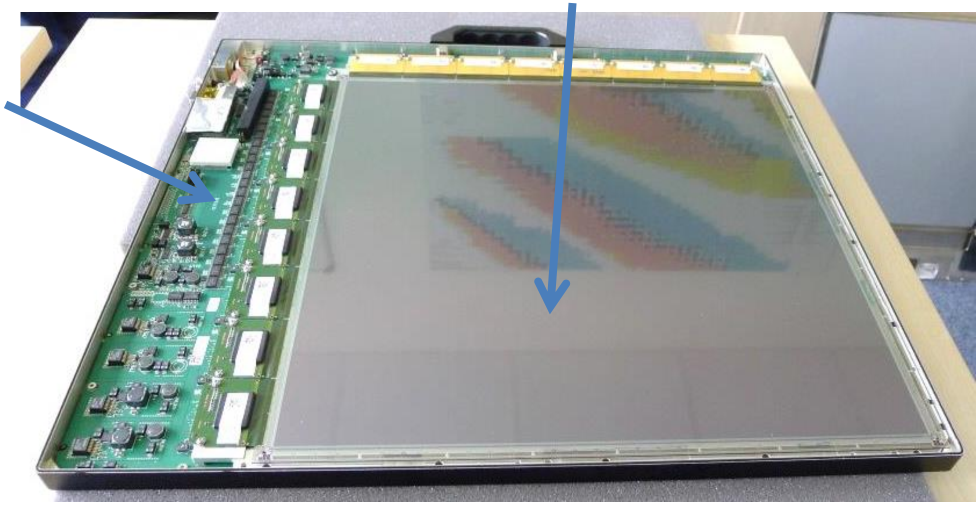
Detector Designs

aSi Flat Panel detector

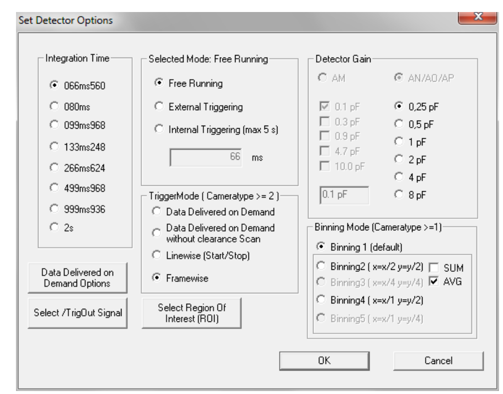
- Commercial X-Ray detector from PerkinElmer
- Special scintillator for neutrons
- 40 cm x 40 cm active area with 1024 x 1024 pixels
- DAQ predefined by PerkinElmer
- Thickness of the scintillator: 3mm

aSi panel

Electronics



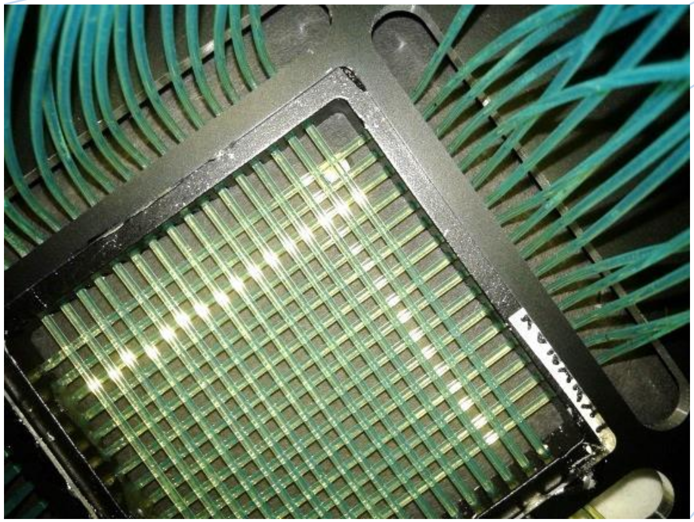
Part of the software



Detector Designs

WLSF Photomultiplier

- Prototype from ZEA-2(FZJ)
- Plastic with ZnS scintillator
- X-Y crossed wavelength shifting fibres
- PMT with TDC readout
- Active Area: 4 cm x 4 cm (16 x 16 fibres)



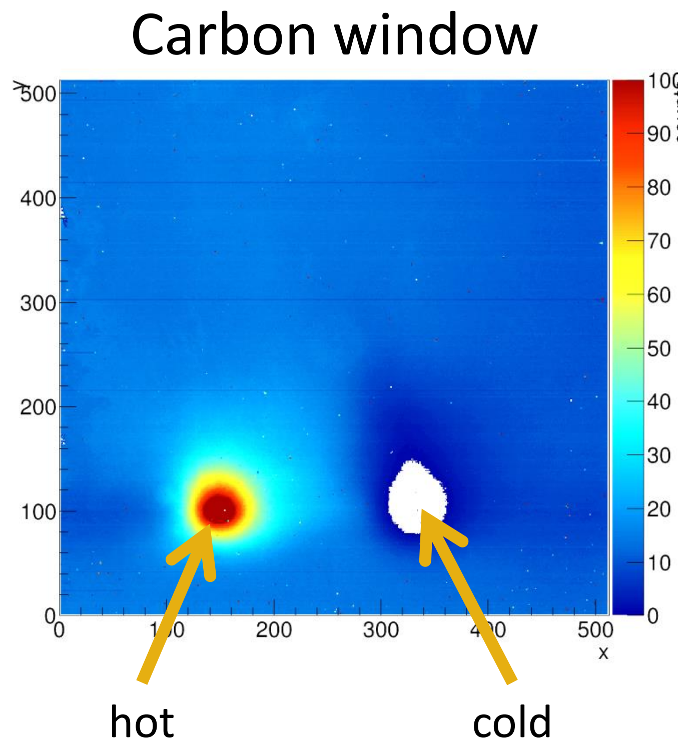
Performance Investigations Flat Panel

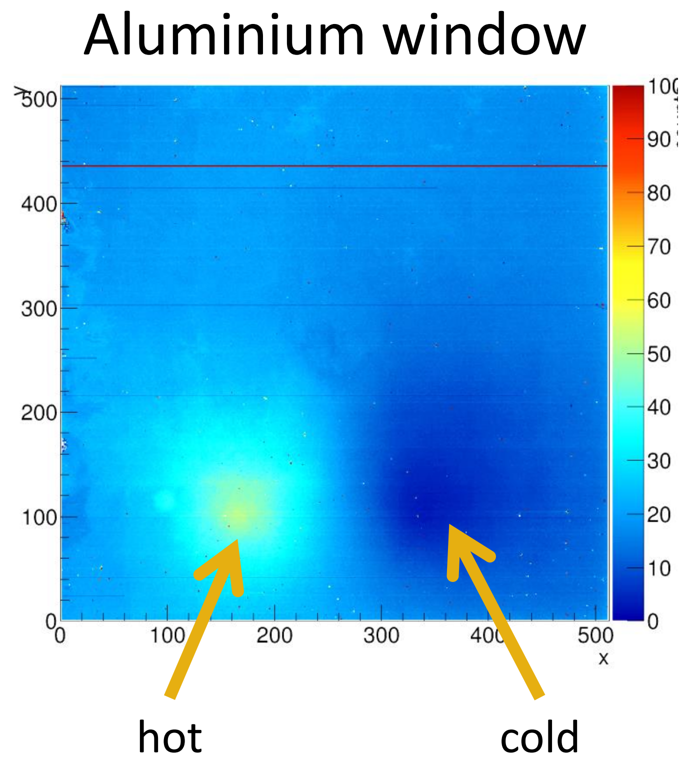
cold room temp. hot

Two different entrance windows:

- carbon fibres
- aluminium

Performance Investigations Flat Panel





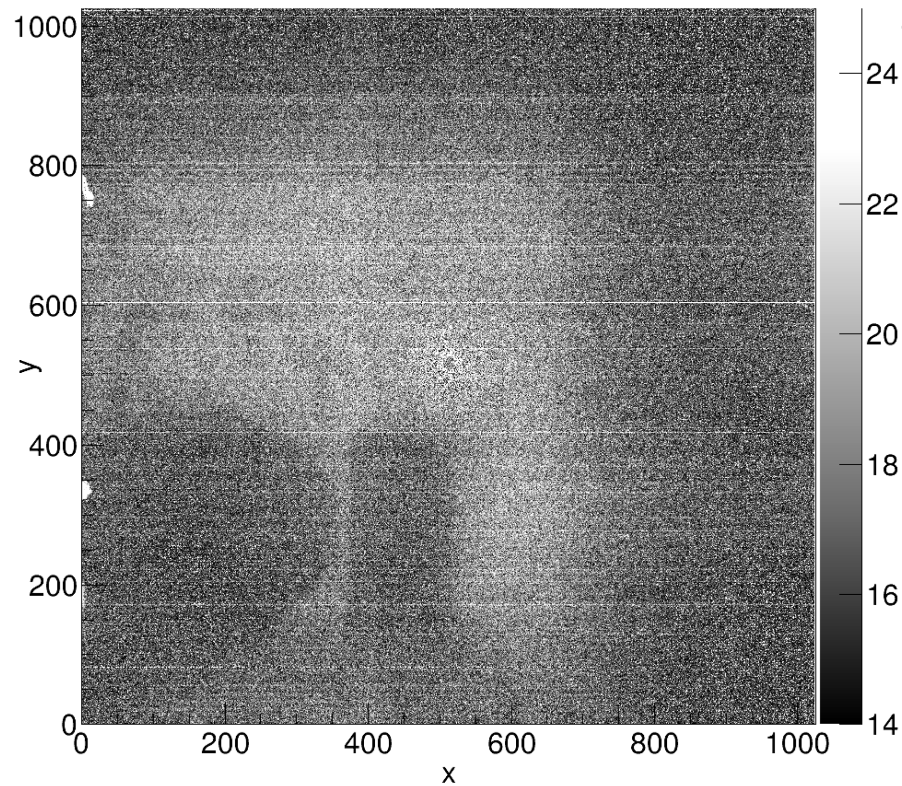
33ms integration time, highest gain, average over 10000 frames

- Detector is very sensitive for temperature differences
- Well known effect of the photo-diodes
- Aluminium window reduces the effect

Performance Investigations Flat Panel

Pb sample

PE sample



WLSF Sensitivity Study - Gamma

- Sources: ^{241}Am, ^{137}Cs, ^{60}Co, all ≈370 kBq
- Scintillator: CsI(Na) for γ, ZnS (58% ZnS) for neutrons
- Distance source to fibres ≈ 40 mm

Rates for gamma sources in s^{-1} per channel

Source \ Scintillator	No	CsI(Na)	ZnS
No	0.10 ± 0.03	0.10 ± 0.02	0.08 ± 0.02
Am-241	0.09 ± 0.02	0.43 ± 0.11	0.14 ± 0.03
Cs-137	0.27 ± 0.12	2.34 ± 0.59	0.31 ± 0.13
Co-60	1.00 ± 0.46	5.05 ± 1.29	1.17 ± 0.52

≈ same activity

"high" discriminator threshold

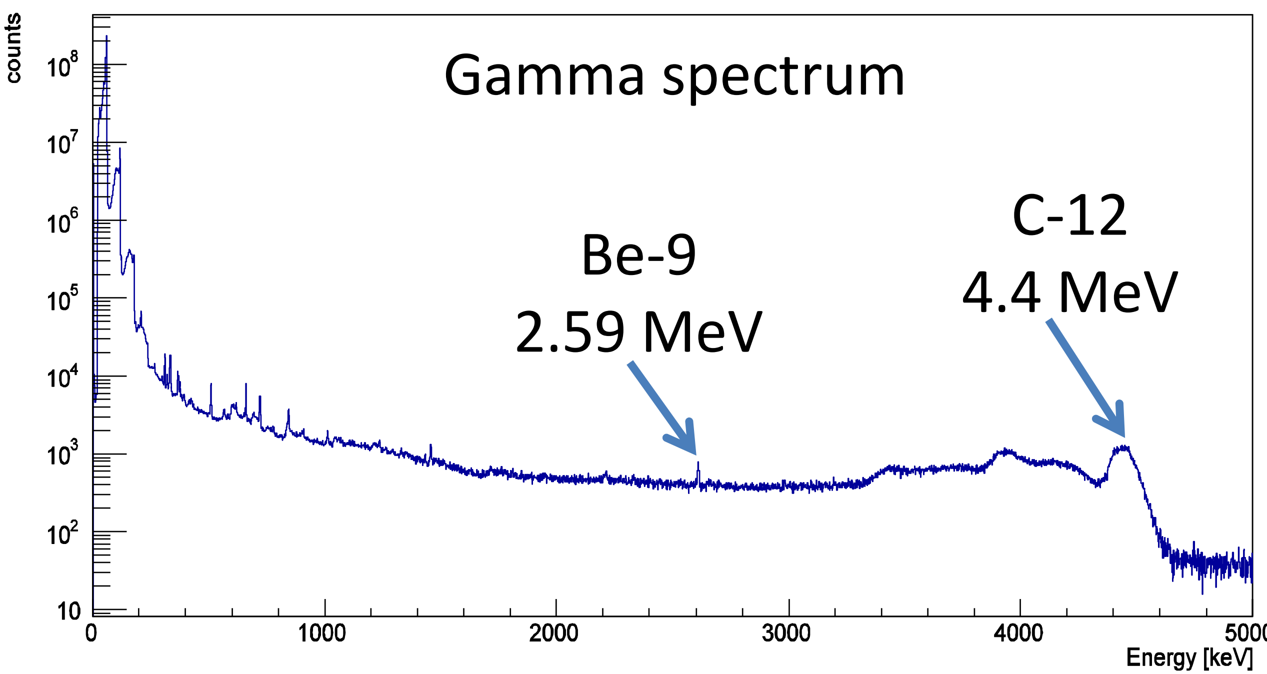
Conclusion:

➢ ZnS is (within uncertainties) not sensitive for gammas

WLSF Sensitivity Study - Neutron

AmBe source:

- Reaction: $^{9}Be\,(\alpha,n)\,^{12}C \Rightarrow E_{\gamma} = 4.4$ MeV
- Not a point source
- Activity of Am-241: 370 MBq
- Neutron emission: $2 \cdot 10^{4}\ n/s$

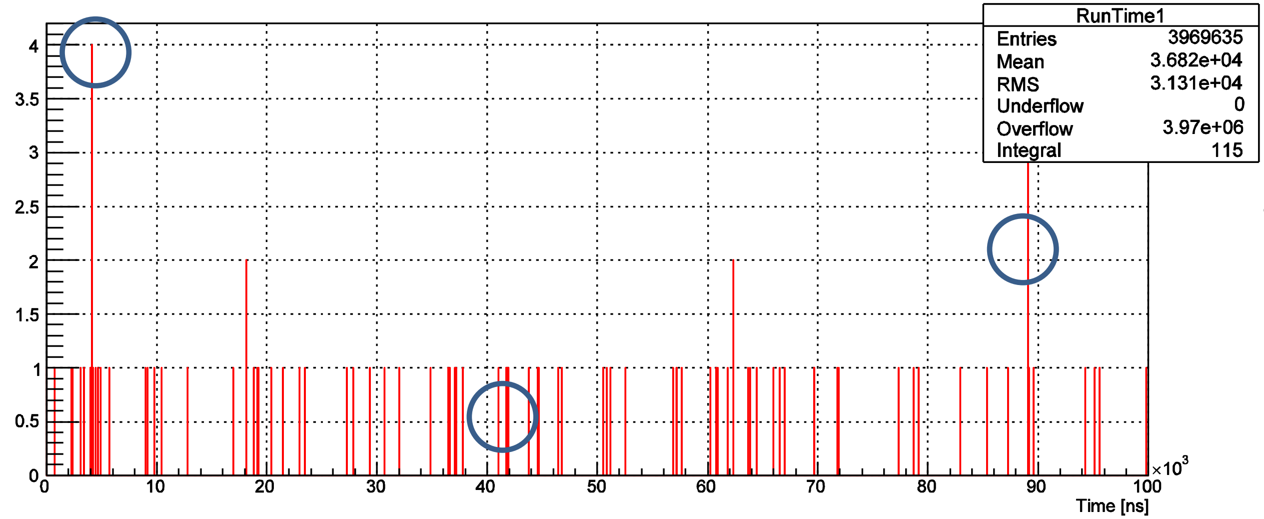


AmBe source

4 mm lead

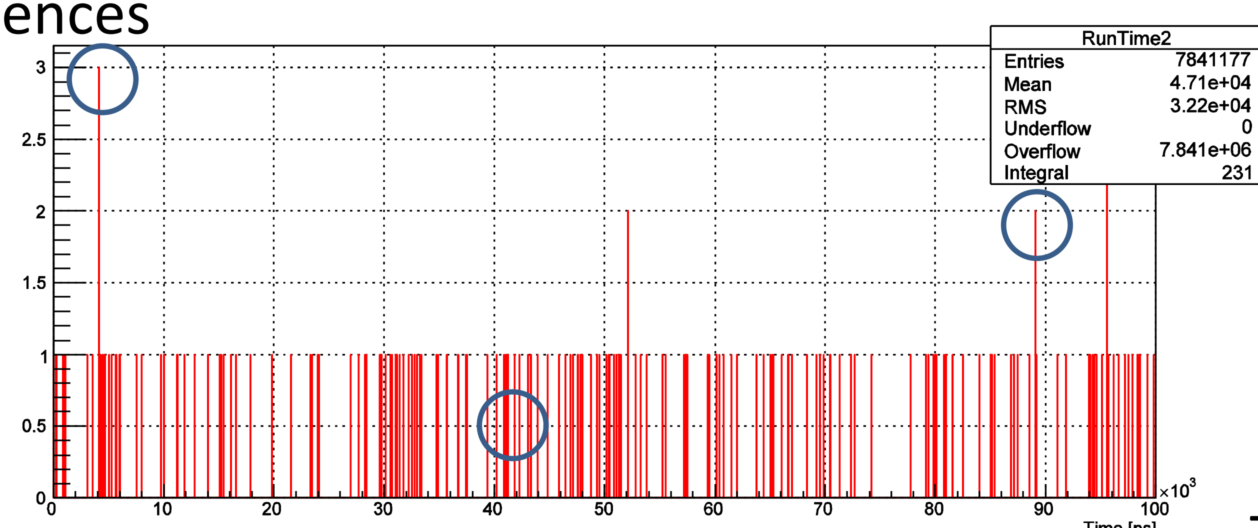
WLSF Sensitivity Study - Neutron

Event display



Total hits in X-Plane

○ Coincidences



Total hits in Y-Plane

Time in µs

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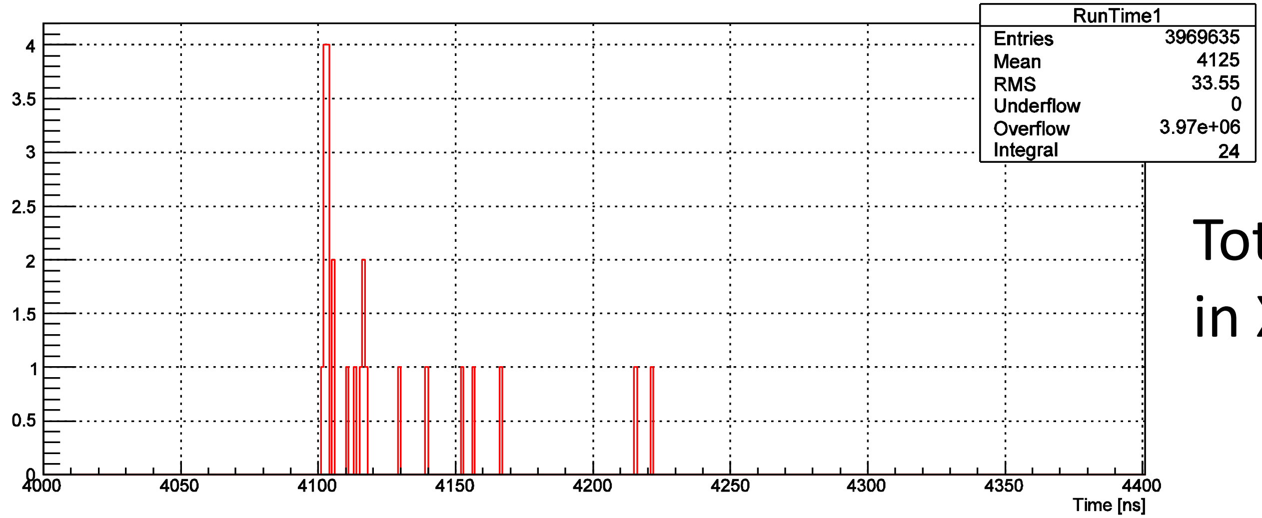
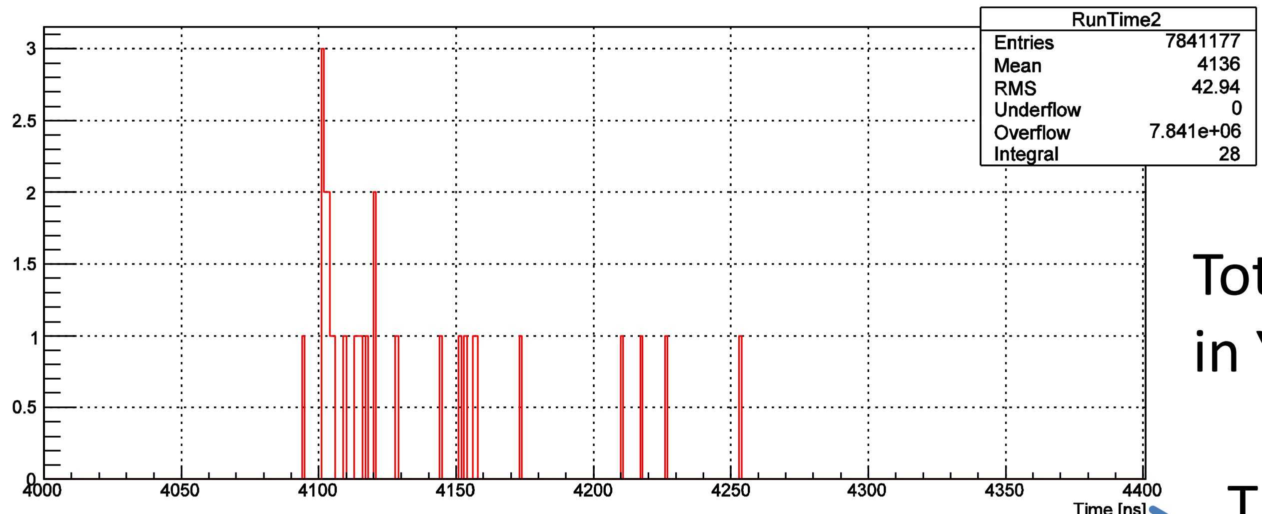
WLSF Sensitivity Study - Neutron

Event display zoom



Total hits
in X-Plane

- Coincidence
- Long event
- Length 250 ns
- Many hits
- ➢ Neutron



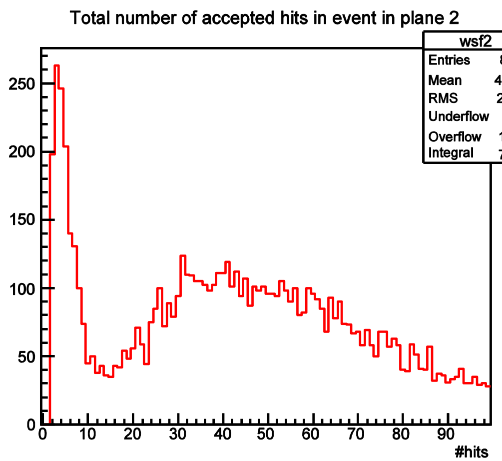
Total hits
in Y-Plane

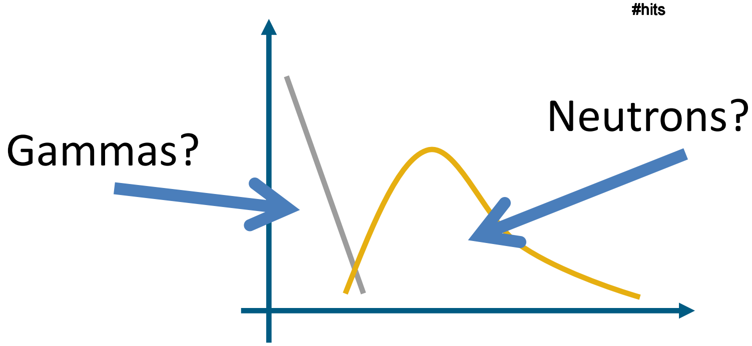
Time in ns

WLSF Sensitivity Study - Neutron

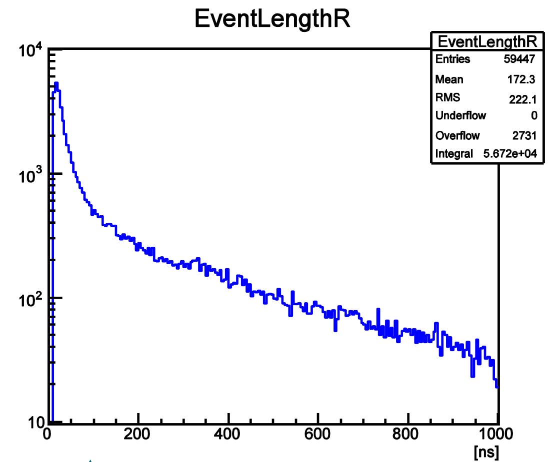
To Do:
Define cuts to find all neutrons
–> γ/n discrimination

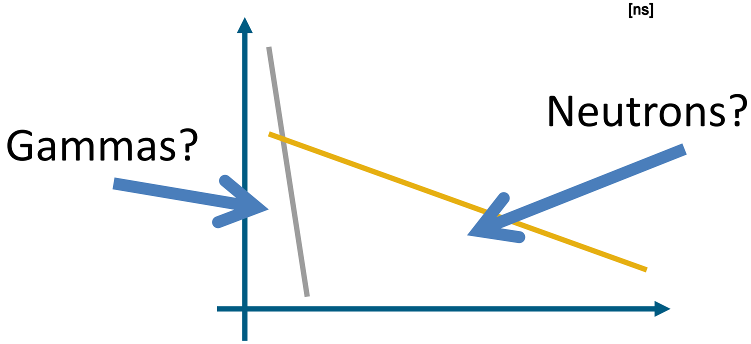
Number of hits in one plane





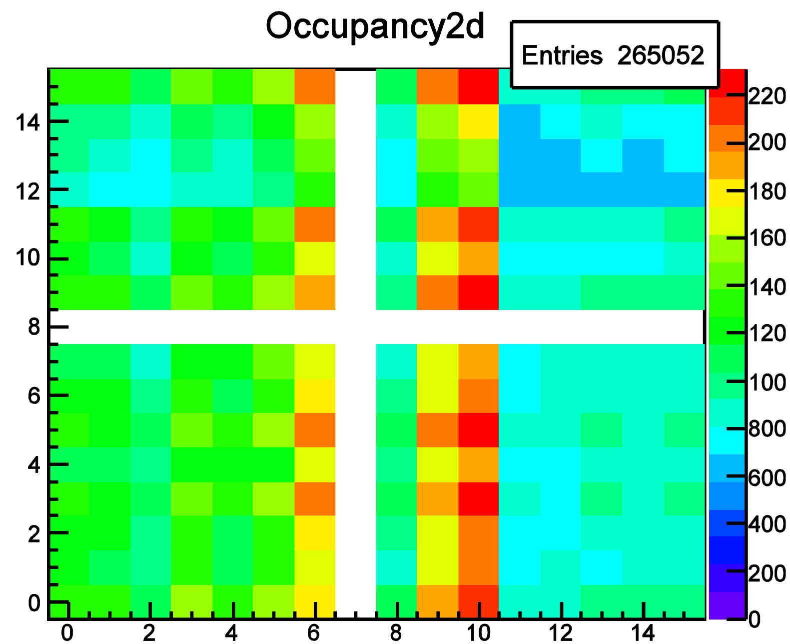
Event length



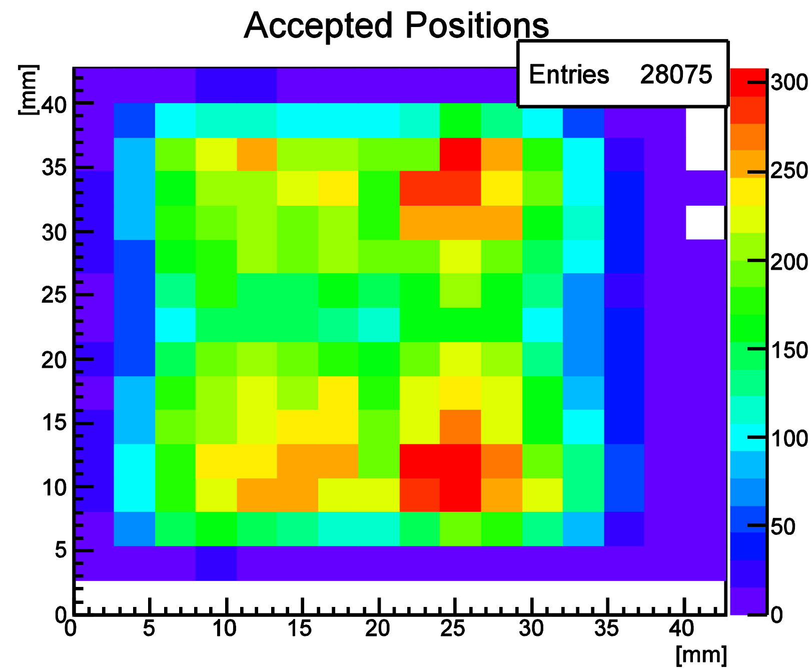


WLSF Sensitivity Study - Neutron

Results:



All coincidence events



Events after all cuts

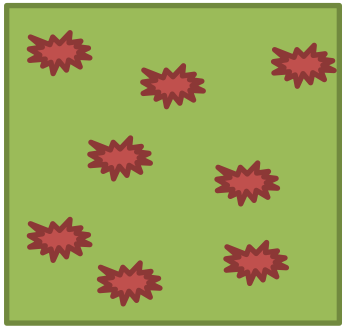
- Position reconstruction with centre of gravity

Simulation Studies

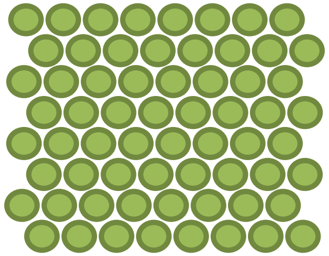
- Geant4 simulations for new scintillator types

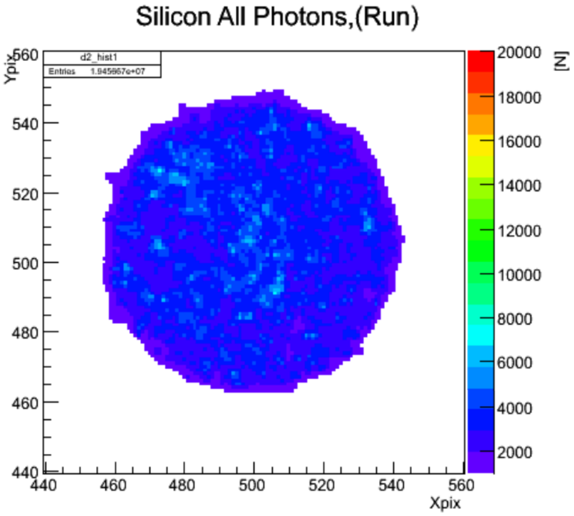
Plastic scintillator

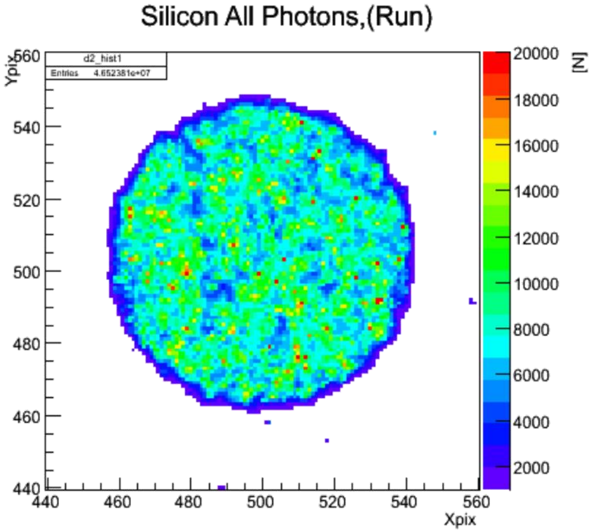
Plastic + ZnS scintillator

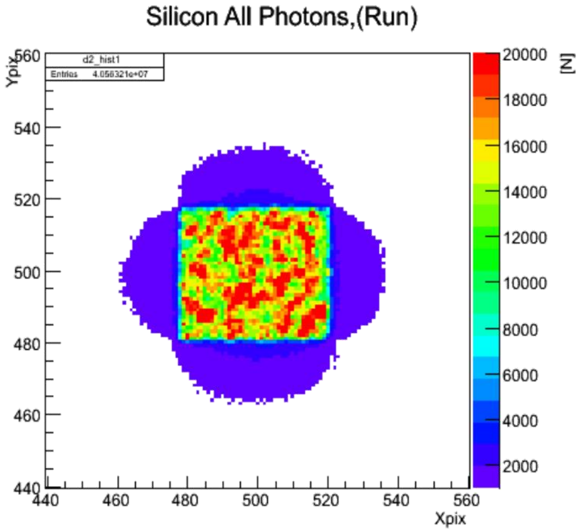


Scintillating fibres









Outlook

- Radiography with test samples
- Technical Development
  - Build new scintillators for aSi and WLSF detector
- Geant4 simulations for scintillator efficiencies

Thank you for your attention!