Neutron Detectors
From Fast to Ultra-cold

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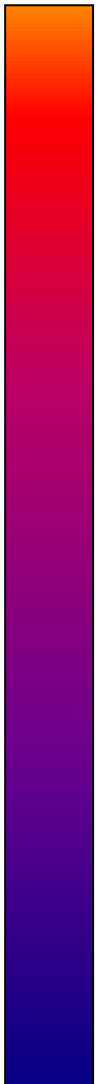
Neutrons with various energies

Since the objects of interaction change according to the energy (wavelength), they show various characteristics.

Fast



Slow

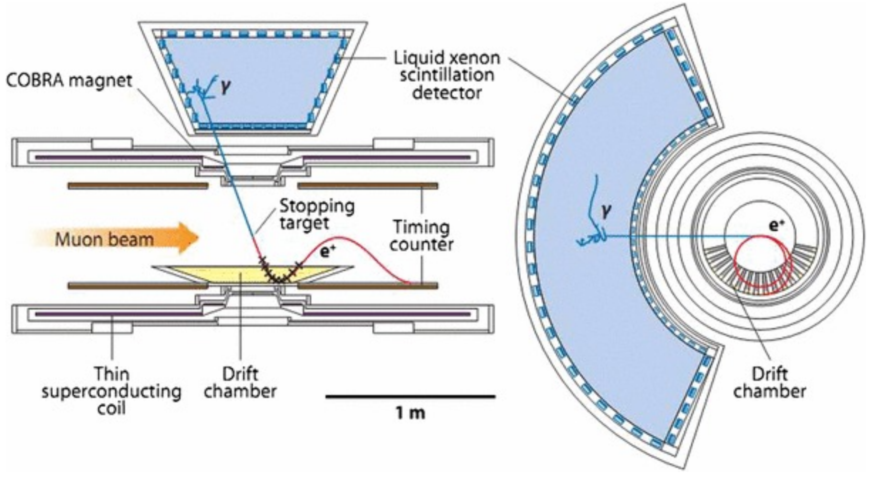
Name	Energy	Velocity	Temperature	Wavelength	Interaction size	Applications
Fast neutron	> 500 keV	$> 10^7$ m/s	$> 6 \times 10^9$ K	<40 fm	Atomic nuclei	Nuclear physics
Thermal neutron	25 meV	2200 m/s	300 K	1.8 Å	Atoms Crystal	Neutron scattering (Inelastic, diffraction)
Cold neutron	2 meV	600 m/s	23 K	6 Å	Molecular structure	Neutron scattering (Small angle, reflectometry)
Very cold neutron	50 μeV	100 m/s	0.6 K	40Å	Large molecular structure	Neutron scattering (Small angle scattering, Interferometer)
Ultra cold neutron	300 neV	8 m/s	3 mK	50 nm	1 million atoms	Fundamental physics

Difficulty of neutron detection

- The difficulty in neutron detection is due to the fact "a neutron is disappear when it is detected".

- Very wide energy range, from MeV to neV
  - 15 order of magnitude!
  - People do not refer to gamma detectors, cameras, and antennas as photon detector groups.
  - You can not say "let us call a guy who can talk all neutron detector"

- Just a detection, is no so difficult, but people require other information :
  - Position
  - Timing
  - Energy
  - Also with good efficiency.



https://doi.org/10.1140/epjc/s10052-018-5845-6

Talk outline

- Principle of neutron detection

Introductions of

- Fast neutron
- thermal/cold neutron detectors at J-PARC

Thanks for slides:
K. Hirota (KEK),
T. Nakamura (JAEA)

- UCN detectors
  - DUNia, CASCADE, Li-glass
  - CF_4 detector at PSI
  - ^{10}B detector at MAINZ
  - Emulsion detector

Thanks for slides:

B. Lauss (PSI), T. Lefort, W. Sáenz (CAEN)

D. Ries, M. Engler, M. Engler, K Franz (MAINZ)

N. Naganawa, N. Muto (Nagoya U.)

Detection principle

- Neutrons are detected by
  - Measuring by recoil (only for fast neutrons)
  - Ion induced nuclear reactions: (n,p), (n,α), (n,gamma), or (n,fission)

- The energy is determined by spectroscopy
  - Time of flight (dE/E = $10^{-2} – 10^{-4}$)
  - Bragg reflection (dλ/λ = $10^{-3} – 10^{-4}$)
  - Gravitational spectrometer (dE/E = $10^{-3} – 10^{-4}$ for UCNs)

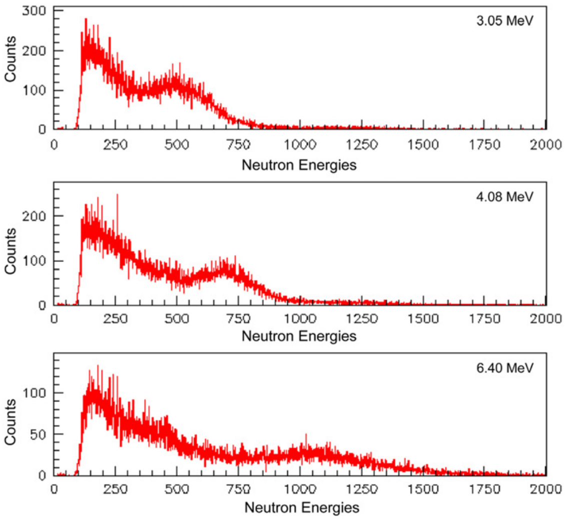
Fast neutron detection

- Neutron detectable by its kinetic energy is classified "Fast" neutrons.

- Easy way to measure is just thermalized, and count by thermal detector.
  - loses almost information of initial one.

Neutron detector in polyethylene

- Liquid scintillator (C_6D_6) is well used for fast neutron detection.
  - Fast timing of ns
  - Not good energy resolution
  - TOF is only way to get energy



M. Ojaruega et al., NIMA 652 (2011) 397-399
https://doi.org/10.1016/j.nima.2010.08.012

Thermal neutron detectors

How to measure neutrons:

1. Convert neutrons to charged particles.
2. Detect the charged particles.

Neutron conversion

- ^{3}**He** + n → t + p + 765 keV (5333 b)
- ^{14}**N** + n → t + p + 626 keV (1.868 b)
- ^{6}**Li** + n → t + α + 4738 keV (940 b)
- ^{10}**B** + n → ^{7}Li + α + 2.3 (or 2.8) MeV (3838 b)
- ^{157}**Gd** + n → Gd+γ's +29-182 keV (48890 b)

Detection

- Gas amplification
  Strong against gamma rays
- Scintillation + PMT/SSD
  Fast
- Semi-conductor detectors
  Not for High radiation condition
- Film (imaging plate, emulsion)
  No time information
  Need special read-out

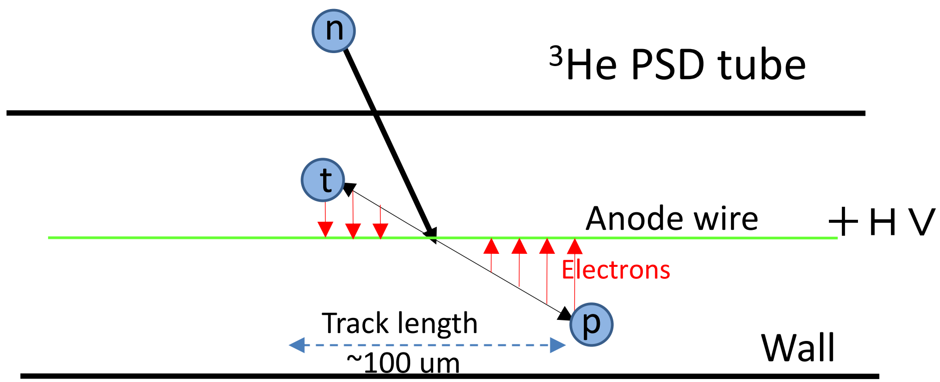
Read-out

- Multi channel
- Resistive divider

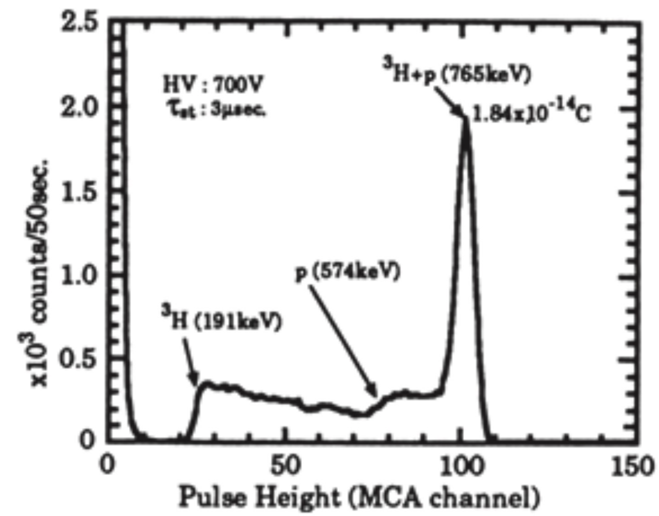
^{3}He proportional counter

^{3}He + n → t (191 keV) + p (572 keV) : 5333+/-7 b

- 10 atm of ^{3}He with 2% of CO_2 in stainless steel (0.5 mm)
- Diameter of one or half inch
- Length of 50 - 100 cm

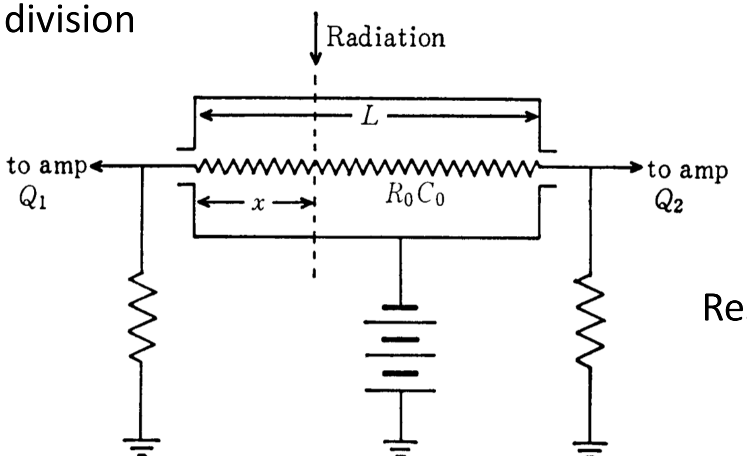


Energy spectrum



Wall effect makes low energy, but have cutoff at 191 keV.

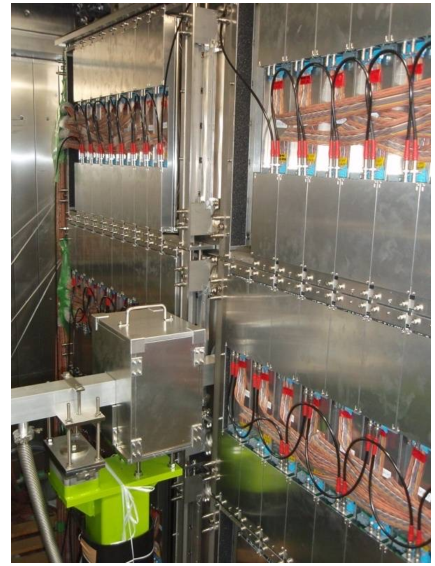
Resistive division



Resolution of the resistive division is ~5 mm

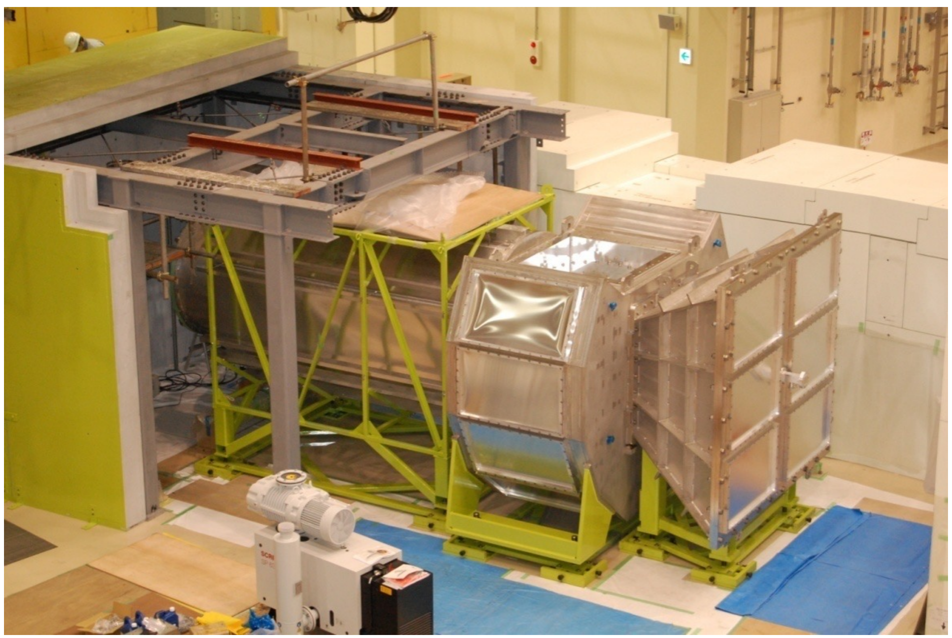
^{3}He tube in MLF

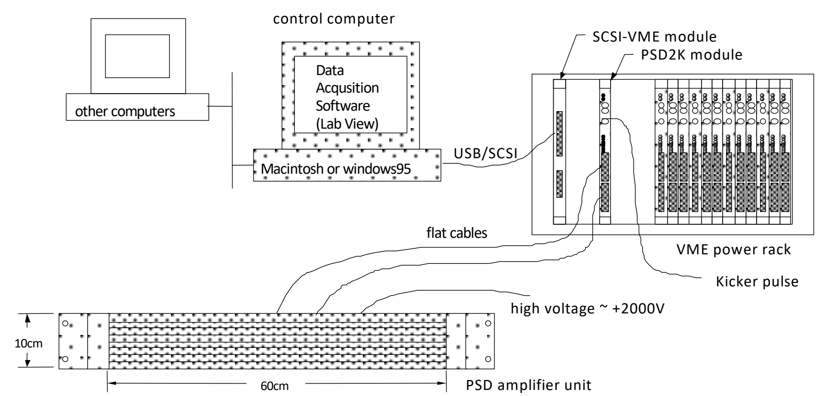
A unit of 8-half inch ^{3}He tubes

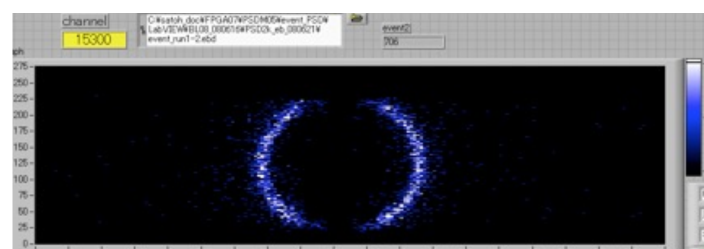


Circuits

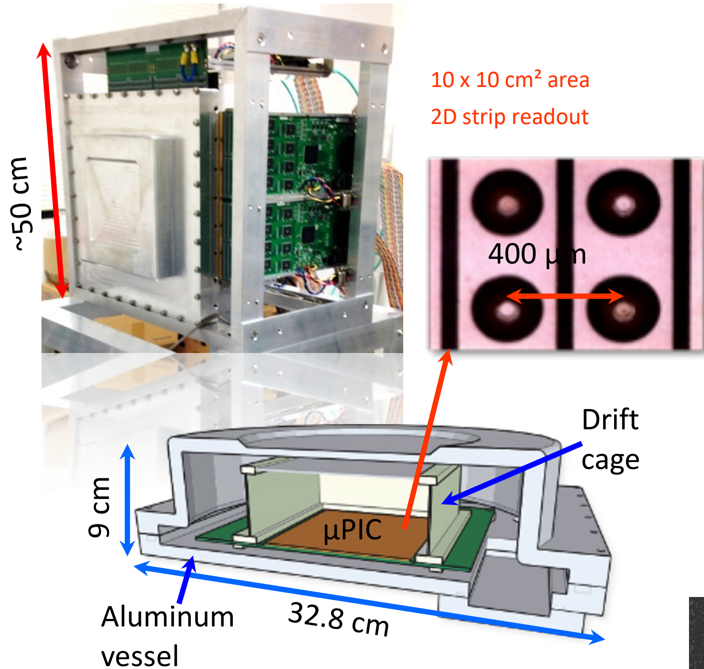
J-PARC BL20 (iMATERIA)



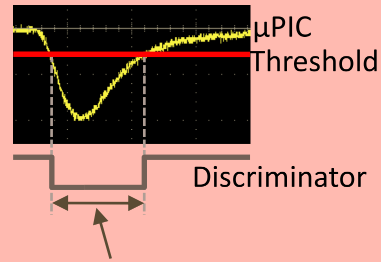


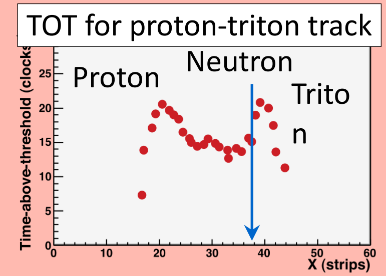


Pixelated neutron imaging detector (μNID)



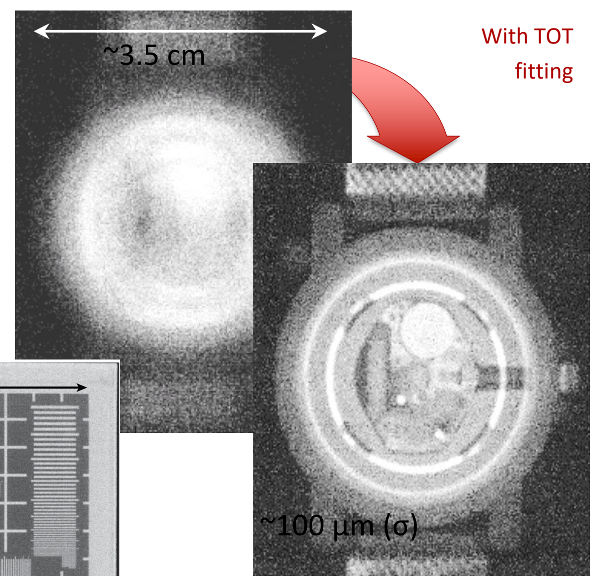
Digital encoder with time-over-threshold (TOT)

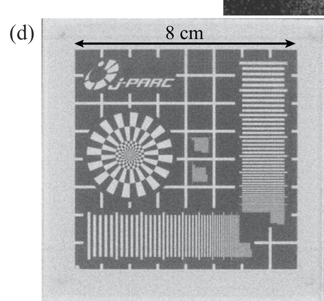




Neutron position reconstruction via template fit to TOT distribution

- Neutron detection via ^{3}He
- 3-dimensional tracking of decay pattern with energy via time-over-threshold (TOT)
- 100 μm spatial resolution
- ~0.6 μs time resolution
- gamma sensitivity $<10^{-12}$
- Mcps rate capability

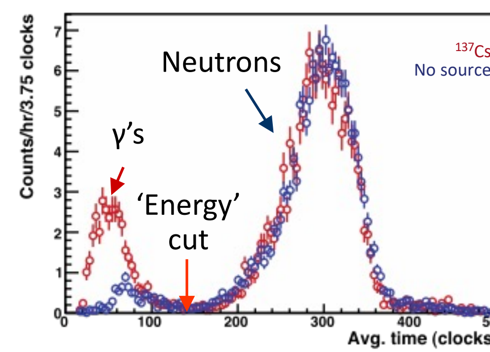




J.D. Parker et. al, NIMA 726 (2013)

Gamma rejection

J.D. Parker et. al, NIMA 697 (2013)

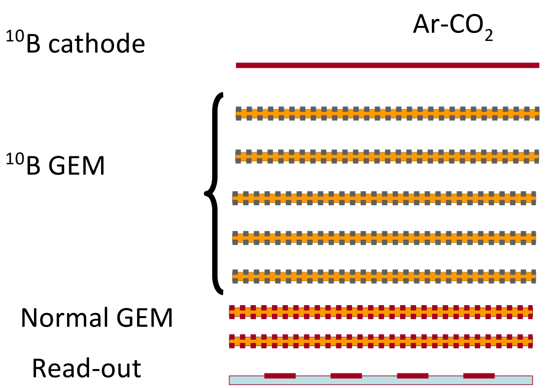


$\varepsilon_{\gamma} < 10^{-12}$(95%CL)

JD Parker, CROSS-Tokai, BL22 Group

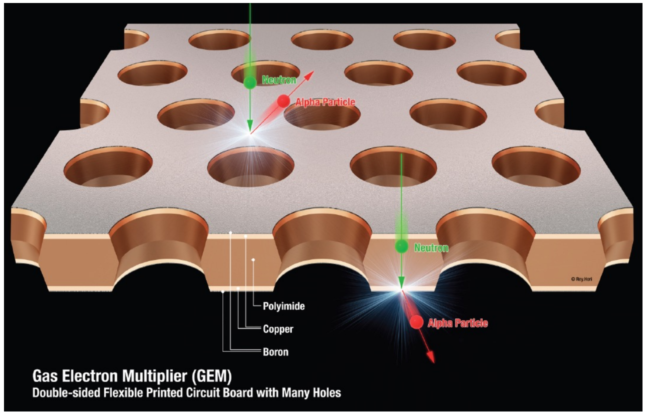
Neutron Gas electron multiplier (GEM) detector

$$^{10}B + n \rightarrow {}^{7}Li + \alpha + 2.792\ MeV \quad 3840\ b$$
$$\phantom{^{10}B + n \rightarrow} {}^{7}Li^{*} + \alpha + 2.310\ MeV$$

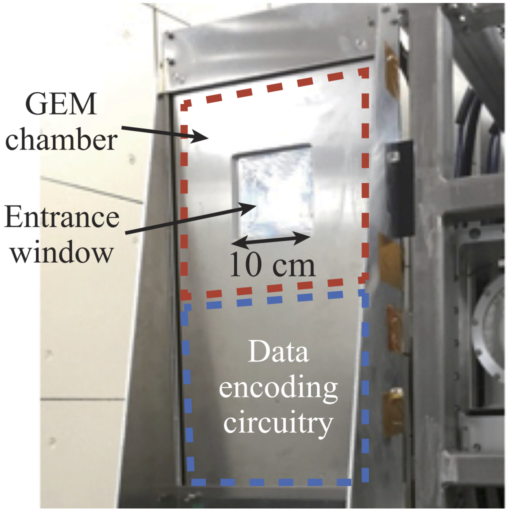


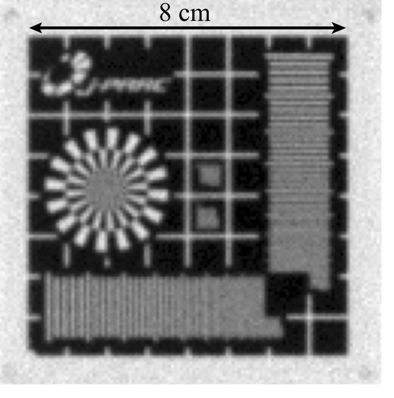
128-128 XY stlips (0.8mm-pitch)

^{10}Boron coated on a GEM



(b)





- No need for expensive ^{3}He gas
- No pressurized chamber

- Good 2D spacial resolution 1 mm (FWHM)
- Fast (15 ns)
- Insensitive for gamma-rays.
- Available for 180 kcps.
- Efficiency is limited.

T. Shinohara *et al.*, Rev. Sci. Instrum. **91**, 043302 (2020); https://doi.org/10.1063/1.5136034

Scintillation-based neutron detector

Reactions for scintillation :

- ^{6}**Li** + n → t + α + 4738 keV (940 b)
- ^{10}**B** + n → ^{7}Li + α + 2.3 (or 2.8) MeV (3840 b)
- ^{157}**Gd** + n → Gd+γ's +29-182 keV (48890 b)

Scintillators for neutrons

Scinti. host	λem (nm)	Light yield (photon)		T (ns)	Density
		neutron	MeV γ		
^{6}Li-glass(Ce)	395	6000	4000	75	2.5
^{6}LiF/ZnS(Ag)	450	160000	75000	～1000	2.6
6LiI(Eu)	470	50000	12000	1400	4.1
$^{6}Li_6Gd(BO_3)_3$	385,415	50000	14000	200/800	3.5
Gd_2O_2S	510	3000	40000	～1000	7.3

Photon detectors :

- PMT Larger detection area, multi-anode, available
- MPPC Low cost, Easy Pixelization, weak for radiation
- CCD High resolution, slow, weak for radiation

RPMT detector

Scintillator + Resistive division 2D-PMT

- Detection area of ϕ100 mm
- Spacial resolution < 1 mm (FWHM)
- Easy to handle

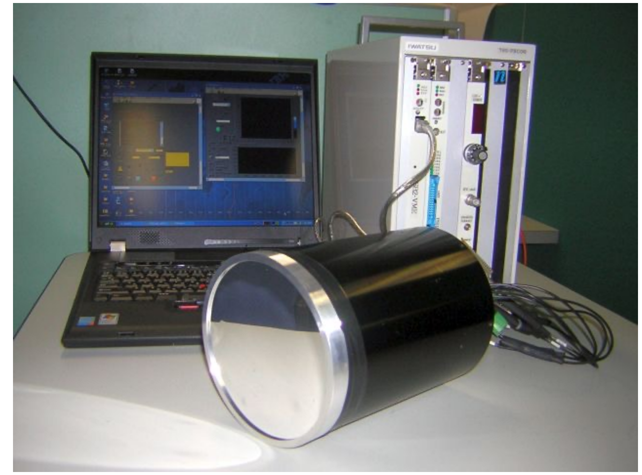
Scintillator: ZnS/^{6}LiF ^{6}Li-glasss
Effective area 35×35mm^2(ϕ3 PMT)
 60×60mm^2(ϕ5 PMT)
spatial resolution （FWHM） 0.5～0.8mm
efficiency 20-30% ＠cold neutron
counting rate 20kcps@10% dead time

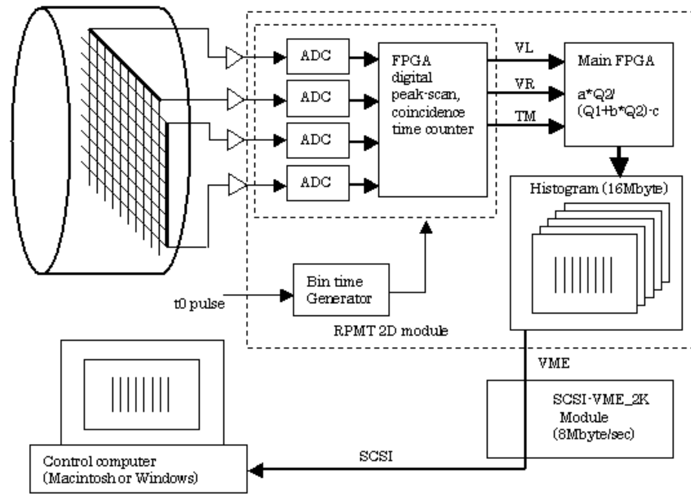
compact DAQ system USB2.0 transfer
→ 100BASE network (NEUNETsystem at J-PARC)

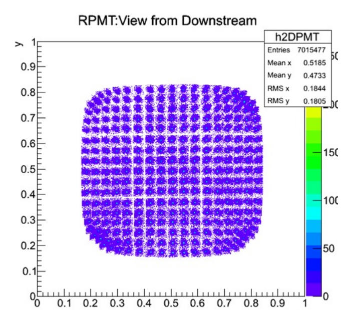
Easy to use and good performance

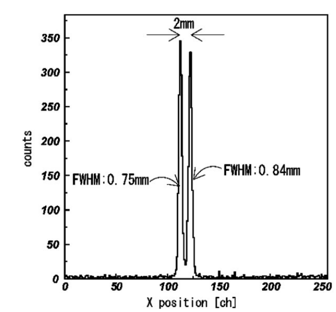
SANS(F-, mf-, vcn-), Spin Echo,
Reflectometer, Pulse Imaging, ・・・

TOF : available









Hirota et.al., Phys. Chem. Chem. Phys. , 2005, 7, 1836

LiTA detector

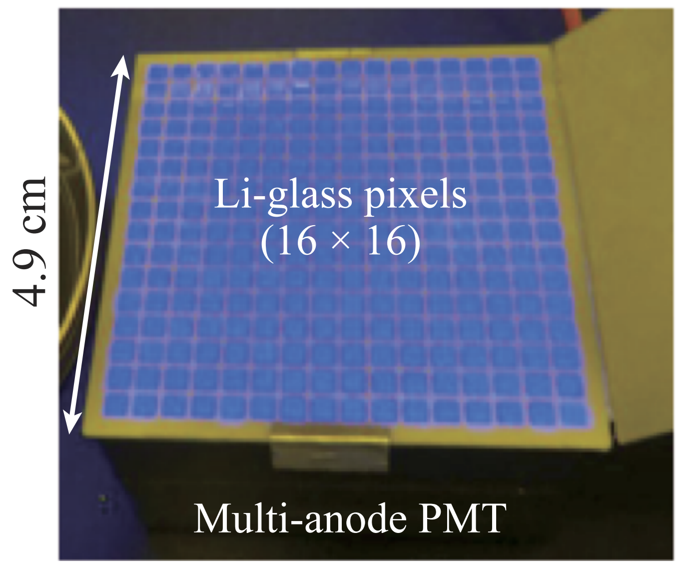
Pixelated scintillators + Grid-PMT

- Fast
- Higher efficiency

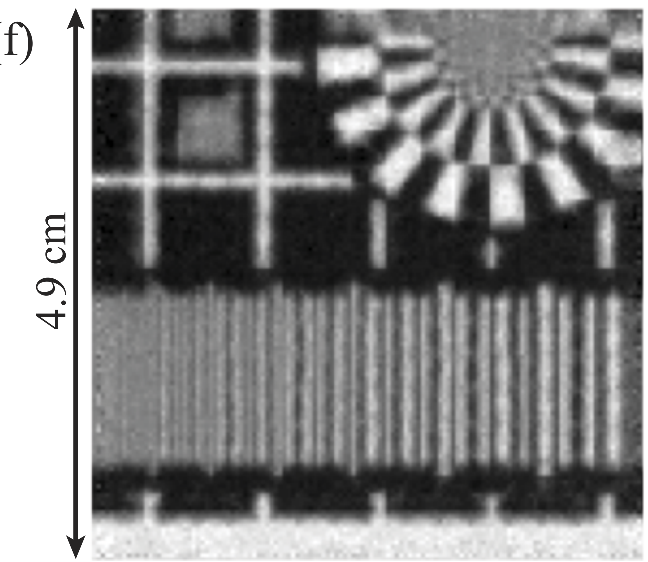
High counting rate Li Pixel Detector

Scintillator: ^{6}Li-glasss (GS20)
16 ×16 pixels (2.1×2.1 × 1 mmt /pixel)
Effective area 50×50 mm^2
spatial resolution 3 mm
efficiency 40% @thermal neutron
counting rate 2-3 Mcps/ detector

(c)



(f)

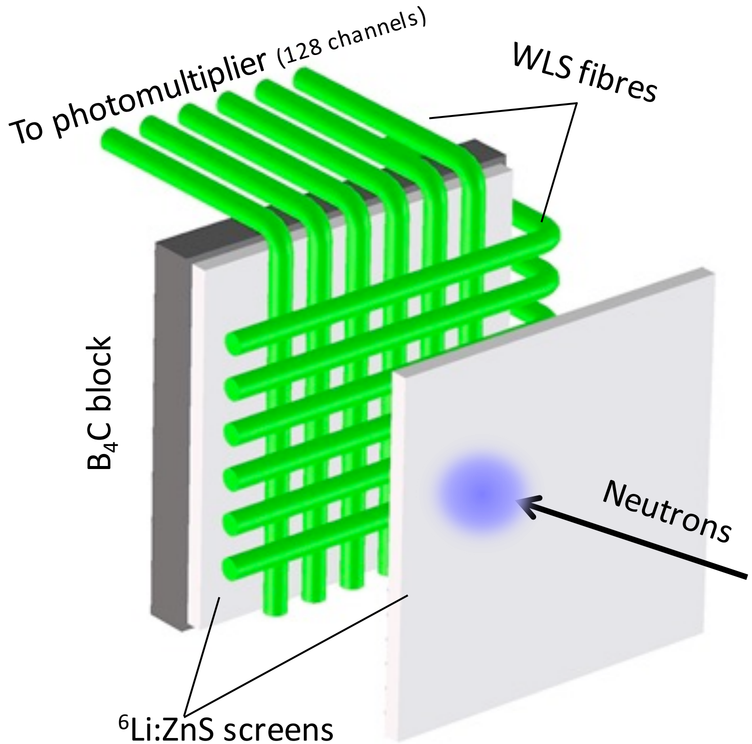


T. Shinohara *et al.*, Rev. Sci. Instrum. **91**, 043302 (2020); https://doi.org/10.1063/1.5136034

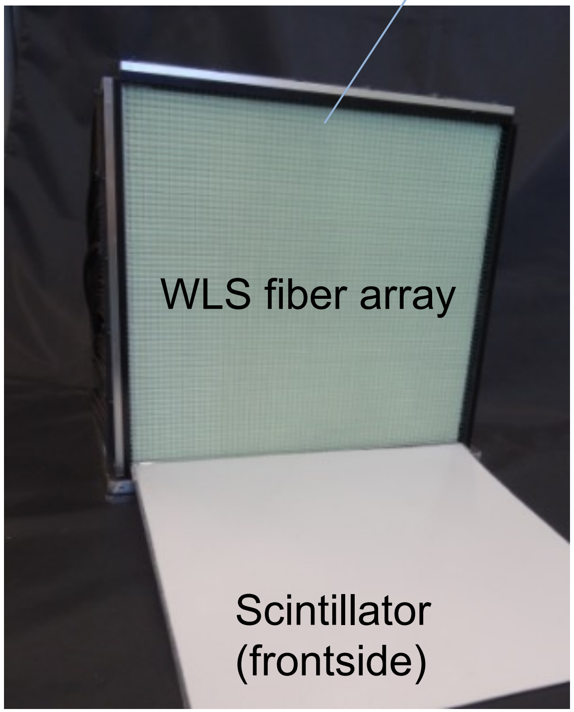
Scintillator / Wavelength shifting fiber detector

- Stable operation with photon counting method
- Simple structure
- High flexibility in detector design

Resolution 2-3 mm (FWHM)



Scintillator (backside)



25 cm

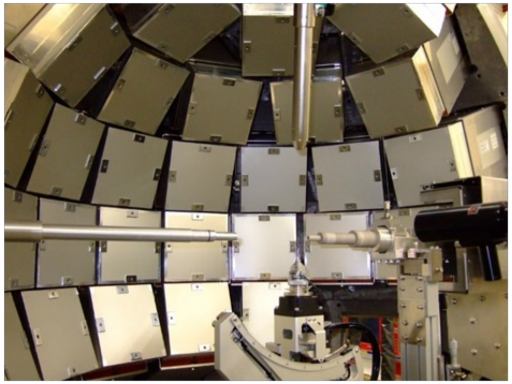
T. Nakamura et al., NIMA 784 (2015) 202–207
https://doi.org/10.1016/j.nima.2014.12.035

Slide from Tatsuya Nakamura (JAEA)

Scintillation detectors installed at the MLF

iBIX	Senju	Takumi
2008-	2011-	2008-
0.5 mm resolution 2d detector	4 mm resolution 2d detector	3 mm resolution Linear (ISIS type)

iBIX (BL03): Bio-single crystal diffractometer



High spatial resolution detector

- WLS Fiber technology
- pixel size : 0.5 x 0.5 mm^2
- sensitive area : 133 x 133 mm^2
- detection efficiency: ~50% for 1.8A
- gamma sensitivity: ~1 x 10^{-6}

34 detectors (in operation)

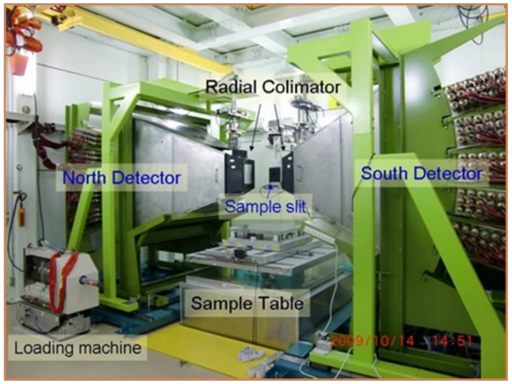
SENJU (BL18): Single crystal diffractometer

Large area detector

- WLS Fiber technology
- pixel size : 4 x 4 mm^2
- sensitive area : 256 x 256 mm^2
- detection efficiency: ~40% for 1.8A
- gamma sensitivity: ~ 3 x 10^{-6}

41 detectors (in operation)

TAKUMI (BL19): Residual Stress diffractometer



One dimensional large area detector

- Coded fiber technology (with ISIS)
- pixel size : 3 x 200 mm^2
- sensitive area : 200 x 1000 mm^2
- detection efficiency: >50% for 1.0A
- gamma sensitivity: < 1 x 10^{-6}

Technology transferred from ISIS(UK)

12 detectors (in operation)

Slide from Tatsuya Nakamura (JAEA)

How accurate can we know the neutron detector efficiency?

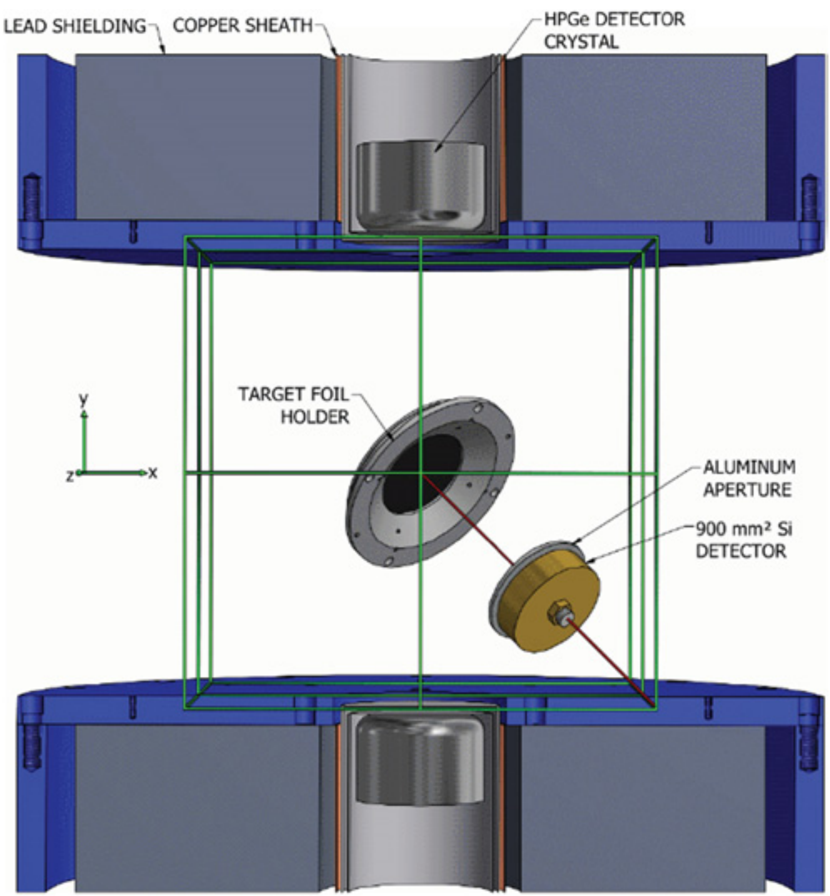


Figure 1. Layout of the Alpha-Gamma target mount showing the detectors. The neutron beam is incident from the right of the image.

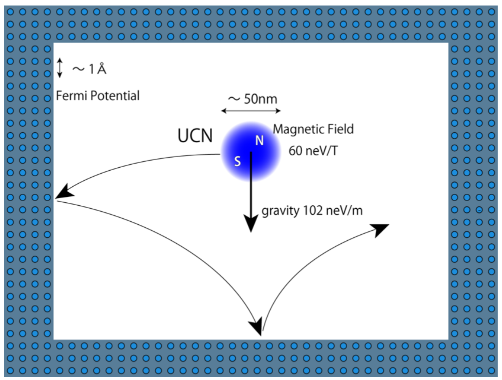
- The neutron detection efficiency can not be 100%.
- The coincidence method at NIST Alpha-Gamma
  - Using coincidence method of two Ge detector gives super accuracy.
  - The accuracy of the efficiency was 4.8×10^{-4}.

Evan R. Adamek et al., EPJ Web of Conferences 219, 10004 (2019) https://doi.org/10.1051/epjconf/201921910004

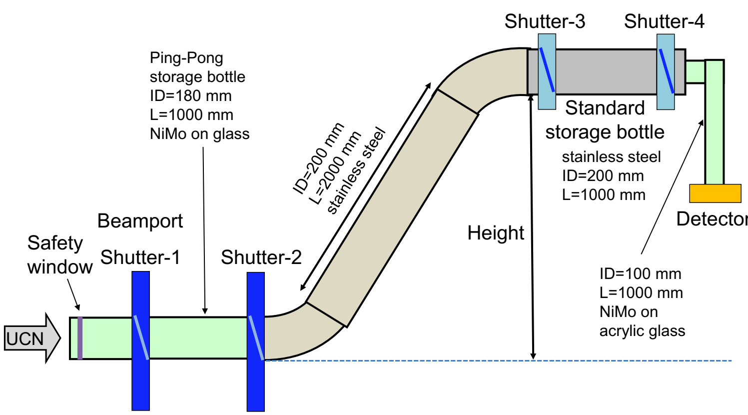
Ultra cold neutron (UCN)

UCN:

Energy	~ 200 neV
Velocity	~ 5 m/s
Wavelength	~ 50 nm



- UCNs are reflected on the surface of materials.
- Thus, we need accelerate UCNs
  - Al window has V_F = 50 neV
  - Usually, falling 100 neV (1 m)
- For spectroscopy
  - UCN cranks
  - TOF with chopper
  - Gravity spectrometer



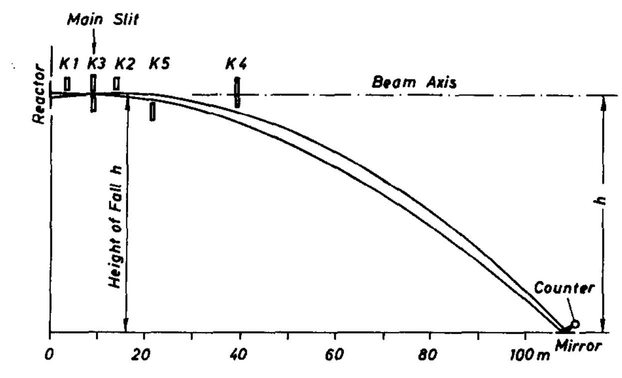


Figure 2. Principle of the neutron-gravity refractometer (after Koester[45,46]).

G. Bison et al., Eur. Phys. J. A (2022) 58:103
https://doi.org/10.1140/epja/s10050-022-00747-1

L. Koester *et al.*,. *At. Data Nucl. Data Tables 49* (1991) 65-120,
https://doi.org/10.1140/epja/i2017-12195-7

Conventional UCN detectors

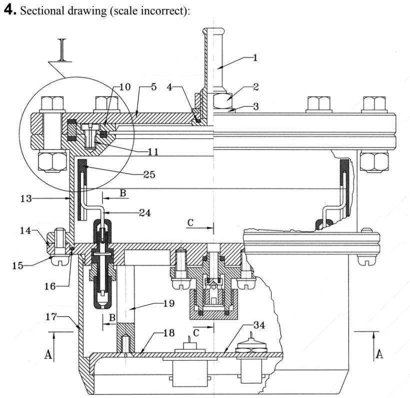
DUNia-10: A simple proportional counter sealed with

^3He — 10±0.5 Torr

CH^4 — 8±0.5 Torr

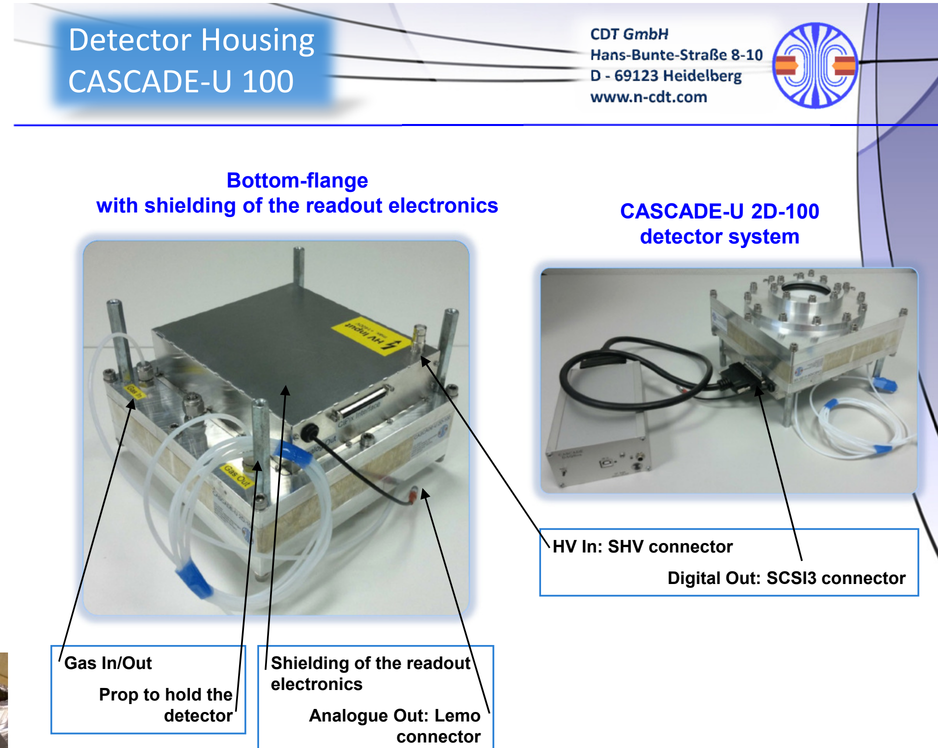
Ar — up to 1.1 atm.

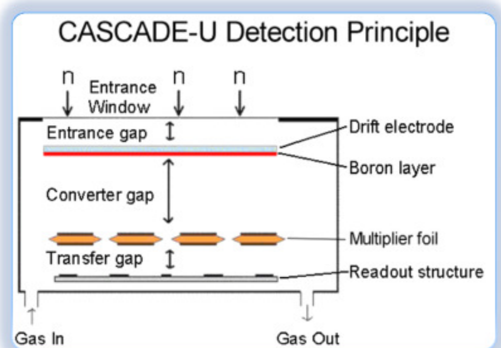
4. Sectional drawing (scale incorrect):



100 um thin Al window with funnels

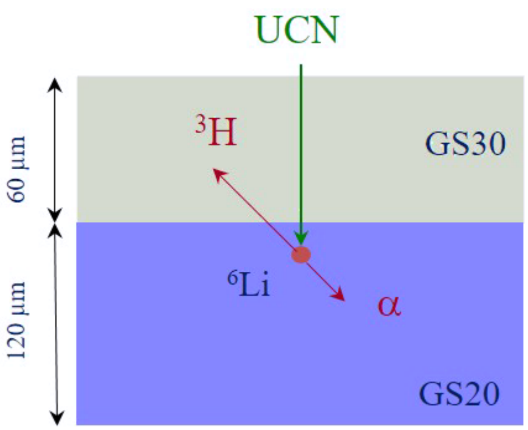
CASCADE :All-in-one 2D-detector





Li-glass detector

Combination of ^{6}Li depleted/enriched can reduce wall effect.

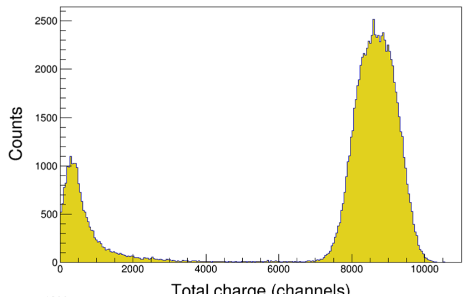


^{6}Li depleted

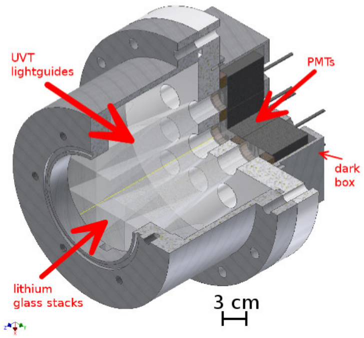
^{6}Li enriched

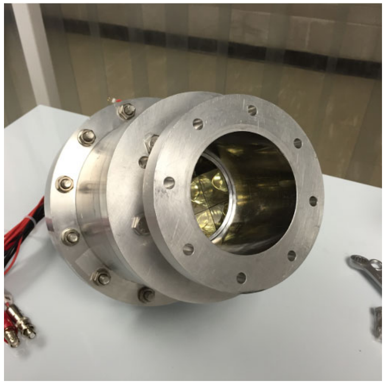
Table 1. Properties of the glass scintillators.

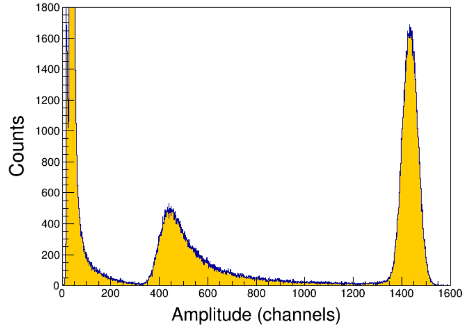
Scintillator	GS20 ^{6}Li enriched	GS30 ^{6}Li depleted
Total Li content (%)	6.6	6.6
^{6}Li fraction (%)	95	0.01
^{6}Li density (cm^{-3}) [17]	1.716×10^{22}	1.806×10^{18}



^{6}Li enriched/depleted stacked







^{6}Li enriched

G. Ban *et al.*, *Eur. Phys. J. A* **52**, 326 (2016).
https://doi.org/10.1140/epja/i2016-16326-4

B. Jamieson *et al.*, *Eur. Phys. J. A* **53**, 3 (2017).
https://doi.org/10.1140/epja/i2017-12195-7

Requirements:

- High detection efficiency
- High counting rate capability (10^5 Hz)
- Low sensitivity to gamma-rays
- Background discrimination

A novel UCN detector

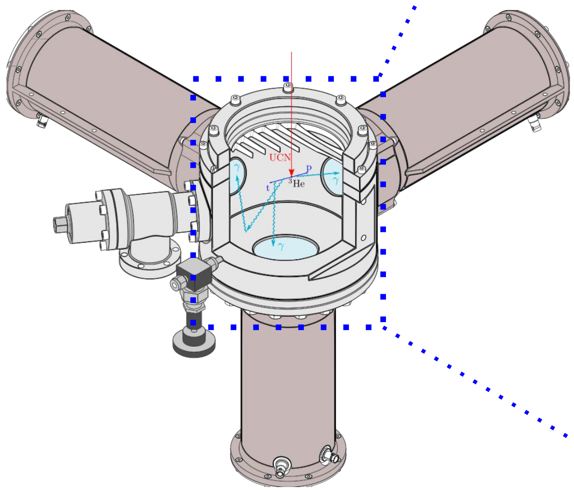
GADGET detector developed by LPC
^{3}He and CF_4 gas mixture:

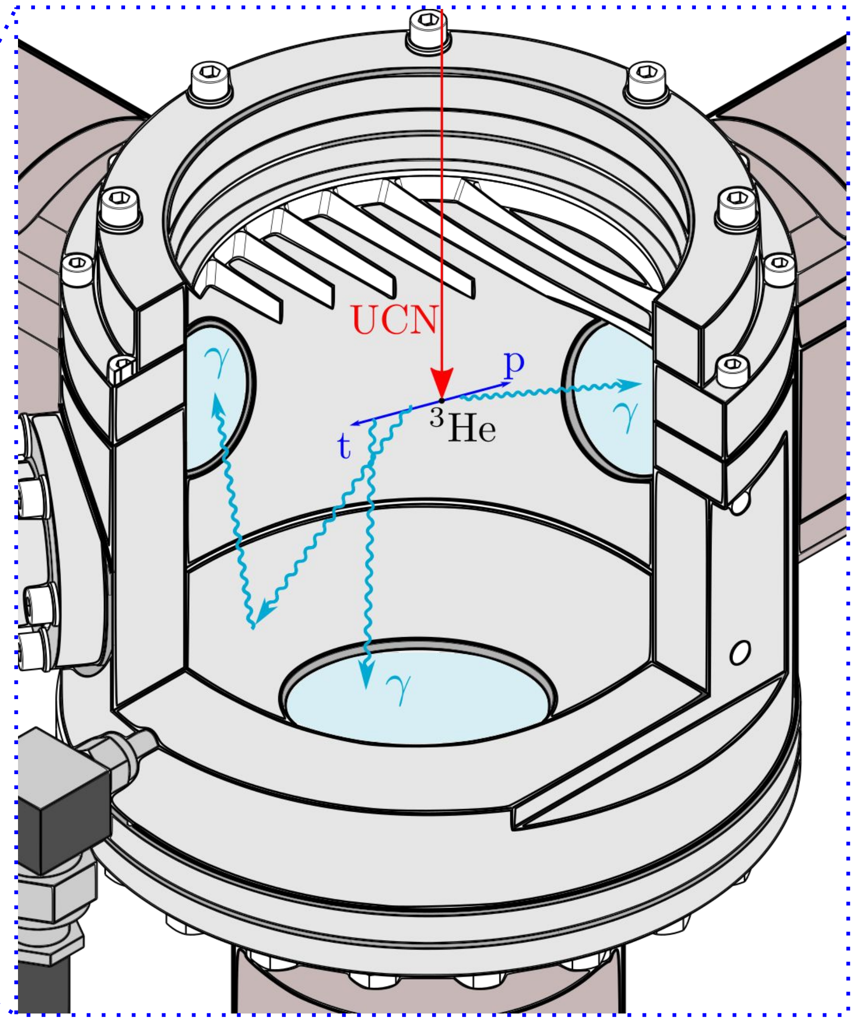
1. UCN absorption

$n + {}^3He \rightarrow p\ (0.57\ MeV) + t\ (0.19\ MeV)$

2. **CF_4** scintillation due to **p** and **t** ionization/excitation.

3. Light collection by 3 PM tubes working in coincidences



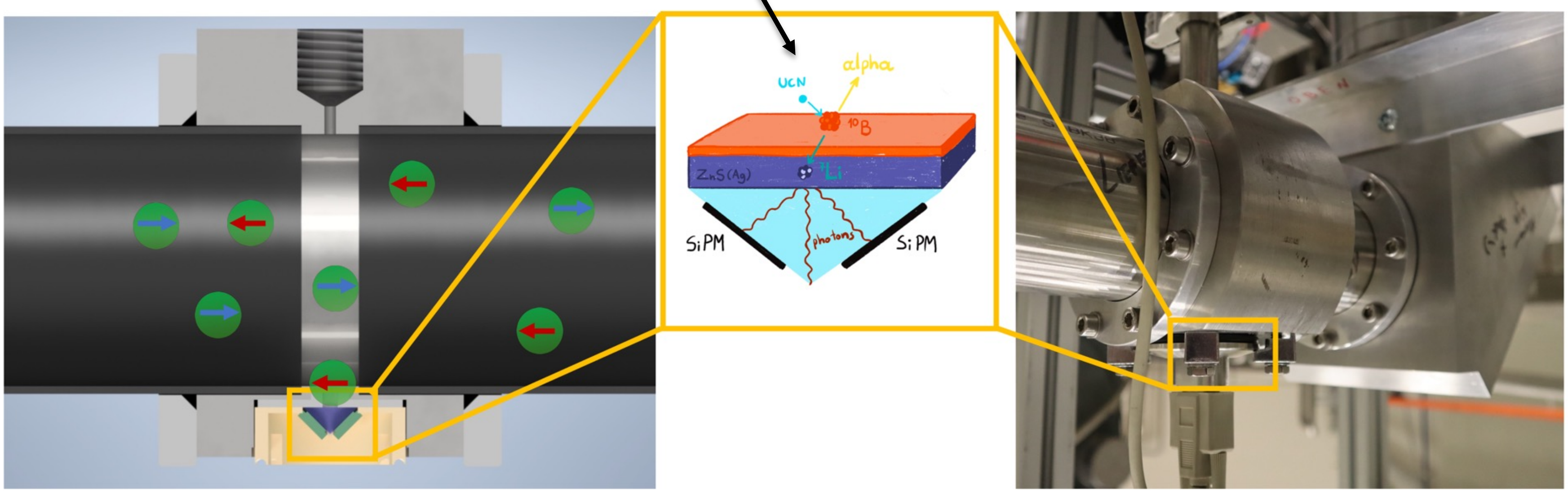


Zero-potential ^{10}B UCN detector

Normalisation detector

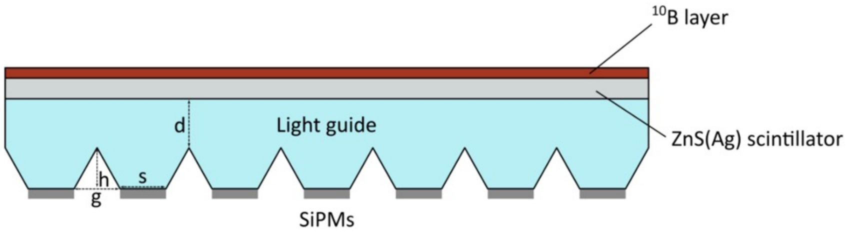
Martin Engler
mengle01@uni-mainz.de

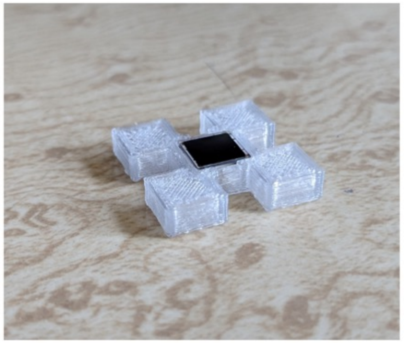
Fermi potential of ^{10}B is -3.2 neV !!

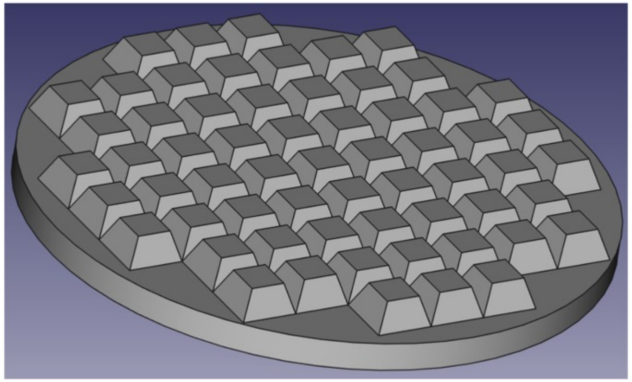


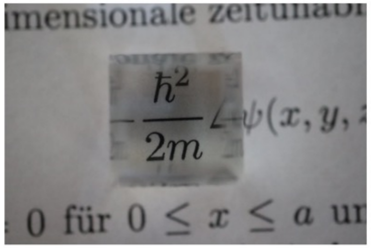
2D UCN detector

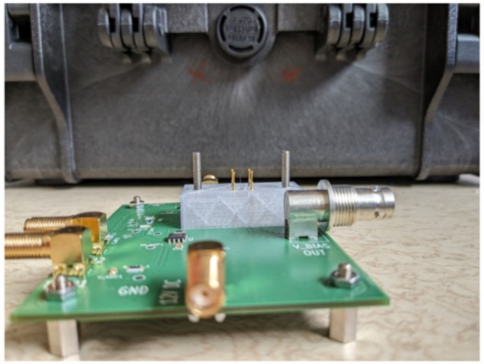
Konrad Franz
kfranz@uni-mainz.de











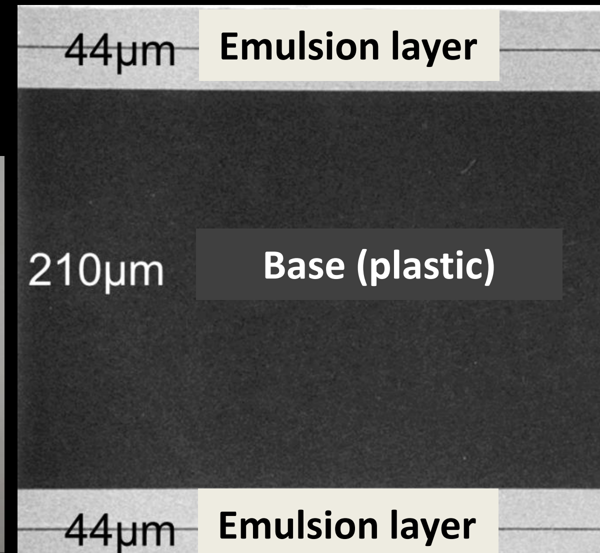
Nuclear emulsion - a high position resolution tracking detector for ionizing particles.

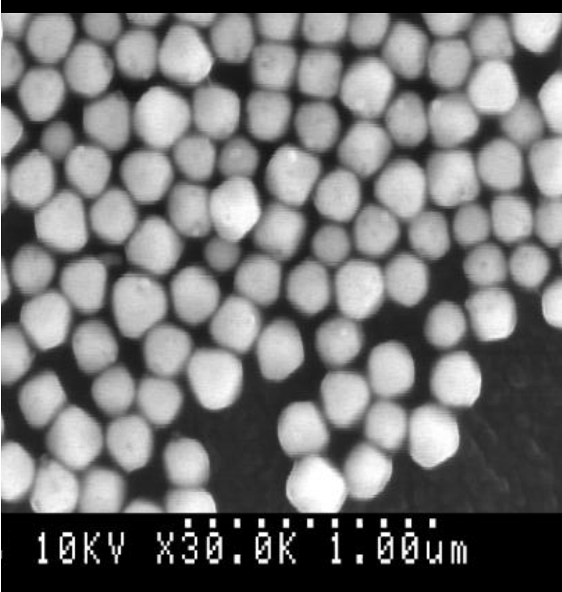
Emulsion gel（AgBr･I crystals dispersed in gelatin）

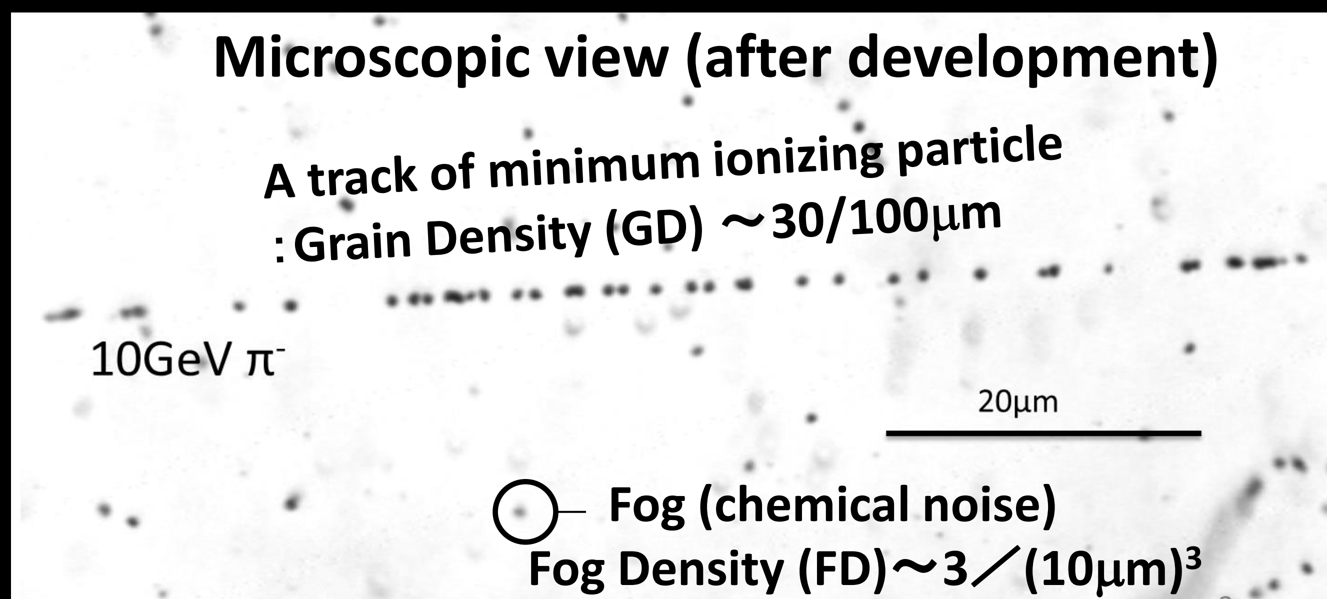
→ coating

emulsion film for OPERA experiment

Cross sectional view



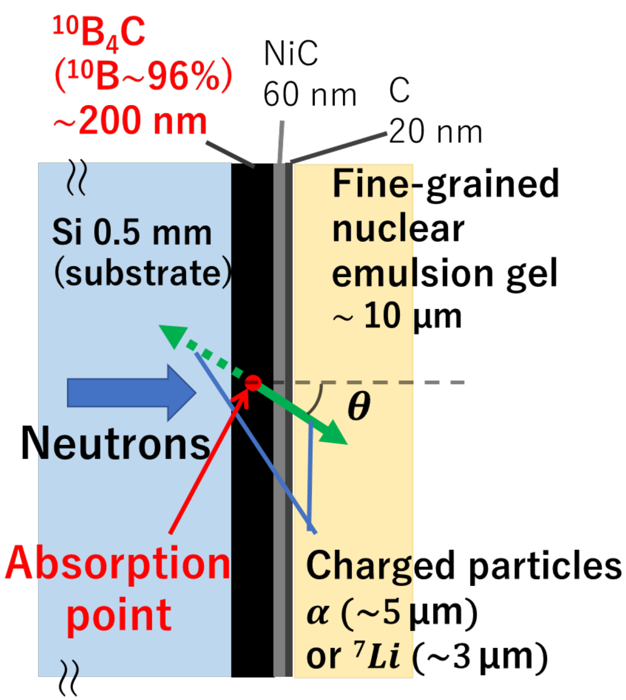




N. Naganawa et al., UCN workshop at Mainz (Mar.2016)

High spatial resolution emulsion for ultracold neutrons

Structure of the detector (cross section)



Sputtered at KURRI

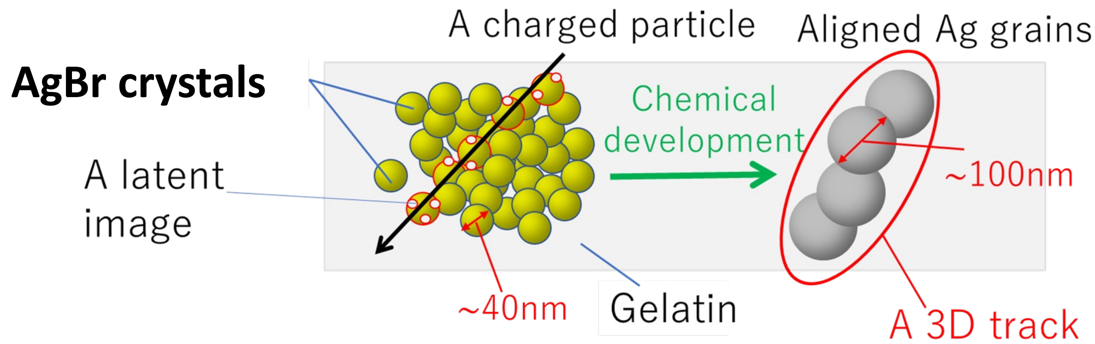
Estimated Resolution < 100 nm ($\theta \leq 0.9$ rad)

→1~2 order higher than existing detectors

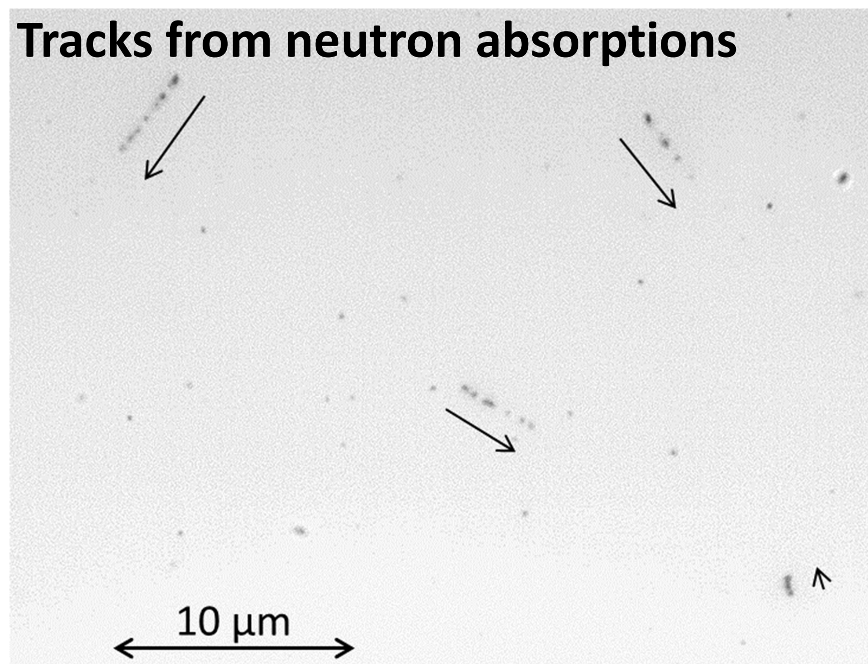
Absorption efficiency ~41%
(velocity of neutrons ~10 m/s)

N. Naganawa *et al.*, Eur. Phys. J. C (2018) 78:959
https://doi.org/10.1140/epjc/s10052-018-6395-7

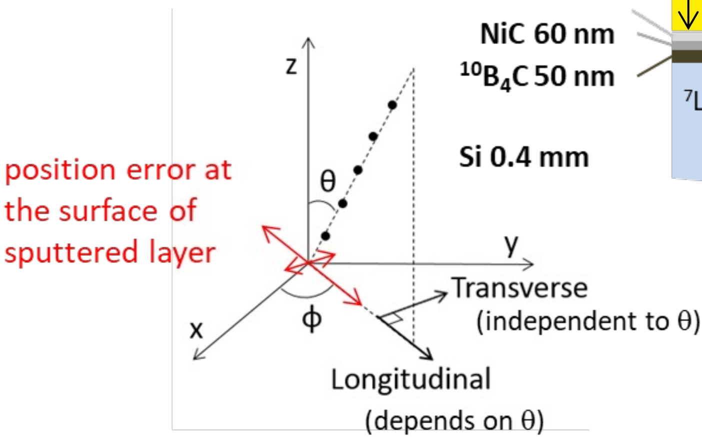
Principle of track formation

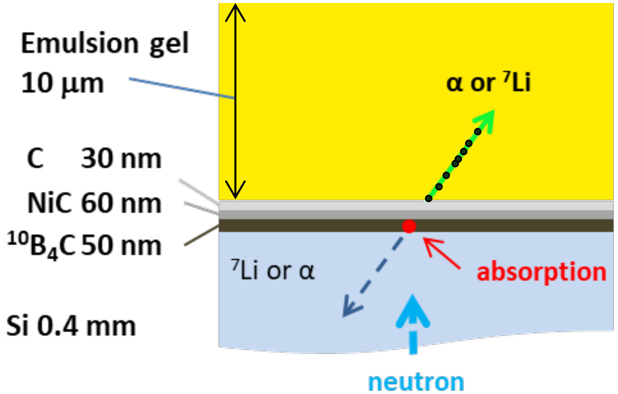


- **Fine-grained nuclear emulsion gel (Nagoya Univ.)**
- **Especially high resolution**
- **Strong against γ –ray background**

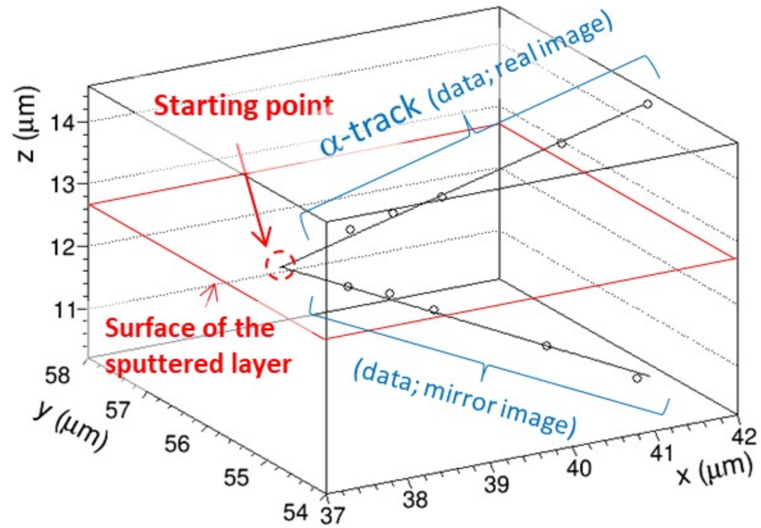


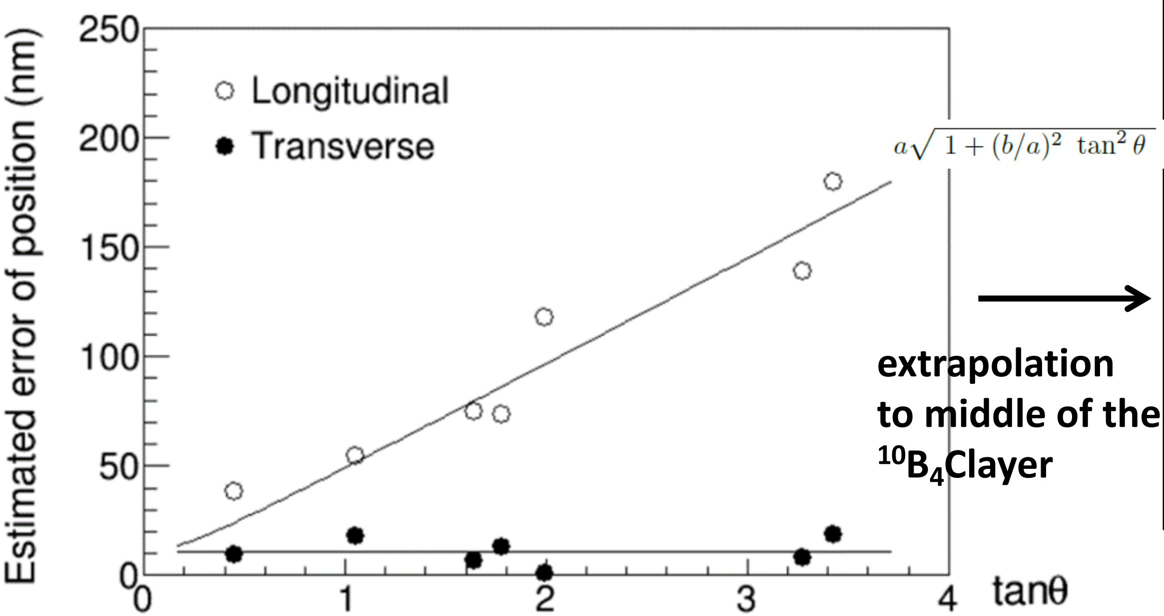
Estimation of spatial resolution using tracks





Position data of grains of alpha tacks from absorption





extrapolation to middle of the $^{10}B_4C$layer →

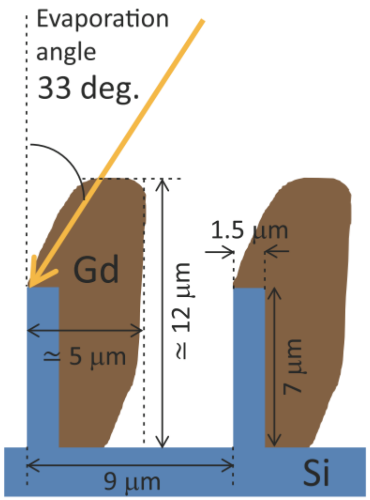
Position errors at middle of $^{10}B_4C$ layer:

- **Transverse: independent to angles**
  →resolution : 11 nm
- **Longitudinal: depend on angles (θ)**
  whole acceptance (0≦tanθ≦13.8)
  →resotution: 11 nm ～ 1μm
  tanθ < 1.9 (34% of whole statistics)
  →resolution: 11 - 99 nm

Eur. Phys. J. C (2018) 78:959

Test with Gd slit

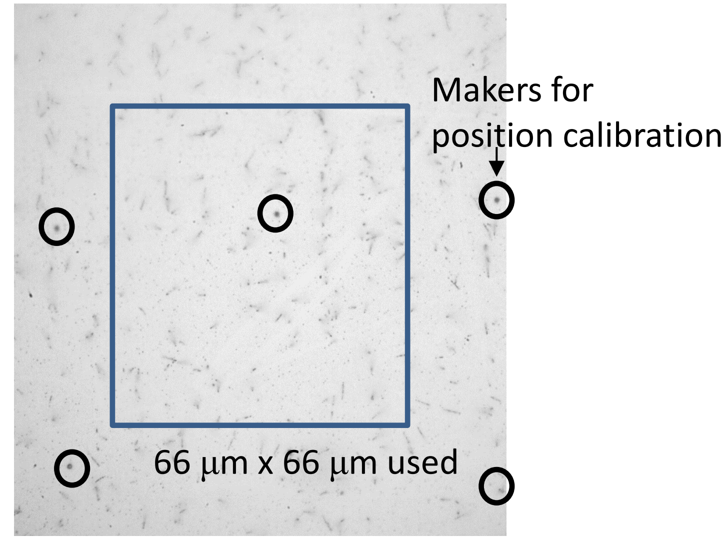
Schematic view of Gd slit



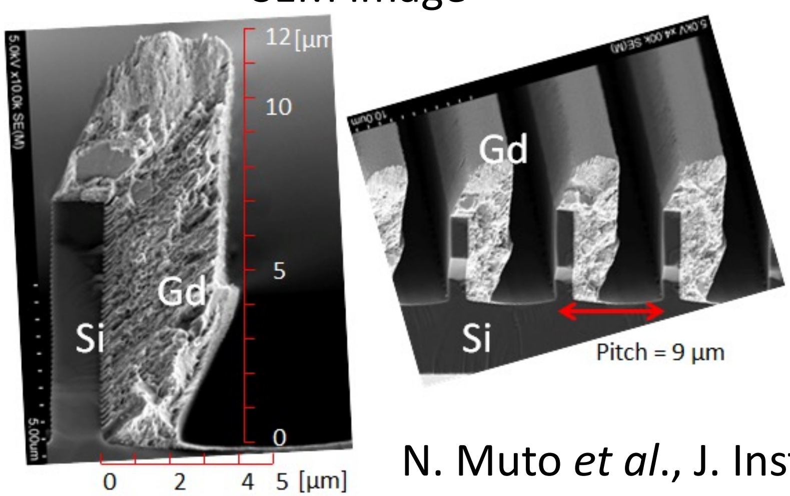
Aperture ~3 mm
Pitch 9 mm
Gd thickness = ~9.8 mm

Fabricated by T. Samoto (Tohoku Univ.),
used BL22 at J-PARC
Physics Procedia 88 (2017) 217 – 223

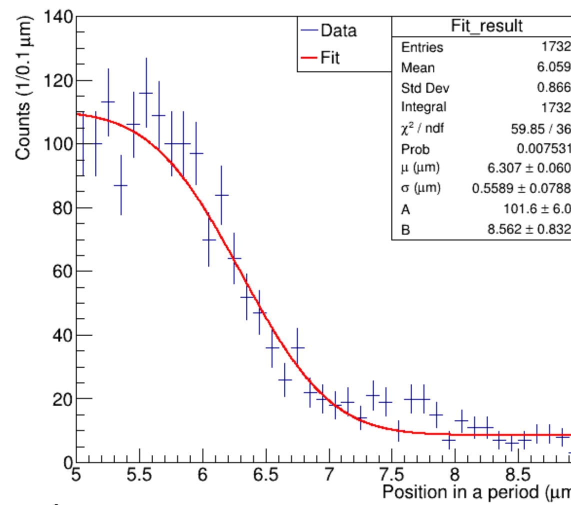
Emulsion image irradiated with the Gd slit



SEM image

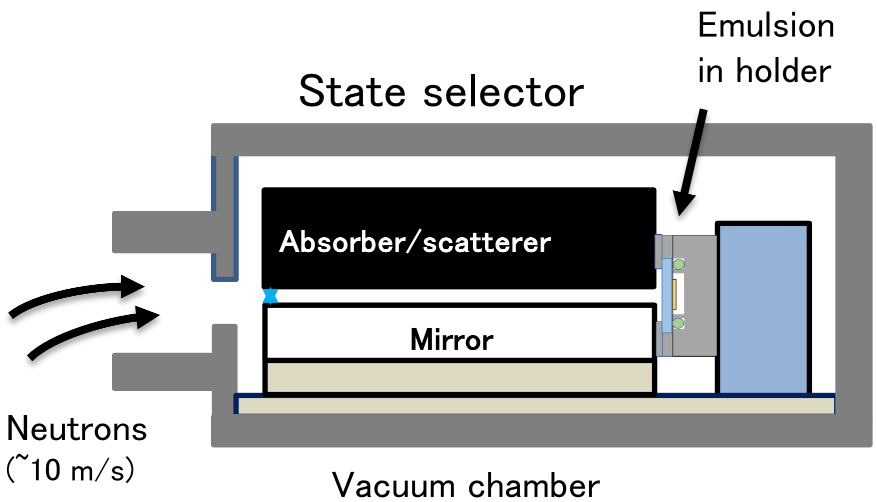


Spacial resolution achieved to 0.56 um(1σ)!

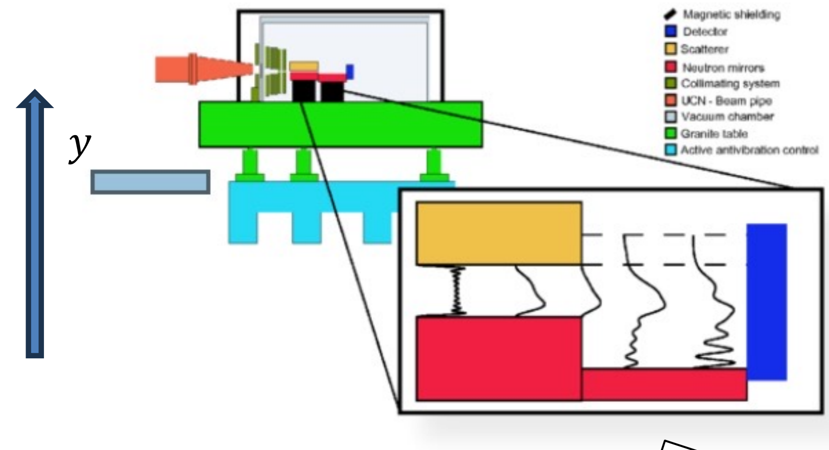


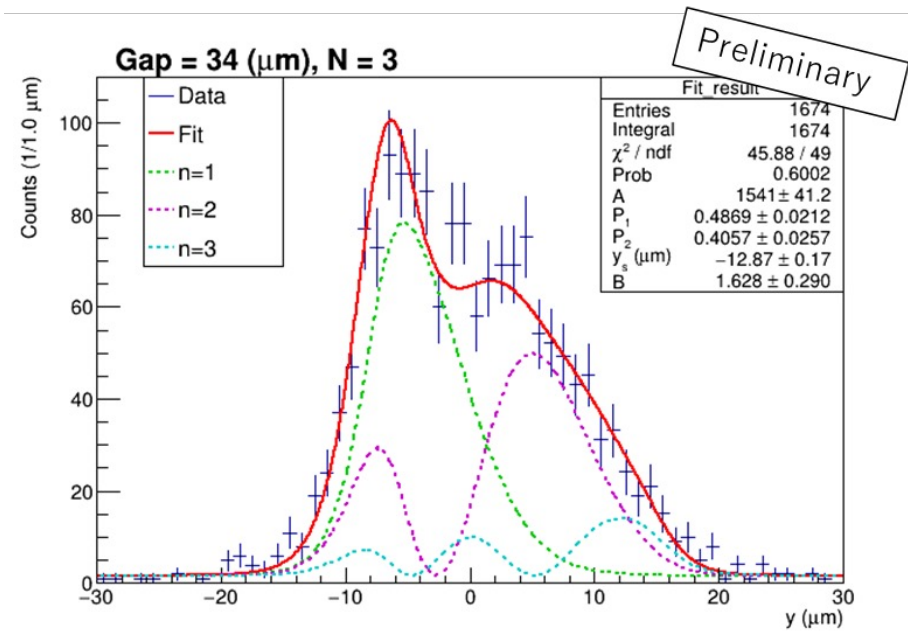
N. Muto *et al.*, J. Instrum, 17 (2022) P07014.
https://doi.org/10.1088/1748-0221/17/07/P07014

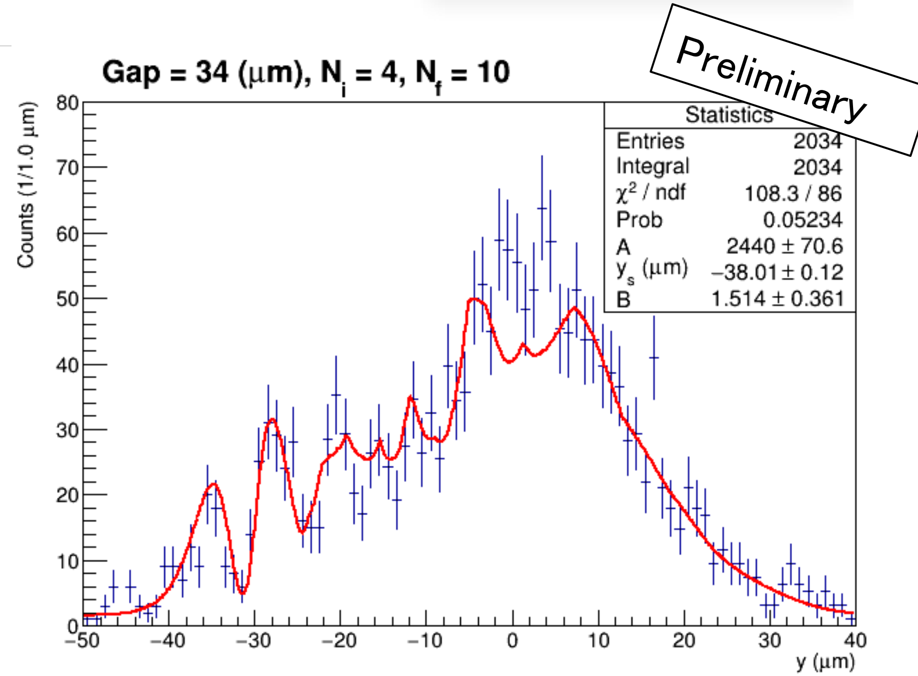
Quantum states by gravity at ILL



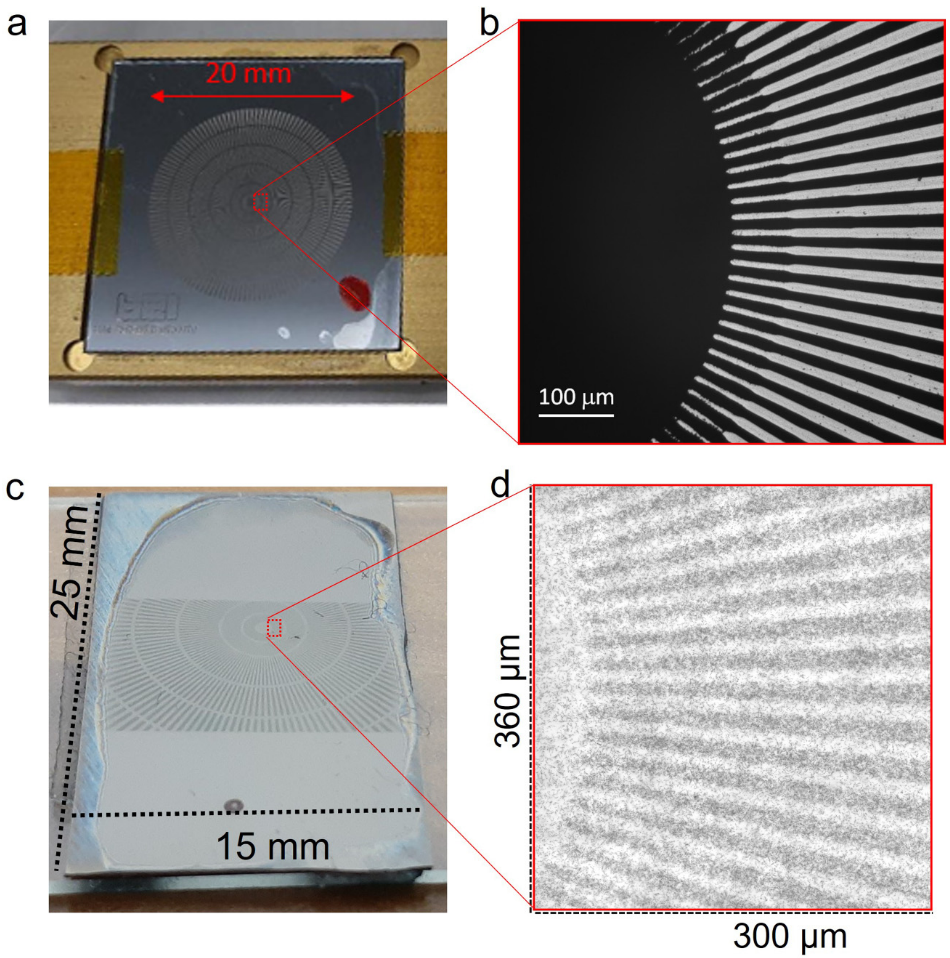
Falling 30 um







Application for Imaging



- The emulsion detector is going to be applied for neutron imaging.
- Tracking is not used.
- But even just black/white photo image, the spacial resolution achieved to be 0.94 um (1σ).
- Efficiency ~1% for cold neutrons.
- Already, available for sub-micro imaging, but the contrast is the challenge.

A. Muneem *et al*., J. Appl. Phys. 133, 054902 (2023)
https://doi.org/10.1063/5.0131098

Summary

- Detection of neutron is difficult, because it disappear when it is detected.
- Many type of thermal neutron used for dedicated purpose.
  - See more in the backup
- UCN detection is more difficult.
- I don’t know any person who know all neutron detectors.
  - Let us share the information!

backup

BL22 detectors and their specifications

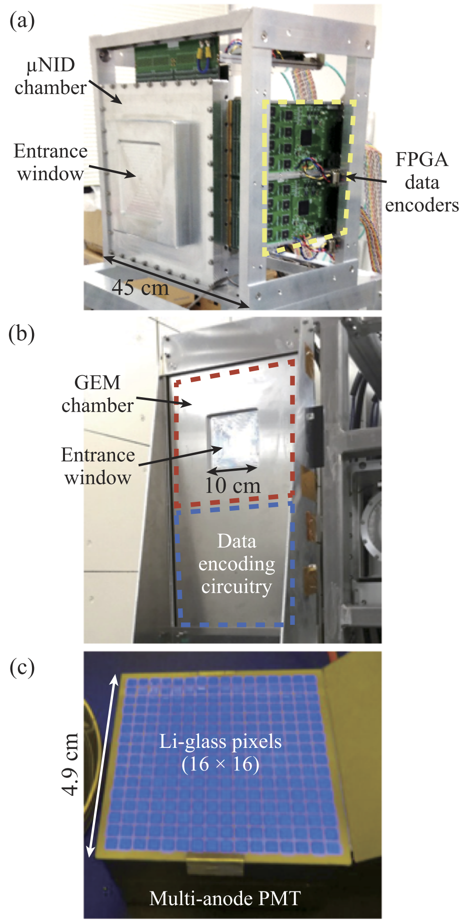


TABLE IV. Performance of counting-type detectors at RADEN. The values for the spatial resolution, peak count-rate capacity, and effective peak count-rate were confirmed at RADEN, where "peak count-rate capacity" and "effective peak count-rate" refer to the global instantaneous peak rates (i.e., peak rates over the entire detection area) at the absolute limit of the DAQ hardware and with less than 2% event loss, respectively.

Detector	μNID	nGEM	LiTA12
Type	Micropattern	Micropattern	Scintillator
Neutron converter	^{3}He	^{10}B	^{6}Li
Area (mm^2)	100 × 100	100 × 100	49 × 49
Time resolution (ns)	250	15	40
Spatial resolution (mm)	0.1	1	3/0.7
Efficiency @25.3 meV (%)	26	10	23
Peak count-rate capacity	8 Mcps	4.6 Mcps	8 Mcps
Effective peak count-rate	1 Mcps	180 kcps	6 Mcps

Rev. Sci. Instrum. **91**, 043302 (2020); doi: 10.1063/1.5136034

T. Shinohara *et al.*, Rev. Sci. Instrum. **91**, 043302 (2020); https://doi.org/10.1063/1.5136034

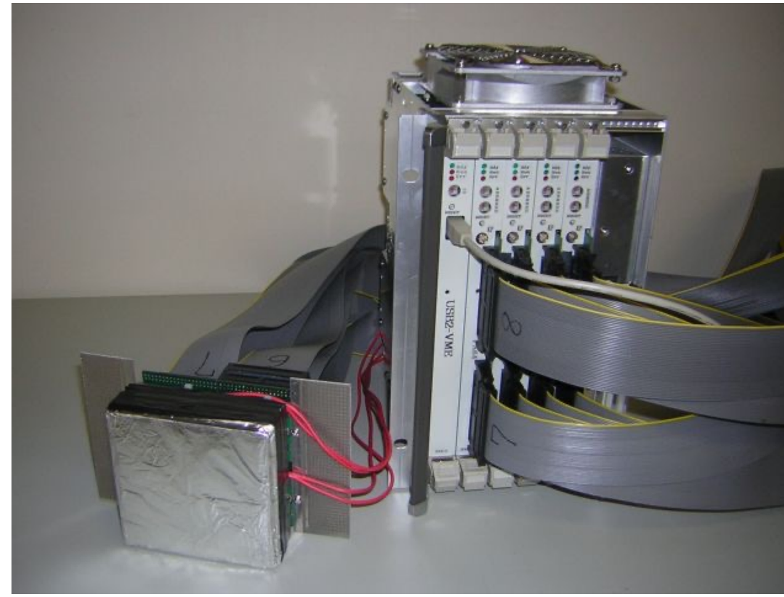
FPMT Anger Detector

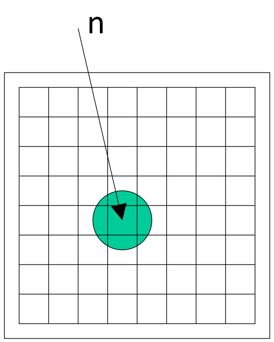
Flat panel PMT : H8500 series is used
Scintillator : ZnS/6LiF

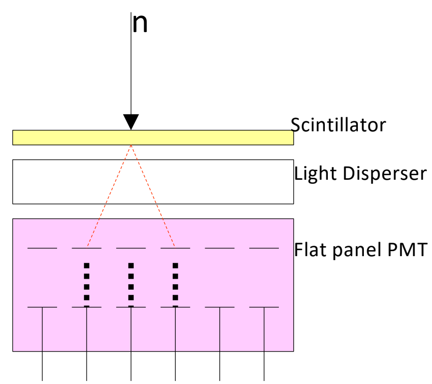
Scintillation emission is measured at several pixels
and calculate the position from the center-of-gravity calculation.

The position resolution of the image is about 1mm.

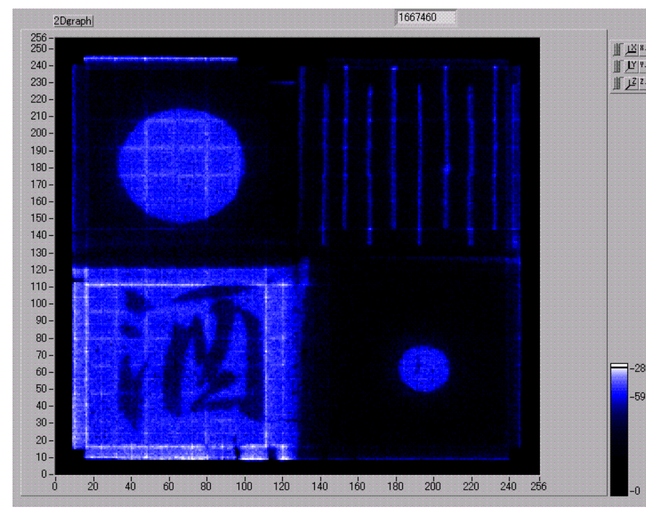
Dead space can be reduced.
Large area is possible because dead space can be reduced.







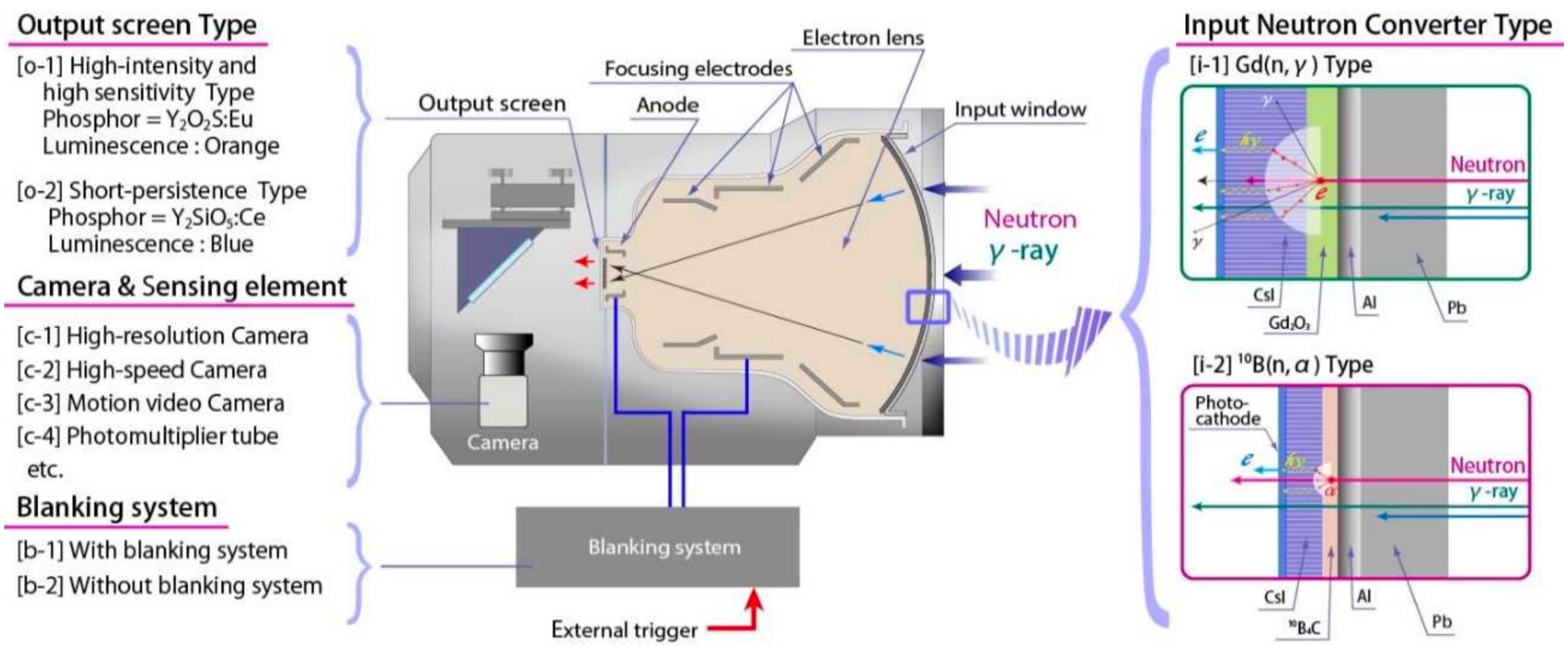
Calculate “center of gravity”



Neutron Image Intensifier

日塔、波紋 22(2012)p322

- After the incident neutrons hit the phosphor and emit light, they are converted into photoelectrons by the photoelectric conversion film, amplified by the accelerating electric field and electron lens, and formed into an image on the output surface.
- The resulting image is captured by a camera such as a CCD.
- Characterized by high neutron sensitivity and good positional resolution.
- TOF measurement is also possible by devising an imaging system.

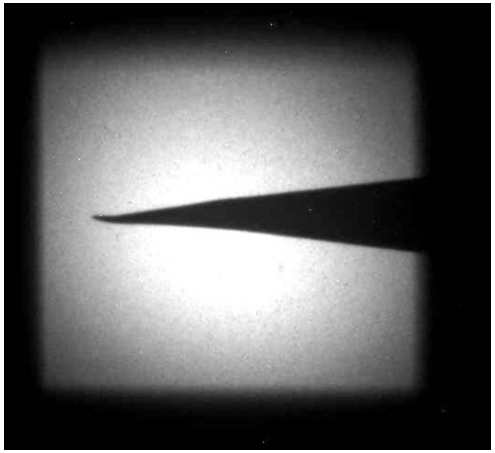


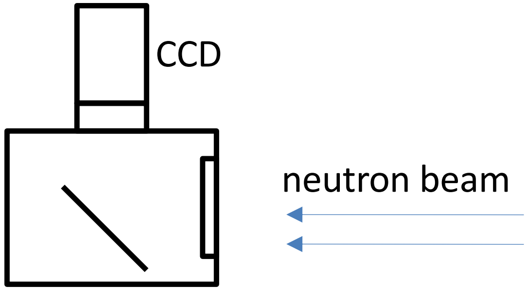
Compact CCD System

TOF : not-available

This system is made for contrast imaging measurement at JRR-3 cold beam line (ULS).
- compact and easy handle
- use at very low background

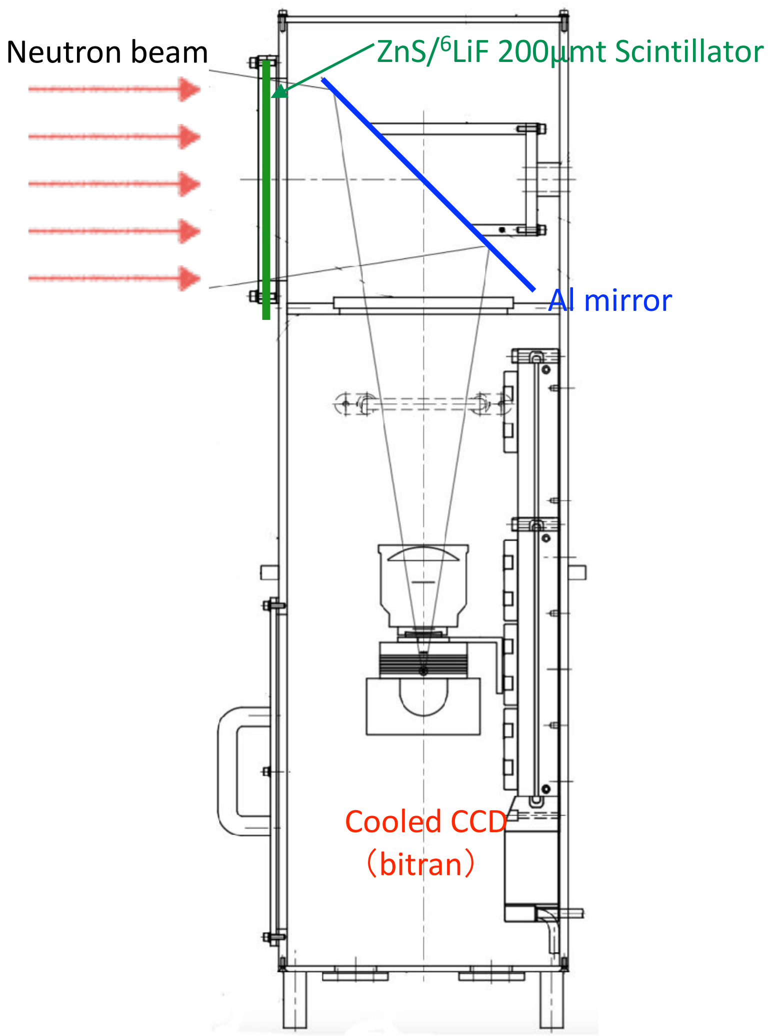
CCD: 1/2inch 656 x 484 pixsel
shutter: 1μsec - 3600 sec
data transfer: G bit ethernet
effective area: 53mm(H) x 40mm(V)
weight : 2kg (w/o shield)
spatial resolution : about 200μm





exposure time:20sec @ 4.4 Å, 3×10^5 n/cm^2/s

Cameras for Neutron Imaging (KUR E2, RANS, NUANS)



CCD and Scintillator system

Position resolution : ~200 μm
Acquisition time : ~ min.
Video also available : (DC beam)

Semiconductor Pixel Detectors

ADVACAM HPC silicon pixel detector: LiF coated

- 55μm per side pixel detector: 256x256 pixel
- Maximum 30 frames/second → 45 fps
- USB2.0 transfer (USB powered)
  Operates on both Win and Mac
- Currently, no TOF capability (another product is available)
- Large area can be achieved by arranging units
- Set a threshold and count only events above the threshold
  ↔ CCD does not allow threshold setting and integrates
- Excellent display program (compared to Bitran's program)

Energy resolution of C_6D_6

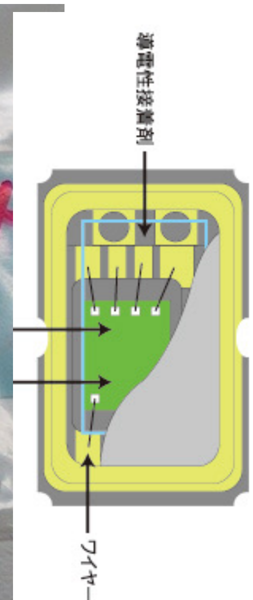
Table 1
Energy resolution data of 50 mm diameter C_6D_6 scintillator

Electron energy (MeV)	C_6D_6 scintillator		NE230 [11] scintillator	
	$\Delta E_c / E_c$ (%)	$(E_h - E_c)/E_c$ (%)	$\Delta E_c / E_c$ (%)	$E_h - E_c)/E_c$ (%)
0.341	21.70 ± 0.2	13.17 ± 2.2	12.9 ± 1.5	10.4 ± 1.9
0.477	18.20 ± 0.2	9.93 ± 1.8	9.2 ± 1.1	5.2 ± 1.6
0.639	16.15 ± 0.2	9.23 ± 1.0	8.8 ± 1.2	3.9 ± 1.1
0.907	12.51 ± 0.3	6.22 ± 0.7	8.0 ± 1.3	3.5 ± 0.4
1.062	11.90 ± 0.5	7.57 ± 1.2	7.1 ± 1.0	2.1 ± 1.0

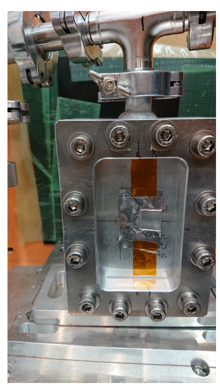
A.A. Naqvi et al., NIMA353(1994) 156-159
https://doi.org/10.1016/0168-9002(94)91626-8

Application for Imaging

A crystal oscillator tip

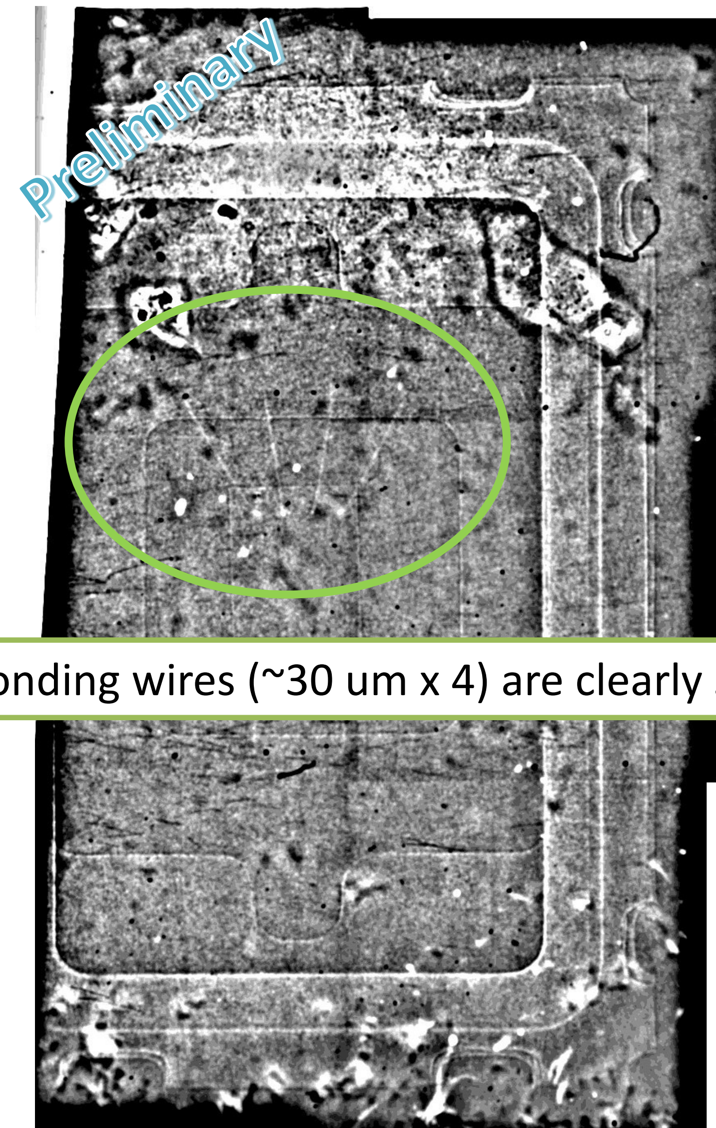


Packaged into Al foil
with emulsion detector.



Irradiation

3 hours of irradiation



Bonding wires (~30 um x 4) are clearly seen.