Detector Fundamentals

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Introduction

Neutron Detector Performance Requirements

3He Gas Detectors

RW 3He Detectors

Other 3He Gas Detectors

Scintillation Detector GS20 Glass

Scintillation Detectors ZnS:Ag/^{6}LiF

Future Developments

Conclusions

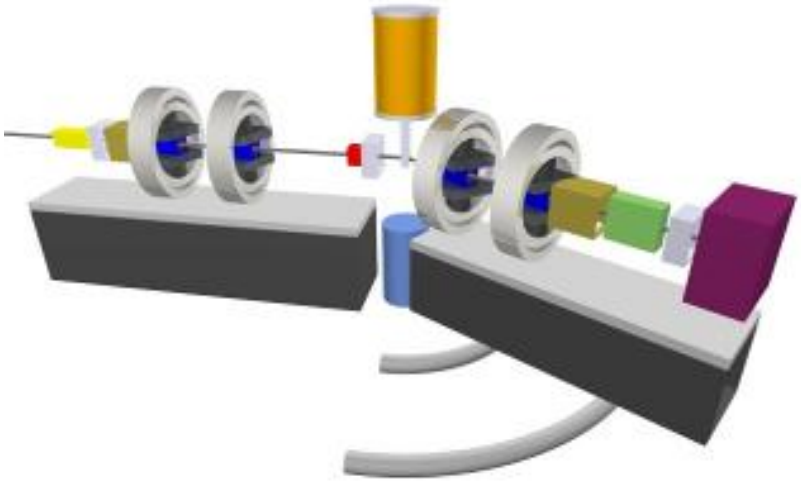
Introduction

What do neutrons do:

Provide scientists and engineers with a tool to investigate the structure and dynamics of materials on the atomic / molecular scale

What do you need for a neutron experiment

Source
Instrument
Sample
Detector
Electronics
Data acquisition and storage



Larger energy range available at accelerator than reactor

Different instruments

Diffractometers

- High Rate Powder
- High Resolution Powder
- High Pressure
- Strain Scanners
- Single Crystal
- Reflectometers
- SANS
- SANDALS

Spectrometers

- DINS
- Excitations
- Molecular
- QENS

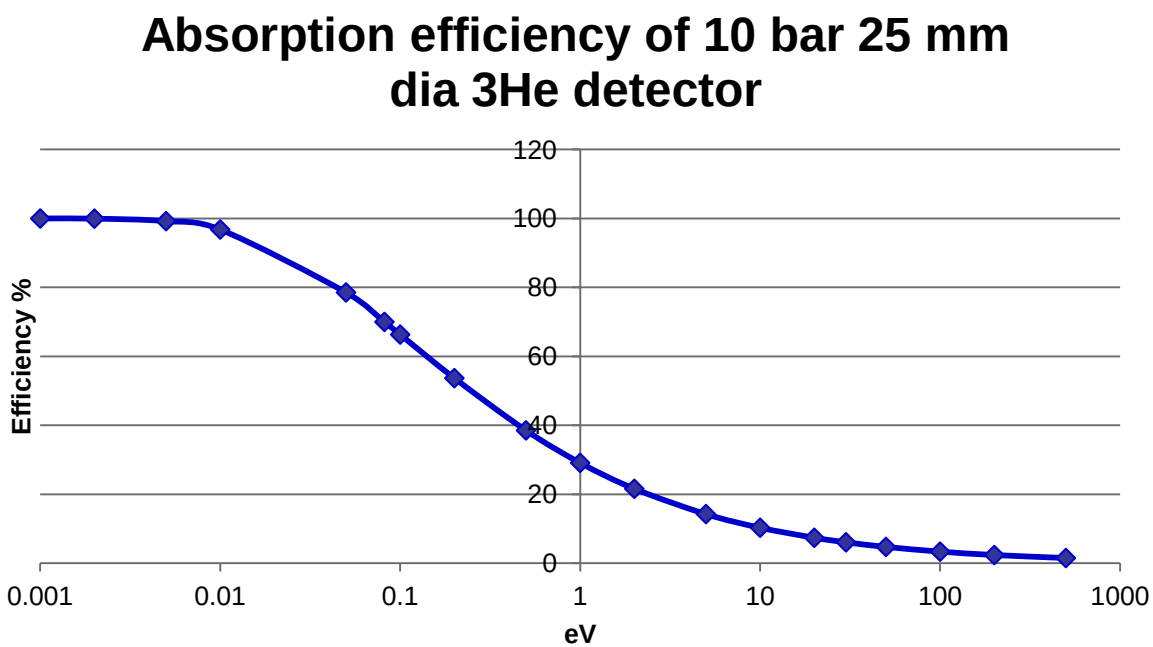
Imaging Detectors

Resonance Detectors

Each of these instruments require detectors optimised to their individual needs

What properties do you require of neutron detectors: Efficiency

Appropriate neutron detector efficiency



At 0.08 eV (1Å)	Eff = 70%
1 eV	Eff = 30%
10 eV	Eff = 10%
2 keV	Eff = 0.8%

What properties do you require of neutron detectors: Low gamma sensitivity

Low Gamma sensitivity

Gamma radiation is produced by

- The source
- From (n,gamma) interactions with:
  - The collimation, choppers, windows etc..
  - Sample environment
  - Sample

Low detector gamma sensitivity to prevent data degradation

Use 60Co (~1 MeV) Express as

[No. gamma detected / No. gamma incident]

What properties do you require of neutron detectors: Low intrinsic background

Low Intrinsic detector background

Response of detector in absence of experimental neutrons

If neutron background is high e.g.

Scattering from pressure cell

Incoherent scattering from sample

Moderate intrinsic background may not be a problem

If neutron background and signal are low

e.g. inelastic scattering

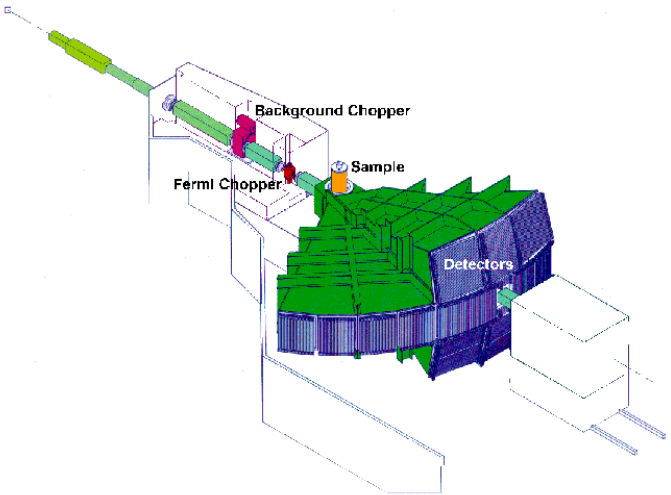
Intrinsic background can degrade data

What properties do you require of neutron detectors: Size

Angular coverage and sample to detector distance (L2) = area

- Diffraction instruments
  - Large L2 to cope with large sample environment
- Inelastic instruments L2 determines energy resolution
  - Larger L2 better Energy resolution
- Large L2 means bigger detector - higher cost
  - Double L2, 4 x area

Imaging detector	1 - 400 cm^2
Reflectometer	200 cm^2 +
SANS	1 m^2
SXD	1 – 2 m^2
Diffractometer	1 – 20 m^2
Excitations spectrometer	10 – 40m^2



What properties do you require of neutron detectors: Position resolution

Position resolution

Fortunately the largest detectors do not require the highest position resolution

Imaging detector	1 - 400 cm^2	50 – 100 μm
Reflectometer	200 cm^2 +	1 x 60 mm^2
SANS	1 m^2	5 x 5 mm^2
SXD	1 – 2 m^2	1 x 1 mm^2
Diffractometer	1 – 20 m^2	5 x 50 mm^2
Excitations spectrometer	10 – 40m^2	25 x 25 mm^2

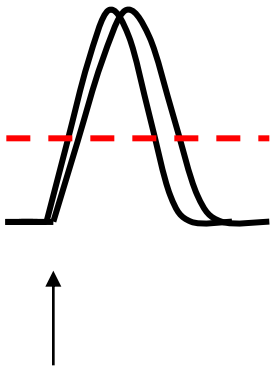
Note: For detectors where the position of a neutron is interpolated:

Size of bins may be smaller than the resolution

Allows scientists to fit the data more accurately, but does not increase the intrinsic resolution of the detector

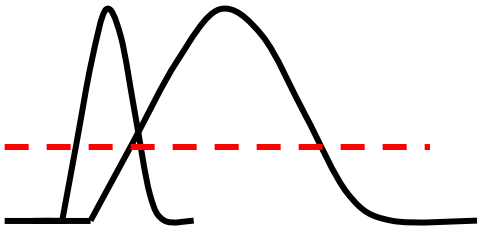
What properties do you require of neutron detectors: Rate capability and timing resolution

Timing resolution



Fast rise time +
small difference between fastest and slowest signals – good time resolution

Count rate



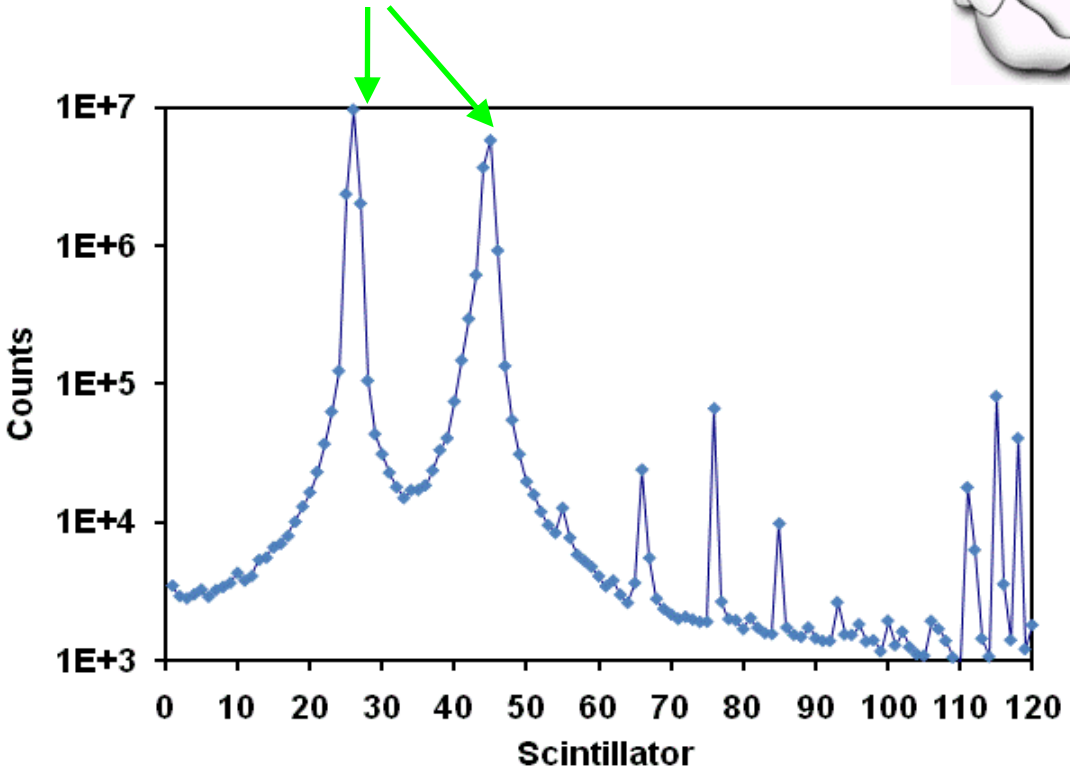
Signal must drop below threshold before new signal can be recorded

Shorter signals – higher cont rate

Ideally signal should return to base line to prevent distortion of next signal

What properties do you require of neutron detectors: Low misplacement error

Direct+reflected beam



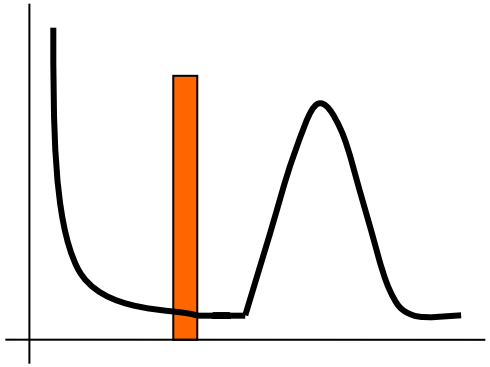
Ghosts

High signal high background – no effect

Low signal low background – degrades data

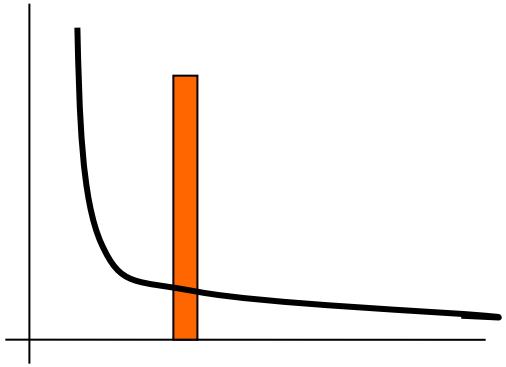
What properties do you require of neutron detectors: Count rate stability

Pulse height spectra



Good pulse height resolution:

Change in gain or threshold has little effect on count rate



Poor / no pulse height resolution

Change in gain or threshold can have significant effect on count rate stability
Care needed to prevent this

Some instruments require ~0.1% stability

What properties do you require of neutron detectors: Environmental immunity

Stray fields from magnets can seriously affect PMT performance

e.g. 10 gauss ~ 50% drop in gain

Magnets in use at ISIS ~ 7 - 14 x 10^4 gauss

(not the largest)

Shielding with:

Cd produces hard gamma

^{10}B materials produces 470 keV gamma

^{6}Li produces no gamma

Needs consideration if detector has significant gamma sensitivity

What properties do you require of neutron detectors: Acceptable cost

Detectors are a small fraction of the cost of a facility

Have a huge effect in output of a facility

Even at the instrument level

£ 7M instrument with 100k detector or 5k monitor

Optimisation is justifiable

For the large area detectors costing 50% of an instrument:

Increased detector costs need to be tensioned with all other instrument components

Performance requirements of detectors

Neutron Detector Efficiency
Gamma Sensitivity
Intrinsic Detector Background
Area
Position Resolution
Timing Resolution
Rate Capability
Placement Accuracy
Count Rate Stability
Environmental Immunity
Cost

Performance requirements of detectors

Neutron Detector Efficiency	50% at 1 Å (0.08 eV) 40% at 10 eV 4% at 2keV
Gamma Sensitivity	10^{-2} -10^{-8} at 1MeV
Intrinsic Detector Background	30c.m^{-1} – 3 c.hr^{-1}
Area	10^{-4} - 10^{2} m^2
Position Resolution	0.1 x 0.1 mm^2 – 300 x 25 mm^2
Timing Resolution	10 ns – 100 μs
Rate Capability	kHz – MHz
Placement Accuracy	As high as reasonably practicable
Count Rate Stability	0.1% over several days
Environmental Immunity	
Cost	As low as reasonably practicable

Neutrons: Ideal and not so ideal

Neutrons

Provide information on the structure and dynamic of materials on an atomic/molecular scale

Ideal probes for Condensed Matter Research

- **Zero charge – highly penetrating**
- **Low KE – probe atomic / molecular dynamics (100 eV – sub meV)**
- **Etc…**

Non idealised particles for detection

- **Zero charge – generally weak interaction**
- **Low KE – generally weak interaction**

Require a nuclear converter

Neutron Converters

			Cross section at 1 Å barnes	
3He + 1n	_____	3H + 1p - 0.77 MeV	3 000	
10B + 1n	_____	7Li + 4He - 2.3 MeV + 0.48MeV γ	2 100	(93%)
		7Li + 4He - 2.7 MeV		(7%)
6Li + 1n	_____	3H + 4He - 4.79 MeV	520	
157Gd + 1n	_____	γs + Conversion electrons	74 000	
natGd + 1n	_____	γs + Conversion electrons	17 000	

Neutron converter options

Radiation interacts with the electrons in materials

Neutrons interact with the nuclei of atoms

Detectors need a neutron converter

Only three realistic possibilities

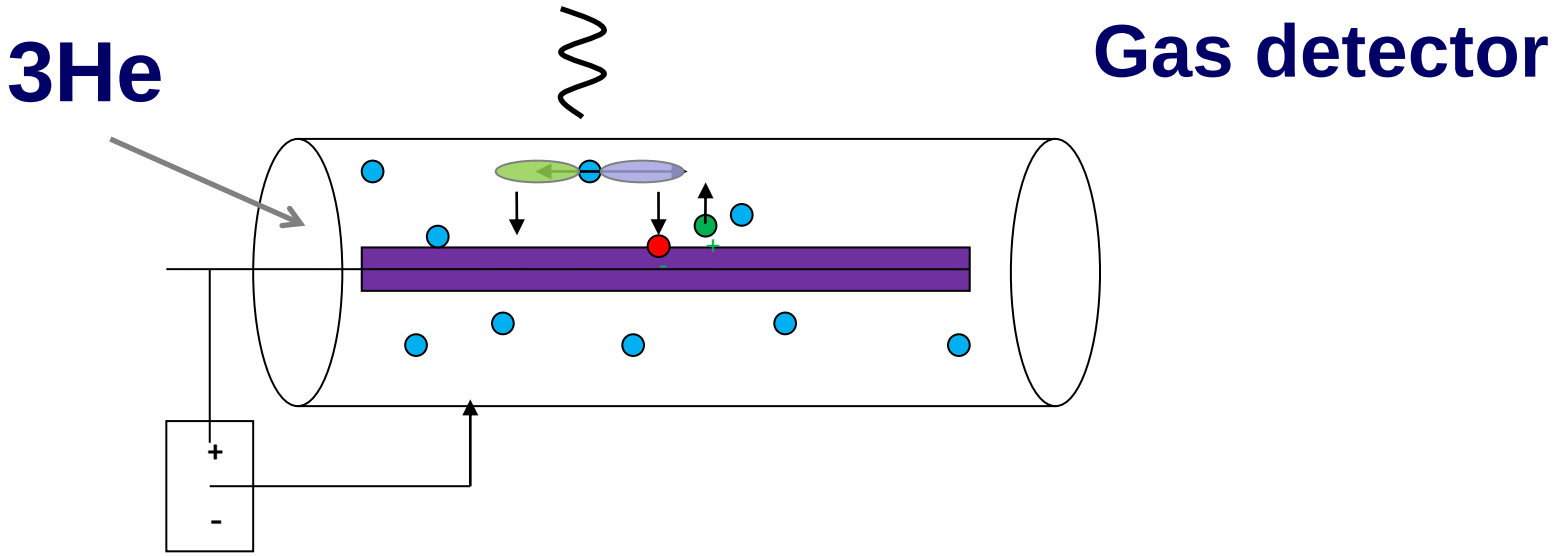
3He	0.000137%
6Li	7.5%
10B	20%

Neutrons: Idea and not so ideal

What types of detectors are available

- Gas detectors by far the biggest use
- Scintillator detectors
- Solid sate detectors

3He Gas Detectors



Increasing tube diameter and maintaining 3He pressure

- **Increases absorption efficiency**
- **Decreases resolution**

Increasing 3He pressure:

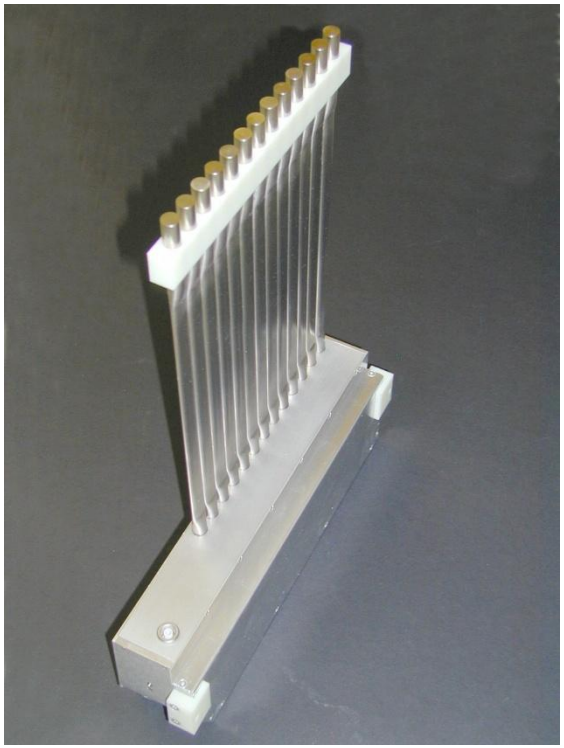
- **Increases efficiency**
- **Preserves resolution**

3He Gas Detectors

Chopper spectrometers MARI and HET

MARI : 900+ detectors –
300 mm long 25 mm diameter
Filled with 10 bar 3He

Molecular spectroscopy TOSCA

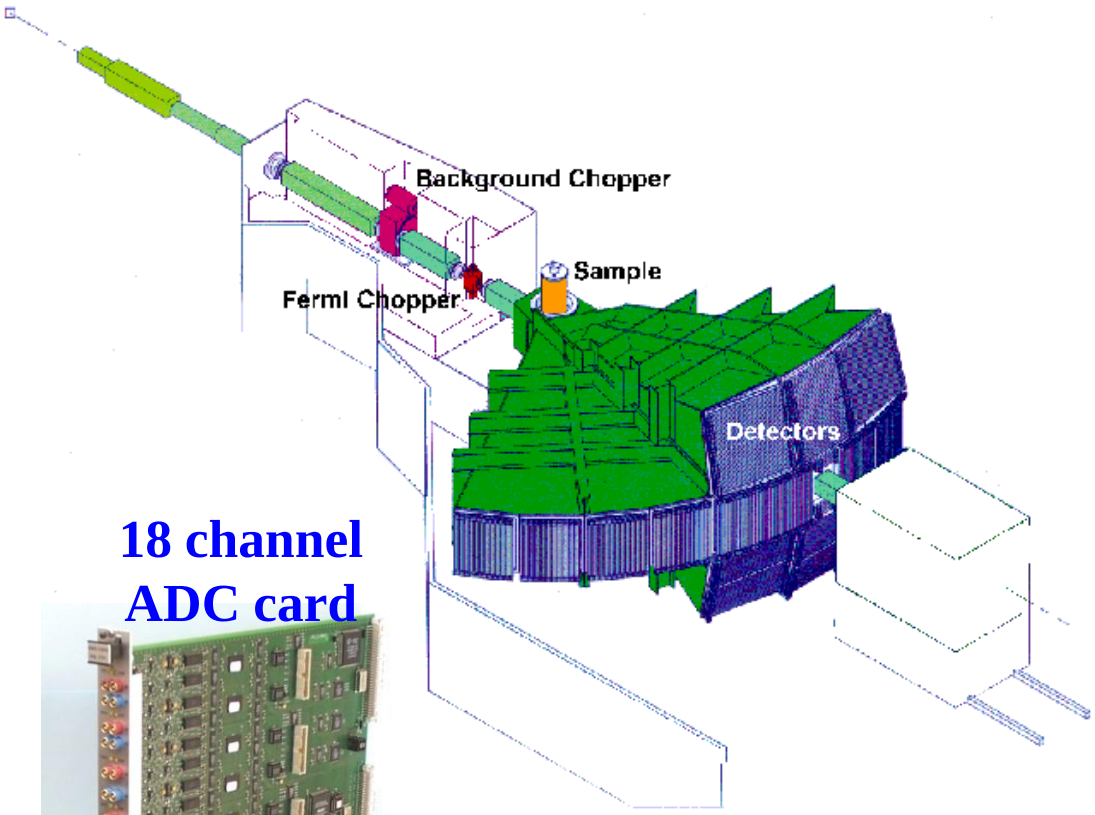


Squashed detectors
for accurate ΔT

3He Gas Detector : Performance

Neutron Detector Efficiency	70% at 1 Å
Gamma Sensitivity	10^{-7} -10^{-8} at 1MeV
Intrinsic Detector Background	3 – 5 c.hr^{-1}
Area	2.5 x 30 cm^2
Position Resolution	2.5 x 30 cm^2
Timing Resolution	0.5 μs
Rate Capability	50 kHz
Placement Accuracy	100%
Count Rate Stability	Good PHR
Environmental Immunity	OK in mag fields
Cost	

RW 3He DETECTORS: MAPS



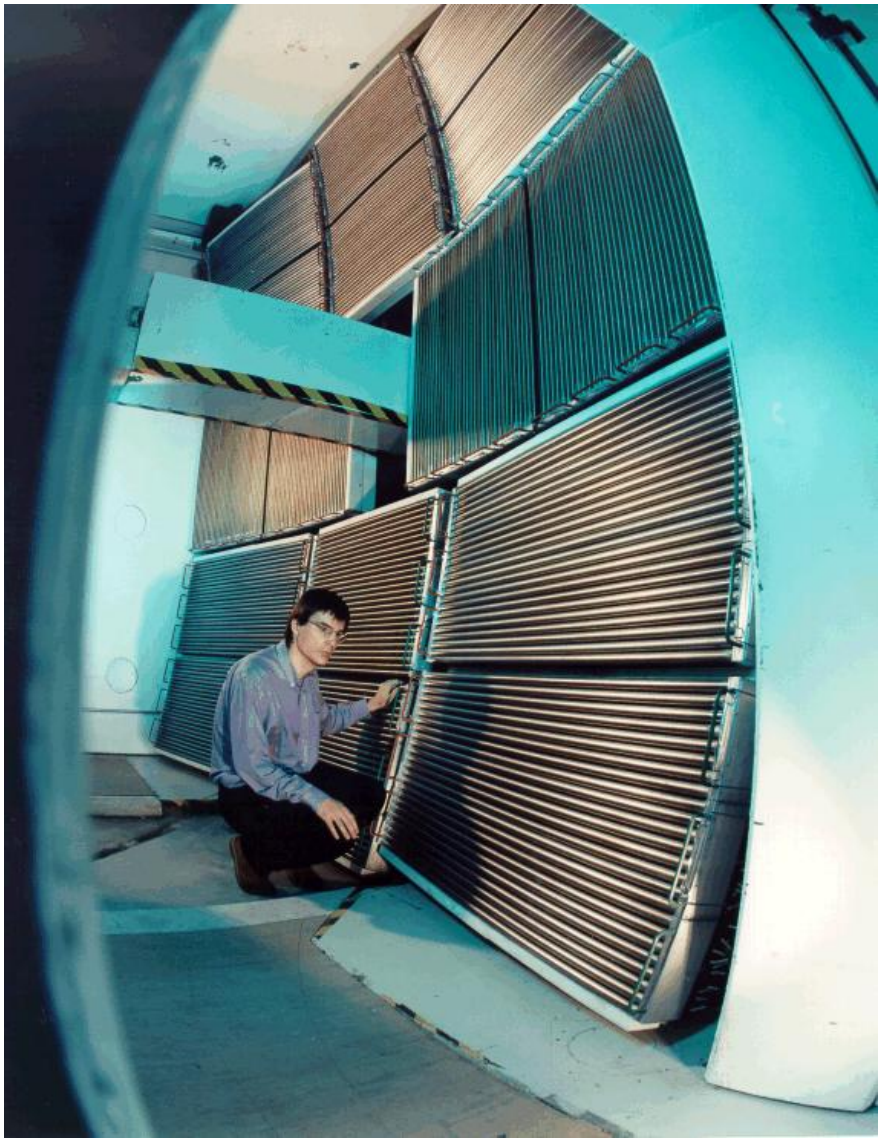
8 channel pre amp card

MAPS 1 m long 8 pack detector array

18 channel ADC card

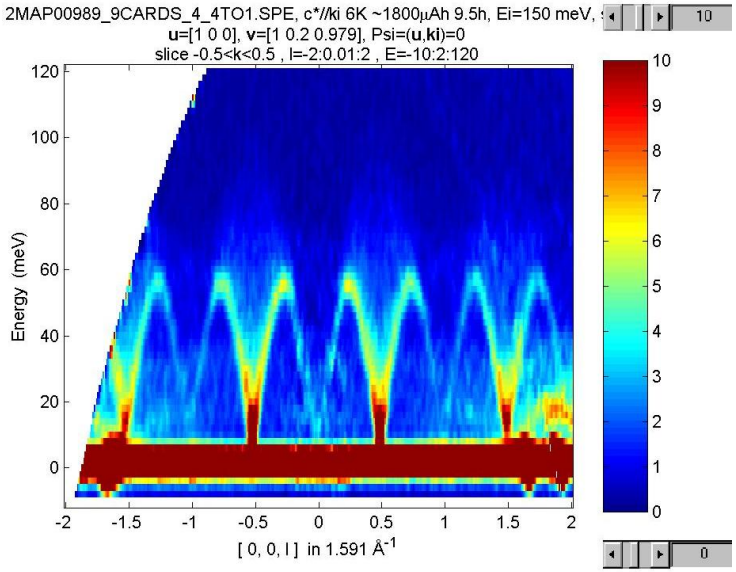
Charge at one end compared with total charge

RW 3He DETECTORS: MAPS

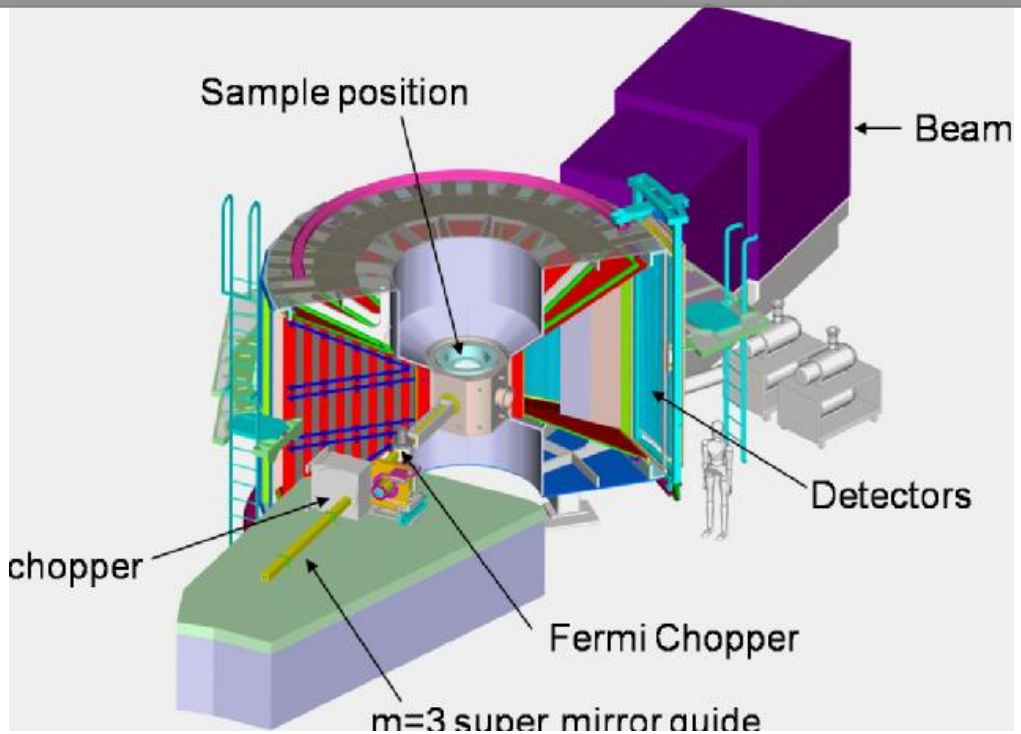


Data Quality truly exceptional

Even some of the simplest structures have revealed complex structures not seen before.

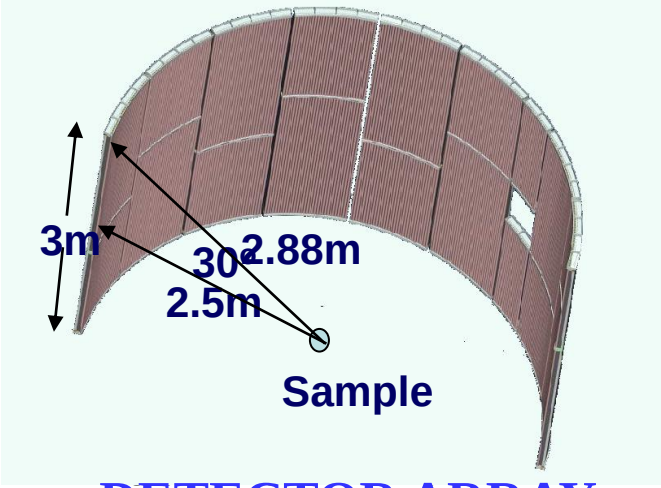


RW 3He DETECTORS: MERLIN



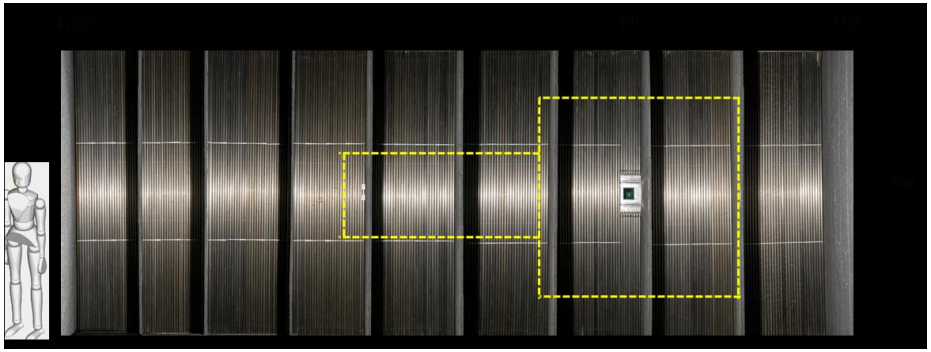
RW technology

- **2.9 m active length**
- **25 mm diameter**
- **17–22 mm resolution**
- **264 off + 16 at 1.2 m**
- **No of Pixels ~ 70,000**
- **Total area 20 m^2**

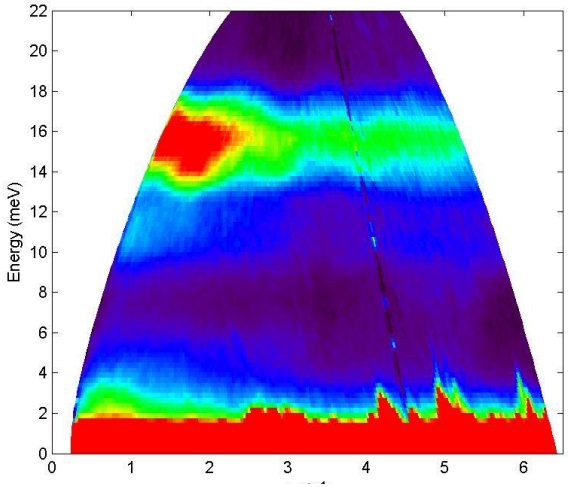


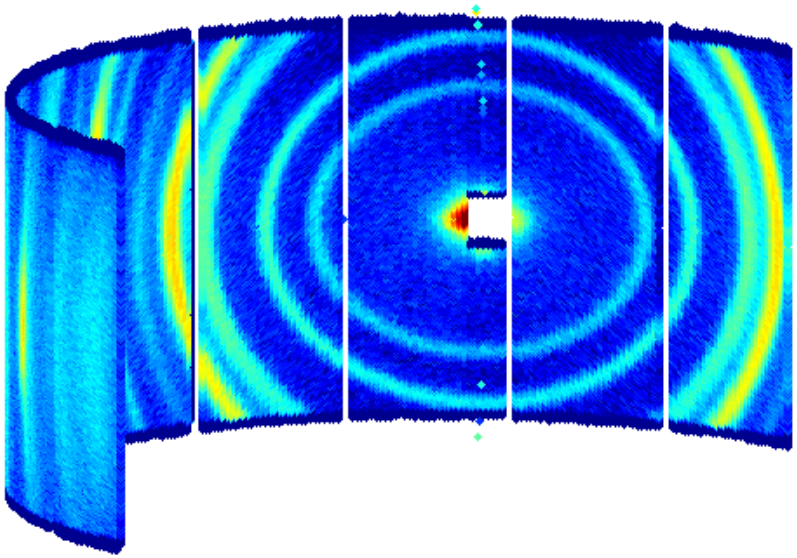
DETECTOR ARRAY

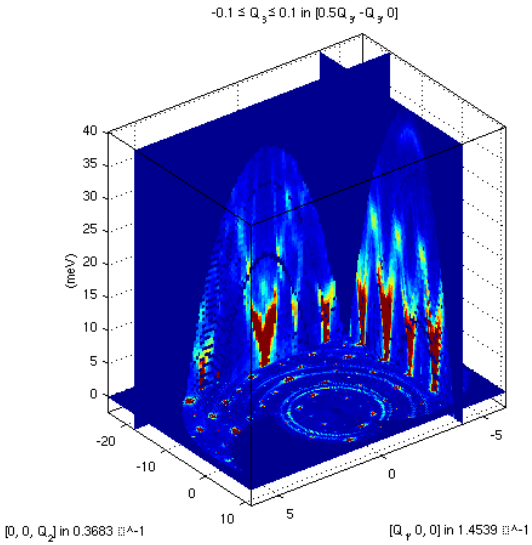
RW 3He DETECTORS: MERLIN



The MERLIN detector projection







Debye Scherer rings from a powder sample

RW 3He DETECTORS: LET

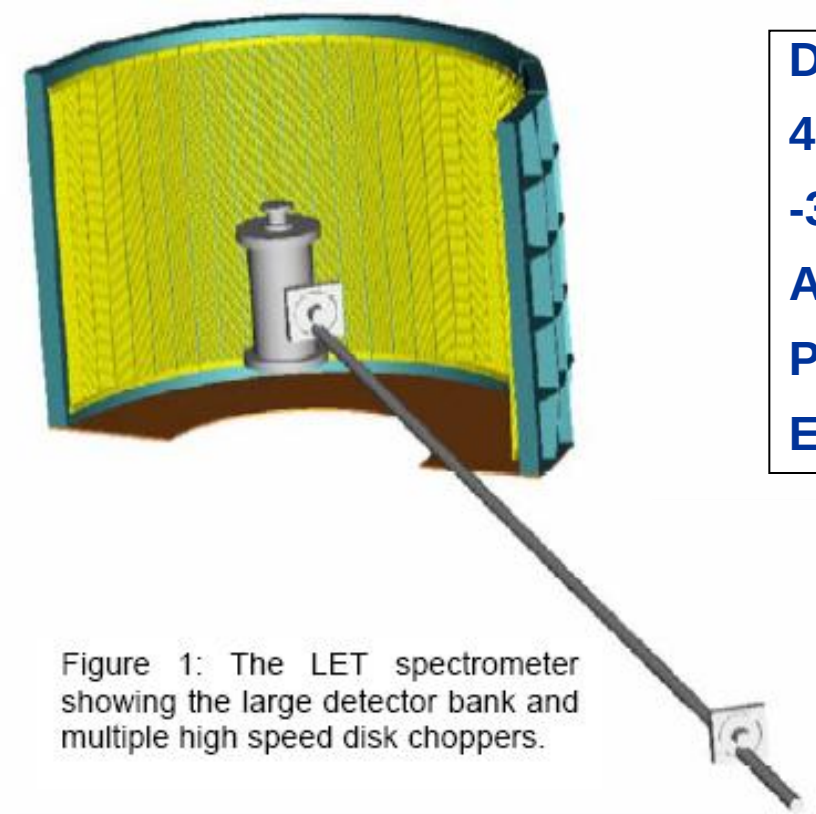


Figure 1: The LET spectrometer showing the large detector bank and multiple high speed disk choppers.

Resistive Wire technology

Detector array

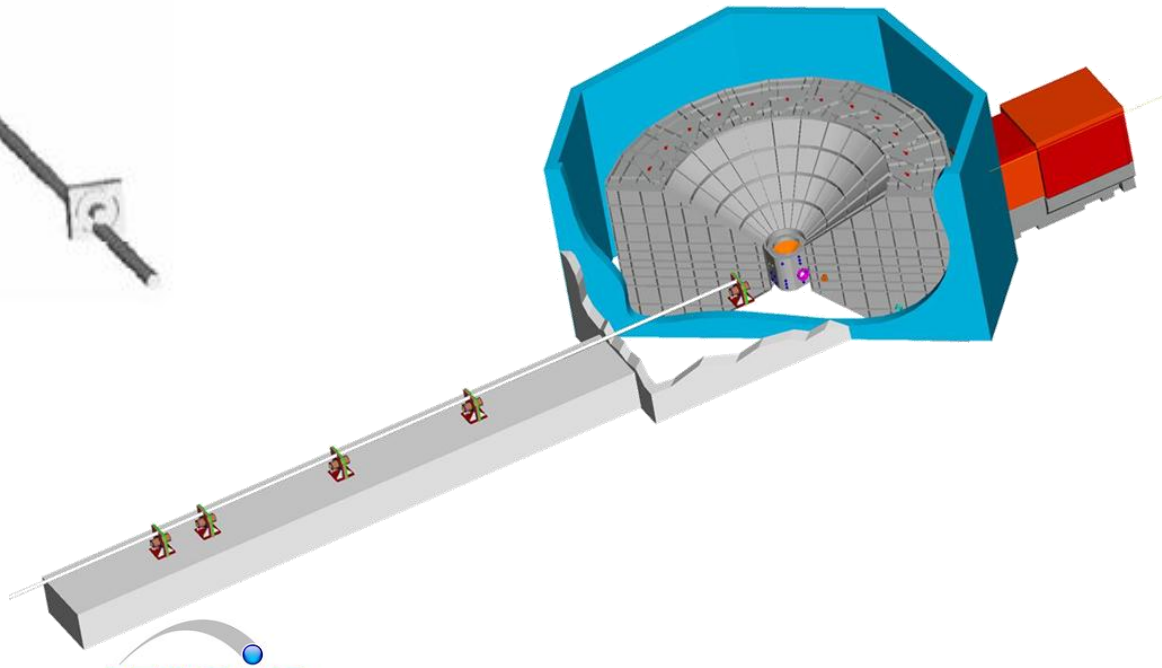
4m high array at 3.5 m radius

-35 to +135 degrees horizontal coverage

Area 40 m^2

Position resolution 25 mm FWHM

Energy range 0 – 80 meV

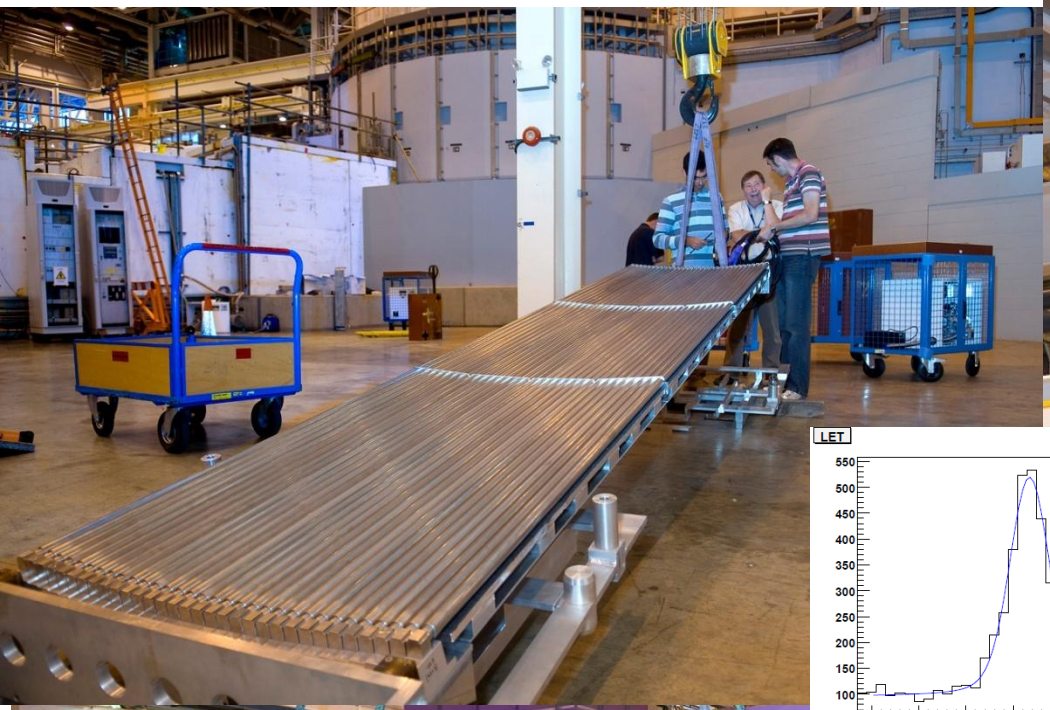


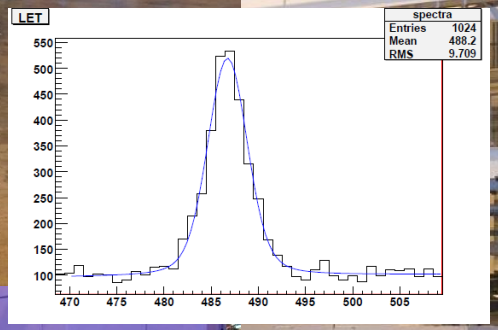
RW 3He DETECTORS: LET

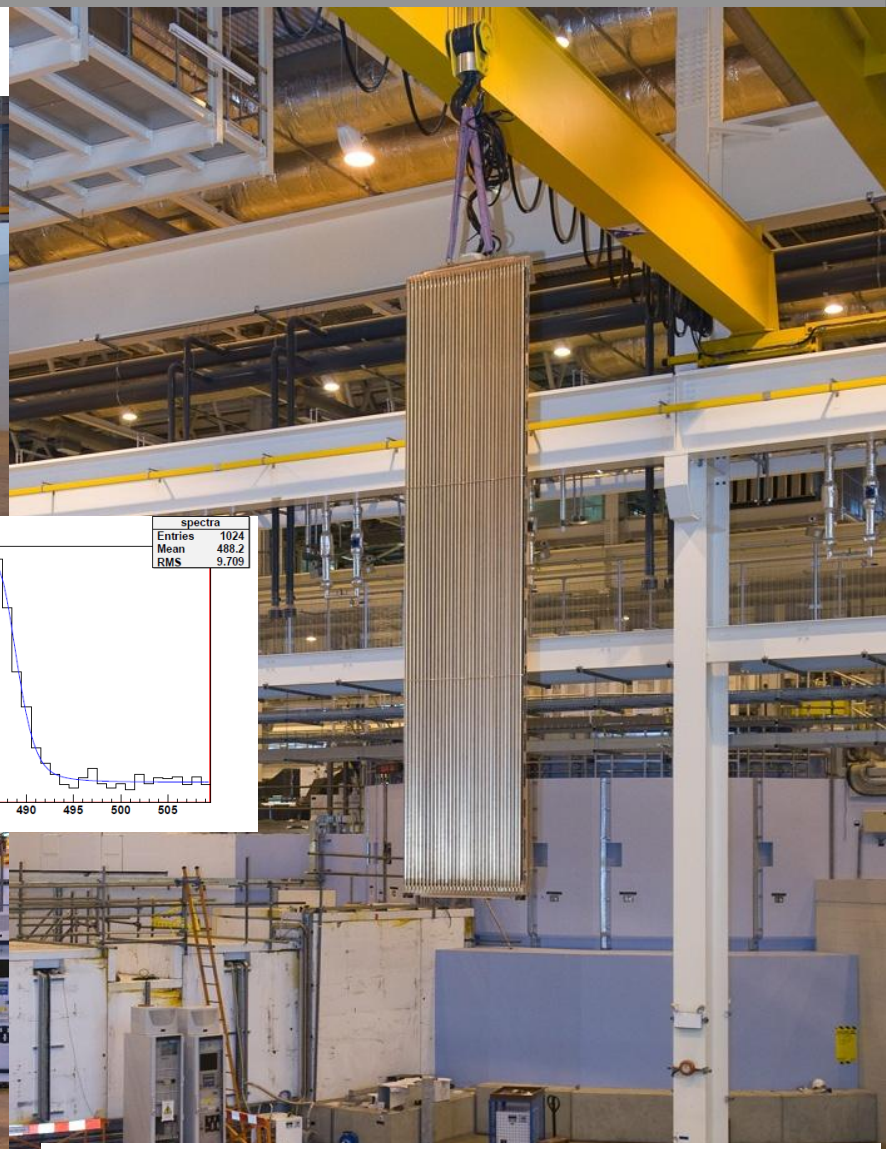
RW 3He DETECTORS: LET

RW 3He DETECTORS: LET

4 m long resistive wire detectors



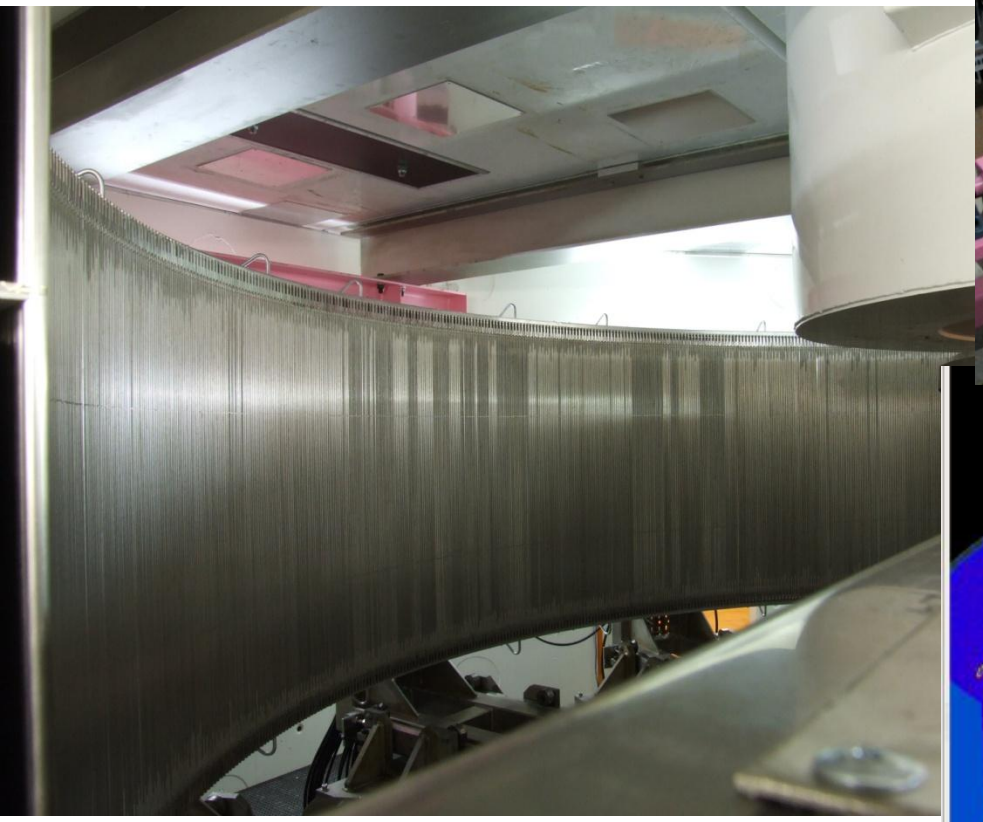




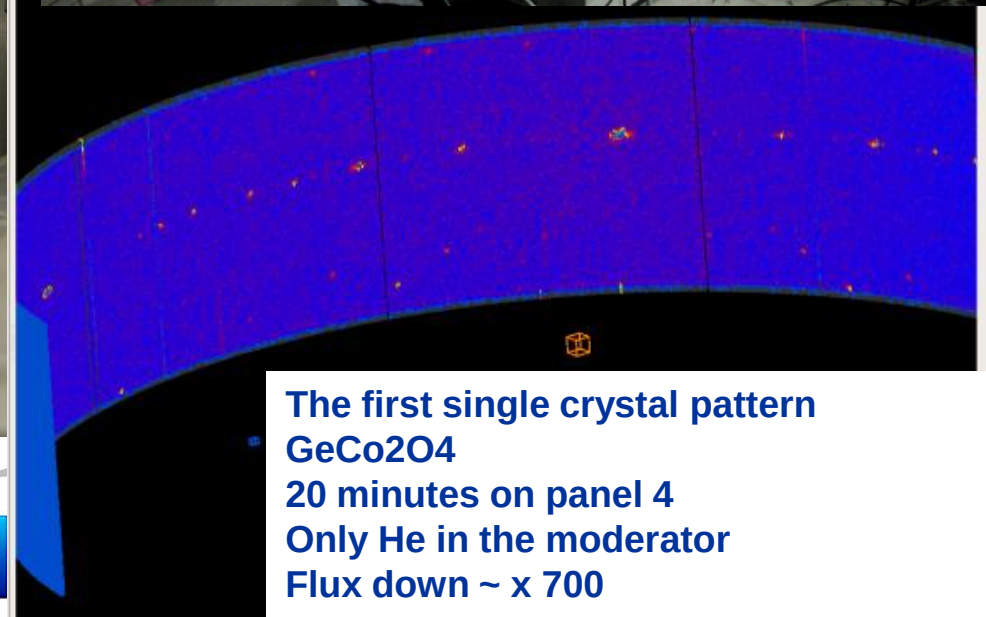
First two frames of 32 detectors each now installed. Detectors and ADC electronics working well. Excellent position resolution

RW 3He DETECTORS: WISH

152 gas detectors per panel
1 m long, 8 mm dia
15 bar 3He + stopping gas
5 panels installed and working



The first complete panel in December 08



The first single crystal pattern
GeCo2O4
20 minutes on panel 4
Only He in the moderator
Flux down ~ x 700

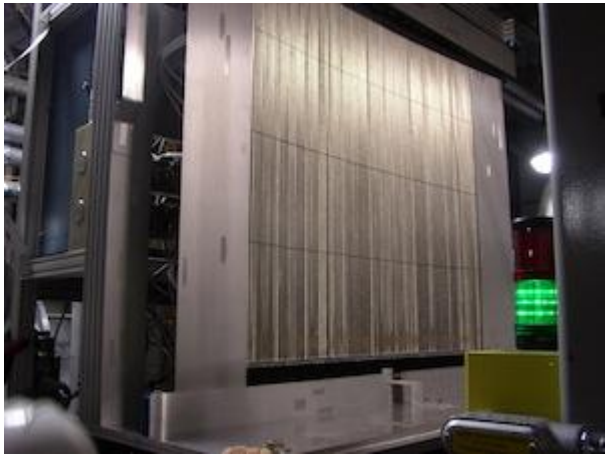
RW 3He DETECTORS:

Arrays of 3He resistive wire detectors have become the detector of choice for large area detectors for inelastic scattering applications

e.g. IN5 at the ILL and ARCS, CNCS and Sequoia at the SNS

8 mm diameter detector arrays are widely used in SANS instruments.

e.g. D22, BRISP, G-SANS and Bio-SANS at HFIR and EQ-SANS at the SNS.



EQ-SANS SNS

RW 3He detectors: Performance

	LET 10 bar 3He	WISH 15 bar 3He
Neutron Detector Efficiency	70% at 1 Å	50% at 1 Å
Gamma Sensitivity	10^{-7} -10^{-8} at 1MeV	
Intrinsic Detector Background	10 – 15 c.m.hr^{-1}	10 – 15 c.m.hr^{-1}
Area	2.5 x 400 cm^2	0.8 x 100 cm^2
Position Resolution (0.5 – 1% of length)	2.5 x 2.5cm^2	0.8 x 0.8 cm^2
Timing Resolution	1 μs	
Rate Capability	50 kHz	
Placement Accuracy	Care needed	
Count Rate Stability	Good PHR	
Environmental Immunity	OK in mag fields	

Other gas detectors: MWPC

Wide range of different gas detectors

MWPC
Wires in a common gas volume
Improves position resolution

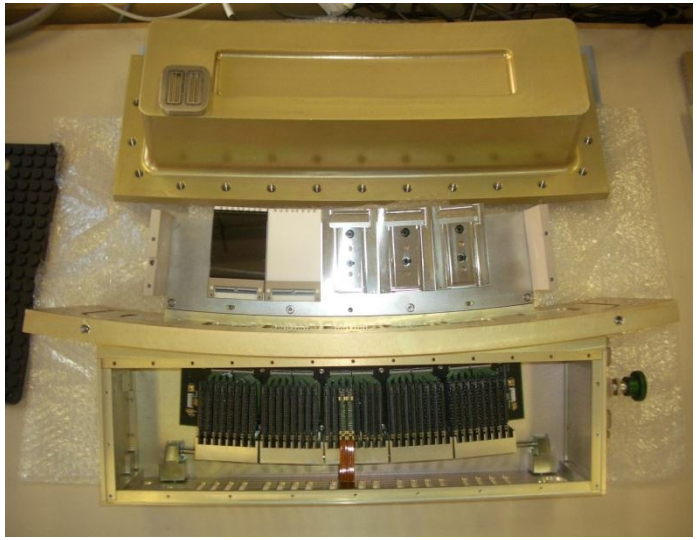
Eg Brookhaven Protein Crystallography detector at Los Alamos

	WISH array	Brookhaven Det
Neutron Detector efficiency	50% at 1 Å	50% at 1 Å
Area	760 x 0.8 x 100 cm^2	3000 cm^2
Position resolution (0.5 – 1% of length)	0.8 x 0.8 cm^2	0.15 x 0.15 cm^2

Other gas detectors: Micropattern

Electrodes on substrate replace wires

Improve rate capability
Improves position resolution

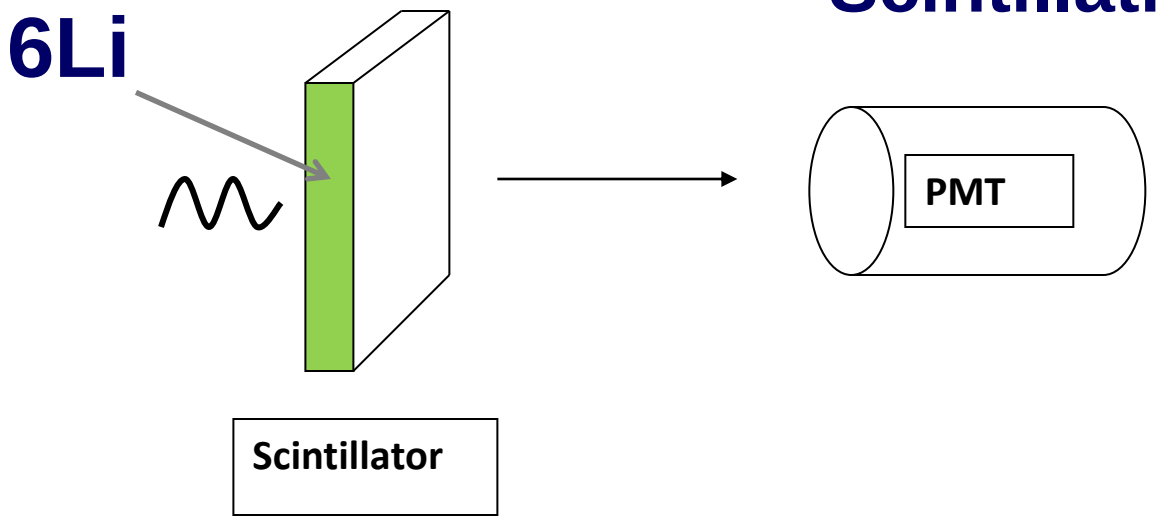


D20 2.57 mm resolution, 50 kHz per pixel

OSMOND detector 0.5 mm resolution

Scintillator Detectors

Scintillation Detector



Increasing thickness of scintillator
Increases absorption efficiency

Increasing 6Li loading
Increases absorption efficiency

Scintillator Detectors: GS20 Glass

Two types of scintillator in common use:

1. GS20 Glass scintillator

AST http://www.appscintech.com

GS20 is an aluminosilicate glass

Contains 19% by weight of Li_2O

Transparent

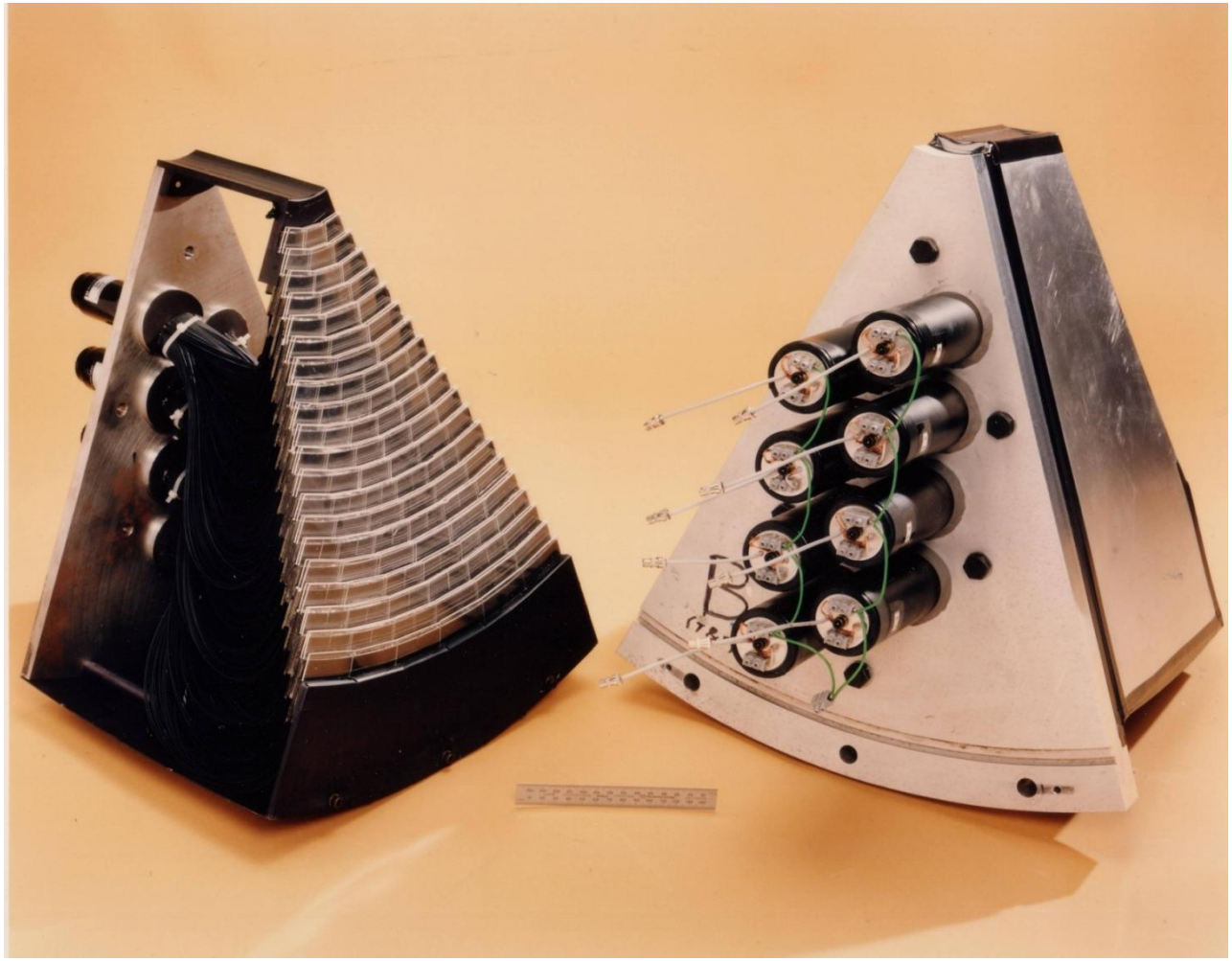
The Li is enriched to + 95% 6Li -

1 mm thick glass: neutron absorption ~56% at 1 Å

6000 photons per absorbed neutron

70 ns decay constant

Scintillator Detectors: GS20 Glass



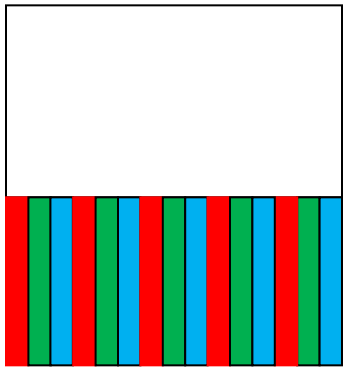
Early HRPD Backscattering Detector

20 elements

3CN fibre code

15 mm resolution

2mm thick GS 20

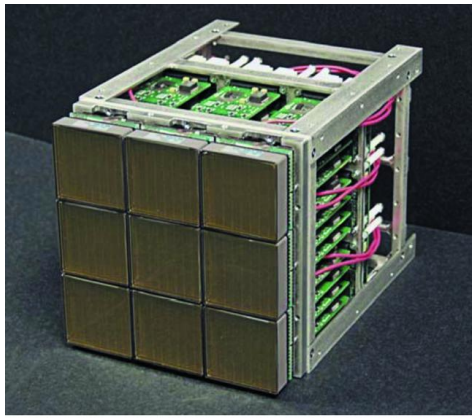


GS20 Glass detector performance

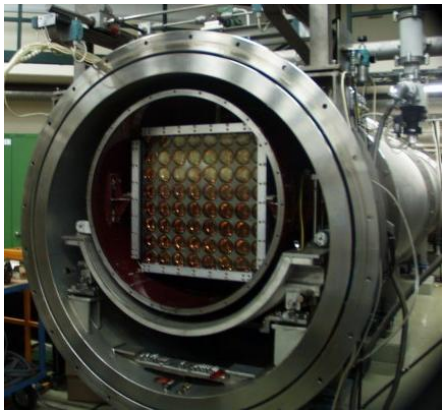
	Gas detector	GS20 glass detector
Neutron Detector Efficiency	70% at 1 Å	85% 1 Å
Gamma Sensitivity	10^{-7} -10^{-8} at 1MeV	10^{-3} at 1MeV
Intrinsic Detector Background	3 – 5 $c.hr^{-1}$	30 $c.cm^{-2}.hr^{-1}$
Area	2.5 x 30 cm^2	320 cm^2
Position Resolution	2.5 x 30 cm^2	15 mm x length segment
Timing Resolution	1 μs	10 ns
Rate Capability	50 kHz	300 kHz
Placement Accuracy	100%	Lots of care needed
Count Rate Stability	Good PHR	Good PHR
Environmental Immunity	OK in mag fields	Shield PMTs

Scintillator Detectors: GS20 Glass

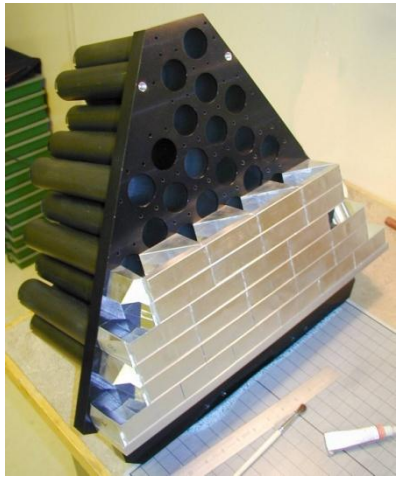
A range of detectors based on GS20 glass scintillator



SNS Anger camera



Julich Anger camera



ISIS Vesuvio resonant detector

PMTs in all these detectors view scintillator directly
Better light collection than fibre coupling

Need to be aware of gamma sensitivity and intrinsic background

Appropriate shielding, sample and sample environment

Scintillator Detectors: ZnS:Ag/^{6}LiF

Two types of scintillator in common use:

2. ZnS:Ag/6LiF

AST, Eljen www.eljentechnology.com + others

Mixture of ZnS and LiF powder + binder

The Li is enriched to + 95% 6Li

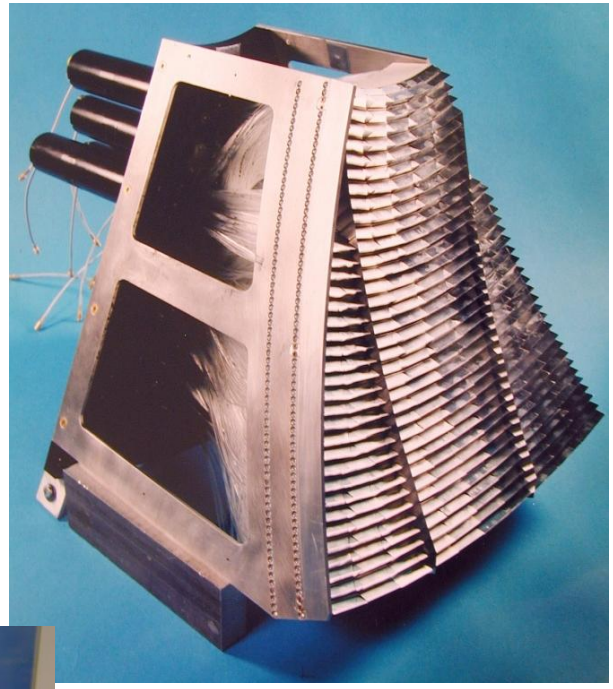
Opaque

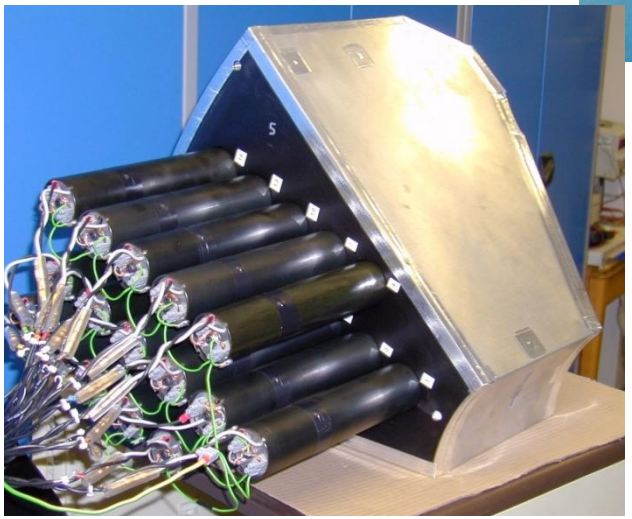
0.4 mm thick screen: neutron absorption ~ 24% at 1 Å

150,000 photons per absorbed neutron

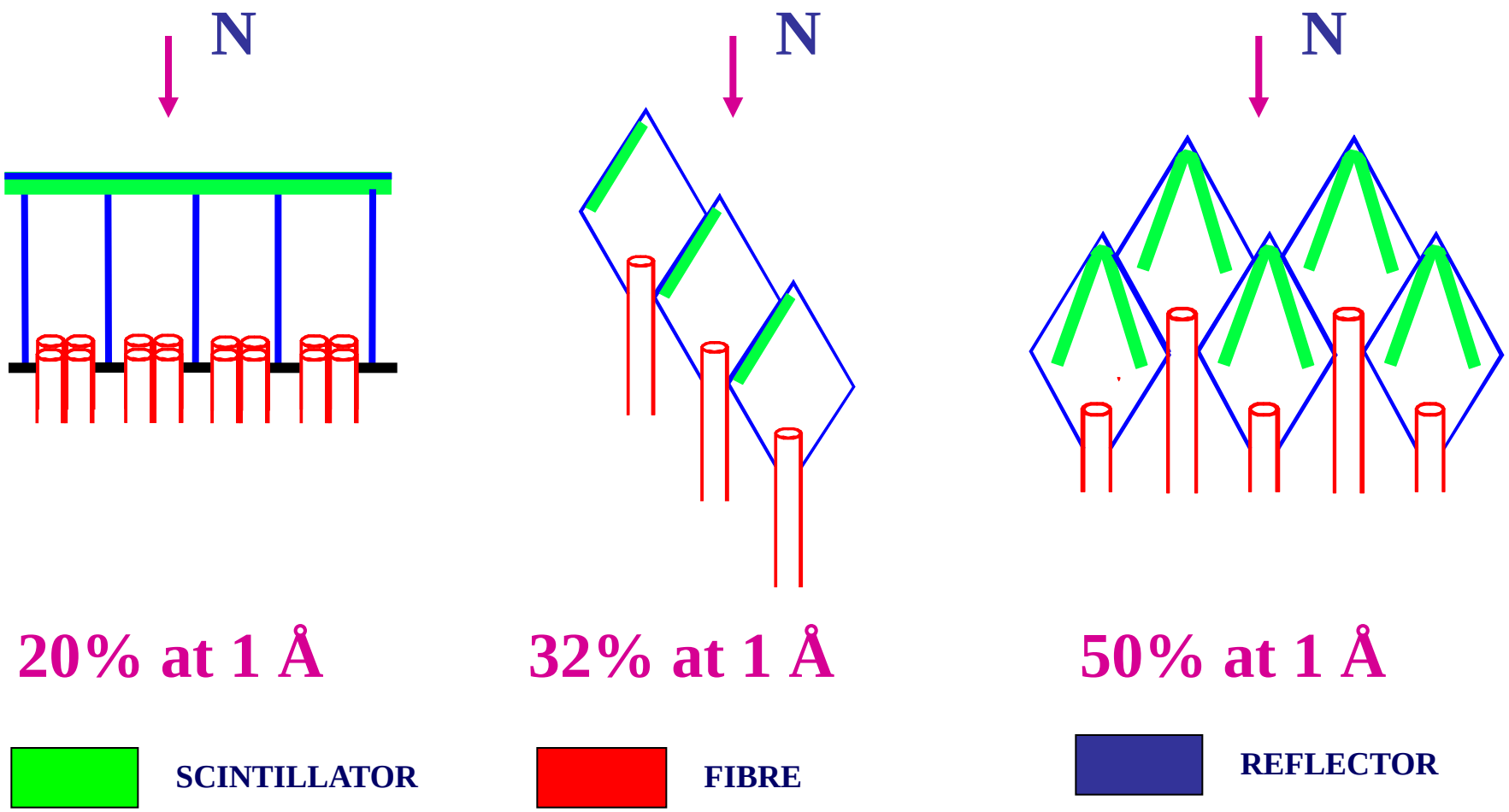
200 ns primary decay constant - Afterglow ~80 μs

ZnS:Ag/^{6}LiF: OSIRIS Detector build



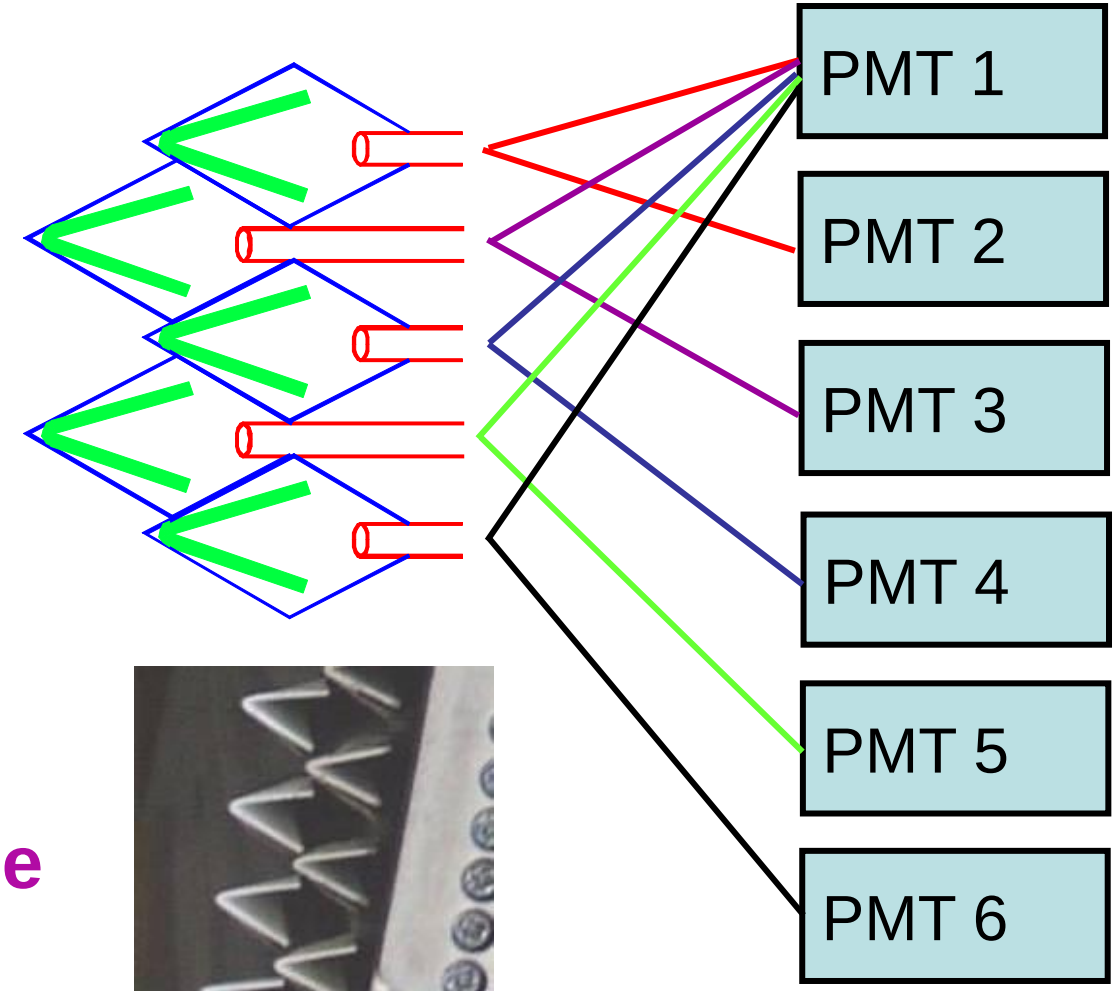


ZnS:Ag/^{6}LiF: Scintillator geometry



ZnS:Ag/^{6}LiF: Fibre code

Code 1,2 Ele 1
Code 1,3 Ele 2
Code 1,4 Ele 3
Code 1,5 Ele 4
Code 1,6 Ele 5

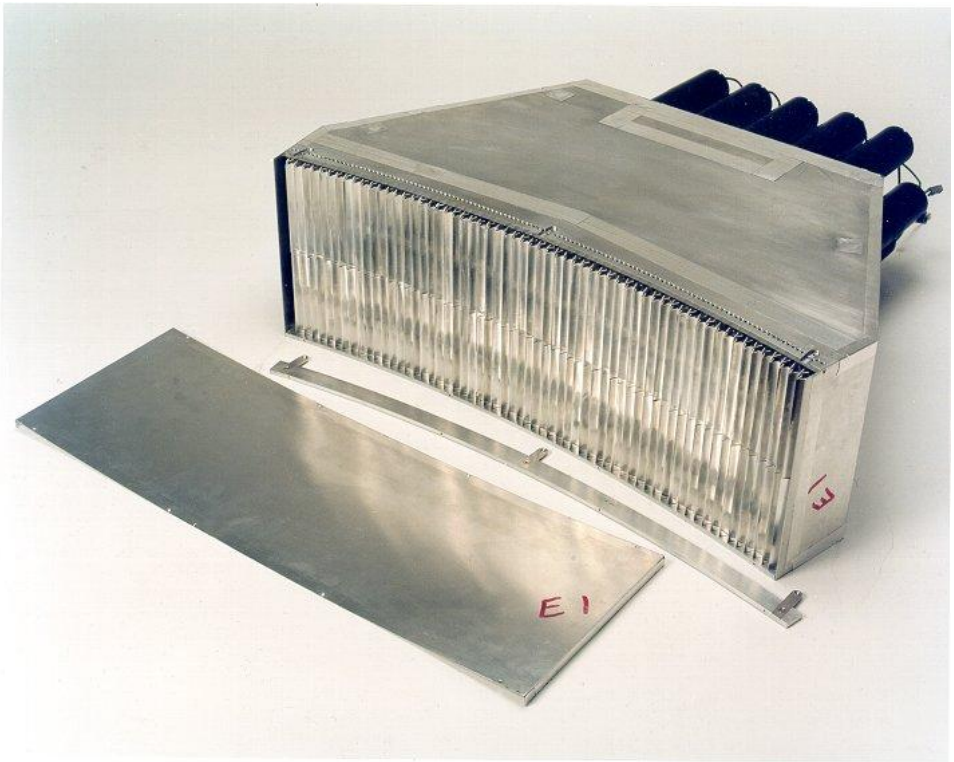


The $^{2}C_{n}$ Code

ZnS:Ag/^{6}LiF: HRPD Detector Performance

	Gas detector	HRPD GS20 glass detector	HRPD ZnS detector
Neutron Detector Efficiency	70% at 1 A	85% at 1 Å	50% at 1 Å
Gamma Sensitivity	10^{-7} -10^{-8} at 1MeV	10^{-3} at 1MeV	10^{-6} -10^{-7} at 1MeV
Intrinsic Detector Background	3 – 5 c.hr^{-1}	30 c.cm^{-2}.hr^{-1}	1.2c.cm^{2}.hr^{-1}
Area	2.5 x 30 cm^{2}	320 cm^{2}	320 cm^{2}
Position Resolution	2.5 x 30 cm^{2}	15 mm x length segment	5 mm x length segment
Timing Resolution	0.5 μs	10 ns	0.5 μs
Rate Capability	50 kHz	300 kHz	16 kHz per PMT
Placement Accuracy	100%	Needs care	Needs care
Count rate Stability	Good PHR	Good PHR	No PHR
Environmental Immunity	OK in mag fields	Shield PMTs	Shield PMTs

ZnS:Ag/^{6}LiF: GEM Detector



120 detector elements

Each element

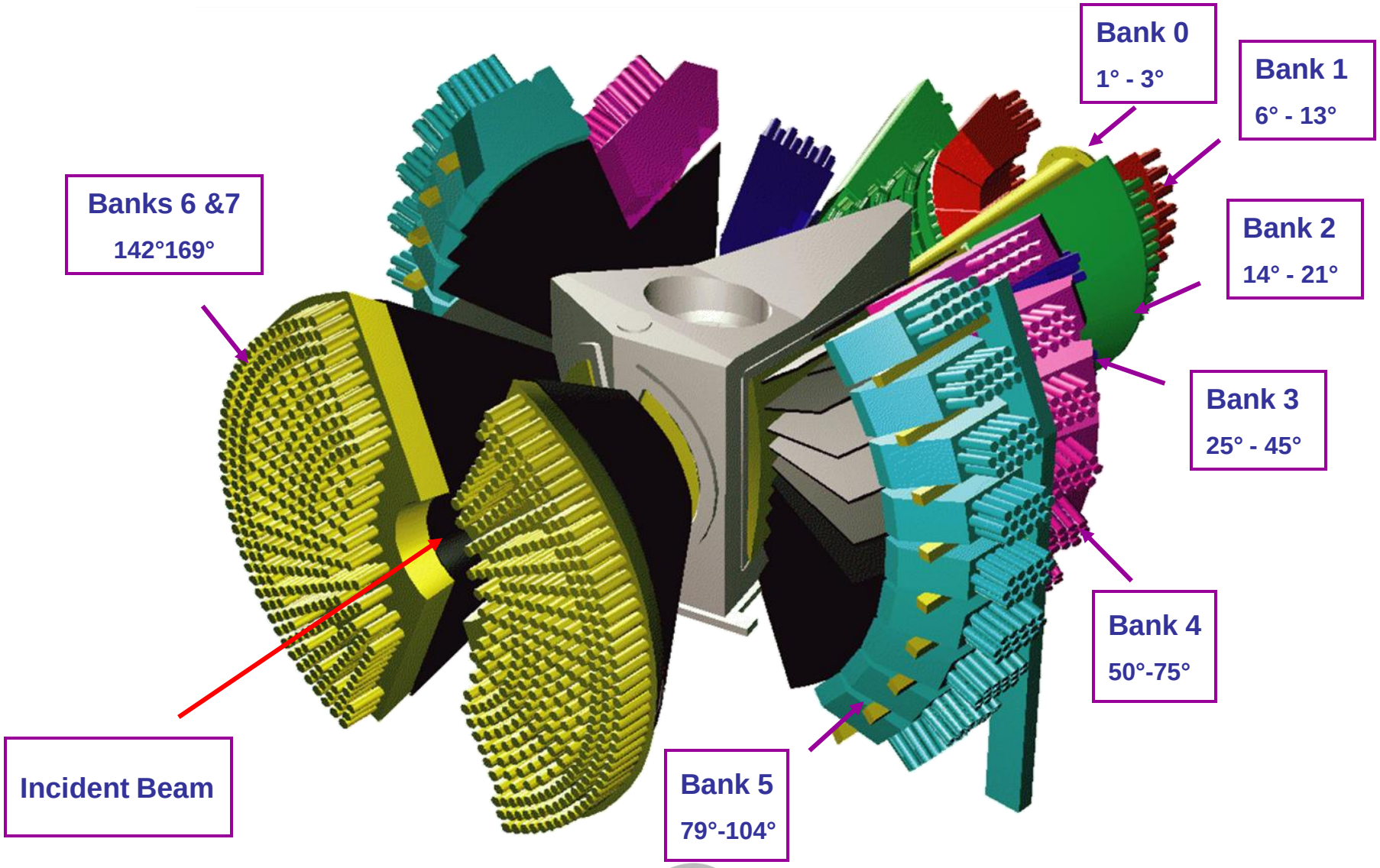
200 mm x 5 mm

on 1.5 m radius

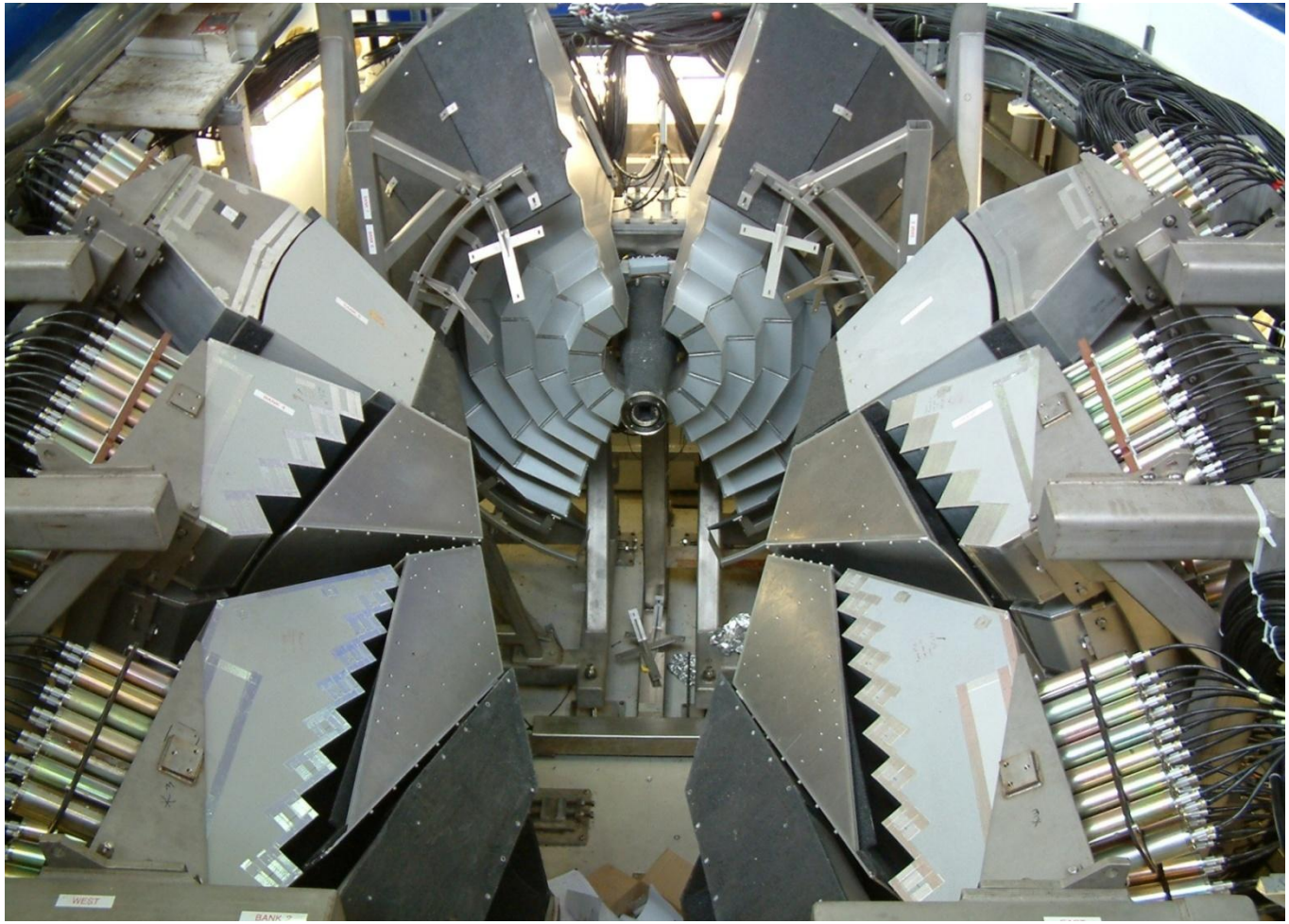
$^{2}C_{n}$ coded to 16 PMTs

Coincident pairs of PMT outputs determine origin of a single neutron interaction

ZnS:Ag/^{6}LiF: GEM Detector

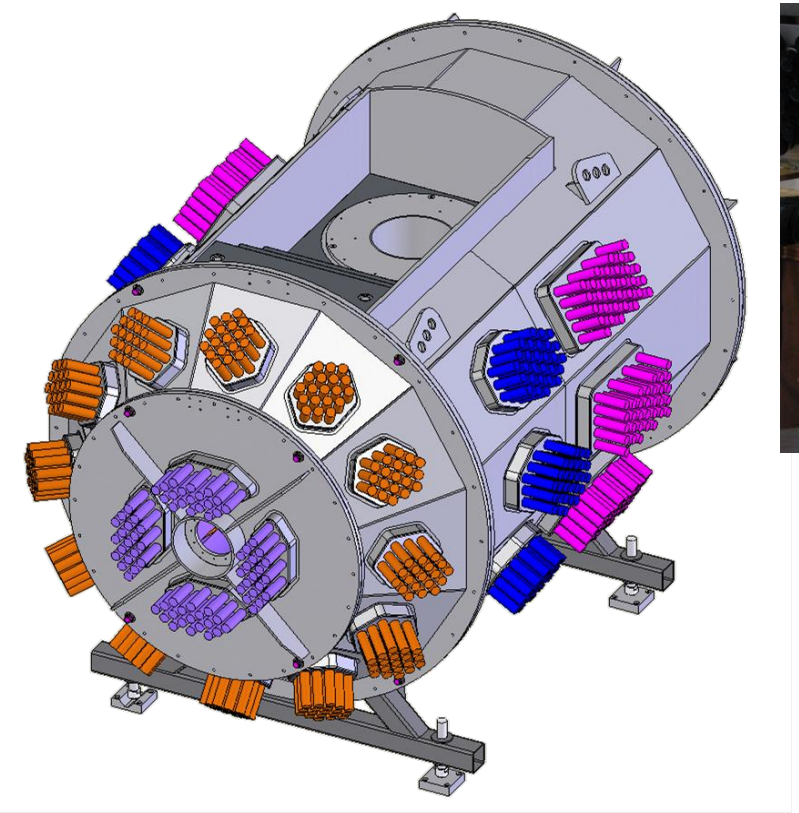


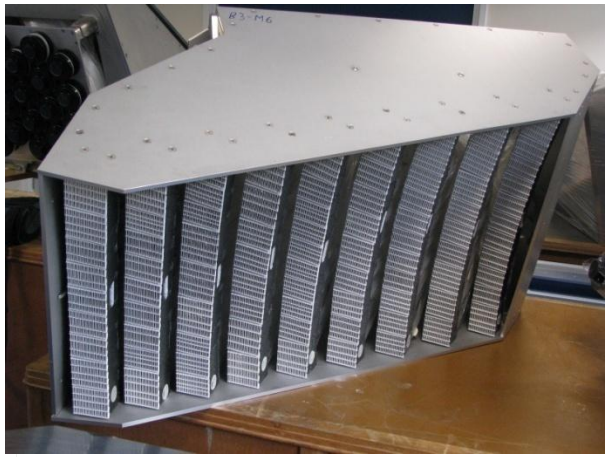
ZnS:Ag/^{6}LiF: GEM Detectors

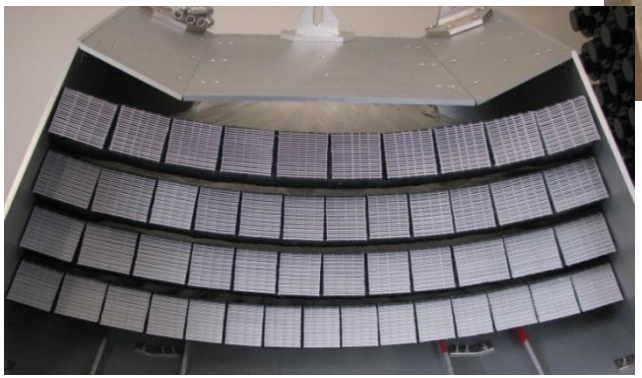


	No. Mods	No. PMTs	No. Elem's	No. Facets
Total	77	1152	7270	11370

ZnS:Ag/^{6}LiF: POLARIS detectors





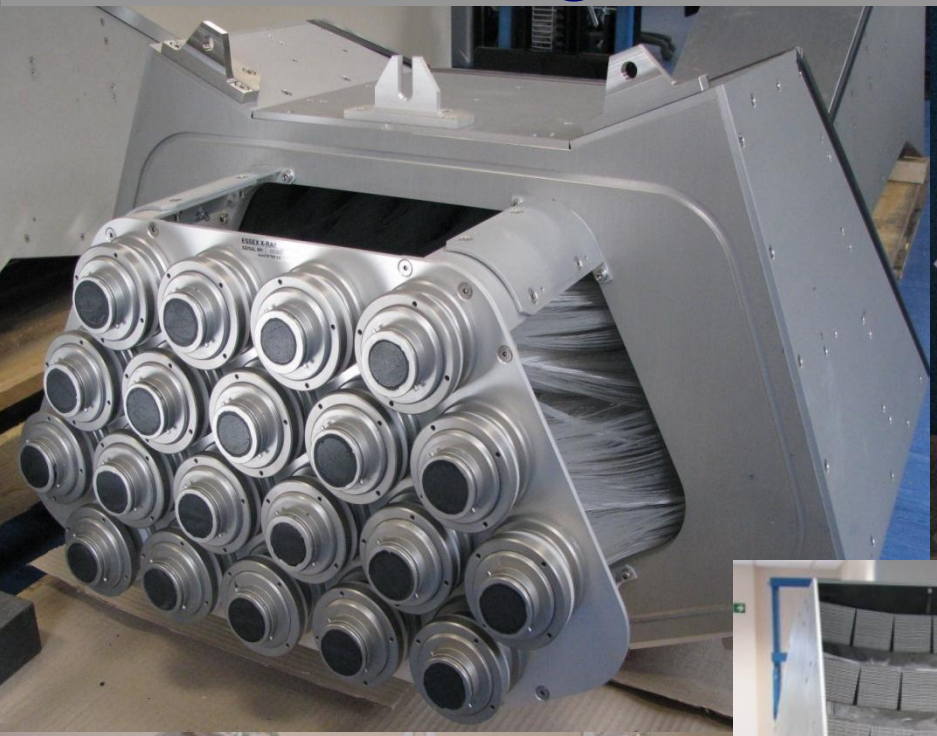


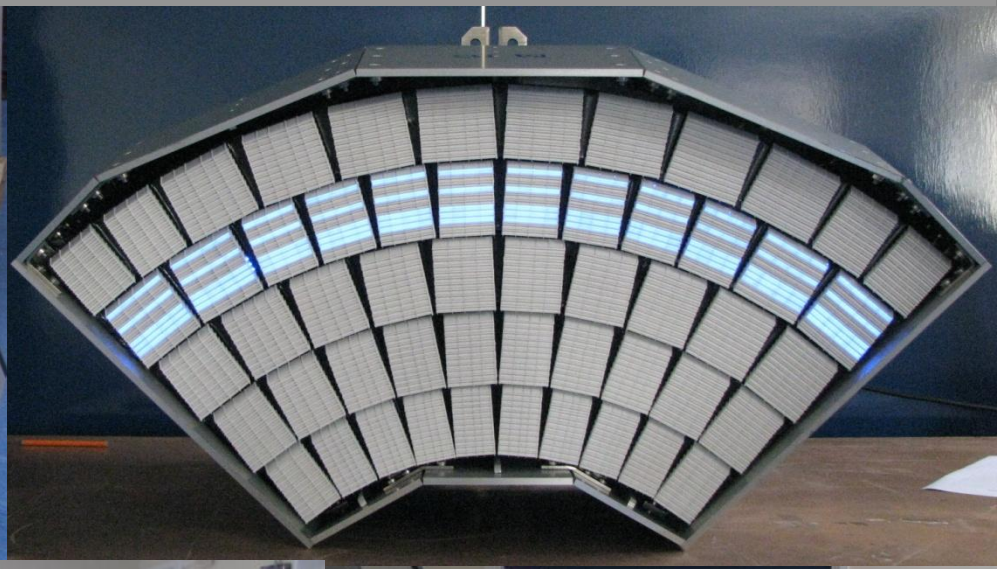
POLARIS Upgrade – 38 GEM like detector modules in vacuum

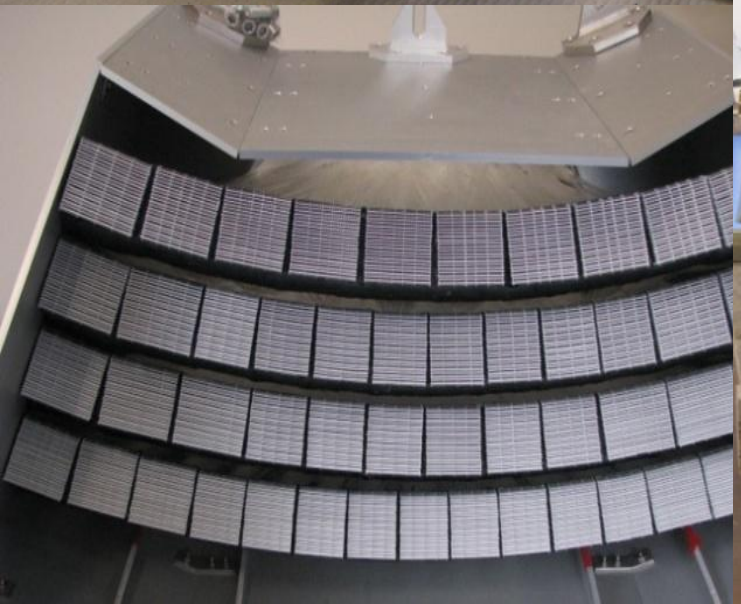
2954 detector elements 924 PMTs 460 Km fibre optic

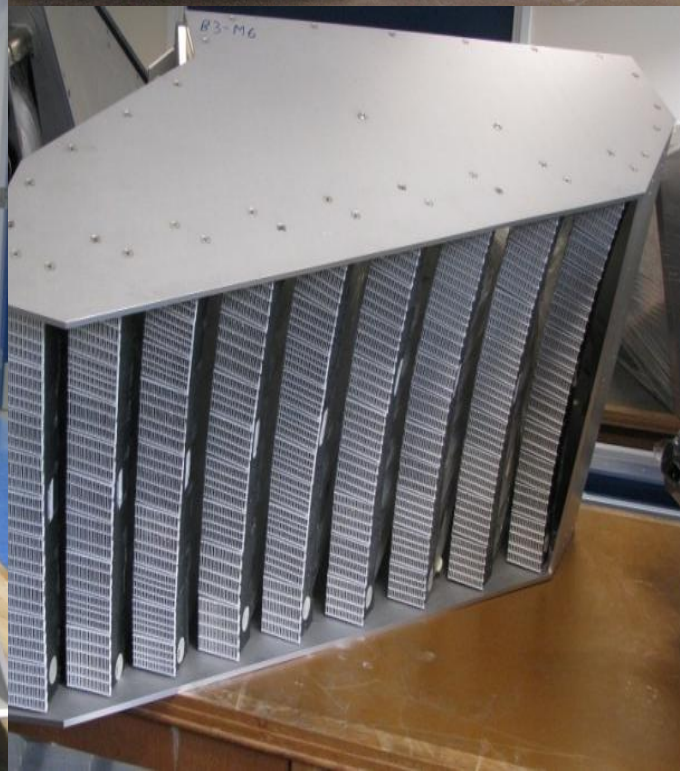
Operational 2011

ZnS:Ag/^{6}LiF: POLARIS detectors





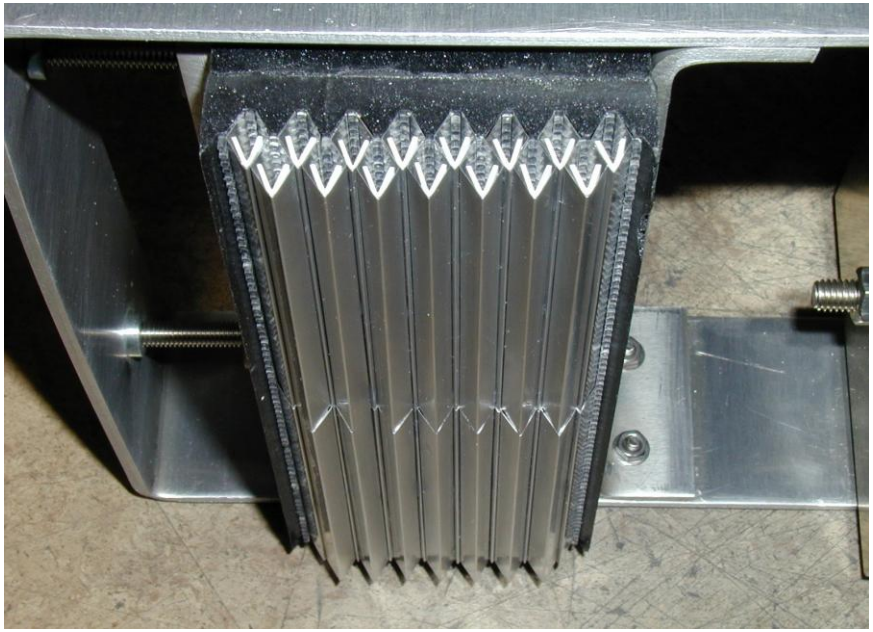




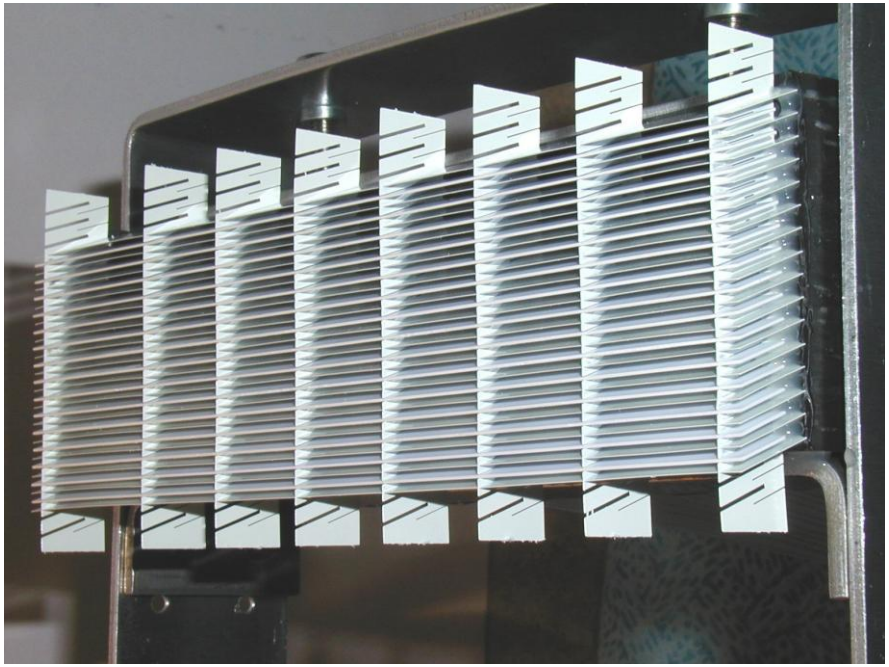
ZnS:Ag/^{6}LiF: POLARIS detectors

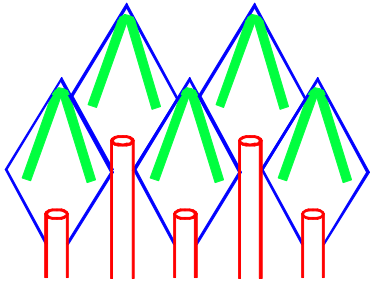
ZnS:Ag/^{6}LiF: ENGIN-X detectors

V DETECTOR



VENETIAN DETECTOR

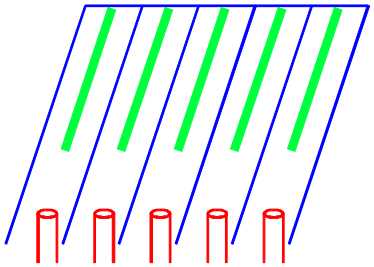




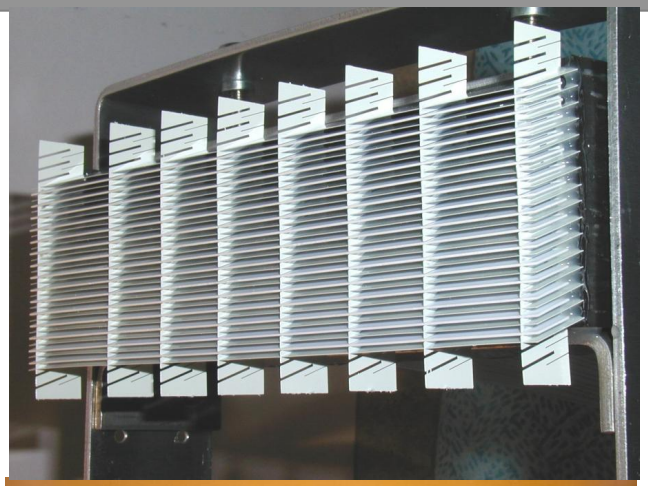
SCINTILLATOR

FIBRE

REFLECTOR

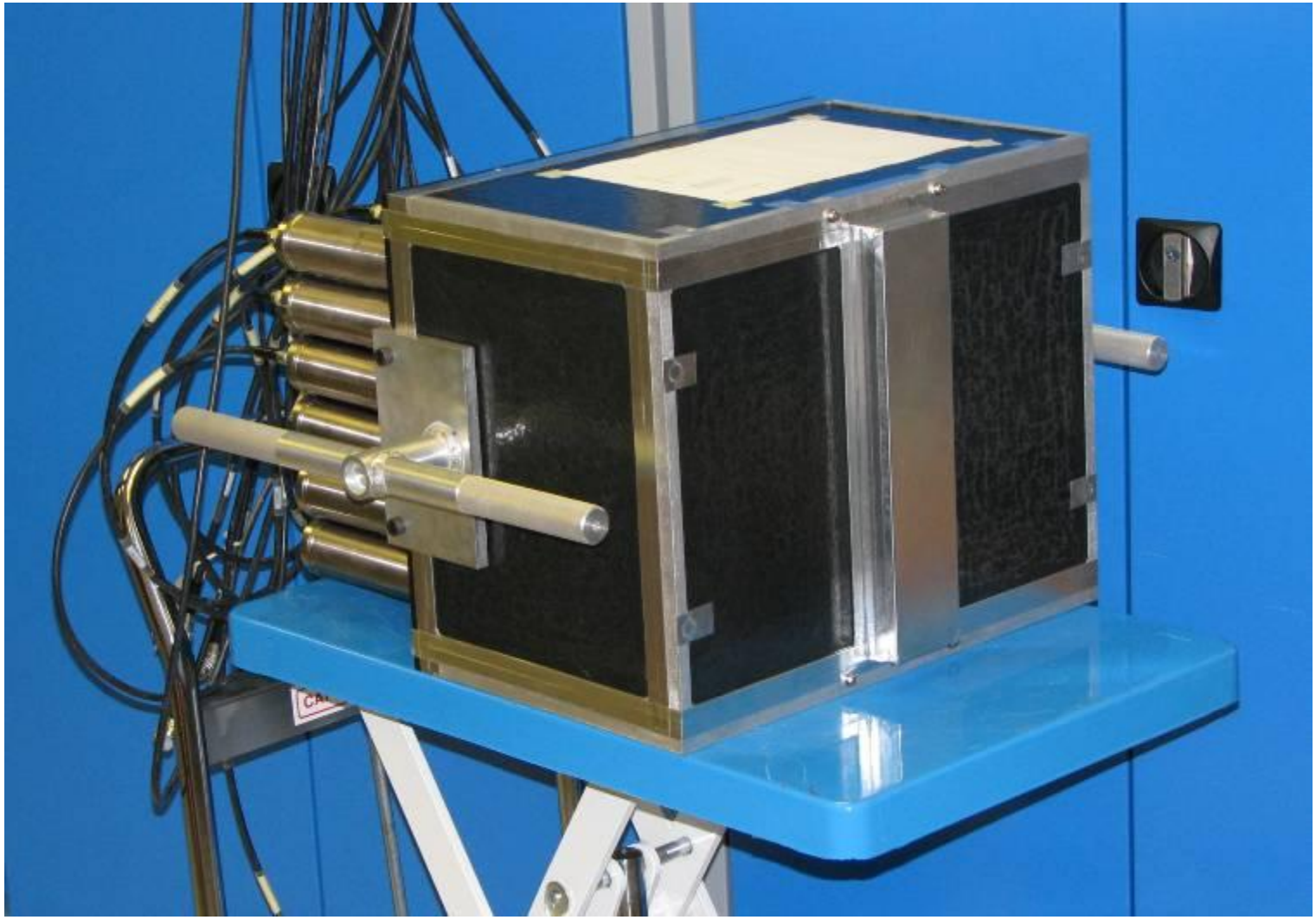


ZnS:Ag/^{6}LiF: ENGIN-X detectors

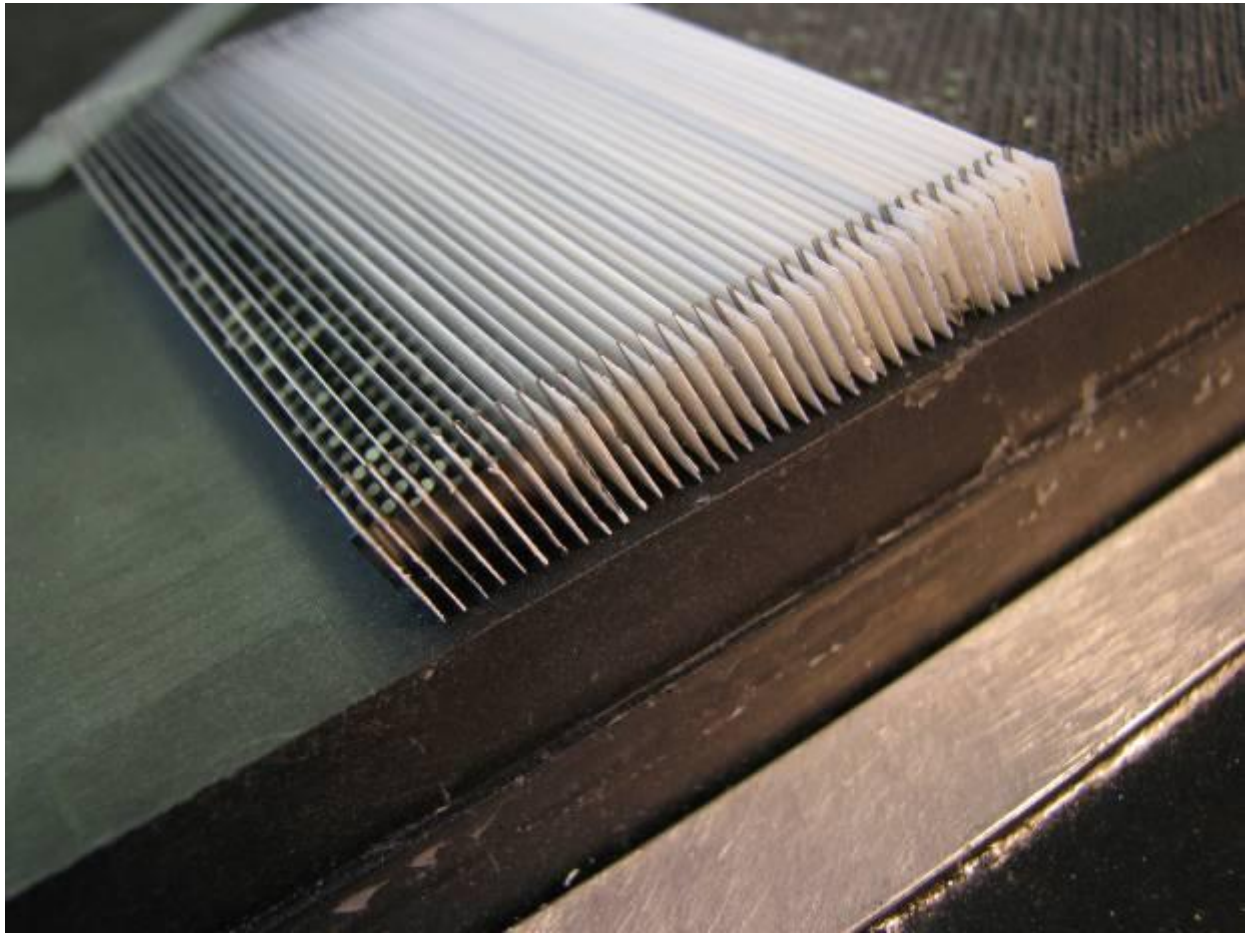


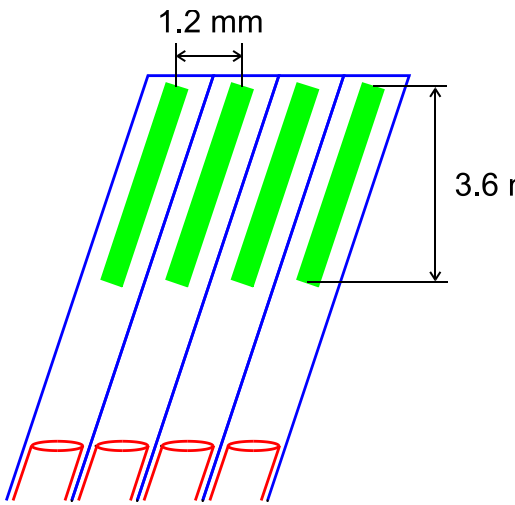
Eventually the Venetian design was selected for use in the final detector array

ZnS:Ag/^{6}LiF: INTER 1.2 mm detector



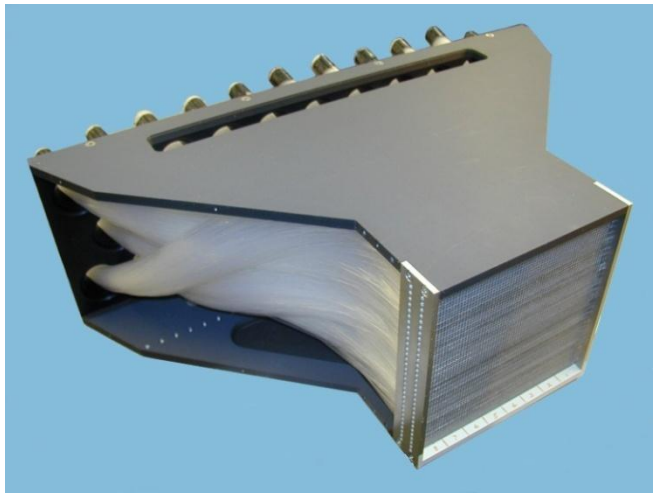
ZnS:Ag/^{6}LiF:INTER 1.2 mm detector





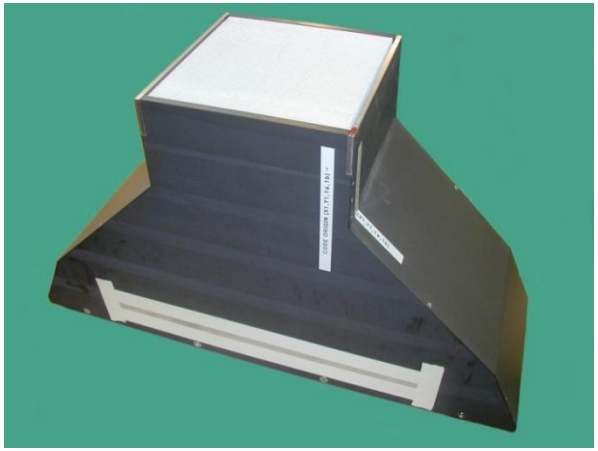
Fibre coupled ZnS scintillation detector
Linear position sensitivity, 1.2 mm resolution

ZnS:Ag/^{6}LiF: 2D SXD Detector



The fibre array

Scintillator and grid



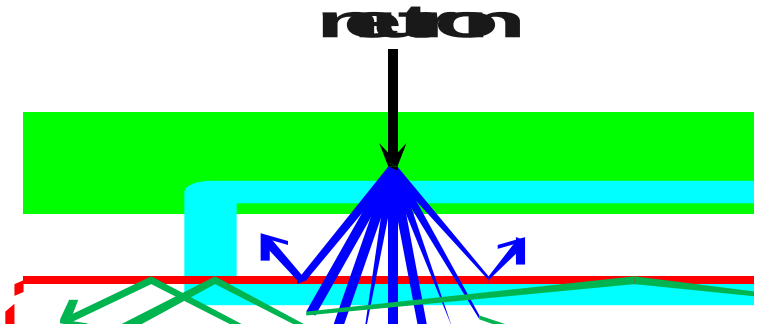
Awaiting covers and PMTS

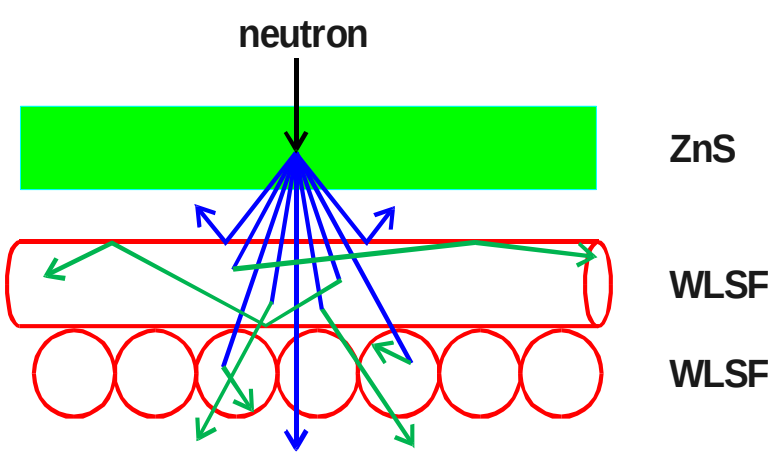
- 11 modules
- 4096 pixels per module
- 45 056 pixels
- 352 readout channels

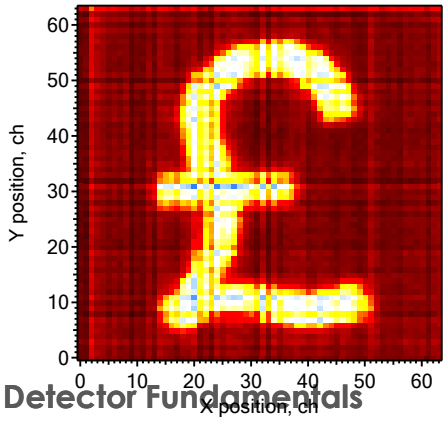
SXD 3 mm Pixel Array

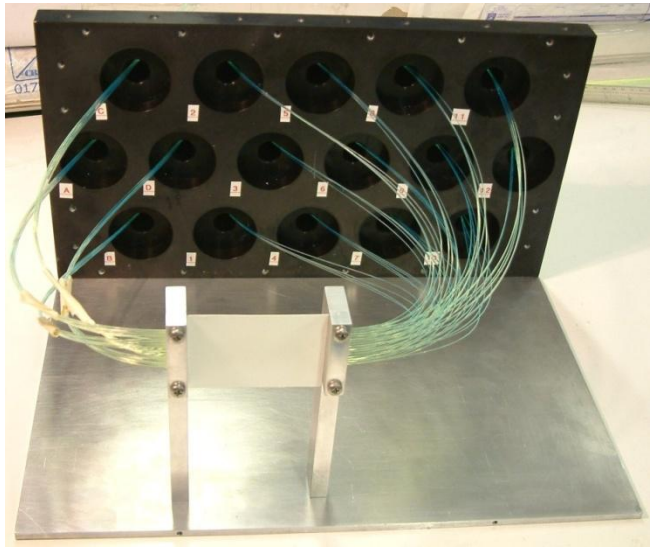
Low parallax, but low efficiency at short wavelengths

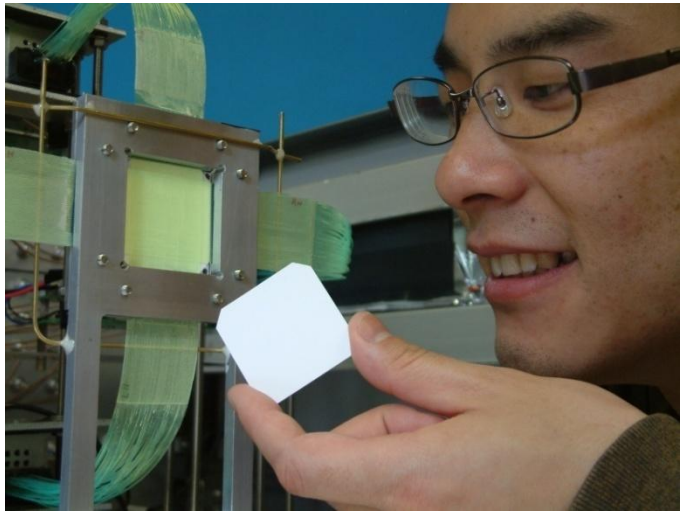
ZnS:Ag/^{6}LiF: 1D and 2D WLSF detectors



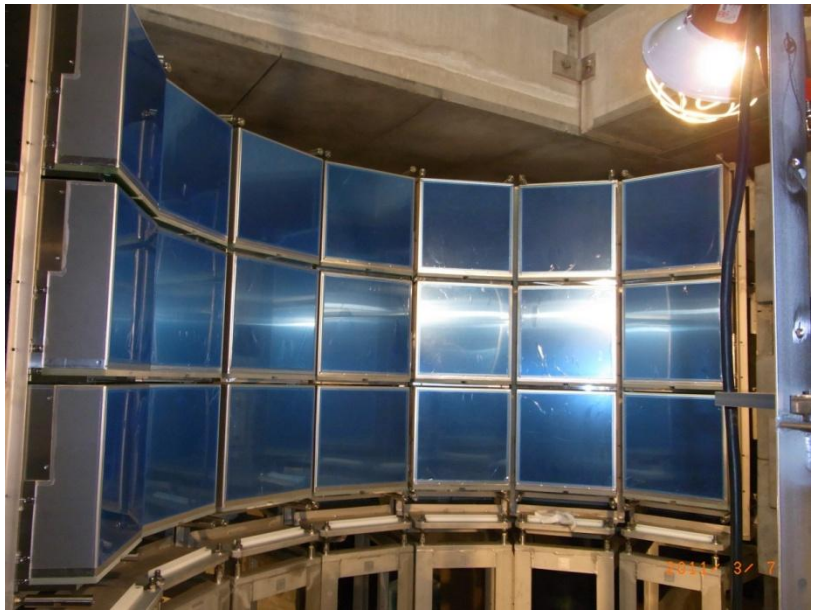




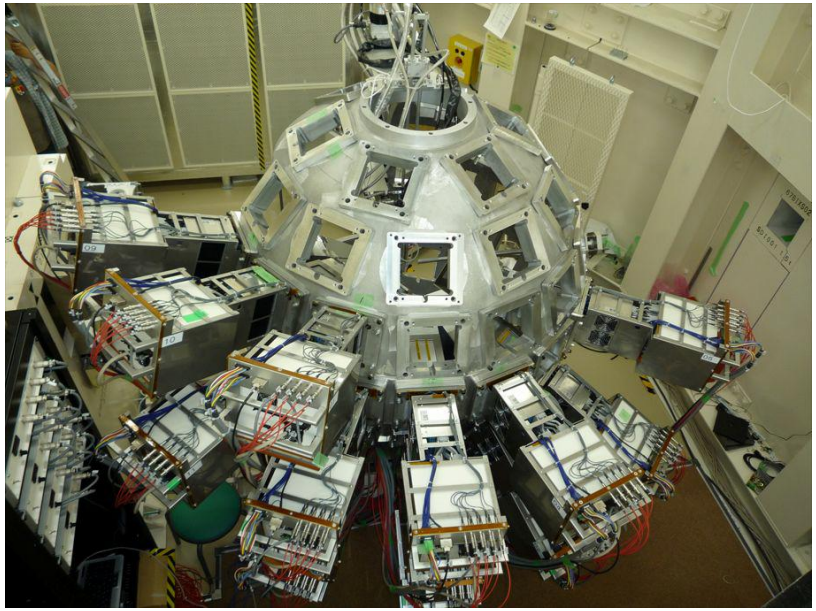




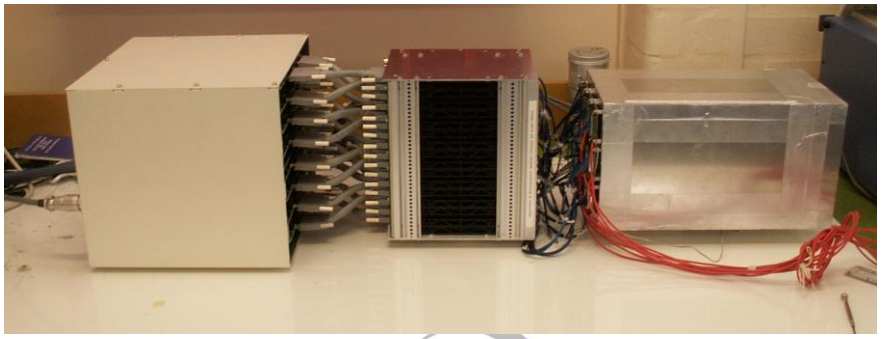
ZnS:Ag/^{6}LiF: 1D and 2D WLSF detectors



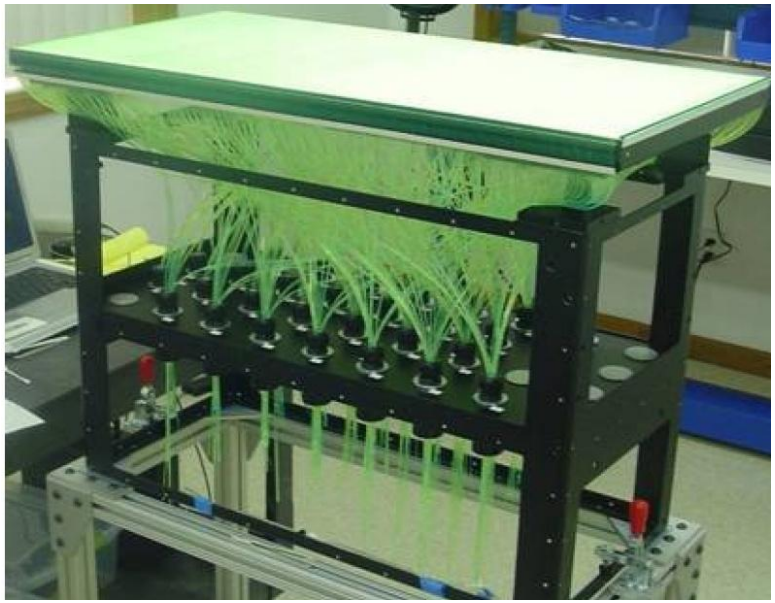
SENJU detector array
J-PARC 4 x 4 mm2 pixels



iBIX detector array
J-PARC 1 x 1 mm^2 pixels



ZnS:Ag/^{6}LiF: 1D and 2D WLSF detectors



Powgen & Vulcan Detectors
SNS 50 x 5 mm2 pixels

Reflectometer detector
ISIS 0.5 x 60 mm^2

WLS fibres - Higher position resolution than clear fibres

Much fewer fibres - Lower cost

ZnS:Ag/^{6}LiF: Higher energies

Making use of Epithermal neutrons – up to 30 eV

Scintillator directly viewed by PMTs

Detector elements 10 x 200 mm^2

18 elements per module

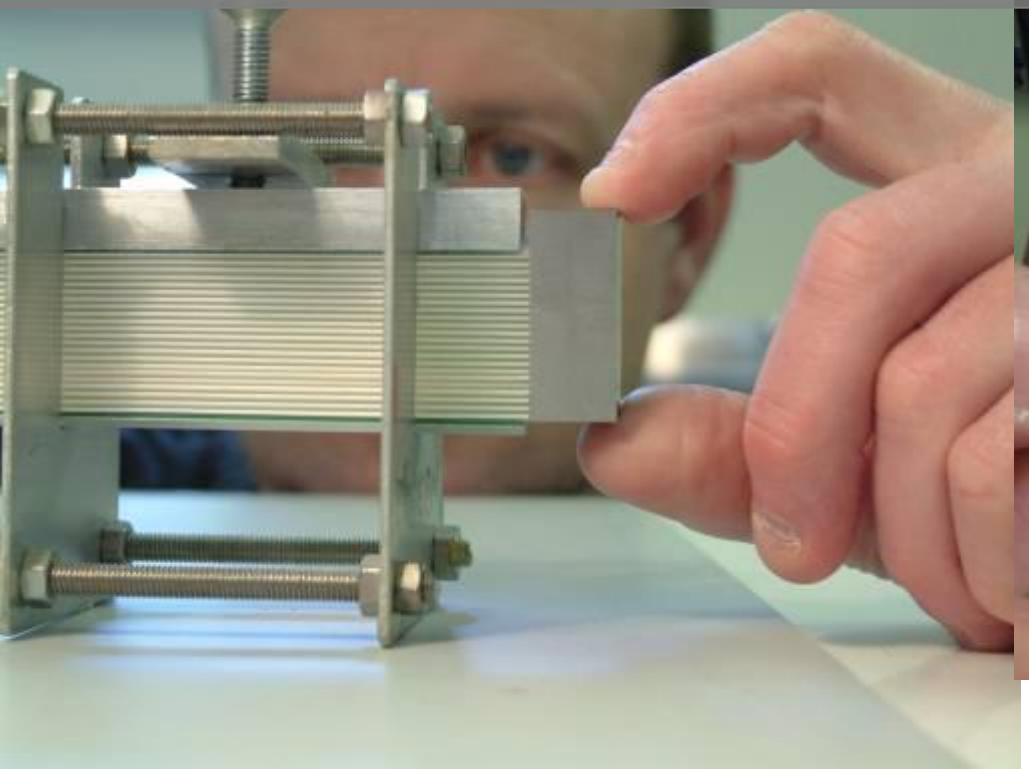
60 modules

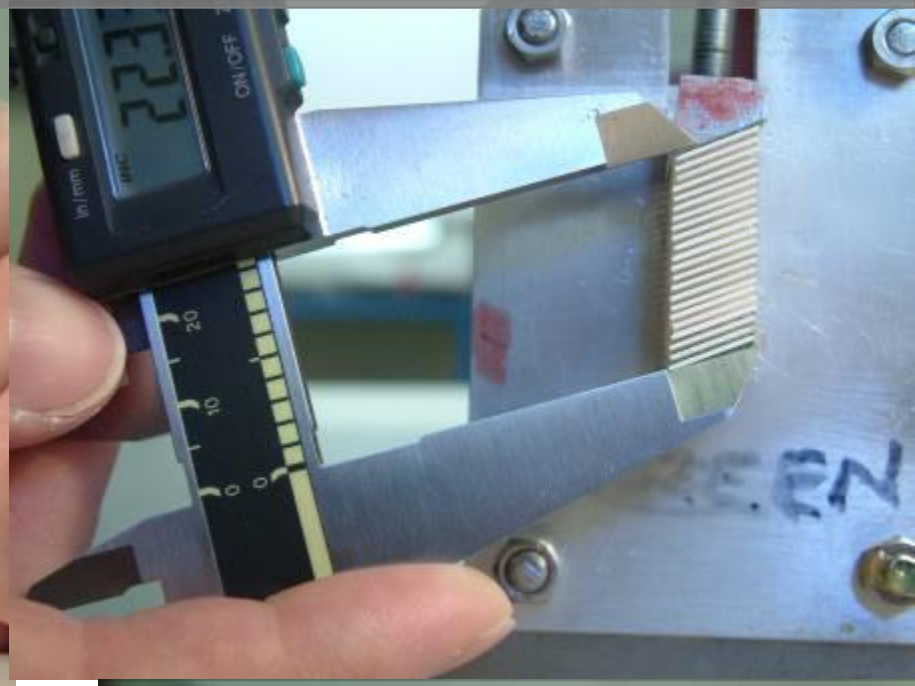
2,16 m^2 detector –

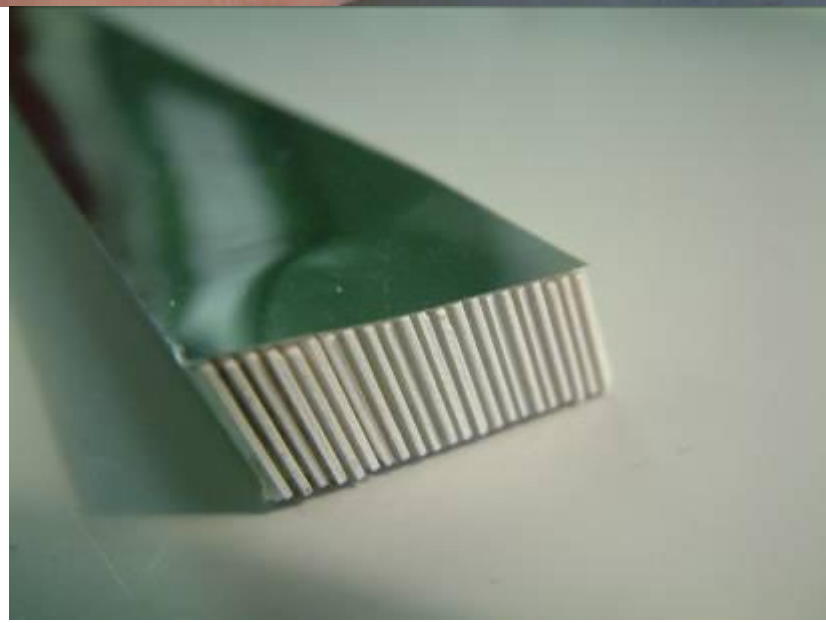
50 m^2 scintillator

NIMROD detector – ISIS:

ZnS:Ag/^{6}LiF: Higher energies



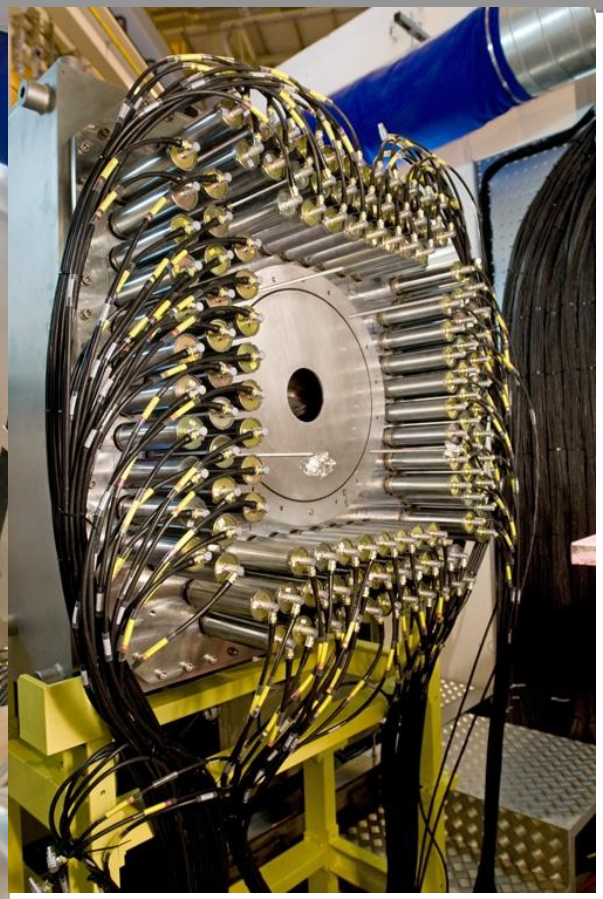


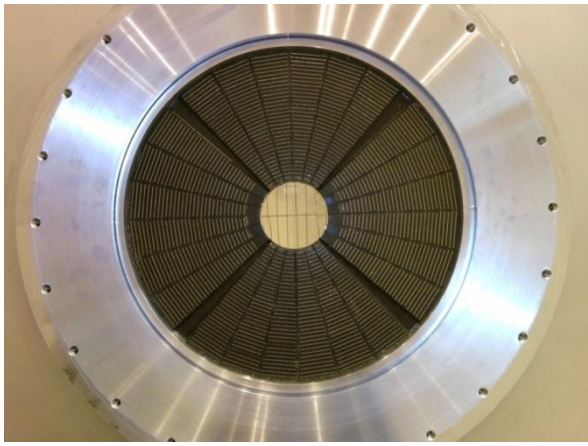


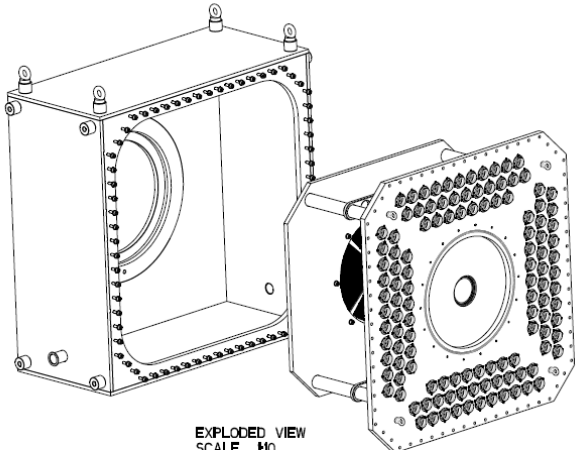
Stages in the scintillator pack preparation

~25% efficient at 10eV

ZnS:Ag/6LiF: Higher energies







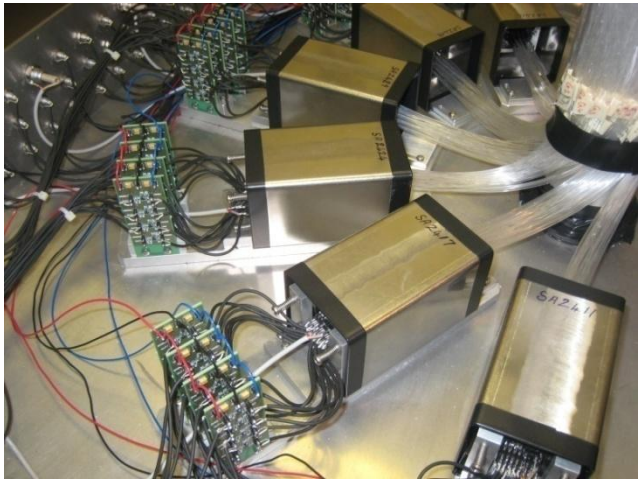
61 Modules installed.

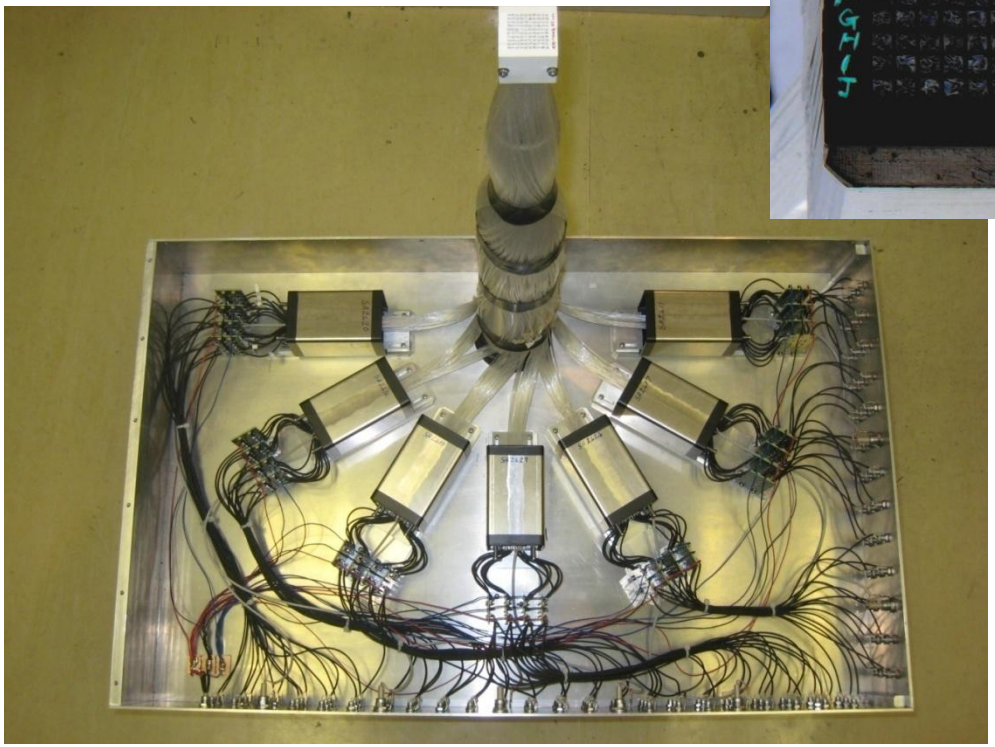
NIMROD phase 1 complete

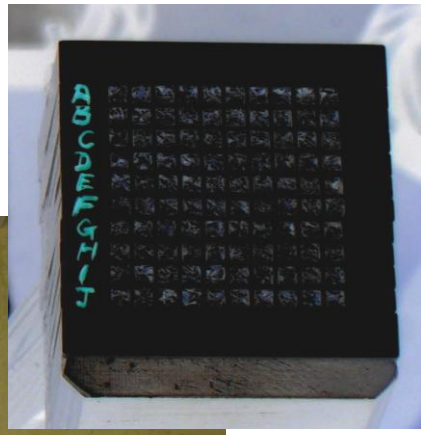
Low Angle Bank:
Comprises of 8 detector modules
756 elements 2Cn fibre coded to 120 PMTs

Back to GS20 Glass: Higher energies still

Ancient Charm – A detector for Cultural Heritage applications



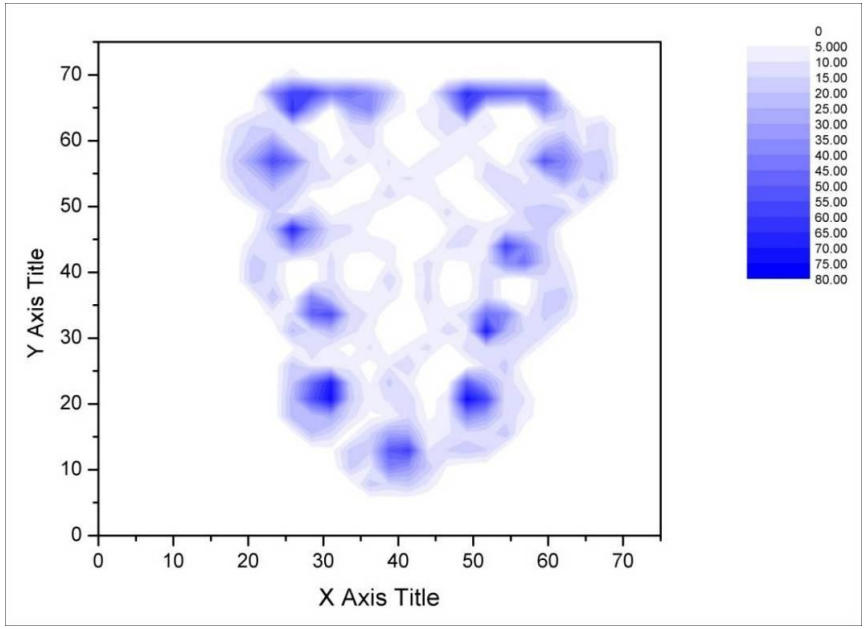


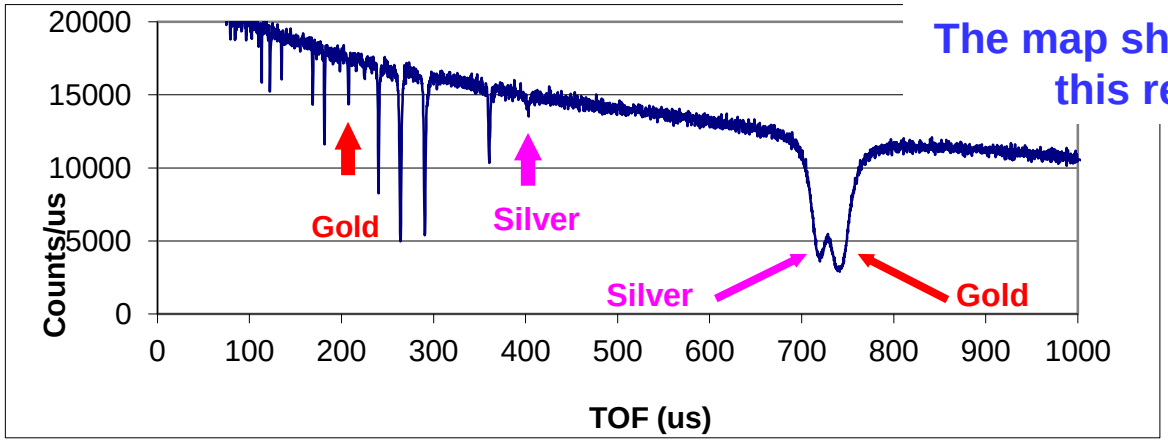


1.8 x 1.8 mm^2 pixels, 9 mm deep on a 2.5 mm pitch

A 100 pixel detector for neutron resonance transmission imaging

Back to GS20 Glass: Higher energies still





The map shows the distribution of silver in this replication of a belt buckle

Narrow resonances:
Up to 2keV
Timing resolution and count rate important

Future developments: The absence of 3He

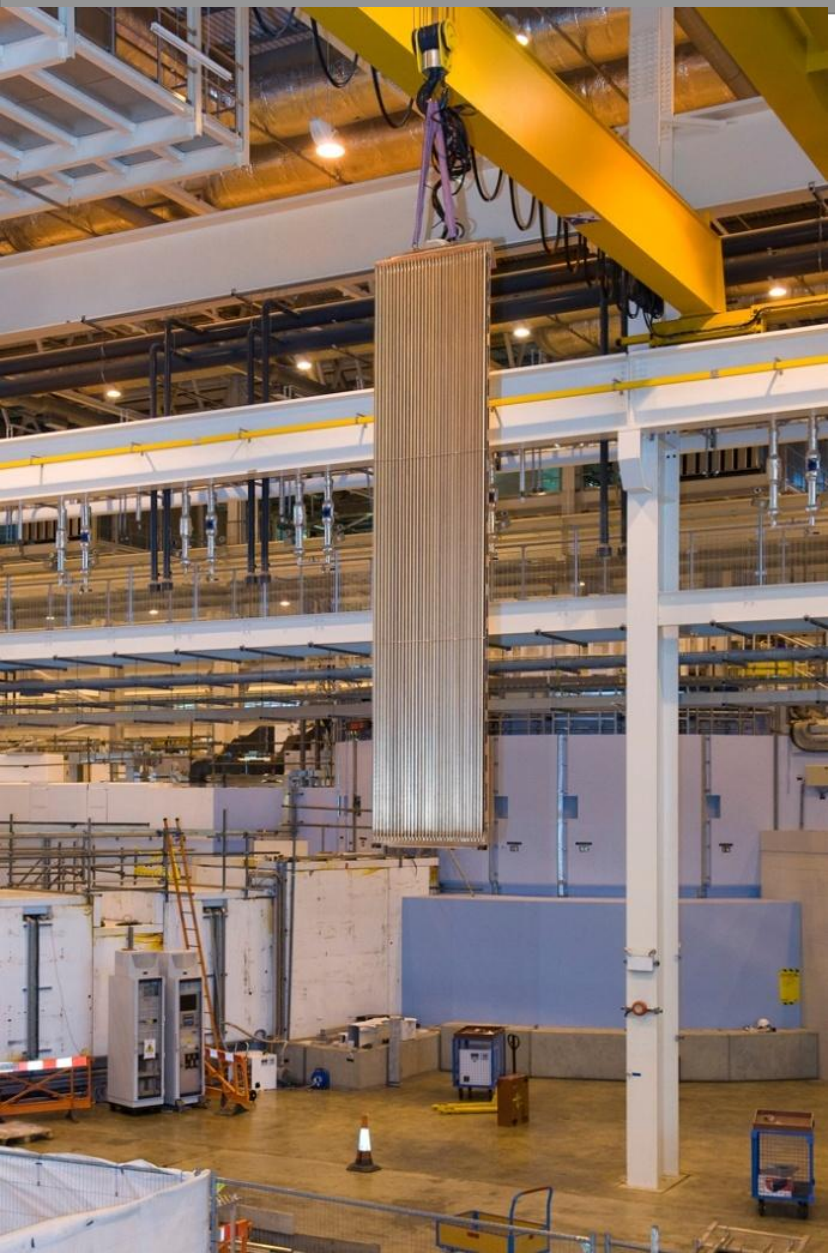
3He demand exceeds supply
Degree is reflected in the price

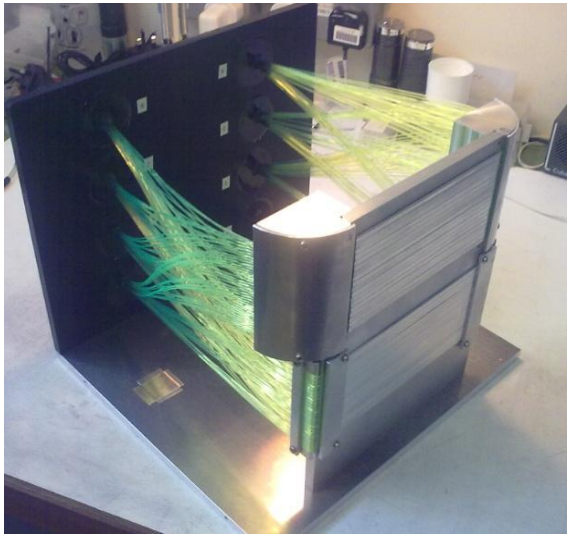
Technical working group set up to investigate alternatives

Three development lines proposed:

- The development of scintillation detectors
- Gaseous detectors based on solid ^{10}boron converter
- $^{10}BF_3$ gas detectors

Challenges: 3He replacement technology
What will the next excitations detector look like?





Performance requirements of detectors

Neutron Detector Efficiency
Gamma Sensitivity
Intrinsic Detector Background
Area
Position Resolution
Timing Resolution
Rate Capability
Placement Accuracy
Count Rate Stability
Environmental Immunity
Cost

Conclusions

- He detectors have dominated neutron scattering applications for a long time
- 3He will not be available for the larger area detectors in the foreseeable future
- Scintillator detectors have been used very successfully for diffraction applications
- ^{10}B and $^{10}BF3$ detectors are being developed/redeveloped
- A lot of effort is required to develop alternative technologies for the large area inelastic scattering instruments

Conclusions

- Brighter sources and ever more sophisticated instruments Require higher performance detectors

- Detector performance needs to be appropriately matched to instrument requirements

- Detector performance is a compromise – not least the cost

- There are plenty of opportunities for even better detectors.