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Detectors for Neutron Scattering Applications

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A short preface to this presentation

Although there exists a vast variety of technologies for neutron detection, I will restrict my presentation to the most common techniques and devices used for neutron scattering applications.

In particular

- Only detectors for *slow neutrons* with energies below the Cadmium cut-off ($E_{kin} < 0.3$ eV) will be discussed
- The discussion will be limited to *“active” detectors,* which provide a pulse or a current signal for each individual neutron recorded in the device. They provide information about impact position and arrival time for each individual neutron. They do not provide information about the energy of the detected neutron.
- Although there is some overlap with neutron scattering applications, I will not speak about *Imaging detectors*

Contents

Fundamentals of slow neutron detection

Nuclear reactions and potential neutron converters

Detection technologies

Gaseous detectors

- ^{3}Helium based proportional counters
- Devices with ^{10}B converters

Scintillation detectors

- ^{6}Li-glass based Anger Cameras
- ^{6}LiF:ZnS and B_2O_3:ZnS based devices with clear or wave length shifting fibre readout

Conclusions

Fundamentals of slow neutron detection

As neutrons do not undergo coulomb interaction, a nuclear reaction is used to produce charged particles which possess sufficient kinetic energy to create ionization in a gas or excitation in a scintillator

Basically any detector for slow neutrons is a combination of a neutron converter providing this nuclear reaction with a conventional charged particle detector

Requirements for detectors applied in neutron scattering

- Reaction cross section of converter should be large in the energy range of interest
- Converter is stable and usable in “real life” conditions of a detector
- Isotope of choice should be cheap, abundant and easily available
- Signals created by neutrons have to be clearly distinguished from response to gammas and other charged particles
- The detector provides 2-D position resolution in the mm-range and time resolution in the µs-range
- Detectors handle count rates in the kHz to MHz range
- Detector & readout electronics are stable in time

Neutron converters

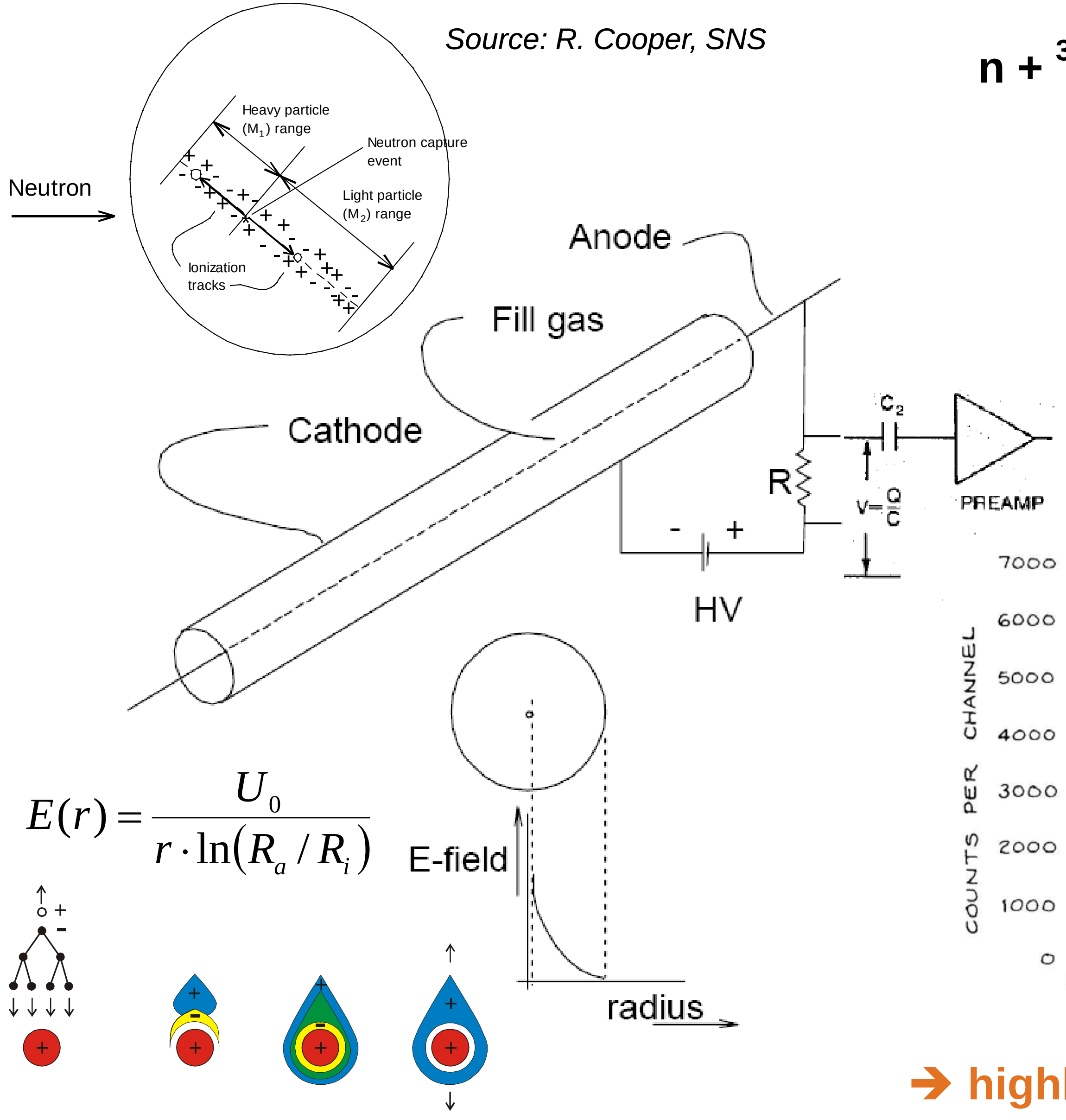
Isotope	State	Reaction	Cross Section (b)	Absorb. Length	Product Energies (keV)	Product Range
^{3}He	gas	$^{3}He(n,p)t$	5333	7.59 bar-cm	P:573, t:191	R_p = 5.4 bar-cm
^{6}Li	solid	$^{6}Li(n,\alpha)t$	940	230µm	t:2727, α:2055	R_t = 130 µm
^{10}B	solid	$^{10}B(n,\alpha)^{7}Li$	3836	19.9µm	α:1472, ^{7}Li:840	R_α = 3.14 µm
$^{10}BF_3$	gas	$^{10}B(n,\alpha)^{7}Li$	3836	9.82 bar-cm	α:1472, ^{7}Li:840	R_α = 0.42 bar-cm
^{nat}Gd	solid	$^{nat}Gd\ (n,\gamma)$	49122	6.72µm	Ce:29-182 (86.5%)	Λ_{ce} =12.3 µm

for 25meV Neutrons

Data from Th. Wilpert, (HZB)

- Cross section $\sigma \sim \lambda \sim (1/v)$ for slow neutrons

^{3}He: Proportional Counter



Source: R. Cooper, SNS

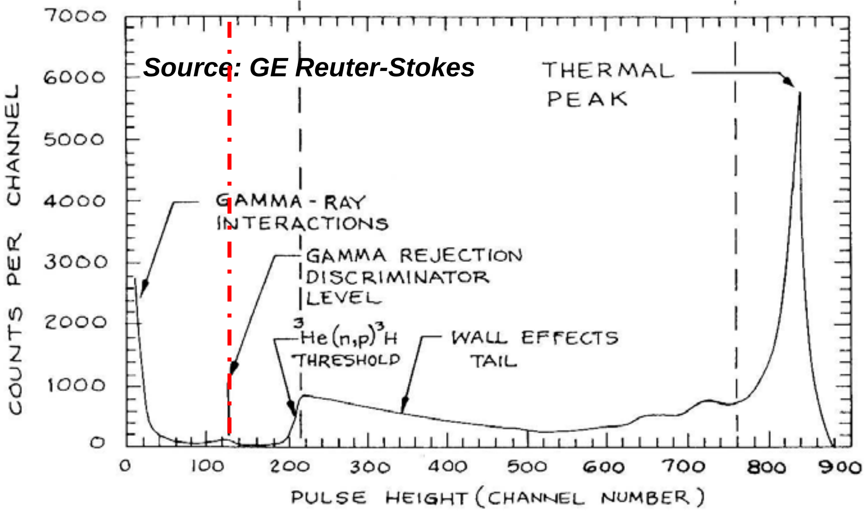
$$E(r) = \frac{U_0}{r \cdot \ln(R_a / R_i)}$$

n + ^{3}He → ^{3}H (191keV) + p (573 keV)

ca. 25,000 primary electrons / n

Typical parameter:
R_a= 4 – 25 mm, R_i = 25 µm;
p = 3 – 20 bar
Gain ~ 30

Charge pulse height spectrum

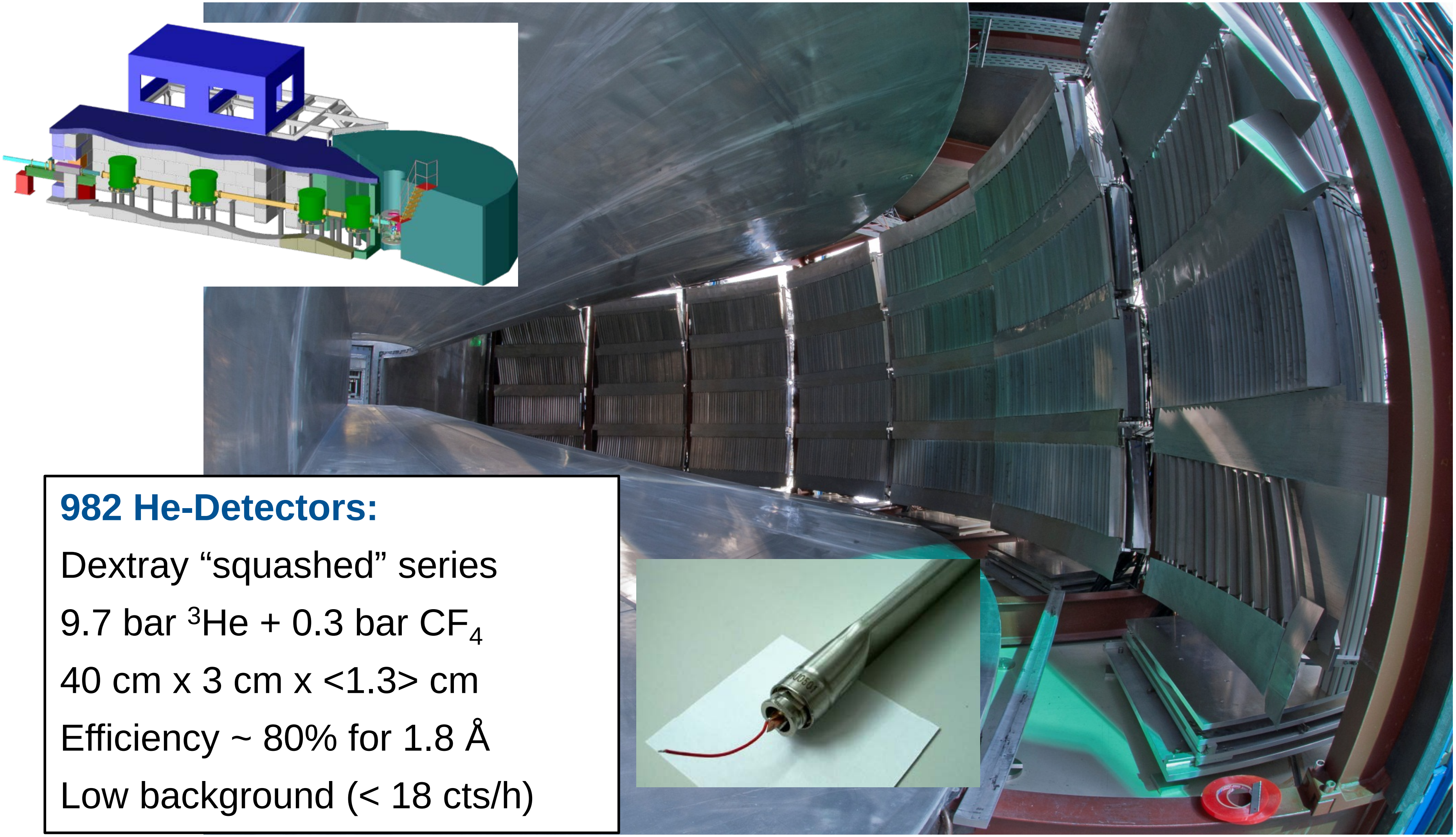


Source: GE Reuter-Stokes

→ highly efficient, n / γ-separation ≤10^{-7}

^{3}He: Proportional Counter

Double Time-of-Flight Spectrometer ToFToF @ FRM II



982 He-Detectors:

Dextray “squashed” series

9.7 bar ^{3}He + 0.3 bar CF_4

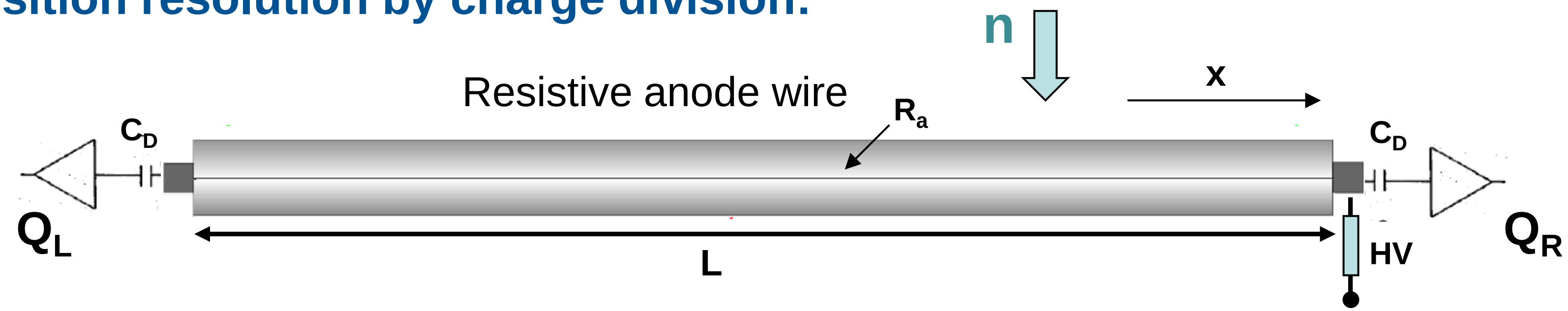
40 cm x 3 cm x <1.3> cm

Efficiency ~ 80% for 1.8 Å

Low background (< 18 cts/h)

^{3}He: Linear Position Sensitive Detector

Position resolution by charge division:



$$x \sim (Q_L - Q_R)\ ;\ Q_0 = (Q_L + Q_R)$$

Performance:

Diameter: d = 8mm - 25mm

Length: 0.3 – 4 m

Resolution: $\Delta x \sim 0.8\% * L$

Excellent position linearity

^{3}He-pressure: 3 – 20 bar

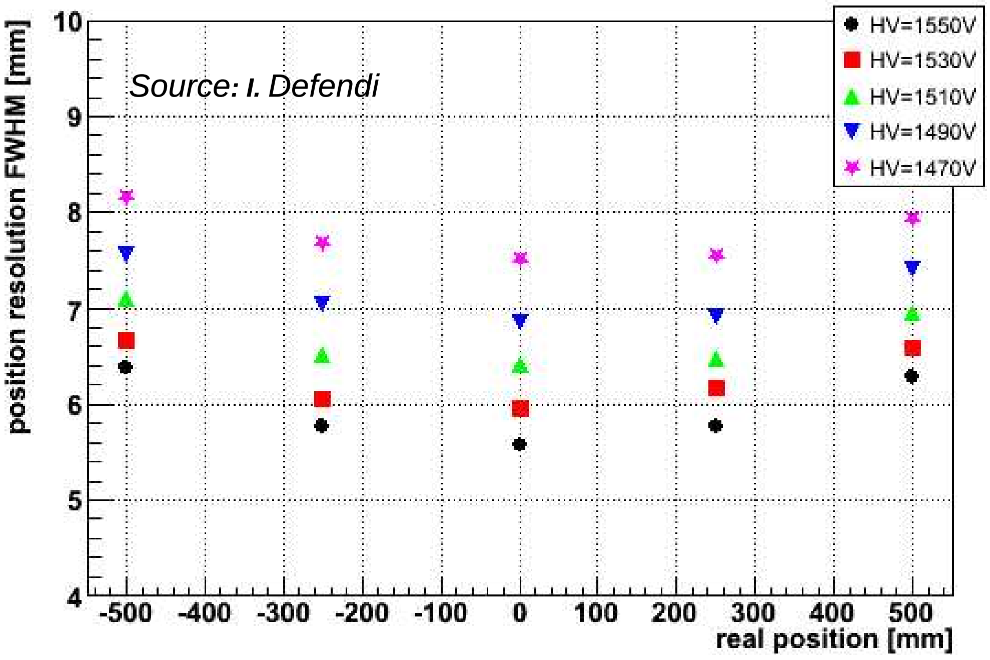
Drawbacks:

Stop gas needed: Argon 1-3 bar

High gas gain ~ 600

Reduced n/γ-separation

Position resolution along a 1m long PSD



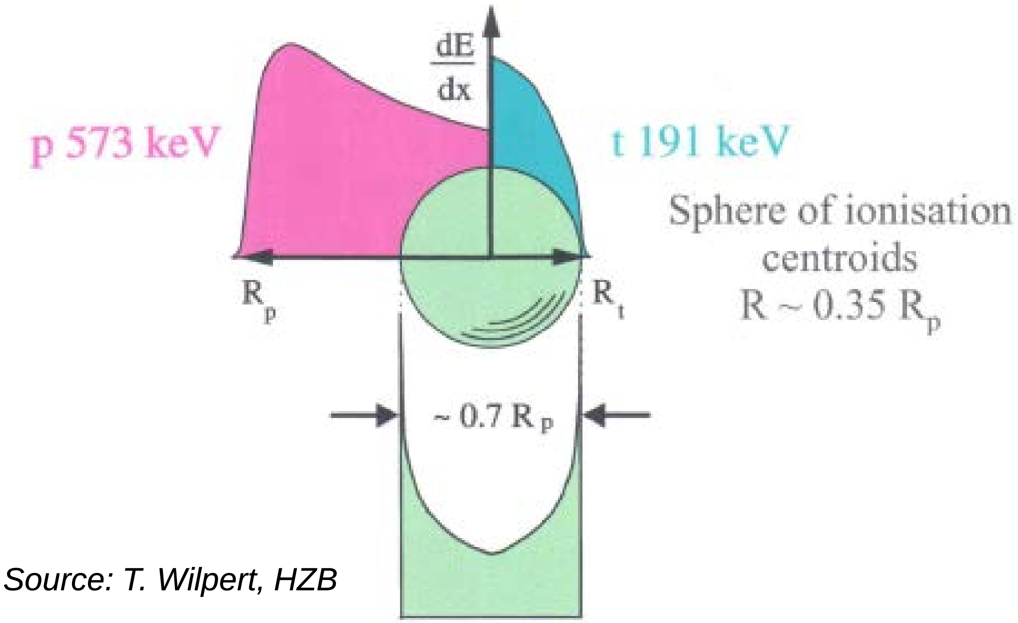
Source: I. Defendi

^{3}He: Position resolution

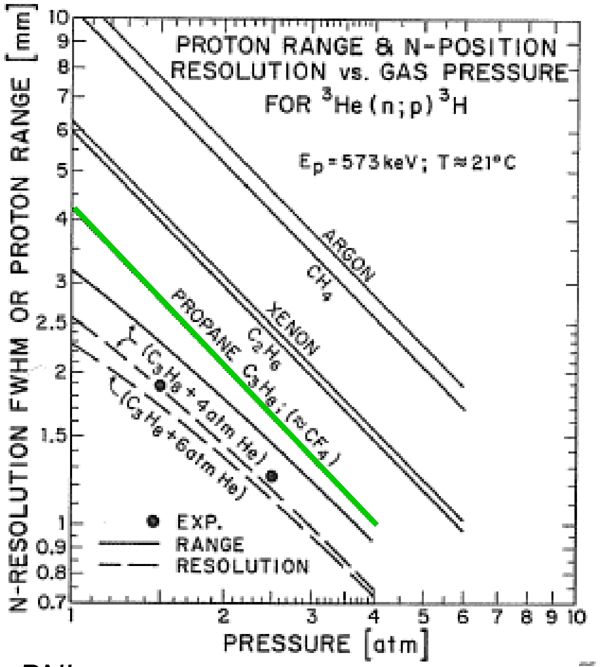
n + ^{3}He → ^{3}H (191keV) + p (573 keV)

- ^{3}H and p are emitted back-to-back due to momentum conservation
- Readout measures the centroid of charge along the ionization track
- Track orientation homogenously distributed in 4π

→ Measured position is dislocated from true interaction point by ~$0.35 \cdot R_p$



Source: T. Wilpert, HZB



Source: J. Fisher, BNL

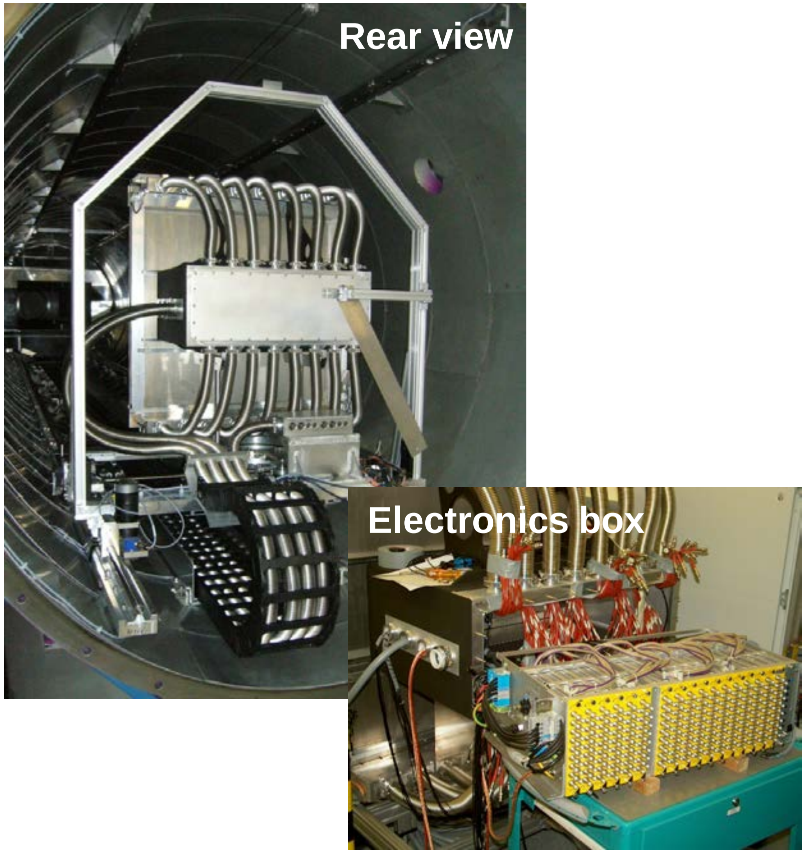
→ Resolution limited to ~$0.7 \cdot R_p$

$$\frac{1}{R_p} = \frac{p_{He}}{54mm} + \frac{p_{CF4}}{4.2mm}$$

^{3}He: Linear Position Sensitive Detector

Small Angle scattering detector

Active Area:	1000 mm × 1000 mm
Resolution:	$\Delta x = \Delta y \approx 8$mm
Global count rate:	≤ 2 MHz at 10% dead time
Local count rate:	~ 100 kHz / wire
Efficiency:	~ 60 % for $\lambda = 6$ Å



SANS1 @ FRM II

Array of 128 LPSDs in vacuum

1m long, Ø = 8mm, 15bar He

Developed for D22 at ILL, similar LPSD arrays are now in routine operation at any Neutron Scattering facility

^{3}He: Linear Position Sensitive Detector

LET chopper spectrometer @ ISIS

4m long 1” LPSDs

Source: N. Rhodes, ISIS

ARCS @ SNS

1m long 1” LPSDs

Source: R. Cooper, SNS

“Multitube” design (ILL)

Tube ends welded in common flange

All tubes share the same gas volume

Stainless steel resistive anode wire

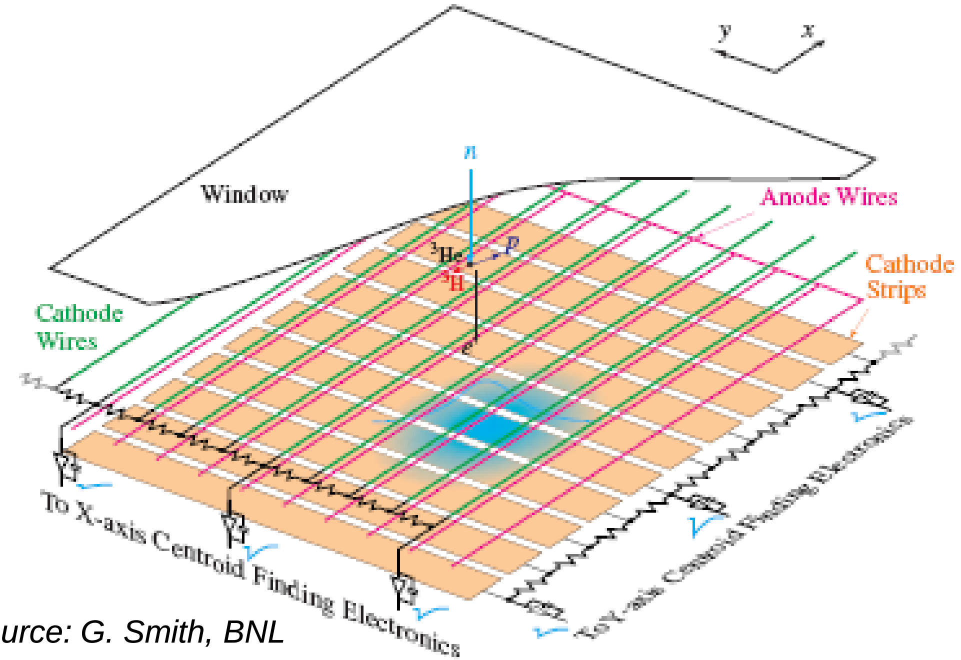
IN5 inelastic spectrometer @ ILL

3m long 1” LPSDs, 4,5bar He,

Source: B. Guerard, ILL

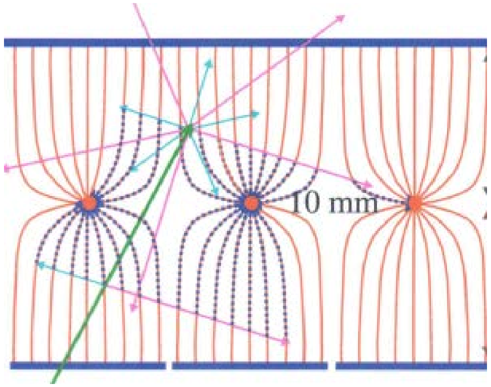
^{3}He: 2D-Position Sensitive Detector

Working principle of a Multiwire Proportional Counter (MWPC)



Source: G. Smith, BNL

anode wires:	8 -15µm
spacing s:	≥ 1 mm
gap h:	≥ 2 mm
gas:	$^3He+CF_4$, C_3H_8
gain:	100 -1000
Al-window:	8 mm
readout:	x,y - cathode



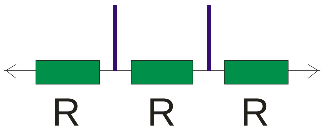
Electric field:

z << s: $E(x,z) \sim Q / (2\pi\varepsilon_o) \cdot 1/r$

z > s: $E(z) \sim Q / (2s\varepsilon_o)$

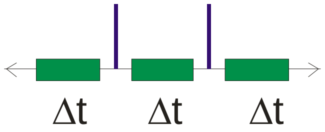
Cathode wire readout schemes:

Resistor line:



$$x = \frac{Q_L - Q_R}{Q_L + Q_R}$$

Delay line:



$$x = \frac{t_L - t_R}{t_L + t_R}$$

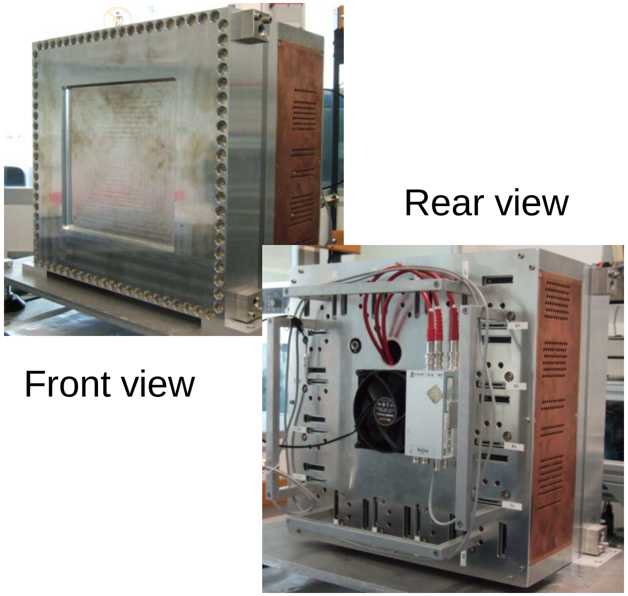
Individual wire:

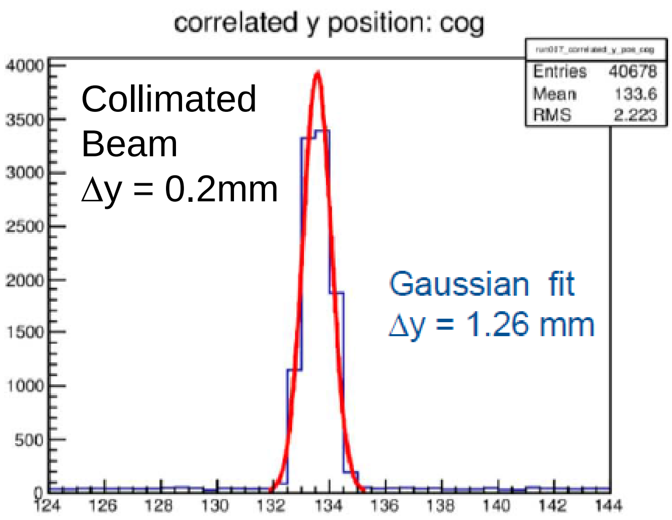
$$x = \frac{\sum_i Q_i \cdot x_i}{\sum_i Q_i}$$

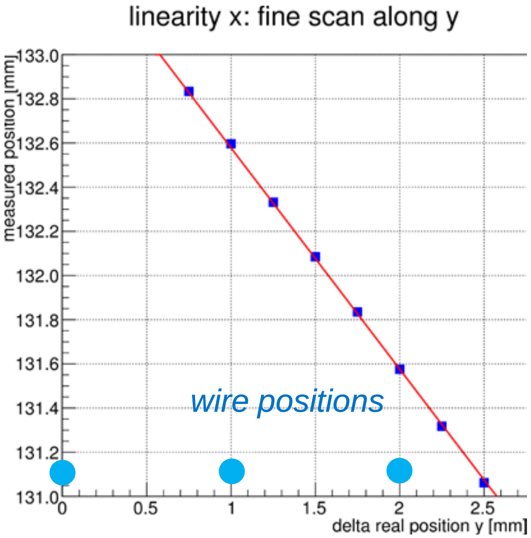
^{3}He: 2D-Position Sensitive Detector

MWPC with individual channel readout

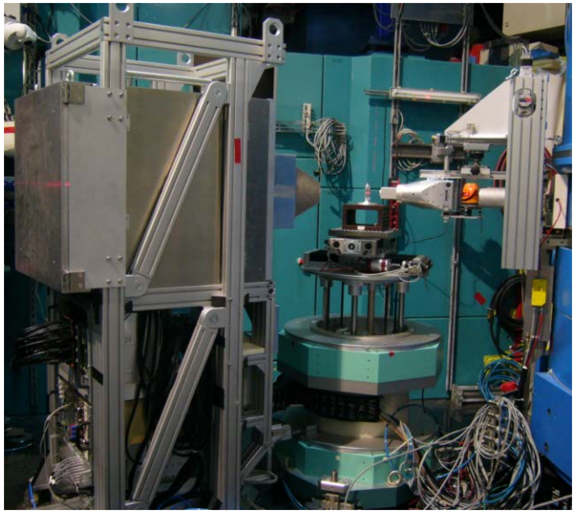
Active Area	250 mm x 250 mm
Efficiency @ 1.8 A	70 %
Position Resolution	Δx, Δy ≤ 1.3 mm (FWHM)
Count rate (global)	≥ 300 kHz (10% dead time)
Gas filling	4 bar ^{3}He + 2 bar CF_4
Anode / Cathode wire pitch	1 mm
Readout channels	256 x 256 cathode wires
List mode data	x, y, energy, time







Diffractometer STRESS-SPEC



$^{10}BF_3$: Proportional Counter

n + ^{10}B → ^{7}Li (0.84MeV) + α (1.47MeV) + γ (0.48MeV) (93%)

→ ^{7}Li (1.02MeV) + a (1.78MeV) (7%)

$^{10}BF_3$ works similar to ^{3}He in any Proportional Counter, LPSD, MWPC

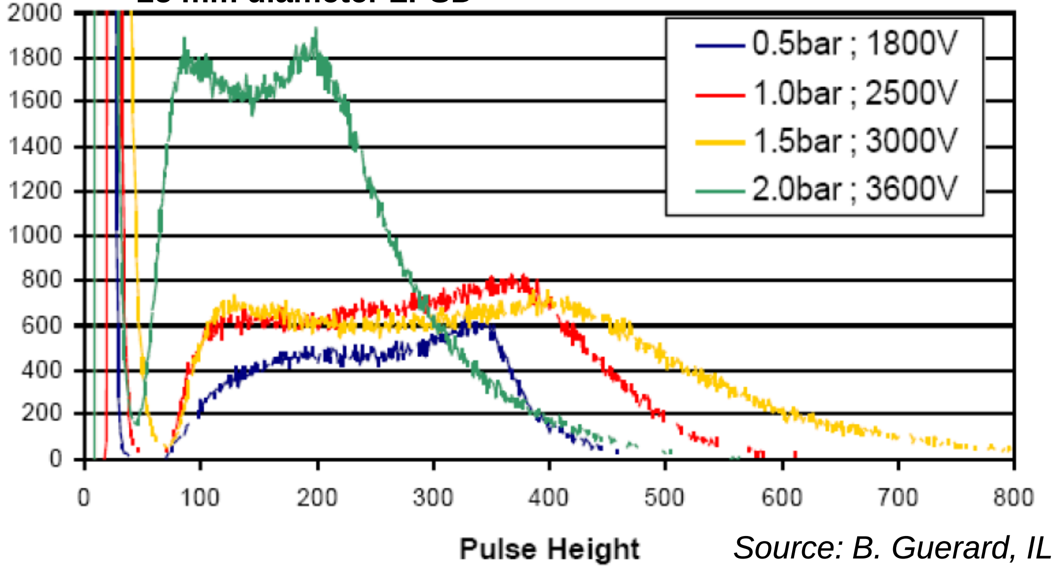
Energy deposit 2.3 MeV / neutron !

- excellent n / γ -separation (superior to ^{3}He)
- large detector signals; good position resolution (ΔL/L = 0.6%)
- Cross section = 72% of Helium
- 96% ^{10}B-enrichment available

Disadvantage

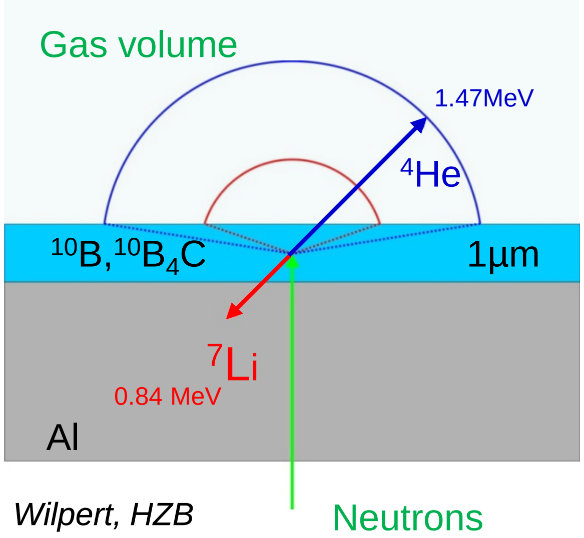
- corrosive and highly toxic
- efficiency limited by low pressure operation (p < 2 - 2.5 bar) due to attachment
- High operation voltage required

25 mm diameter LPSD



Source: B. Guerard, ILL

^{10}Boron: Proportional Counter



T. Wilpert, HZB

$$n + {}^{10}B \rightarrow {}^{7}Li\ (0.84MeV) + \alpha\ (1.47MeV) + \gamma\ (0.48MeV) \quad (93\%)$$

$$\rightarrow {}^{7}Li\ (1.02MeV) + a\ (1.78MeV) \quad (7\%)$$

Boron lined tubes or Multilayer devices

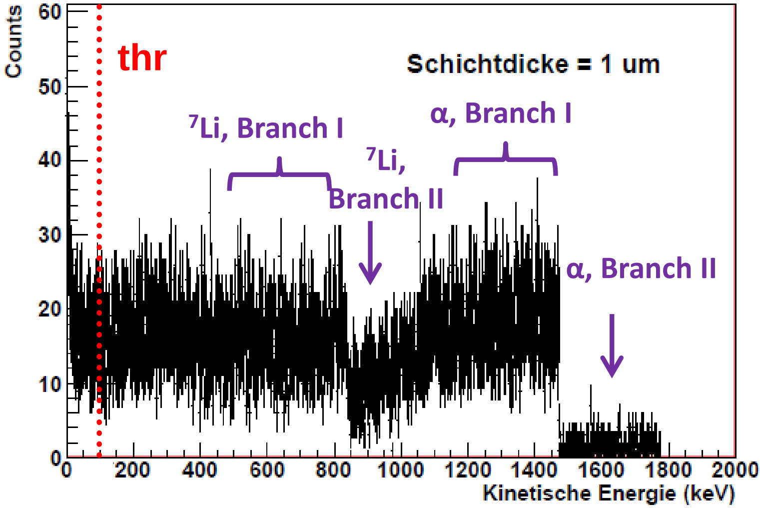
n-Absorption in ^{10}B: $\lambda_{abs} \sim 20$ µm for n_{therm}

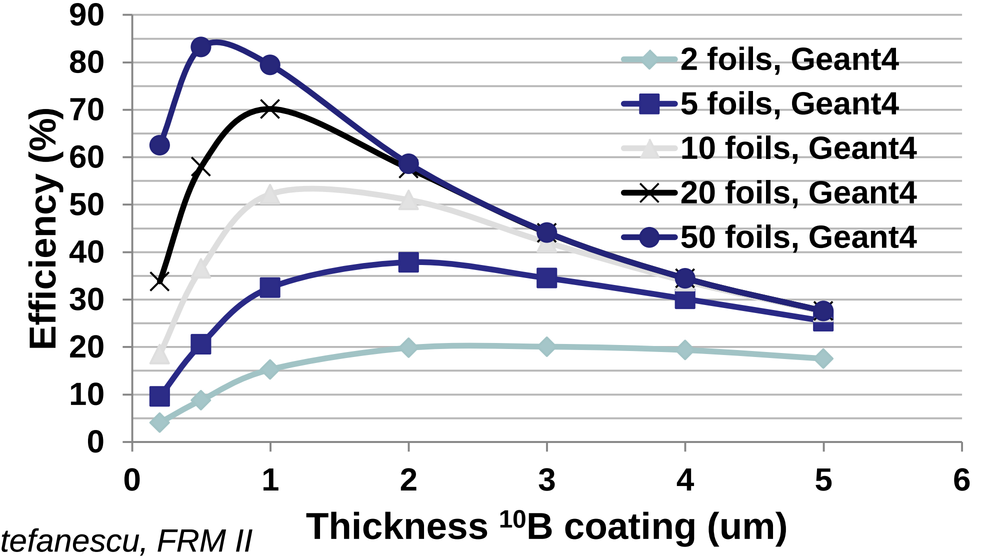
Range in ^{10}B: $\alpha = 3.14$ µm; Li = 1,53 µm

Single layer: $\varepsilon_{det} < 5\%$ for therm. Neutrons

➔ 20 -30 layers required for adequate efficiency !

Pulse height spectra simulated with GEANT4



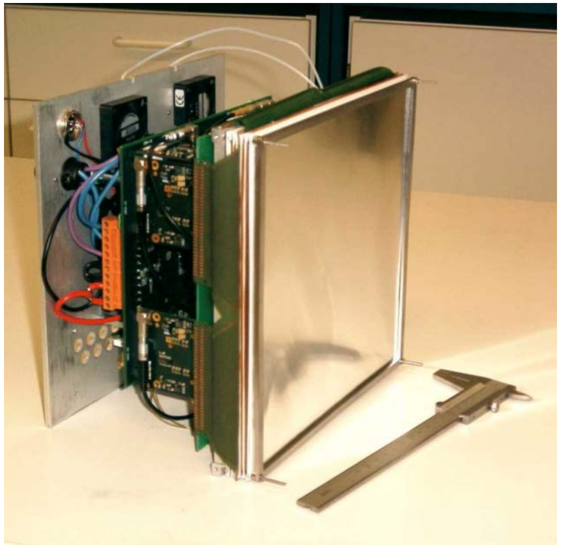


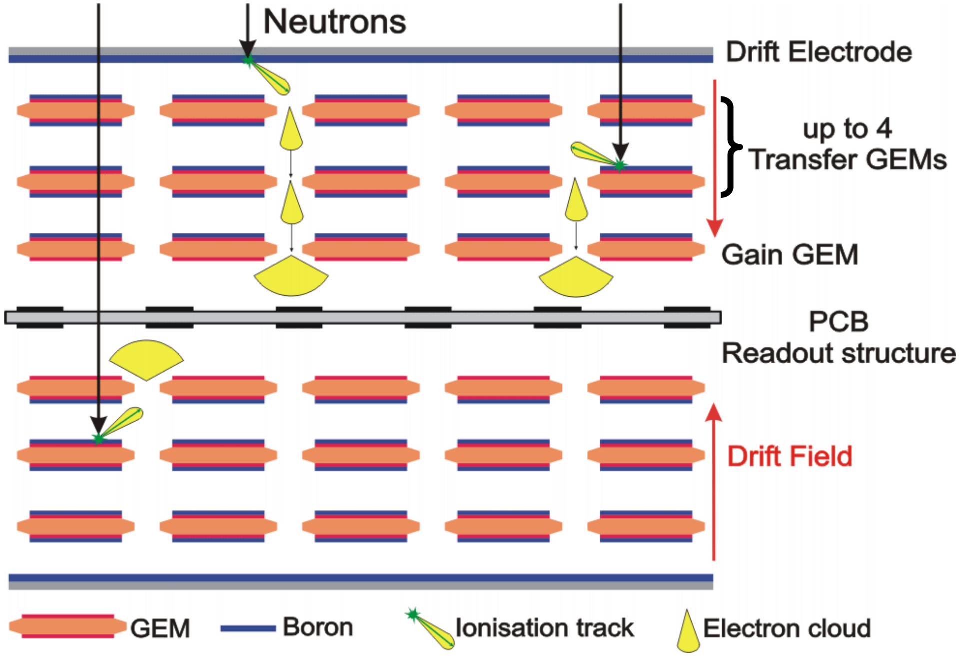
I. Stefanescu, FRM II

^{10}B: 2D-Position Sensitive Detector

“CASCADE”-Detector
developed at Univ. Heidelberg

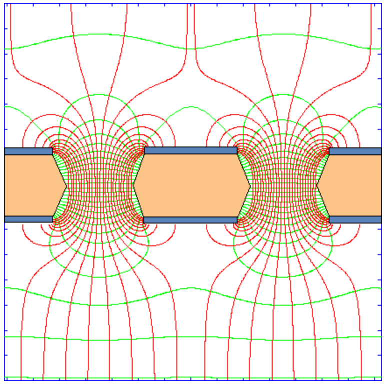
Stack of ^{10}B-coated GEM foils



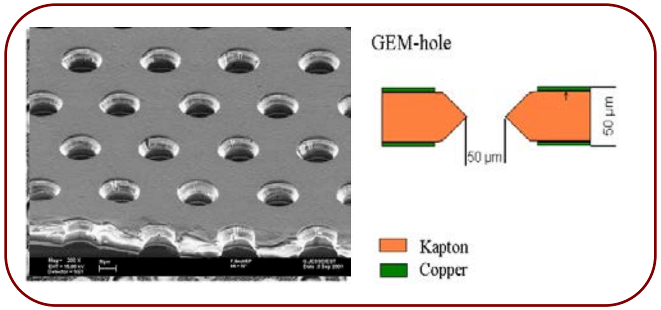


M. Klein, Univ. Heidelberg & CDT GmbH

Electric field



GEM-foil



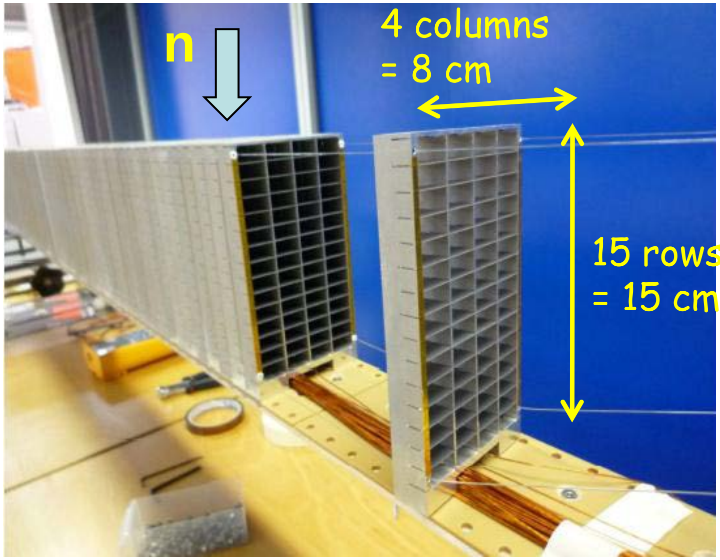
Sauli et al.: http://www.cern.ch/GDD

Performance:

Area: 20 x 20 cm^2
High local rate: > MHz
Fast timing: 100 ns
Resolution: 2.6 mm x 2.6 mm

MIEZE at RESEDA & MIRA

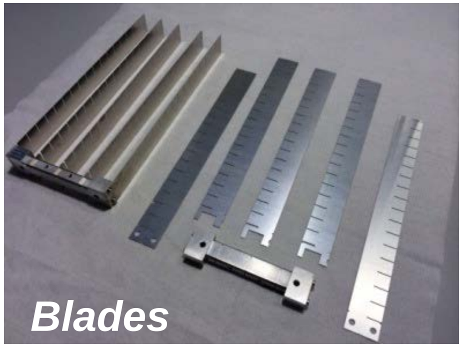
^{10}B: 2D-Position Sensitive Detector



10 x 20 mm^2 pixels

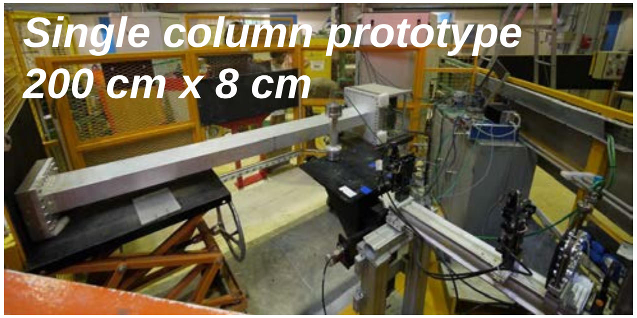
CRISP: The “MultiGrid” Concept for large area detectors

Linear array of cathode grids stacked with 0.5mm gap
Wires run through grids to form anodes
Grids consist of Al-blades sputtered with 1µm $^{10}B_4C$



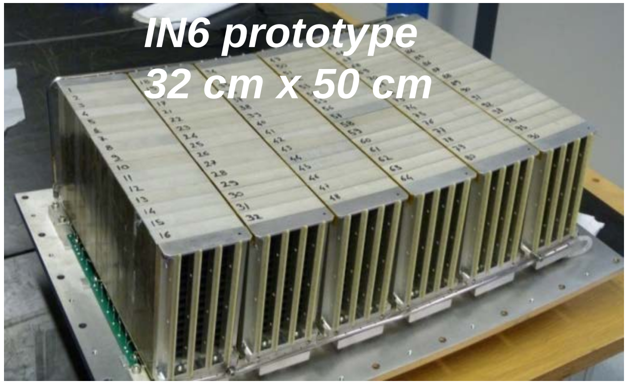
Blades

Sputter facility



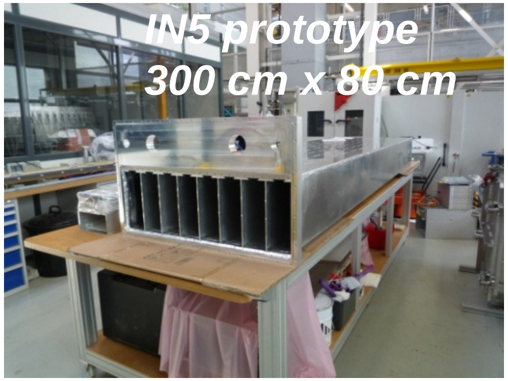
Single column prototype
200 cm x 8 cm

96 Grids / 60 wires



IN6 prototype
32 cm x 50 cm

96 grids / 360 wires



IN5 prototype
300 cm x 80 cm

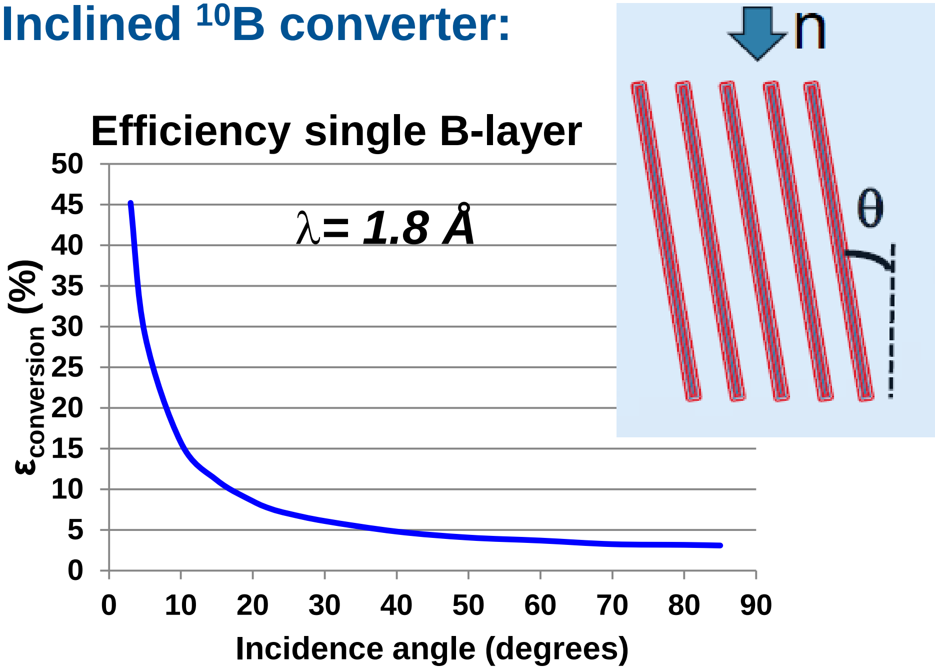
1024 grids / 512 wires

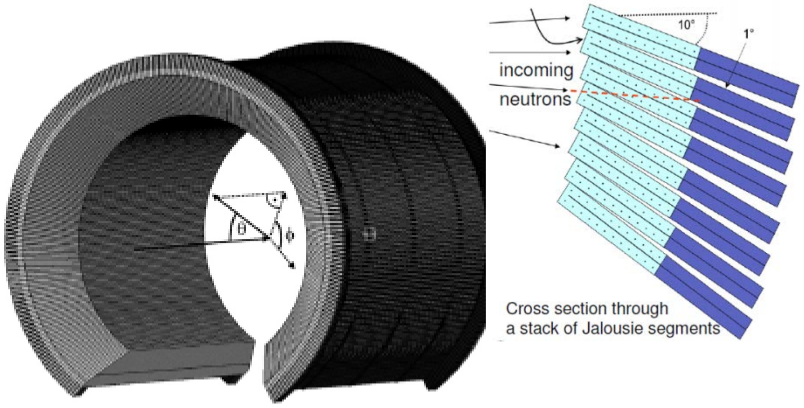
Detection efficiency ε ~ 47% for 2.5Å
Gamma sensitivity < 5×10^{-5} (1.2MeV)

Candidate for CSPEC @ ESS

^{10}Boron: Development projects

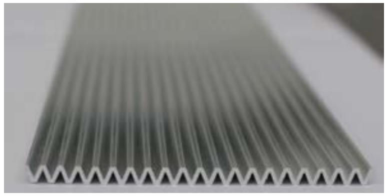
Inclined ^{10}B converter:

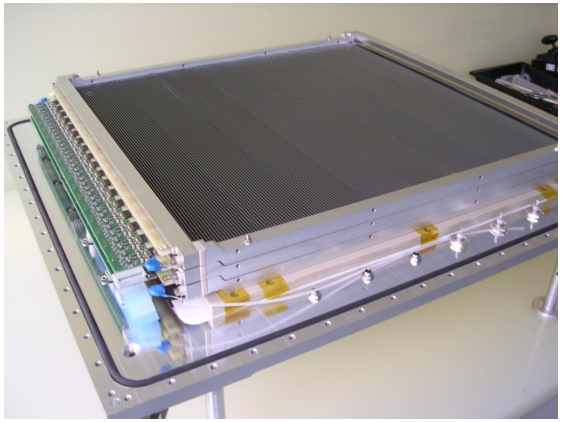




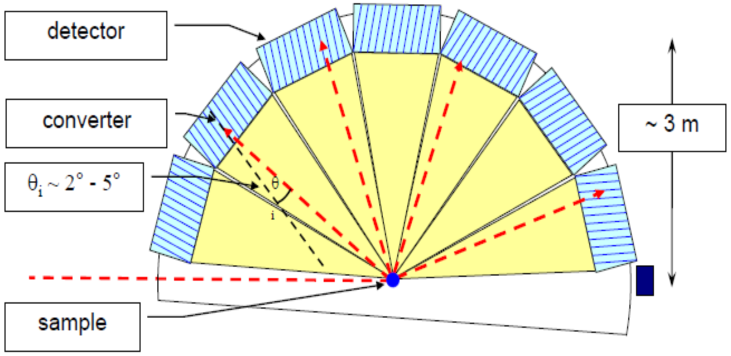
Jalousie Detector for POWTEX developed by CDT Heidelberg

Grooved converter





Multiple MWPC Stack developed by FRM II 40 cm x 40 cm



B-10 detector with inclined geometry, proposed by HZG for ESS

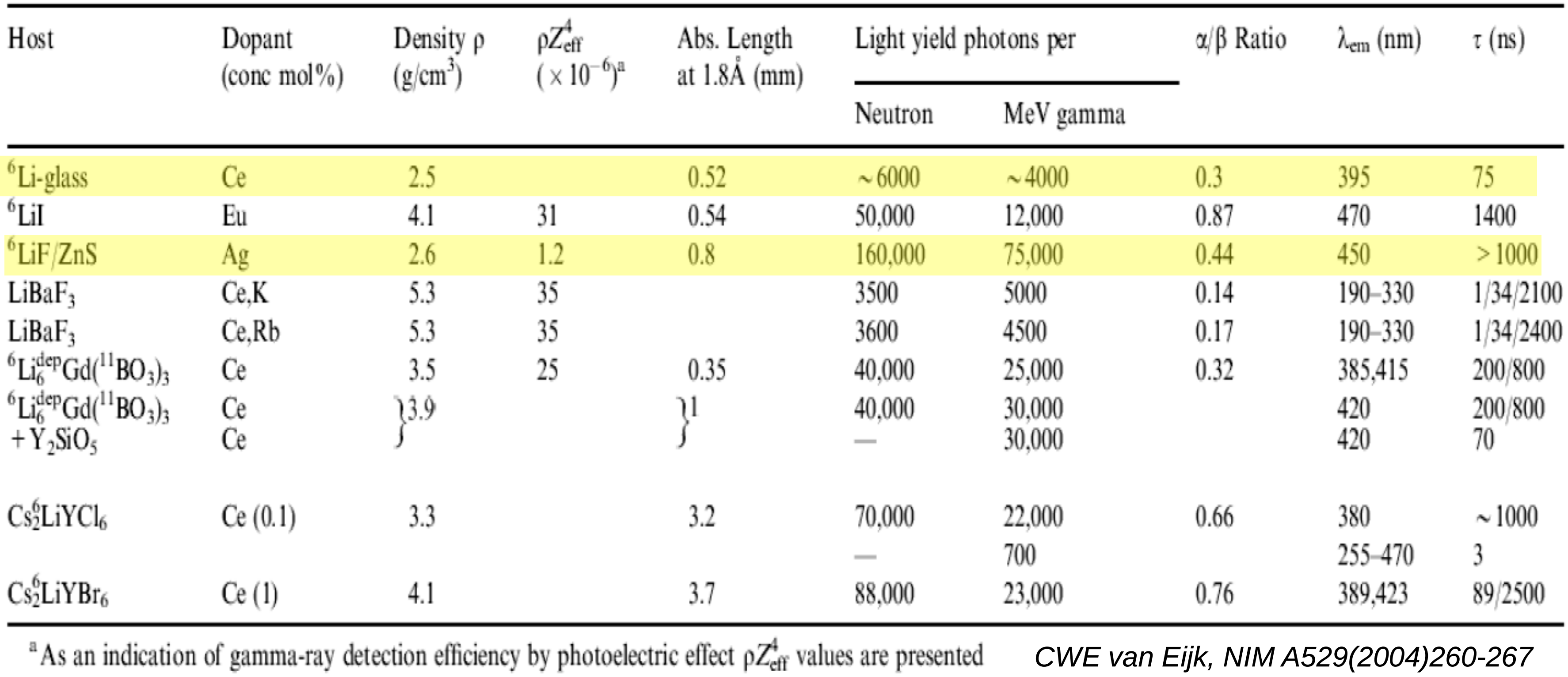
Scintillation Detectors

Ideally scintillators should provide:

- Strong neutron absorption, high light output
- Fast decay time, low quenching

Practically only inorganic scintillators combined with a Li or Boron neutron converter are used for neutron scattering applications

➔ ^{6}Li-glass(Ce), ^{6}LiF:ZnS(Ag) and $^{10}B_2O_3$:ZnS(Ag)



Host	Dopant (conc mol%)	Density ρ (g/cm³)	ρZ_{eff}^4 ($\times 10^{-6}$)[a]	Abs. Length at 1.8Å (mm)	Light yield photons per: Neutron	MeV gamma	α/β Ratio	λ_{em} (nm)	τ (ns)
^{6}Li-glass	Ce	2.5		0.52	~6000	~4000	0.3	395	75
^{6}LiI	Eu	4.1	31	0.54	50,000	12,000	0.87	470	1400
^{6}LiF/ZnS	Ag	2.6	1.2	0.8	160,000	75,000	0.44	450	>1000
$LiBaF_3$	Ce,K	5.3	35		3500	5000	0.14	190–330	1/34/2100
$LiBaF_3$	Ce,Rb	5.3	35		3600	4500	0.17	190–330	1/34/2400
$^6Li_6^{dep}Gd(^{11}BO_3)_3$	Ce	3.5	25	0.35	40,000	25,000	0.32	385,415	200/800
$^6Li_6^{dep}Gd(^{11}BO_3)_3$	Ce	3.9		1	40,000	30,000		420	200/800
$+Y_2SiO_5$	Ce				—	30,000		420	70
$Cs_2^6LiYCl_6$	Ce (0.1)	3.3		3.2	70,000	22,000	0.66	380	~1000
					—	700		255–470	3
$Cs_2^6LiYBr_6$	Ce (1)	4.1		3.7	88,000	23,000	0.76	389,423	89/2500

[a] As an indication of gamma-ray detection efficiency by photoelectric effect ρZ_{eff}^4 values are presented

CWE van Eijk, NIM A529(2004)260-267

^{6}Li-glass(Ce^{3+})

n + ^{6}Li → ^{3}H (2.73 MeV) + ^{4}He (2.06 MeV)

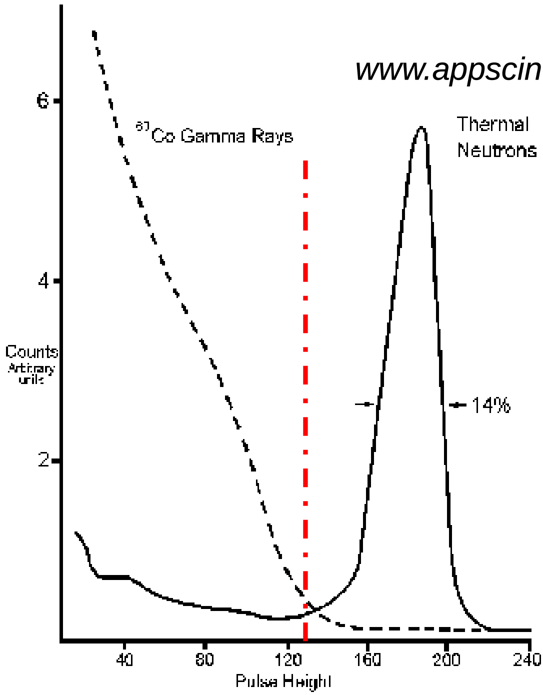
GS20 ^{6}Li-glass scintillator

- 6.6 weight% Li, 95% ^{6}Li-enriched
- transparent
- efficiency $\varepsilon_{therm} \approx 75\%$ for 1mm glass
- decay time τ = 75 ns → high count rates

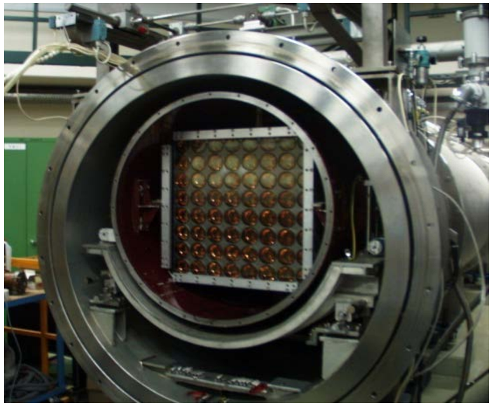
Anger Camera

Thin GS20 glass plate read out by an array of photomultiplier tubes

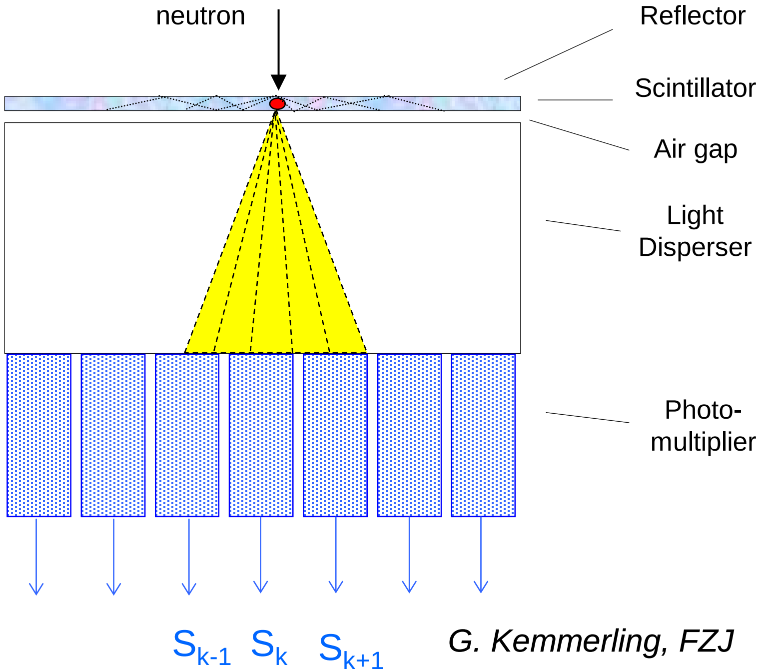
- Disperse light cone on PMT array
- Derive impact position from light intensity of individual PMTs by Center-of-gravity, max. likelihood..



www.appscintech.com

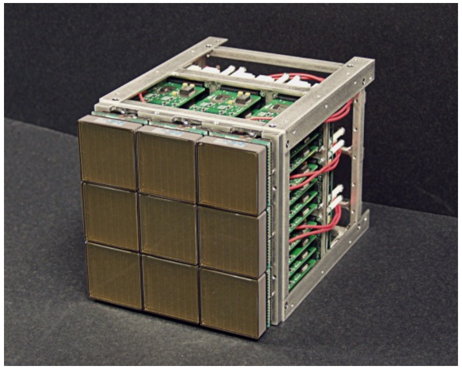


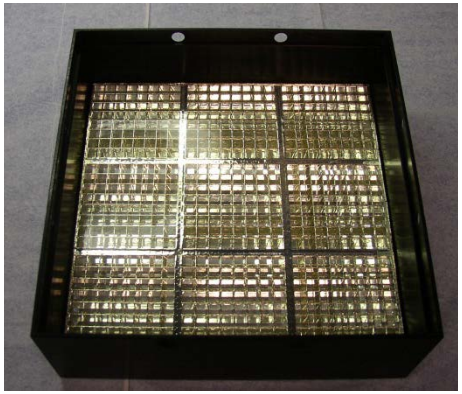
KWS2 @ FRM II



G. Kemmerling, FZJ

^{6}Li-glass(Ce^{3+}) Anger Camera





Source: R. Cooper, SNS

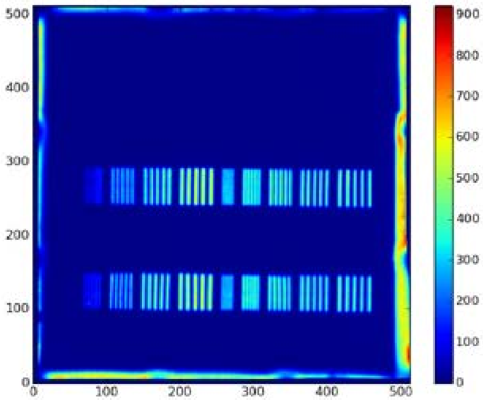
Anger Camera @ SNS

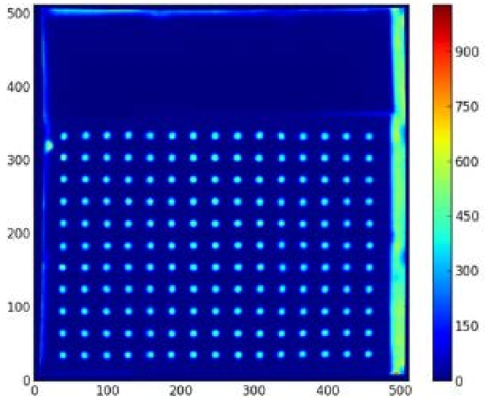
Module:

- Active area: 15cm x 15cm
- Scintillator: 2 mm GS20 Li glass
- 9 MaPMT: H8500, 64 pixel
- Pixels gain compensated
- Modules tillable

Resolution about 1.0mm (FWHM)
Distortion < 0.5mm

Single crystal diffractometer TOPAZ @ SNS



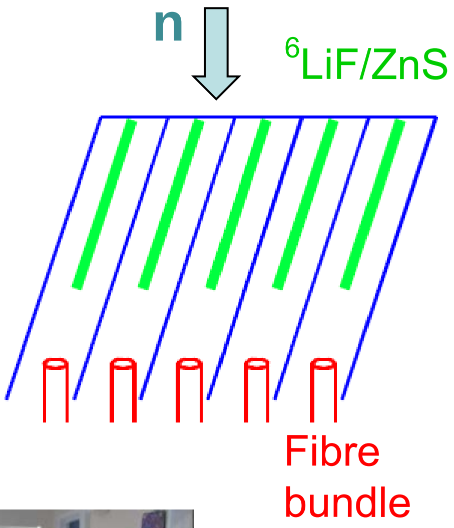


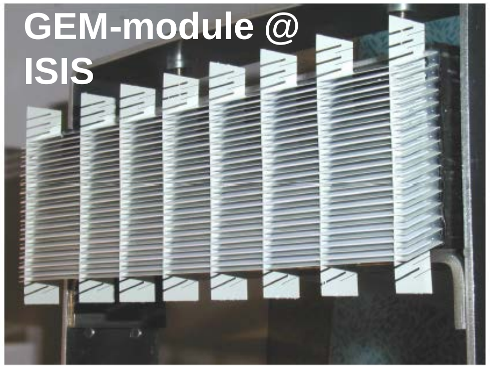
23 Anger Cameras installed at SCD TOPAZ

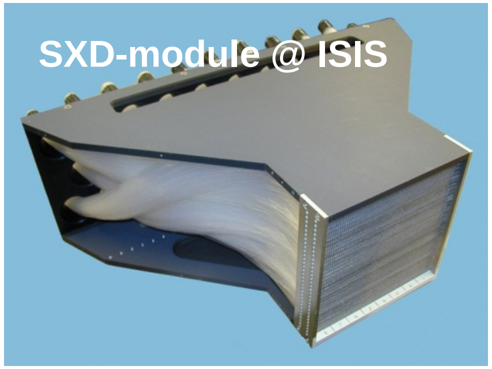
^{6}LiF/ZnS with clear fibre readout

Principle:

- The incident neutron is captured in the 0.3mm thick ^{6}LiF/ZnS:Ag scintillator
- Some blue scintillation light from ZnS is collected by a bundle of clear fibres
- Fibres from a pixel are coded to different PMTs in coincidence to determine the position





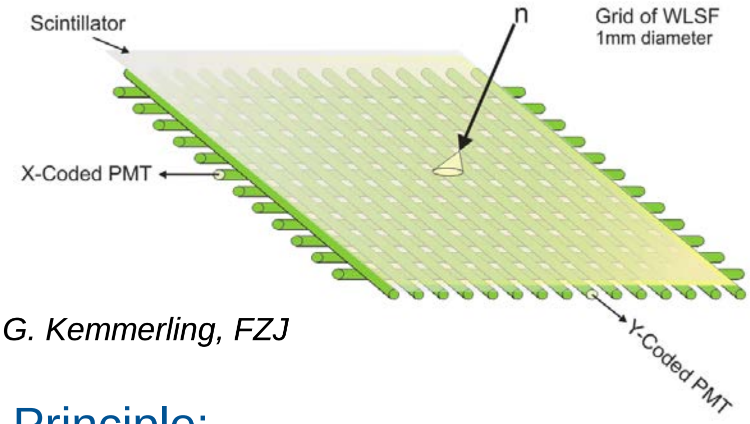


POLARIS Upgrade – 38 modules in vacuum
2954 detector elements; 924 PMTs; 460 Km fibre optic

Performance:

Efficiency:	~ 20% at 1 Å
γ-sensitivity:	~ 10^{-6} -10^{-7}
Speed:	200ns primary, 80µs afterglow
Background:	0.5 cm^{-2} hr^{-1}

^{6}LiF/ZnS with WLS-fibre readout



G. Kemmerling, FZJ

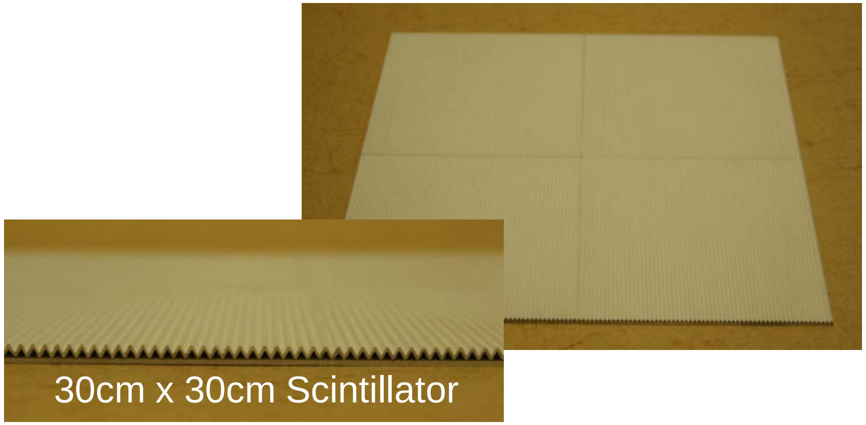
Principle:

- The incident neutron is captured in the 0.5mm thick ^{6}LiF/ZnS:Ag scintillator
- Some blue scintillation light from ZnS is shifted to green and trapped in the WLS-fibre (Ø=0.5mm)
- This light is detected by PMTs in coincidence to determine the position

Drawbacks:

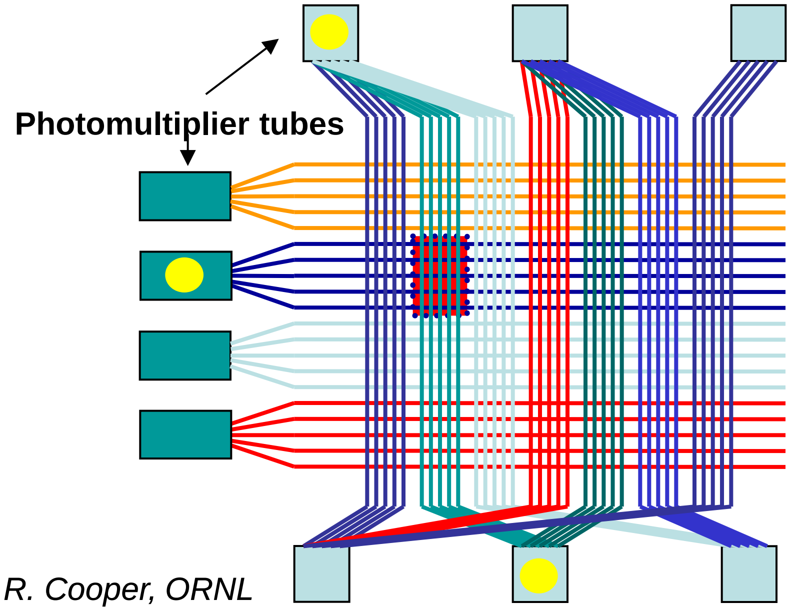
- Opaqueness limits efficiency
- Low light output of WLS-fibres
- "Ghosting" due to "afterglow"

^{6}LiF/ZnS



30cm x 30cm Scintillator

Coding of WLS-fibre ends to PMTs



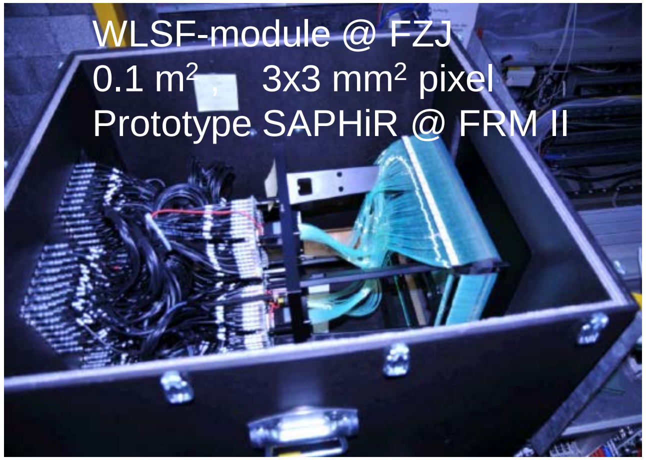
R. Cooper, ORNL

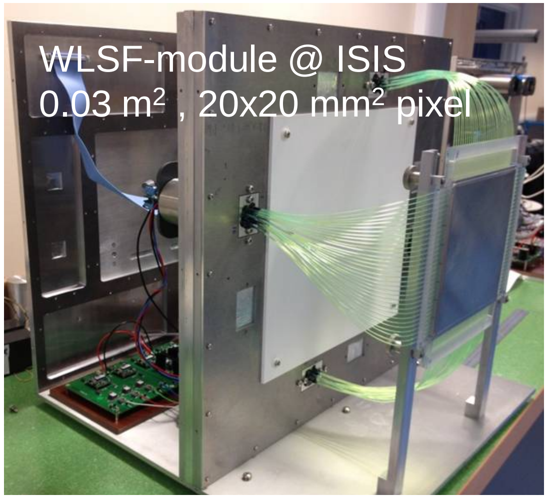
LiF & B_2O_3 / ZnS with WLS-fibre readout

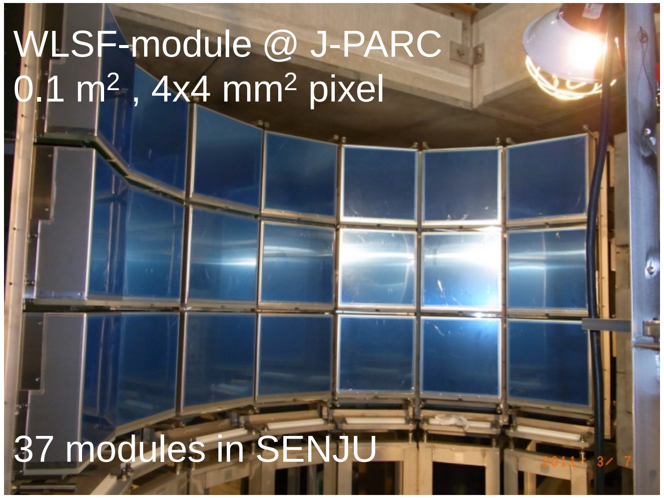
Large detectors in use at SNS & J-PARC, prototypes at ISIS and FZJ

- *Detection efficiency typically $\varepsilon \approx 40\%$ for 1.8Å,*
  in "sandwich" configuration $\varepsilon \approx 40\%$ for 1.0Å achieved with ISIS-prototype
- *Pixel size Δx~4mm – 20mm*
- *Gamma sensitivity ~10^{-6} (1.2MeV)*
- *Development of new B_2O_3 scintillator at J-PARC*
- *Appropriate Coding reduces "ghosting" to 0.1%*
- *Local count rate still limited: R< 20kHz*
- *Single pixel readout with MaPMT - electronics*


WLSF-module @ SNS
0.3 m^2 , 5x50 mm^2 pixel
30 modules installed
@ VULCAN and POWGEN


WLSF-module @ FZJ
0.1 m^2 , 3x3 mm^2 pixel
Prototype SAPHiR @ FRM II


WLSF-module @ ISIS
0.03 m^2 , 20x20 mm^2 pixel


WLSF-module @ J-PARC
0.1 m^2 , 4x4 mm^2 pixel
37 modules in SENJU

Conclusion

There is a broad variety of technologies used for slow neutron detection.

All devices consist of a combination of a neutron converter (^{3}Helium, ^{10}Boron, ^{6}Lithium) with a charged particle detector

All technologies allow to build detectors that cover all ranges of position resolution, efficiency, rate capability, n/γ-separation capability required for neutron scattering application.

There is no “best” technology or detector

In practice, it’s not all about efficiency, rate capability etc. Stability, robustness, homogeneity are important, too.