Neutron Detection Alternatives to ^{3}He: ^{10}B

Thomas Wilpert

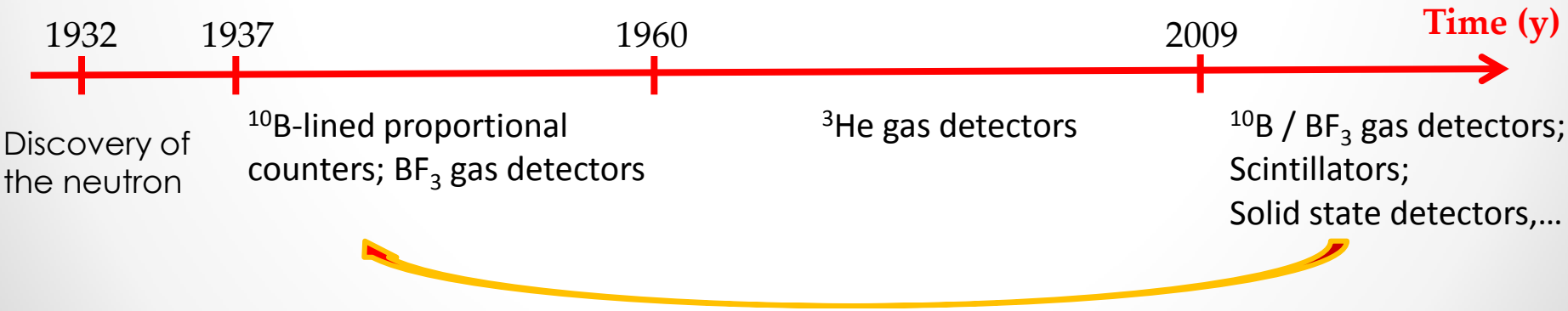
Helmholtz-Zentrum Berlin

^{10}B - Detectors

- Motivation
- ^{10}B - basics
- PVD coating - basics
- Detector concepts
  - Cascade detector
  - Flat inclined detectors
    - Multi-blade detector (ILL)
    - Multi-grid detector (ILL, ESS)
    - Inclined geometry (HZG)
    - Jalousie detector (NDT)
  - Macrostructured detectors
  - Straw tubes
- Conclusion

^{3}He Shortage

- He-3 shortage noticed by US government officials in 2009;
- prompted the search of replacement technologies;
- new technologies need years of R&D;
- switching to detectors based on ^{10}B solid converters and BF_3 gas is given great consideration;
- alternative solid converters: ^{6}Li, ^{155,157}Gd;
- alternative technologies: ^{6}Li-loaded scintillating glass-fiber, plastic scintillator fibers, solid state detectors (small area neutron detectors).

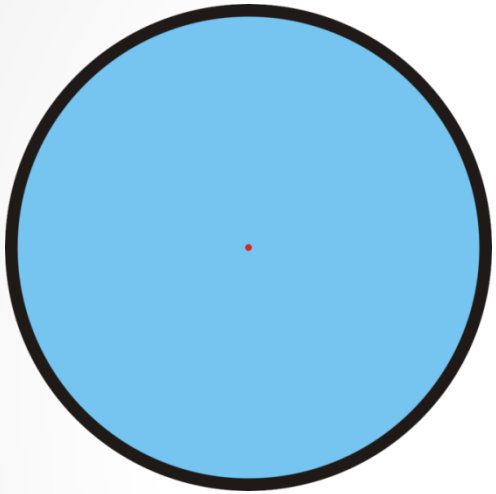


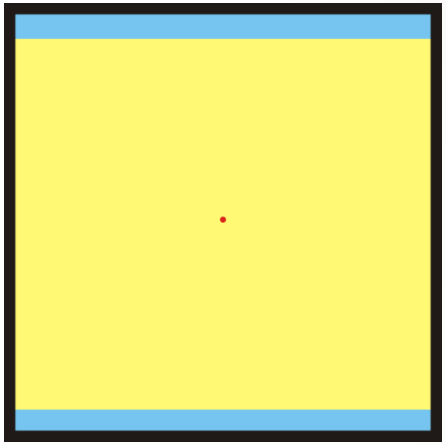
courtesy of I. Stefanescu/FRM-II

Overview Neutron Converter

Isotope Abundance	State	Reaction	Cross Section [b]	Abs. Length	Ejectile Energies [keV]	Ejectile Atten. Length/ Range
^{3}He 0.00014%	gaseous	^{3}He(n,p)t	5,333	7.59 bar·cm	p: 573 t: 191	R_p 0.43 bar·cm (CF_4)
^{6}Li 7.5%	solid	^{6}Li(n,a)t	940	230 µm	t: 2727 a: 2055	R_t = 130 µm
^{10}B 19.9%	solid	^{10}B(n,α)^{7}Li	3,836	19.9 µm	α:1472 ^{7}Li: 840	R_α = 3.14 µm
$^{10}BF_3$ 19.9%	gaseous	^{10}B(n,a)^{7}Li	3,836	9.82 bar cm	a:1472 ^{7}Li: 840	R_a = 0.42 bar·cm
^{nat}Gd	solid	^{nat}Gd(n,g)	49,122	6.72 µm	ce: 29-181 keV (86.5%)	l_{ce} = 12.3 µm
^{157}Gd 15.7%	solid	^{157}Gd(n,g)^{158}Gd	255,000	1.3 µm	ce: 29-181 keV (87.3%)	l_{ce} = 11.6 µm

Neutron Converter - Gas vs Solid

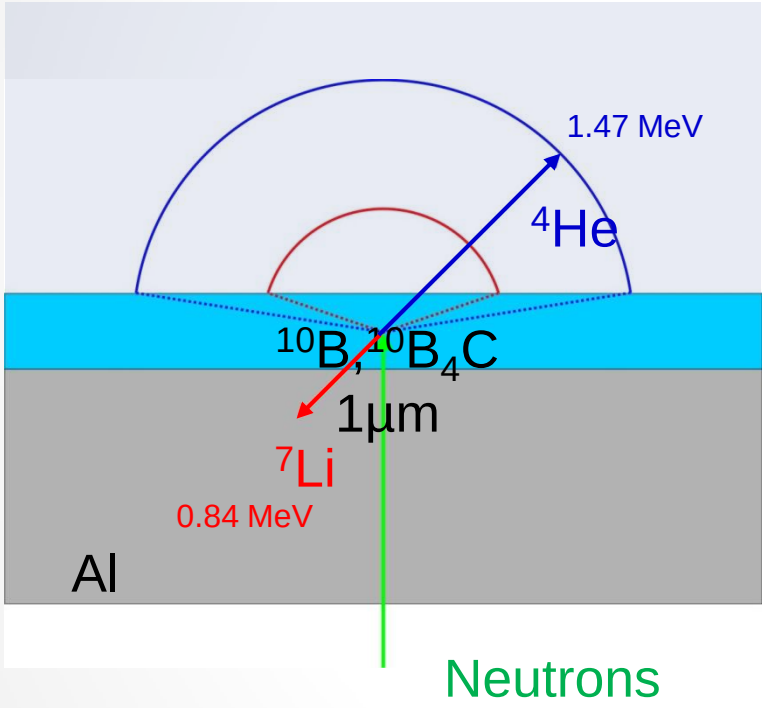


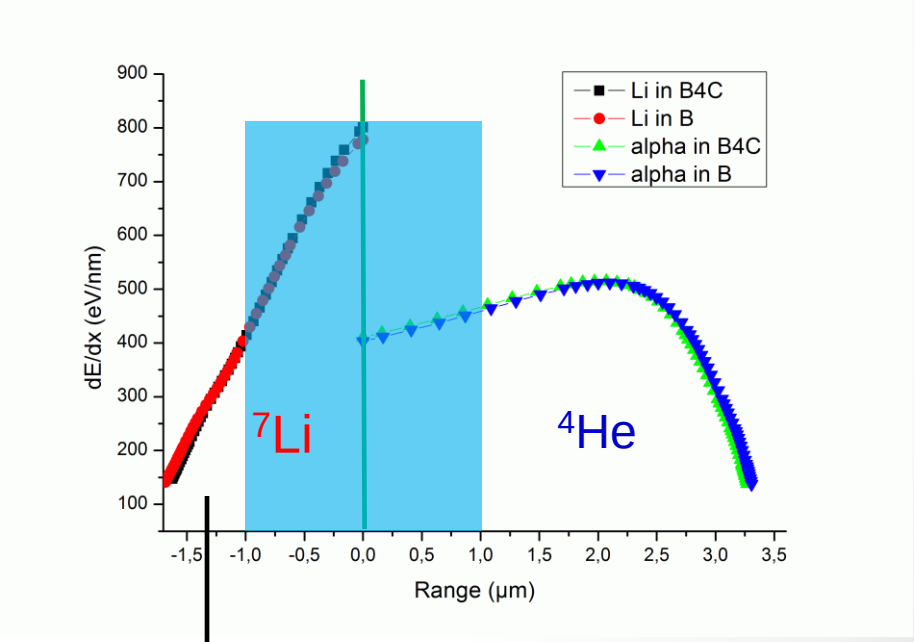


Converter:	^{3}He	Converter:	^{10}B
Counting gas	$^{3}He + CO_2$ (CF_4)	Counting gas	Ar/CO_2 (90/10)
Pressure:	2-15 bar	Pressure:	≤ 1 bar

Gas amplification not discussed in this talk

Neutron Conversion in ^{10}B Layer

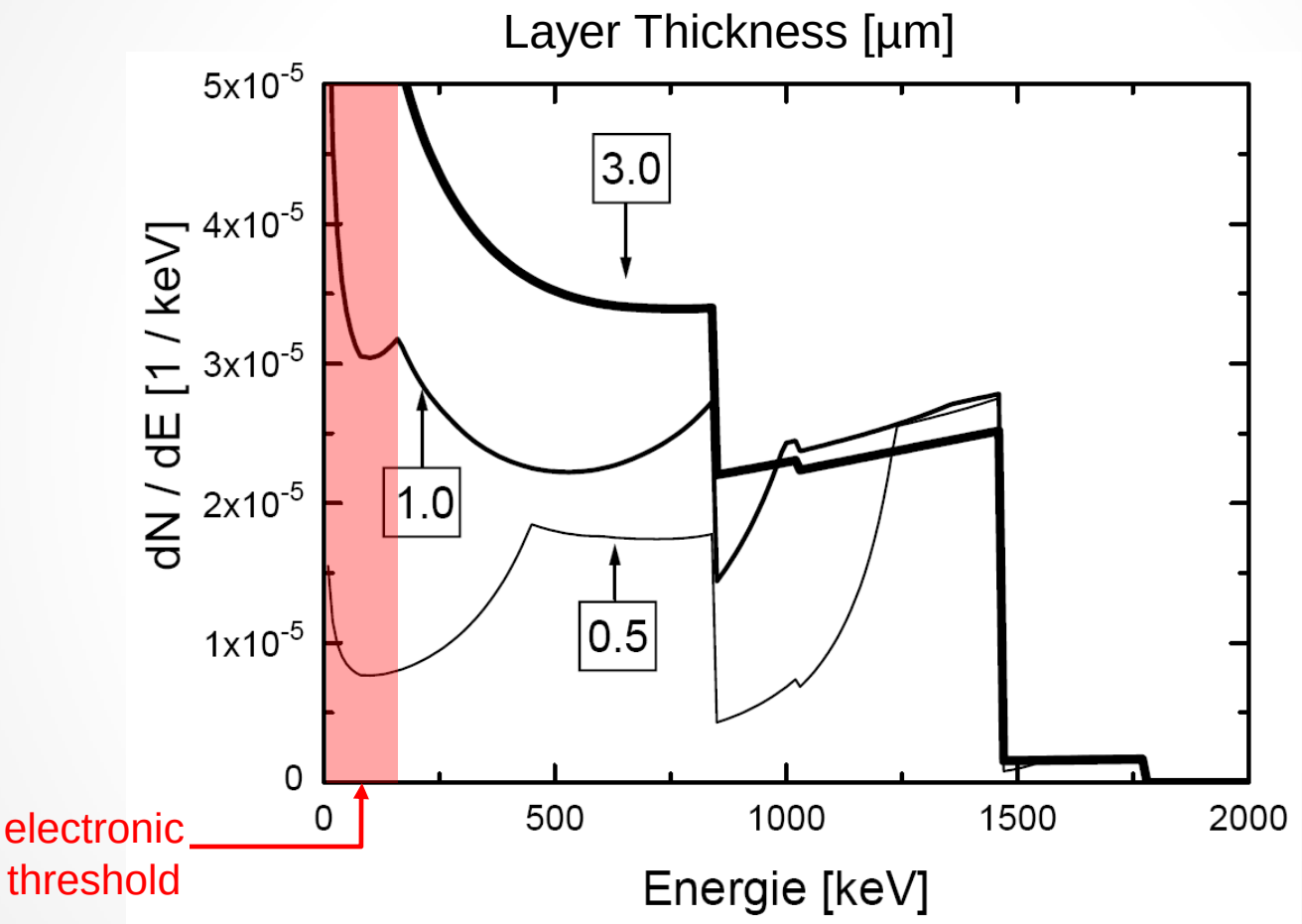




little energy left

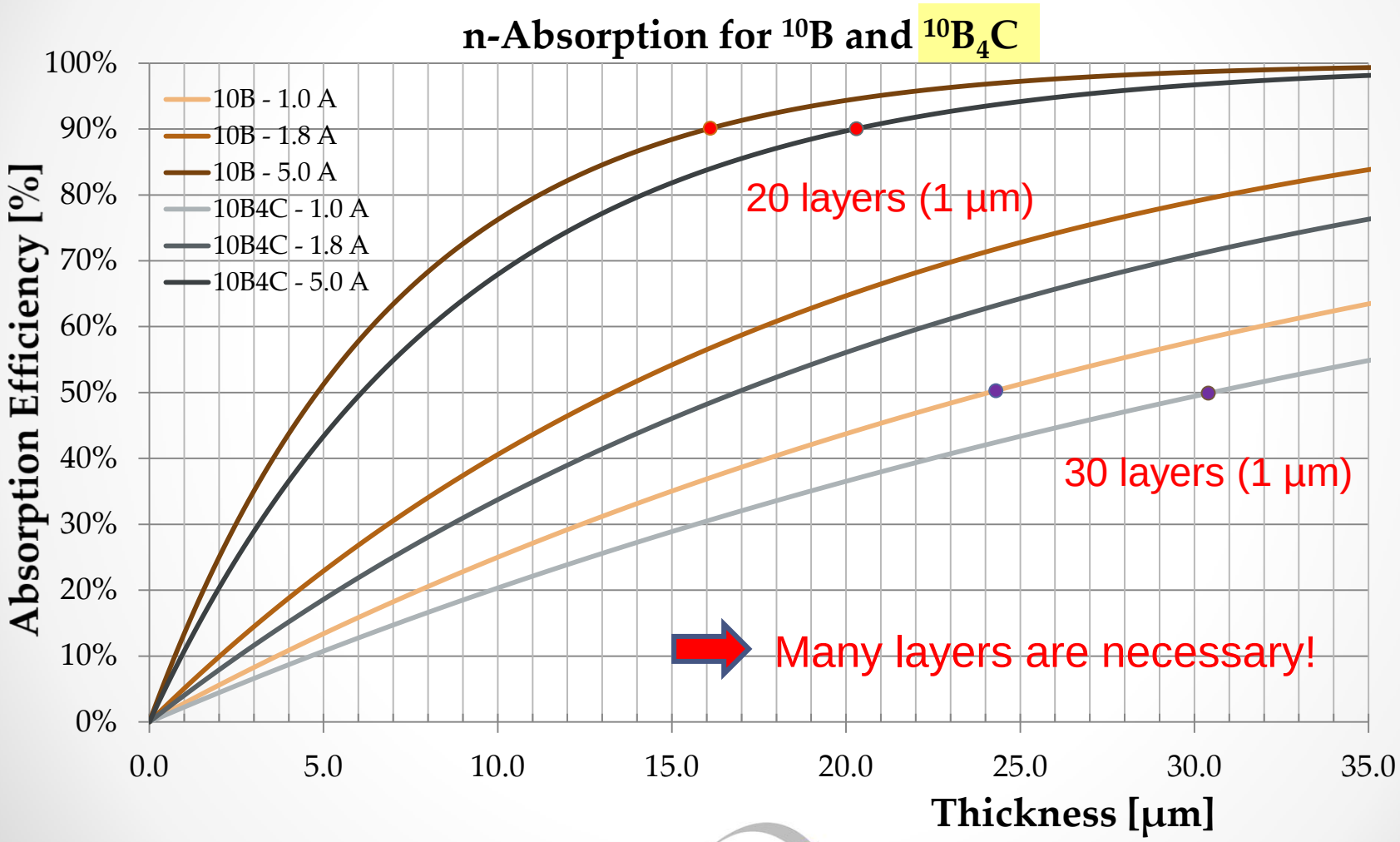
Energy loss calculated with SRIM (www.srim.org)

^{10}B Layer- Energy Spectrum



source PHD of M. Klein, Uni Heidelberg, 2000

^{10}B Layer- Absorption Efficiency



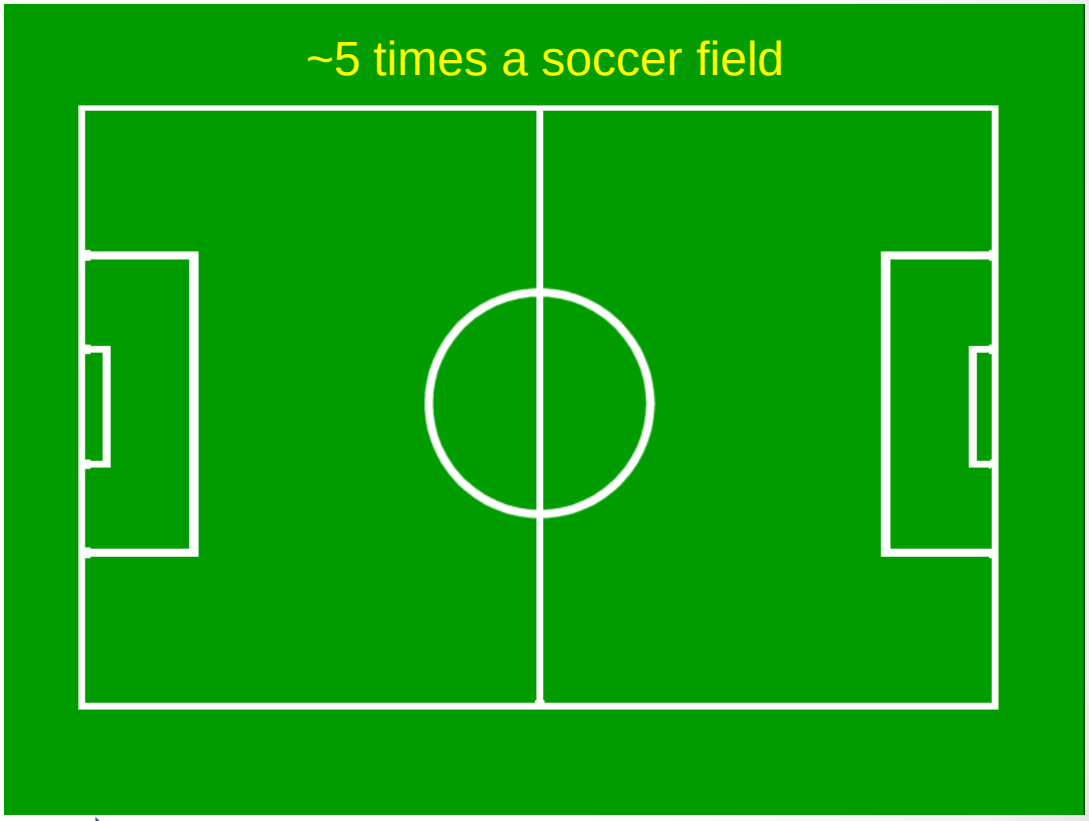
^{10}B Layer - Requirements

ICND*): world wide demand (until 2015):

34 x 34 m² = 1156 m² ^{3}He

Replacement by ^{10}B:

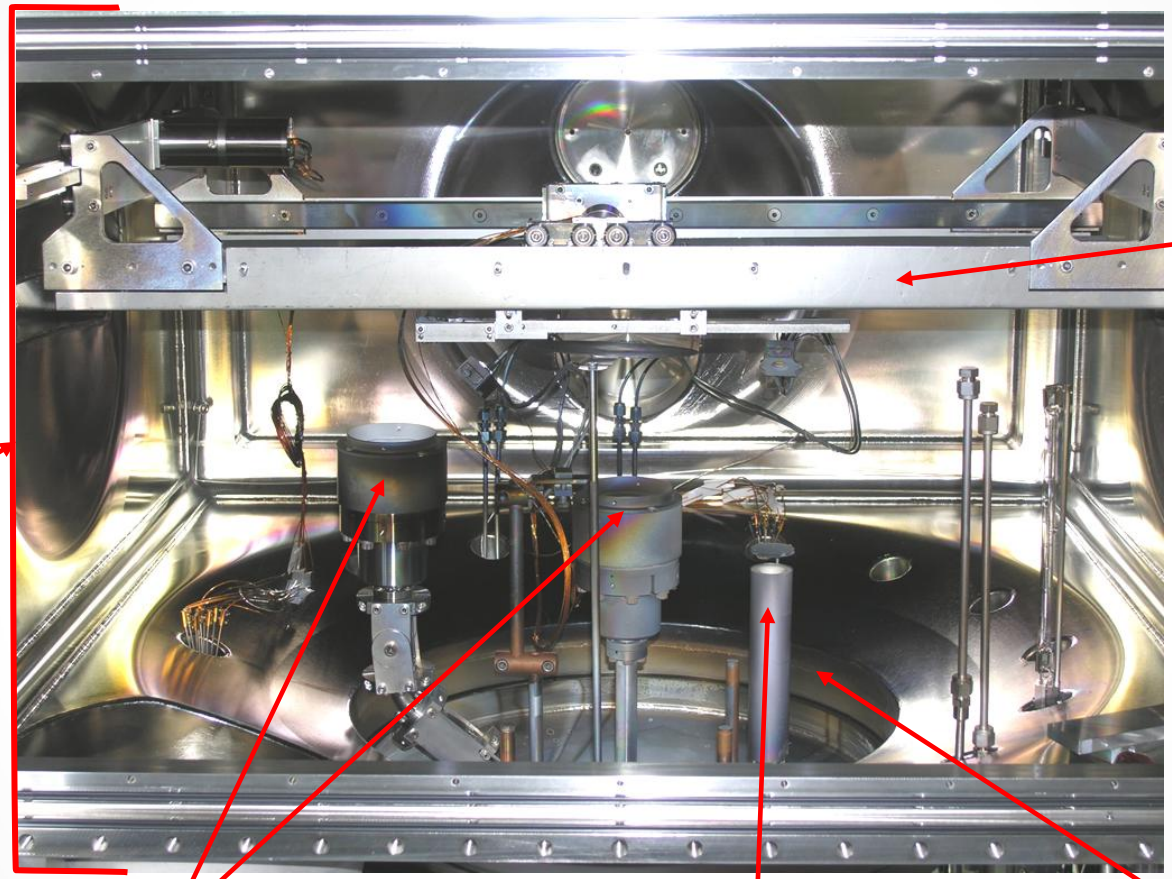
30 x 1156 m² = 34.680 m²



Industrial process necessary!

*) ICND = International Collaboration For the Development of Neutron Detector, www.icnd.org

Coating of ^{10}B, $^{10}B_4C$



Substrate holder

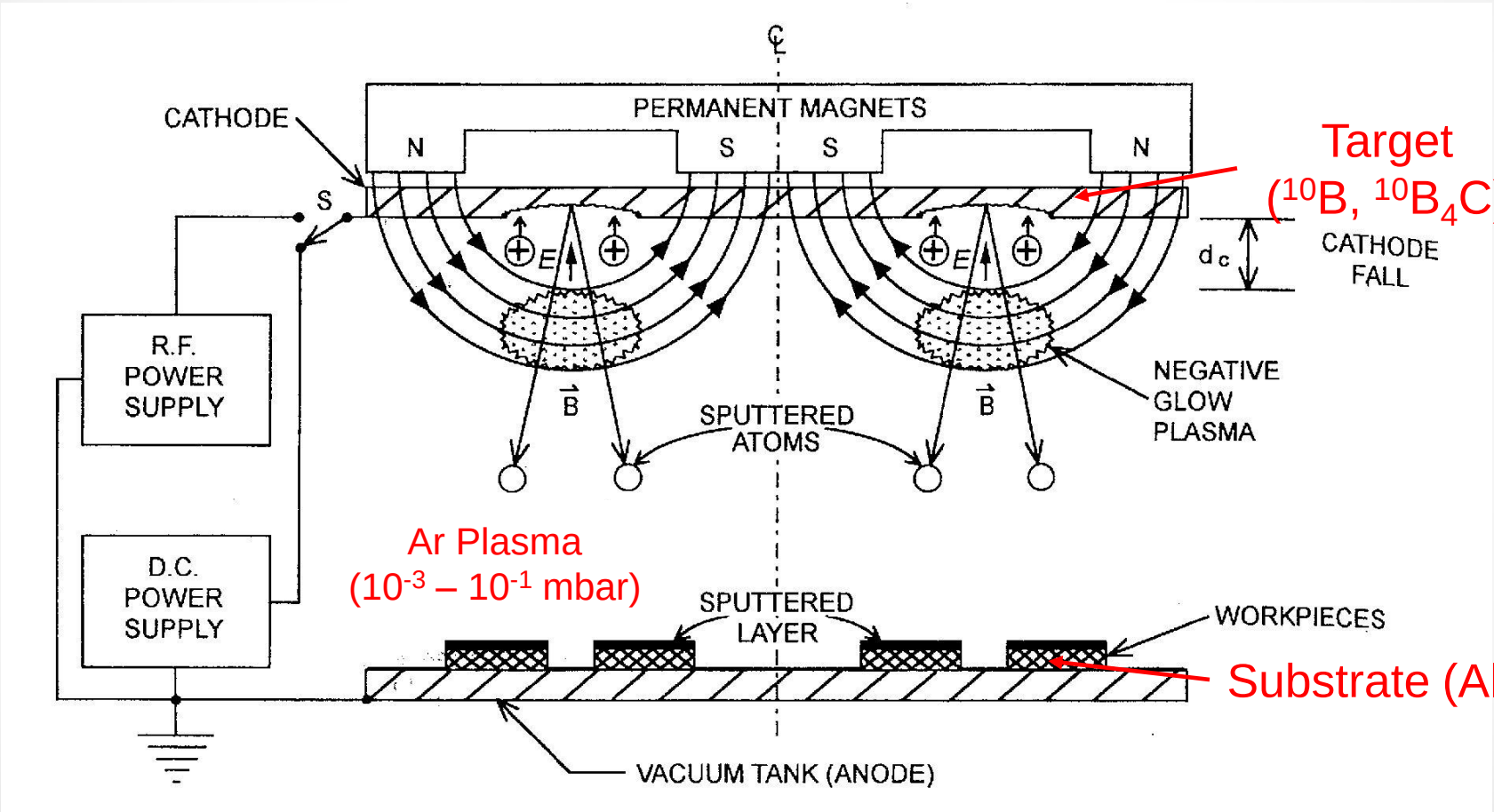
Vacuum chamber

Magnetron sputter sources

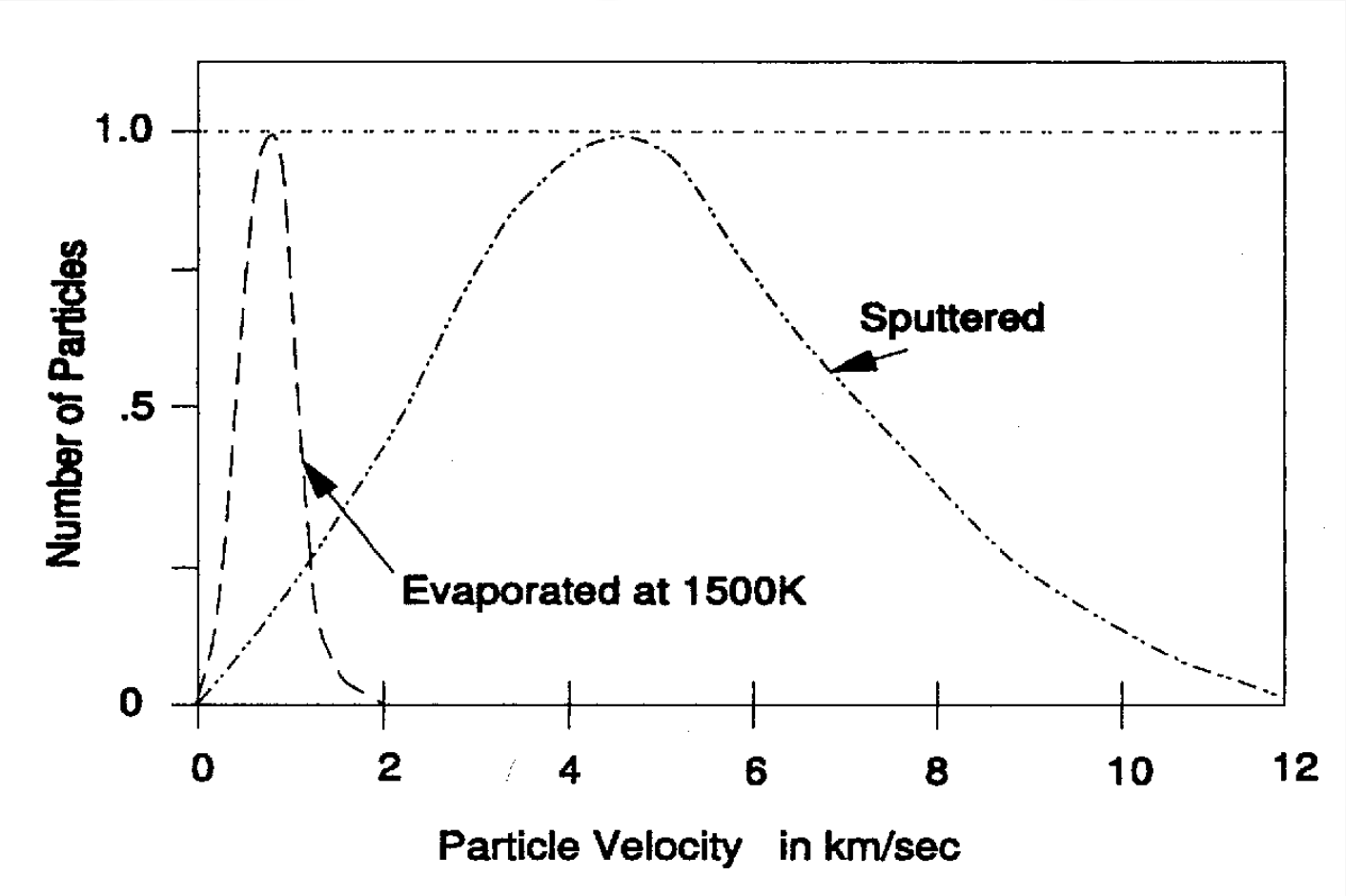
Effusion cell

e-beam evaporator (not built in)

How Does Magnetron Sputtering Work?

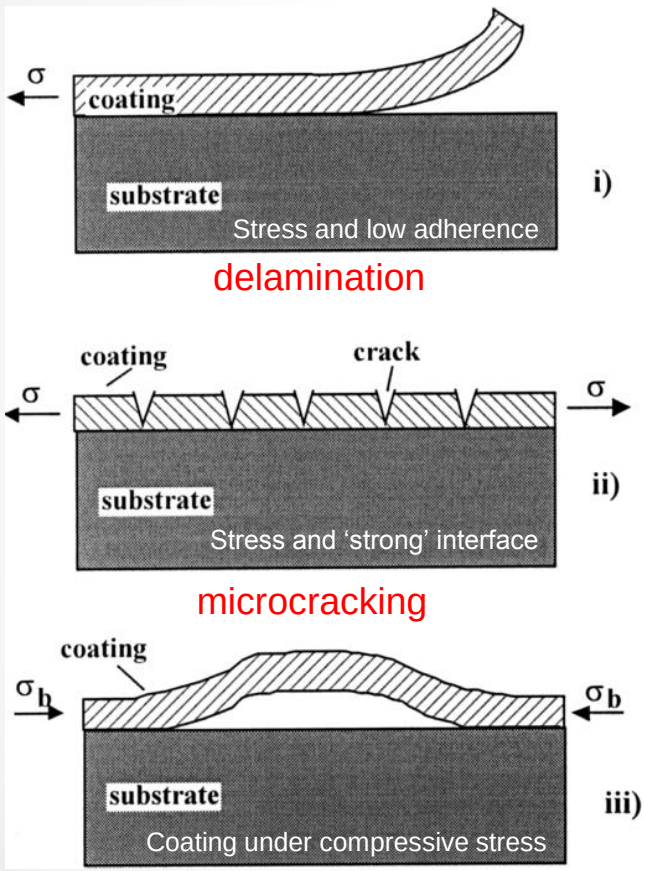


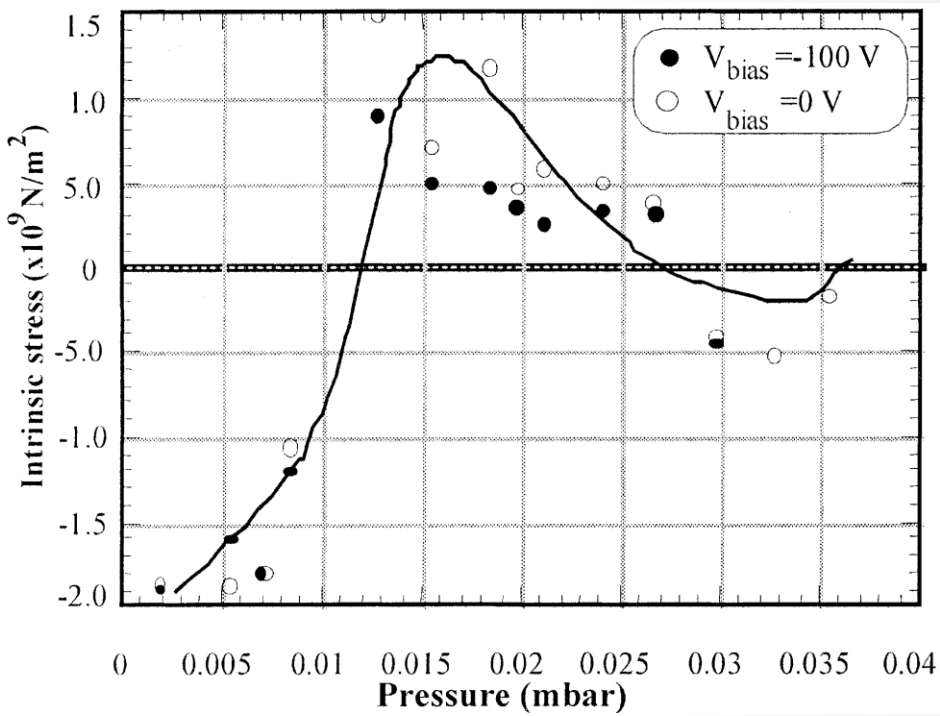
Comparison: Evaporation - Sputtering



Residual Stress in Coatings

Failure modes





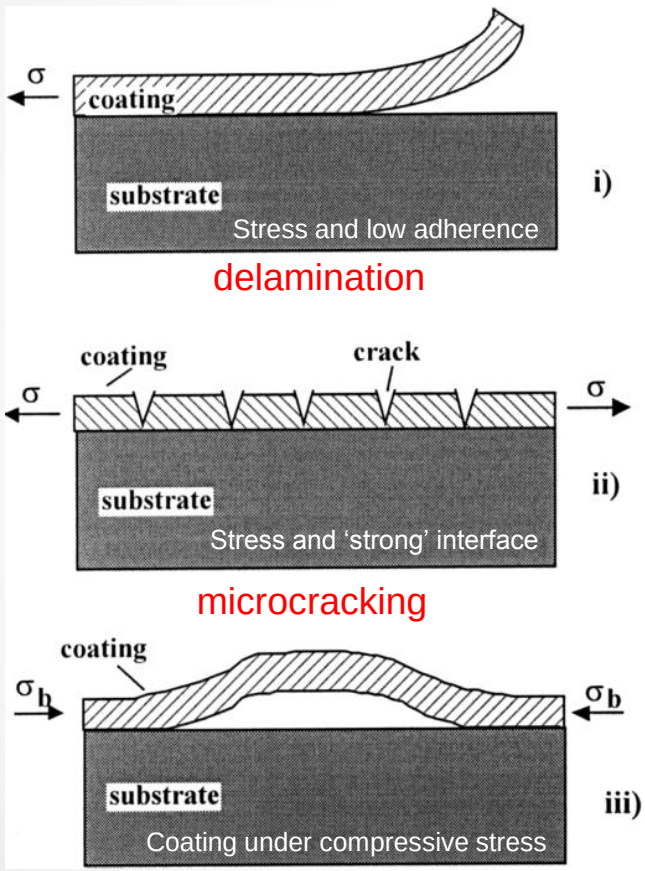
Biaxial intrinsic stress as function of argon pressure for

Mo-coatings produced by magnetron sputtering with and without applied bias

(V. Teixeira, M. Andritschky, Multicomponents and Multilayered Thin Films for Advanced Microtechnologies: Techniques, Fundamentals and Devices, NATO series E-Applied Sciences, vol. 234, Kluwer Academic Publishers, 1992, pp. 121-127)

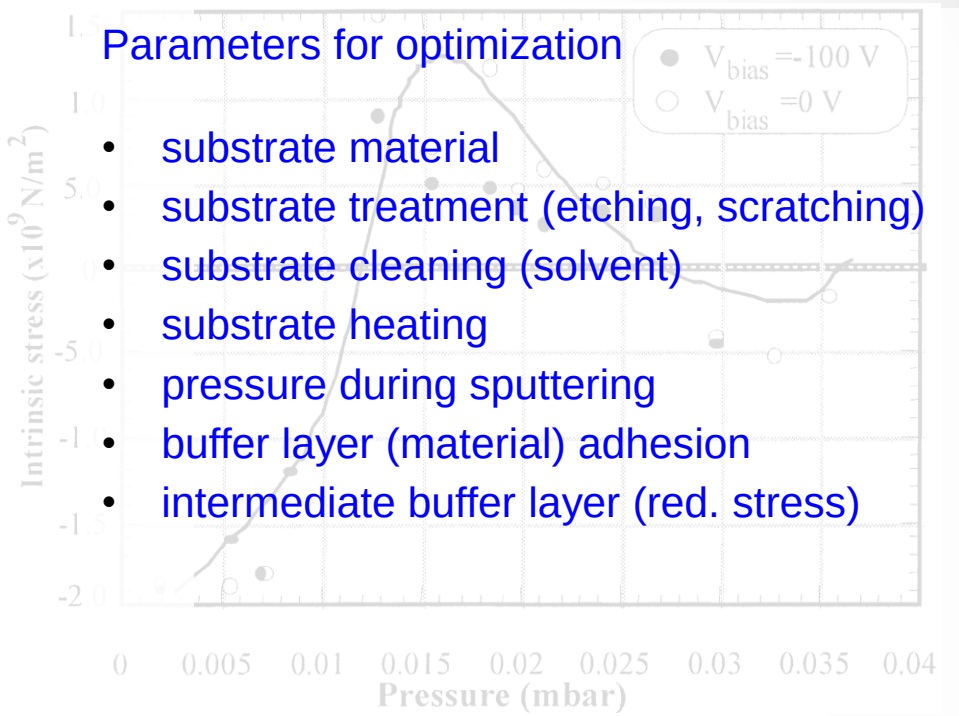
Residual Stress in Coatings

Failure modes



Parameters for optimization

- substrate material
- substrate treatment (etching, scratching)
- substrate cleaning (solvent)
- substrate heating
- pressure during sputtering
- buffer layer (material) adhesion
- intermediate buffer layer (red. stress)



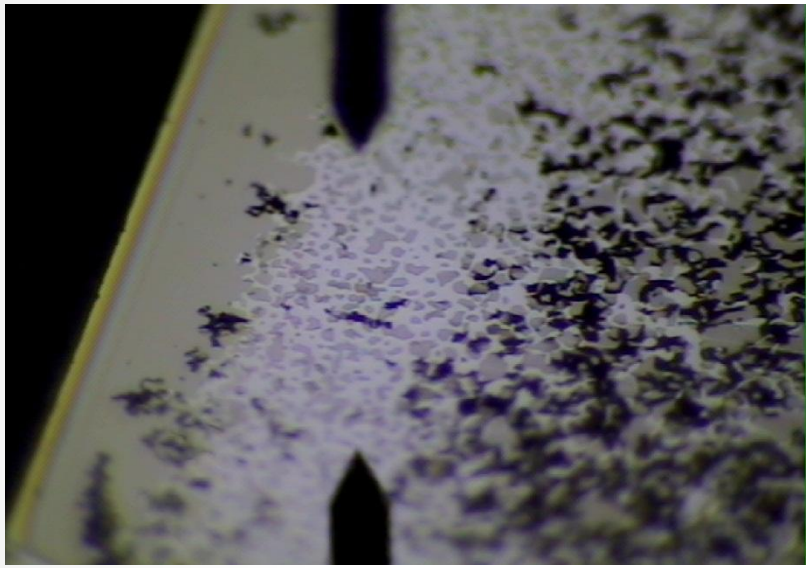
Biaxial intrinsic stress as function of argon pressure for

Mo-coatings produced by magnetron sputtering with and without applied bias

(V. Teixeira, M. Andritschky, Multicomponents and Multilayered Thin Films for Advanced Microtechnologies: Techniques, Fundamentals and Devices, NATO series E-Applied Sciences, vol. 234, Kluwer Academic Publishers, 1992, pp. 121-127)

Residual Stress in Coatings

1.0 µm thick B_4C layer:
deposited directly on Si wafer



Loss of adhesion → peel off on air
Film wrinkling due to stress

1.1 µm thick B_4C layer
with Ti bonding layer on Si wafer

- no wrinkling: continous coating
- stable for 12 months (!)
- Tesa: adhesion test
- Scratch test: stable

slide: courtesy M. Störmer/HZG

Coating of ^{10}B, $^{10}B_4C$

DC magnetron sputtering

- $^{nat}B_4C$ and $^{10}B_4C$
- Good adhesion on 2-side coated substrates
- High density and minimal amount of impurities
- Thickness control and uniformity
- Large area depositions for demonstrators

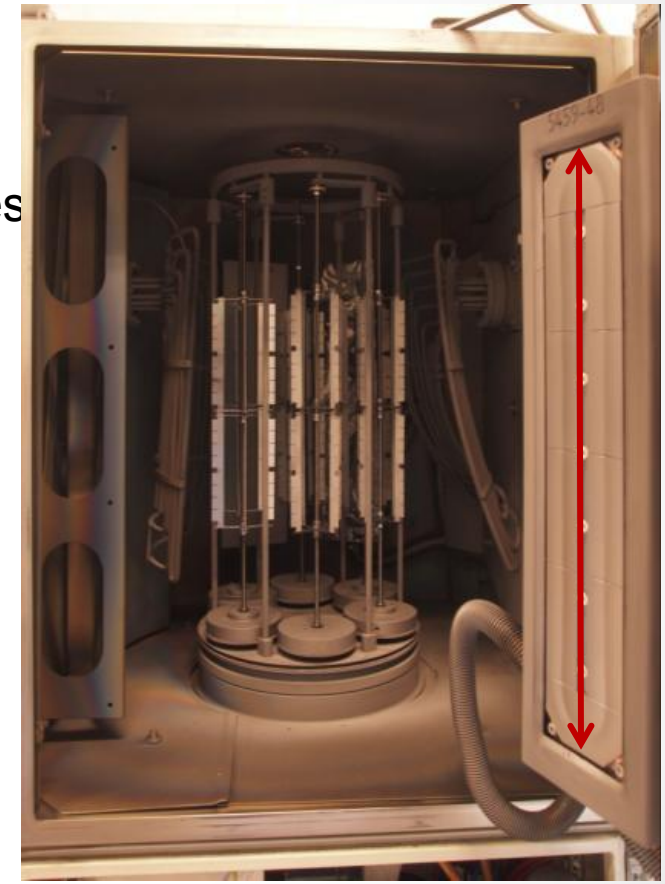
Develop thin films that maximize the neutron detection efficiency Chemical vapor deposition

- Thermally activated CVD
- Plasma assisted CVD

Linköping University

Collaboration: Linköping, ESS, ILL

source: C. Höglund – 2nd Int. ^{10}B-BF_3 Workshop, ILL, 2012



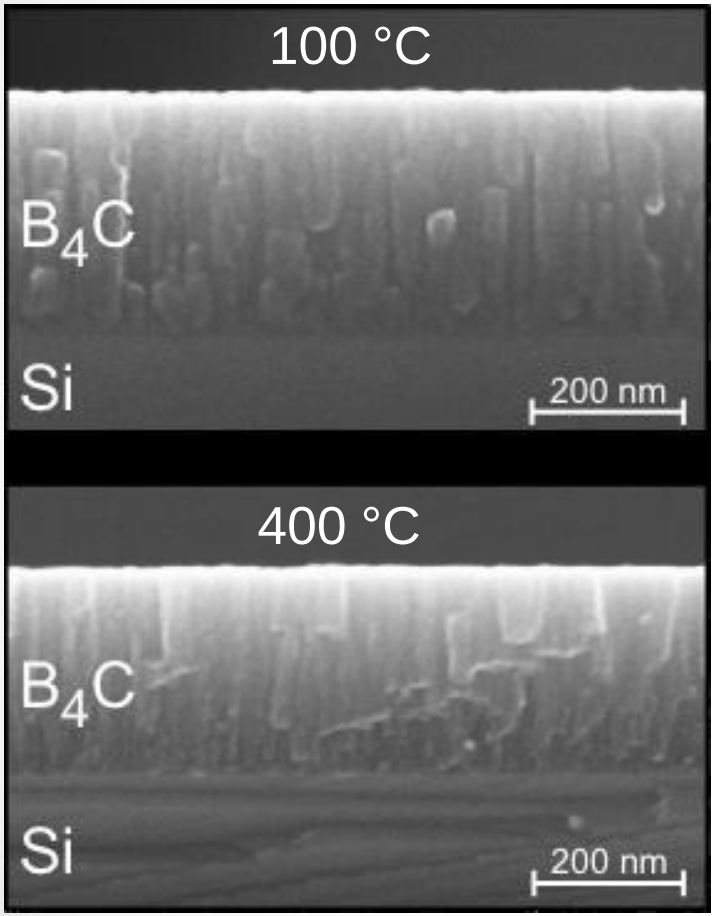
CC 800®/9 ML

Industrial apparatus!

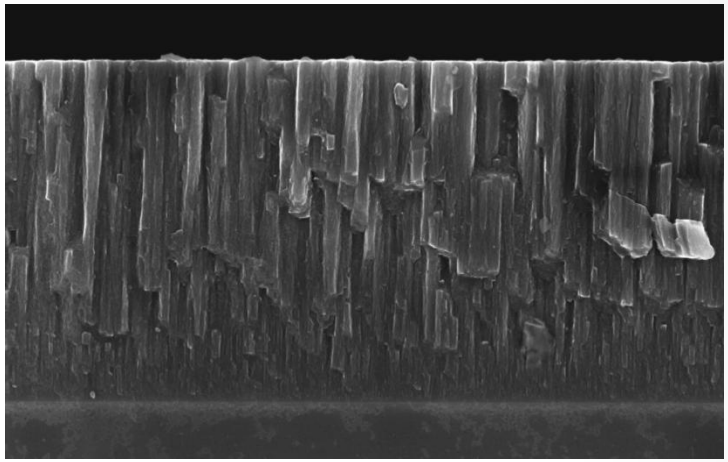
INSIS

Coating of ^{10}B, $^{10}B_4C$

~0.3 µm $^{nat}B_4C$



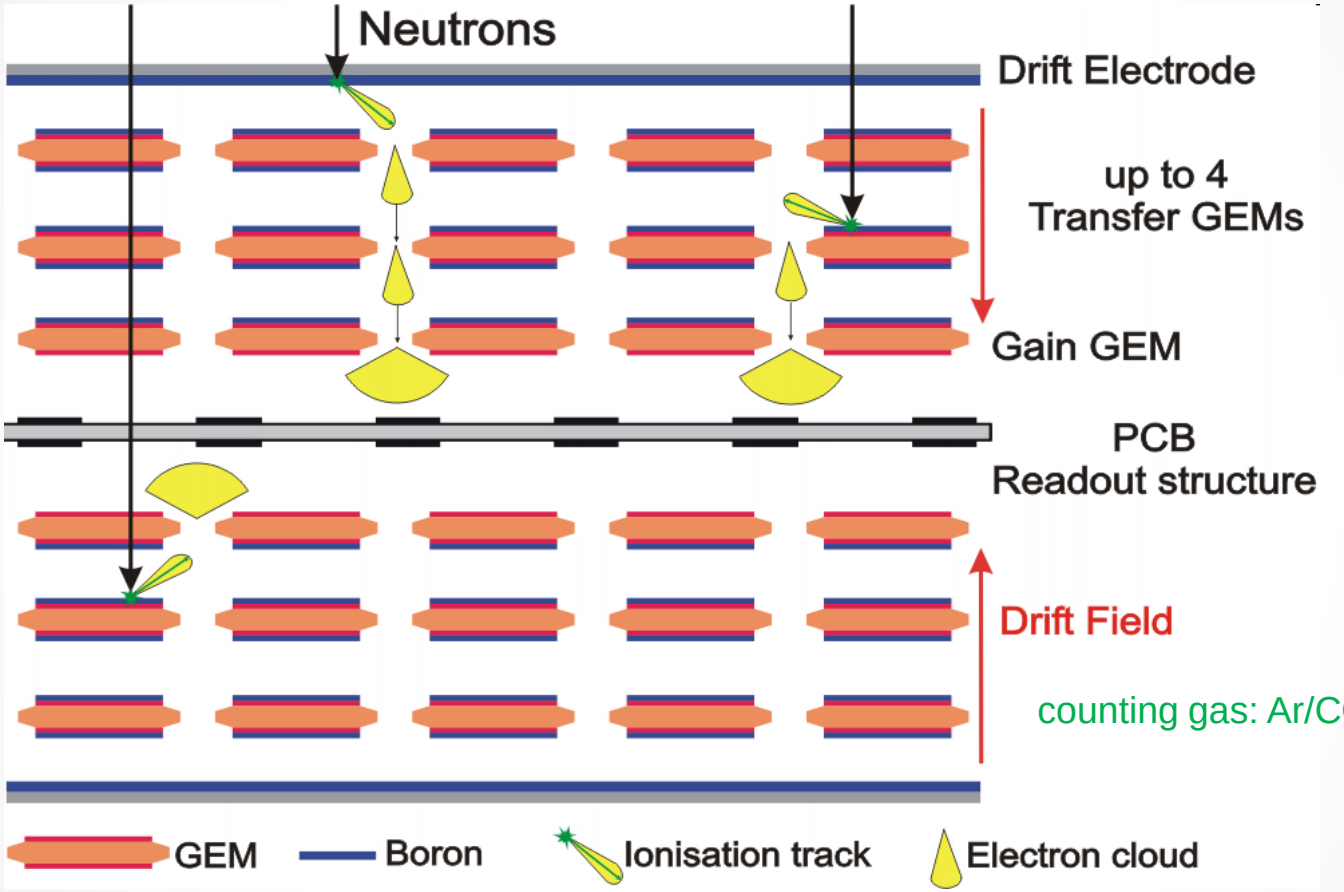
~3 µm $^{10}B_4C$



- Dense films with columnar structure
- Good adhesion and uniform thickness
- No significant change…
  … with increased temperature
  … with increased thickness
  … when sputtering $^{nat}B_4C$ or $^{10}B_4C$

source: C. Höglund – 2nd Int. ^{10}B-BF_3 Workshop, ILL, 2012
J. Appl. Phys. 111, 104908 (2012); doi: 10.1063/1.4718573

Cascade Detector - Principle



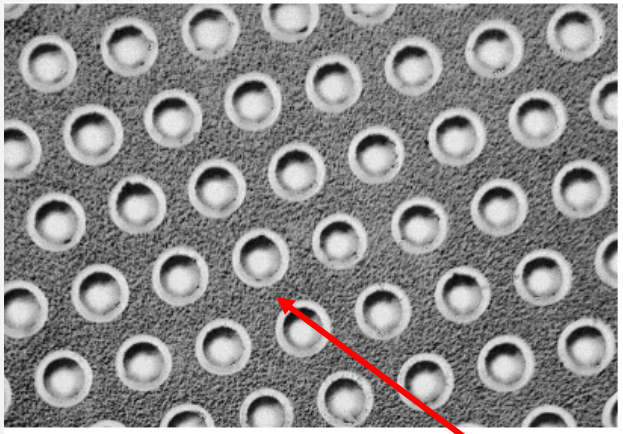
counting gas: Ar/CO_2 (90:10), 1 bar

M. Klein, Ch. Schmidt, NIM A628(2011)9–18

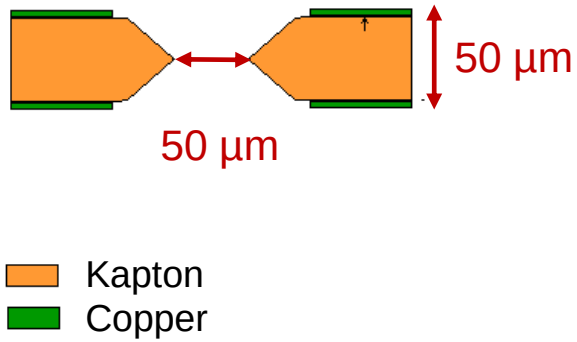
www.n-cdt.com

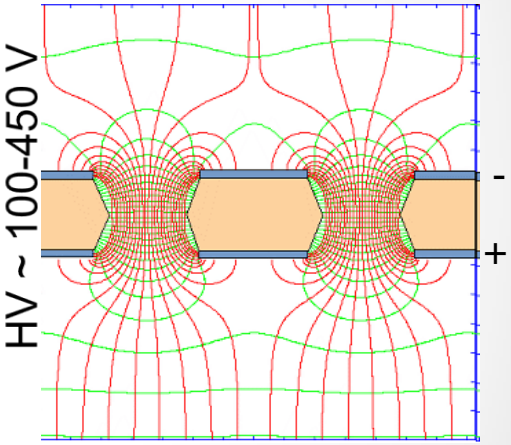
Cascade Detector - GEM

GEM = Gas Electron Multiplier (F. Sauli, CERN)



GEM hole

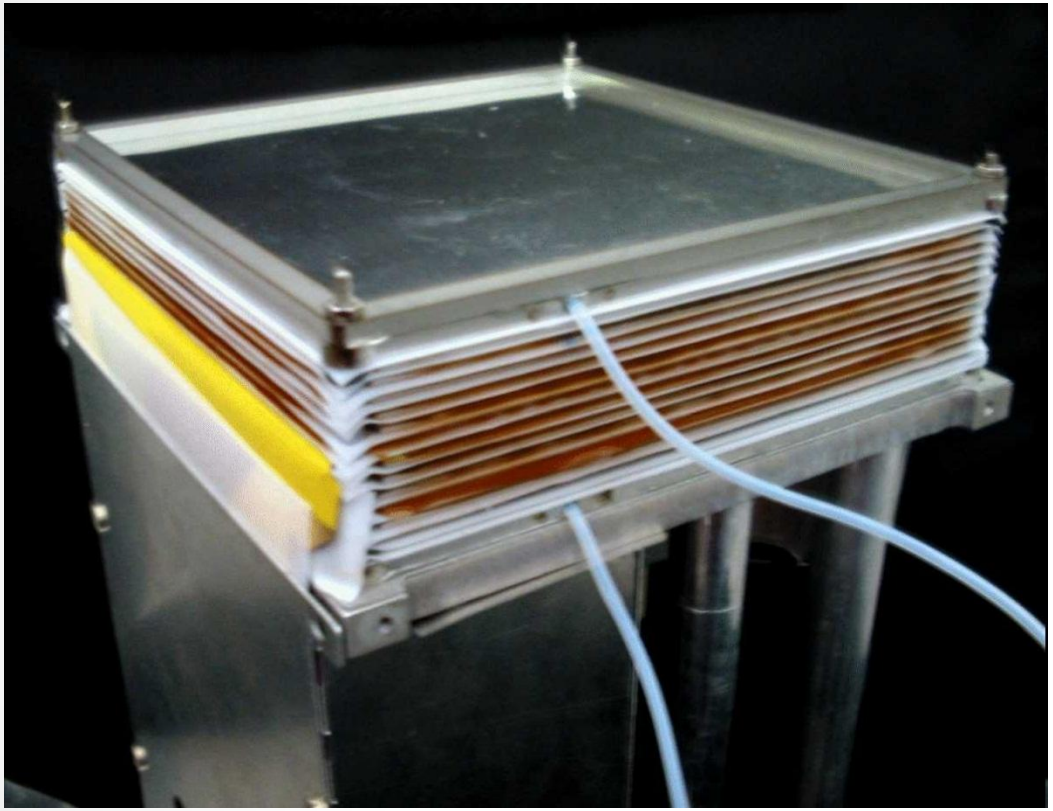




for CASCADE covered with ^{10}B

M. Klein (Uni Heidelberg), Ch. Schmidt (GSI)

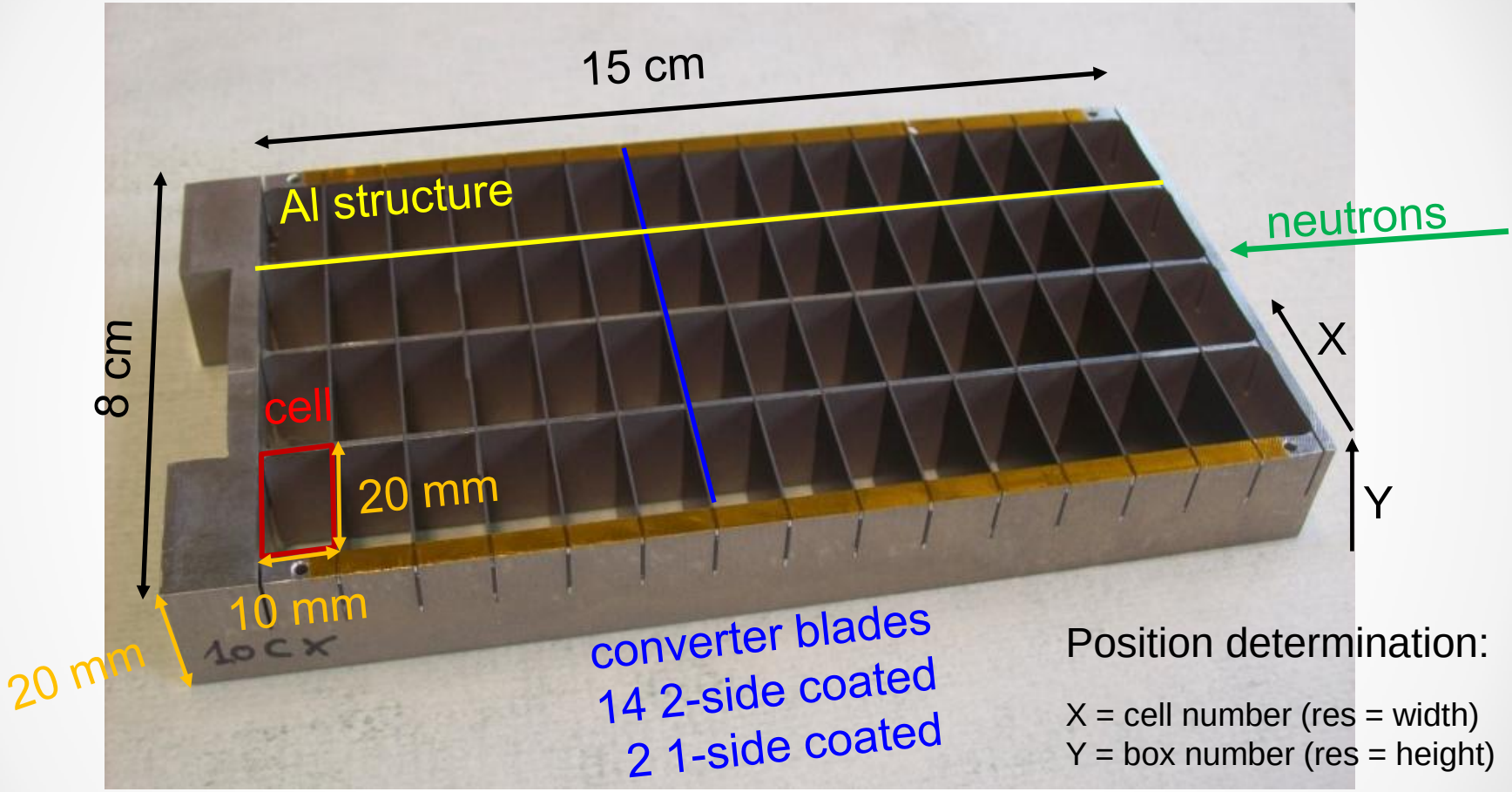
Cascade Detector



- Area: 30 x 30 cm²
- Modular (small dead zones)
- Efficiency ~50% (10 layers)
- Position res. ~ 1 mm
- Fast timing: 100 ns
- Gas: 1 bar Ar/CO_2 (90:10)
- High counting rate: $4x10^6$
- Readout with ASIC: (CIPIX, n-XYTER)

M. Klein (Uni Heidelberg), Ch. Schmidt (GSI)

Multi-Grid Detector – Single Grid



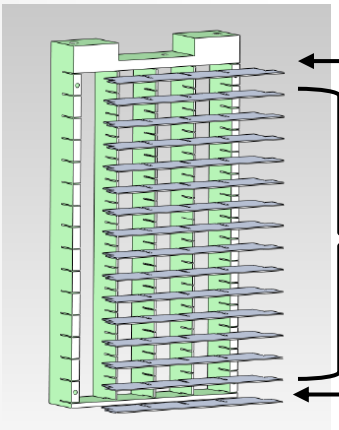
single grid – can be stacked

source: A. Khaplanov – 2nd Int. ^{10}B-BF_3 Workshop, ILL, 2012

Multi-Grid Detector - Preparation

$^{10}B_4C$ depositions

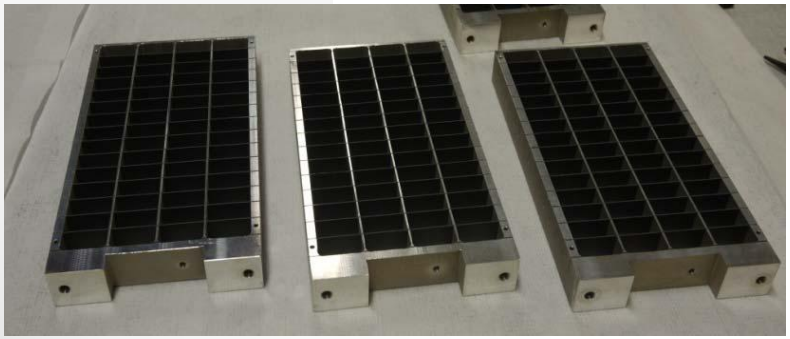
17 Aluminium blades, 0.5 mm thick, 2 cm height, for each grid



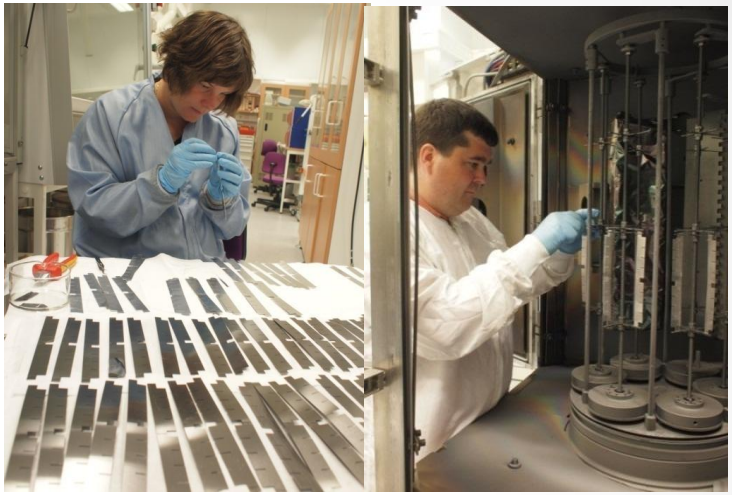
1-side coated (not mounted)

15 2-side coated

1-side coated (not mounted)



source: B. Guerard – IEEE, Valencia, 2011



ERDA analysis → 79.3 at% ^{10}B + 2.4 at% ^{11}B + 17.1 at% C + 1.2 at% contaminants (N, O, H)

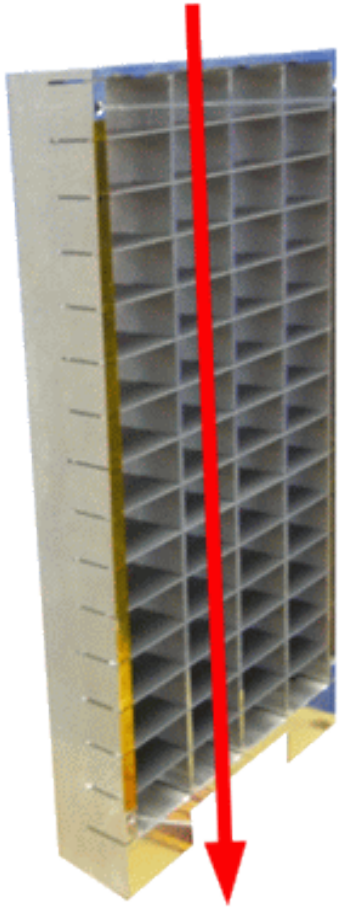
X-ray reflectivity → density = ~2.25-2.30 g/cm^3

bulk 2.46 g/cm^3

1854 2-sided blades (1440 mounted)
264 1-sided blades (not mounted)

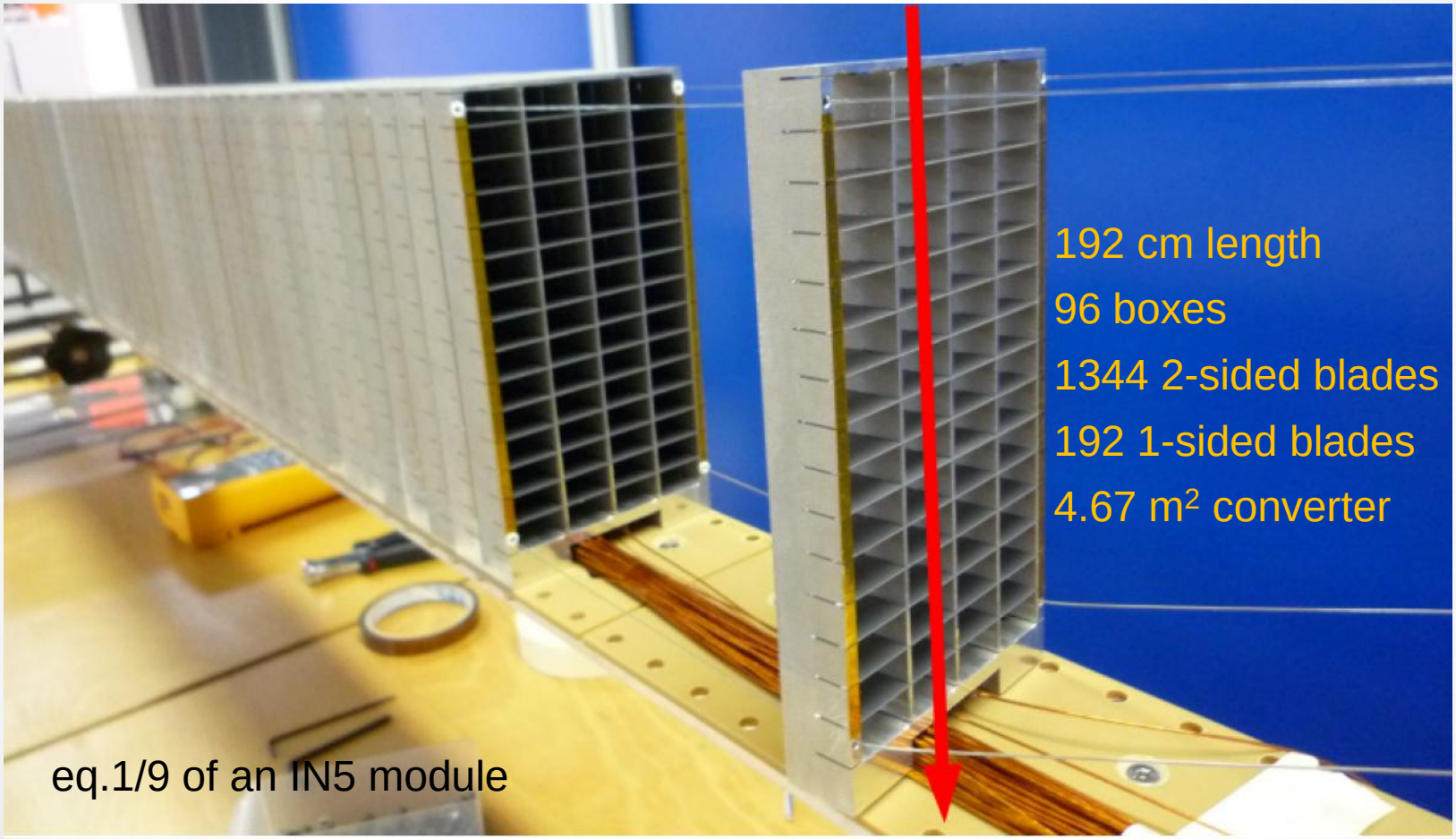
Total surface coated = 6.3 m^2
2 weeks work!

Multi-Grid Detector - Assembly



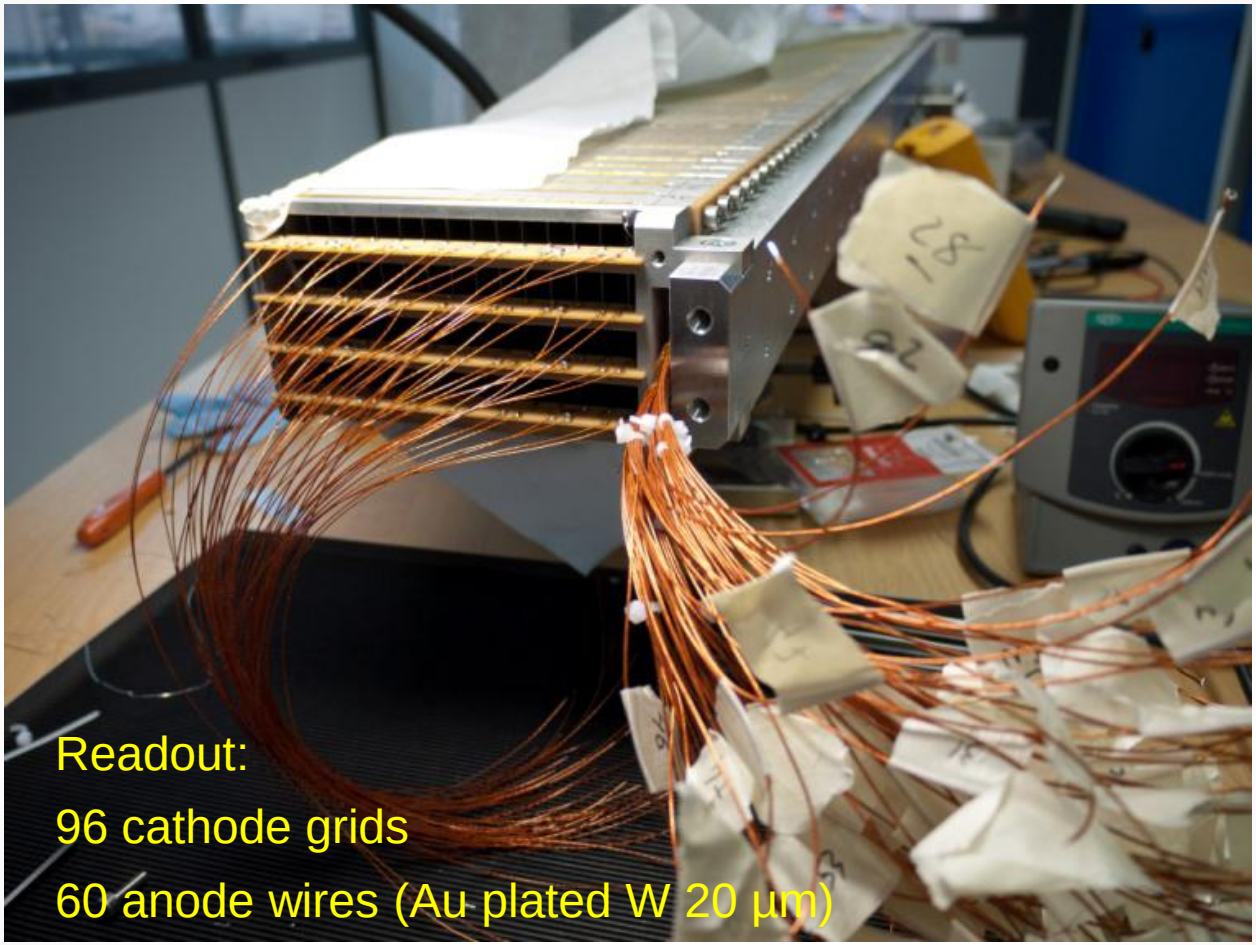
courtesy of J. Correa – 2nd Int. ^{10}B-BF_3 Workshop, ILL, 2012

Multi-Grid Detector - Assembly



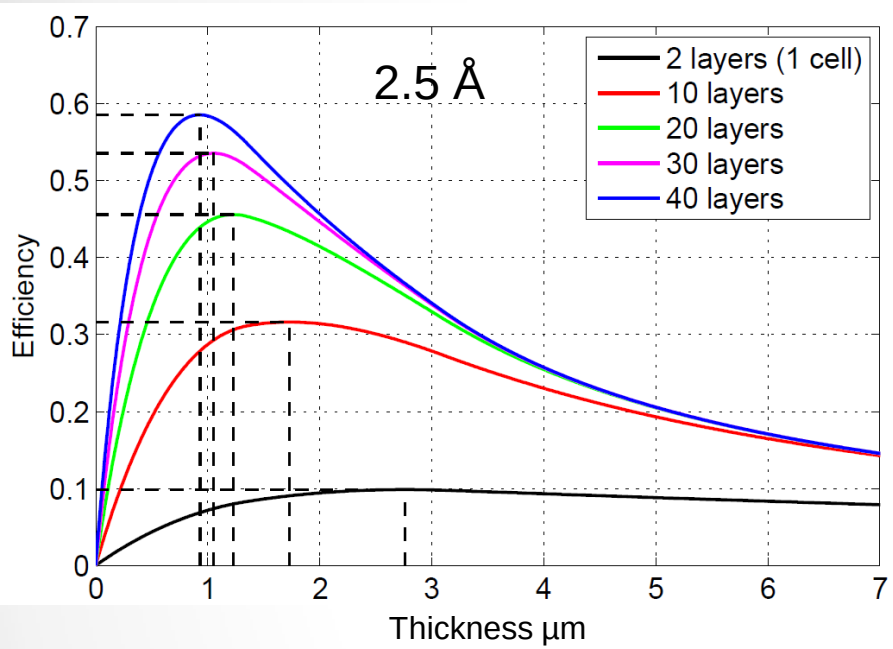
courtesy of J. Correa – 2nd Int. ^{10}B-BF_3 Workshop, ILL, 2012

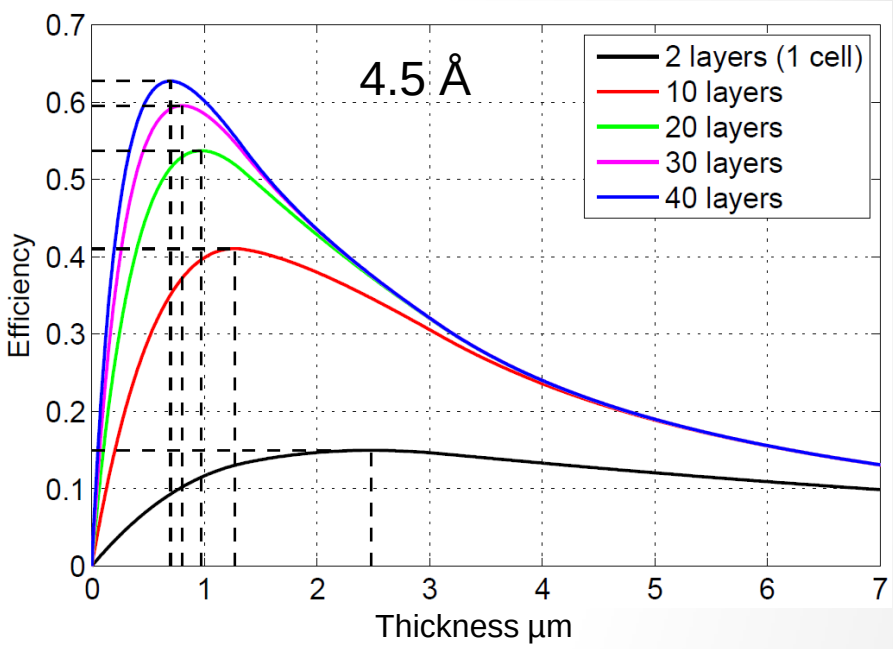
Multi-Grid Detector - Assembly



source: A. Khaplanov – 2nd Int. ^{10}B-BF_3 Workshop, ILL, 2012

Multi-Grid Detector - Efficiency



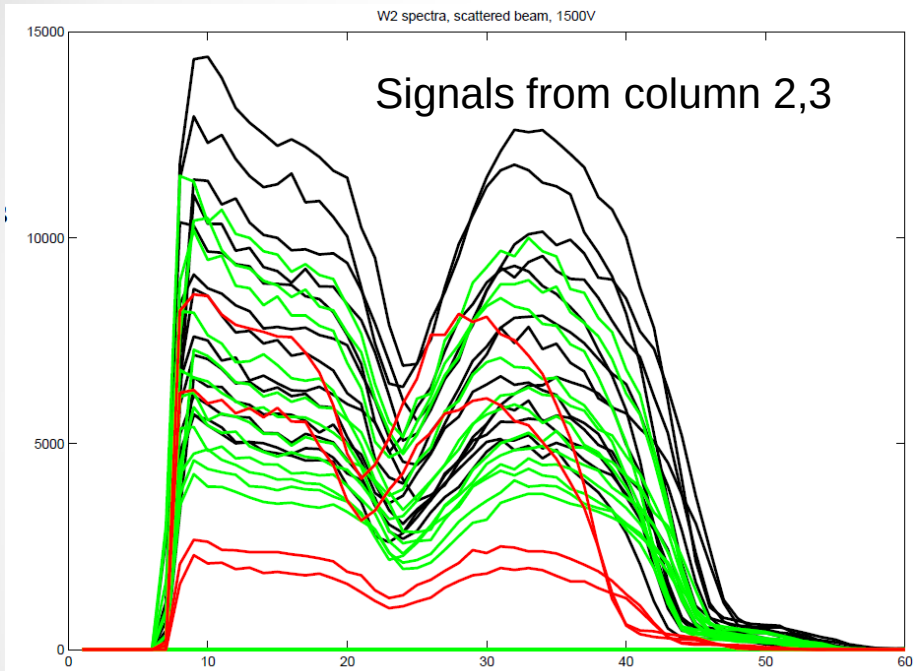


- composition from ERDA
- density from x-ray reflectivity
- 100 keV threshold
- 0.5 mm Al substrate included

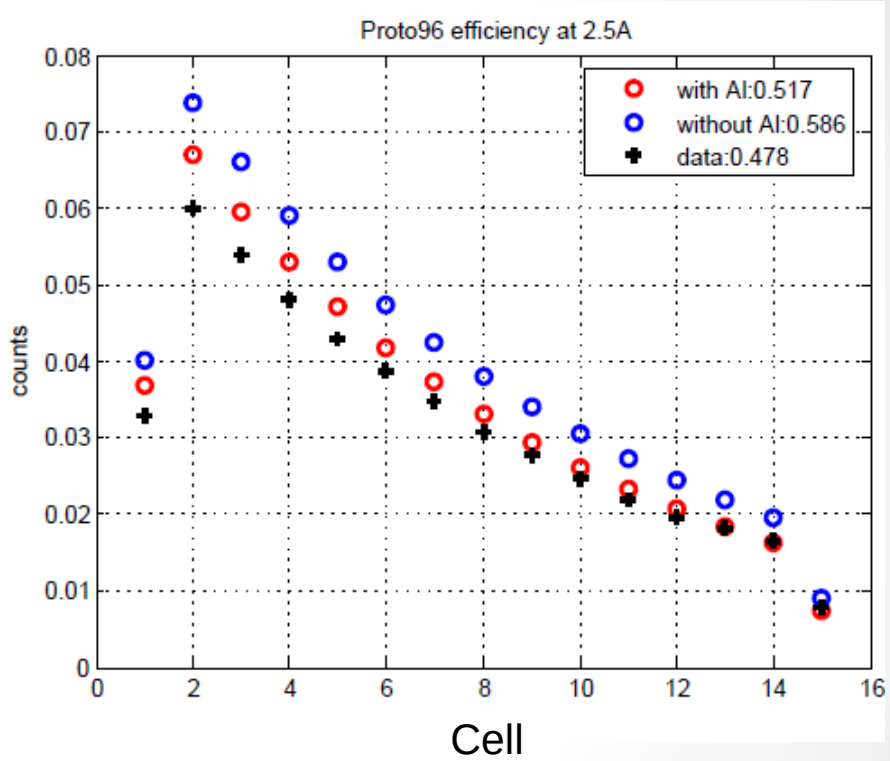
20 → 40 layers
efficiency improvement is laborious

source: A. Khaplanov – 2nd Int. ^{10}B-BF_3 Workshop, ILL, 2012

Multi-Grid Detector - Efficiency



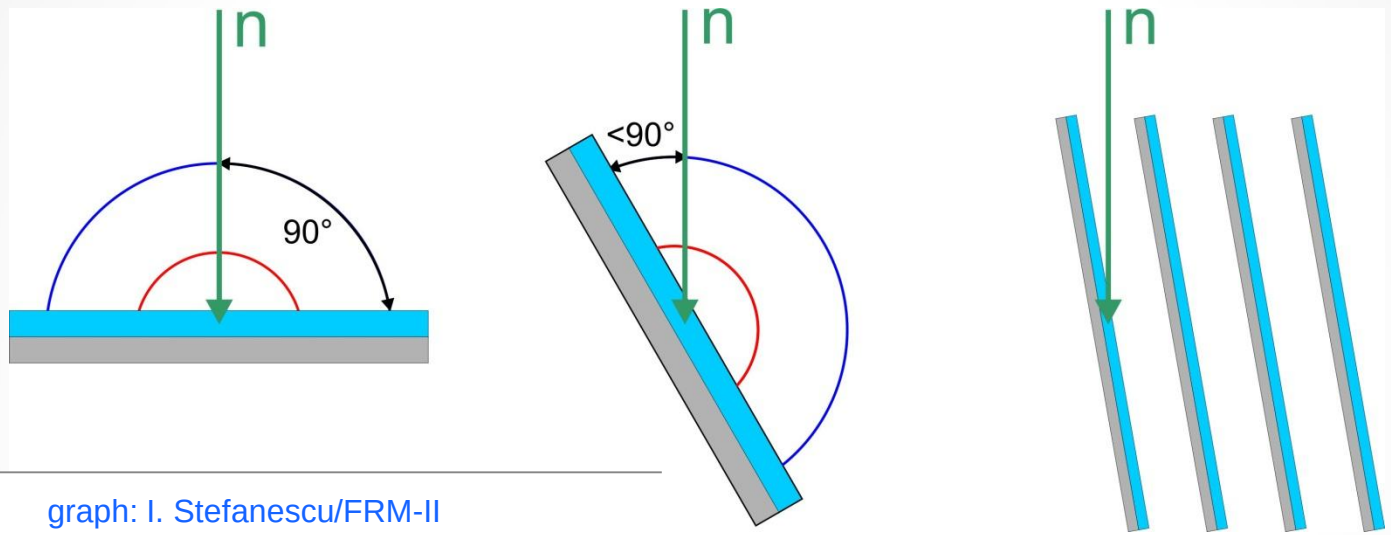
In black, wires 2 to 14 of colomn 2
In green, wires 2 to 14 of colomn 3
In red, wires 1 and 15 from colomn 2 and 3
only one B4C film is viewed by wires 1 and 15
the gain is reduced due to a larger anode-blade distance

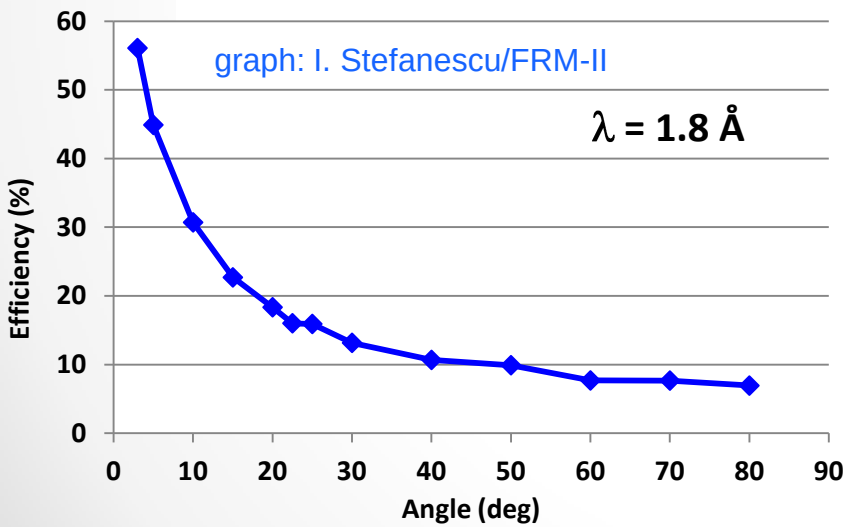


measured efficiency: 48%
calculated efficiency: 52% (100 keV thr.)
calculated efficiency: 56% (0 keV thr.)
calculated efficiency: 59% (no Al)

source: B. Guerard – IEEE, Valencia, 2011

Inclined Converter (flat)

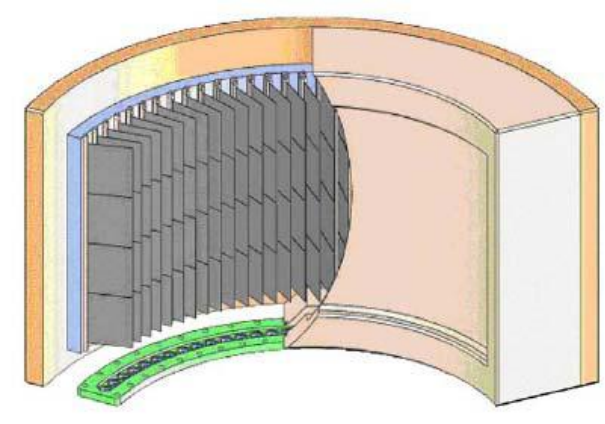




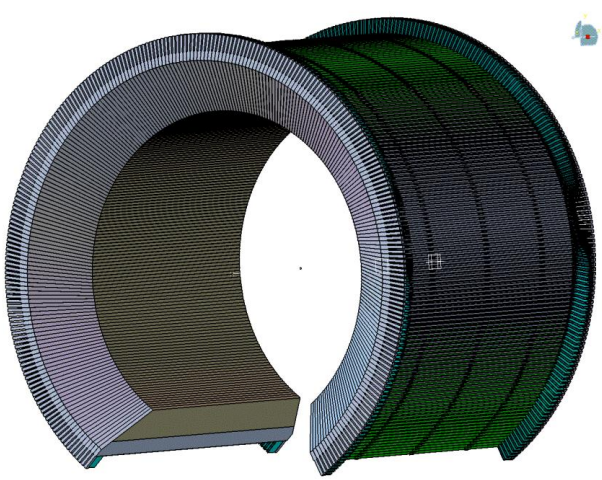
- Absorption length for neutron increases
- Same escape probability for sec. ions
- In extreme: no substrate for neutron
- But: long converter &
- Very little space for gas detector

Remember: total ~30 µm ^{10}B converter!

Inclined Converter – Divers Approaches

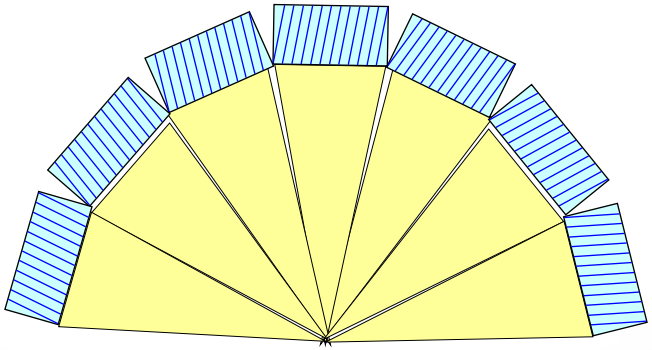


Multi-Blade Detector, ILL, 2005*)



Jalousie-Detector, CDT, 2012

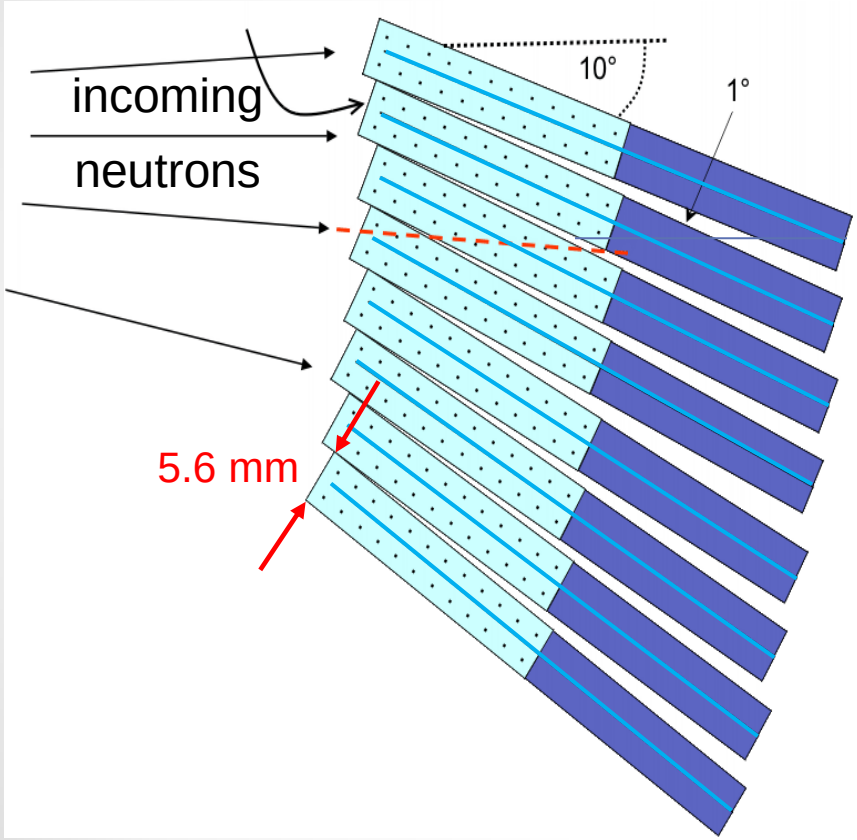
Inclined Geometry Detector, HZG, 2010



J.C. Buffet et al. NIMA 554(2005)392–405

The Jalousie Detector Concept

Feasibility study by CDT for the RWTH Aachen Instrument POWTEXin cooperation with Physikalisches Institut Heidelberg (BMBF funded).



courtesy of Ch. Schmidt, M. Klein CDT: www.n-cdt.com

The concept:

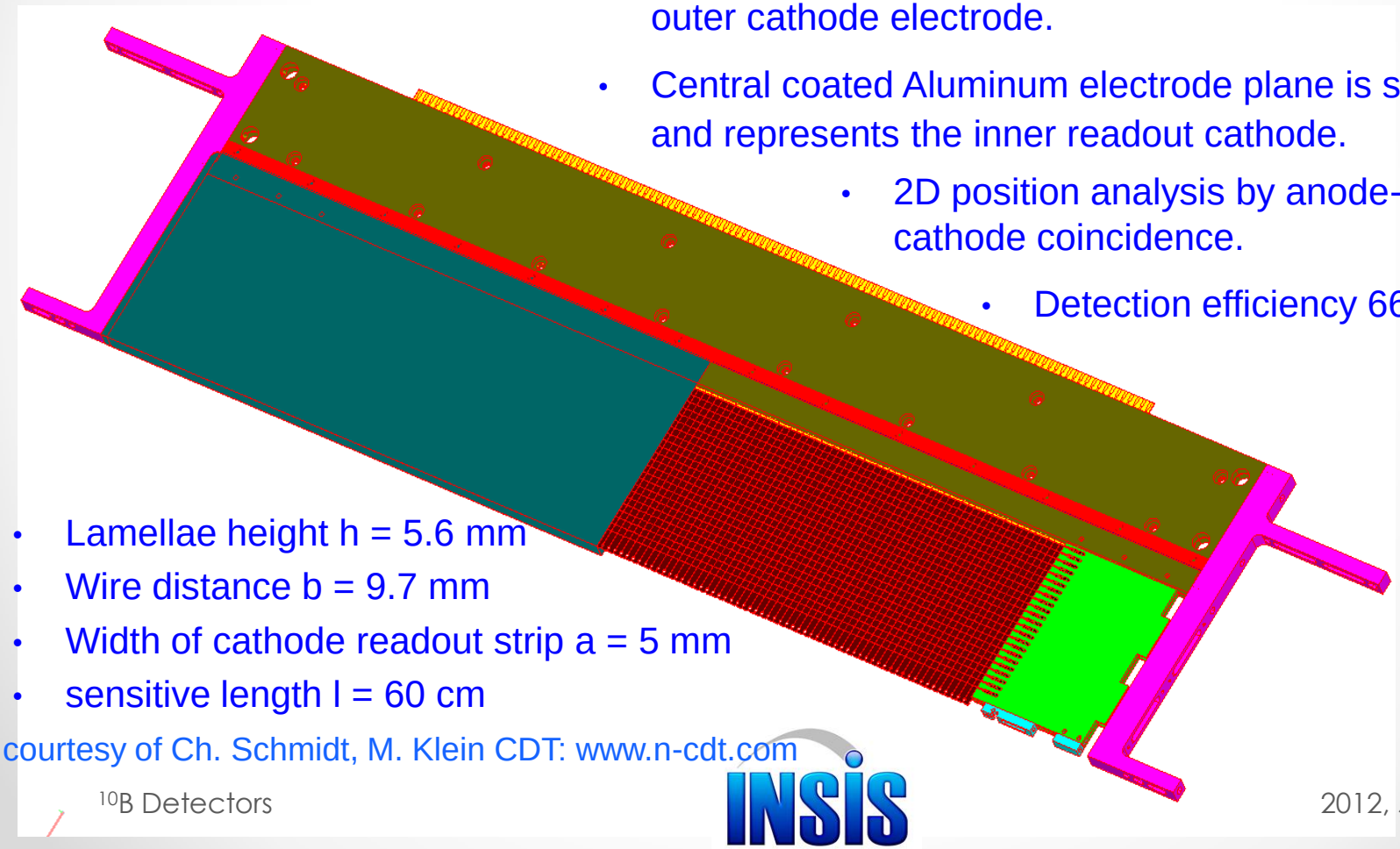
- Any Neutron path encounters 8 layers of ^{10}B coated onto 4 lamellae.
- Lamellae are inclined (~10°) to reach high detection efficiency (no principle limitation)
- Module design suitable to cover large areas.
- TOF capable through depth information.
- Operation at ambient pressure, no pressure vessel!

- **Actual modular segment design:**
- 2 lamellae make up one gas detector segment:
  - 2 anode wire planes and 3 cathode planes.
  - Entrance window 100% active, no blind area
  - Electronics on the back

For the incoming neutrons: the stack of inclined lamellae will look like a „Jalousie“ or Venetian blind.

Pre-Prototype Design, Proof of Principle

- 2 lamellae form one segment, an individual gas detector.
- Thin Aluminum cover (300µm thick) defines gas detector volume. The cover is coated inside and represents the outer cathode electrode.
- Central coated Aluminum electrode plane is segmented and represents the inner readout cathode.
  - 2D position analysis by anode-cathode coincidence.
    - Detection efficiency 66% at 1.8 Å

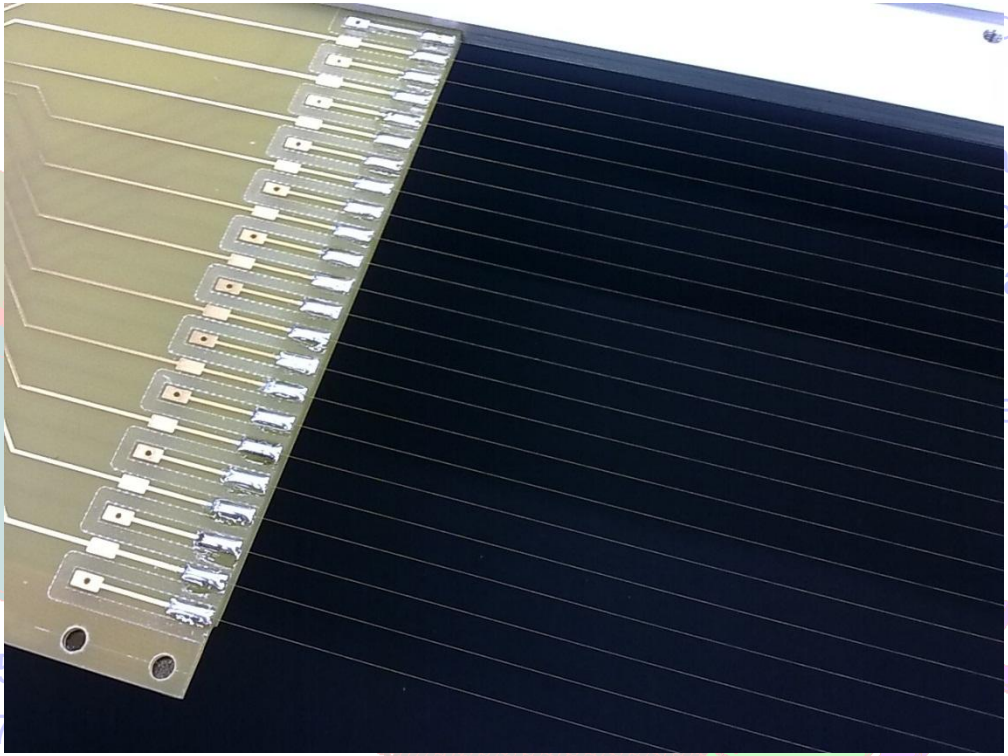


- Lamellae height h = 5.6 mm
- Wire distance b = 9.7 mm
- Width of cathode readout strip a = 5 mm
- sensitive length l = 60 cm

courtesy of Ch. Schmidt, M. Klein CDT: www.n-cdt.com

Pre-Prototype Design, Proof of Principle

- 2 lamellae form one segment, an individual gas detector.
- Thin Aluminum cover (300µm thick) defines gas detector
  l represents the



ne is segmented
ode.
anode-

ency 66% at 1.8 Å

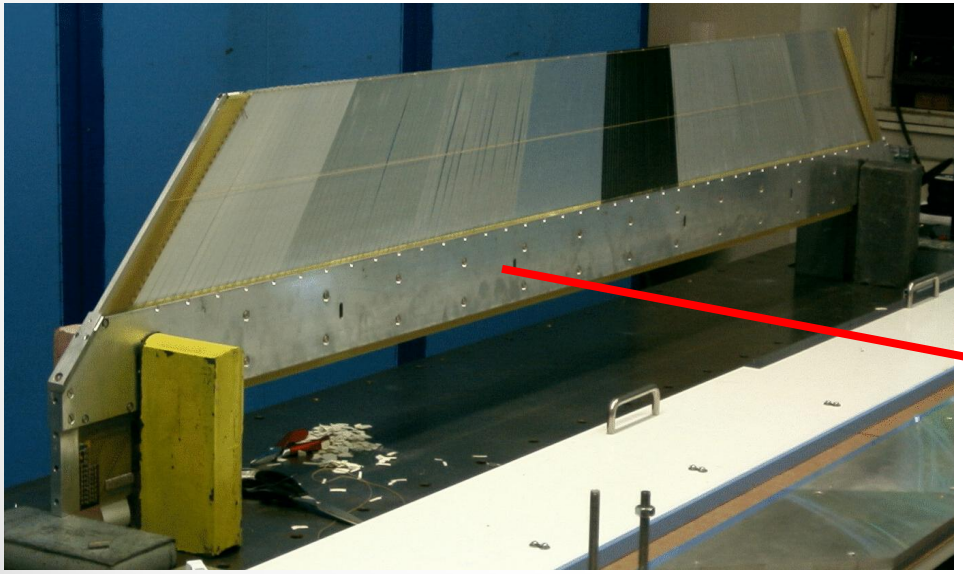
- Lamellae height h = 5
- Wire distance b = 9.7
- Width of cathode readout strip a = 5 mm
- sensitive length l = 60 cm

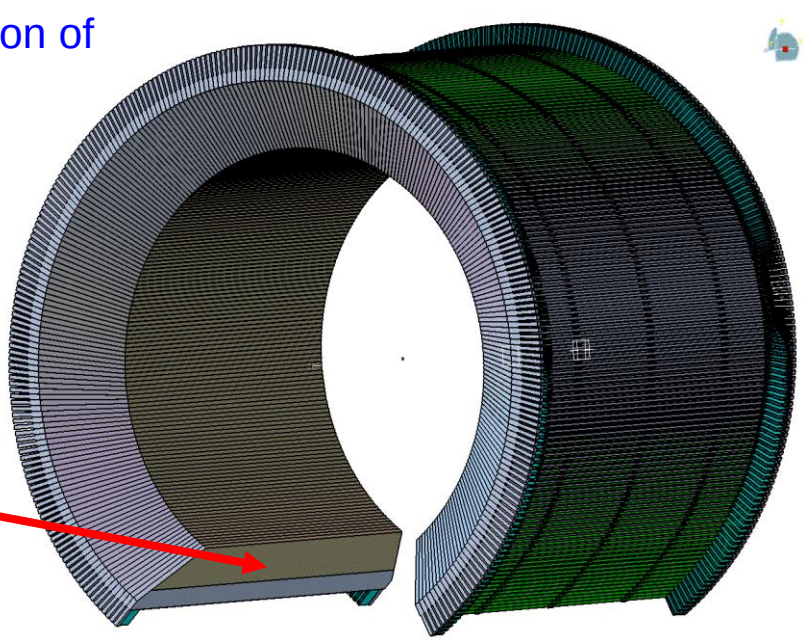
courtesy of Ch. Schmidt, M. Klein CDT: www.n-cdt.com

Design Study for POWTEX

- Active length l = 1,60 m.
- Distance to the scattering sample r = 80 cm.
- 45 design at the far ends to fit the cylinder end-caps of the detector with minmal blind area.
- Strips of central readout cathode are confocally oriented towards the scattering sample (integration of scattering intensity per θ).

- **9 m² sensitive area,**
- **250 lamella segments,**
- **cylinder end-caps**
- **not shown here**





~110 m² coating!

courtesy of Ch. Schmidt, M. Klein CDT: www.n-cdt.com

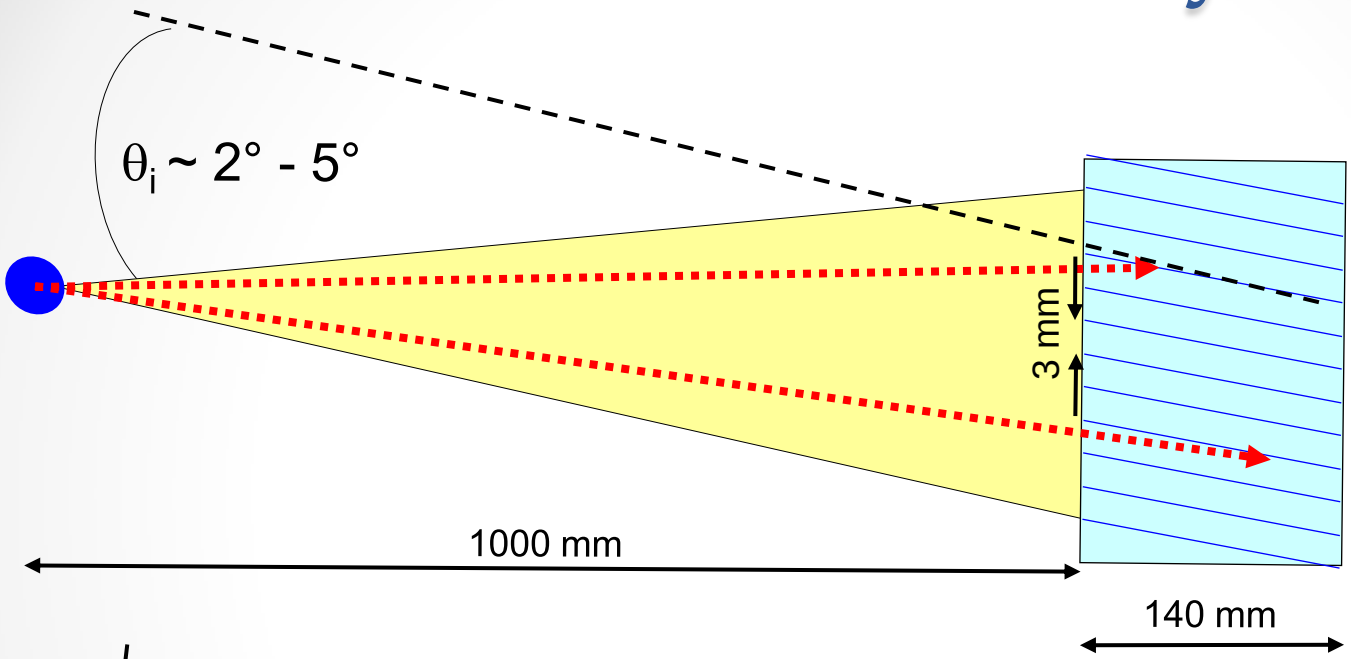
Test of 2 Jalousie Segments

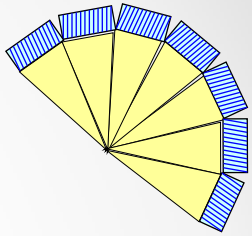
Experiment at HEIDI/FRM-II

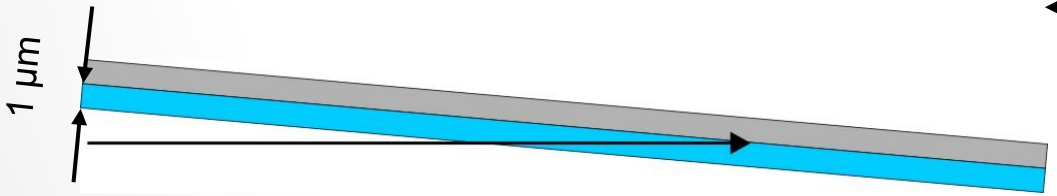
measured 98% of the calculated detection efficiency at 1.17 Å (58%)!

courtesy of Ch. Schmidt, M. Klein CDT: www.n-cdt.com

HZG -Inclined Geometry Detector







low homogeneity possible
only surface is sensitive

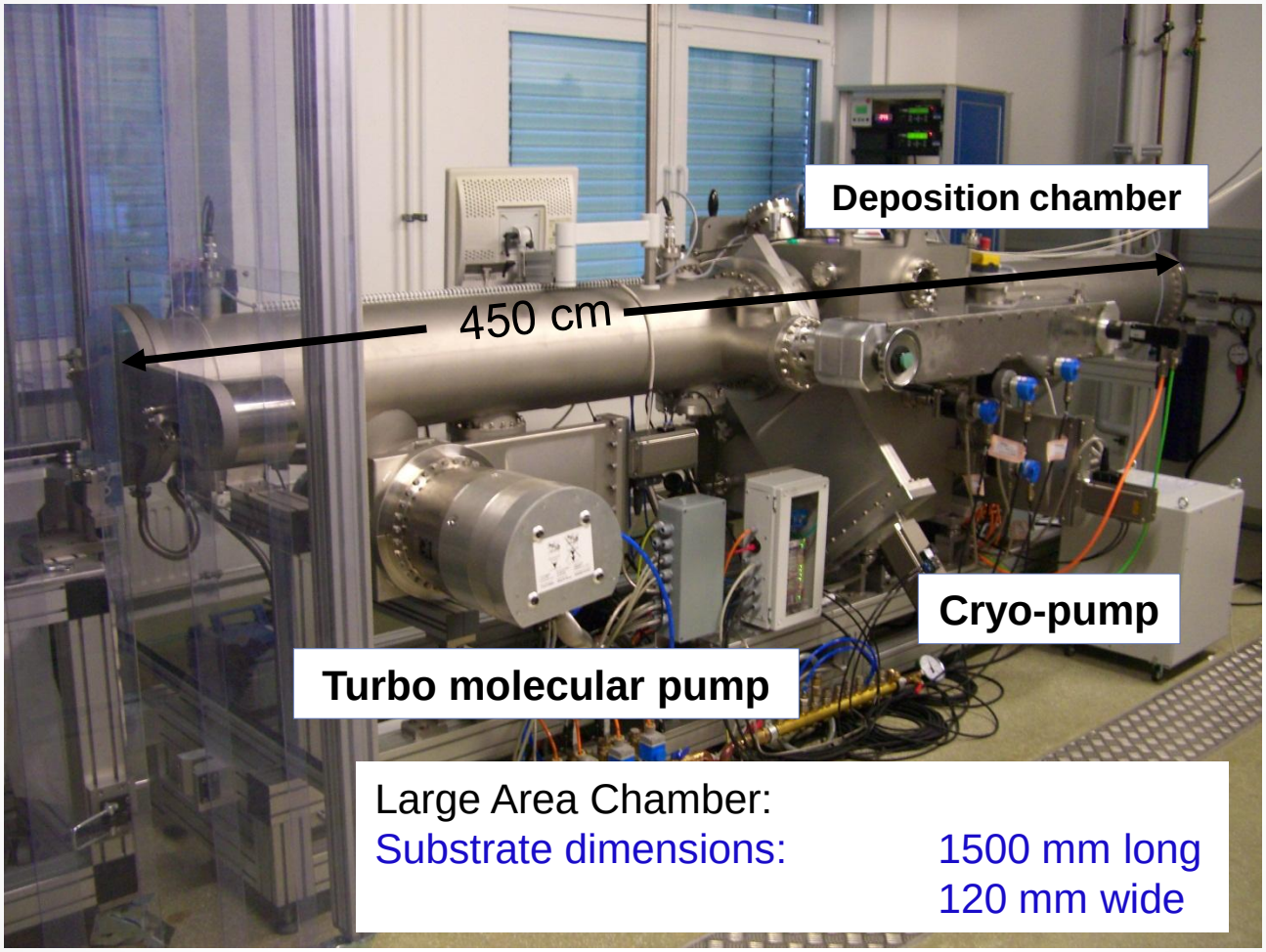
1 µm conv. layer = 1.5 - 28.5 µm abs. length

very thin gas detectors
to be dev. at DENEX

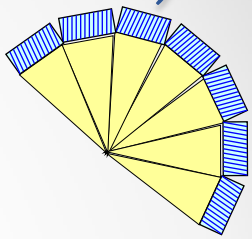
courtesy of R. Kampmann/HZG

www.denex.de

HZG – Coating System (X-Ray Mirrors)

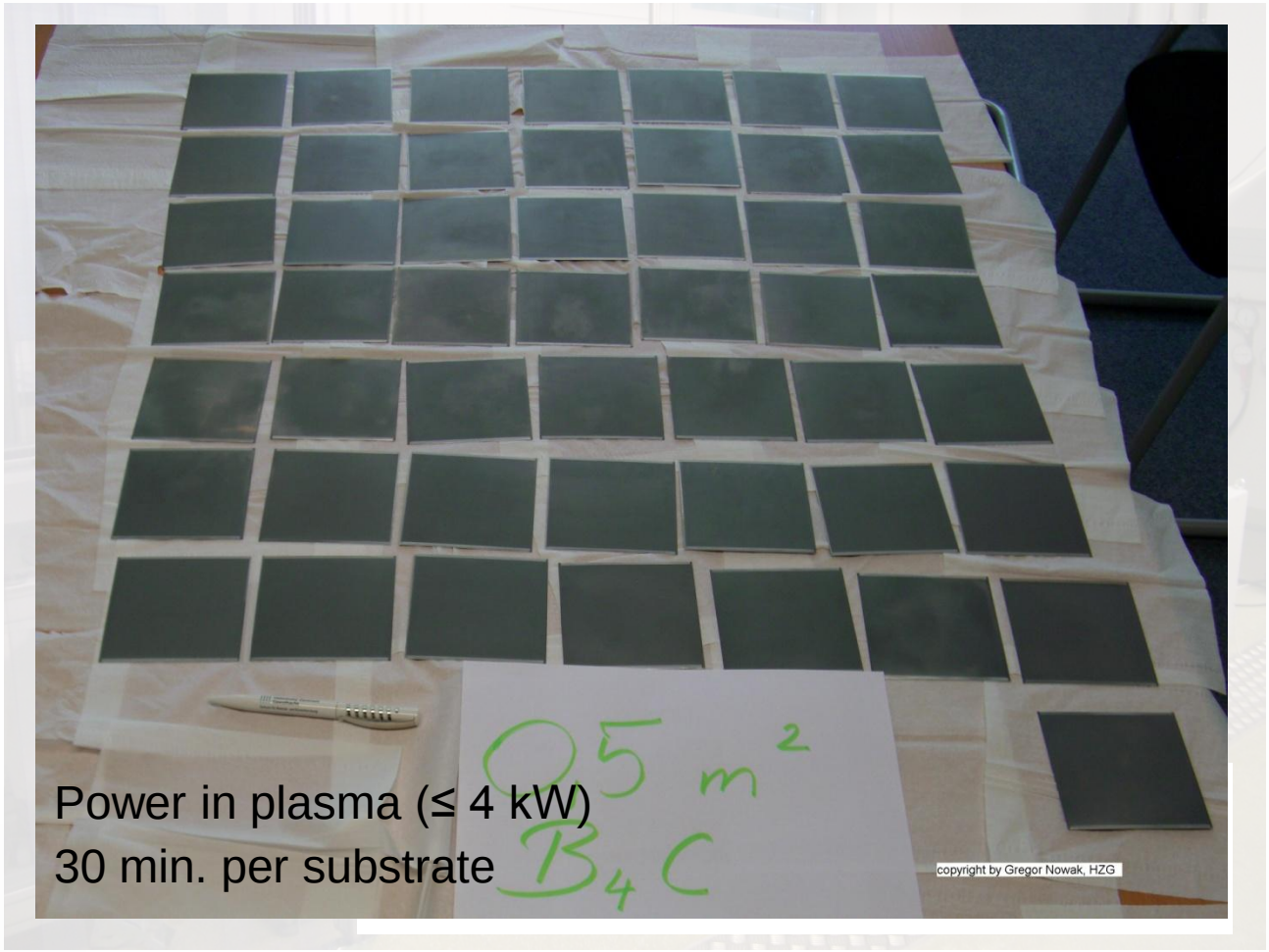


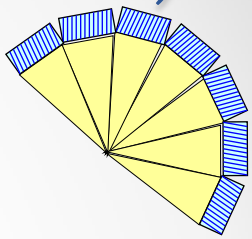
Large Area Chamber:
Substrate dimensions: 1500 mm long
120 mm wide



courtesy of M. Störmer, G. Nowak/HZG

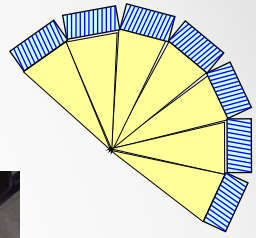
HZG – Coating System (X-Ray Mirrors)



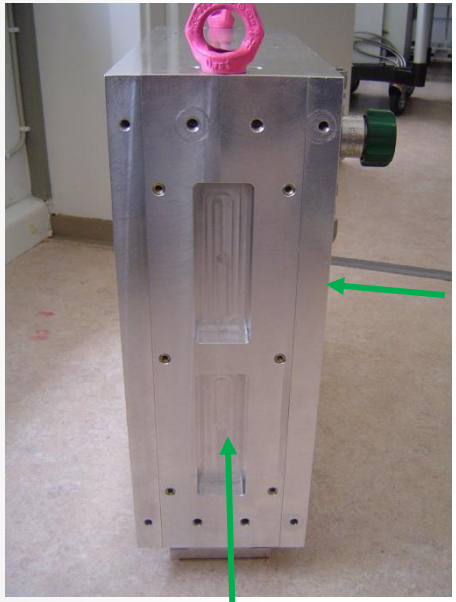


courtesy of M. Störmer, G. Nowak/HZG

HZG – IGD Test Preparation

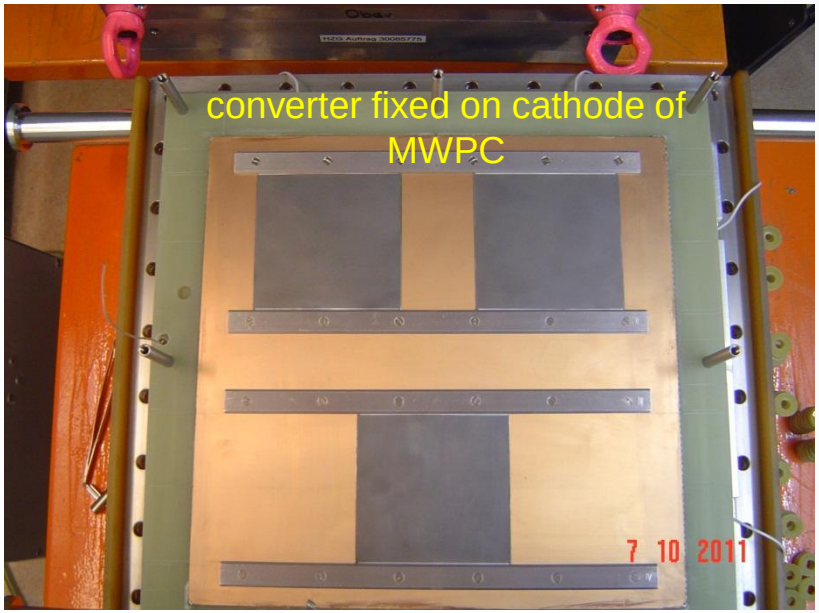


Modified DENEX MWPC



neutrons
AmBe

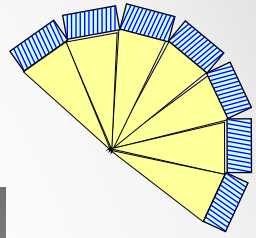
neutrons
REFSANS



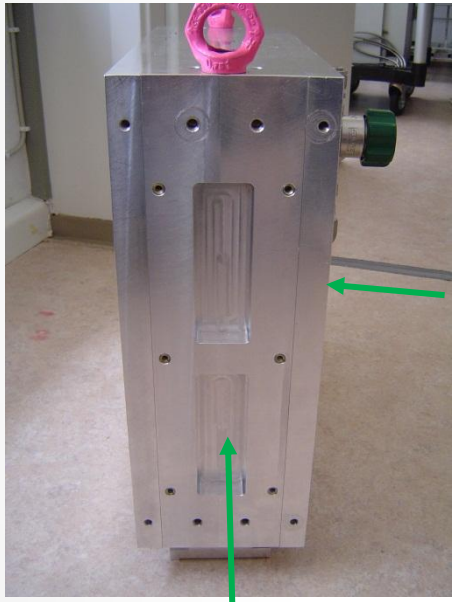
courtesy of R. Kampmann/HZG

www.denex.de

HZG – IGD Test Preparation



Modified DENEX MWPC



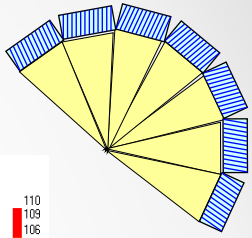
neutrons
AmBe

neutrons
REFSANS

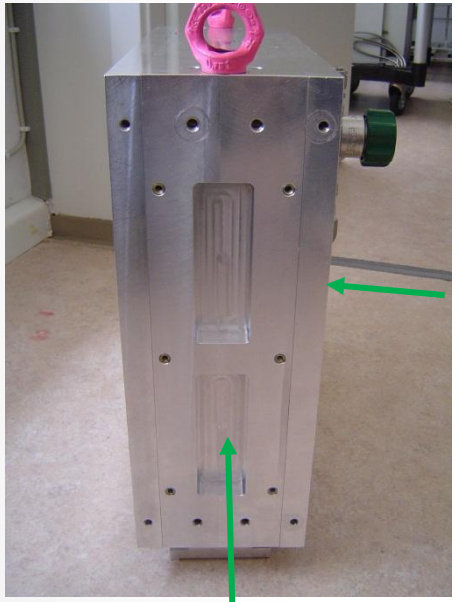
courtesy of R. Kampmann/HZG

www.denex.de

HZG – IGD Test Preparation

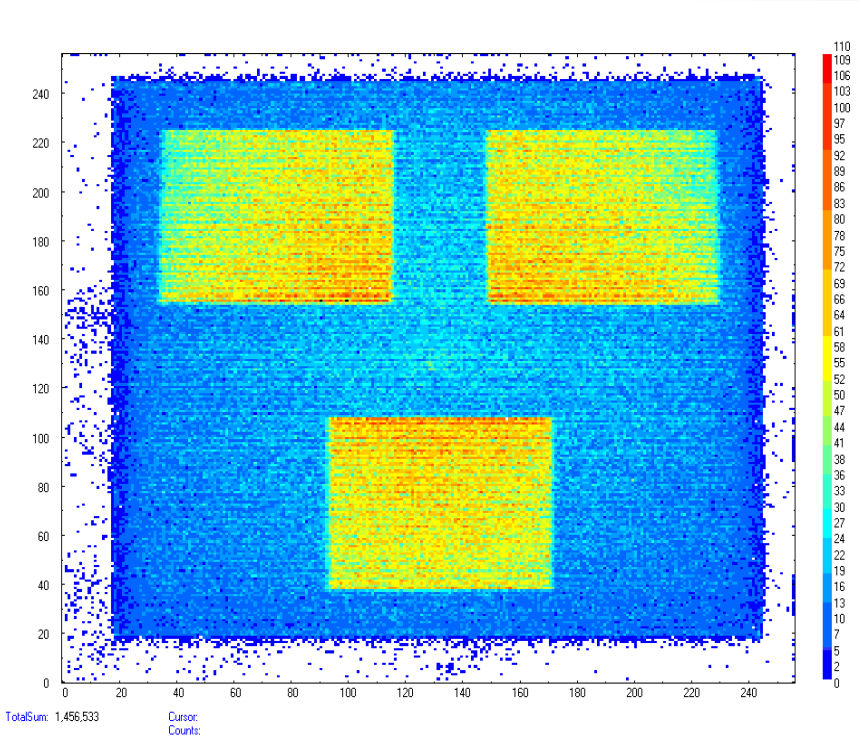


Modified DENEX MWPC



neutrons
AmBe

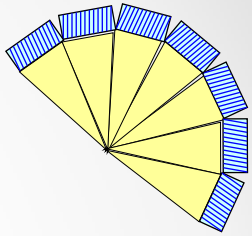
neutrons
REFSANS

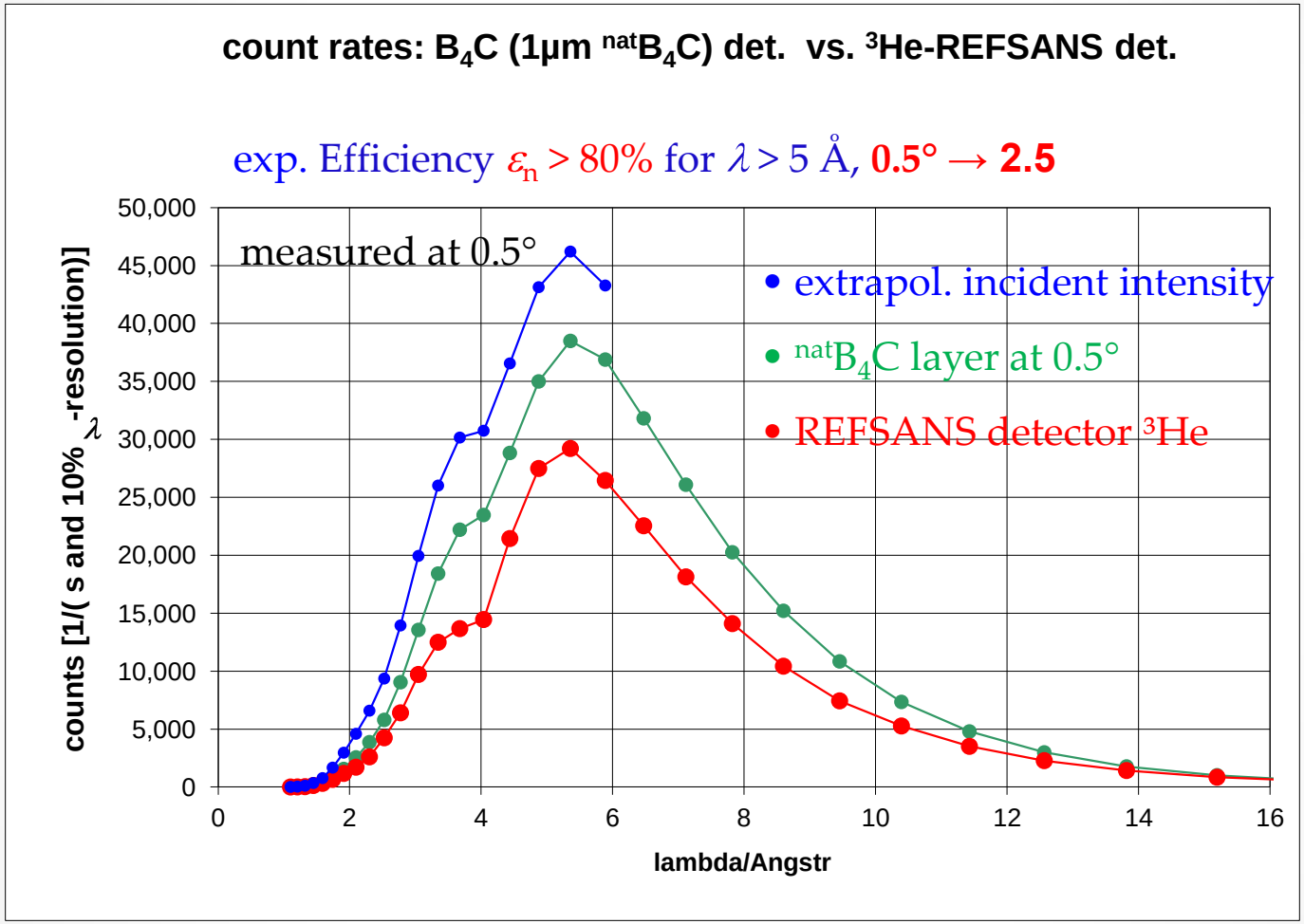


courtesy of R. Kampmann/HZG

www.denex.de

HZG – IGD First Results

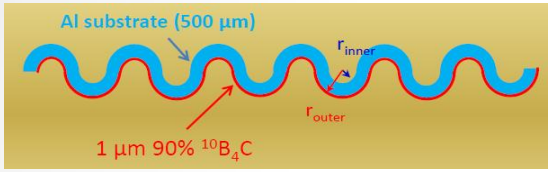




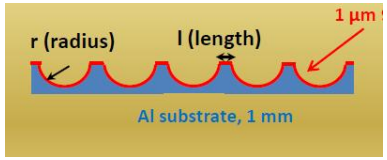
courtesy of R. Kampmann/HZG

Macro Structured Converter

The efficiency of a boron-based neutron detector can be enhanced without altering its physical volume by replacing the flat Al-substrate with one containing a regular pattern that will provide a larger sensitive area.

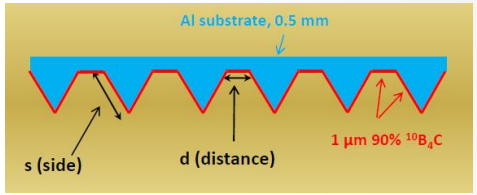


$\varepsilon_{enh.}$ ~ 40%

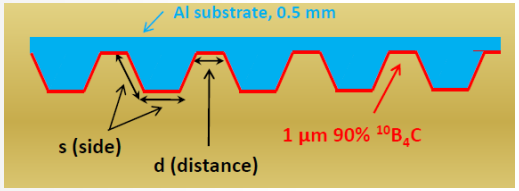


$\varepsilon_{enh.}$ ~ 30%

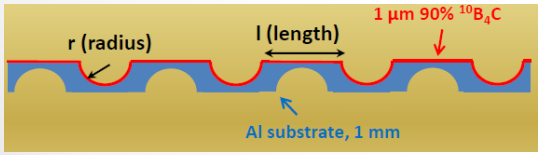
s ~ 1 mm
d ~ 0.5 mm



$\varepsilon_{enh.}$ ~ 140 %



$\varepsilon_{enh.}$ ~ 40%

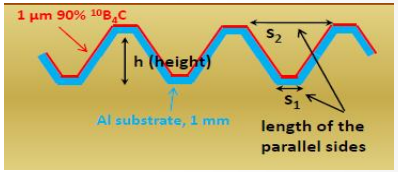


$\varepsilon_{enh.}$ ~ 20%

Simulation results:

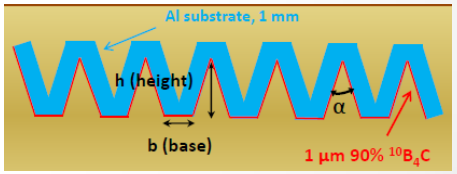
- GEANT4
- only neutron abs.
- idealized layer
- no threshold

s_1 ~ 0.5 mm
s_2 ~ 0.5 ÷ 1.1 mm
h ~ 2.2 mm



$\varepsilon_{enh.}$ ~ 150 ÷ 250%

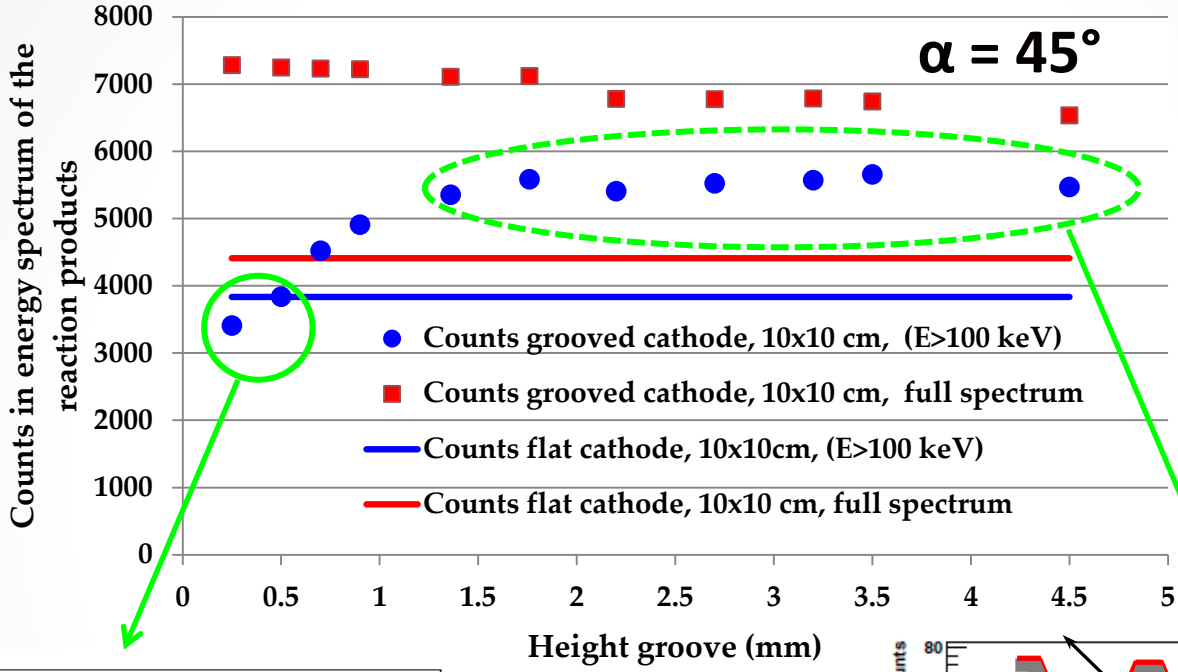
b ~ 0.9 mm
h ~ 2 ÷ 5 mm

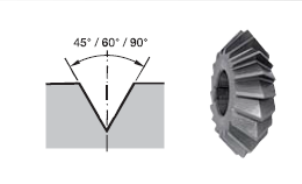


$\varepsilon_{enh.}$ ~ 110 ÷ 210%

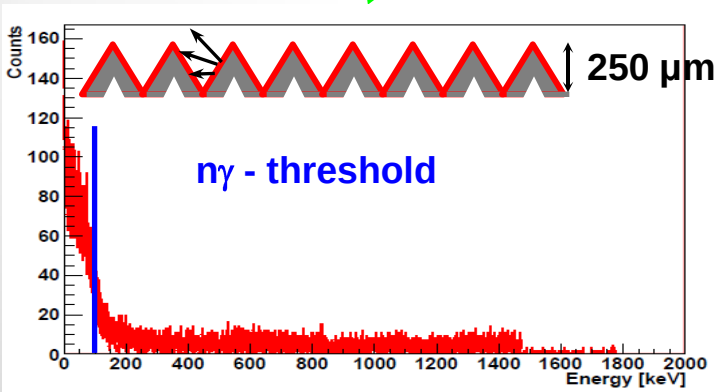
courtesy of I. Stefanescu/FRM-II

Groove Optimization by Simulation



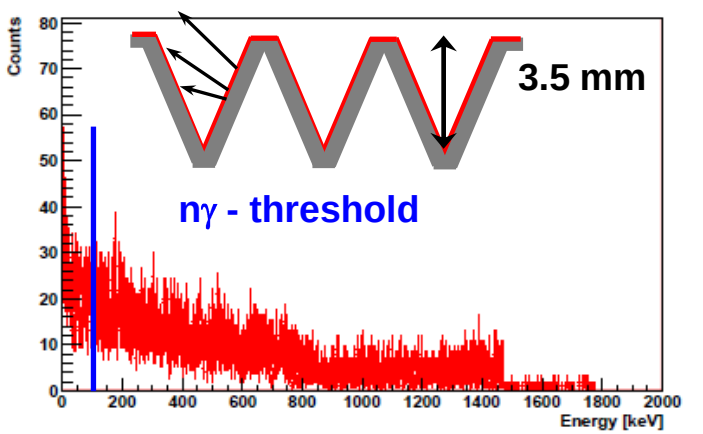


Limits for fabrication: depth (height) > 1 mm; α = 45°, 60°, 90°.

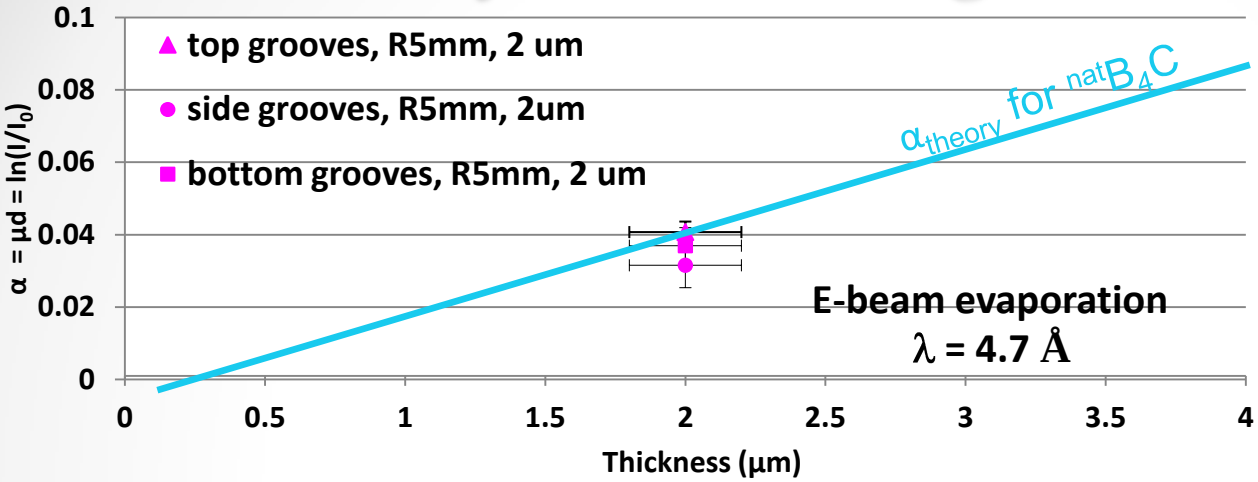


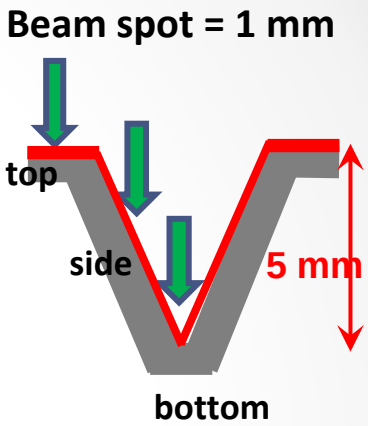
courtesy of I. Stefanescu/FRM-II

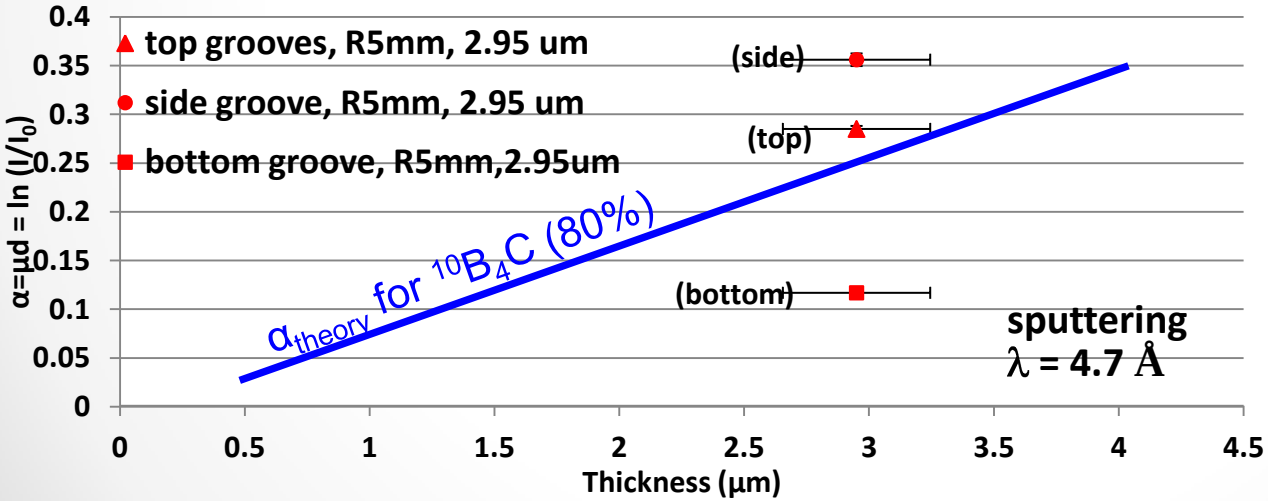
Geant4



Uniformity of Coatings – Transmission



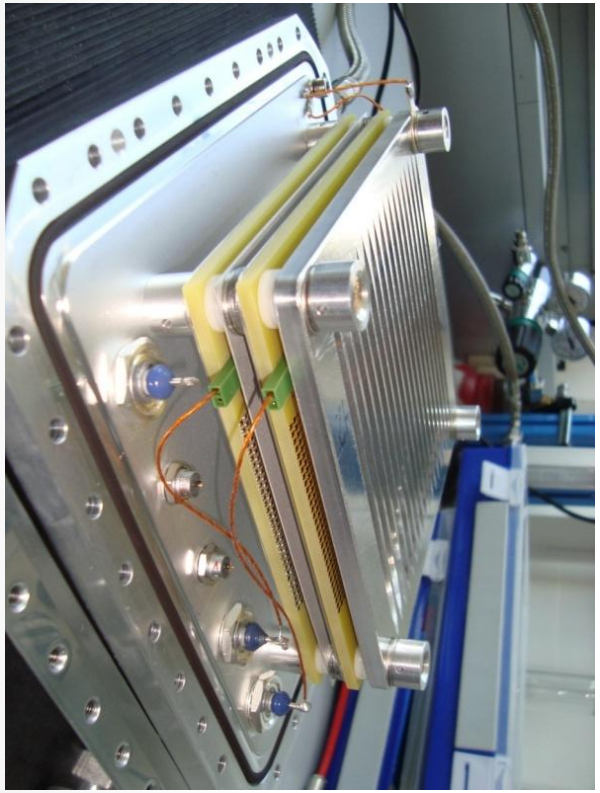




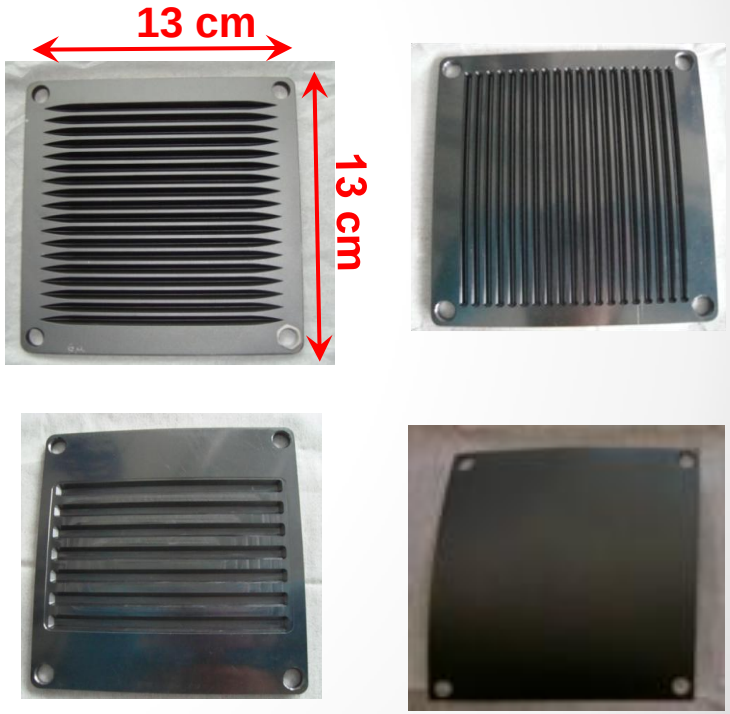
$t_{side} = t_{top} * \sin(\alpha/2)$
not valid for the sputtered groove!

courtesy of I. Stefanescu/FRM-II

Enhancement by Grooves - Experiment

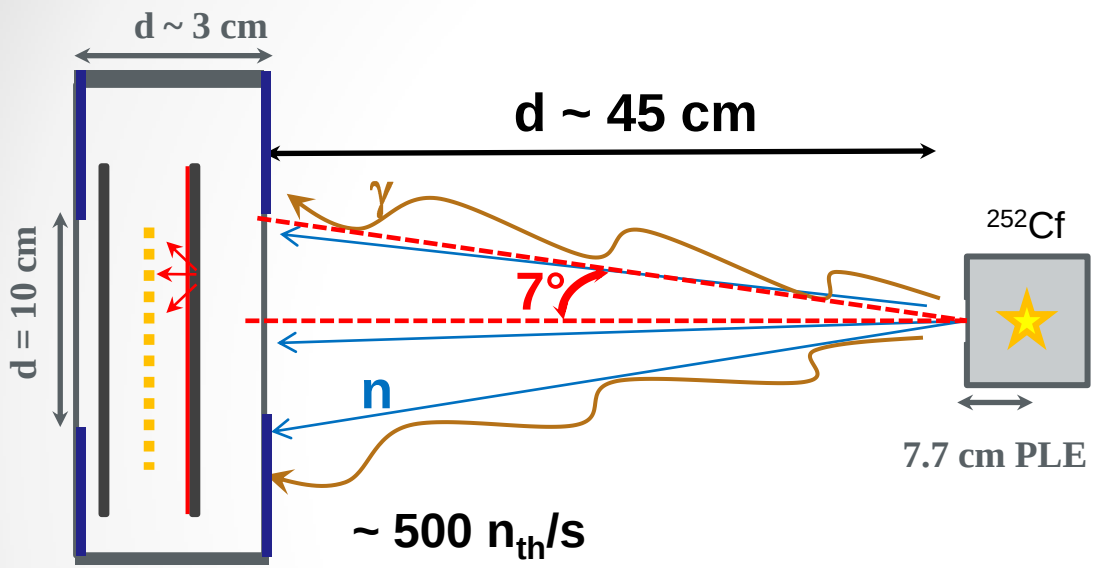


All samples coated with various thicknesses of $^{10}B_4C$ (77% ^{10}B) by magnetron sputtering at Univ. of Linköping.



courtesy of I. Stefanescu/FRM-II

Enhancement by Grooves - Experiment



All samples coated with various thicknesses of $^{10}B_4C$ (77% ^{10}B) by magnetron sputtering at Univ. of Linköping.

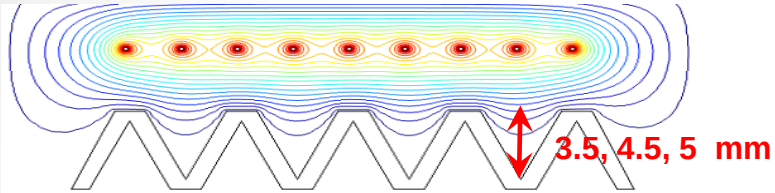
Cathode to be investigated

$$\varepsilon_{ratio} = \frac{Counts_{grooved} > 100\ keV}{Counts_{flat} > 100\ keV}$$

courtesy of I. Stefanescu/FRM-II

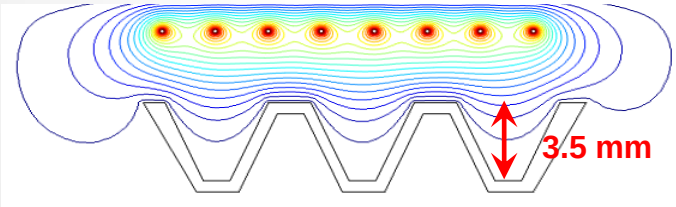
Enhancement by Grooves - Results

- GEANT4: no gas amplification
- Garfield: no unconventional electrodes
- COMSOL: calculates electrical field



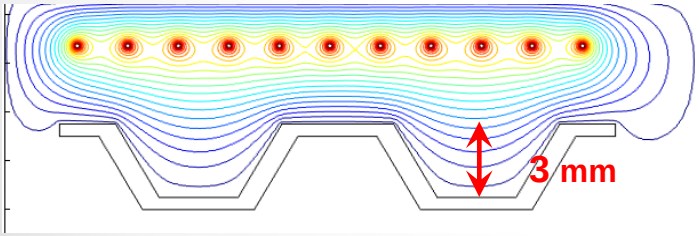
Exp: $r = N_{grooved} / N_{flat\ cathode} \sim 1.6$

Geant4: $r = 1.52$ ($\varepsilon_{charge\ collection} = 100\ \%$)



Exp: $r = N_{grooved} / N_{flat\ cathode} \sim 1.44$

Geant4: $r = 1.42$ ($\varepsilon_{charge\ collection} = 100\ \%$)



Exp: $r = N_{grooved} / N_{flat\ cathode} \sim 1.23$

Geant4: $r = 1.22$ ($\varepsilon_{charge\ collection} = 100\ \%$)

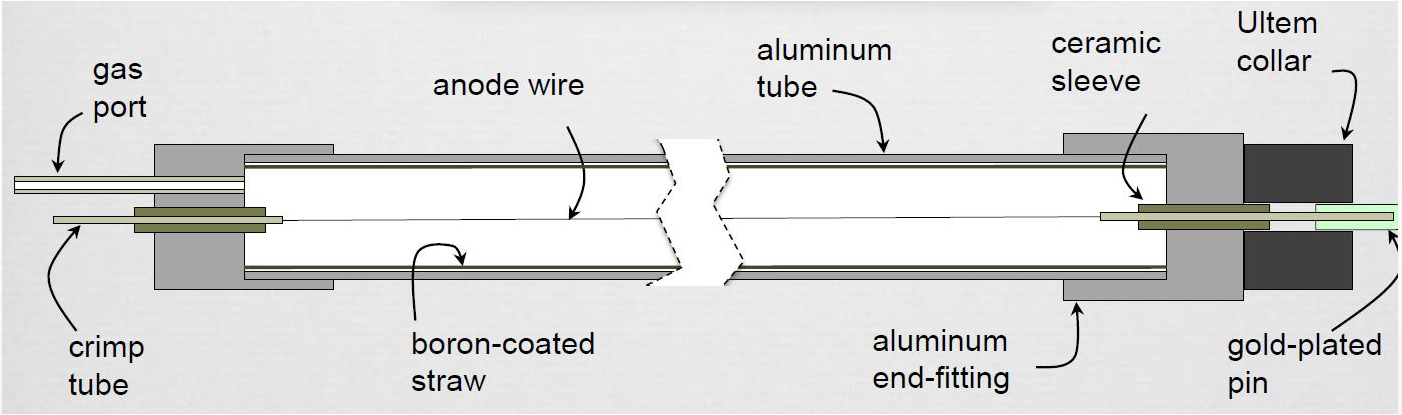
Large demonstration detector with many converters in preparation

courtesy of I. Stefanescu/FRM-II

Boron Coated Straw Tubes (BCS)

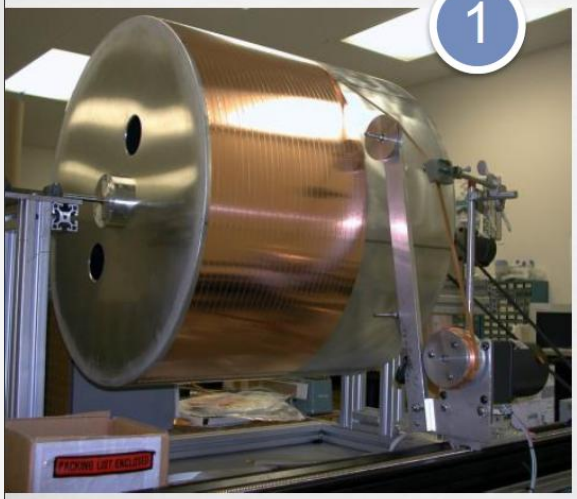
Straw tubes

- established technology
- 372,000 straw tubes in ATLAS
- diameter >=4 mm
- must be coated with ^{10}B



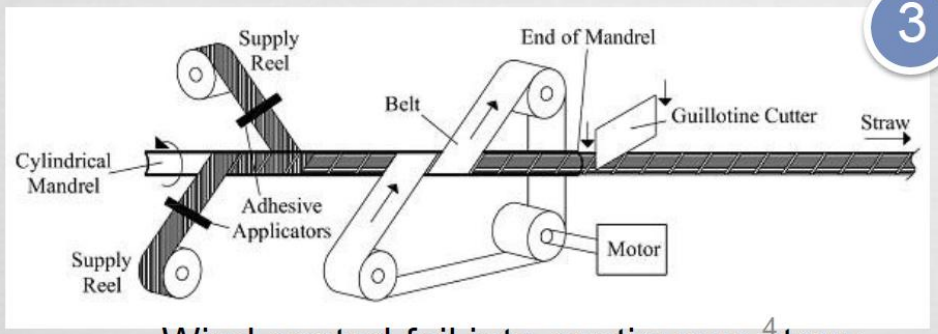
courtesy of J. Lacy, www.proportionaltech.com

Boron-Coated Straw - Construction



Wind copper foil 50 µm

Coat foil with enriched $^{10}B_4C$ in PVD chamber



Wind coated foil into continuous straw

courtesy of J. Lacy, www.proportionaltech.com

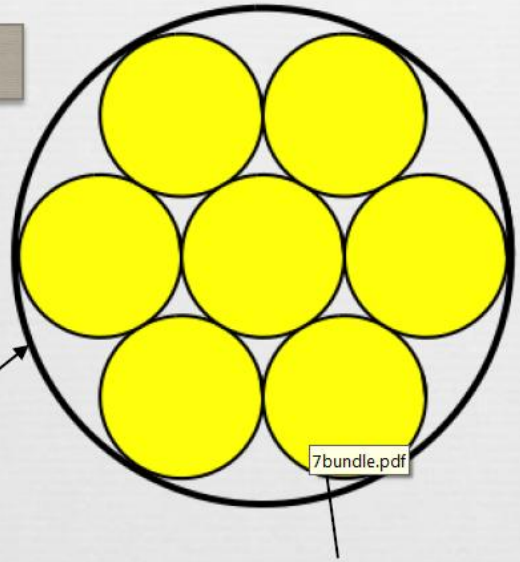
BCS - 2nd Generation (sealed)

Each straw is sealed at 10.5 psi gas mixture (Ar/CO_2, 90/10).

0.7 bar

7-straw

HV = 1000 V



Ø2..54 cm
Aluminum tube
Ø1.27 cm × 100 cm
(diameter × length)

Ø7.5 mm,

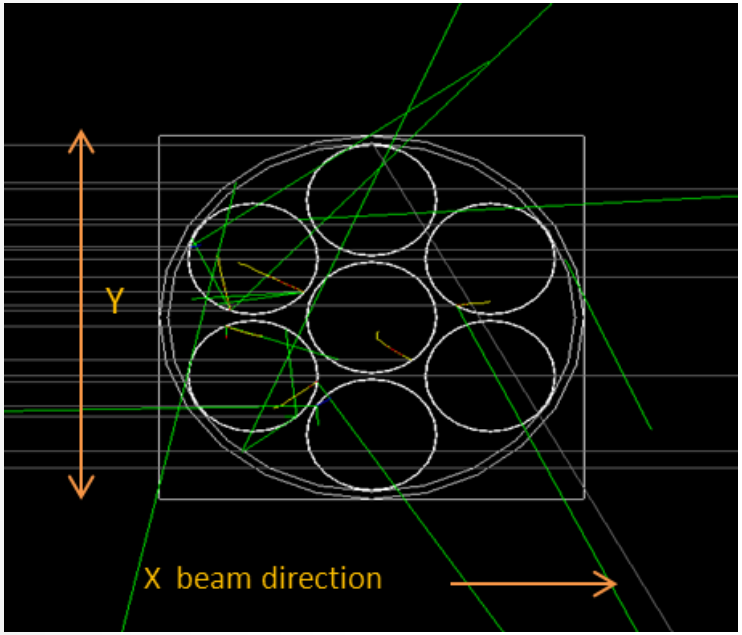
Boron-coated straw detector
Ø4 mm × 100 cm
(diameter × length)

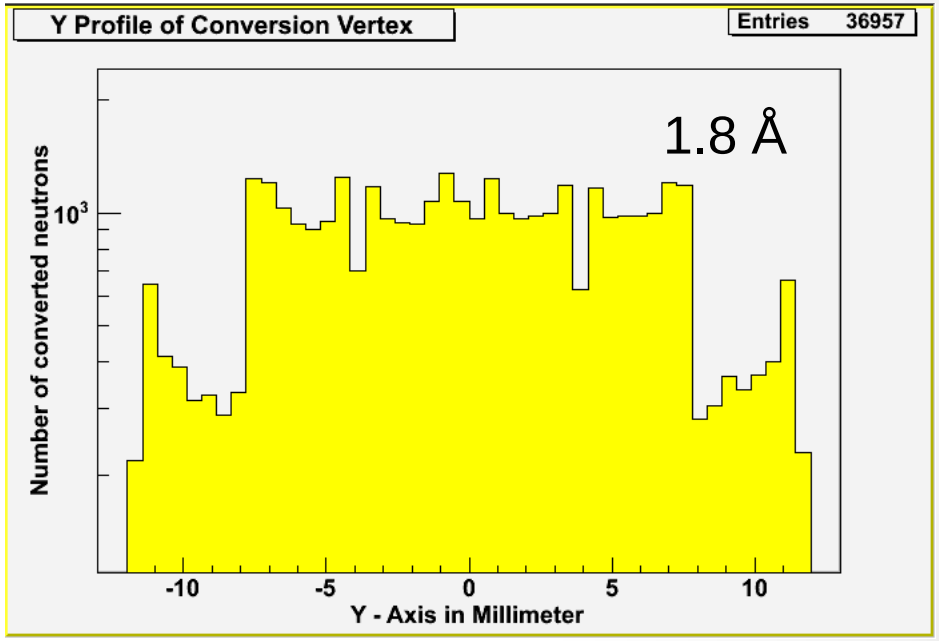
Number of straws	Neutron Detection Efficiency (thermal), %	Neutron Sensitivity (thermal), cps/nv
7	18.4	23.4
19	26.6	56.4
37	33.3	98.9
61	38.8	148
91	43.3	202

courtesy of J. Lacy, www.proportionaltech.com

Boron Coated Straw - Simulation

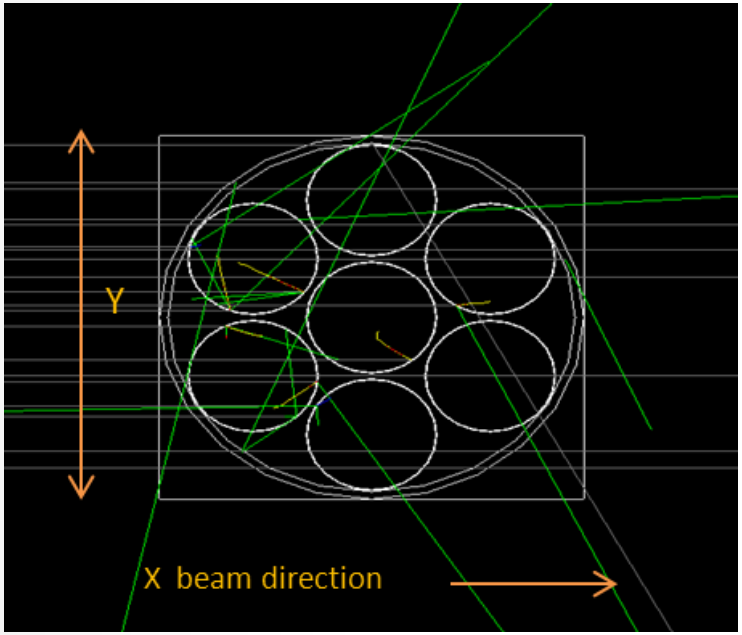
GEANT4 simulation results

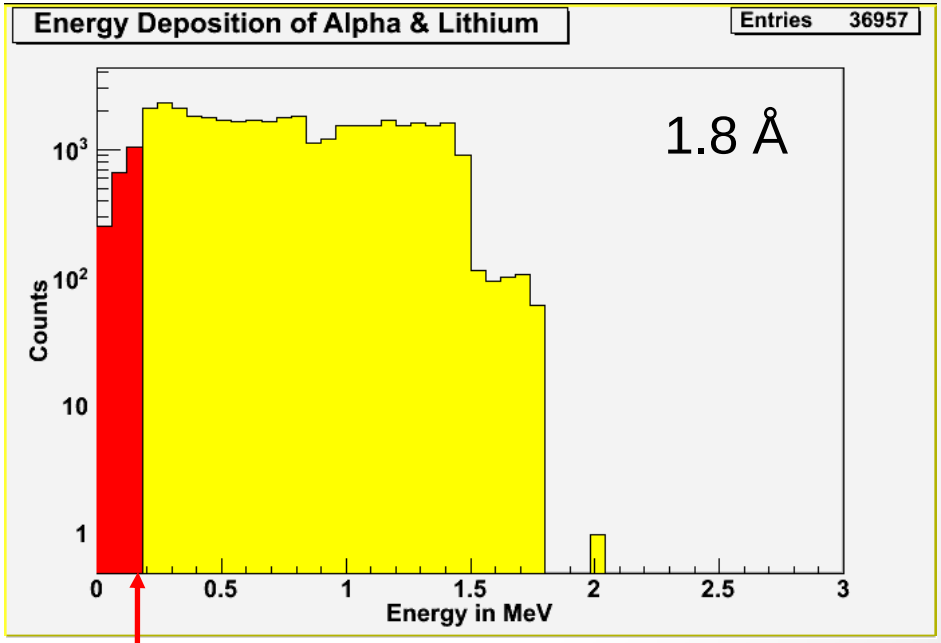




Boron Coated Straw - Simulation

GEANT4 simulation results





threshold 170 keV

Efficiency 18.5% @1.8 Å

Efficiency 33.1% @5.0 Å

Summary & Outlook

- High quality ^{10}B layers produced by magnetron sputtering
  - long-term stability/performance to be studied
  - production efforts (costs, time) must be reduced (^{10}B material ~50 €/m²)
  - other (non-vacuum) coating methods to be studied
- Divers geometric solutions under investigation
  - CASCADE, multi-grid, Jalousie, inclined, macrostructured, straw tubes
  - complexity of connected gas detectors: easy to ambitious
- Demonstrators have to prove performance in real experiments (e.g. background)
- Electronics: many channels to be readout (20 to 30 layers)
  - Low-noise (!), parallelization, coding, single channel with ASICs?

Thank you!

Material for slides with the help of

J. Correa	ILL
B. Guerard	ILL
C. Höglund	ESS/Linköping Univ.
R. Kampmann	HZG
A. Kaplanov	ILL/ESS
M. Klein	Univ. Heidelberg, n-CDT
J. Lacy	Proportional Technology, Inc.
G. Nowak	HZG
Ch. J. Schmidt	GSI, n-CDT
I. Stefanescu	FRM-II
M. Störmer	HZG
K. Zeitelhack	FRM-II

HZB Detector Group (S. Alimov, Ch. Schulz, Ch. Rethfeldt, ThW)