Status and Challenges for Neutron Detectors for Neutron Scattering

- Neutron Scattering
- Neutron Detectors and He-3 Crisis
- ESS
- Examples of detector R+D ongoing

ERDIT Meeting@CERN

11 April 2013

Richard Hall-Wilton

Detector Group Leader, ESS

Caveat Emptor

- Presented here is a biased sample
- ...chosen what is going on associated with ESS as indicative of general direction
- ... wide variety, difficult to generalise ...

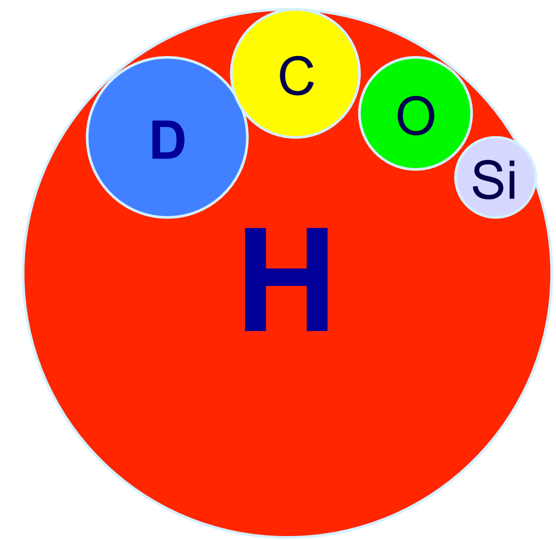
Neutron Scattering

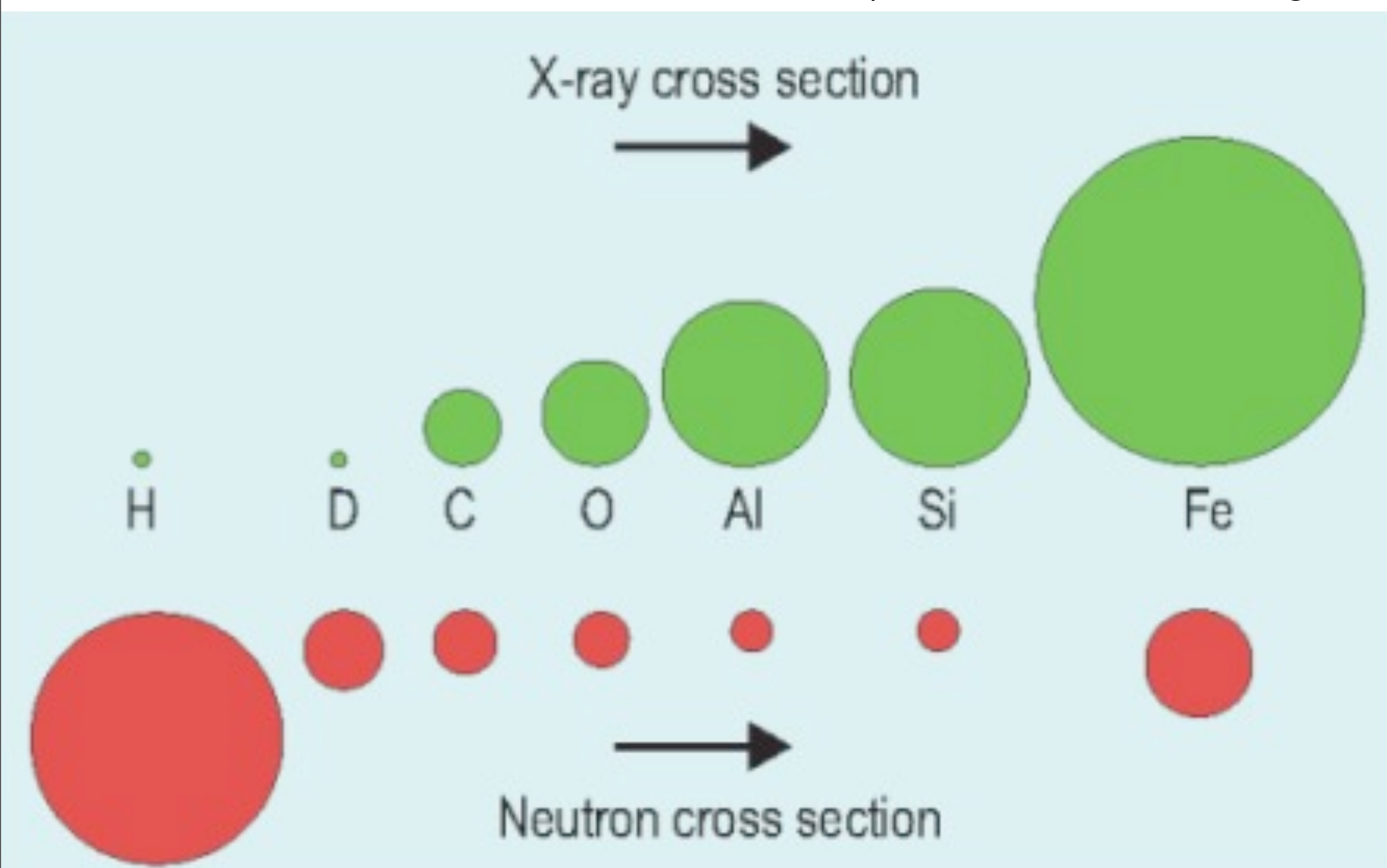
EUROPEAN SPALLATION SOURCE

Why Neutrons?

Neutrons are
- low energy
- non-damaging
- penetrating
- broad wavelength range

1) Ability to measure both energy *and* momentum transfer
   Geometry of motion
2) Neutrons scatter by a nuclear interaction => different isotopes scatter differently
   H and D scatter very differently
3) Simplicity of the interaction allows easy interpretation of intensities
   Easy to compare with theory and models
4) Neutrons have a magnetic moment





thermal and cold neutrons
meV
"with a small m"
wavelength ca. Å

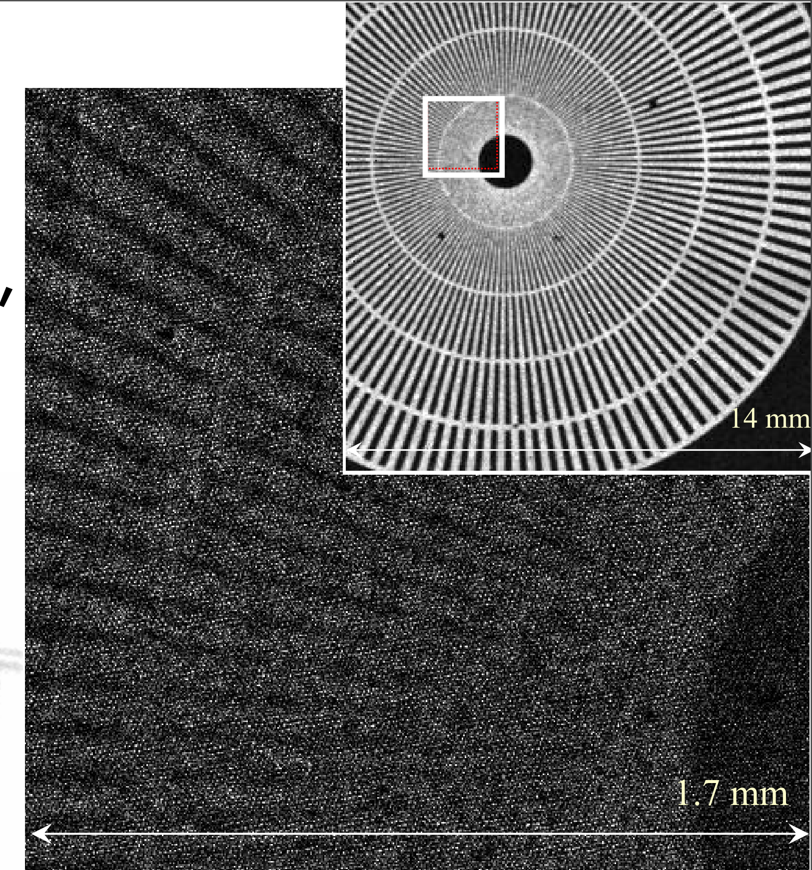
What do the detectors need to measure?

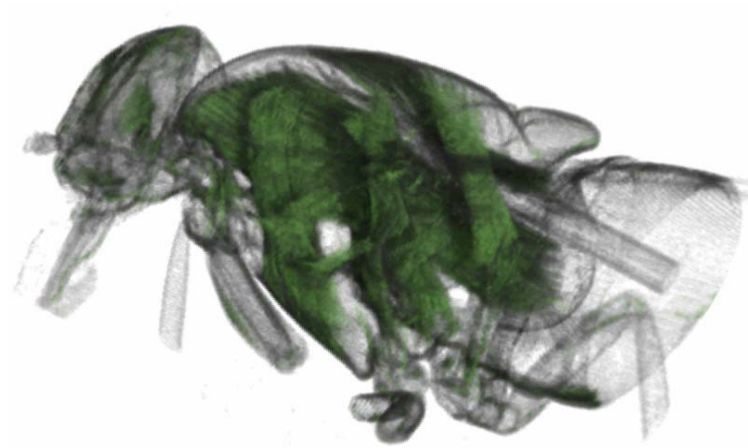
- Neutron Scattering for materials science comprise a great variety of instruments as tools for studying materials
- High efficency is expected
- Each has its own “figure of merit”

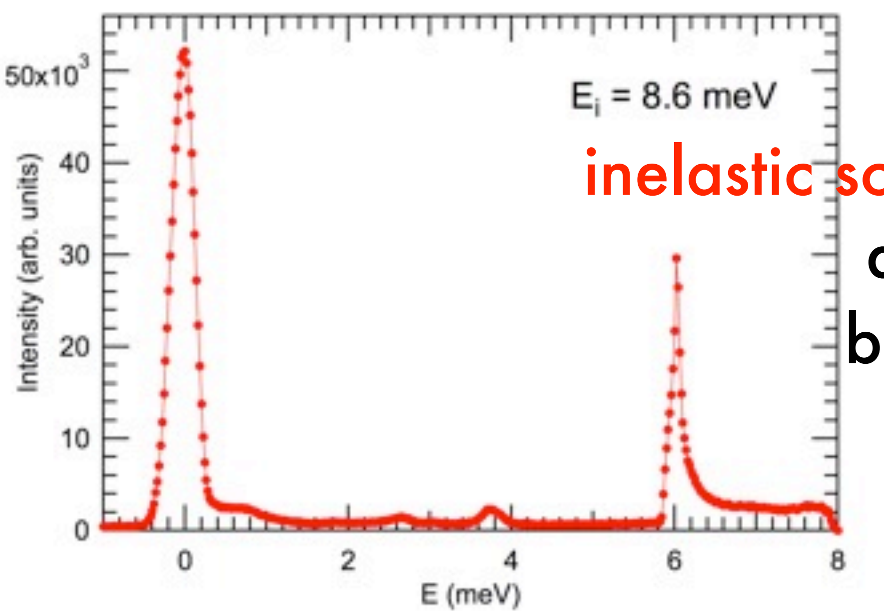
“horses for courses ”

imaging

resolution (<100um), rate

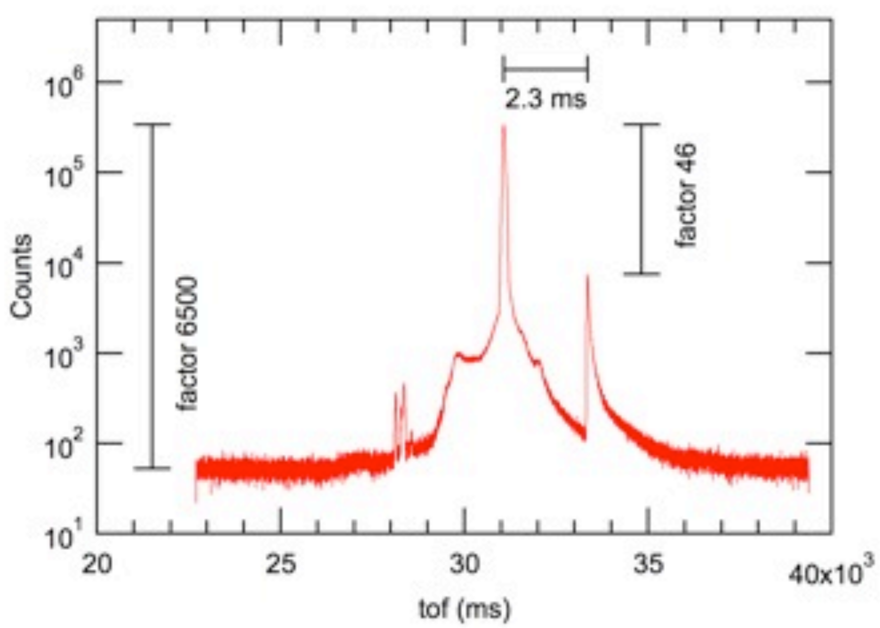






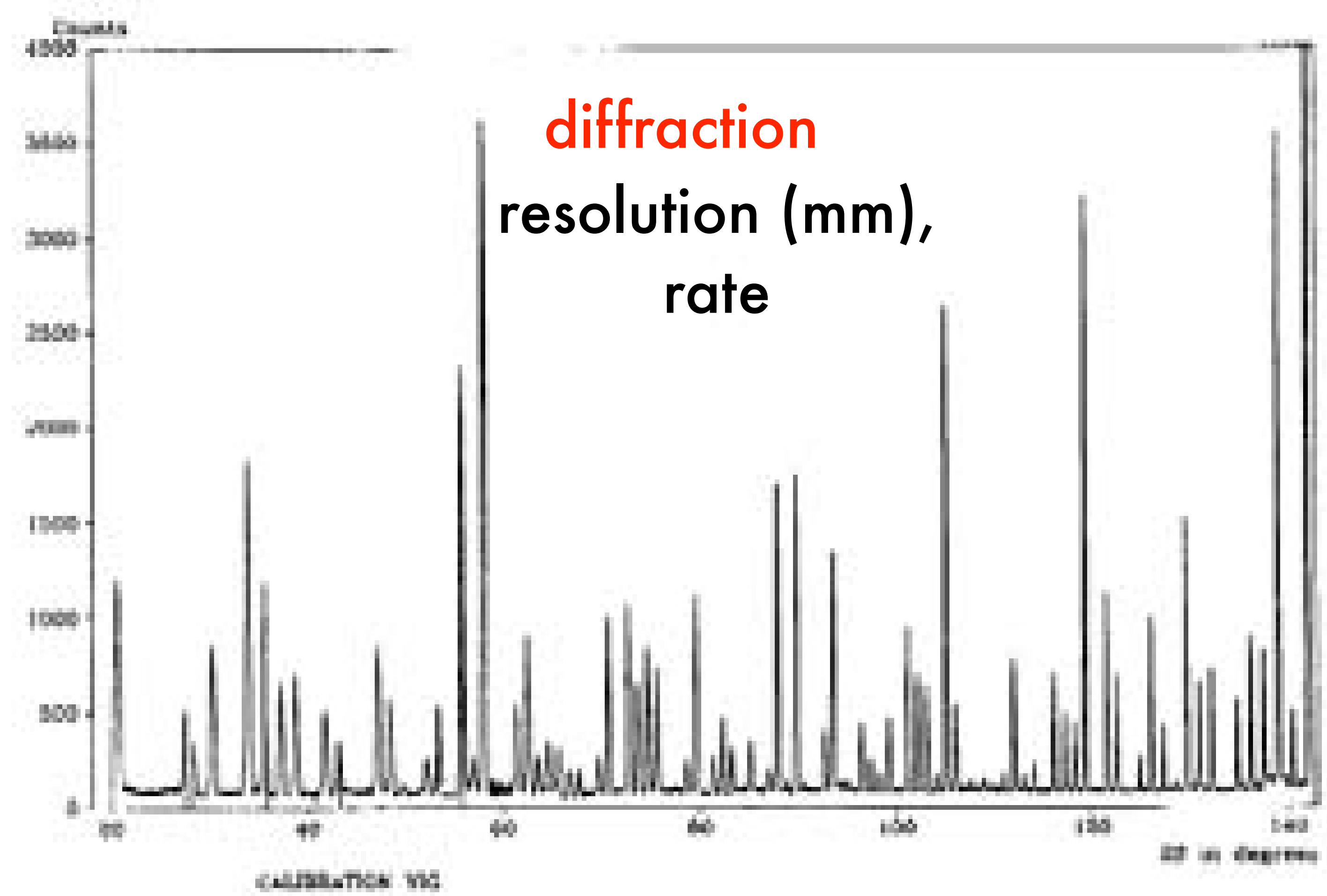
inelastic scattering

area, cost, background



diffraction

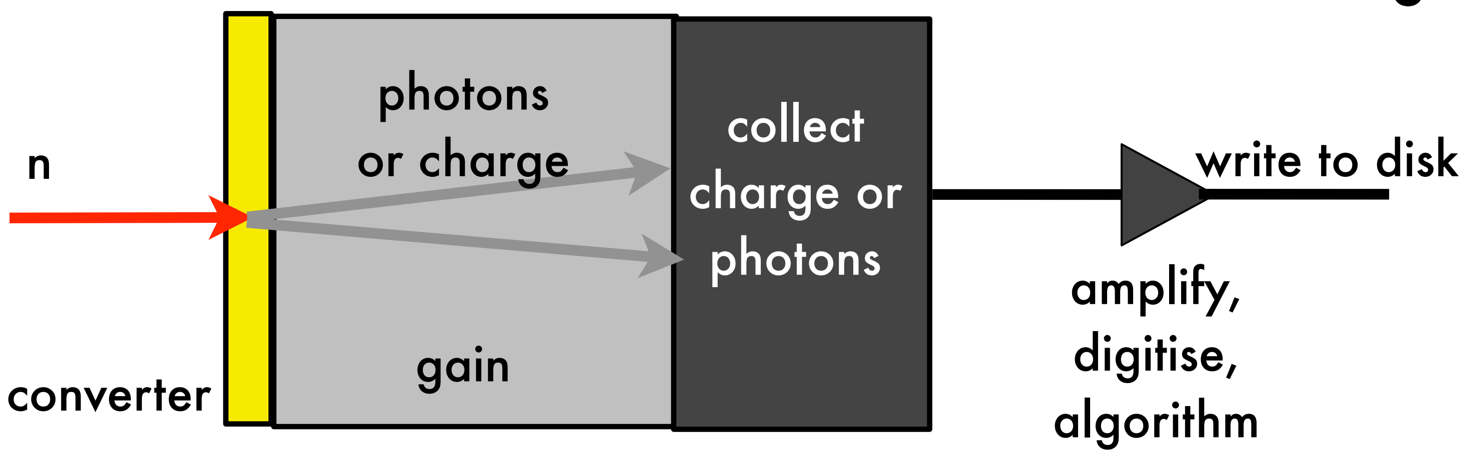
resolution (mm), rate

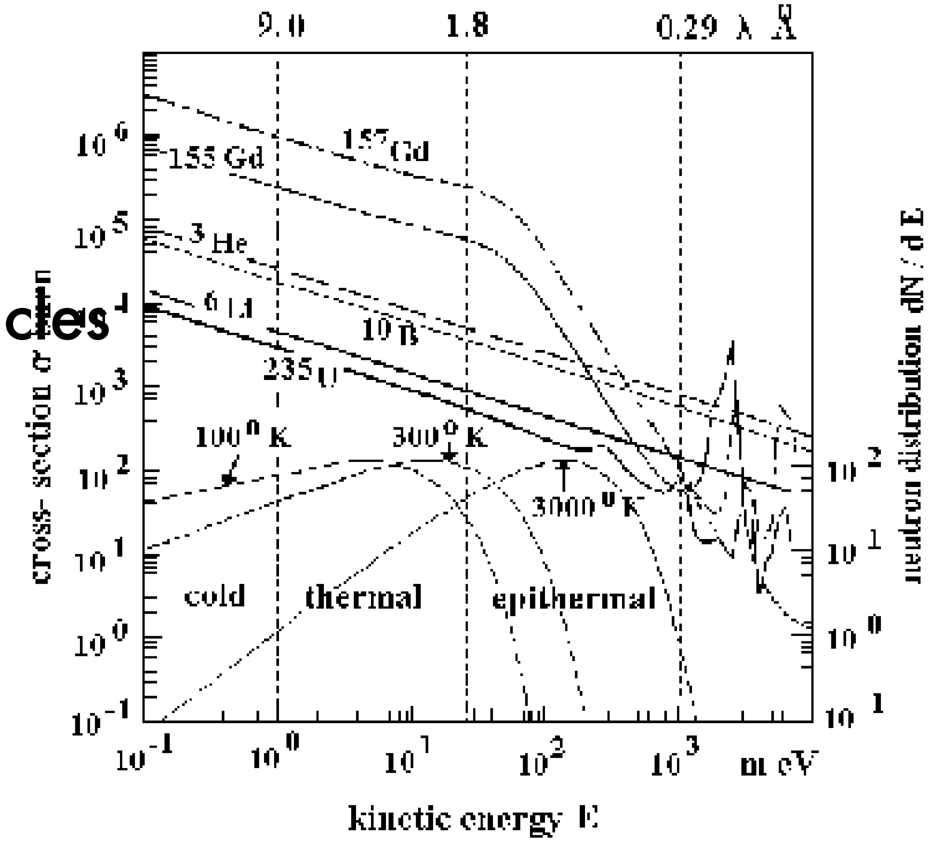


Neutron Detectors and the Helium-3 Crisis

Basic Principles of Neutron Detectors

- Not possible to directly detect slow neutrons
- Use nuclear reactions to convert neutrons to charged particles





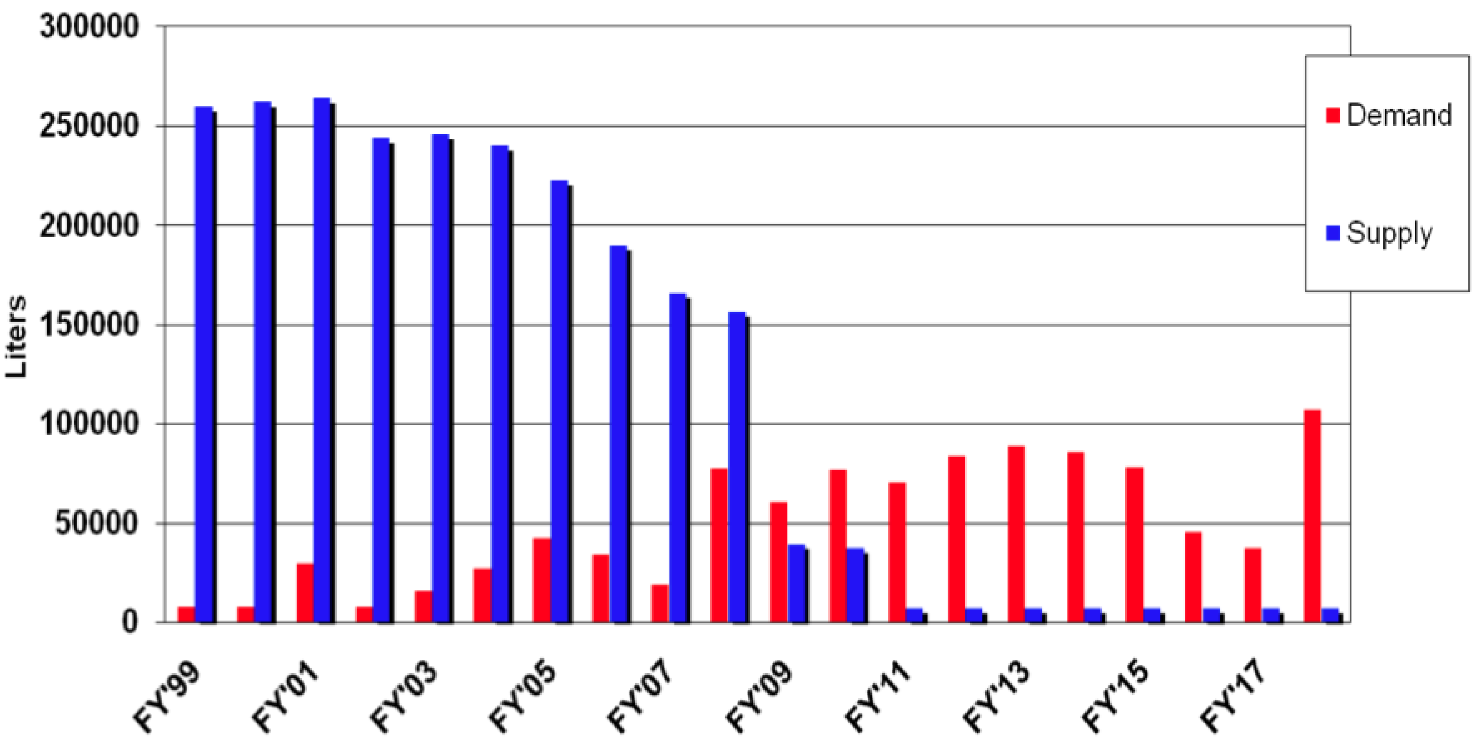
- Count neutrons: all other information lost in nuclear reaction

reaction	energy	particle	energy	particle	energy
n (^{3}He, p) ^{3}H	+0.77 MeV	p	0.57 MeV	^{3}H	0.19 MeV
n (^{6}Li, α) ^{3}H	+4.79 MeV	α	2.05 MeV	^{3}H	2.74 MeV
93 % n (^{10}B, α)^{7}Li +2.3 MeV + γ (0.48MeV)		α	1.47 MeV	^{7}Li	0.83 MeV
7 % n (^{10}B, α) ^{7}Li	+2.79 MeV	α	1.77 MeV	^{7}Li	1.01 MeV
n (^{235}U, Lfi) Hfi	+ ~ 100 MeV	Lfi	< = 80 MeV	Hfi	< = 60 MeV
n (^{157} Gd, Gd) e$^-$	+ < = 0.182 MeV	conversion electron			0.07 to 0.182 MeV

Table 1: Commonly used isotopes for thermal neutron detection, reaction products and their kinetic energies.

... Old News Now ...

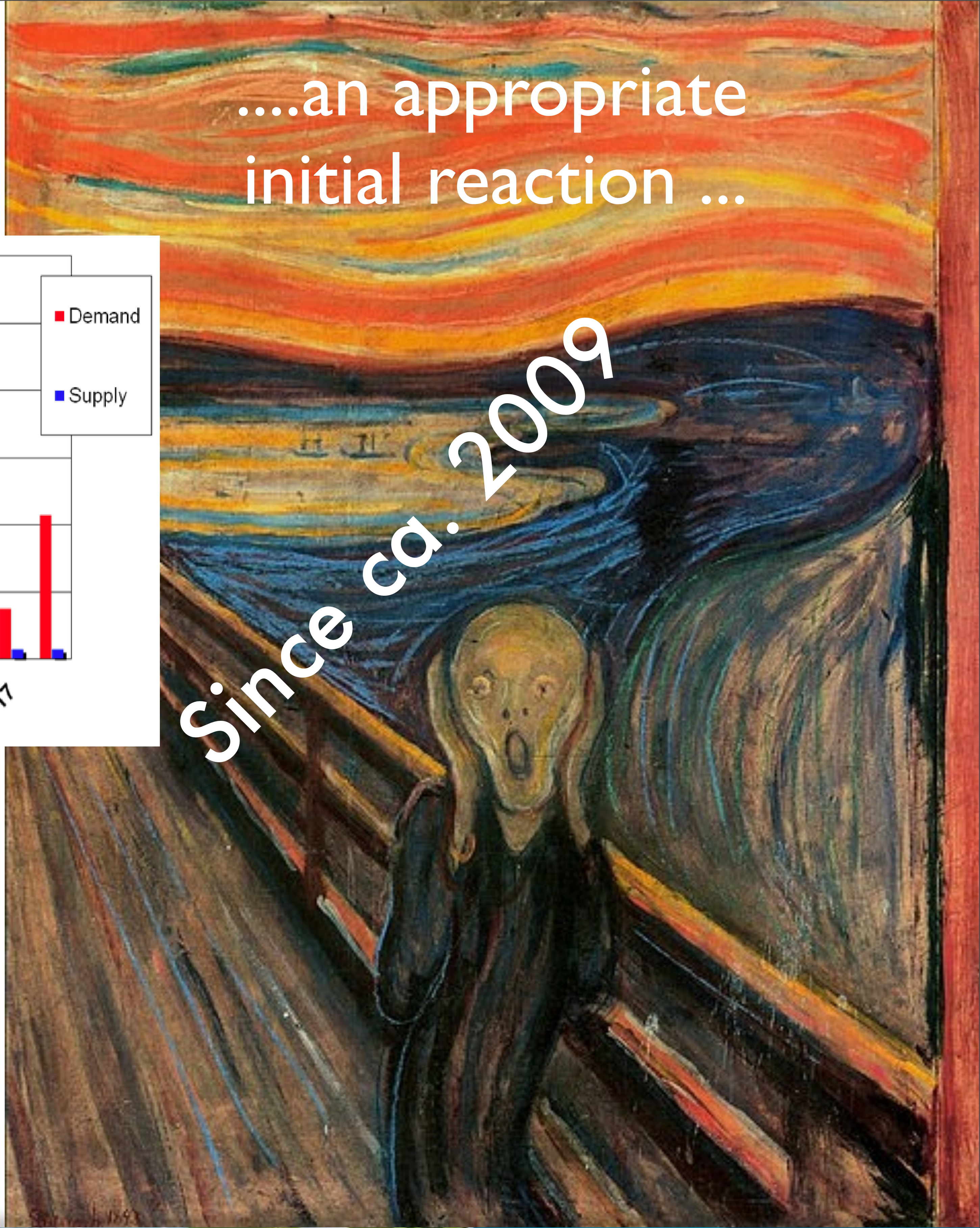
He-3 Crisis



Little or None Available

Aside ... maybe He-3 detectors are anyway not what is needed for ESS? eg rate, resolution reaching the limit ...

Crisis or opportunity ... ?




... lots of work
ongoing now ...
Since ca. 2010

icnd.org {

INTERNATIONAL COLLABORATION FOR THE DEVELOPMENT OF NEUTRON DETECTORS }

Home
Collaboration
Working Groups
Publications
News & Events
Imprint

Collaboration

Participating Facilities

ESS	European Spallation Source, Sweden
FRM II	Forschungs-Neutronenquelle Heinz Maier-Leibnitz, Germany
HZB	Helmholtz Zentrum Berlin, Germany
ILL	Institut Max von Laue – Paul Langevin, France
ISIS	Science and Technology Facilities Council, UK
JCNS	Jülich Centre for Neutron Science, Germany
J-PARC	Japan Proton Accelerator Research Complex, Japan
NIST	Centre for Neutron Research, USA
ORNL	Neutron Science Directorate, Oak Ridge National Laboratory, USA

Coordination

K. Zeitelhack, FRM II, GER; E-Mail: karl.zeitelhack@frm2.tum.de

Working Group Coordination

Scintillation detectors:	N.J. Rhodes, STFC, UK;	E-Mail: nigel.rhodes@stfc.ac.uk
B10 – detectors:	B. Guerard, ILL, France;	E-Mail: guerard@ill.fr
BF3 – detectors:	T. Wilpert, HZB, GER;	E-Mail: wilpert@helmholtz-berlin.de

(... but no BF3 detectors for ESS ...)

The European Spallation Source

High-intensity spallation sources

Plus many reactor sources, including ILL, Grenoble - worlds leading research reactor

(Note that many existing sources planning upgrades presently)

The ESS Site

The ESS Site

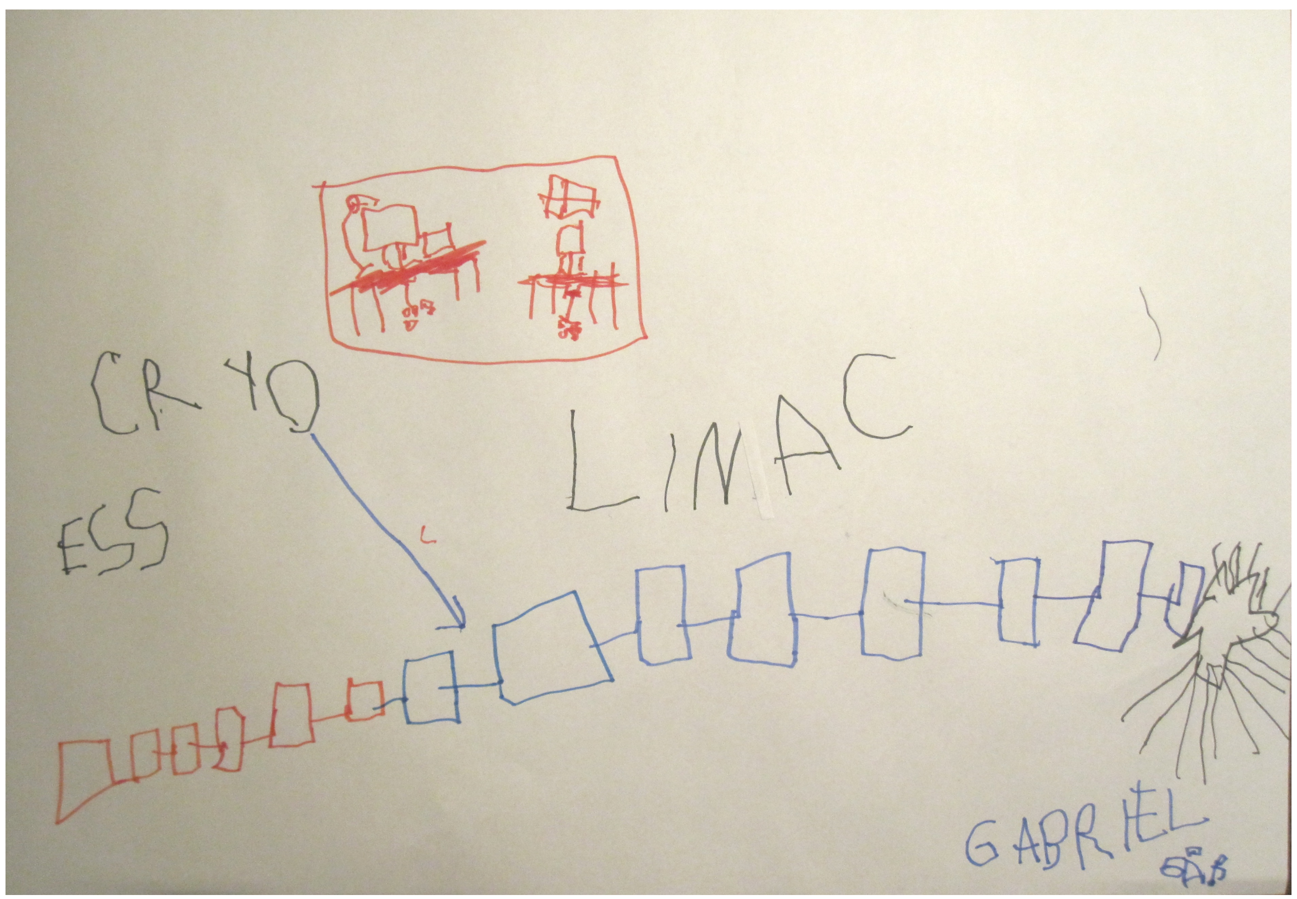

webbkameror.se
EUROPEAN
SPALLATION
SOURCE
23 October 2012

ESS Technical Design Report

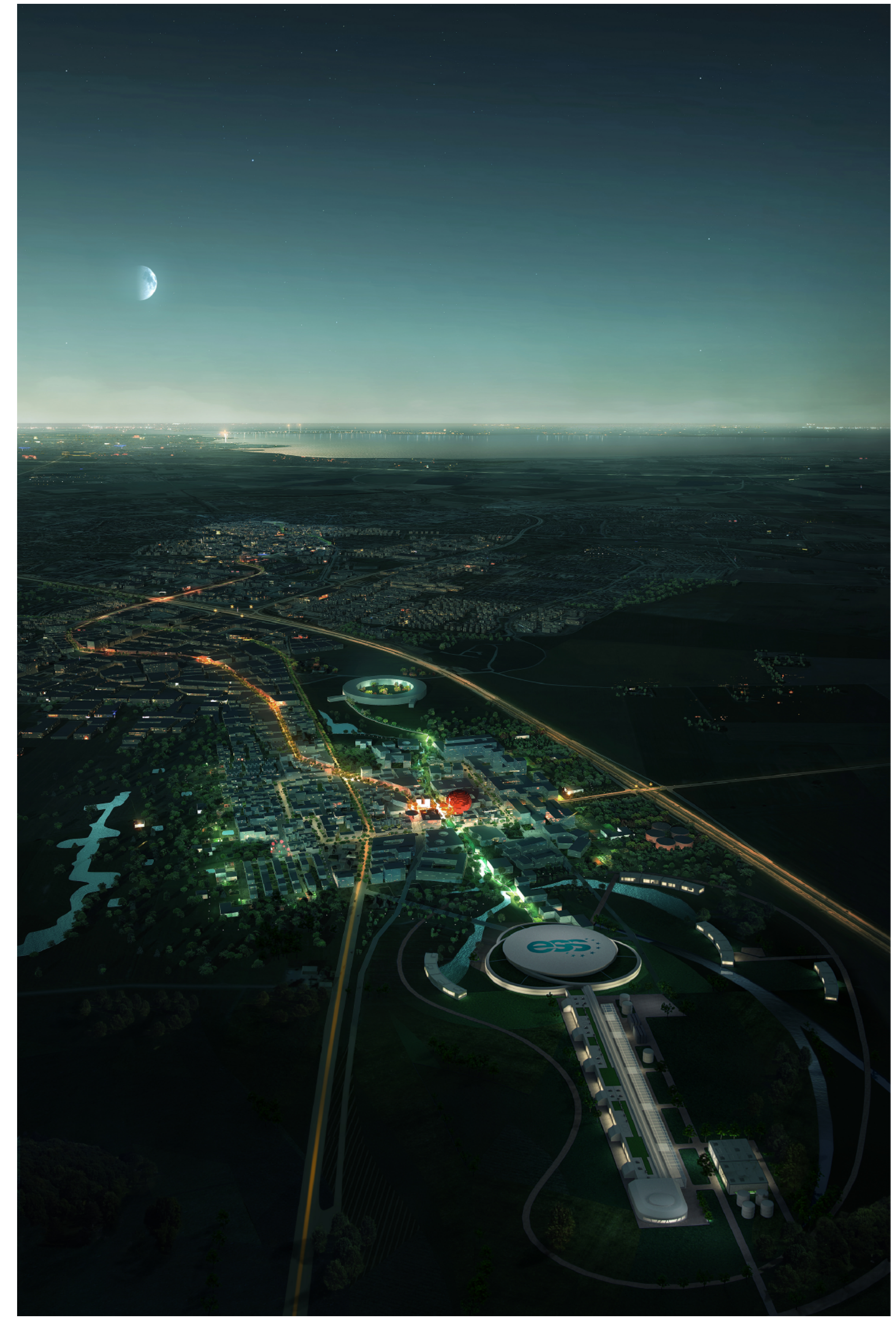
- ESS TDR about to be published
- Will serve as a baseline for construction

Feb '12

ESS Conceptual Design Report



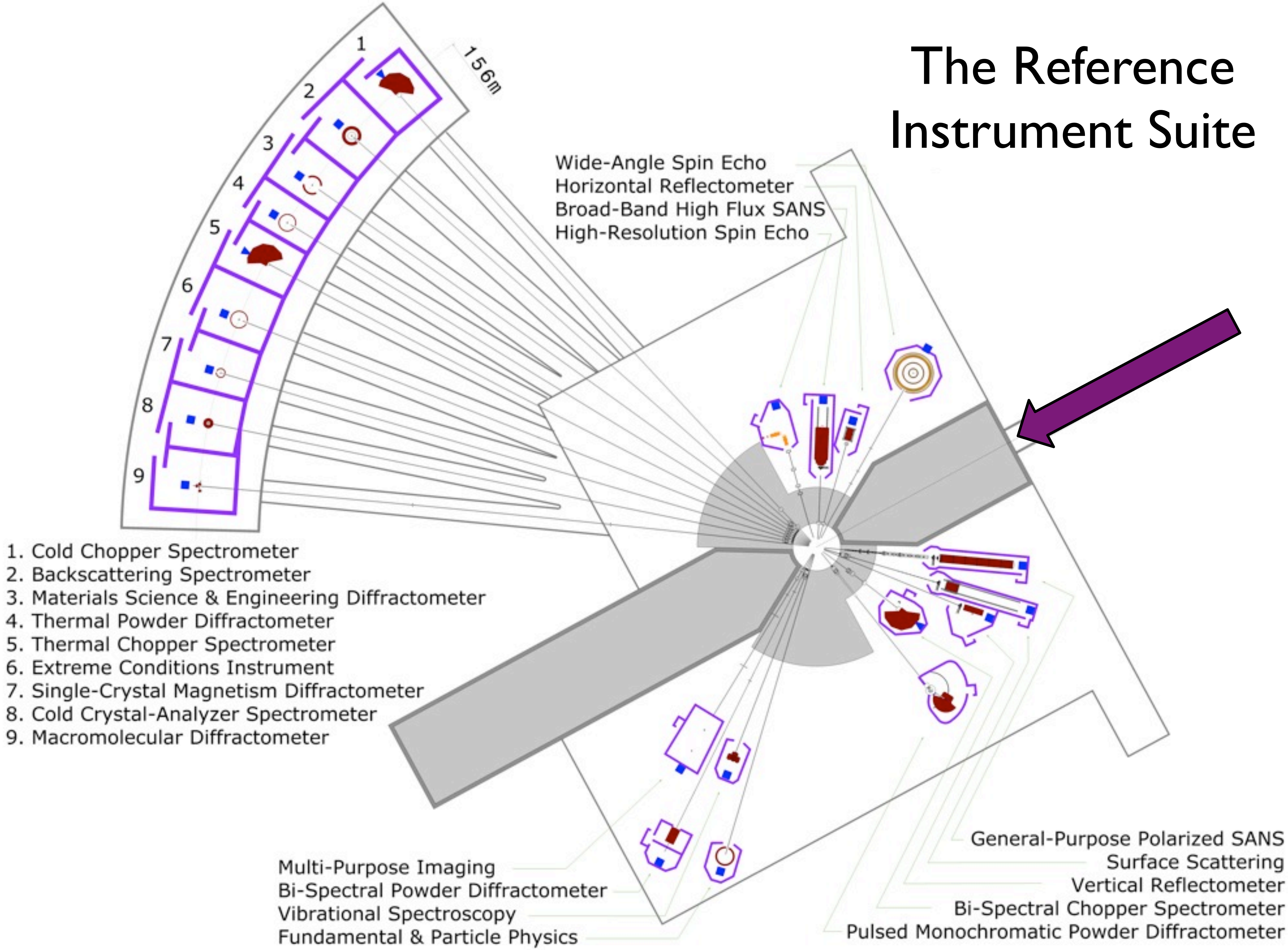
ESS Technical Design Report



Release 2.0

February 5, 2013

The Reference Instrument Suite



Detector R+D going on connected with ESS

Detector Requirements for Baseline TDR Suite

Instrument	Detector Area [m^2]	Wavelength Range [Å]	Time Resolution [μs]	Resolution [mm]
Multi-Purpose Imaging	0.5	1-20	1	0.001 - 0.5
General Purpose Polarised SANS	5	4-20	100	10
Broad-Band Small Sample SANS	14	2-20	100	1
Surface Scattering	5	4-20	100	10
Horizontal Reflectometer	0.5	5-30	100	1
Vertical Reflectometer	0.5	5-30	100	1
Thermal Powder Diffractometer	20	0.6-6	<10	2x2
Bi-Spectral Powder Diffractometer	20	0.8-10	<10	2.5x2.5
Pulsed Monochromatic Powder Diffractometer	4	0.6-5	<100	2 x 5
Material Science & Engineering Diffractometer	10	0.5-5	10	2
Extreme Conditions Instrument	10	1-10	<10	3x5
Single Crystal Magnetism Diffractometer	6	0.8-10	100	2.5x2.5
Macromolecular Diffractometer	1	1.5-3.3	1000	0.2
Cold Chopper Spectrometer	80	1 -20	10	10
Bi-Spectral Chopper Spectrometer	50	0.8-20	10	10
Thermal Chopper Spectrometer	50	0.6-4	10	10
Cold Crystal-Analyser Spectrometer	1	2-8	<10	5-10
Vibrational Spectroscopy	1	0.4-5	<10	10
Backscattering Spectrometer	0.3	2-8	<10	10
High-Resolution Spin Echo	0.3	4-25	100	10
Wide-Angle Spin Echo	3	2-15	100	10
Fundamental & Particle Physics	0.5	5-30	1	0.1
Total	**282.6**			

Estimates

Table 2.5: Estimated detector requirements for the 22 reference instruments in terms of detector area, typical wavelength range of measurements and desired spatial and time resolution.

- Specifications very varied
- Typically superior to what is presently state-of-the-art at existing sources

- In many cases, instrument performance dominated by S:B rather than raw specifications here

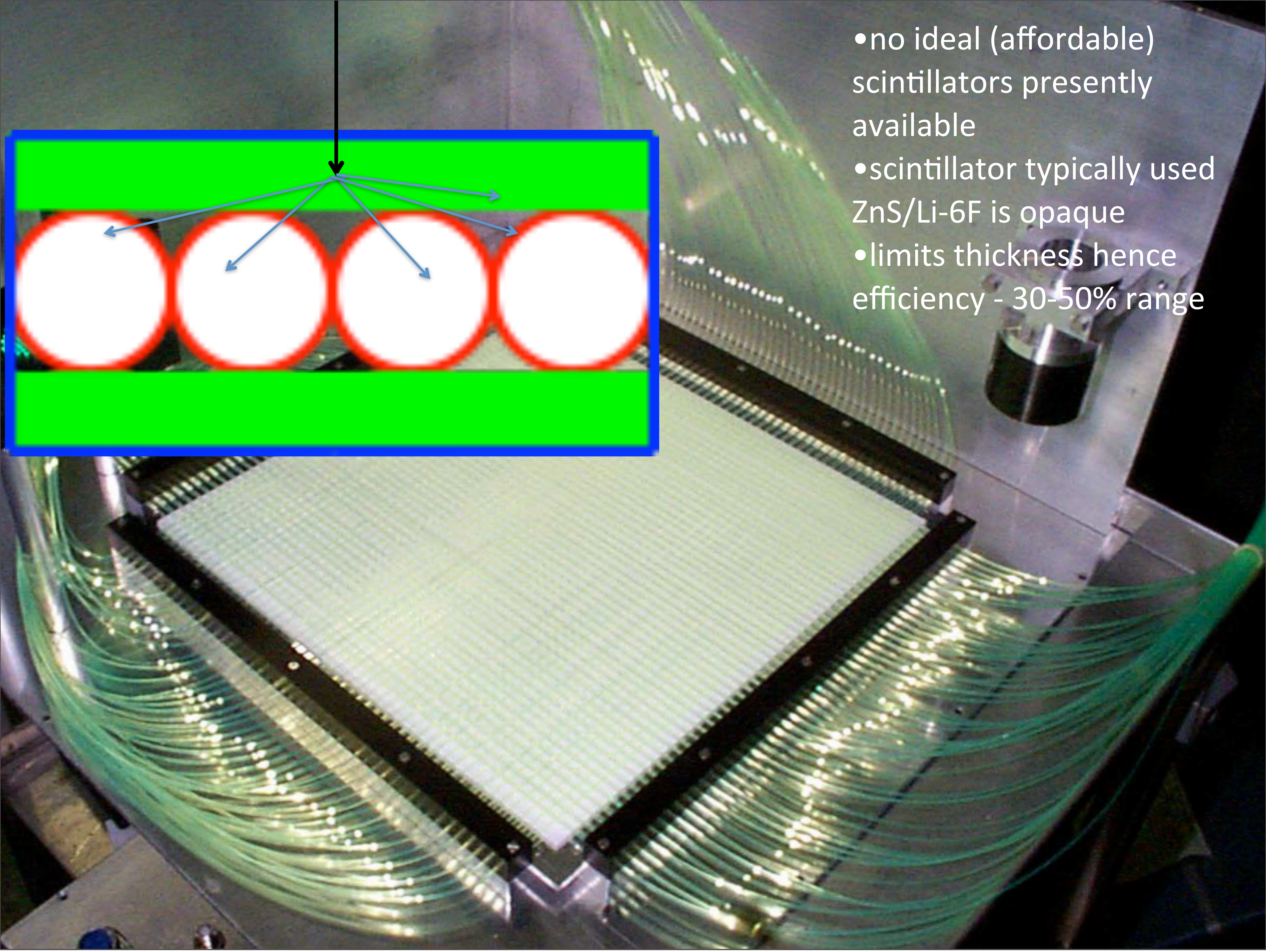
Detector Options for Baseline TDR Suite

Instrument	Detector Technology						
	^{10}B Thin Films		Scintillators		^{3}He	Micropattern	
	⊥	∥	WLS	Anger		Rate	Resolution
Multi-Purpose Imaging	-	-	-	-	-	o	+
General Purpose Polarised SANS	o	+	-	+	o	+	-
Broad-Band Small-Sample SANS	o	+	-	+	-	+	-
Surface Scattering	o	+	-	+	o	+	-
Horizontal Reflectometer	-	o	-	+	+	o	-
Vertical Reflectometer	-	o	-	+	+	o	-
Thermal Powder Diffractometer	o	+	+	-	-	o	-
Bi-Spectral Powder Diffractometer	o	+	+	-	-	o	-
P-M Powder Diffractometer	o	+	+	-	-	o	-
MS Engineering Diffractometer	o	+	+	-	-	o	-
Extreme Conditions Diffractometer	o	+	+	-	-	o	-
Single Crystal Diffractometer	o	+	+	-	-	o	-
Macromolecular Diffractometer	-	o	o	o	-	+	+
Cold Chopper Spectrometer	+	o	o	-	-	-	-
Bi-Spectral Chopper Spectrometer	+	+	o	-	-	-	-
Thermal Chopper Spectrometer	+	+	+	-	-	-	-
Cold Crystal Analyser Spectrometer	-	o	-	+	+	-	-
Vibrational Spectrometer	-	o	-	o	+	-	-
Backscattering Spectrometer	-	o	-	+	+	-	-
High-Resolution Spin Echo	-	o	-	o	+	+	-
Wide-Angle Spin Echo	-	o	-	o	+	+	-
Fundamental & Particle Physics	-	-	-	-	+	+	+

Preliminary

+ = favoured option
o = option
- = disfavoured option

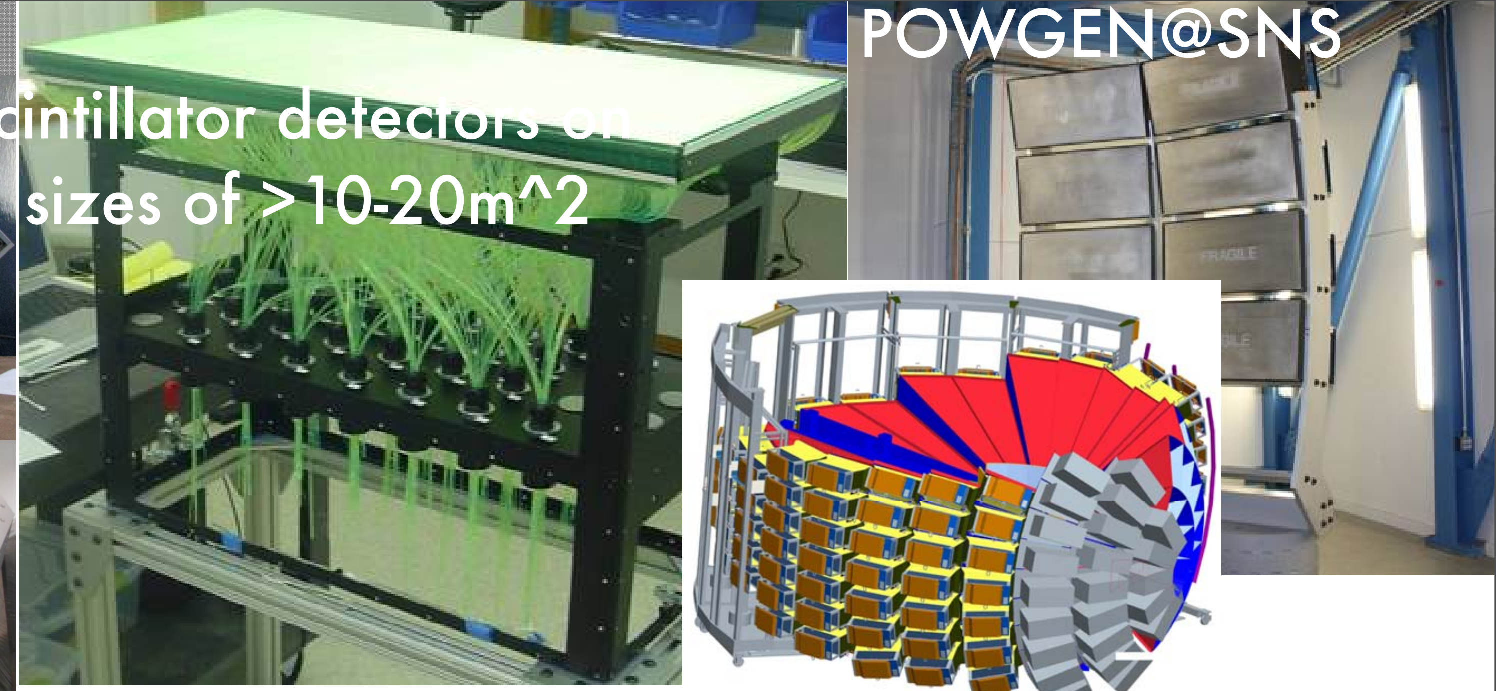
- Most instruments have "He-3-free" options
- Requirement for He-3 significantly reduced
- An array of technologies will be used
- dependent upon a wide range of sources for detectors



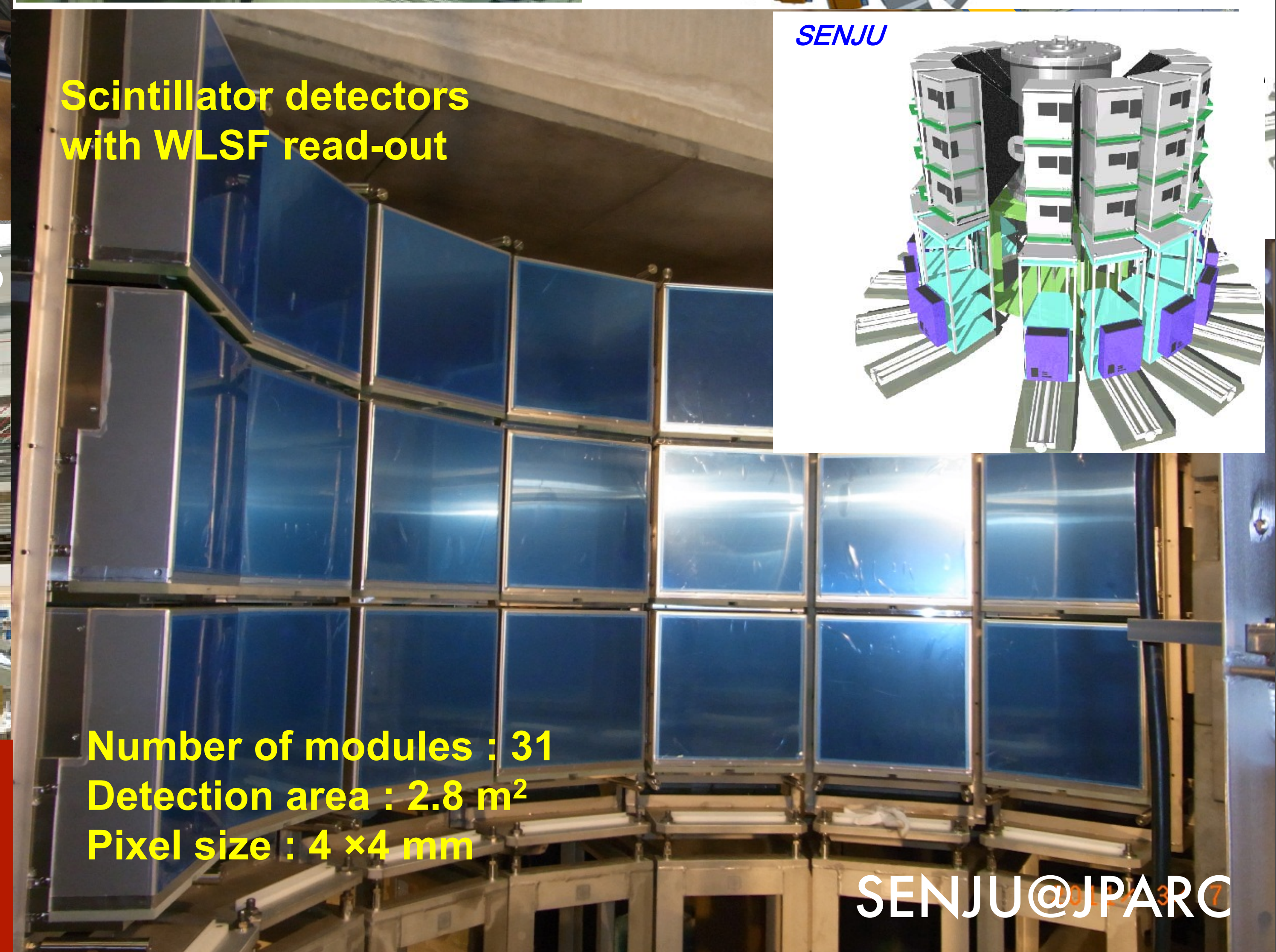
- no ideal (affordable) scintillators presently available
- scintillator typically used ZnS/Li-6F is opaque
- limits thickness hence efficiency - 30-50% range

POLARIS DETECTORS

Latest generation of scintillator detectors on instruments reaching sizes of >10-20m^2



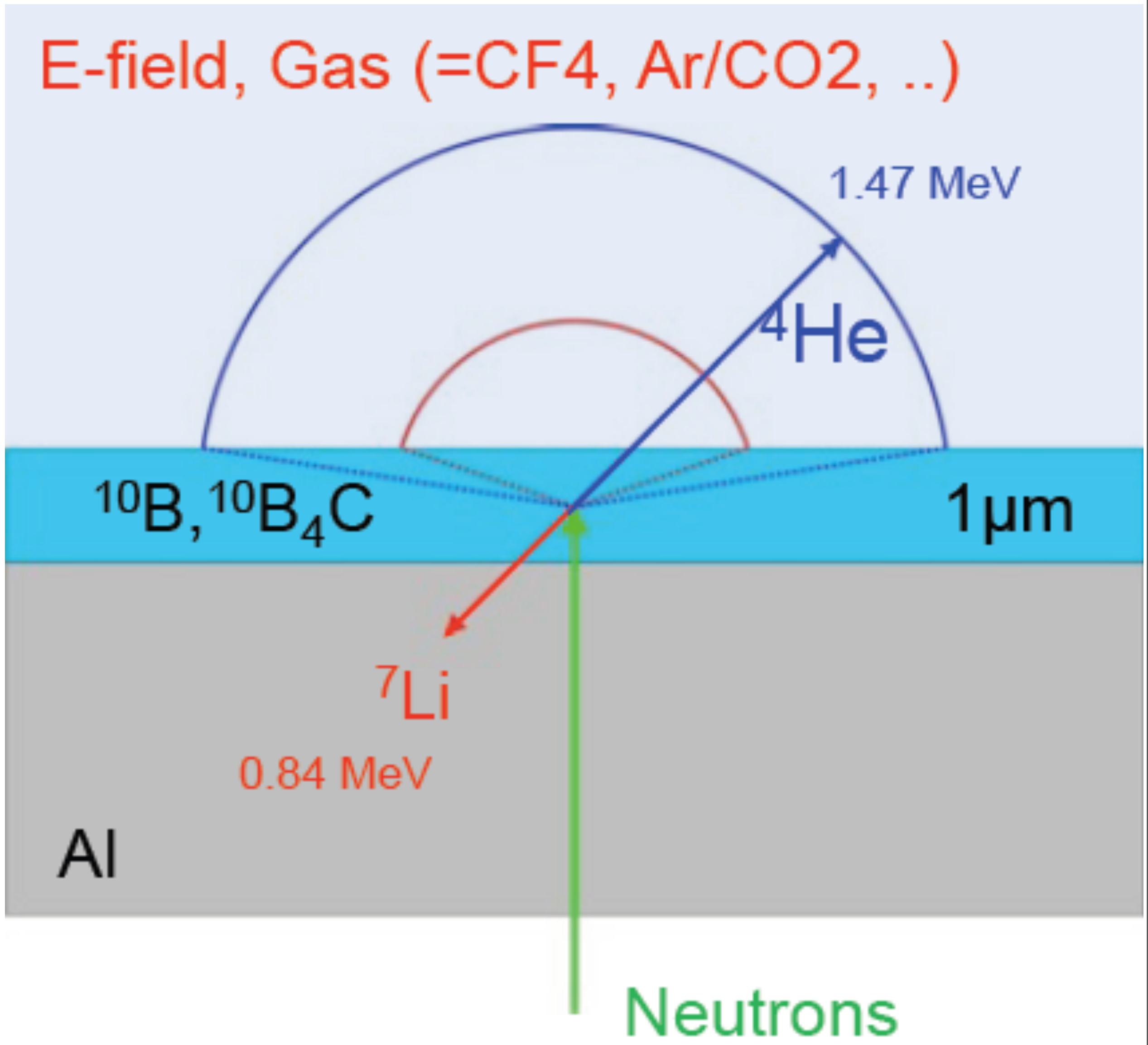
If we needed instruments tomorrow, scintillators or BF3 only option
For B-10 it is a matter of "catch-up"



The Boron-10 Detector Principle

- ^{10}B has a neutron absorption of 70% compared to ^{3}He at $\lambda = 1.8$ Å
- ^{nat}B contains
  80 at.% ^{11}B and
  20 at.% ^{10}B
- $^{10}B + n \rightarrow {}^{7}Li + \alpha + 2.3$ MeV

•charged products emitted back to back
•only 1 enters gas volume
•anode wire / electric field to amplify
•collect signal from ionisation process (anode and/or cathode)



Thin precise coatings of Boron Carbide with good adhesion are the key ingredient

2nd International 10B BF3 Detectors' Workshop

Institut Laue Langevin
Grenoble, France
13-14 March 2012

NEUTRONS FOR SCIENCE ®
Institut Laue-Langevin

For larger detectors, pathway is becoming clearer ...

Tuesday 13 March 2012

K. Zeitelhack: "Detector development based on ^{3}He alternatives"

Session 1: ^{10}B detectors (part 1)

M. Koza: "Guidelines for a time-of-flight spectrometer detector optimized for material science"
J. Lacy: "A large-area, multi-tube neutron imaging detector based on $^{10}B_4C$ coated straws"
M. Klein: "the ^{10}B based Jalousie neutron detector - an alternative for ^{3}He filled position sensitive counter tubes"
J. Correa: "On the efficiency of the $^{10}B_4C$ MultiGrid Neutron Detector"
JF Clergeau: "Study of a MultiGrid prototype for IN6"

Session 2: Coating techniques

Y. Yang: "Boron lined gaseous detector research in Tsinghua University"
P. Chaudhari: "Neutron absorber boron carbide thin films by hot-wire chemical vapor deposition technique"
C. Höglund: "$^{10}B_4C$ thin films for neutron detection"
A. Khaplanov: "Optimization and diagnostics of $^{10}B_4C$ coatings for the MultiGrid detector"
G. Nowak: "Recent progress of magnetron sputtered B4C - converter layers onto Si substrates and Al detector plates"

Wednesday 14 March 2012

N. Rhodes: "Detector JRA in FP7-2"
R. Hall-Wilton: "Latest news from ESS"

Session 3: ^{10}B detectors (part 2)

A. Menelle: "A Micromegas thermal neutron detector with ^{10}B layers"
I. Stefanescu: "Development of a cathode design for large area neutron detectors based on Boron-10 converters"
F. Piscitelli: "Gamma-ray sensitivity of ^{10}B based MultiGrid detectors"
R. Kampmann: "First tests of Thin Conversion Layers in Inclined Geometry"

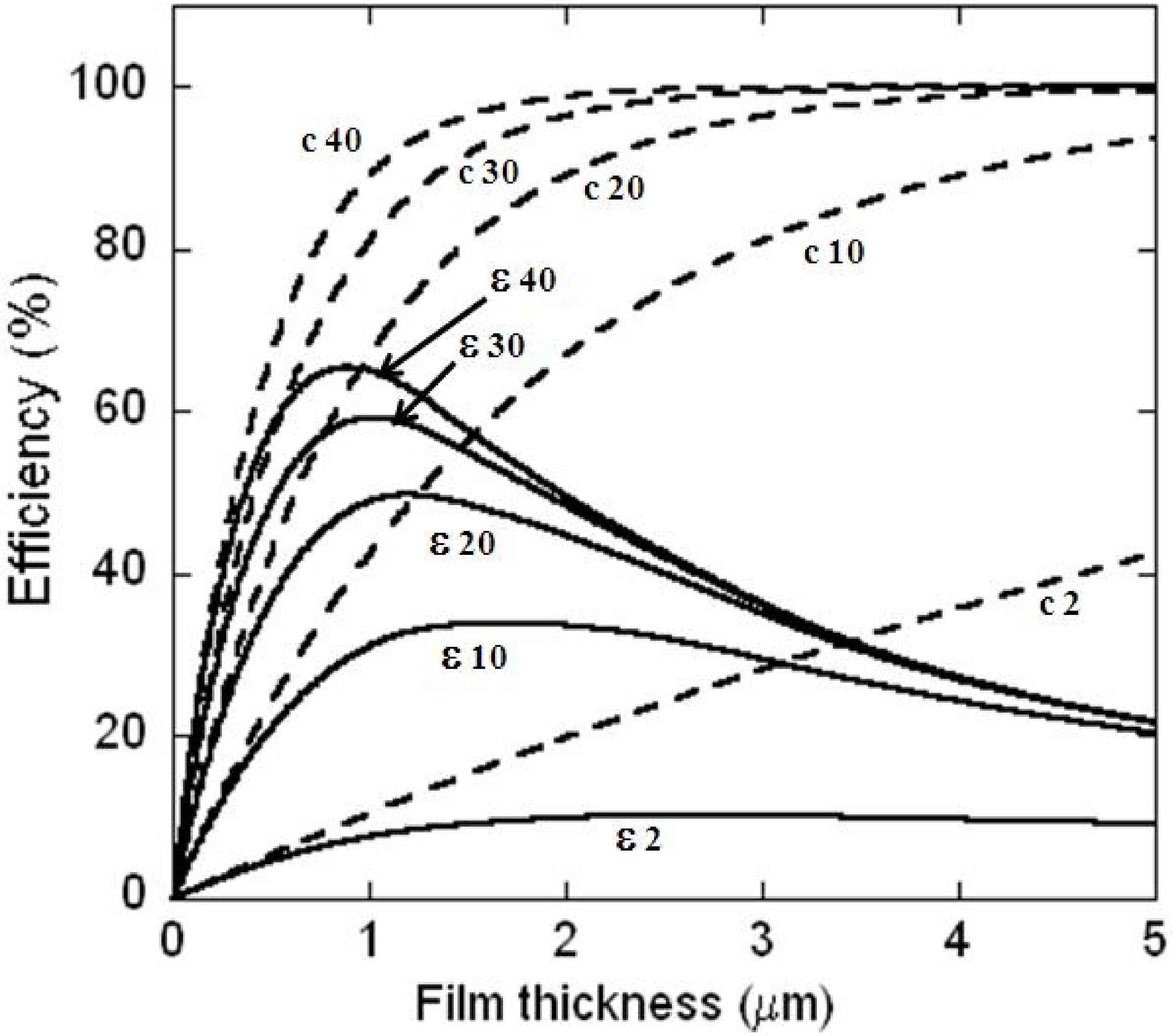
Session 4: BF_3 detectors

S. Alimov: "First tests of Linear-Position-Sensitive Twin Tubes with BF_3"
J. Orban/L. Cser: "New development for two dimensional multiwire position sensitive detectors filled with BF_3 at the Budapest Neutron Centre"
S. Desai: "BF_3 Based Position Sensitive Detectors: Performance and Challenges"
B. Guérard: "BF_3 detector development at the ILL"

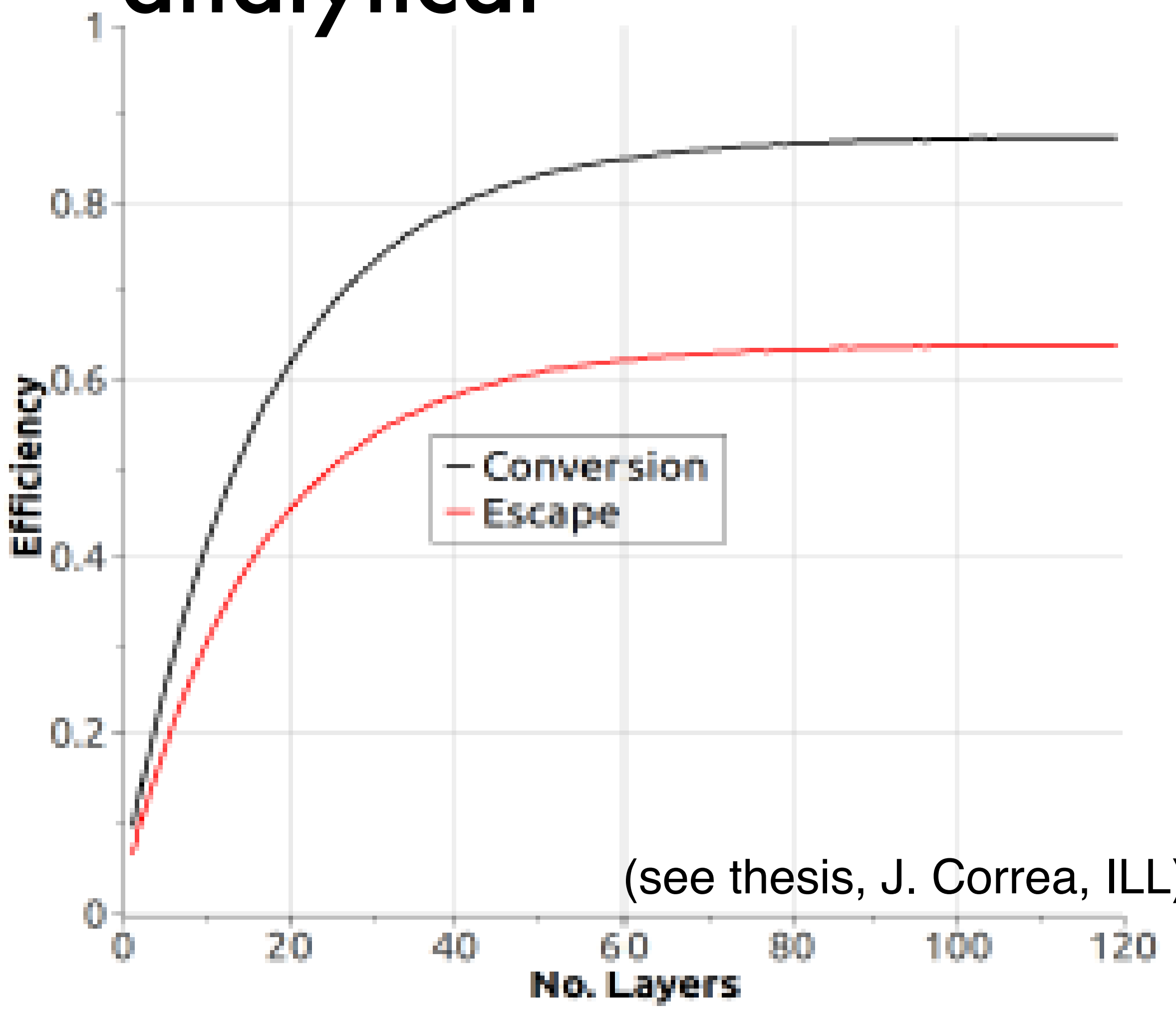
http://www.ill.eu/news-events/events/2nd-international-10b-bf3-detectors-workshop/home/

MC simulation (2.5 Å neutron wavelength)

F. Piscatelli, ILL



analytical



(see thesis, J. Correa, ILL)

Efficiency vs thickness
(interaction with Aluminium substrates is NOT taken into account)

Efficiency vs number of layer (1 μm thick)

Complicated optimisation needed - many layer detector

(Also implementing thermal neutron treatment in GEANT)


Linköping, Sweden
1st May 2011

10-Boron Carbide Thin Films for Neutron Detection

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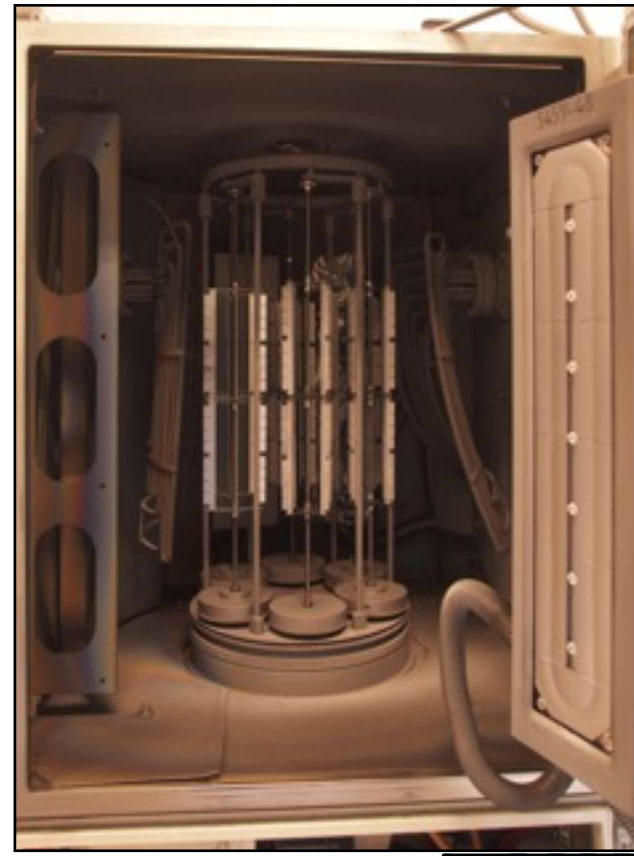
DC magnetron sputtering: ${}^{nat}B_4C$, ${}^{10}B_4C$

- 2-side coated substrates
- Good adhesion on Al, Si, etc.
- High density, Minimal impurities
- Thickness control and uniformity
- Large area depositions
- Patent

C. Höglund, et. al., J. Appl. Phys. **111**, 104908 (2012)

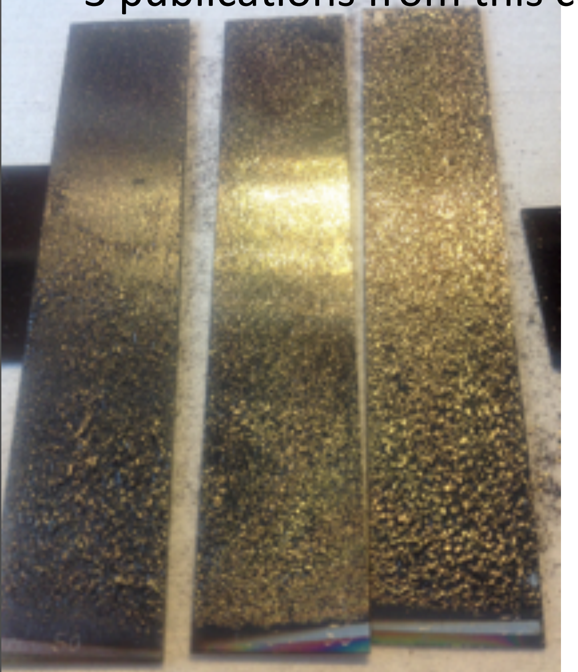
- Many attempts by other groups failed
- Boron Carbide has high internal stress
- Key ingredient here: experience!
- Expertise of Linkoping thin film group
- 3 publications from this collaboration



ESS – Linkoping U collaboration

interdisciplinary

~3 μm ${}^{10}B_4C$



Linkoping - ESS - ILL Collaboration on B-10 Thin Films Detectors

Linköpings universitet
INSTITUTE OF TECHNOLOGY

Jens Birch
Lars Hultman
Jens Jensen

EUROPEAN SPALLATION SOURCE

Carina Höglund*
Anton Khaplanov**
Richard Hall-Wilton
Kalliopi Kanaki
Thomas Kittelmann
Oliver Kirstein

*stationed at Linköping University
**stationed at ILL

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Jonathan Correa
Francesco Piscitelli
Bruno Guerard
Patrick van Esch
Thierry Bigault
Jean-Claude Buffet
Jean-Francois Clergeau
Jerome Pentenero
Gilbert Viande

CERN

Wilhelmus Vollenberg

CRISP

Linköpings universitet INSTITUTE OF TECHNOLOGY

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ESS Activity Report

Large Prototype '2' for Boron-10 Thin Films Detectors - Summer 2011

ILL Bulletin

And it works! Signs of success for a new boron-layer detector

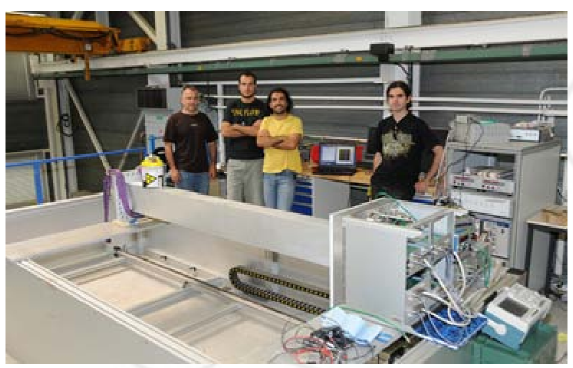
A prototype boron-layer detector has been undergoing initial testing with an AmBe source in the SDN lab. It has a detection surface of 8cm x 200cm and the neutrons are captured by 30 layers of 10B4C, each a micron thick.

The energizing signal produced by the capture is amplified by proportional counters, and these also supply one of the position coordinates. The other coordinate is provided by reading the signal in the segmented cathode. We have baptised the detector a "multi-grid detector" and it was patented in 2010.

The prototype has yielded encouraging results in terms of measurement efficiency and this has raised hopes for the next phase, the production of a module similar in size to those on IN5, vacuum-compatible. The technique has been developed in collaboration with the ESS and is destined to replace current 3He-based technology.

Bruno Guérard

From left to right: Jean-Claude Buffet, Francesco Piscitelli, Jonathan Correa of the ILL, and Anton Khaplanov from ESS.



De gauche à droite: Jean-Claude Buffet, Francesco Piscitelli, Jonathan Correa from the ILL, and Anton Khaplanov from ESS

Ca marche ! Premier succès du prototype de détecteur à couches de bore

Le prototype de détecteur à couches de Bore a été testé avec succès au laboratoire du SDN, durant les premiers tests avec une source américium-beryllium(AmBe).

La surface de détection est de 8 cm x 200 cm; la capture des neutrons est assurée par 30 couches de 10B4C, d'épaisseur 1 micron chacune; le signal de charge produit par cette capture est amplifié par des compteurs proportionnels, qui fournissent en même temps l'une des coordonnées de position; l'autre coordonnée est donnée par la lecture de la cathode segmentée. Le principe de ce détecteur appelé Multi-grille a été breveté en 2010.

Les bons résultats obtenus avec ce prototype en mesure d'efficacité permettent d'envisager avec une certaine confiance la phase suivante, qui consiste à produire un module de même taille que ceux d'IN5, compatible avec le vide. Cette technique développée en collaboration avec ESS a pour but de remplacer la technique actuelle à base d'3He.

What might a Cold Chopper Spectrometer look like for ESS?

Let's try and make a guess:

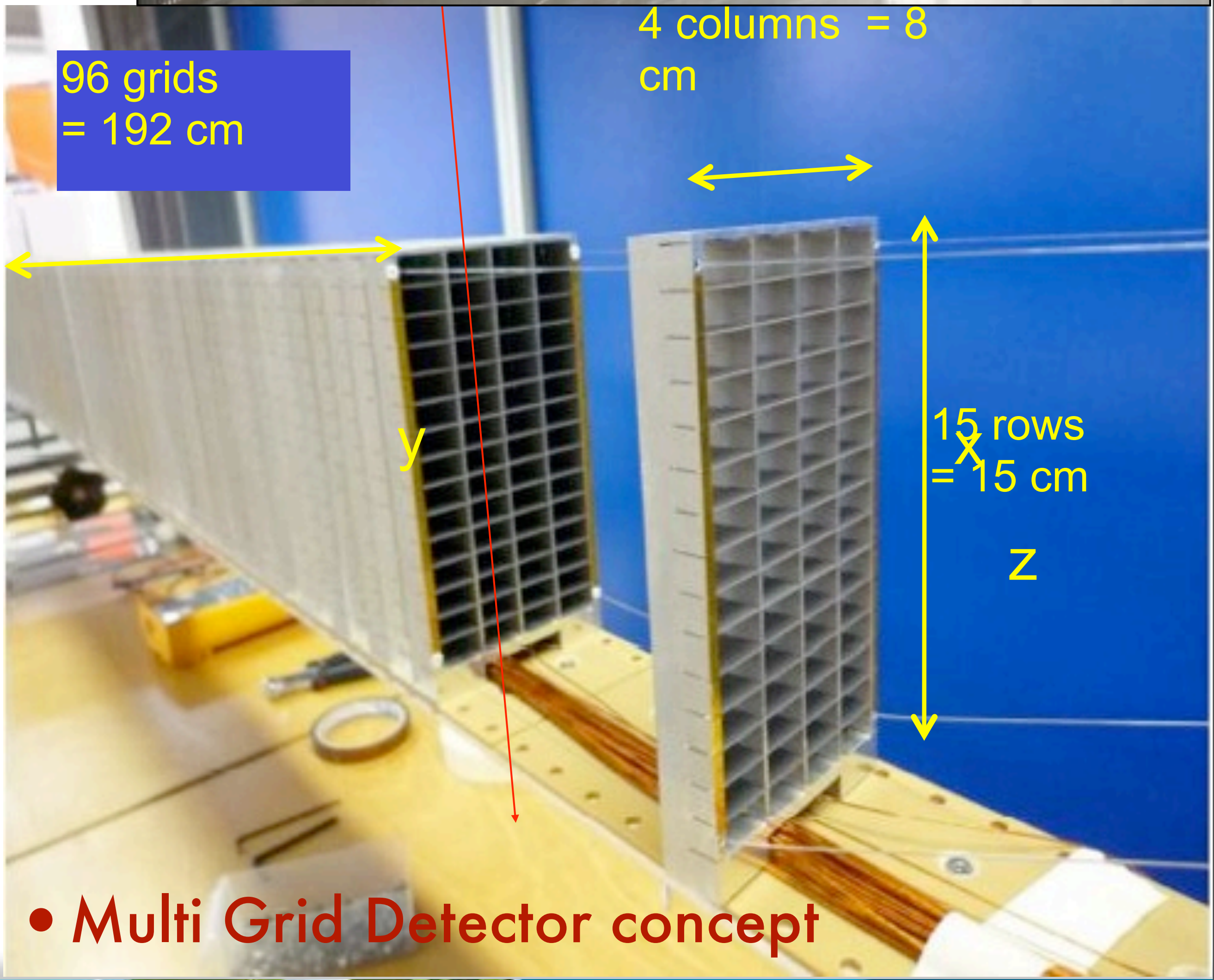
- •Reference instrument suite has 80m^2 active area
- •Position resolution: 1cm
- •Say: 4m height x 20m circumference
- •Lets assume here that this is a day 1 instrument

Pixels and Readout Channels:

- •x: 2000 pixels
- •y: 400 pixels
- •z: 15 pixels
- •Total: 12 Mpixel

- •In terms of readout channels, this implies:
  - •Grids/Cathodes: 200 stacks, 200 grids = 40k
  - •Anodes: 200 stacks, 150 anode wires = 30k
  - •Total: 70 k readout channels

Needs to be as cheap as possible



• Multi Grid Detector concept

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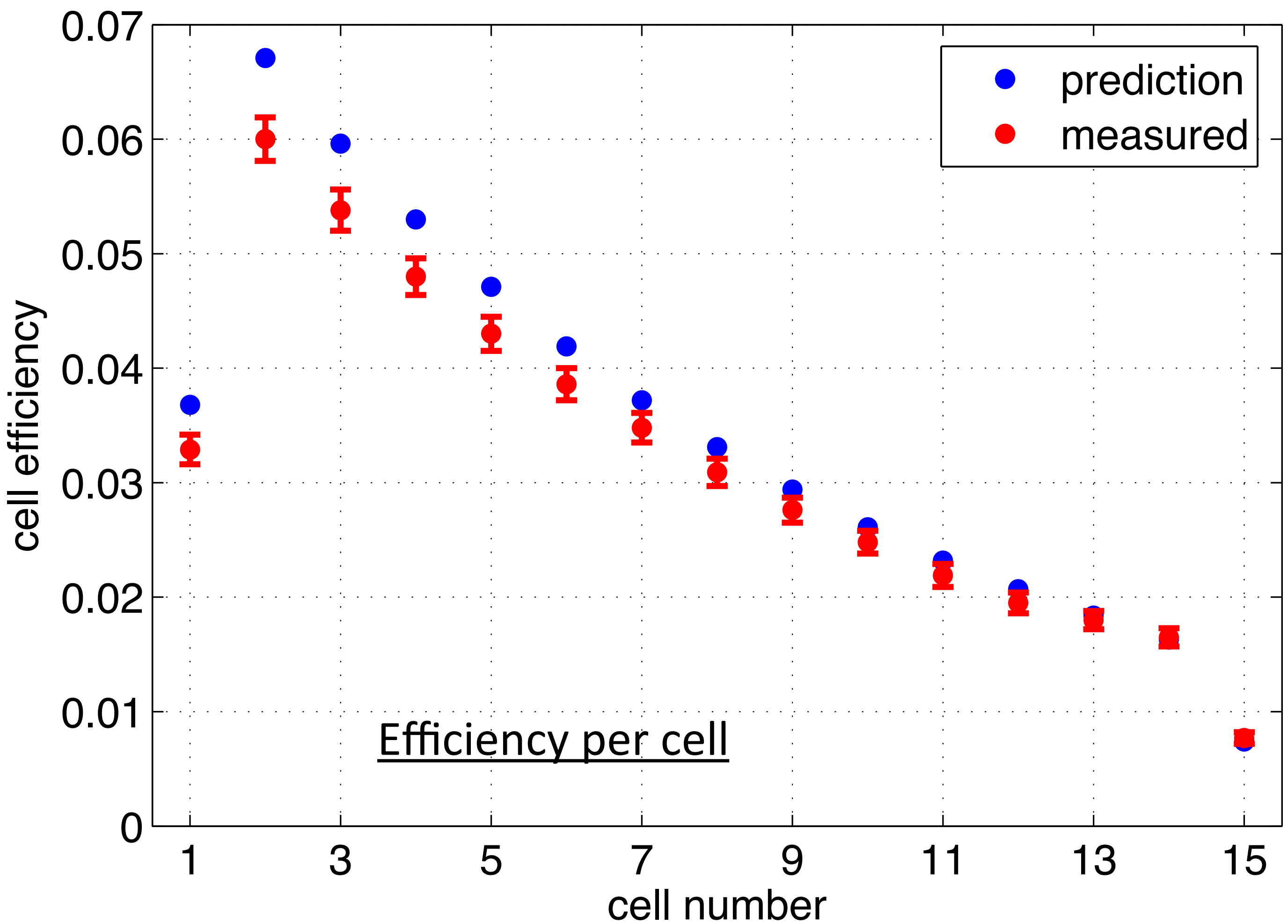
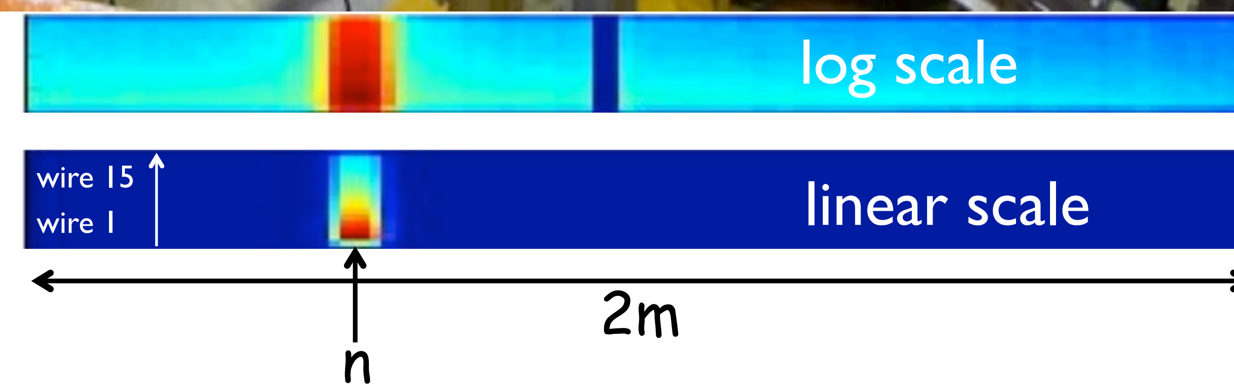
Results from tests with beam of Prototype ‘2’

- Each cell performs as predicted
- ~50% detection efficiency for 2.5 Å neutrons

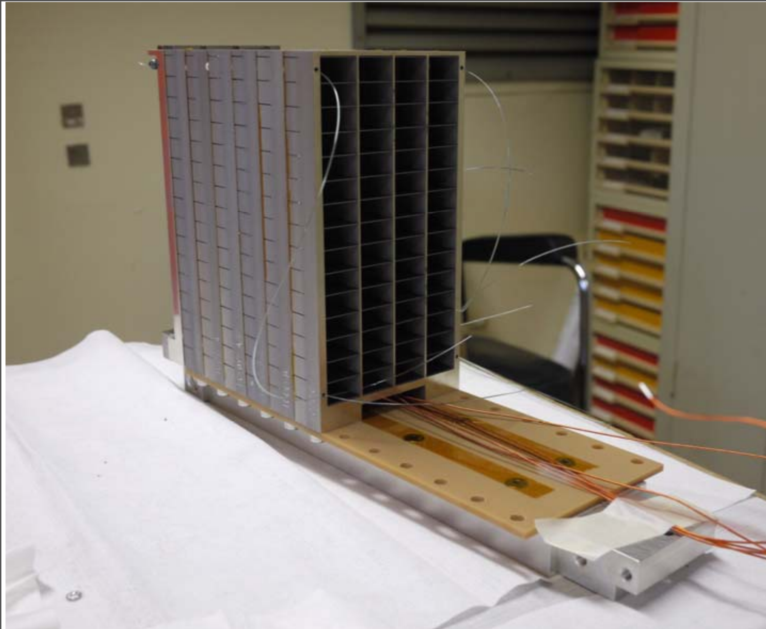


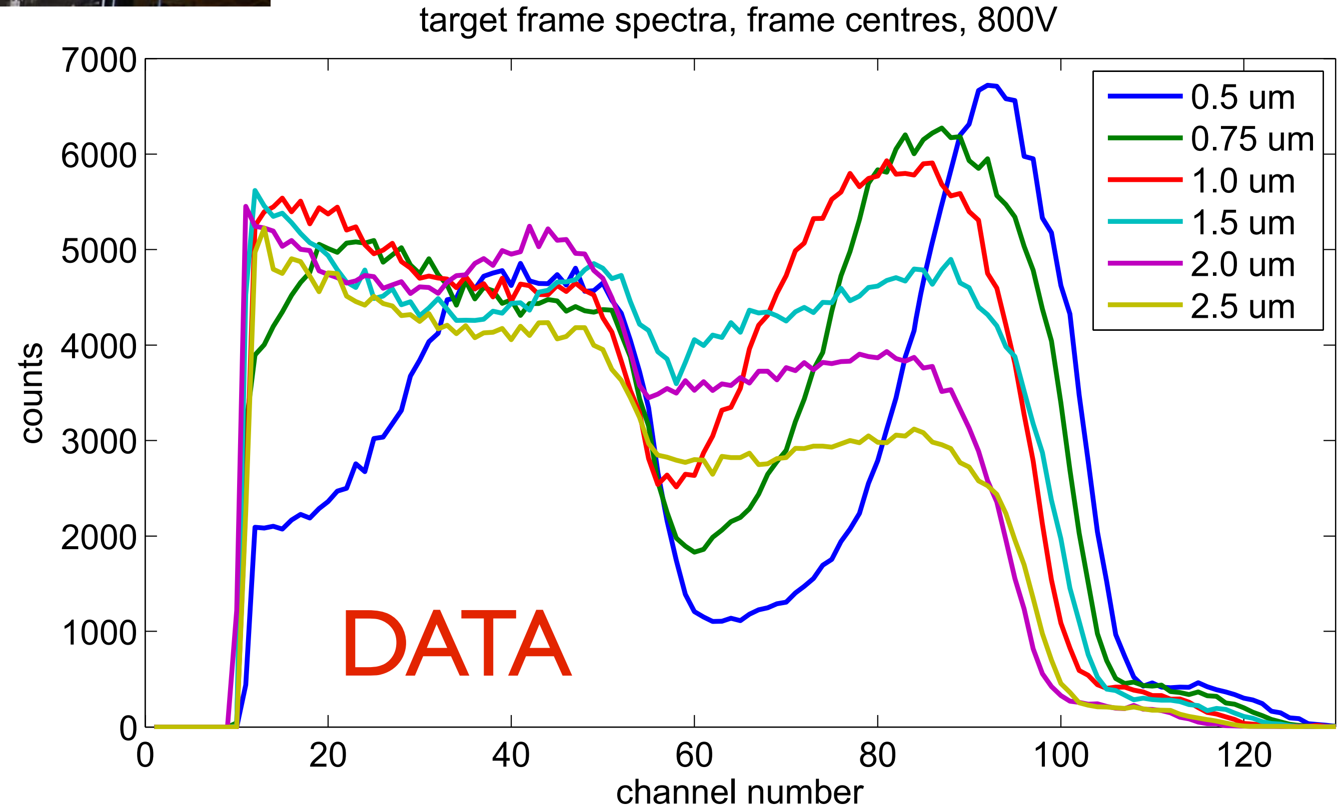


$^{10}B_4C$-based multi-grid detector feasible

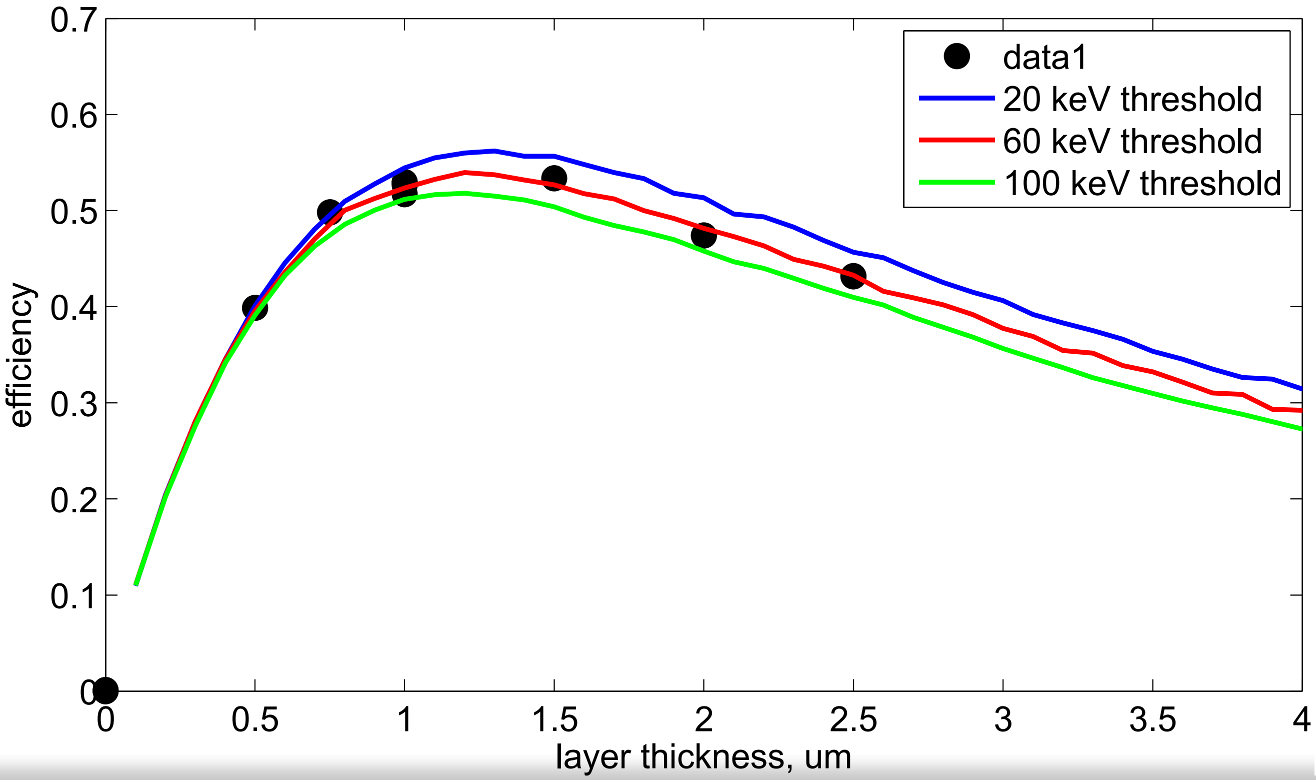
B, Geraud et al., subm. NIM A (2011).
A. Khaplanov, K. Andersen, R. Hall-Wilton et al., Proc. of ICANS XX, Bariloche, Rio Negro, Argentina, 2012.
J. Correa et al., subm. TNS (2012)
J. Correa, PhD Thesis (2012)

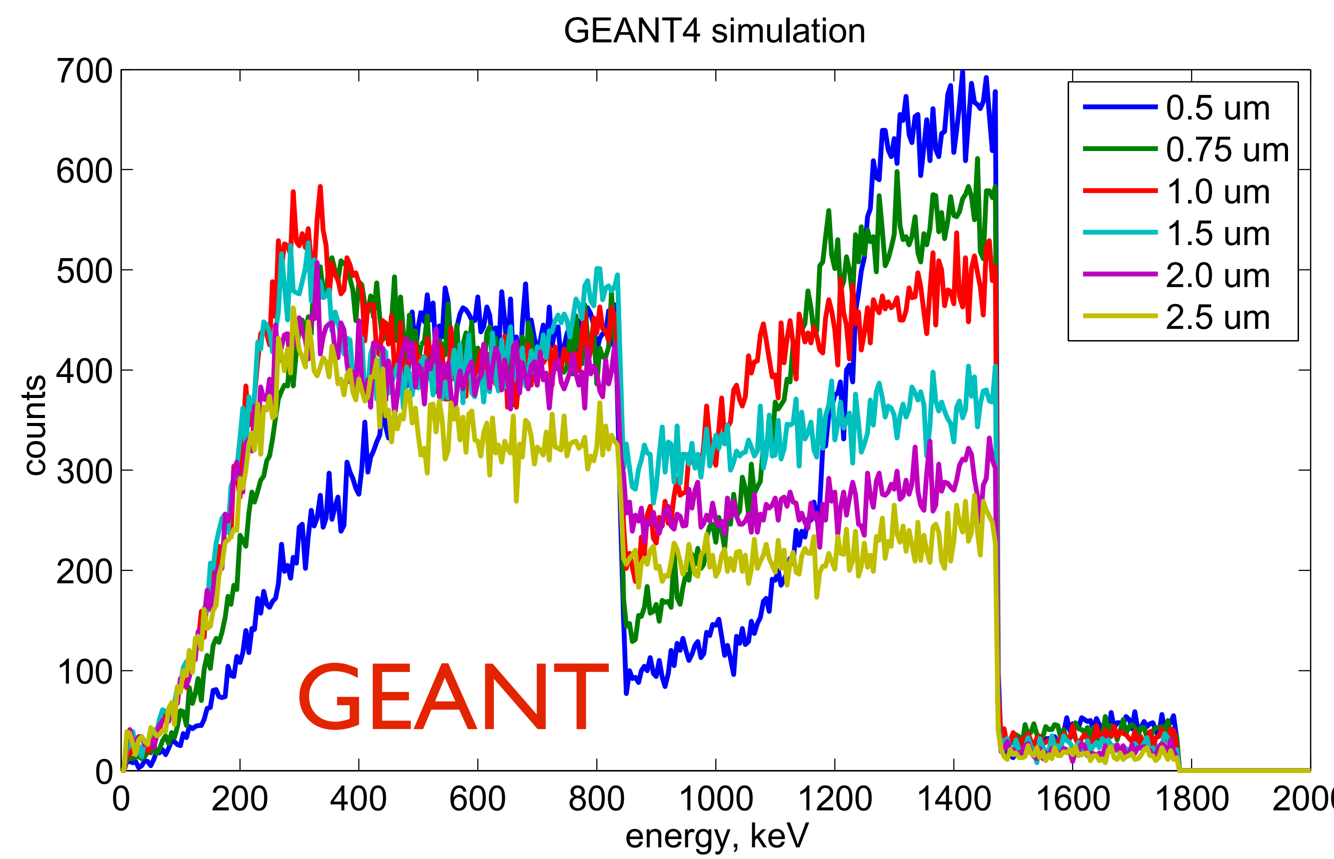
P1.1 - 2x20cm (2012)



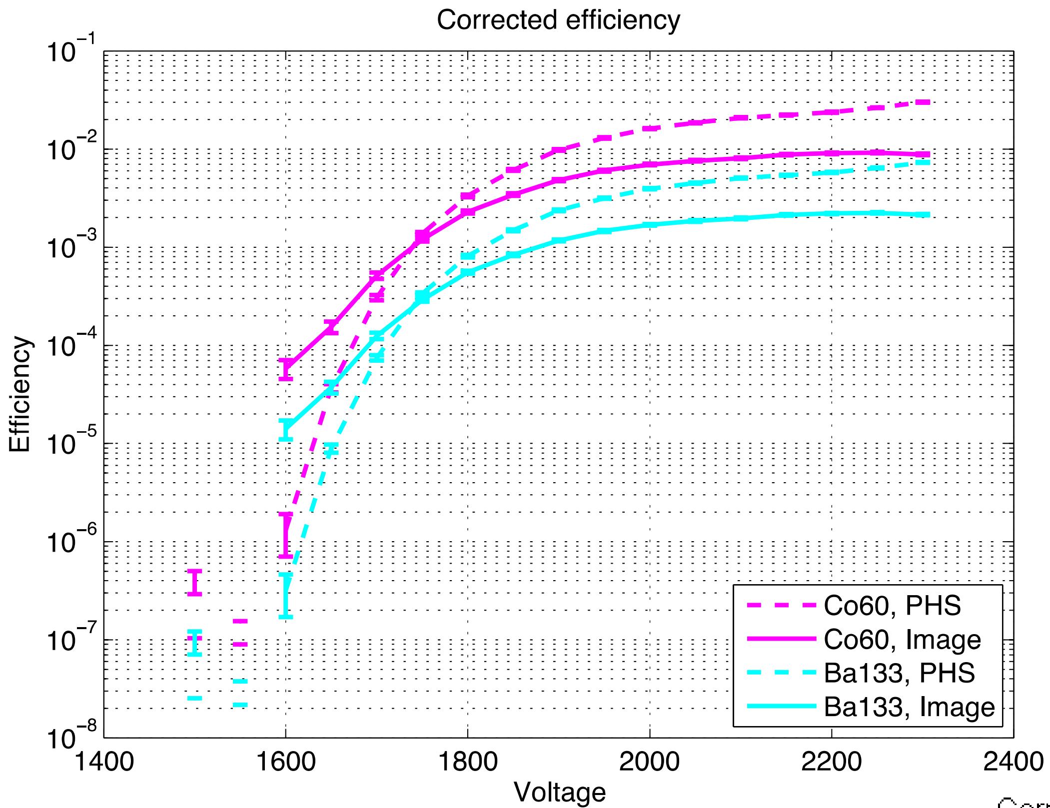


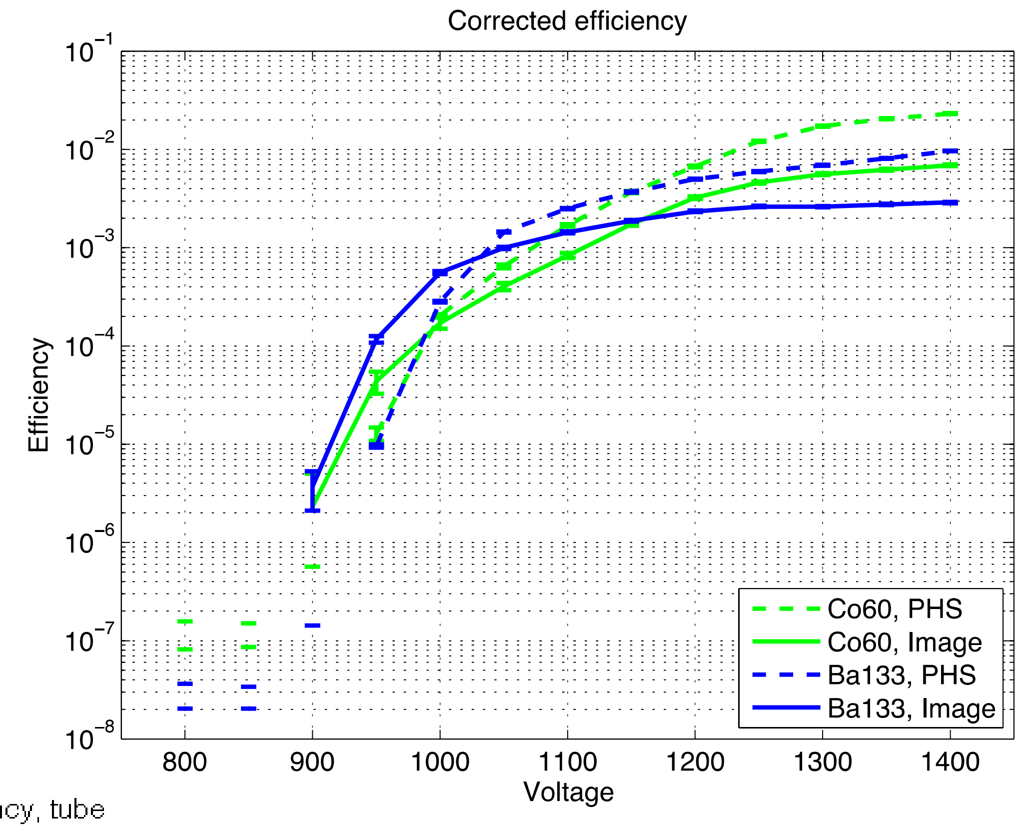
- Efficiency and pulse-height spectra understood as function of layer thickness



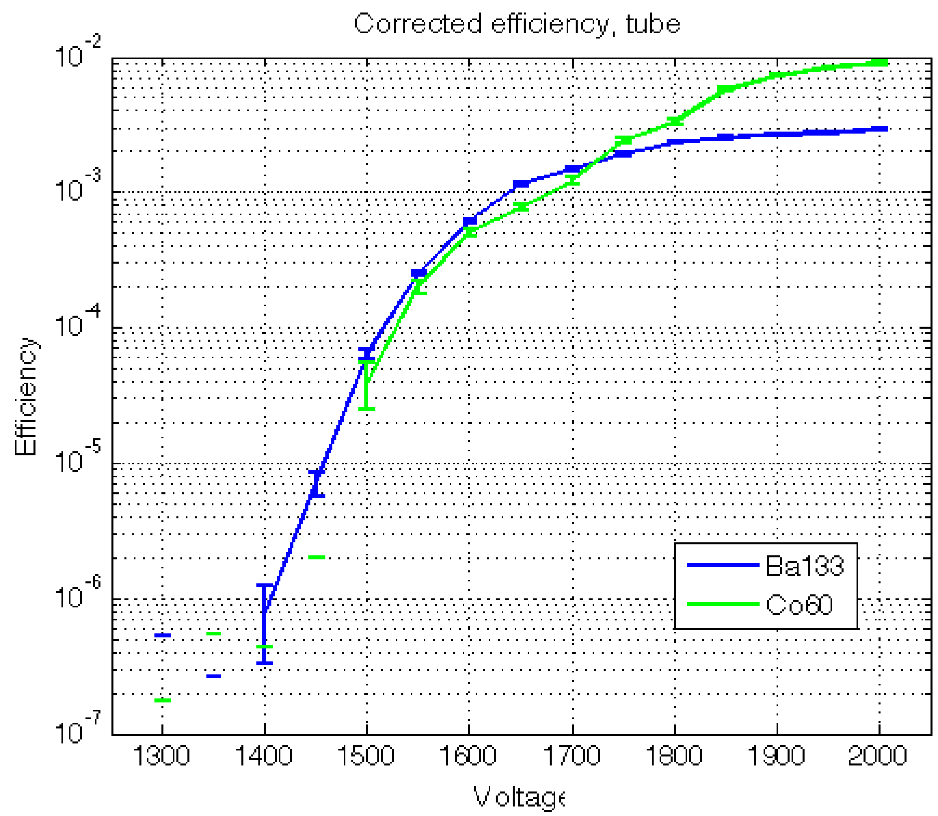


Gamma efficiency, P11, He3





P11, CF4



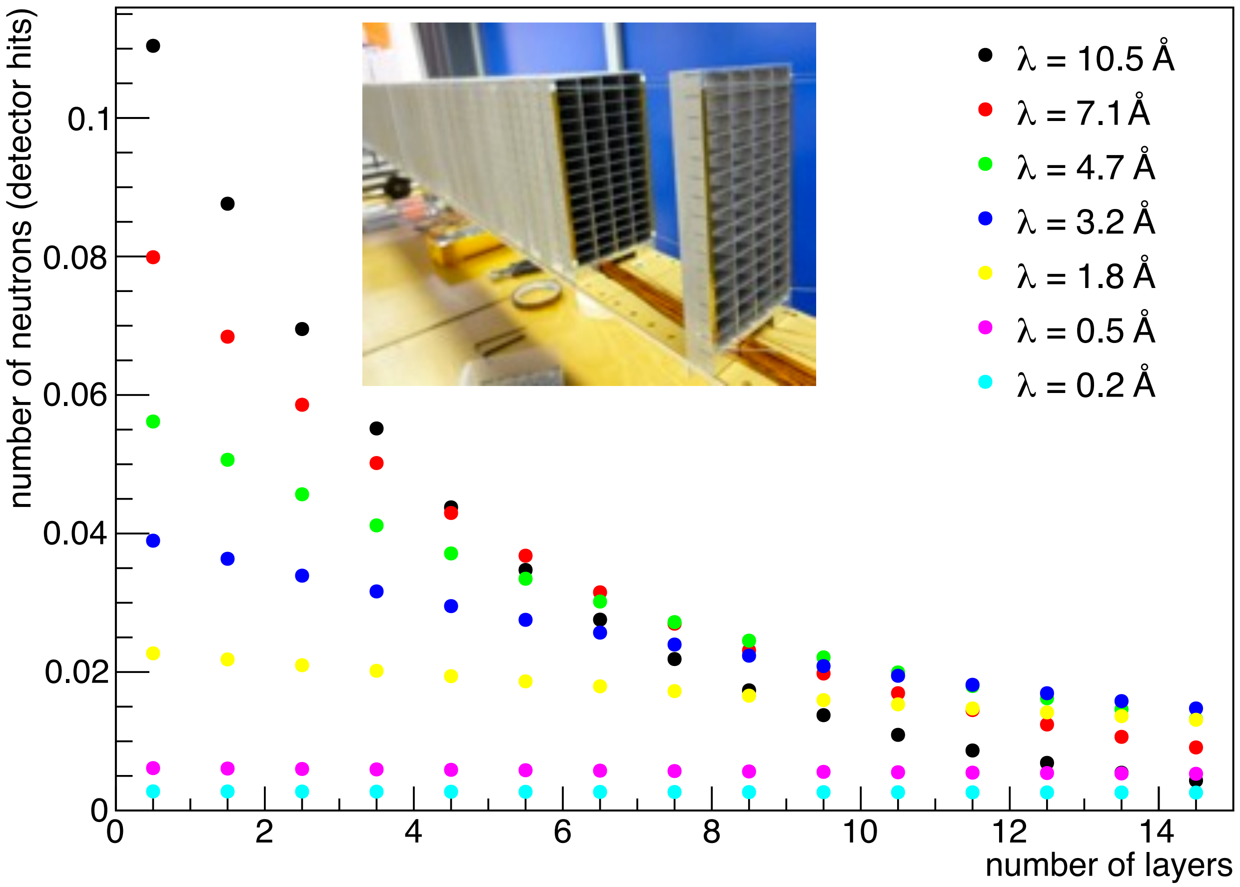
P11, ArCO2

Hexagonal He3

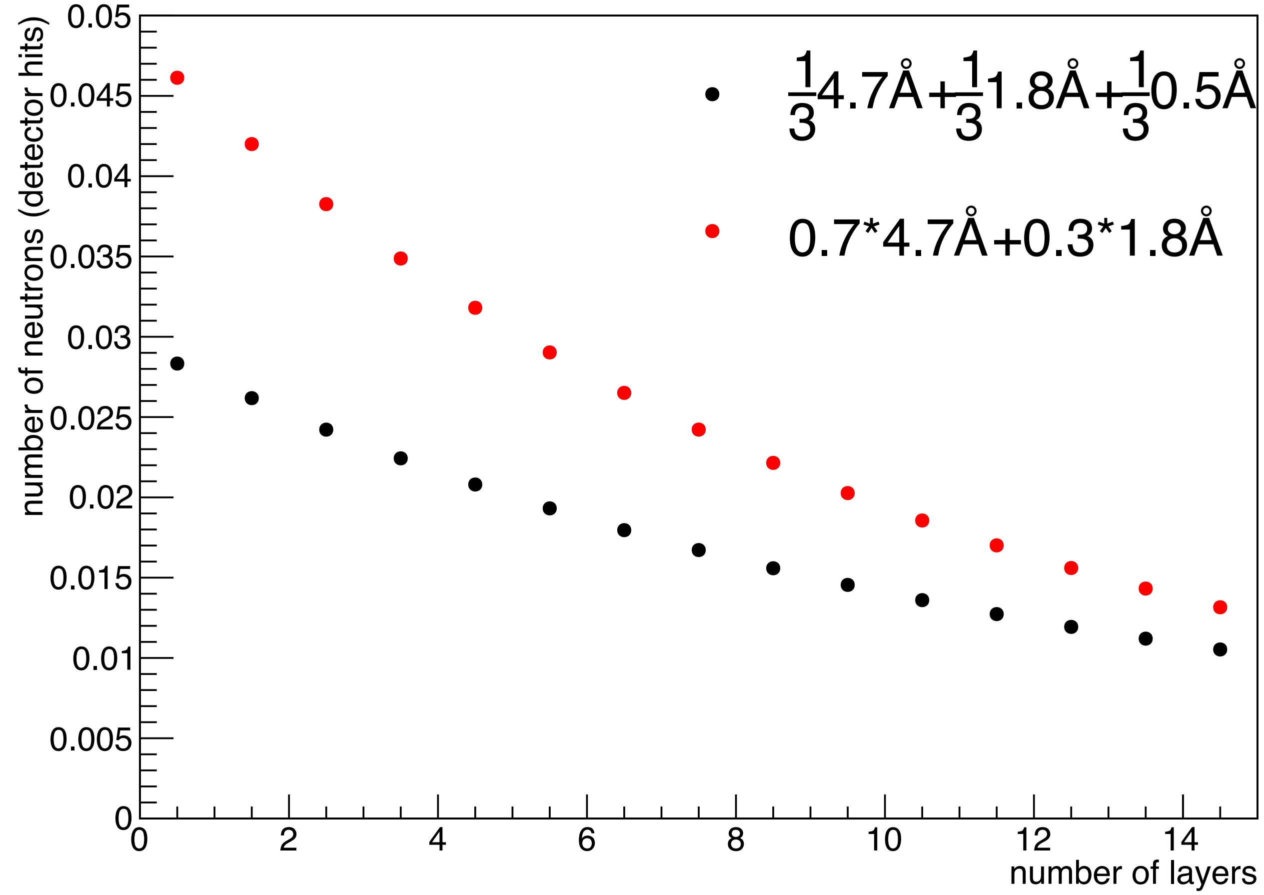
- gamma rejection as good as He-3 possible
- part of optimisation process efficiency vs gamma efficiency

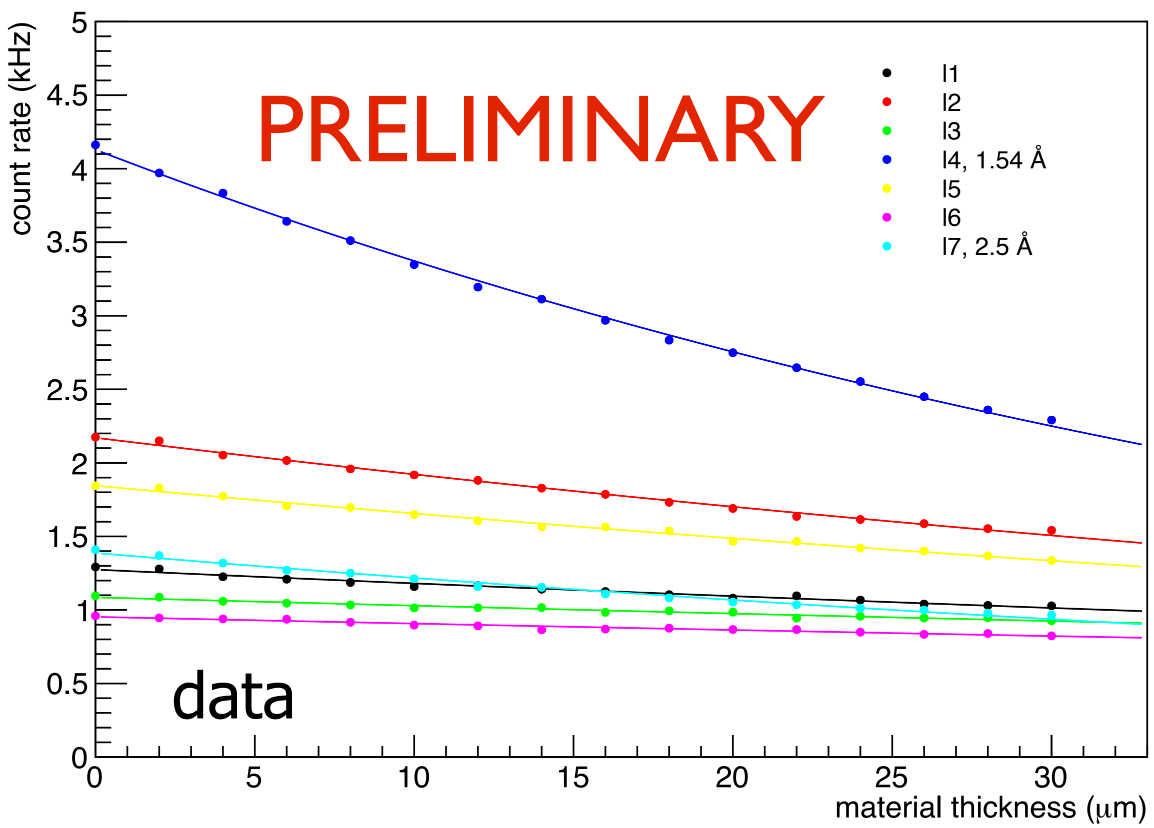
Neutron energy determination using statistical methods

neutrons detected vs. conversion layer



neutrons detected vs. conversion layer





Mathematical approach on discriminating wavelength admixtures from the shape of the measured neutron spectrum

Not disimilar to the Bonner Sphere method

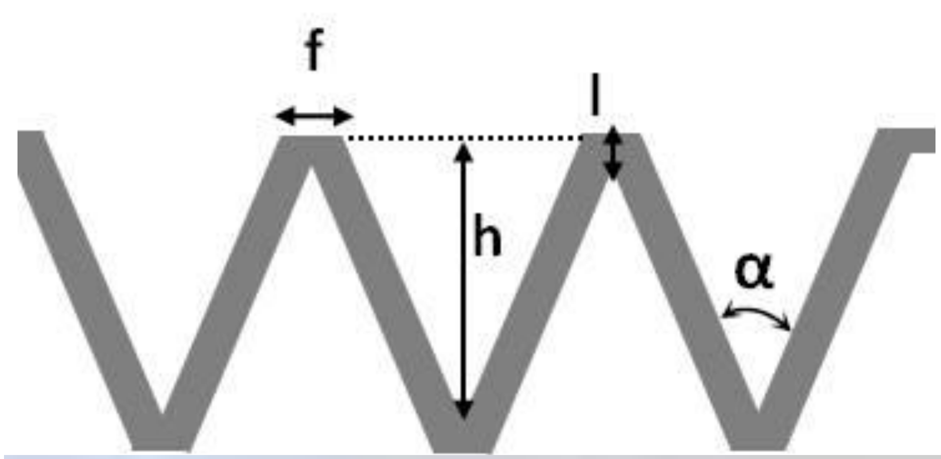
Unfolding the neutron energy spectra?

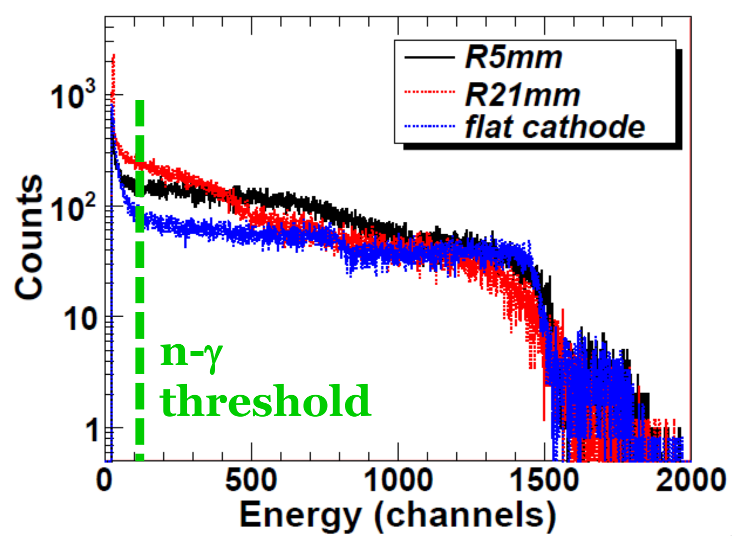
Macro-Structures

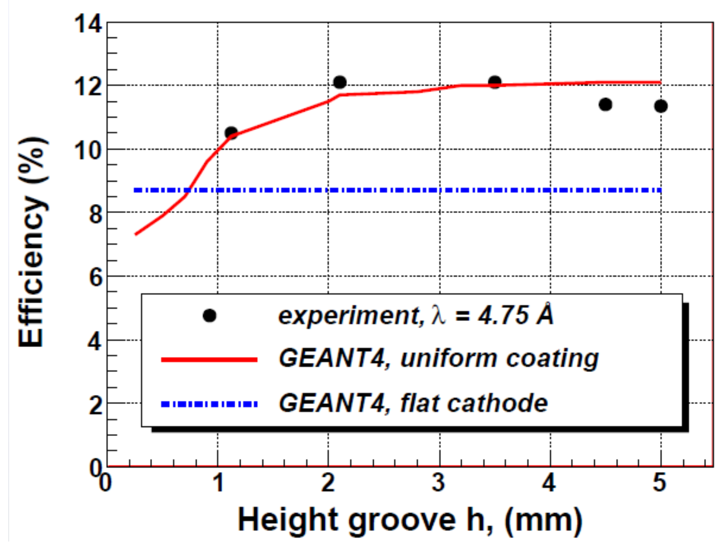
•Irina Stefanescu and Karl Zeitelhack (FRM-II)
•A different take on inclined geometry ...

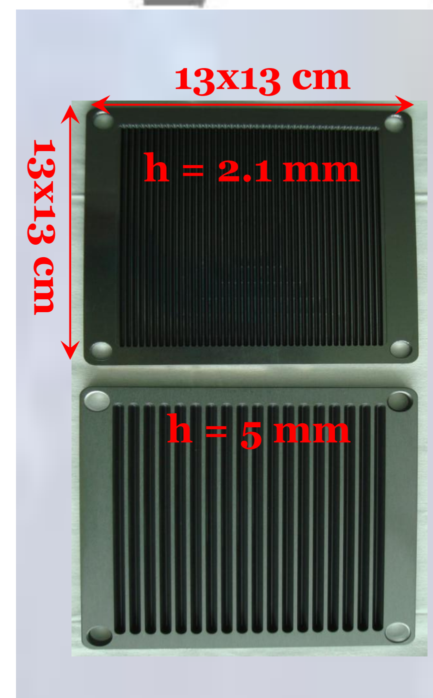
FRM-II Design - Macro-structured cathodes

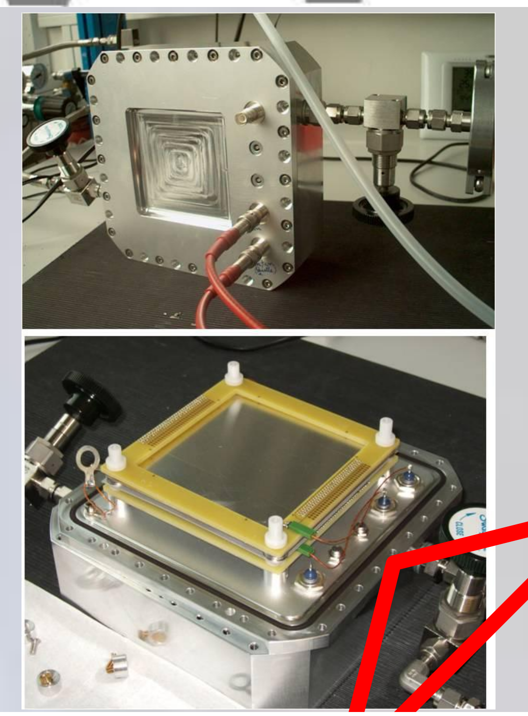
- Why not add an inclined surface to a flat cathode?
  - 45 degree opening angle chosen
  - 30% increase in efficiency per plane as predicted by the simulation
  - Pulse-height spectra not significantly degraded
  - Now working on a prototype to see if behaviour scales as expected

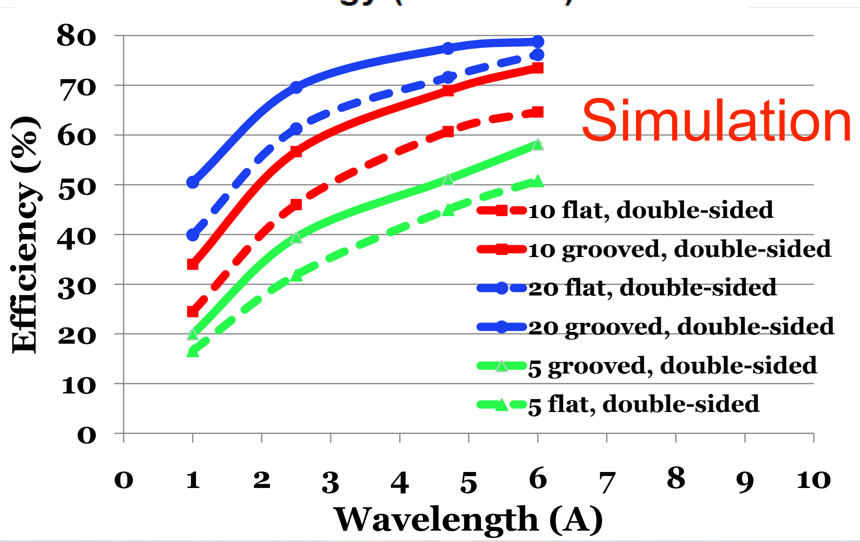


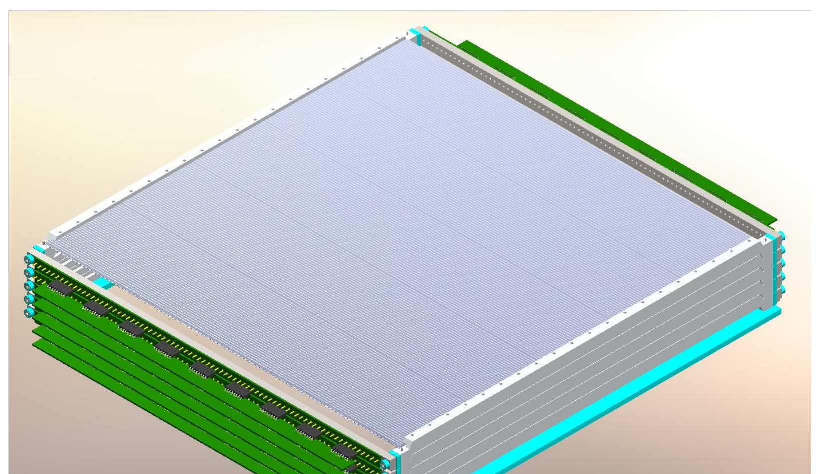












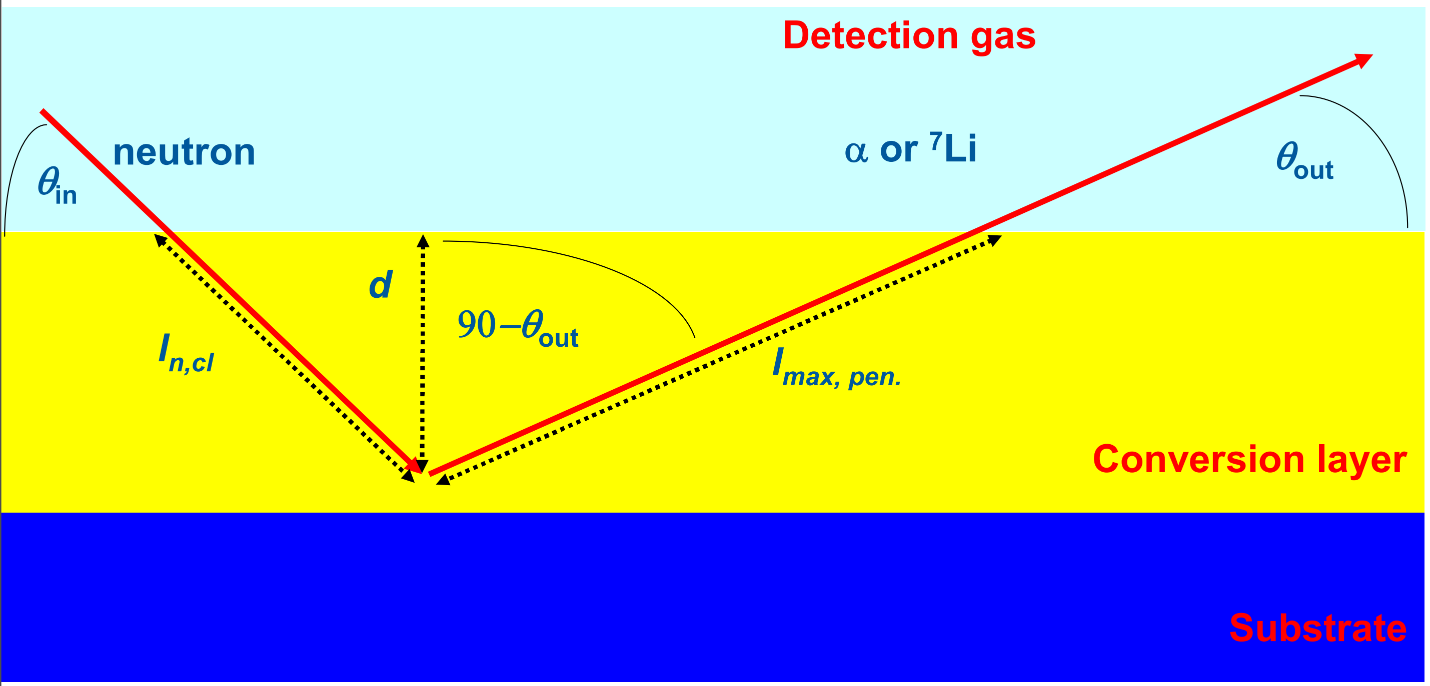
¹⁰B -prototype under construction

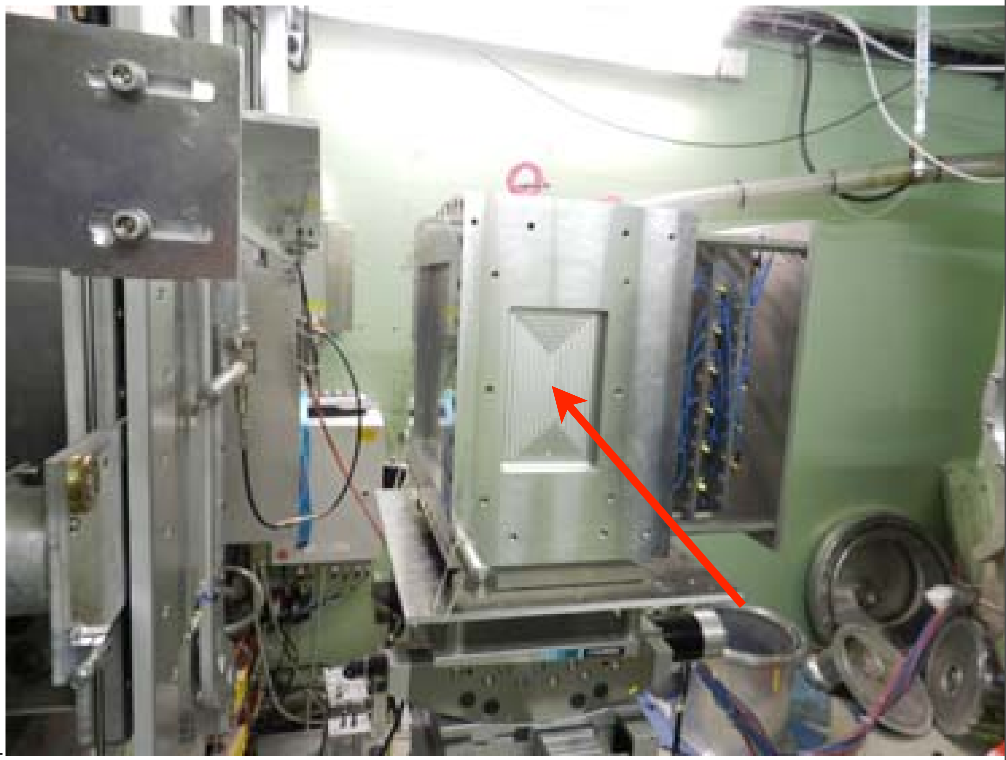
Interesting ....

Paper submitted to NIM A

(extreme) Inclined Geometry

•Helmholz-Zentrum Geesthacht and DENEX Gmbh
•Gregor Nowak, Reinhard Kampmann, Michael Stoermer





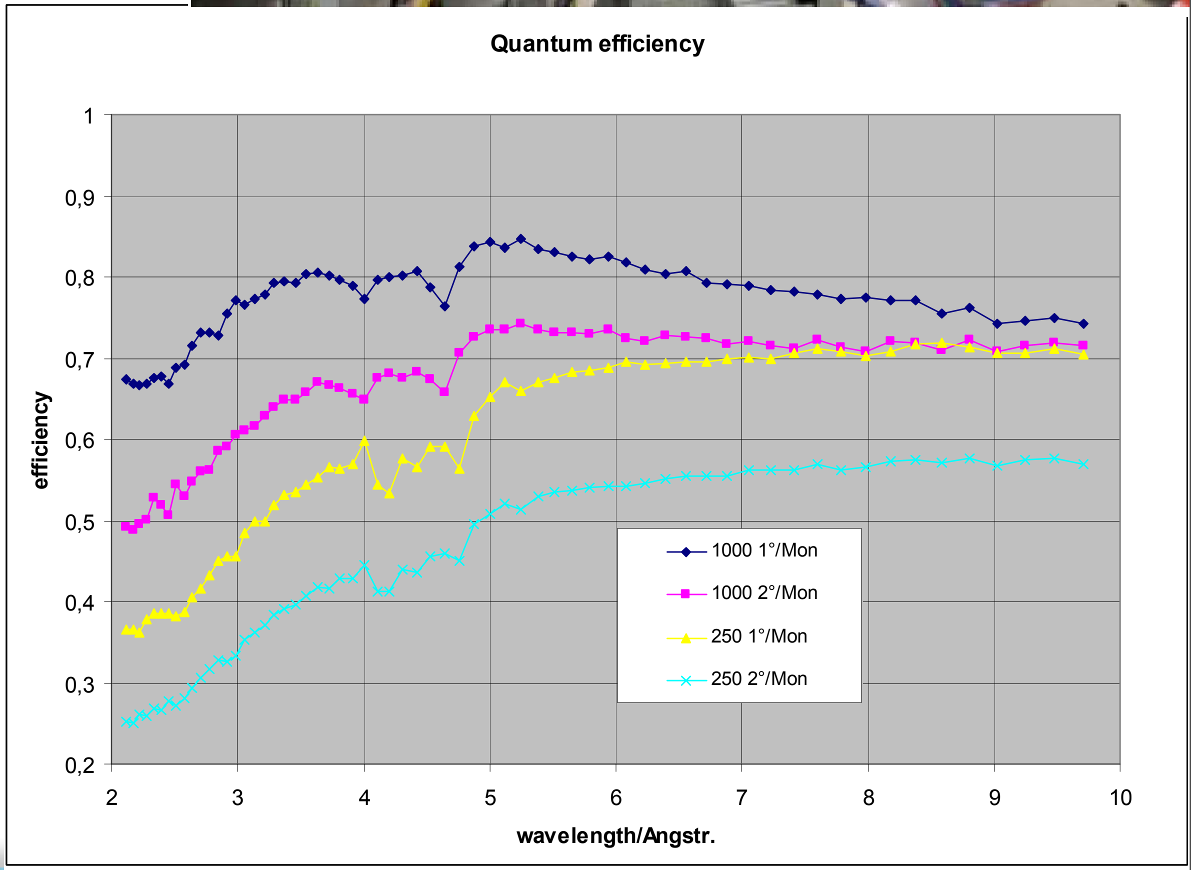
HZGeesthacht design (A1-CLD design)

•A prototype detector currently operated with three stacks of electrodes each comprising one anode and two delay-line based readout cathodes has further been tested at REFSANS.
•Shell mechanics are a standard DENEX-type detector
•Incidence angle of 1 and 2 degrees (!) shown

•Very encouraging results in-line with expectation on efficiency
•Relatively flat across a wide wavelength range

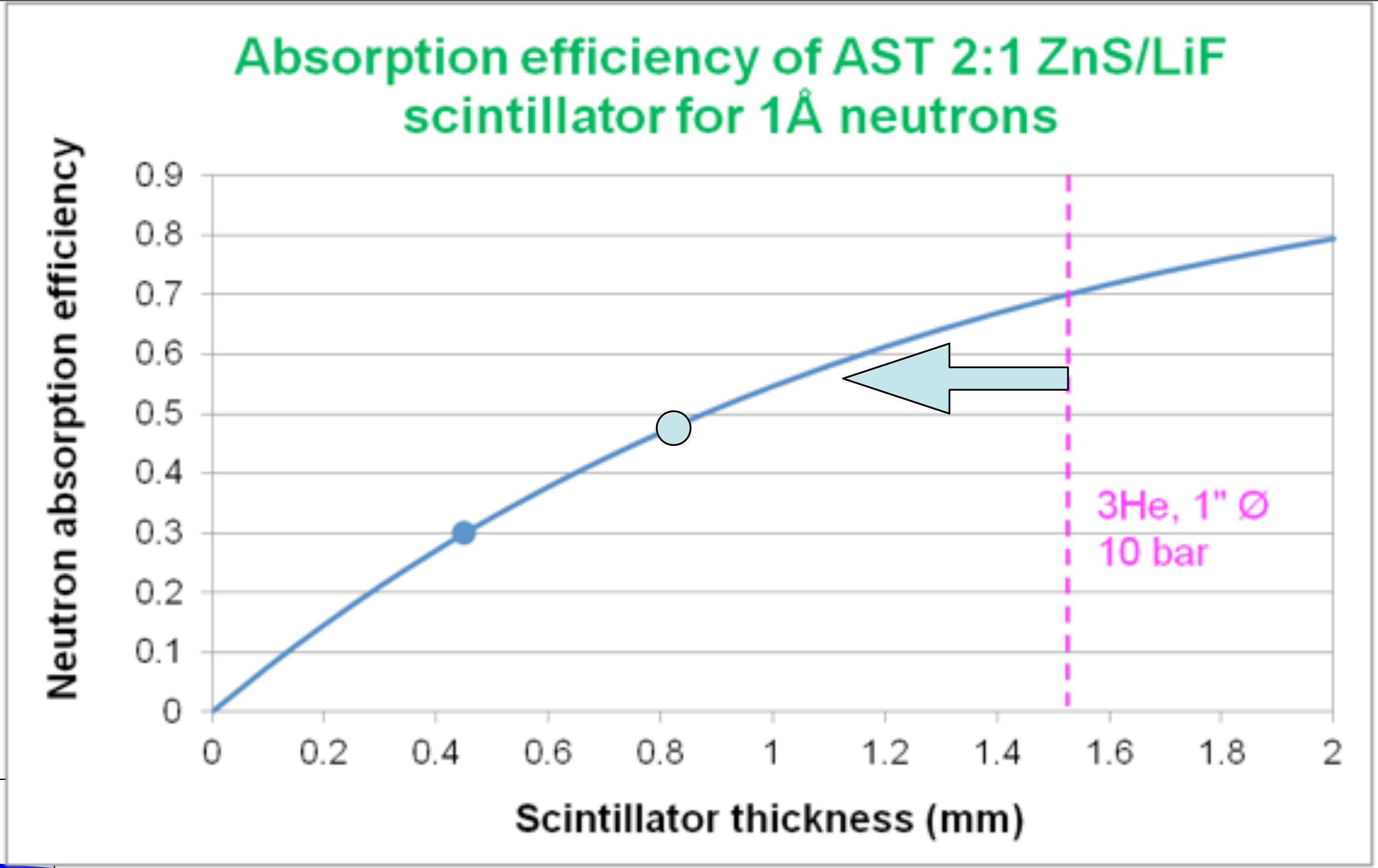
•Results very encouraging
•Many technical challenges still to address

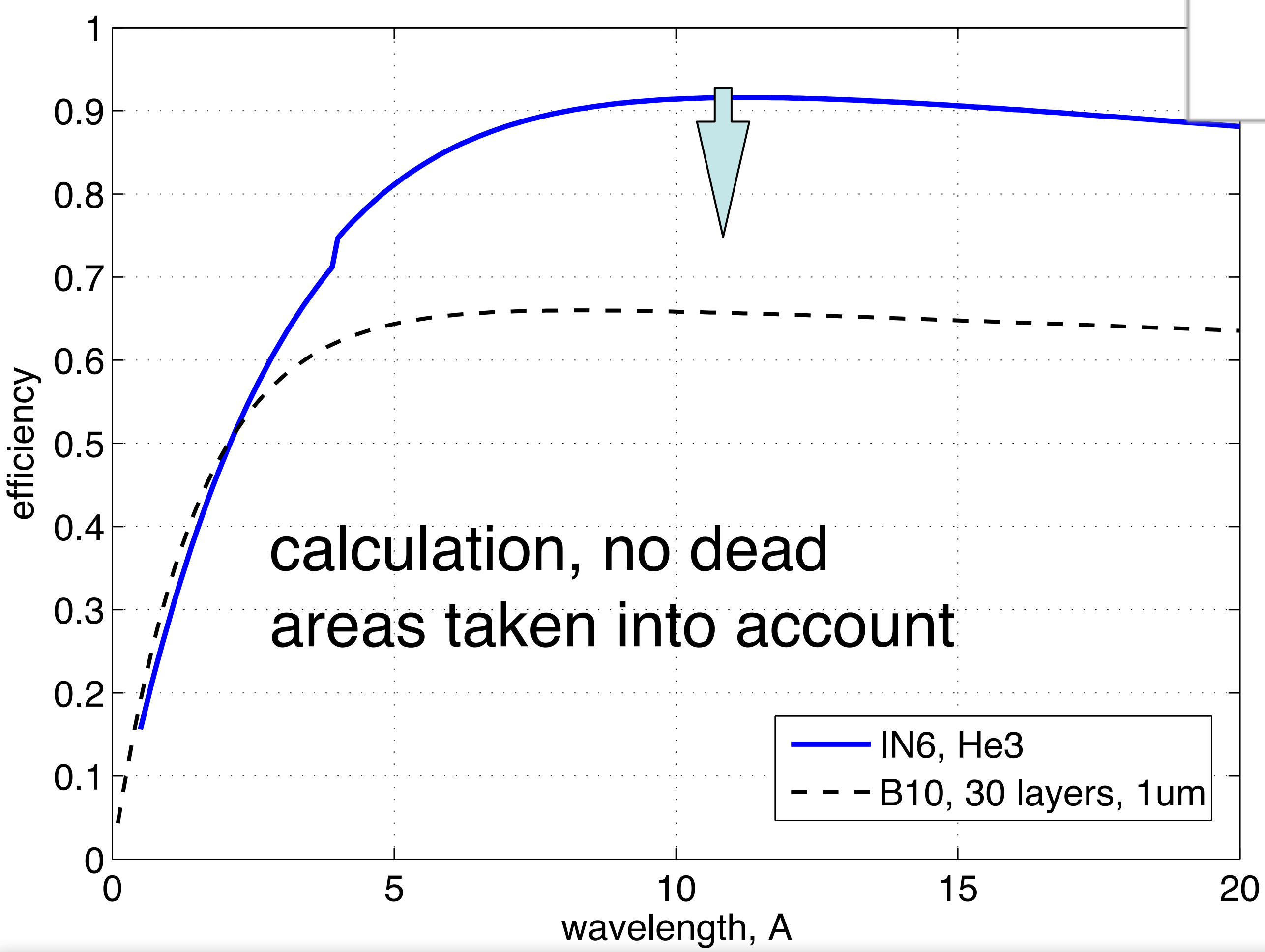
•Also less extreme examples



Detection Efficiency

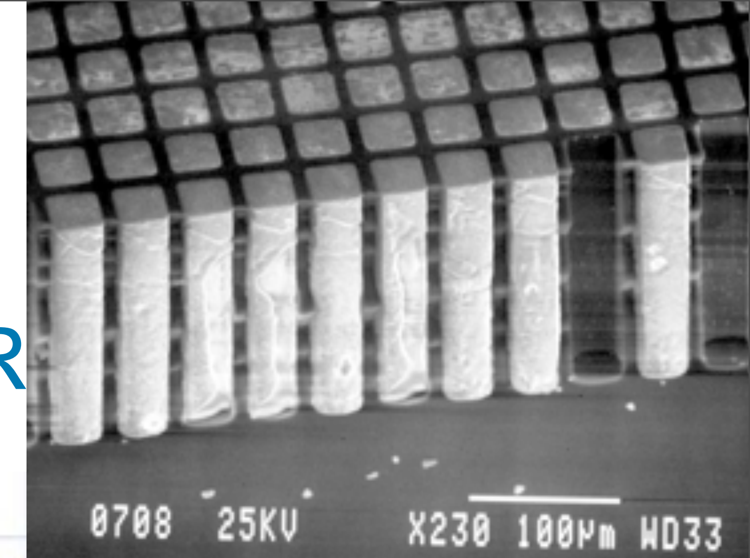
•Helium-3 is the gold standard, in particular in terms of detection efficiency
•However, efficiency numbers have rarely compared like-with-like





•Arrow indicate effect of dead regions into account with He-3 tubes
•Alternate technologies starting to approach raw efficiency numbers
•There is a need to compare like-with-like for the detailed instrument operating conditions
•Gamma rejection is a similar issue

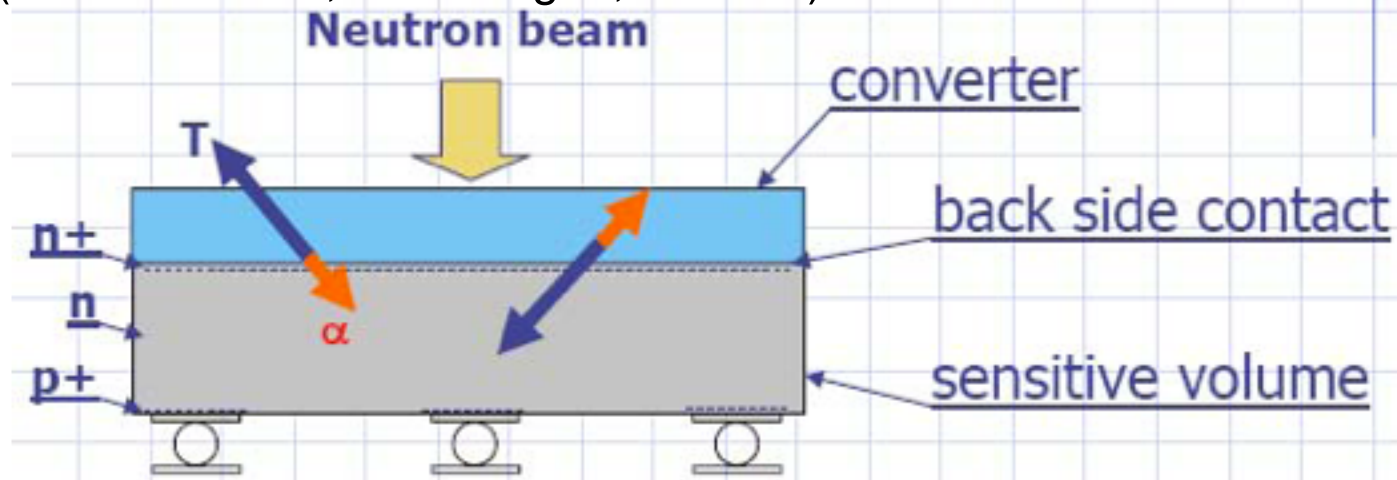
Semiconductor Detectors - “Structured Converter Layer”

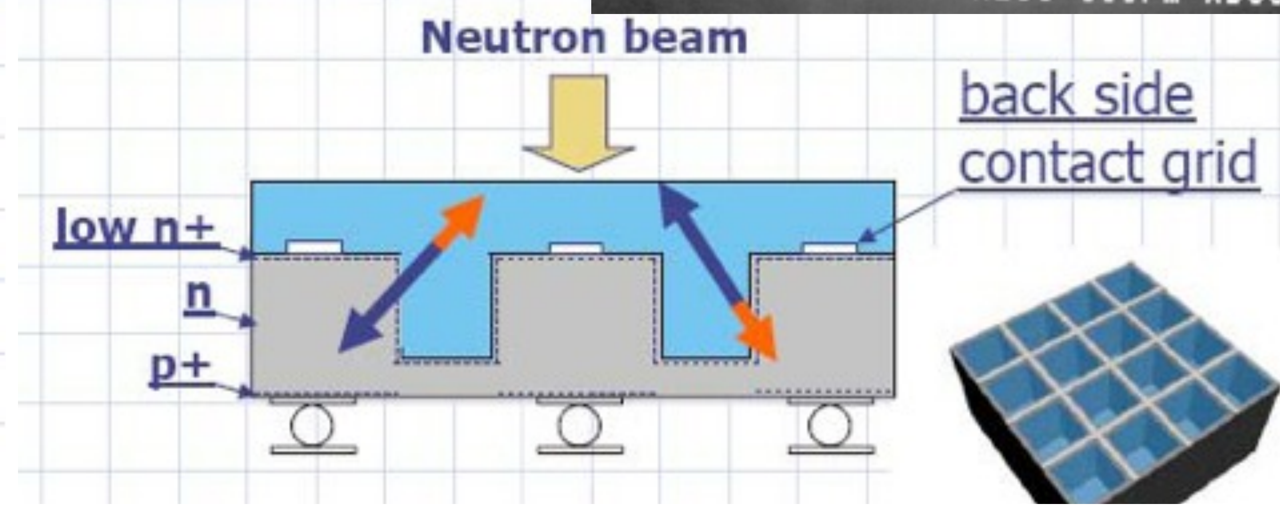


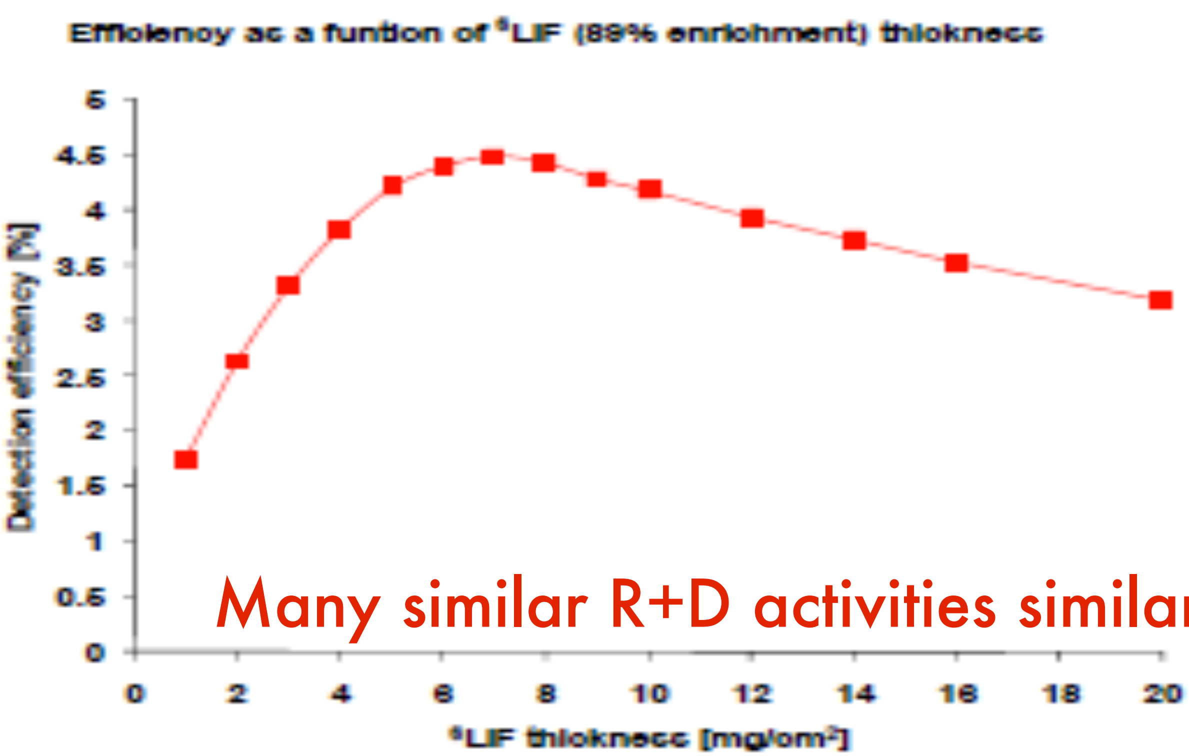
“HIGH EFFICIENCY” - THE *STUFFED* DETECTOR

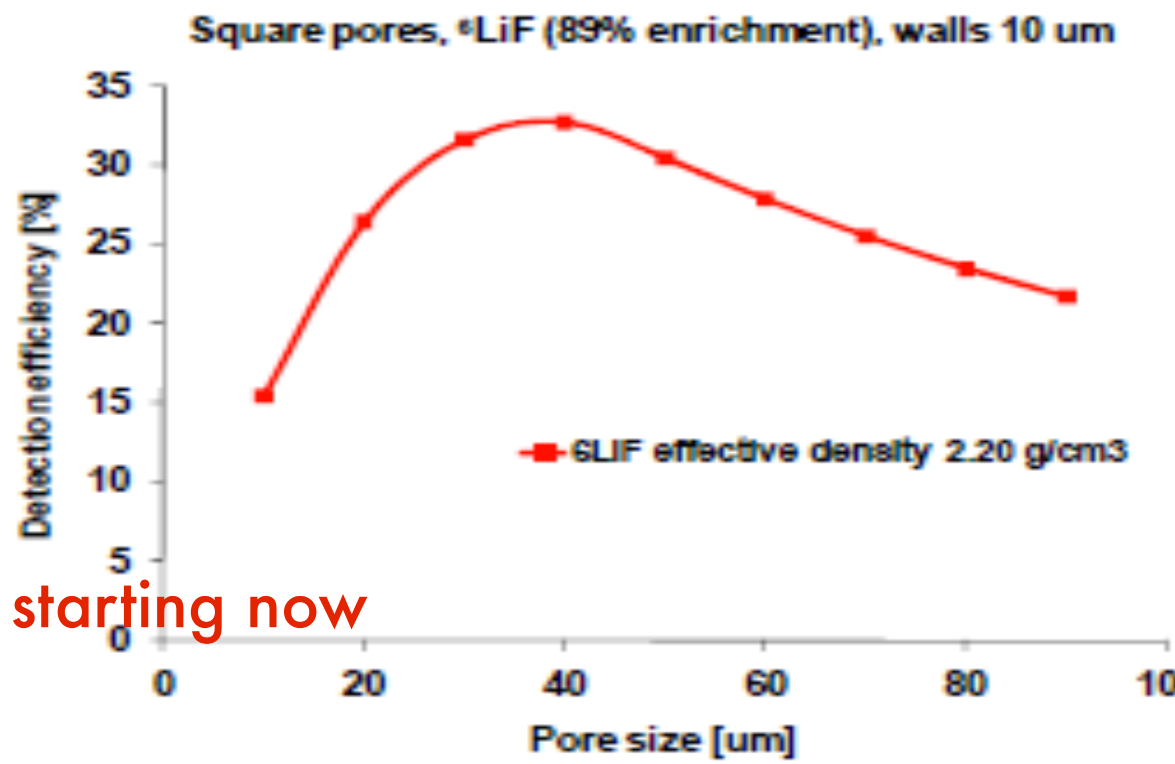
Pores are etched in the silicon sensor and filled with a neutron converter.

(Mid-Sweden U, IAEP Pague, ACREO)









Many similar R+D activities similar to this starting now

b)

EUROPEAN SPALLATION SOURCE

Another Analogy: the Research and Development as now ...

- About 530M years ago was the "Cambrian explosion" following an extinction event

- There has been an explosion of detector types following the He-3 crisis
- In the long term it is likely to settle down to a few categories
- Hard to pick the winners today ...
- This is fun. Lots of work in the next 10 years++

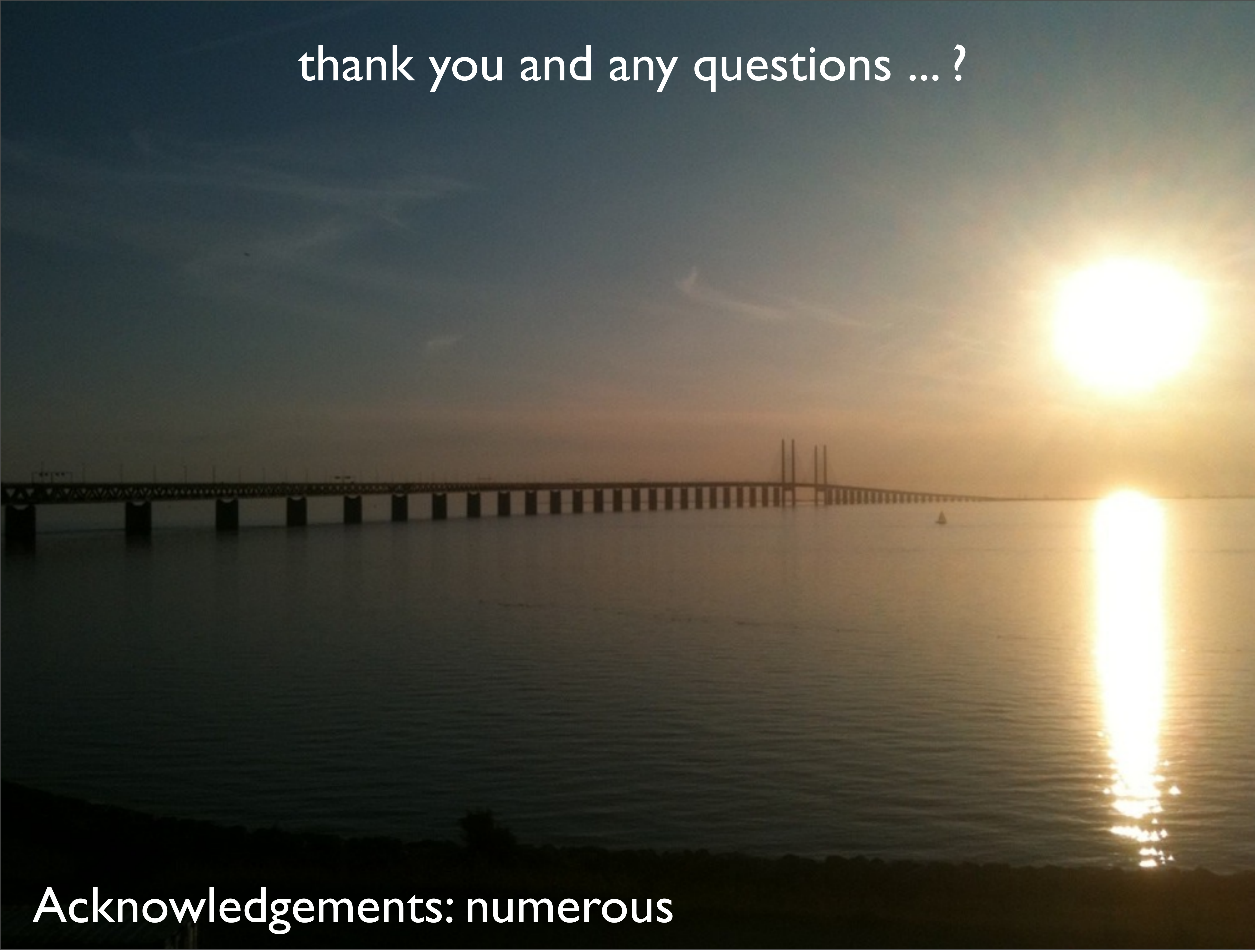
Summary

Common for all detector needs:

- "Good" efficiency - not too much lower than He-3 equivalents
- Low "background" (noise, gamma rejection, scattering, ...) defines performance for many of the instruments
- In general large areas are needed and high number of detector readout channels
- The higher brightness means that care must be taken to avoid saturation of detectors
- Time resolution needed due to the use of time of flight of the neutrons

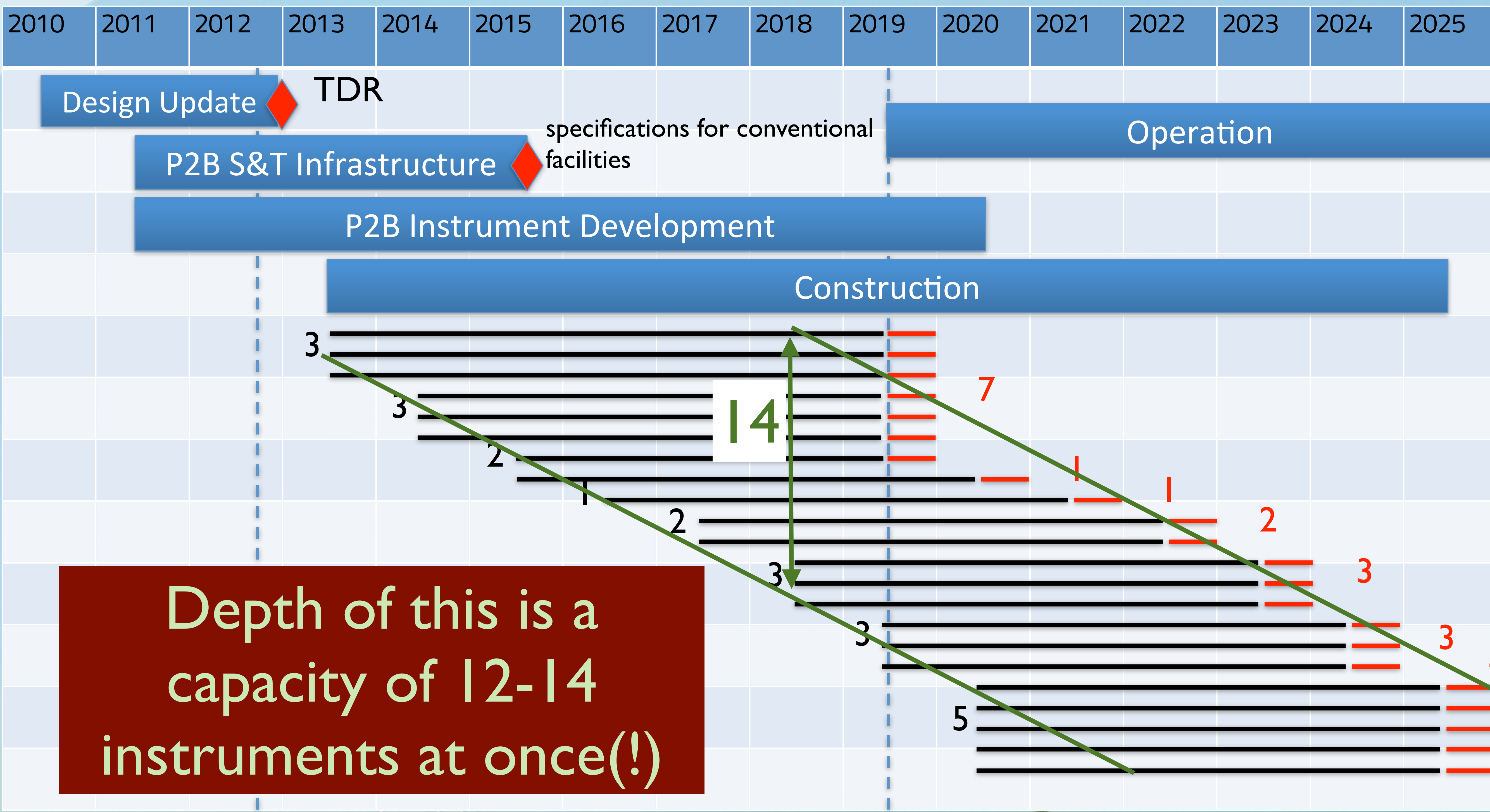
Detectors Development:

- A lot of activity, a lot of progress within the last year
- It is certainly interdisciplinary
- eg electronics wasnt mentioned because I assume that this will come from developments already extant in other fields
- Needs for detector simulation: signal and background sensitivity
- Outside scope of this talk - but also background reduction through modelling, improving design and shielding
- Already many contacts with relevant industry
- Many industrial applications need neutron detectors: demand in security and industrial production


thank you and any questions ... ?
Acknowledgements: numerous

ESS Timeline

2019: First 7 instruments on-line
2025: Full suite of 22 instruments on-line

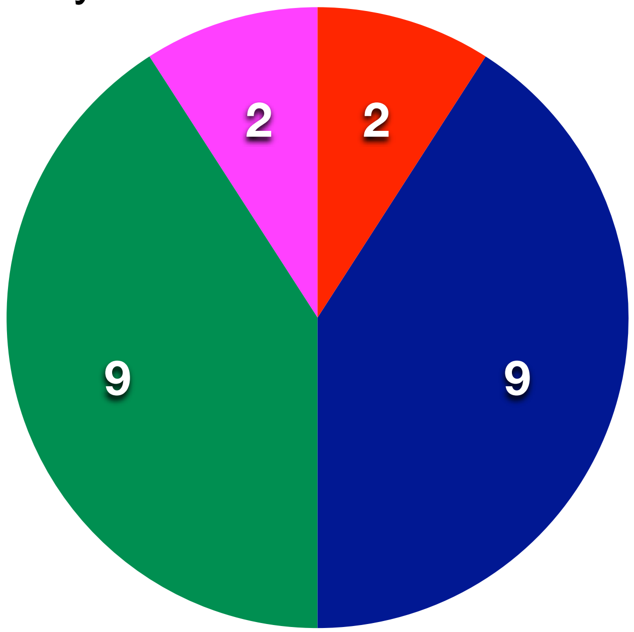


Detector Requirements for TDR Instruments

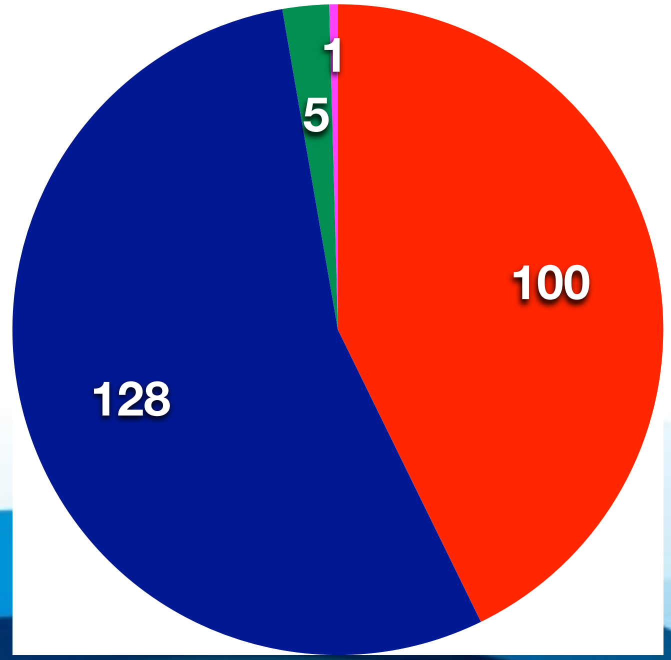
How to fulfill these 4 broad categories of detector requirements:

- Large area (>30m^2)
  - B-10 Thin Film Detectors
  - Exclude BF3 for safety reasons
- Medium area, high resolution
  - Scintillator detectors
  - B-10 Thin Film Detectors
- Small area: 1m^2 or less
  - A wide variety of technologies ...
  - "even" a few He-3 detectors :-)
- Ultra Resolution / imaging
  - Developments coming fast in this field from several directions ...

By Number of Instruments



By Detector Area (m^2)



NB: Preliminary numbers