Detectors for Neutron Facilities

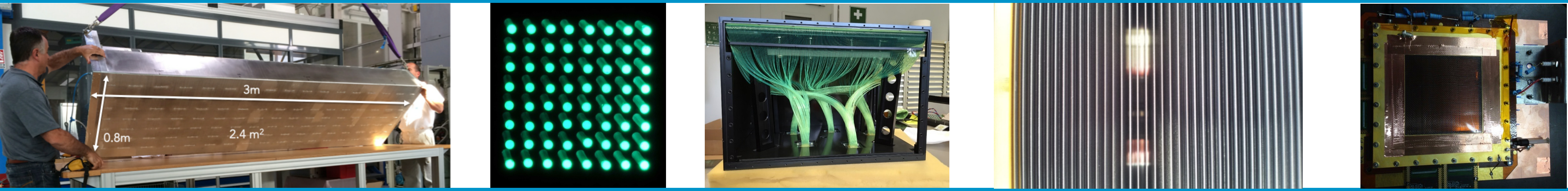
Richard Hall-Wilton

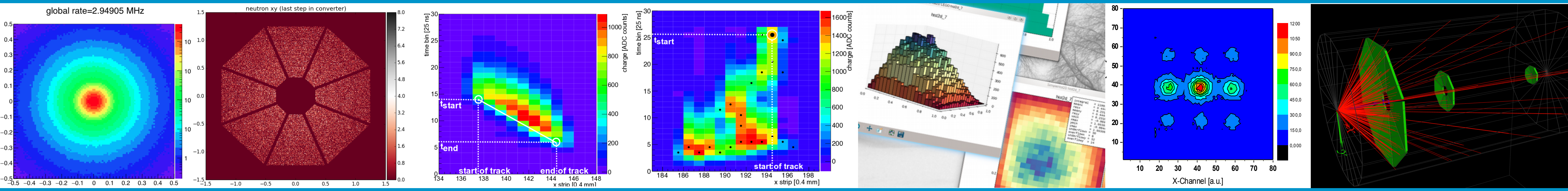
Detector Group Leader

On behalf of ESS Detector Group and Collaborators

www.europeanspallationsource.se

PSD12, Birmingham, 14 September 2021

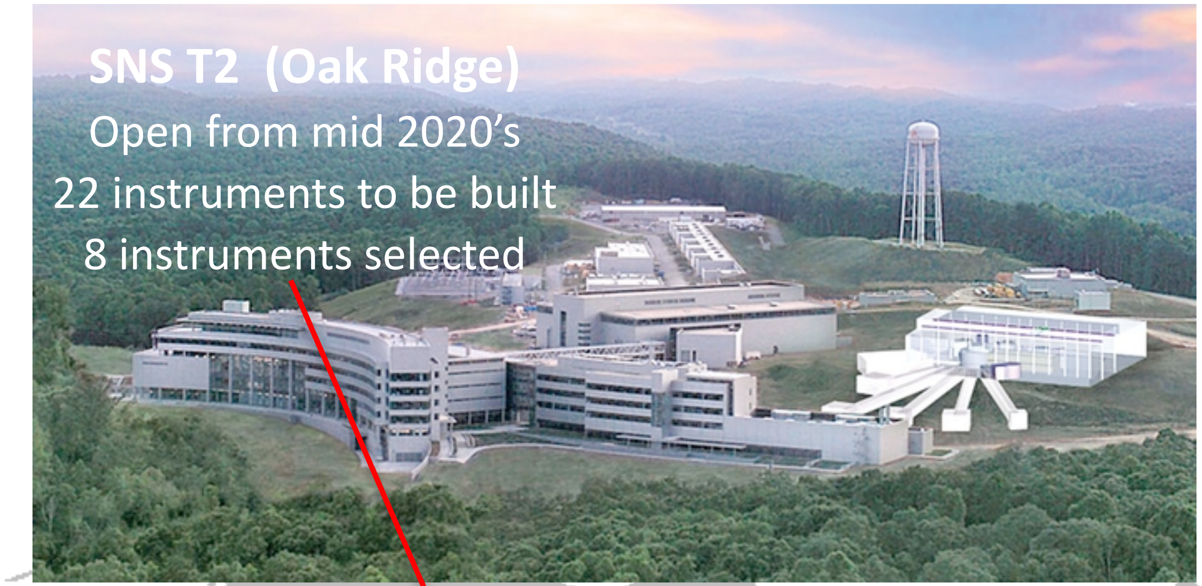




- Why this is Topical?
- What is Neutron Scattering Science?
- New Generation of Neutron Detectors
- Summary

Future Neutron Instrumentation

A lot of novel instrumentation and new ideas needed …



SNS T2 (Oak Ridge)
Open from mid 2020's
22 instruments to be built
8 instruments selected

PIK (St Petersburg)
Open from 2019
>30 instruments to be built

New facilities needed to:

- **replace capacity from closing research reactors**
- **enhance capability to enable new science**

And many new instruments at:
ILL, ISIS, PSI, FRM-II, JPARC, NIST, …

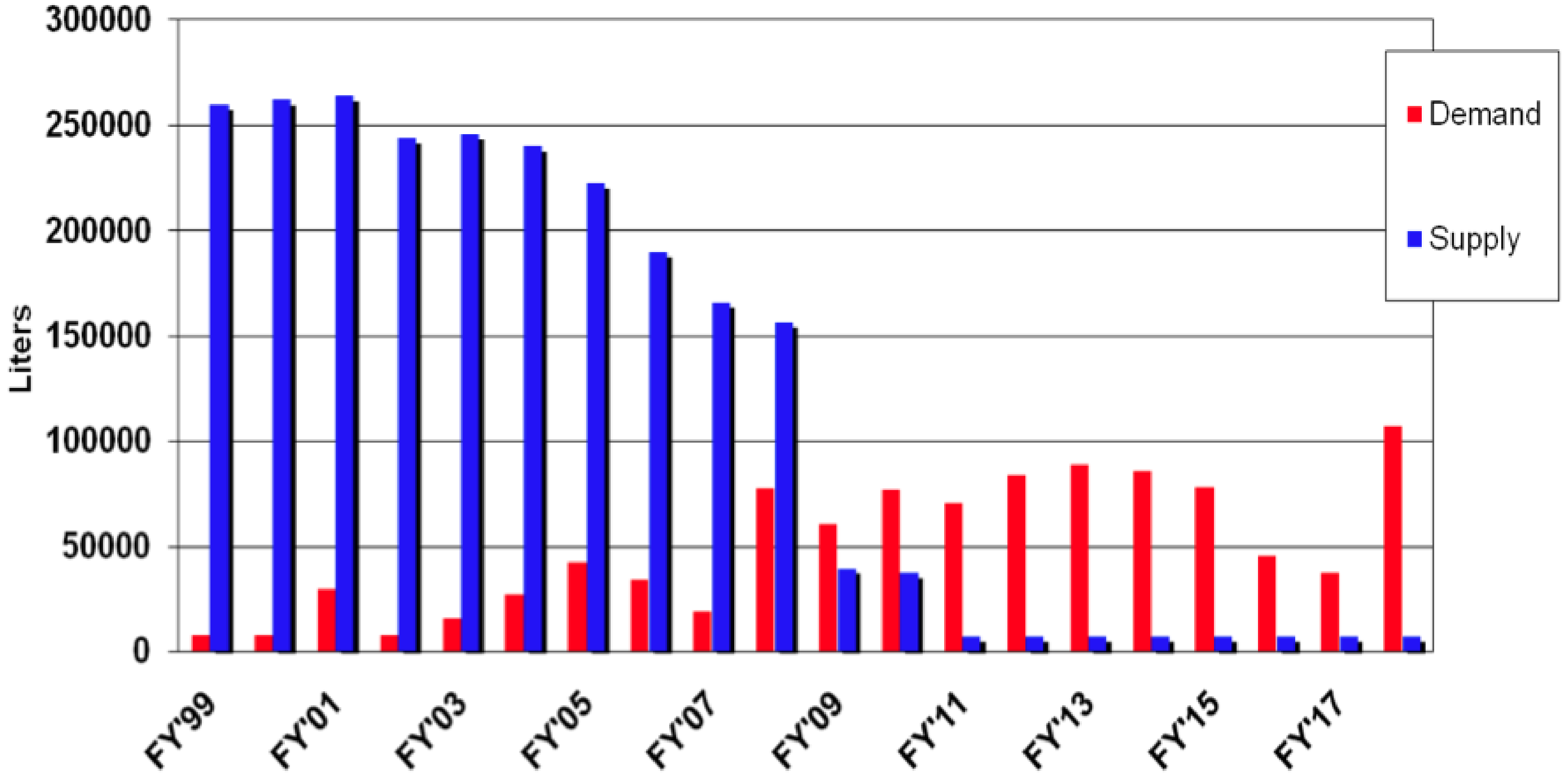
Additionally, there is a growing trend towards small/medium sized accelerator based neutron sources

"towards university scale"

ESS (Lund)
Start in 2023
22 instruments to be built

CSNS (Dongguan)
Started in 2018
20 instruments to be built

Helium-3 Crisis



....an appropriate initial reaction ...

Since ca. 2009

Comment: seems to be some naivety at the moment as stocks are being emptied rapidly

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

Crisis or opportunity ... ?

Neutron Science Pushes the Boundaries

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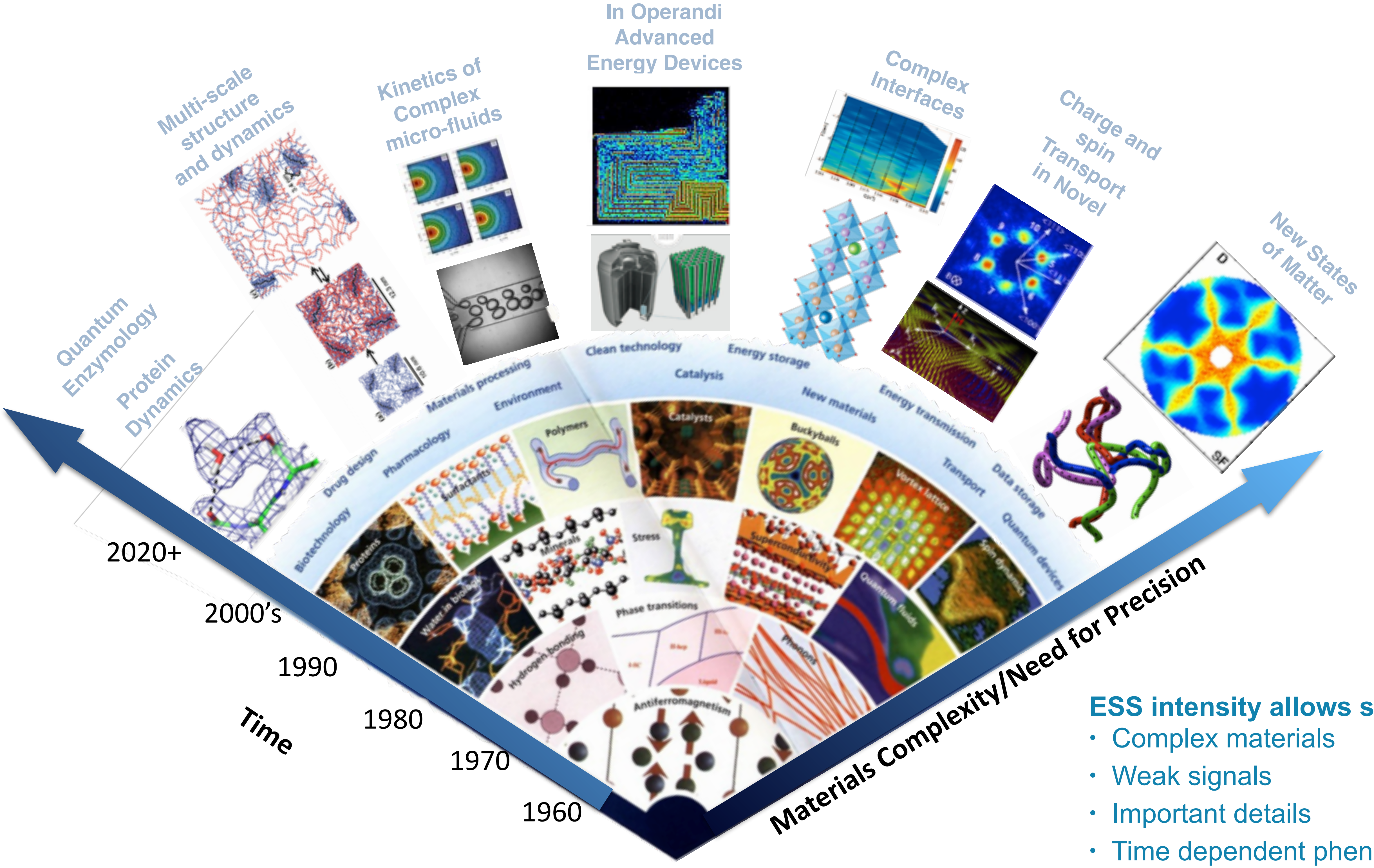
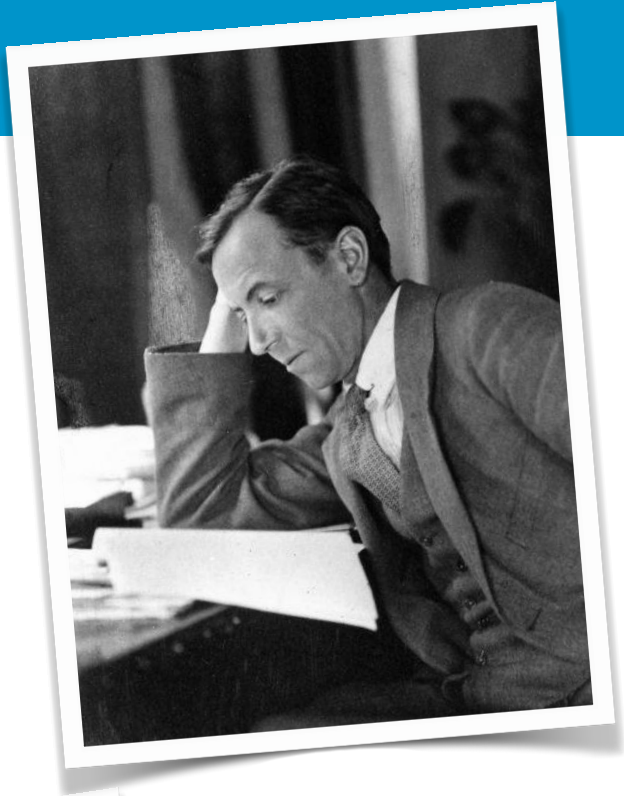


ESS intensity allows studies of:

- Complex materials
- Weak signals
- Important details
- Time dependent phenomena

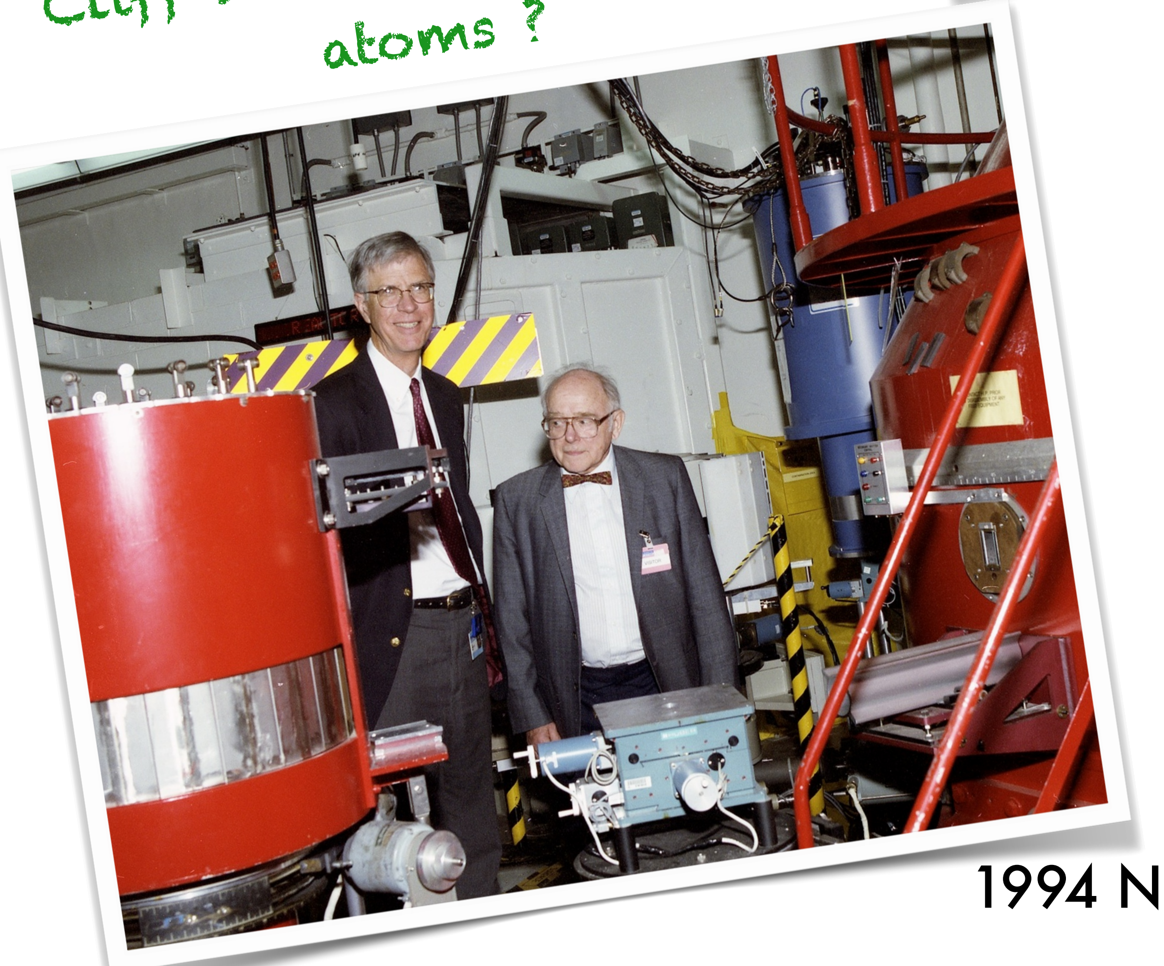
What is Neutron Scattering Science?

Neutrons



1932: Chadwick discovers "a radiation with the more peculiar properties", the neutron.

Cliff Shull: where are the atoms ?



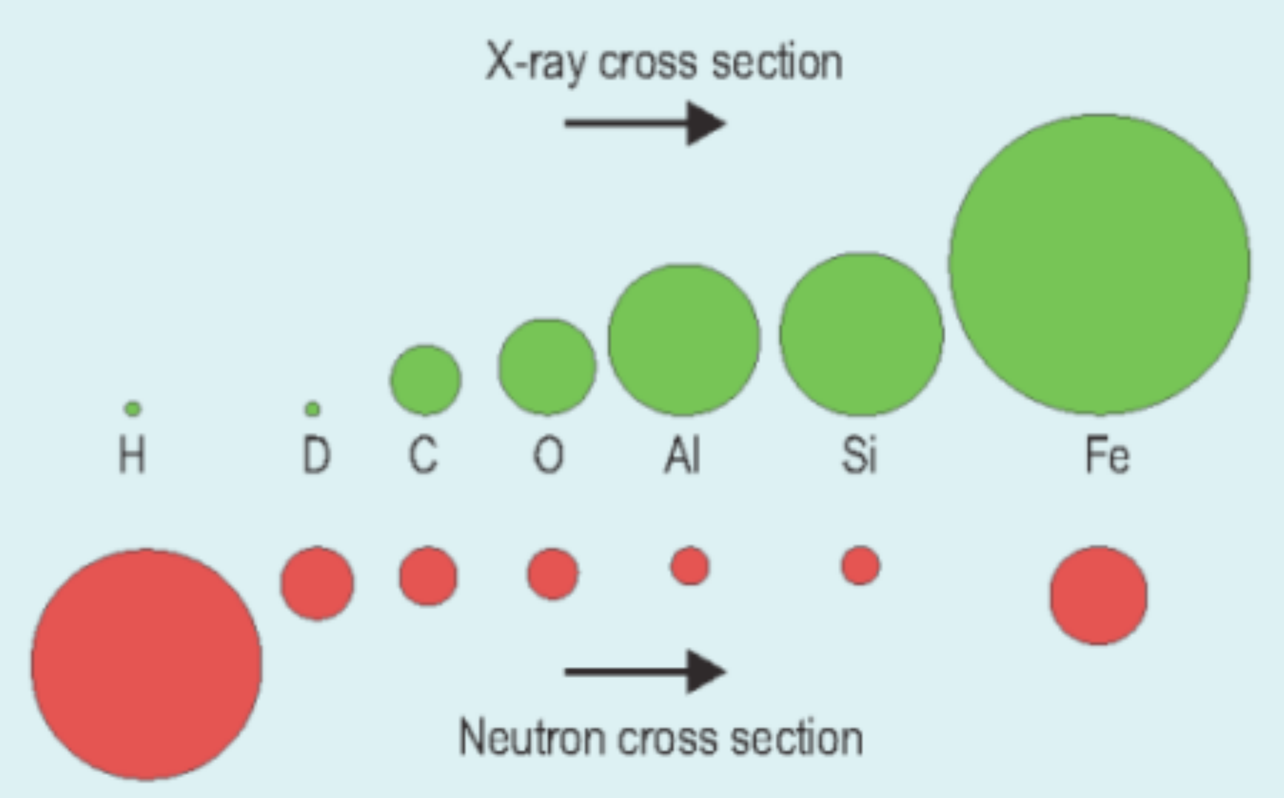
Bert Brockhouse: what do they do ?

1994 Nobel Prize in Physics

Why Neutrons?

Neutrons are:

- **low energy**
- **non-damaging**
- **penetrating**
- **broad wavelength range**



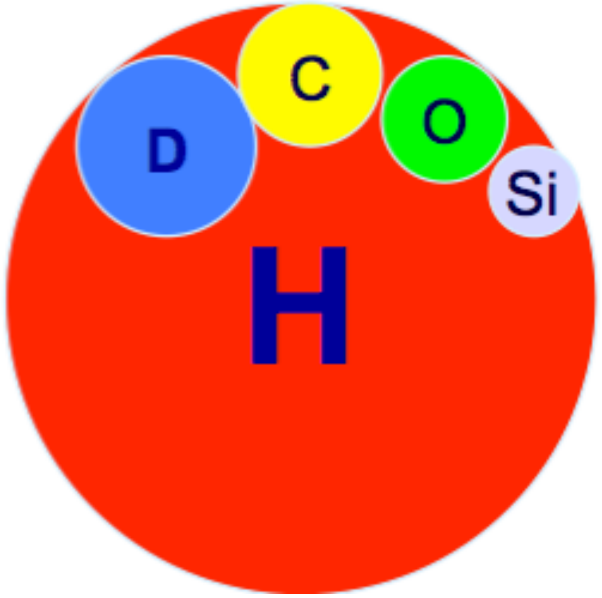
thermal and cold neutrons

meV

"with a small m"

wavelength ca. Å

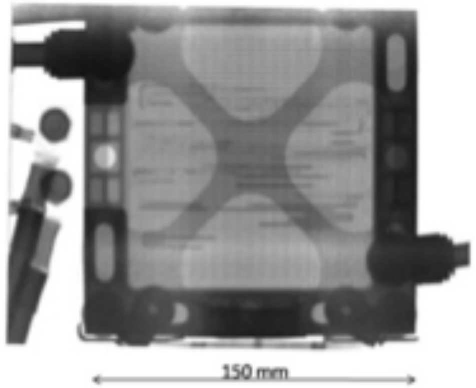
1) Ability to measure both energy and momentum transfer
   Geometry of motion
2) Neutrons scatter by a nuclear interaction => different isotopes scatter differently
   H and D scatter very differently
3) Simplicity of the interaction allows easy interpretation of intensities
   Easy to compare with theory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



Applications of Neutron Science

Charge neutral

Deeply penetrating

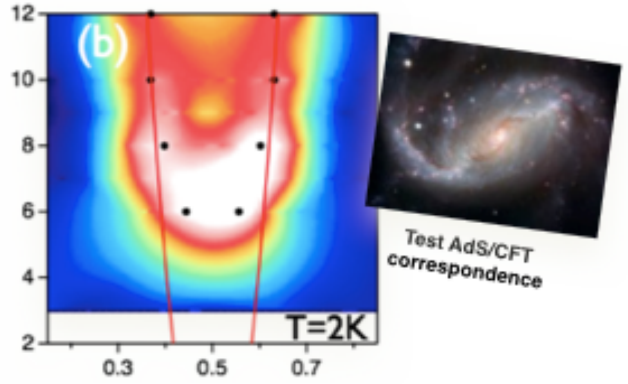


Li motion in fuel cells

Help build electric cars

S=1/2 spin

Directly probe magnetism

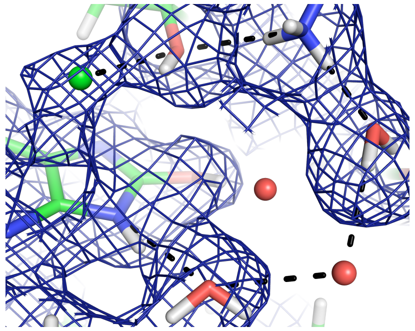


Solve the puzzle of High-Tc superconductivity

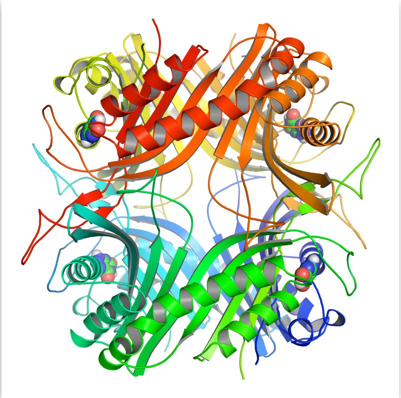
Efficient high speed trains

Nuclear scattering

Sensitive to light elements and isotopes

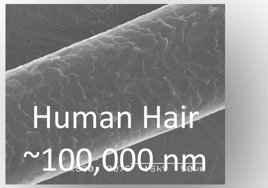


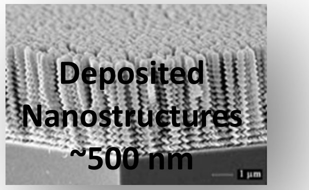
Active sites in proteins

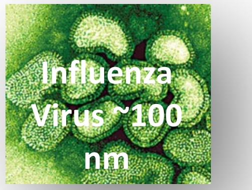


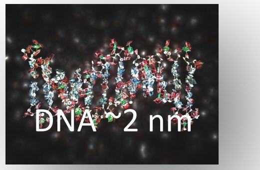
Better drugs

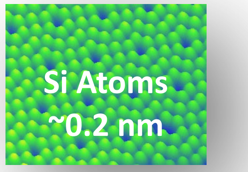
Probing length scales and dynamics











European Spallation Source

The European Spallation Source: view to the Southwest in 2025

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Science City – a new part of town

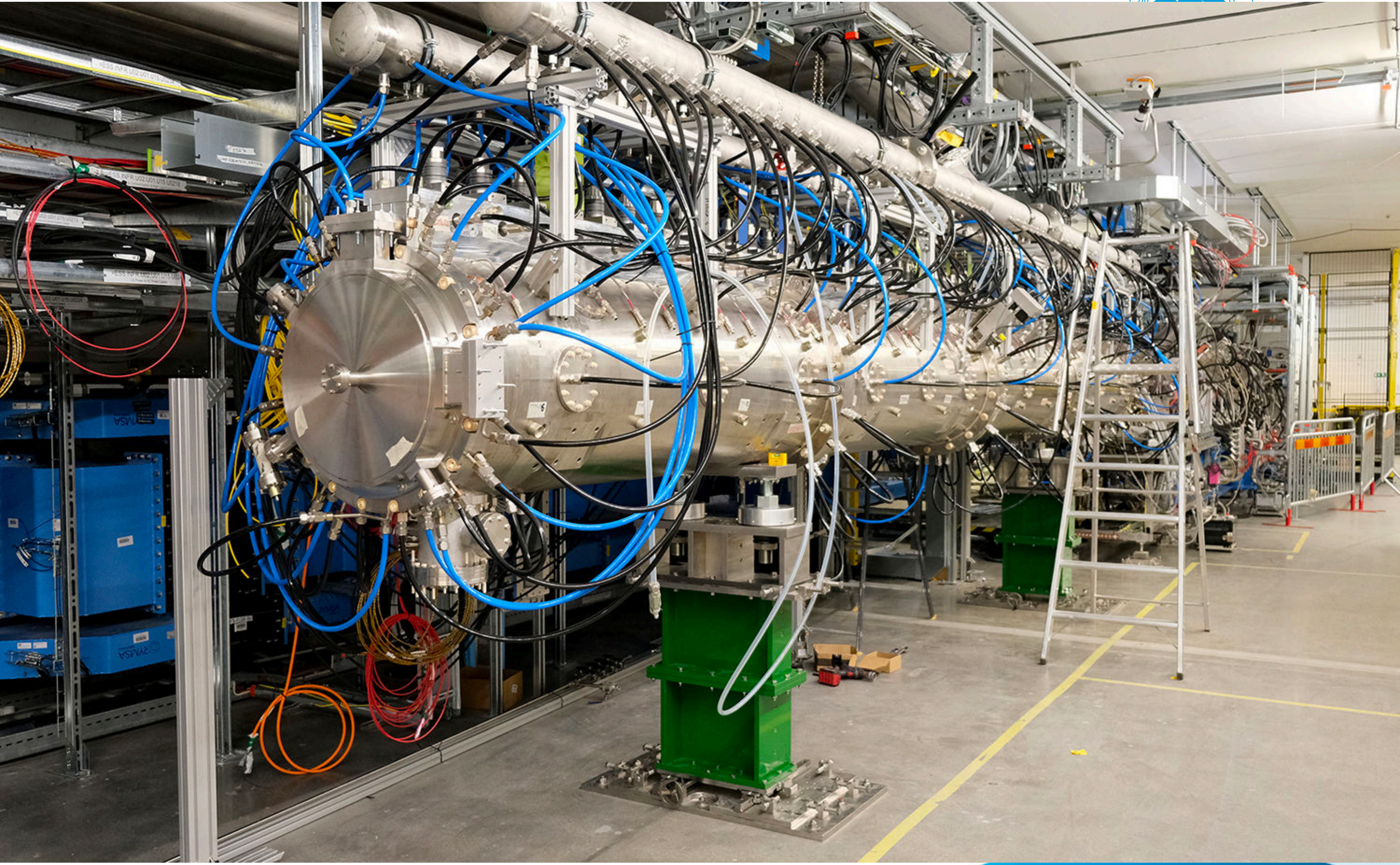
Max IV – a national research facility, under construction, opened in 2016

The ESS site
2011

ESS Construction - October 2020


SKANSKA
elajo
Mekanik

DTL tank 1 under installation in the normal conducting linac.



Instrument Halls starting to come together

Neutron Bunker Installation Activities. West, North & South sector complete. All base plates installed and surveyed. Bunker project remains on schedule.

Neutron Bunker construction of North and west sector D03

Neutron Bunker construction of East and South sectors D01

ESTIA instrument Selene vessel installed

NMX Cave and Control hutch EO1

Bifrost Detector vessel EO1

Bifrost Cave and Crane EO1

NSS Project scope: *15 neutron instruments + test beamline + support labs*

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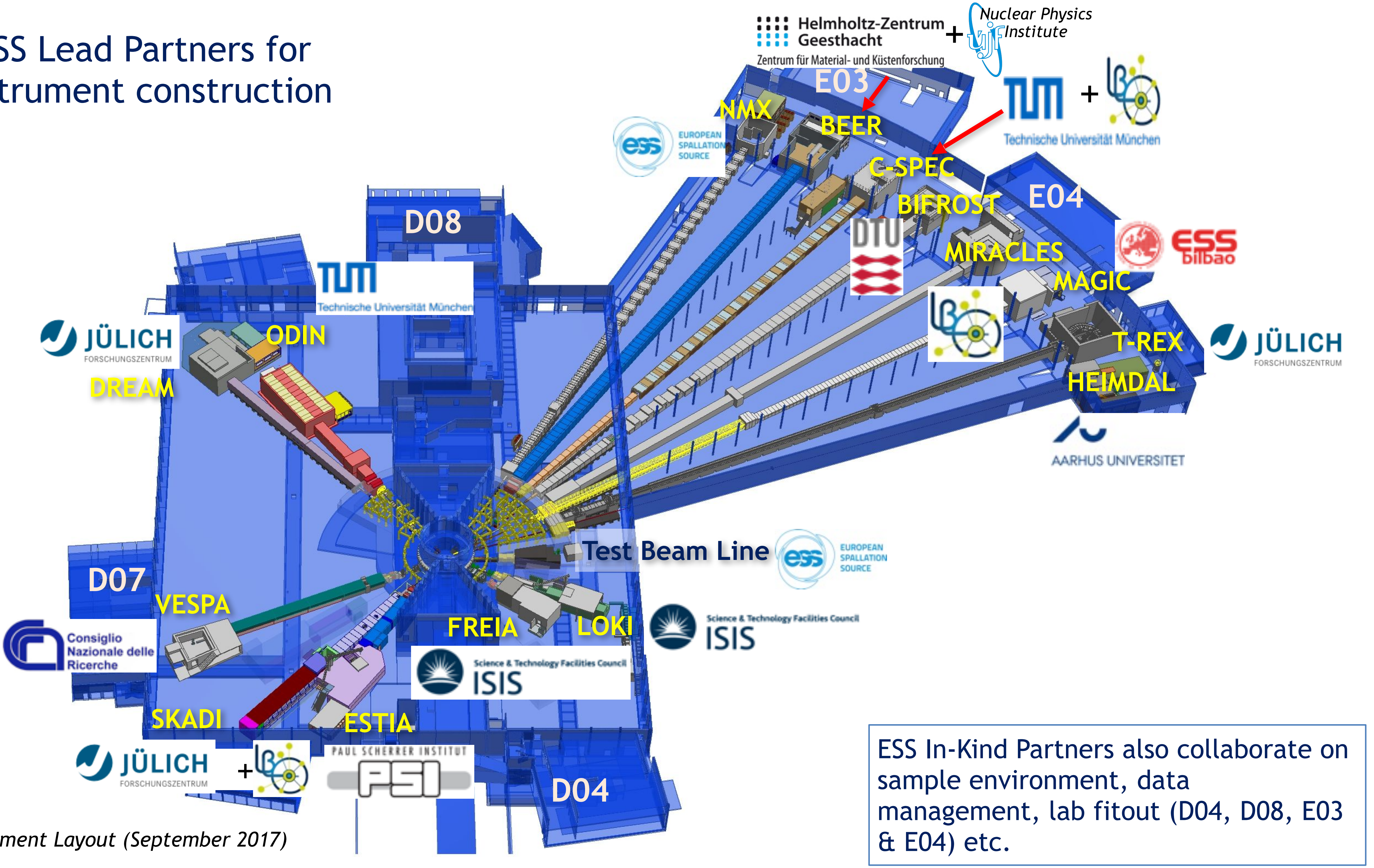
ESS Lead Partners for instrument construction



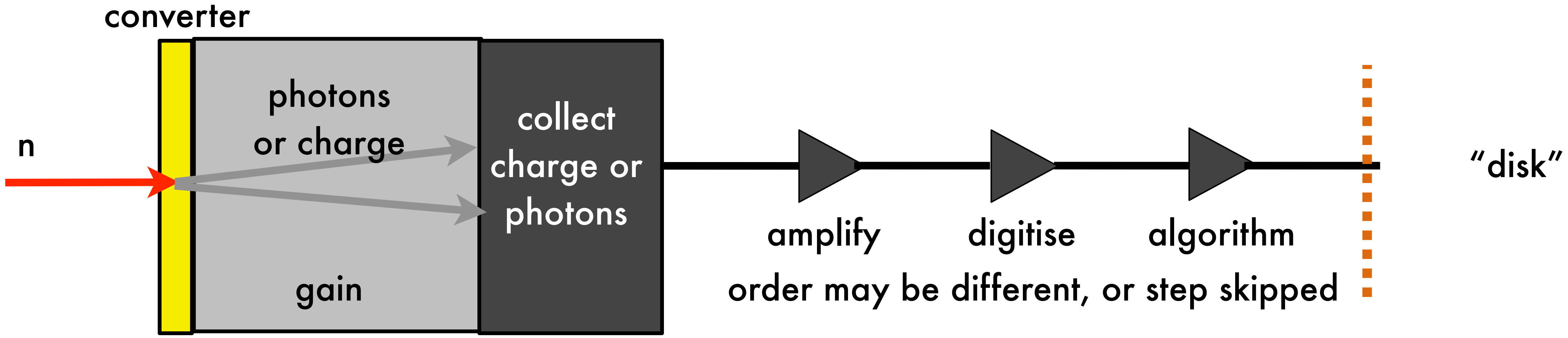
ESS Instrument Layout (September 2017)

ESS In-Kind Partners also collaborate on sample environment, data management, lab fitout (D04, D08, E03 & E04) etc.

Neutron Detectors

Neutron Detectors

Efficient neutron converters a key component for neutron detectors



converter

n

photons
or charge

gain

collect
charge or
photons

amplify

digitise

algorithm

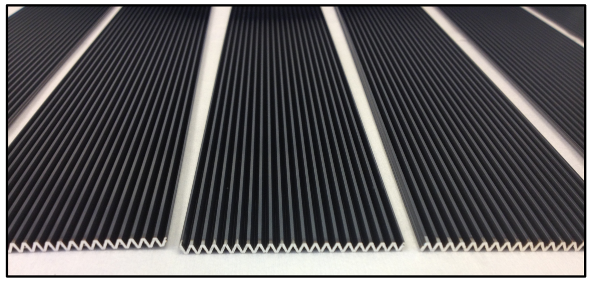
order may be different, or step skipped

“disk”

“Converter”

“Detector”

“Electronics”



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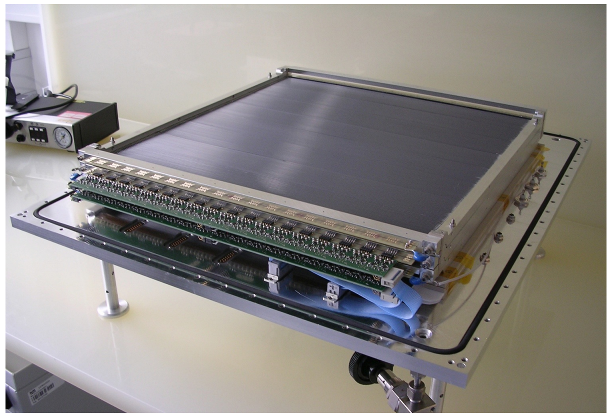

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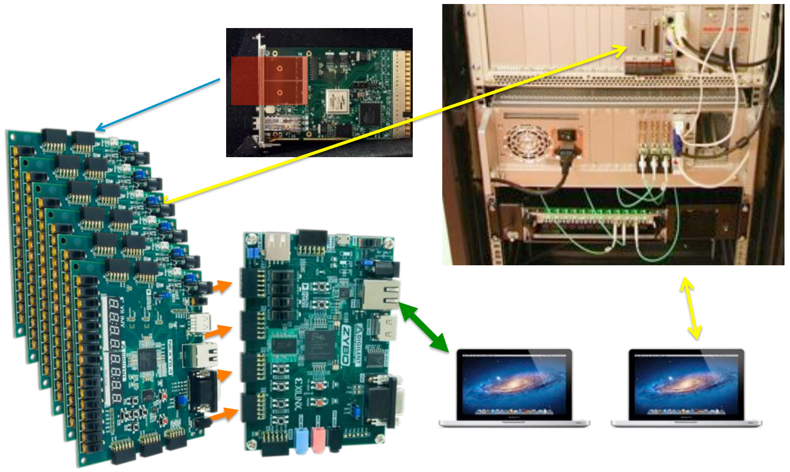
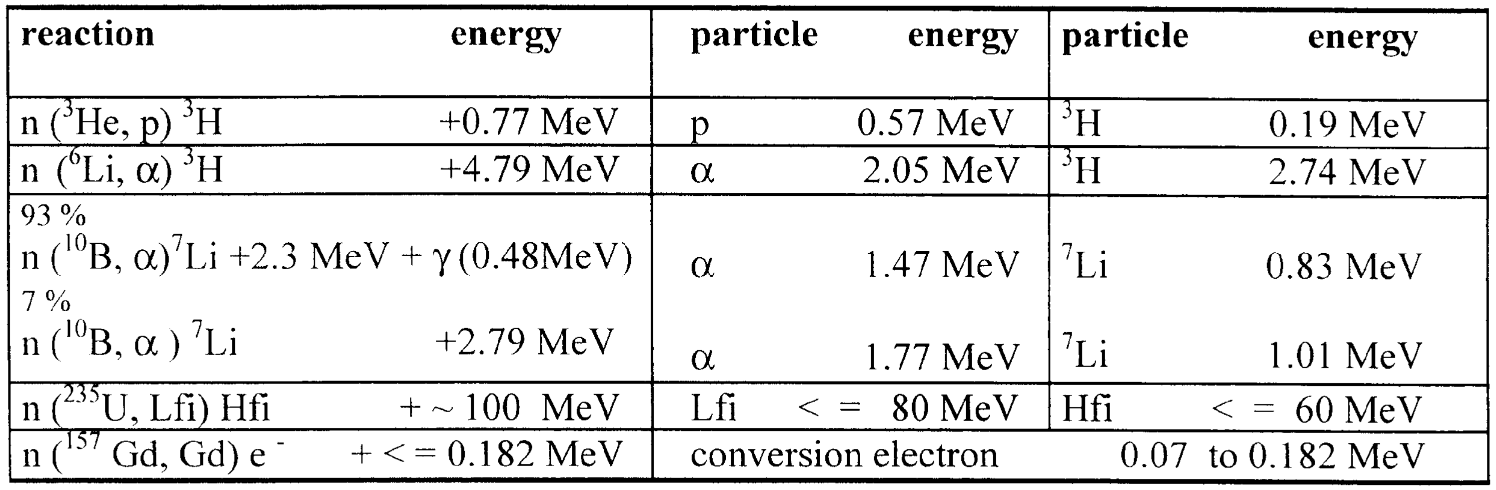


Isotopes Suitable as Cold and Thermal Neutron Convertors



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	

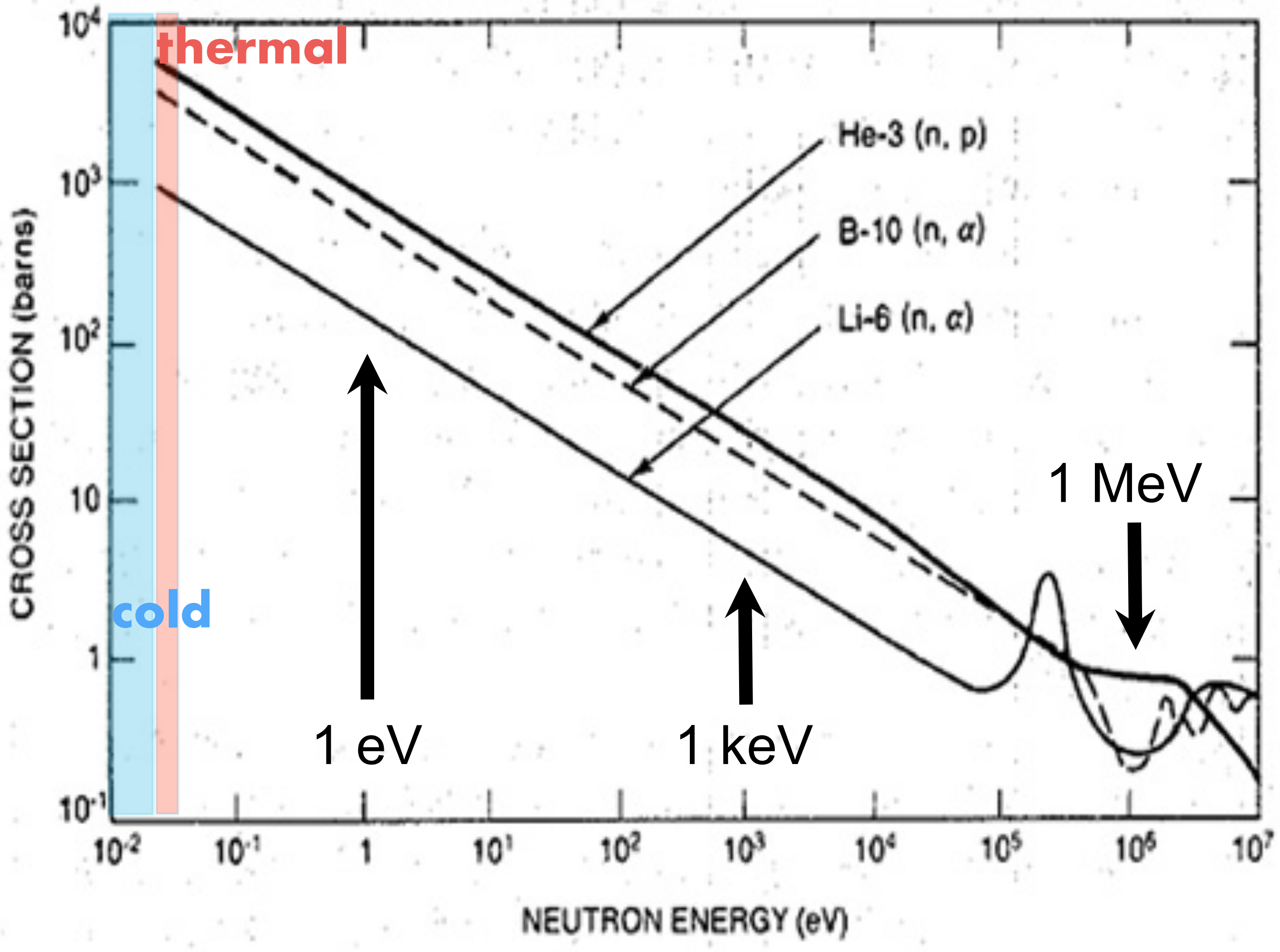
Table 1: Commonly used isotopes for thermal neutron detection, reaction products and their kinetic energies.

ILL Blue Book

- Only a few isotopes with sufficient interaction cross section
- To be useful in a detector application, reaction products need to be easily detectable

- In region of interest, cross sections scale roughly as 1/v
- G. Breit, E.Wiegner, Phys. Rev., Vol. 49, 519, (1936)

- Presently >80% of neutron detectors worldwide are Helium-3 based
- Most of the rest are scintillator-based



State of the Art of Neutron Detectors

- Helium-3 Tubes most common
- Typically 3-20 bar Helium-3
- 8mm-50mm diameter common
- Using a resistive wire, position resolution along the wire of ca. 1% possible

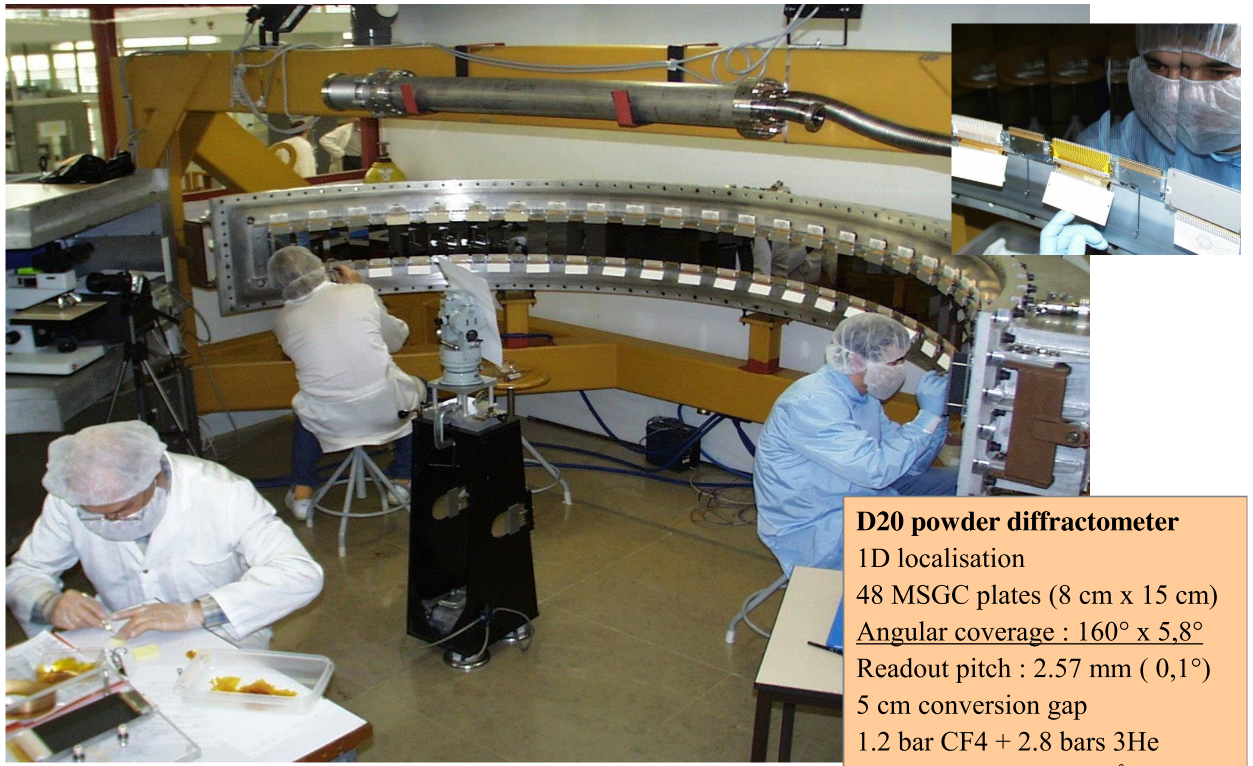

can be large arrays of 10s of m²

IN5@ILL

- First micro pattern gaseous detectors was MSGC invented by A Oed at the ILL in 1988
- Rate and resolution advantages
- Helium-3 MSGCs in operation

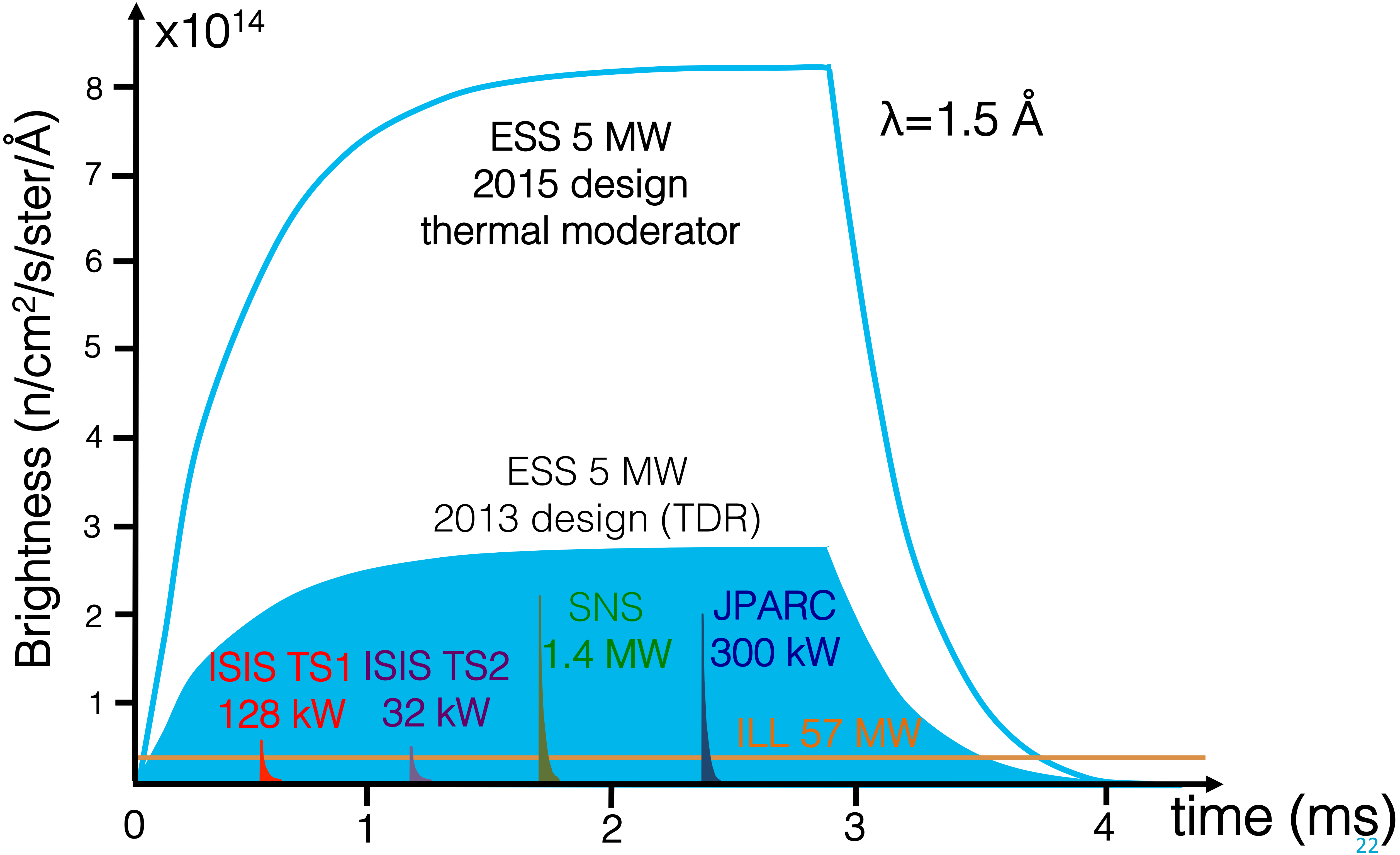
NEUTRONS FOR SCIENCE

Curved 1D MSGC for the D20 Powder Diffractometer (2000)



D20 powder diffractometer
1D localisation
48 MSGC plates (8 cm x 15 cm)
Angular coverage : 160° x 5,8°
Readout pitch : 2.57 mm (0,1°)
5 cm conversion gap
1.2 bar CF_4 + 2.8 bars ^3He
Efficiency 60% @ 0.8 Å

Challenge for Rate



Requirements Challenge for Detectors for ESS: *beyond detector present state-of-the art*

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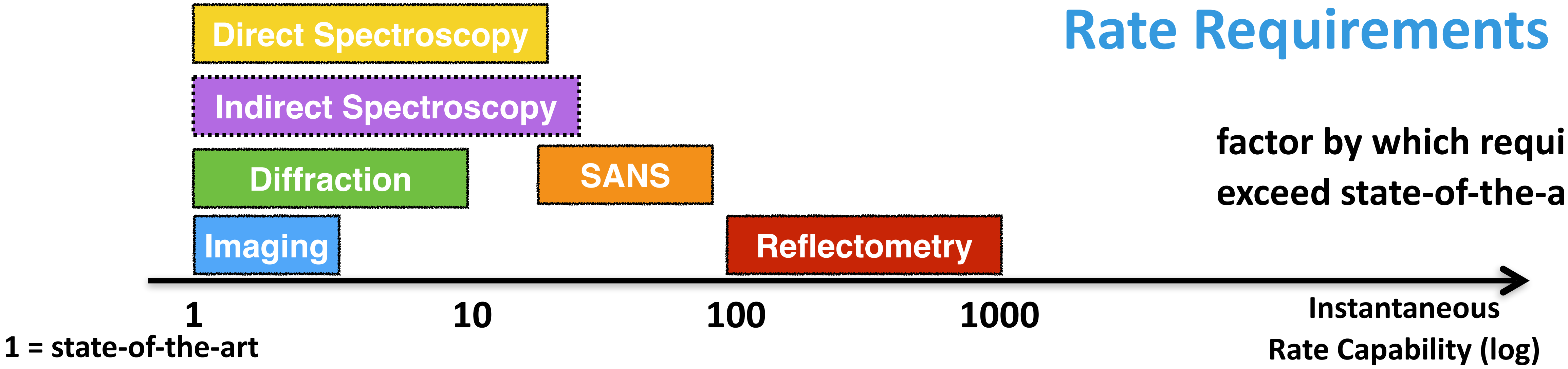
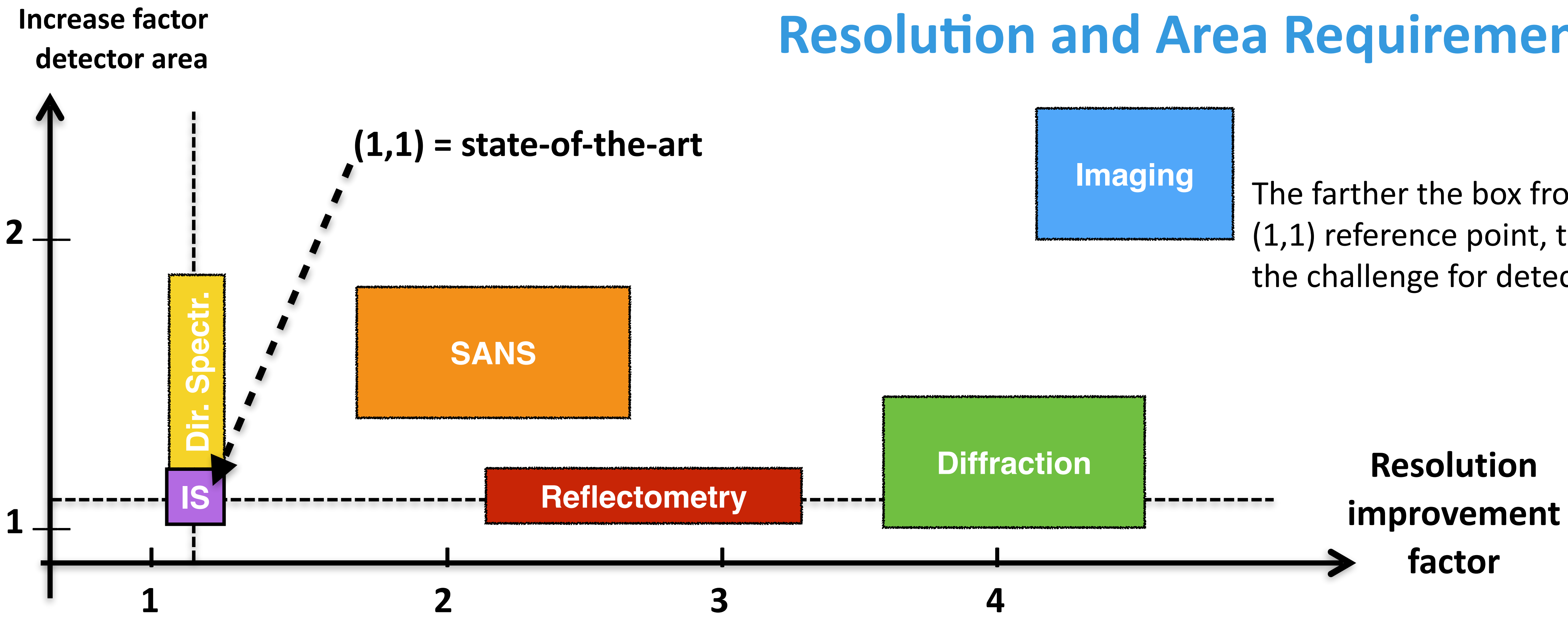
Rate Requirements



factor by which requirements exceed state-of-the-art

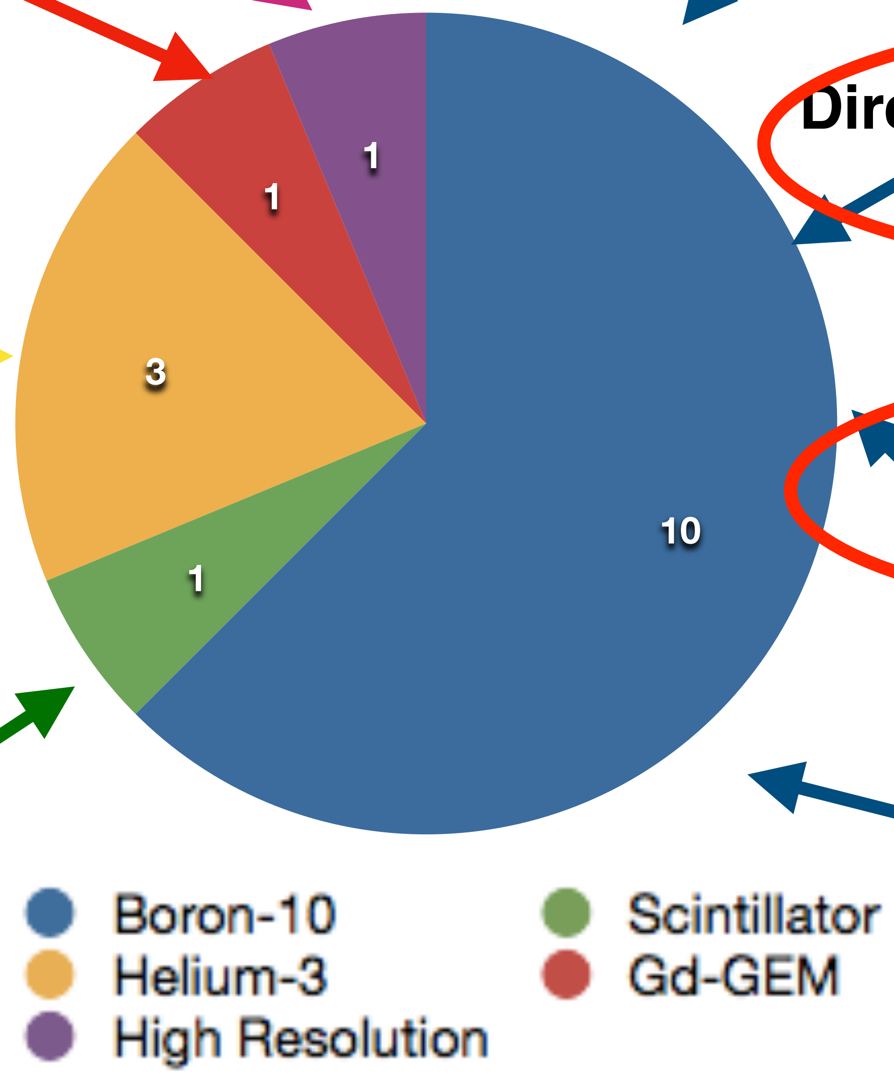
Resolution and Area Requirements



The farther the box from the (1,1) reference point, the bigger the challenge for detectors.

Baseline Detector Technologies for Initial Suite

Detectors for ESS will comprise many different technologies



Imaging: 1 instrument
Various

Diffraction: 4 instruments
Jalousie (3)
Am-CLD (1): B-10 MWPC

NMX: 1 instrument
Gd-GEM

Direct Spectroscopy: 3 instruments
Multi-Grid

Indirect Spectroscopy: 3 instruments
He-3 PSD Tubes

Reflectometry: 2 instruments
Multi-Blade

SANS: 1 instruments
SoNDe

SANS: 1 instrument
Boron Coated Straws

Detectors for ESS Instruments

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Instrument	Neutron Converter	Detector Type	Gas Gain	Number of Channels	Front-End Type/ASIC
CSPEC	10B4C	MWPC	ca. 10	ca.20k	VMM3A
TREX	10B4C	MWPC	ca. 10	ca. 15k	VMM3A
ESTIA	10B4C	MWPC	ca. 10	ca. 6k	VMM3A
FREIA	10B4C	MWPC	ca. 10	ca. 4k	VMM3A
NMX	Gd	GEM	ca. 1000	ca. 15k	VMM3A
DREAM	10B4C	MWPC	<100	400k	CDT/CIPIX
MAGIC	10B4C	MWPC	<100	165k	CDT/CIPIX
HEIMDAL	10B4C	MWPC	<100	250k	CDT/CIPIX
LOKI	10B4C	Straws	>1000	5k	Discrete Preamp/ CAEN R5560
BIFROST	3He	Tube	>1000	ca. 100	Discrete Preamp/ CAEN R5560
VESPA	3He	Tube	>1000	ca. 100	Discrete Preamp/ CAEN R5560
MIRACLES	3He	Tube	>1000	ca. 100	Discrete Preamp/ CAEN R5560
SKADI	6Li	Scintillator	N/A	25000	IDEAS/IDE3465
ODIN	6Li	Various	N/A	ca. 1M	TIMEPIX4
BEER	10B4C	MWPC	>100	40	Delay Line + Custom FPGA
Beam Monitors	Various	MWPC/GEM/IC	1-100	50	Discrete Preamp / ADC OHWR FMC-ADC-100m14b4Cha
TestBeam Line	10B4C	MWPC	ca. 10	ca. 1k	VMM3A

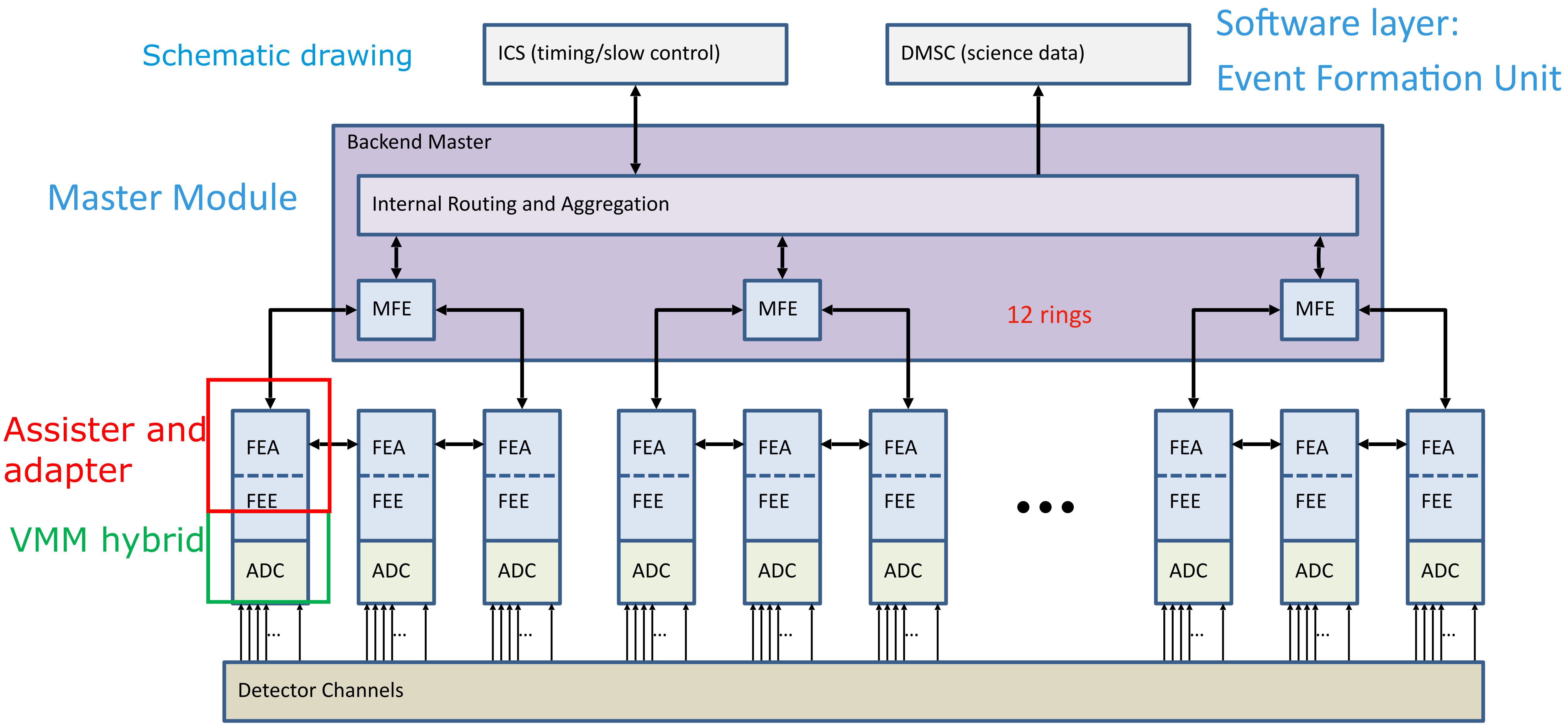
- Step change # channels cf. current instruments
- From 100's to 10k's

- Need for using ASICs to handle large channel count at moderate cost
- Different detector partners means a variety of choices for front-end

- Key requirement for DAQ system is to be able to integrate a multiplicity of detector types and approaches
- Unify the "look and feel" within the electronics DAQ

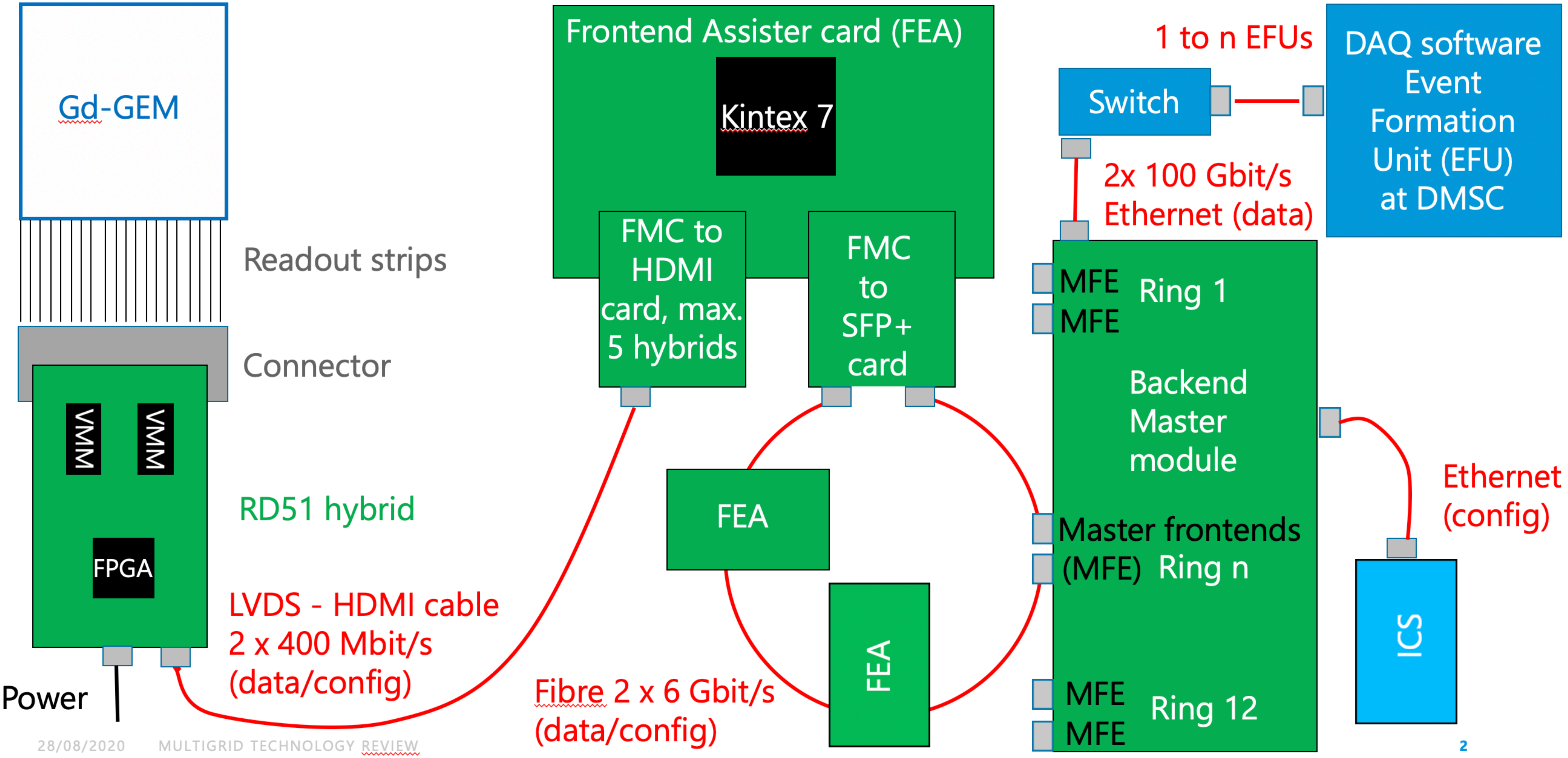
Detector Electronics

- Standardised Instrument Data Acquisition at the Electronics Backend: All instruments will use the "Master Module" using a commercial FPGA dev board (VCU118)
- Front-ends handled using 12 data rings of “assistor" boards
- Facility ("accelerator”) timing distributed to the front-end via the rings



Readout Architecture is described in BrightnESS Deliverable D4.1:
https://dx.doi.org/10.17199/BRIGHTNESS.D4.1

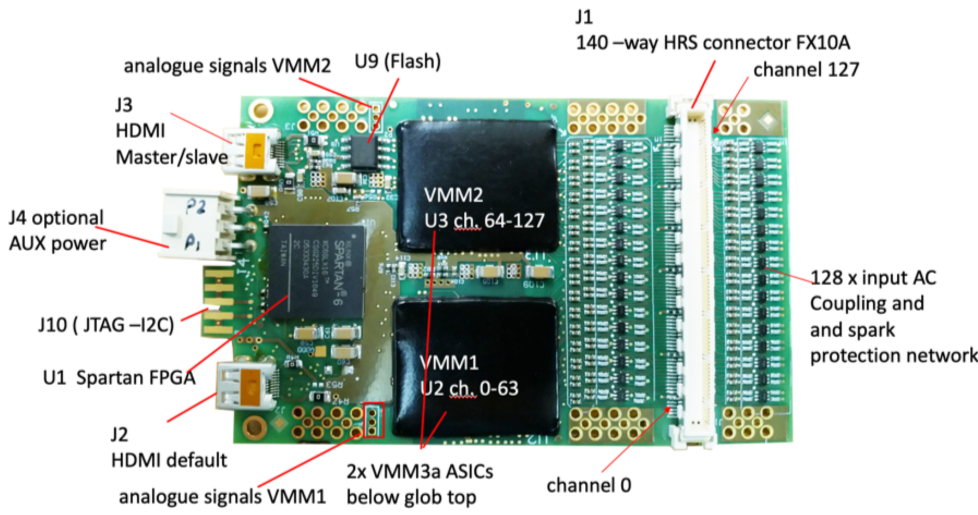
Readout chain NMX



Front End Electronics: VMM3A ASIC

- VMM3a is the 4th version of an ASIC developed by Brookhaven National lab for the ATLAS New Small Wheel upgrade at CERN
- ASIC developed to read out Micro Pattern Gaseous detectors (MPGD)
- ASIC is high rate, sub-ns time resolution

- RD51 VMM3A hybrid common ESS-CERN project: successful integration of the VMM3a ASIC into the CERN Scalable Readout System (SRS) during BrightnESS
- 7.3 Mhits/s per VMM3a ASIC
- Per single VMM3a channel 4 Mhits/s
- Works well also for wire-based gaseous detectors



- First 107 available now
- 75% yield of highest quality hybrids

- 25 wafers of VMM chips on order
- Placed Purchase Order for first production batch of 271 hybrids

Backgrounds

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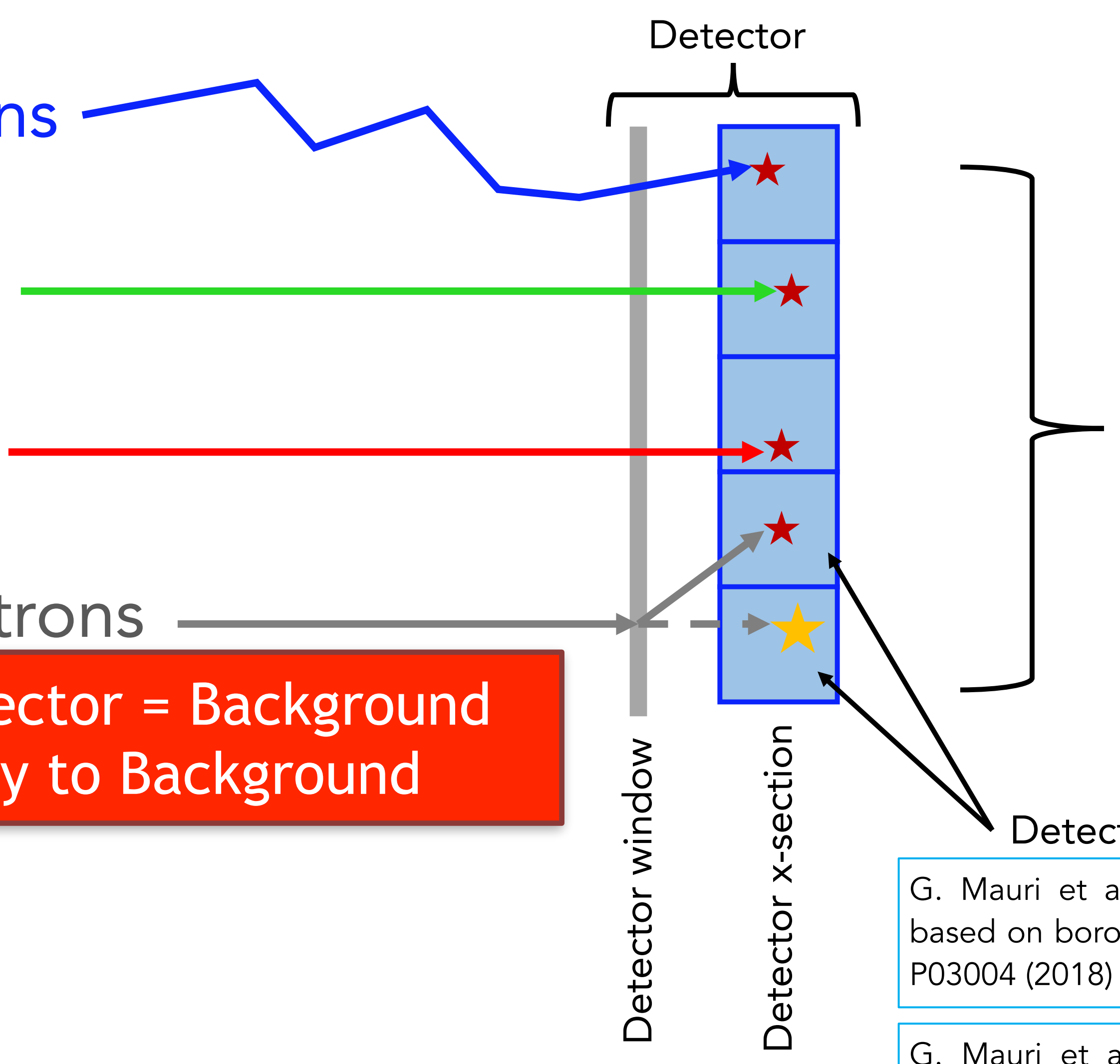
DETECTOR BACKGROUND

- Cosmic neutrons
- Gamma-rays
- Fast Neutrons
- Scattered Neutrons



LEGEND

★	Good events
★	Unwanted events

He-3 vs B-10

Background Observed in Detector = Background Flux at Detector X Sensitivity to Background

Thermal neutron ~0.6

Fast neutron ~ 10^{-5}

Gamma ~10^{-8}

G. Mauri et al., Fast neutron sensitivity of neutron detectors based on boron-10 converter layers. arXiv:1712.05614 JINST 13 P03004 (2018)

G. Mauri et al., Evidence of fast neutron sensitivity for 3He detectors and comparison with Boron-10 based neutron detectors, *EPJ TI 6 (2019) 3, arXiv:1902.09870*

At the detector*, it is 100 times more important to remove *fast neutrons* than *gamma
At the detector*, it is 10000 times more important to prevent *scattering and local thermalisation* than remove *fast neutrons
Historically the emphasis has been opposite

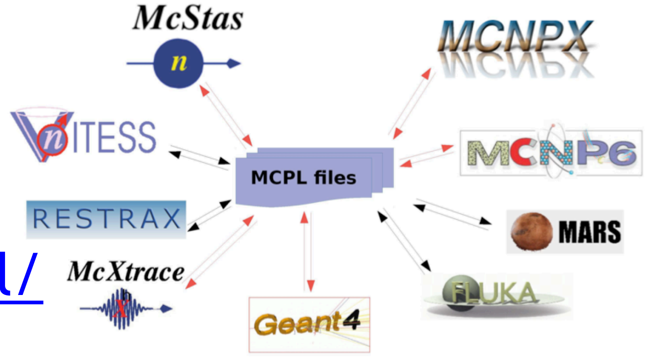
Simulation tools

- New tools & utilities are recently developed for neutron studies
  - Physics
    - Coherent scattering
    - Inelastic scattering
    - Single- and poly-crystals…
  - And more
    - Communication
    - Visualisation
    - Ready-to use…

NXSG4
doi:10.1016/j.cpc.2014.11.009
http://nxsg4.web.cern.ch/nxsg4/

NCrystal
https://github.com/mctools/ncrystal/wiki

MCPL -
Monte Carlo Particle List
https://mctools.github.io/mcpl/



ESS Coding Framework -
Geant4 simulation framework Developed by ESS Detector Group
doi:10.1016/S0168-9002(03)01368-8
doi:10.1088/1742-6596/513/2/022017

K. Kanaki et al., "Simulation tools for detector and instrument design", Physica B https://doi.org/10.1016/j.physb.2018.03.025 arXiv.org:1708.02135

Risø DTU
National Laboratory for Sustainable Energy

Simulation of Neutron Scattering in Crystalline Materials

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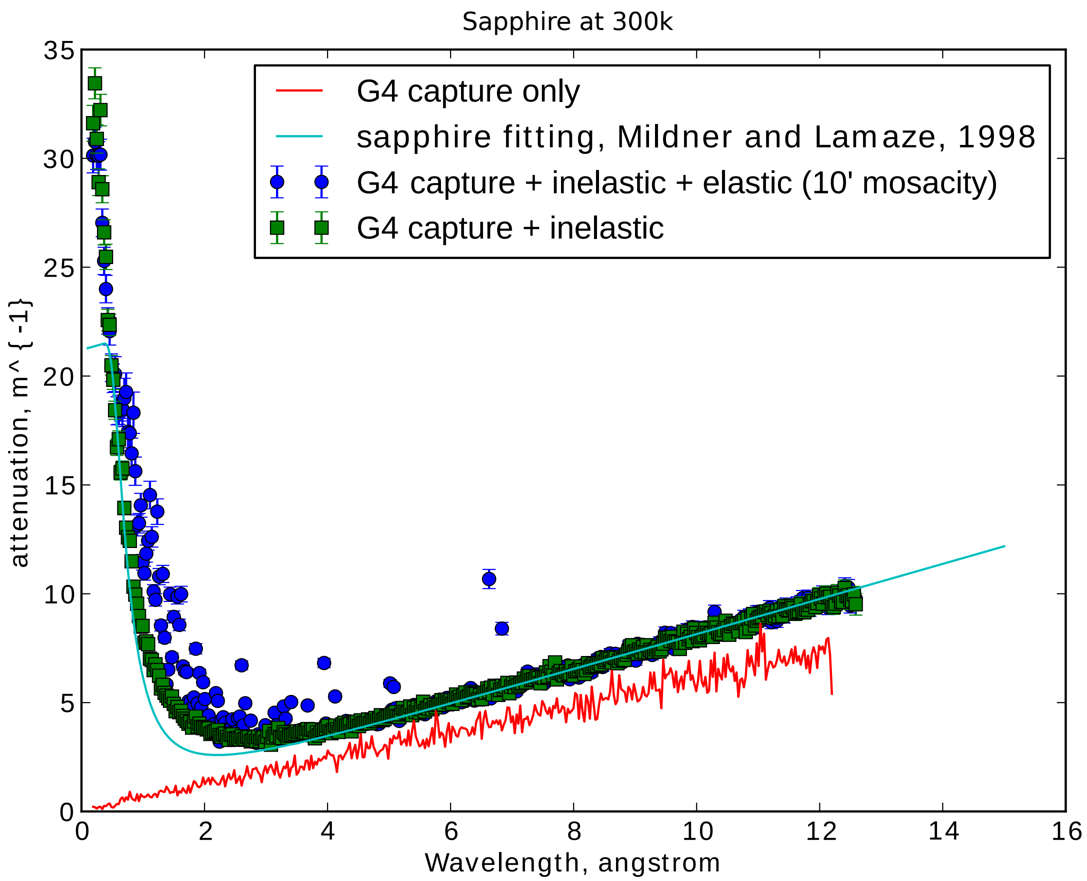
- “NCrystal" models physics of thermal neutron transport in poly- and single-crystalline materials
- Interface to MC models: GEANT4, MCNP, McStas

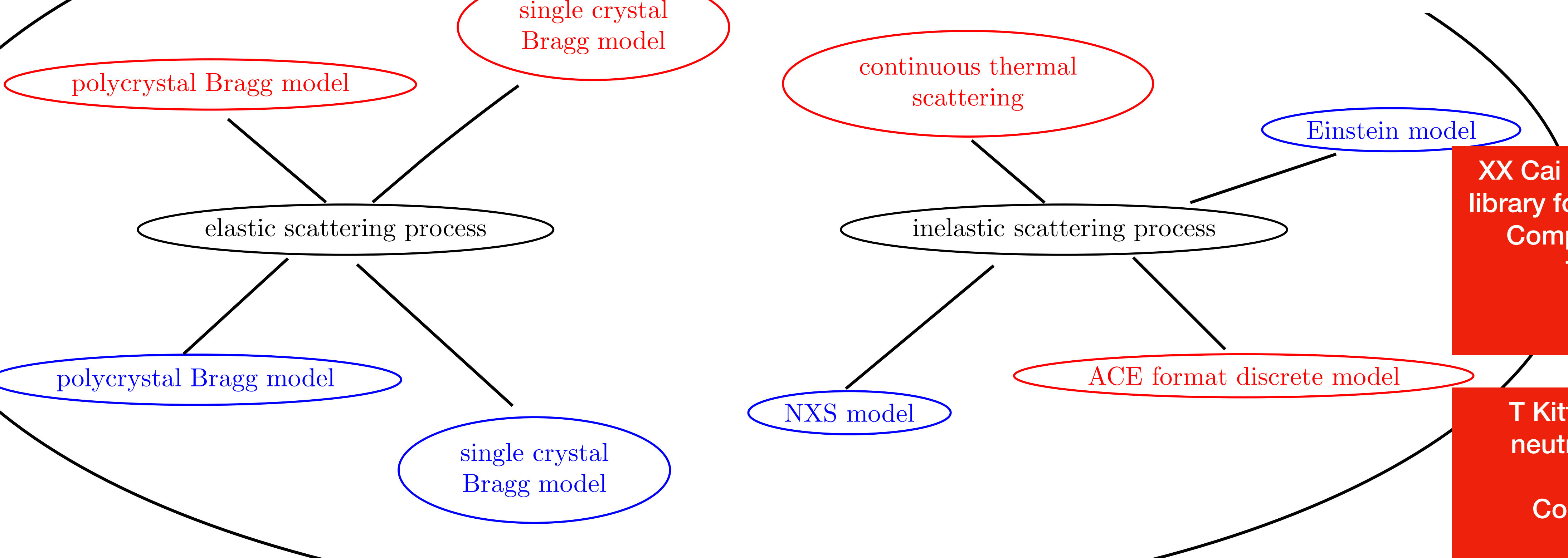
The scattering physics in NCrystal is a combination of the inelastic and elastic scattering processes. The double differential cross section describes the likelihood of a neutron being scattered into a small solid angle $d\Omega$ with final energy between E' and $E' + dE'$. It can be expressed as

$$\frac{\partial^2\sigma}{\partial E'\partial\Omega} = \frac{\partial^2\sigma_{in}}{\partial E'\partial\Omega} + \frac{\partial^2\sigma_{el}}{\partial E'\partial\Omega}$$



NCrystal

data-driven models in red
therory-driven models in blue



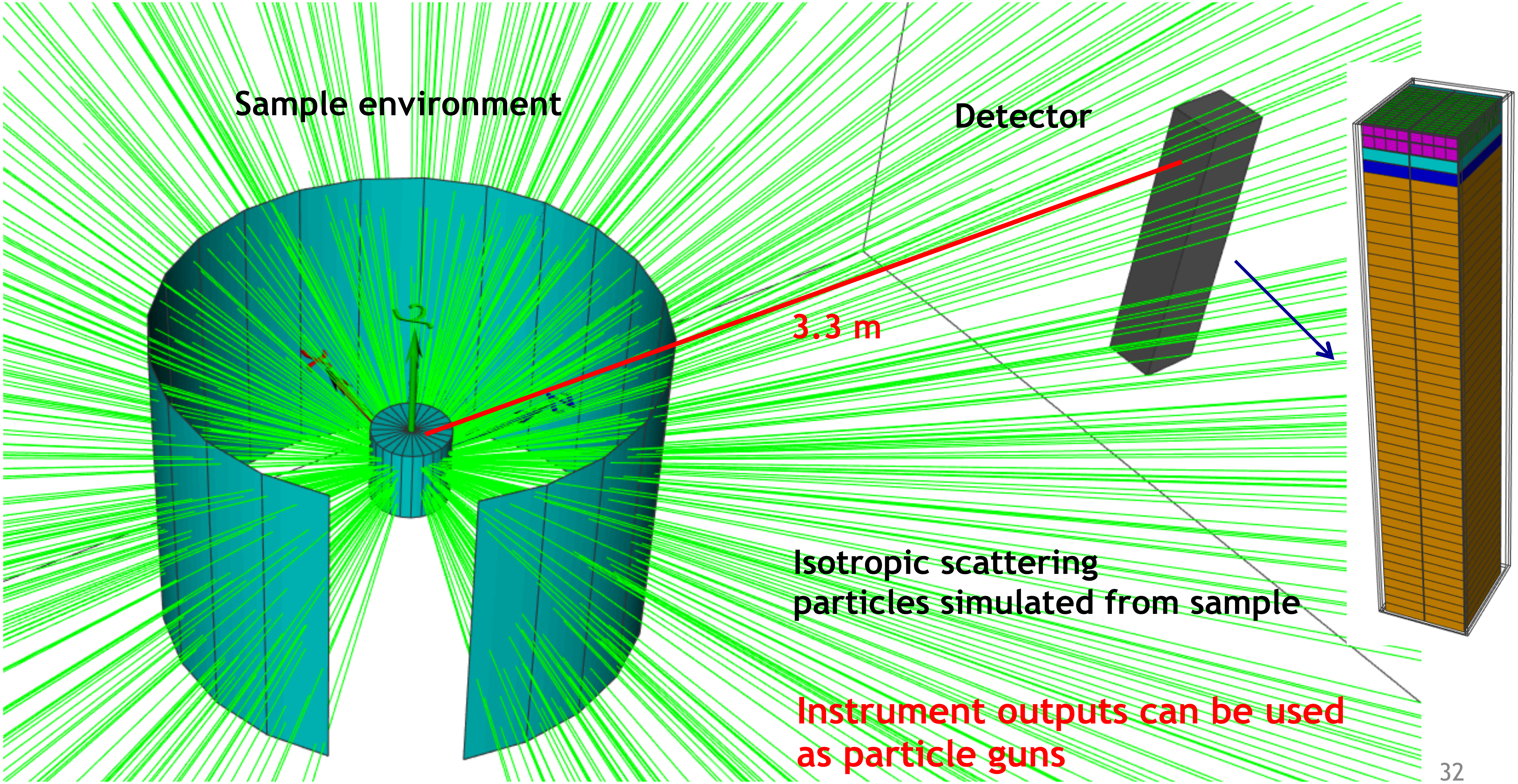
XX Cai & T Kittelmann, NCrystal : a library for thermal neutron transport, Comp.Phys.Comm. 246 (2019) 106851 DOI 10.1016/j.cpc.2019.07.015 arXiv:1901.08890

T Kittelmann & XX Cai, Elastic neutron scattering models for NCrystal, accepted Comp.Phys.Comm. (2021) arxiv:2012.04294

Multi-Grid detector test at CNCS, SNS

Geant4 @Coding Framework

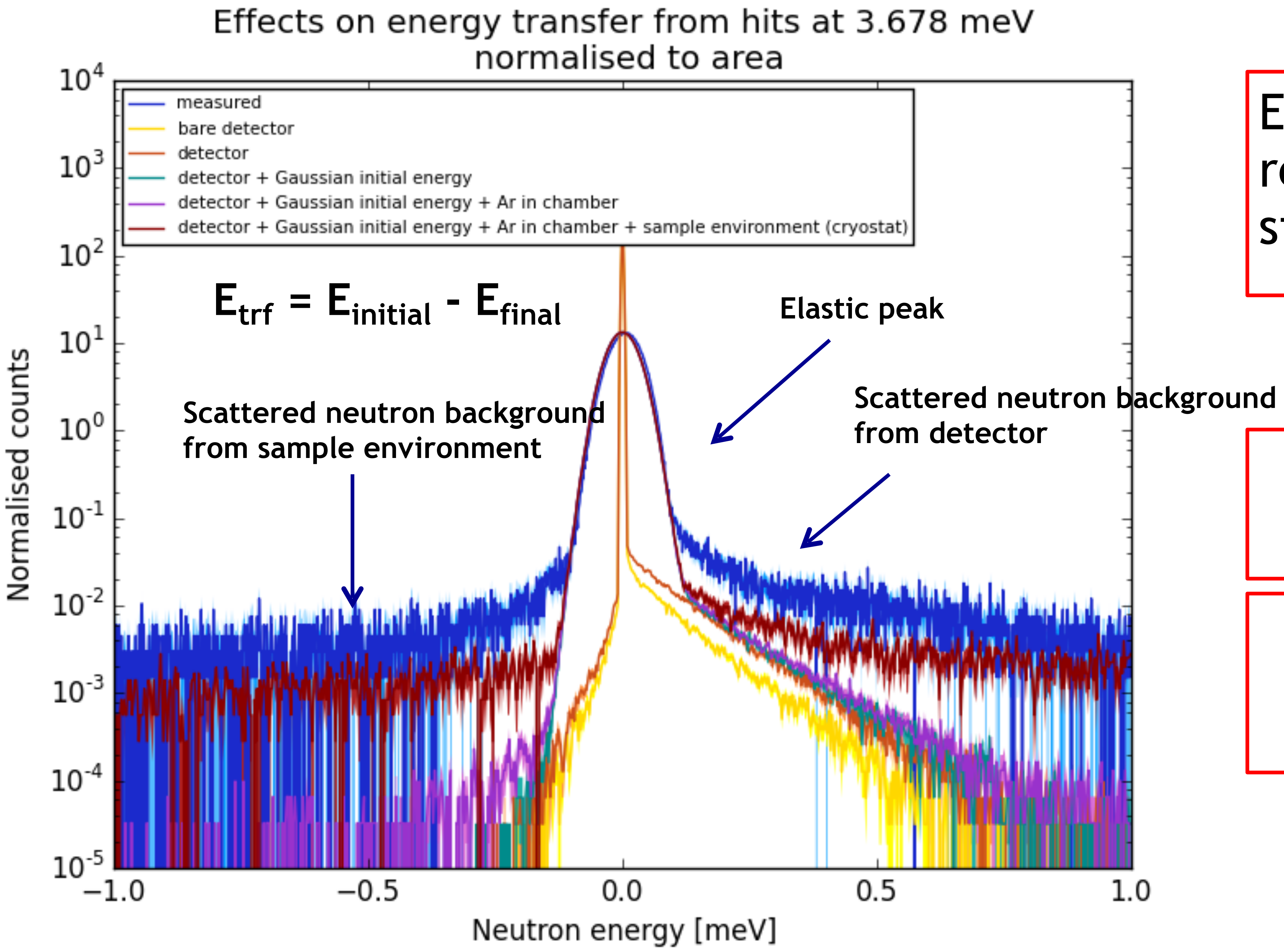
NXSG4



Isotropic scattering
particles simulated from sample

Instrument outputs can be used
as particle guns

MultiGrid detector test at CNCS, SNS



$E_{trf} = E_{initial} - E_{final}$

Elastic peak

Scattered neutron background from sample environment

Scattered neutron background from detector

Validation

Energy transfer reproduced with simulation at 3.678 meV ✓

Distinguish different sources of background

Detailed analysis and quantification of background effects

↓

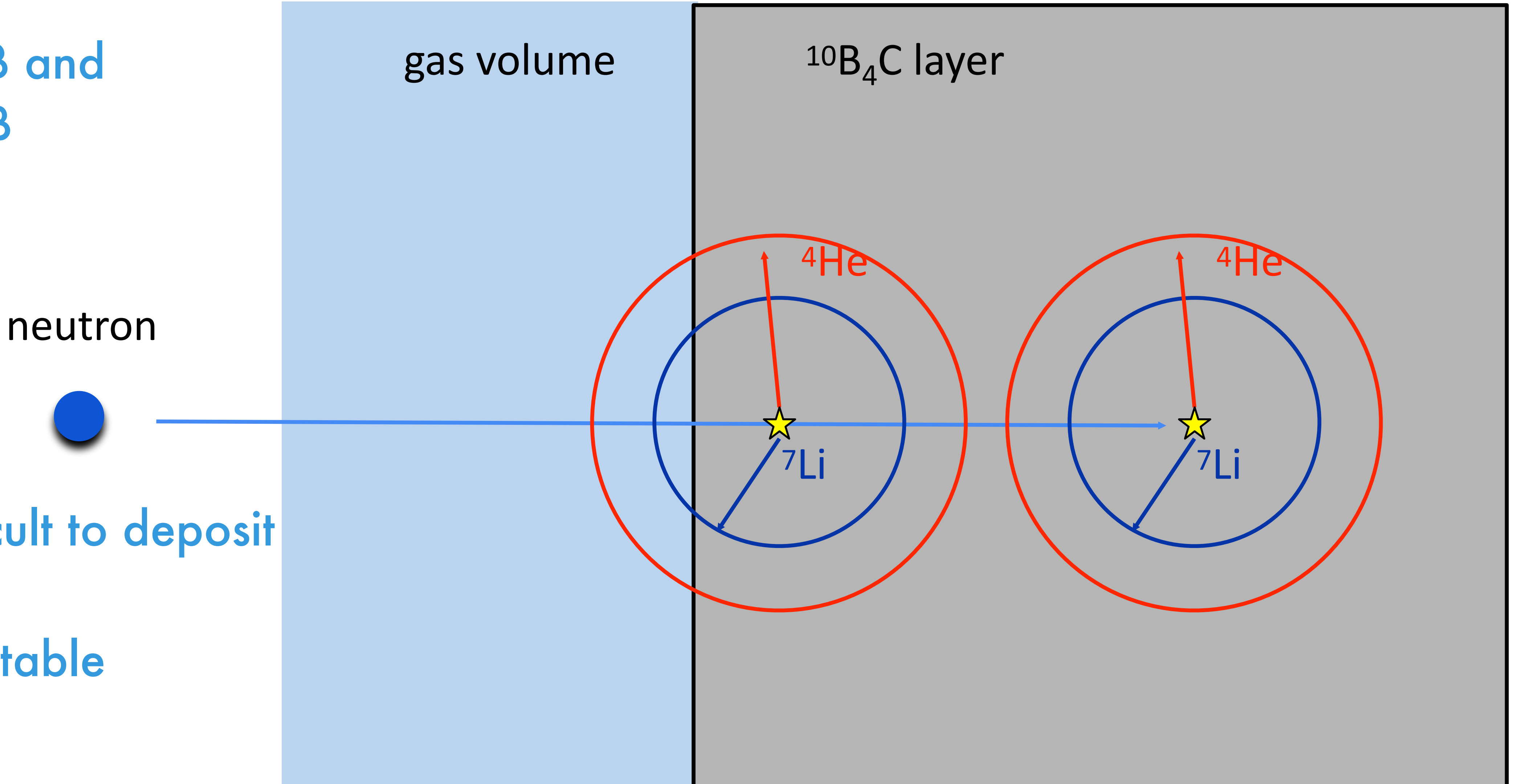
Optimization

^{10}Boron-based Thin Film Gaseous Detectors

$$\begin{array}{lr} {}^{10}B + n \rightarrow {}^{7}Li^{*} + {}^{4}He \rightarrow {}^{7}Li + {}^{4}He + 0.48MeV\,\gamma\text{-ray} + 2.3\ \ MeV & (94\%) \\ \qquad\qquad\qquad\qquad\quad \rightarrow {}^{7}Li + {}^{4}He \qquad\qquad\qquad\qquad\qquad\quad + 2.79\,MeV & (6\%) \end{array}$$

Efficiency limited at ~5% (2.5Å) for a single layer

- ^{nat}B contains
  80 at.% ^{11}B and
  20 at.% ^{10}B



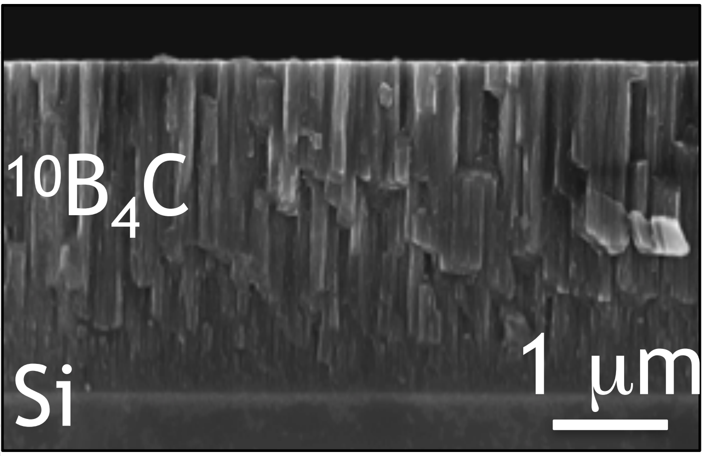
- Boron is difficult to deposit
- Use $^{10}B_4C$
- Conductive, stable

$^{10}B_4C$ Thin Film Coatings
ESS Thin Films Workshop

SOLVED

- Co-located w/ Linkoping University for synergies: expertise&facilities
- Industrial coatings machine and production line setup
- Capacity: several times ESS needs & cheap
- If interested in coatings: contact us

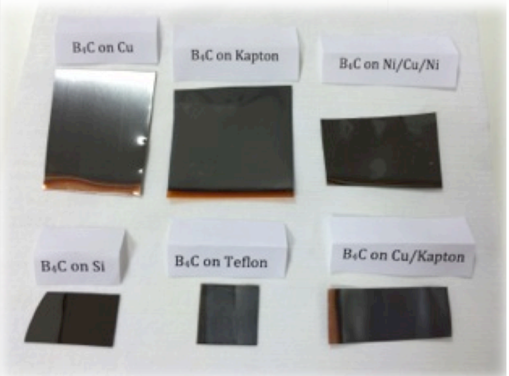
Required property	Result	OK?
Good adhesion	> 5 μm on Al, Si, Al_2O_3, etc	☺
Low residual stress	0.09 GPa at 1 μm $^{10}B_4C$	☺
Low impurities	H + N + O only ~1 at.%	☺
High ^{10}B content	79.3 at.% of ^{10}B	☺
n-radiation hard	Survive 10^{14} neutrons/cm^2	☺

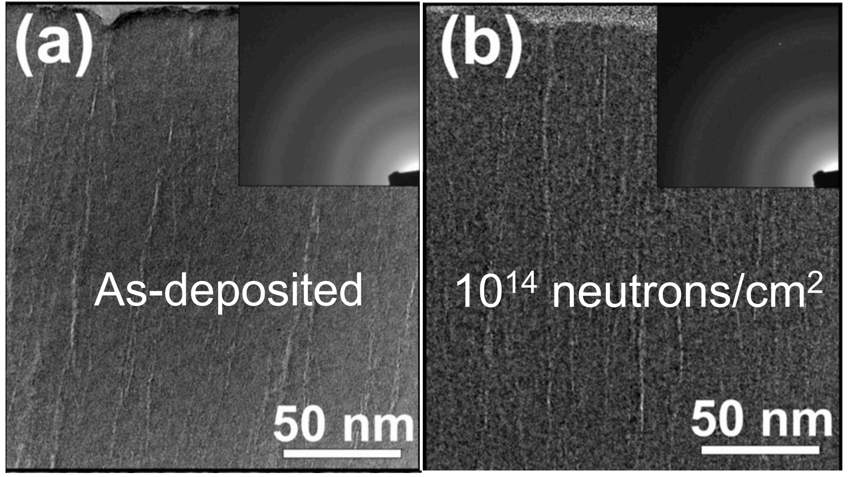


- PVD magnetron scattering
- Highly interdisciplinary effort

- Many substrates possible:

Solved	Ongoing
Al	Glass - ok solution
Al-foil	Ni and Ni-coated - ok solution
Stainless steel	Cu coat. Kapton
Al_2O_3	MgO
Si	
G10	
Ti	
Cu	
Teflon	
Kapton foil	
Kapton tape	

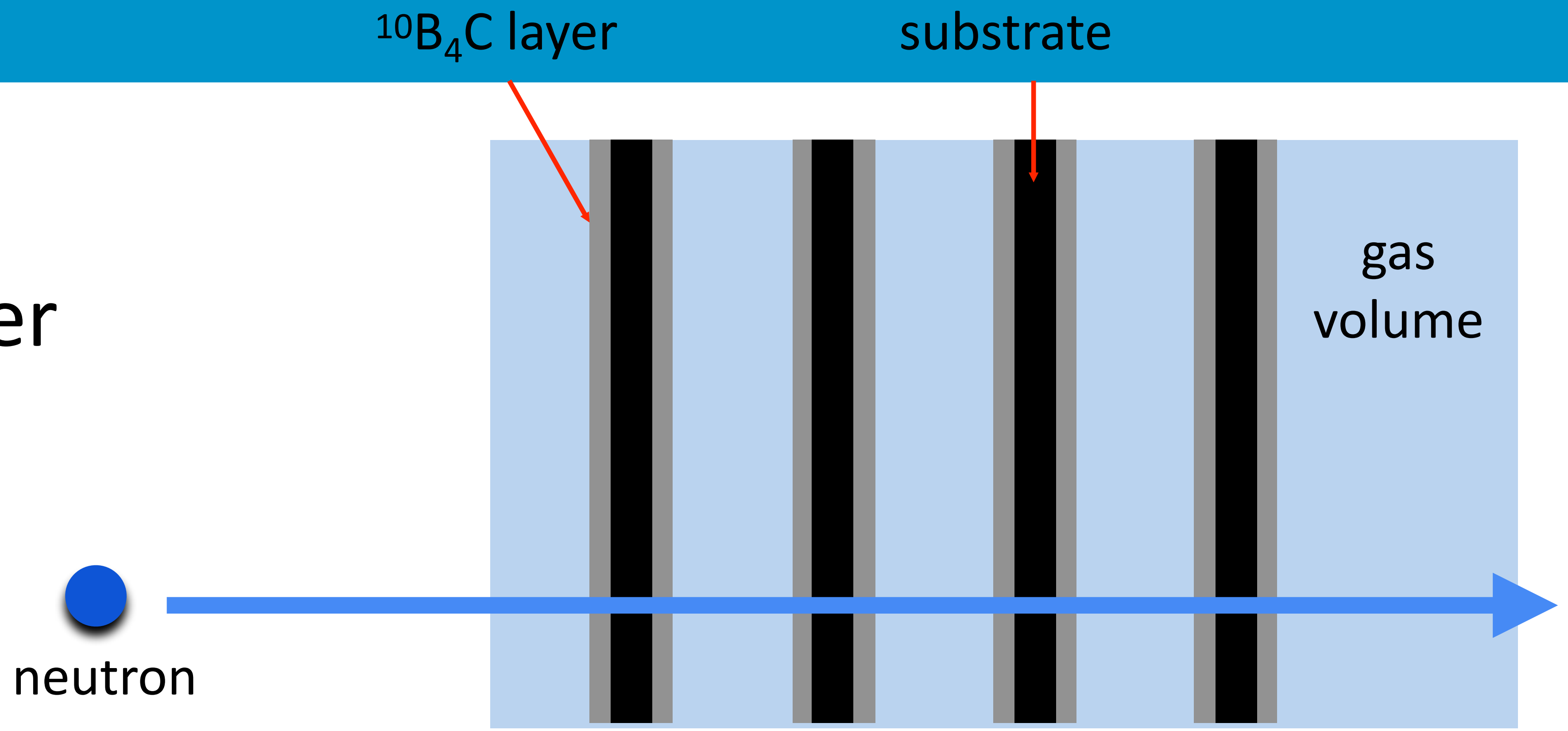




Publications:
*C. Höglund et al, J of Appl. Phys. 111, 104908 (2012)
*S. Schmidt et al, J. of Materials Science 51, Issue 23 (2016)
*C. Höglund, Rad. Phys. and Chem. 113 , 14-19 (2015);

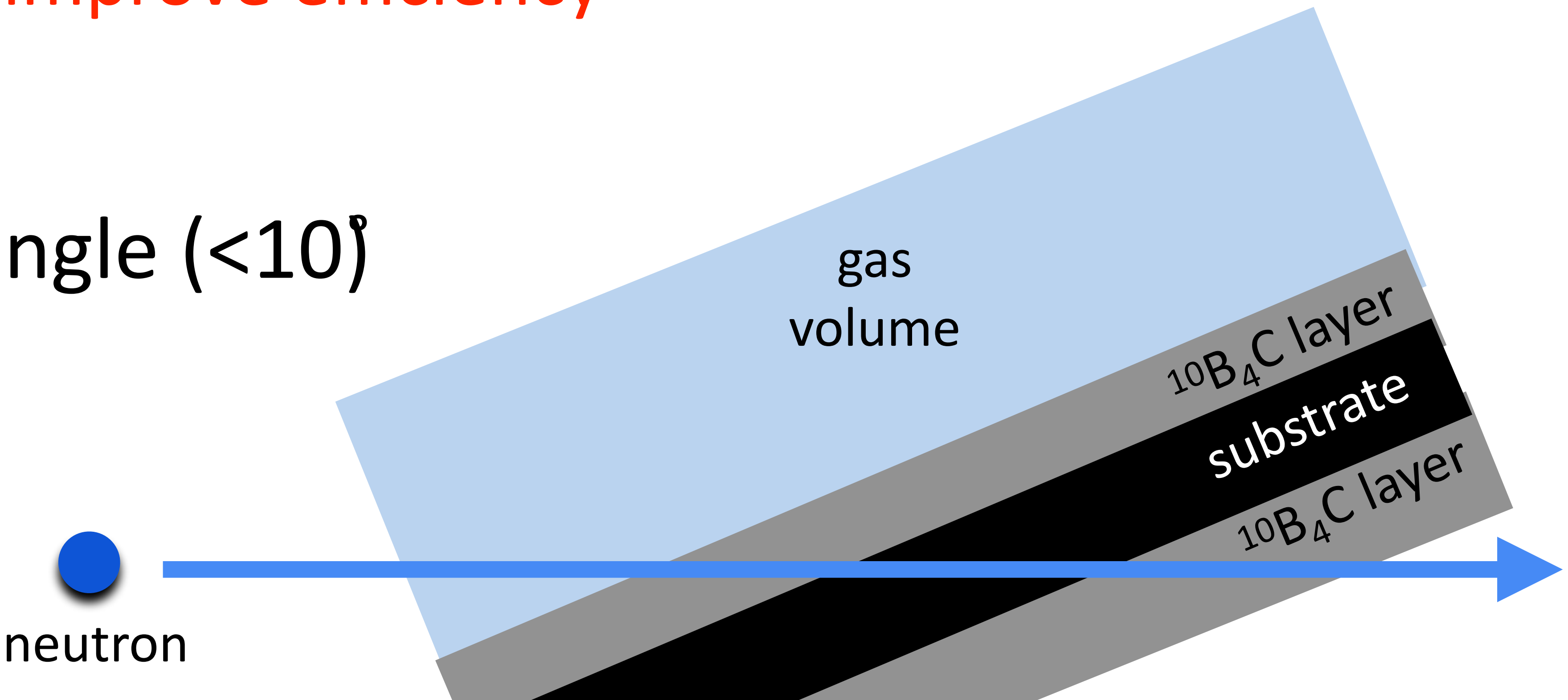
Enhancing the efficiency of ^{10}B-based Neutron Detectors

① Multi layer



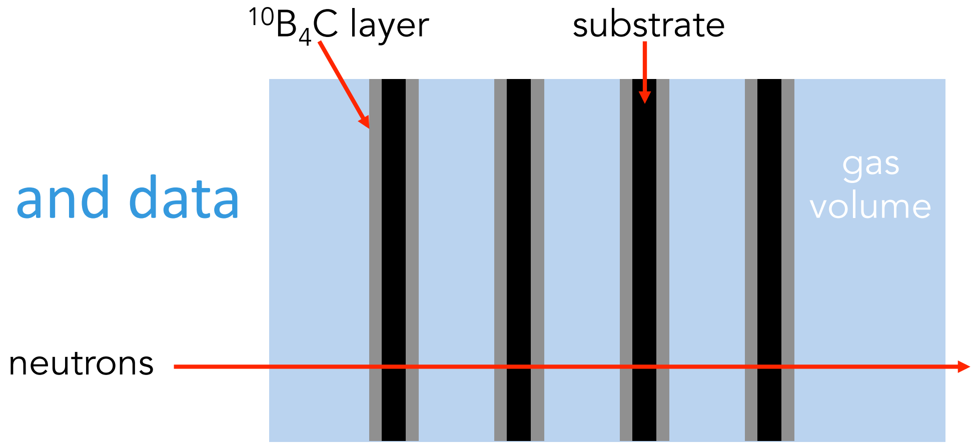
Generic approaches to improve efficiency

② Grazing angle (<10°)



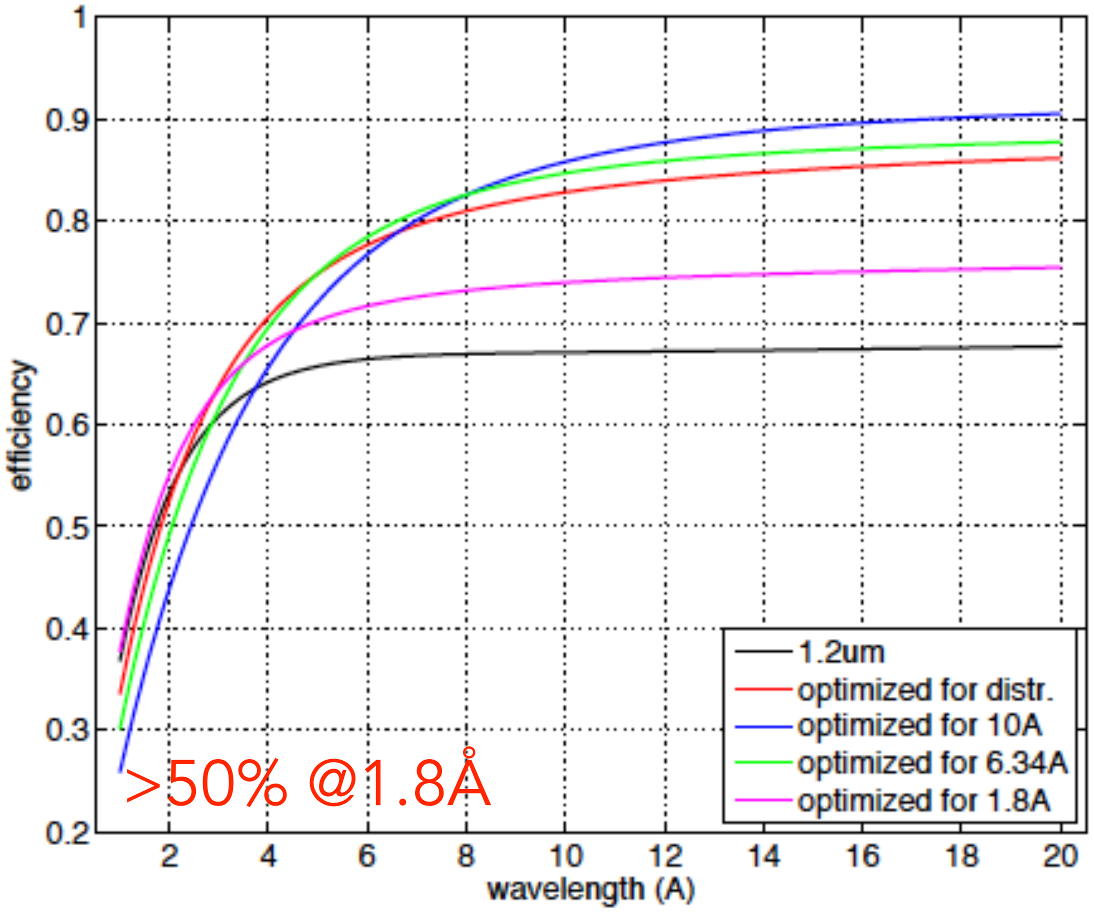
Efficiency of ^{10}B Detectors: Perpendicular Geometry

- Single layer is only ca.5%
- Calculations done by many groups
- Analytical calculations extensively verified with prototypes and data
- Details matter: just like for ^{3}He



- Multilayer configuration (example):

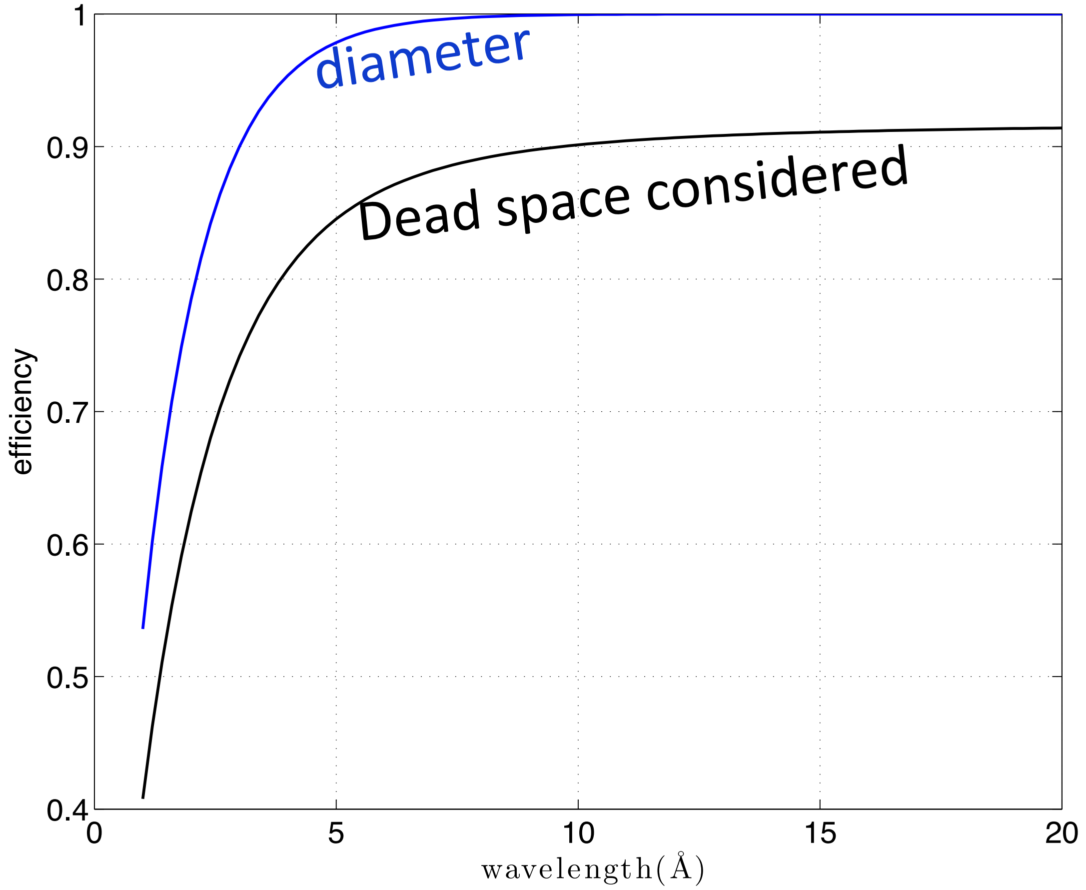
Multi-Grid



JINST 8 (2013) P04020

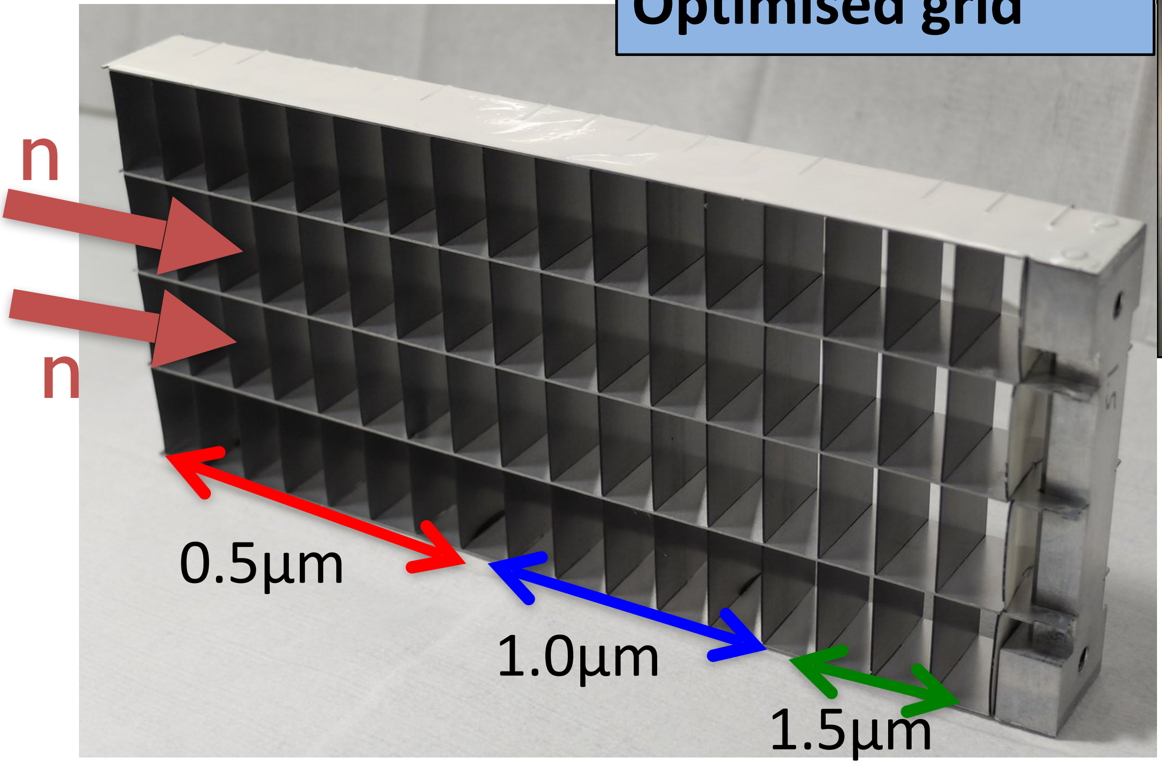
Calculator:
arXiv:1801.07124

^{3}He tubes – 1 inch – 4.75 bar



Multi-Grid Detector Design

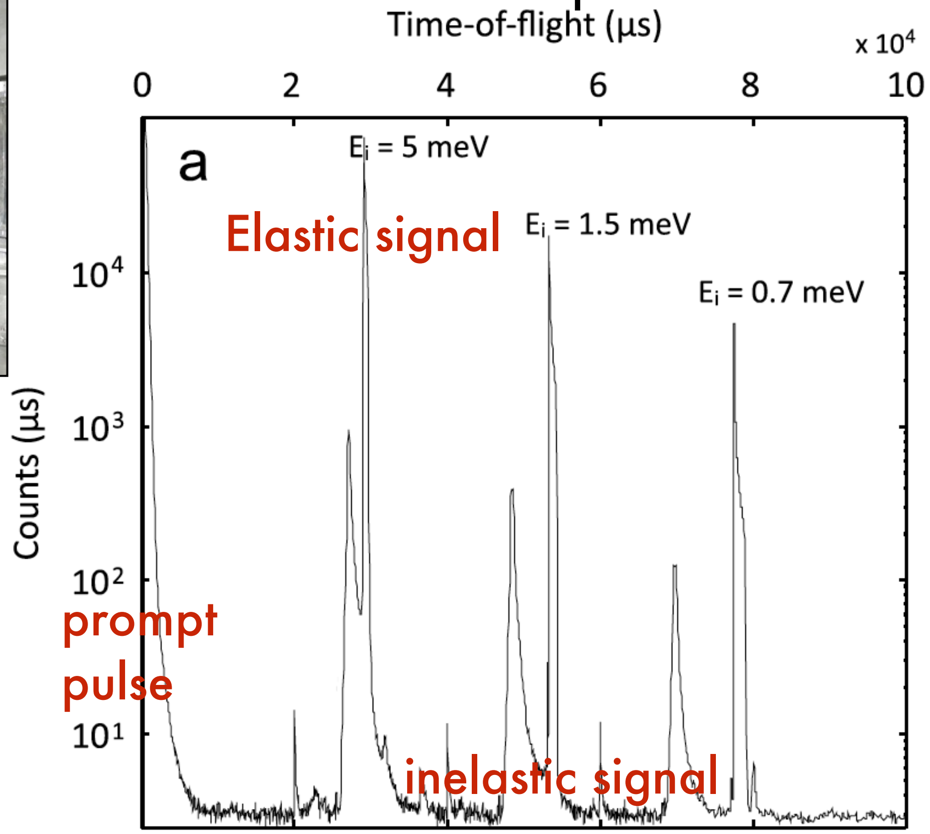
Optimised grid



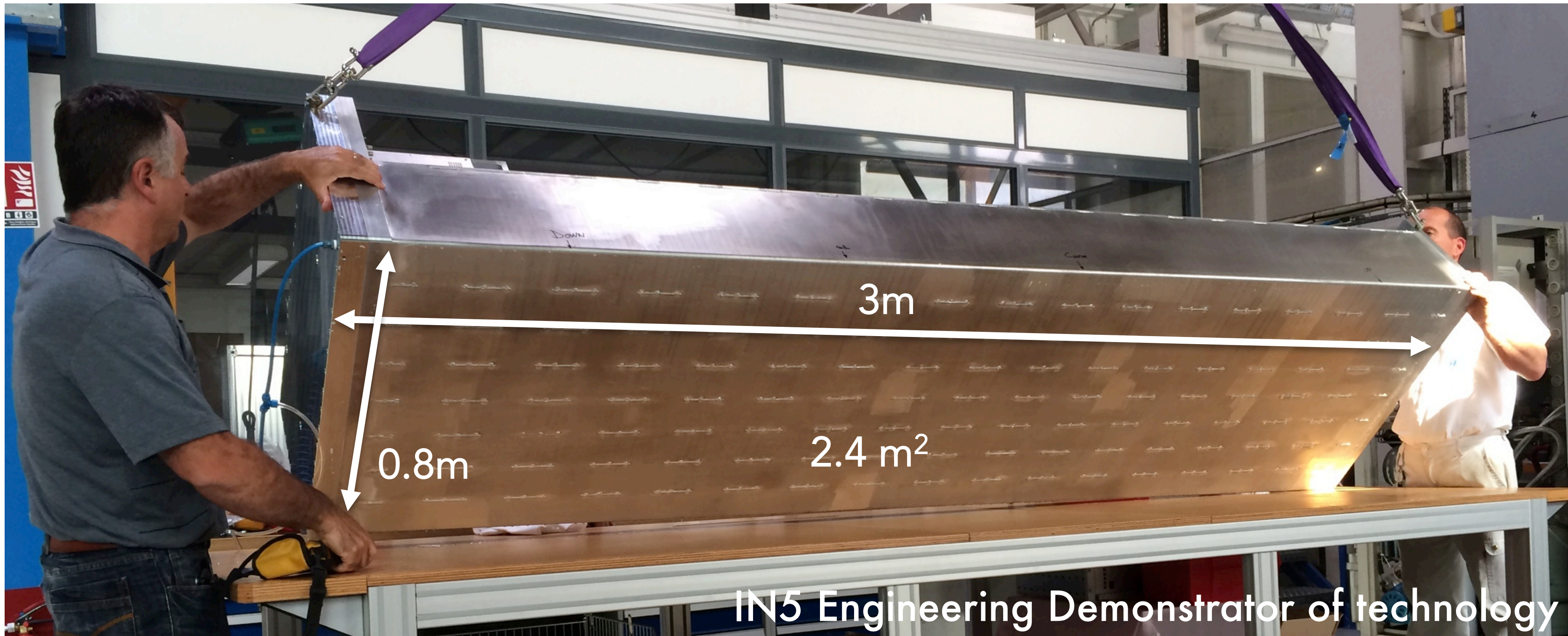

aim: replace He-3 for this

Very background sensitive technique

example from LET@ISIS

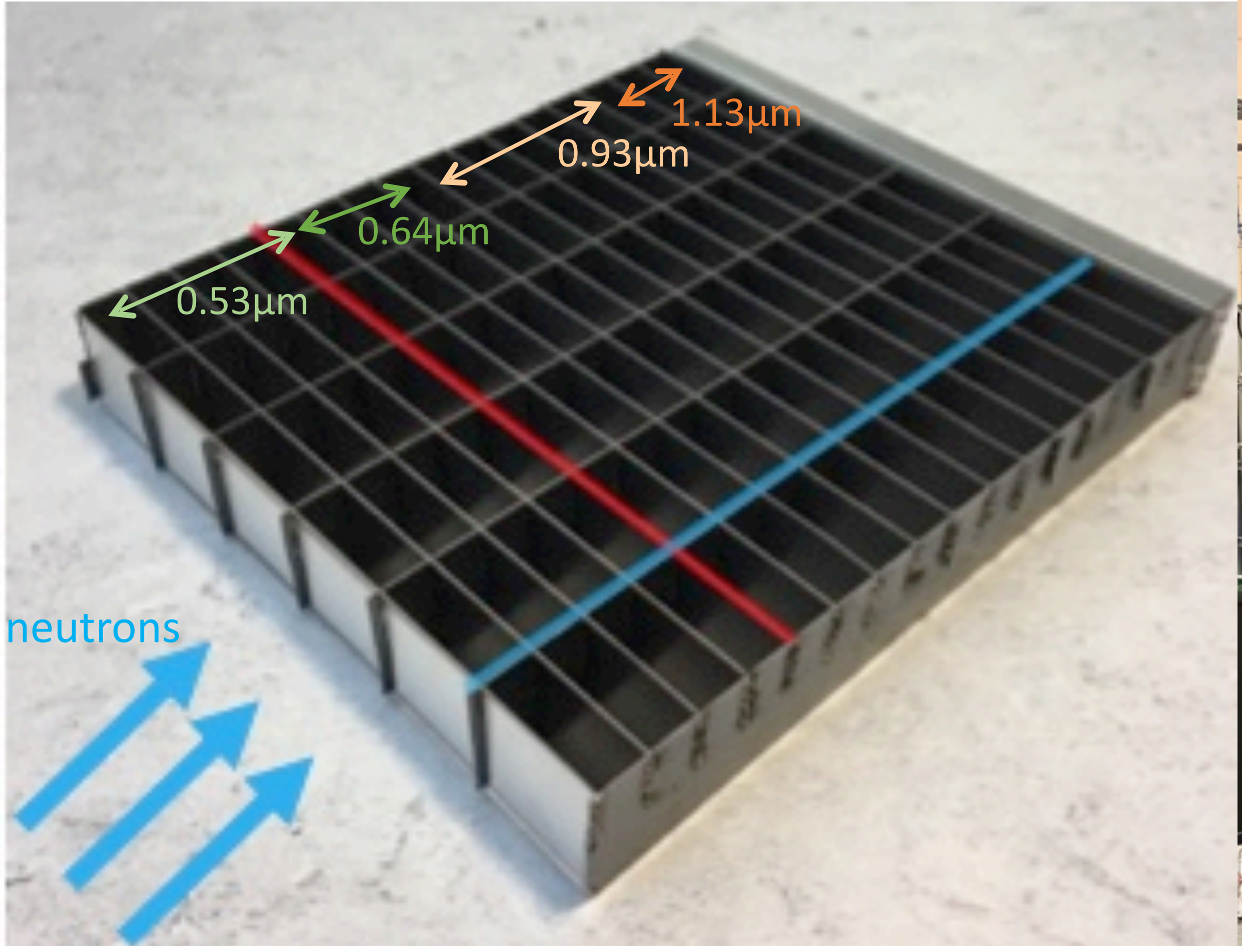


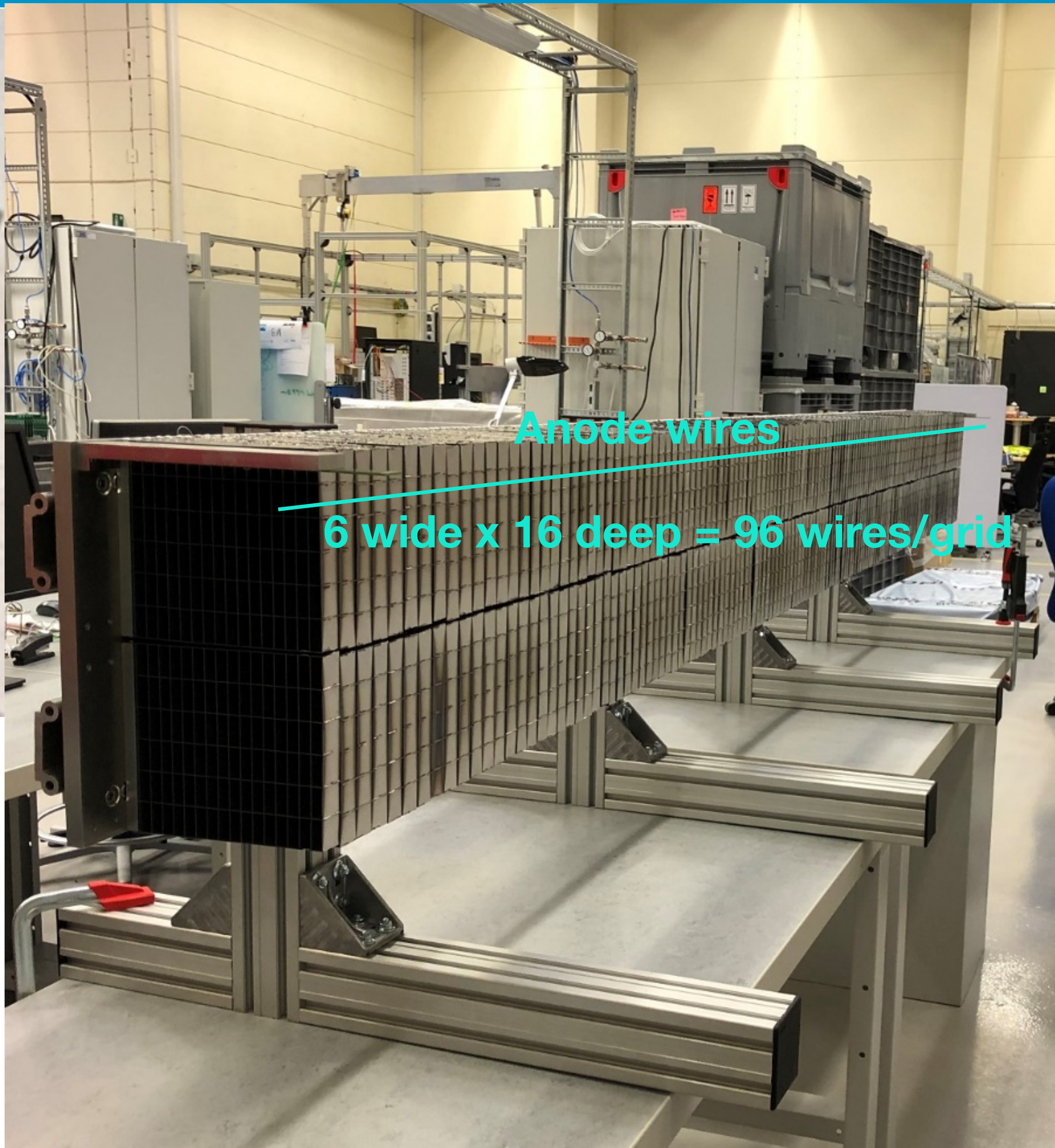
- Design introduced by the ILL
- Designed as replacement for He-3 tubes for largest area detectors
- Cheap and modular design
- Possible to build large area detectors again
- 20-50m^2 envisaged@ESS



IN5 Engineering Demonstrator of technology

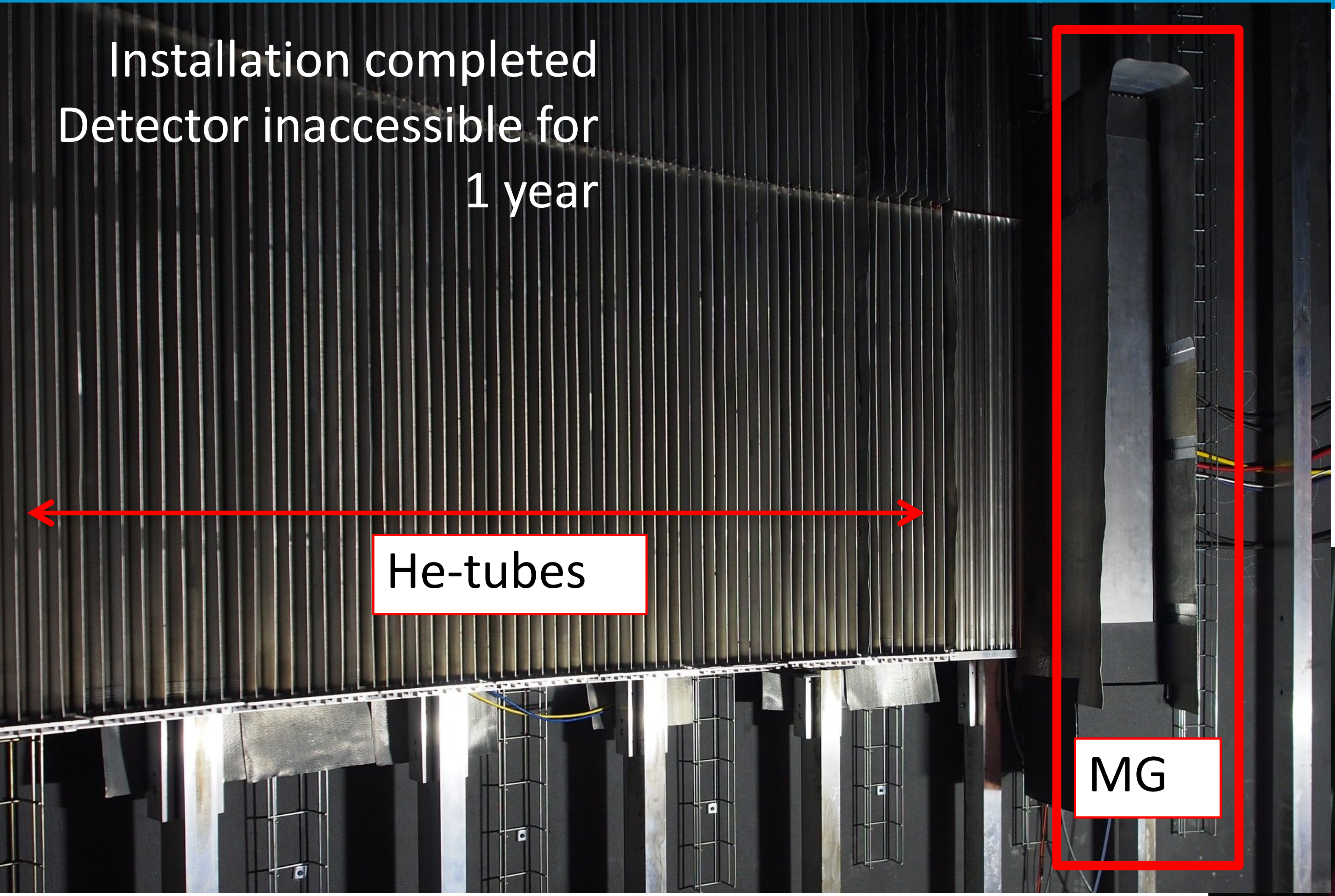
Multi-Grid Detector Design





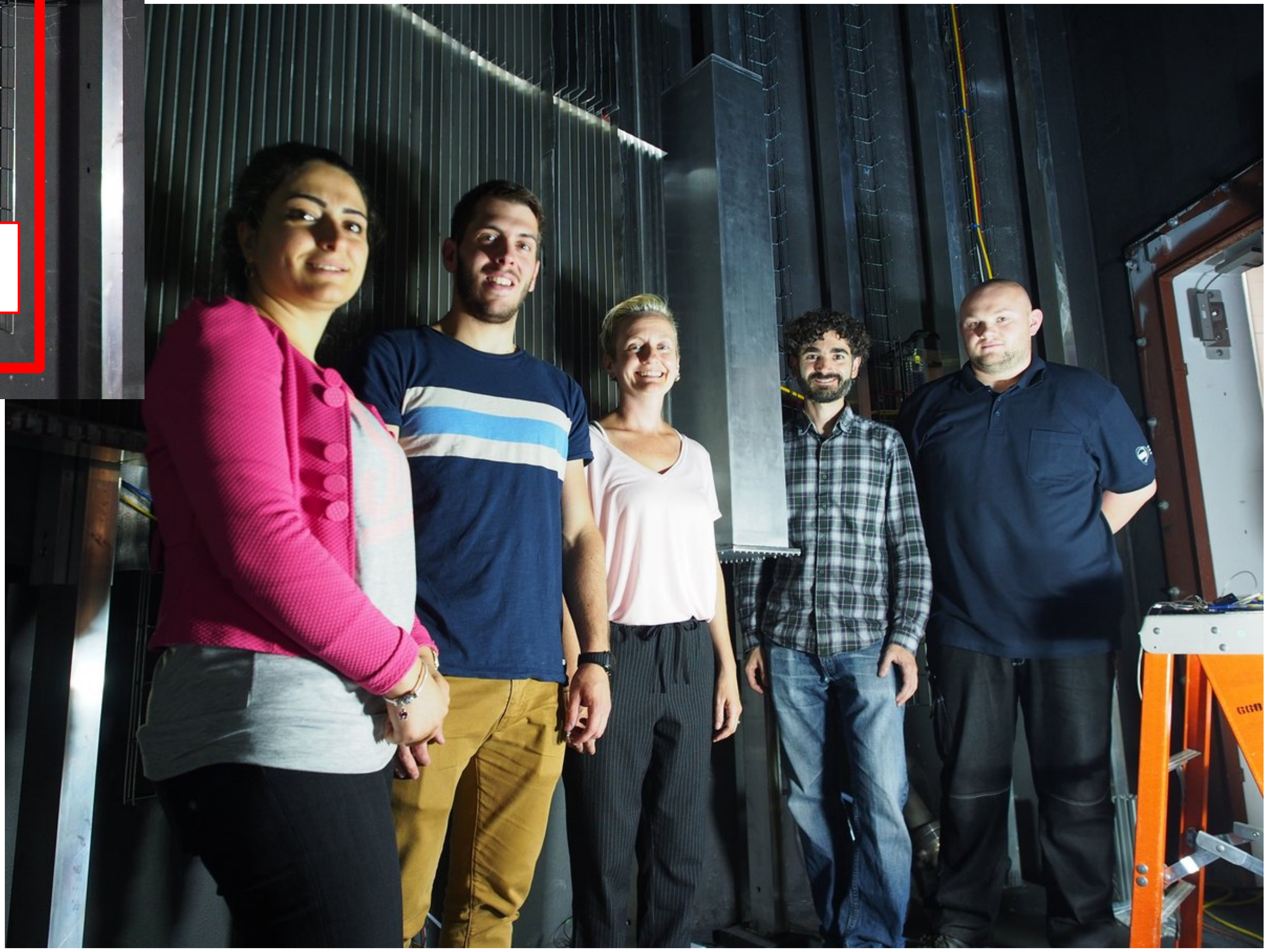
- Cheap and modular design
- Anode wires through each cell
- Both anode wires and grids (cathodes) are readout
- Position given by coincidence between a anode wire and grid hit
- Large energy deposited in gas (100keV - 1.5 MeV) and threshold discrimination: low gain operation possible

Multi-Grid test at CNCS



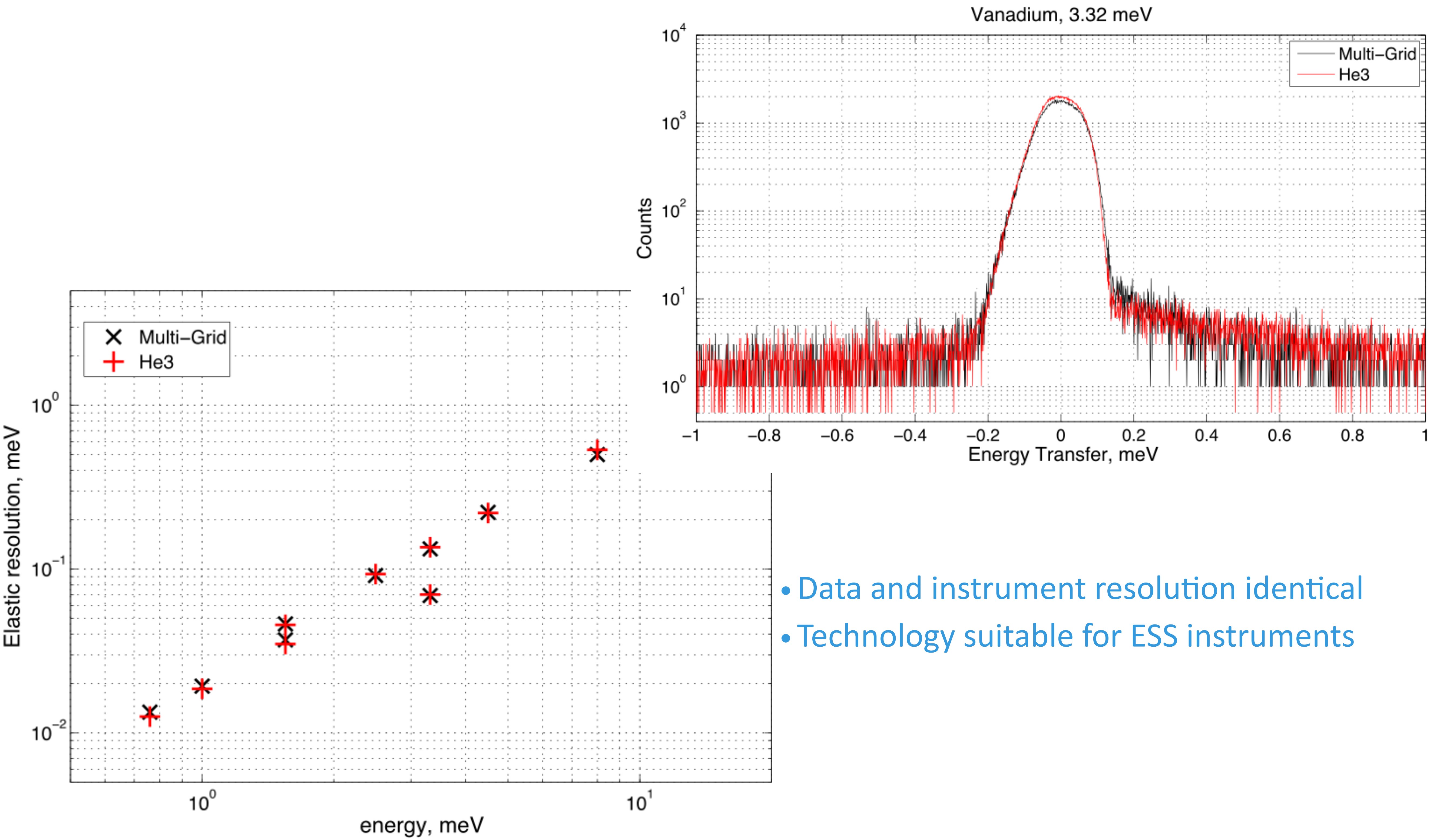
B10 Multi-Grid Detector Performance is equivalent to that of He-3 detectors

A.Khaplanov et al. *"Multi-Grid Detector for Neutron Spectroscopy: Results Obtained on Time-of-Flight Spectrometer CNCS"* https://arxiv.org/abs/1703.03626
2017 JINST 12 P04030



- Test side-by-side with existing technology in world leading instrument
- Realistic conditions. Long term test.
- "Science" or application performance
- 2 different technologies on the same instrument

Multi-Grid test at CNCS



- Data and instrument resolution identical
- Technology suitable for ESS instruments

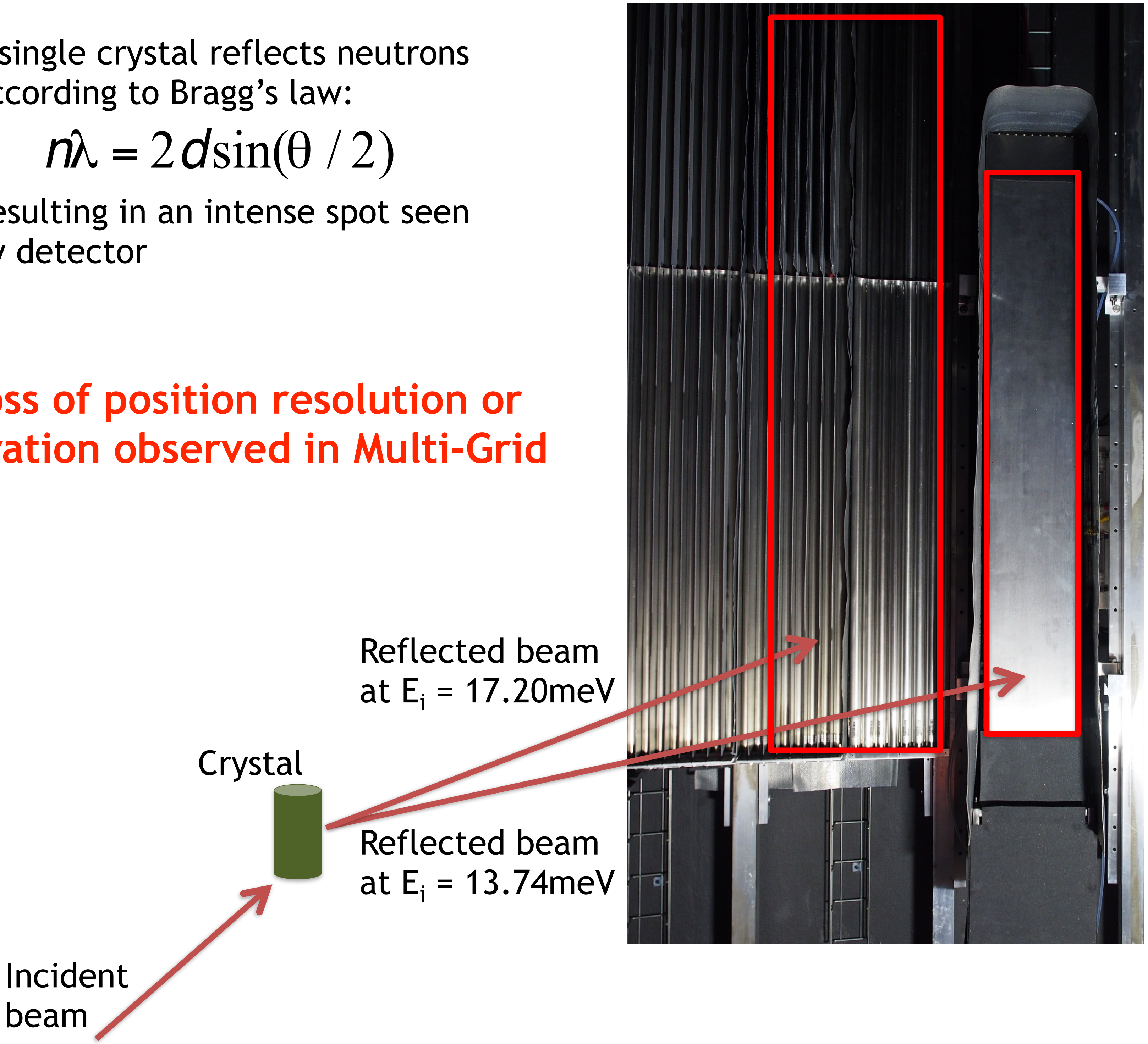
Single Crystal Reflection

A single crystal reflects neutrons according to Bragg's law:

$$n\lambda = 2d\sin(\theta / 2)$$

Resulting in an intense spot seen by detector

No loss of position resolution or saturation observed in Multi-Grid

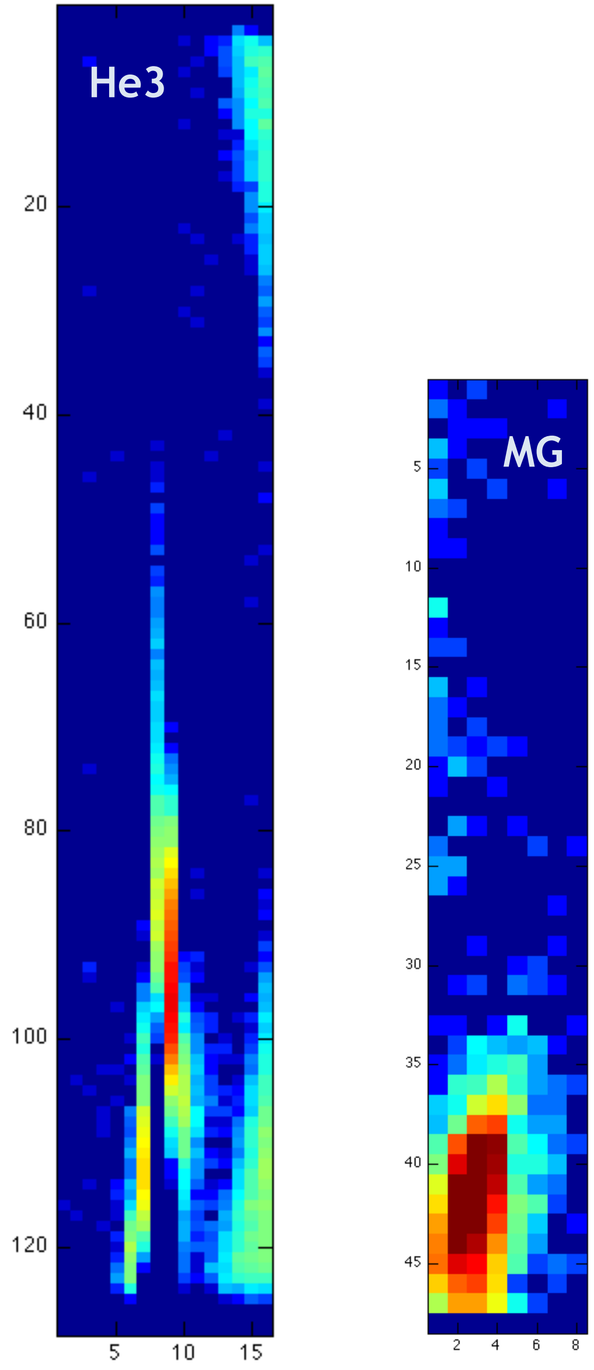


Reflected beam at E_i = 17.20meV

Crystal

Reflected beam at E_i = 13.74meV

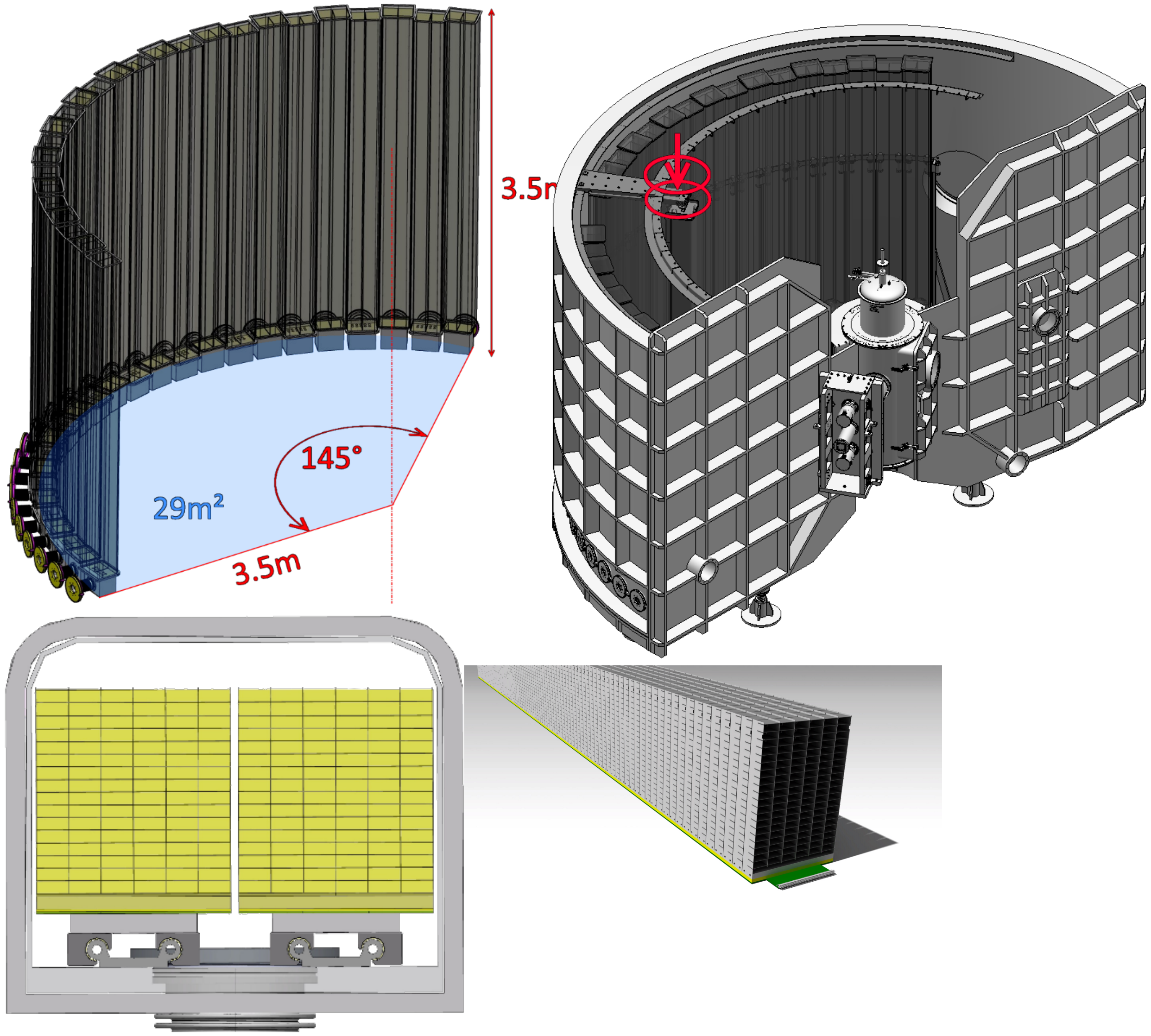
Incident beam



Realising Large Area Detectors

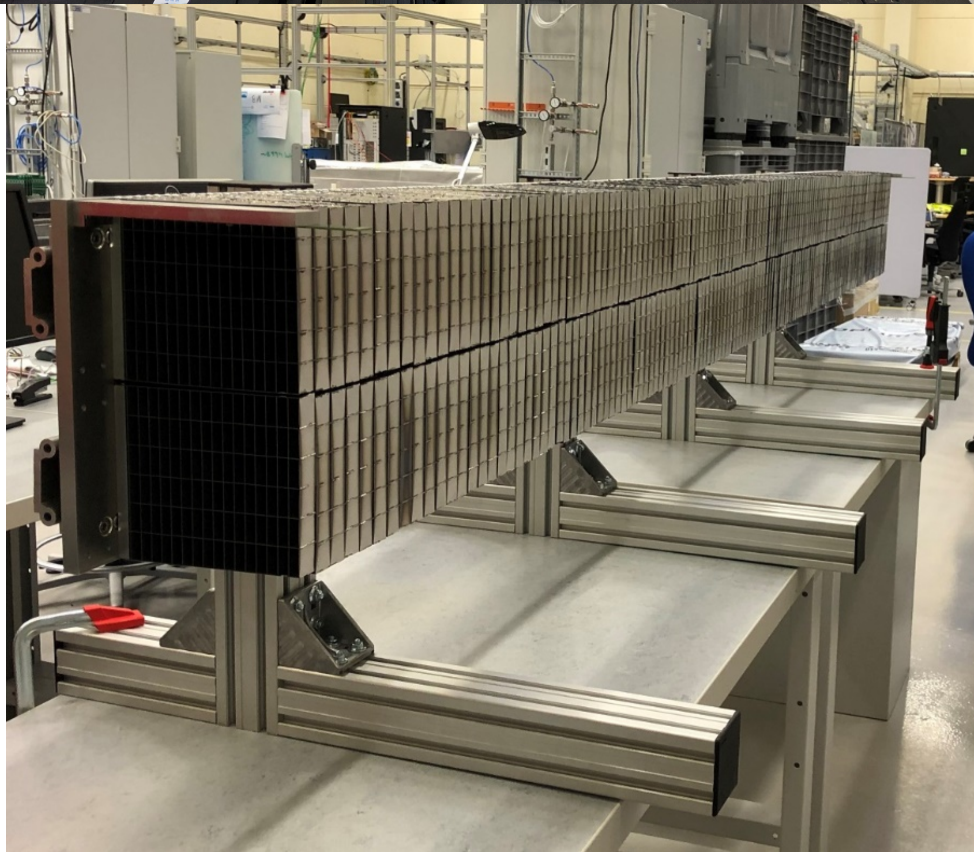
EUROPEAN
SPALLATION
SOURCE

CSPEC instrument



Gaseous detector working at low gas gain

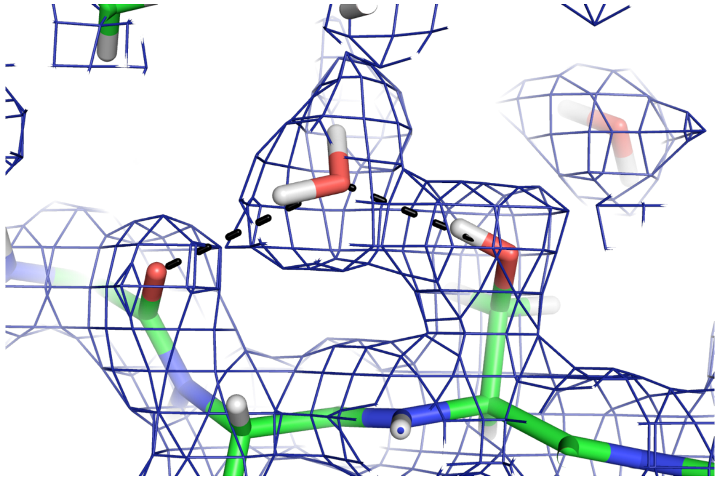
Under Construction Now



Received:
2.5 tonnes of Ultrapure Al
With custom 3% Mg alloy
50kg of 10B4C powder

Neutron Macromolecular Crystallography

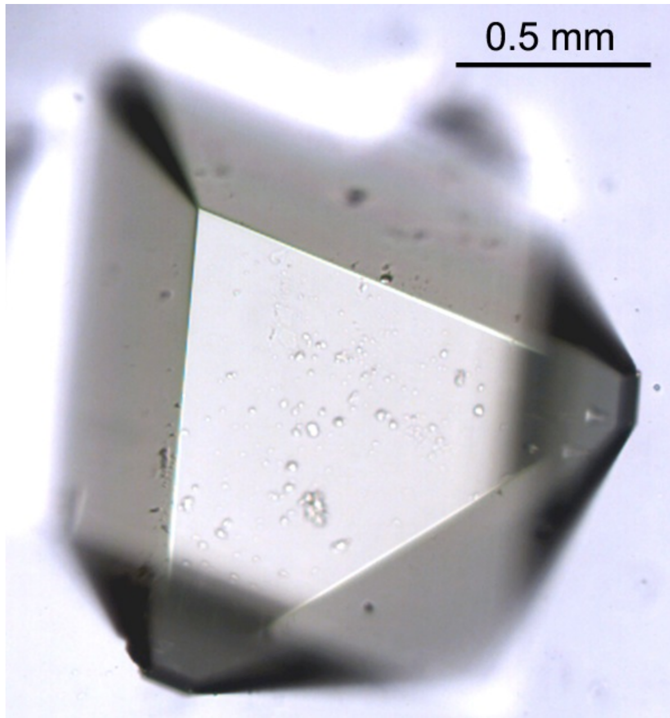
EUROPEAN SPALLATION SOURCE



☺ Hydrogens are visible
☺ No radiation damage
☹ Large crystals needed
☹ Data collection takes weeks
☹ Few instruments available

X-Ray structures: >100 000
Neutron Structures <100
A huge opportunity?

design principle analogous to synchrotron macromolecular diffractometer: low barrier to user acceptance

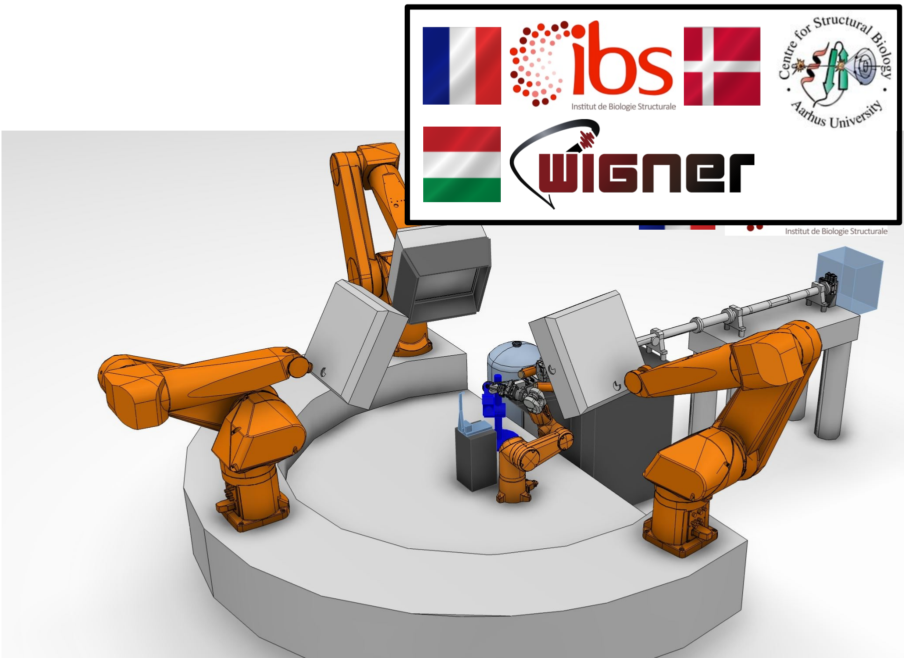


Oksanen, E *et al. J. R. Soc. Interface* **2009**, *6 Suppl 5*, S599-610.

Key advantages of ESS:

- Macromolecular Diffractometer
- Smaller crystals needed (200 µm vs. 1 mm)
- Data collection faster (days vs. weeks)
- Larger unit cells possible (300 Å vs. 150 Å)

NMX Instrument



Bovine heart

cytochrome c oxidase

$P2_12_12_1$

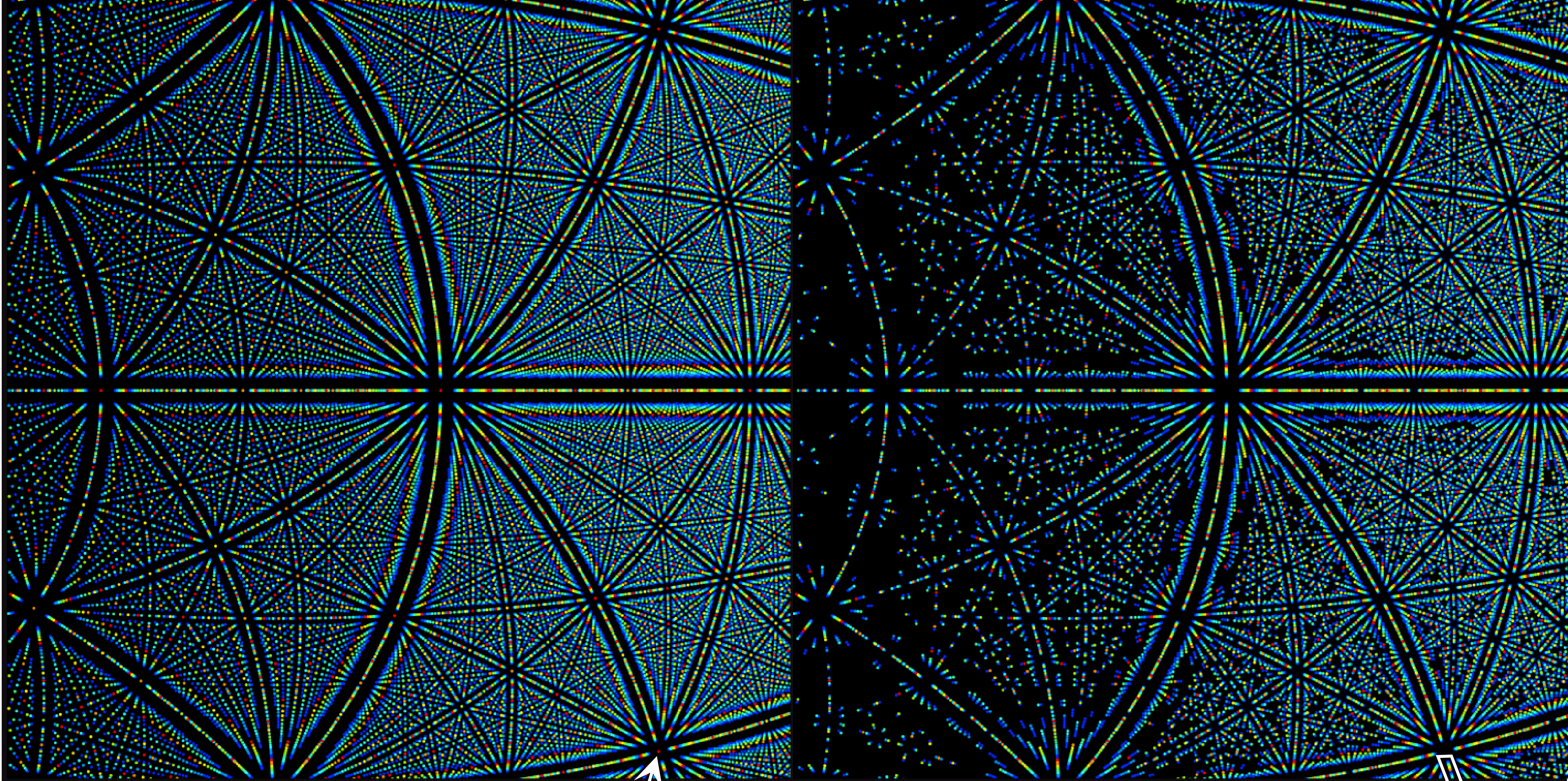
a = 182.59 Å

b = 205.40 Å

c = 178.25 A

Detector distance 1 m

<<1mm spatial resolution to be able to integrate intensities



All reflections

14 28 42 (3.409 Å, 134.4 ms) 21 35 49 (2.809 Å, 110.8 ms)
15 29 43 (3.309 Å, 130.5 ms) 22 36 50 (2.739 Å, 108.0 ms)
16 30 44 (3.215 Å, 126.8 ms) 23 37 51 (2.672 Å, 105.4 ms)
17 31 45 (3.124 Å, 123.2 ms) 24 38 52 (2.608 Å, 102.9 ms)
18 32 46 (3.040 Å, 119.9 ms) 25 39 53 (2.548 Å, 100.5 ms)
19 33 47 (2.959 Å, 116.7 ms) 26 40 54 (2.489 Å, 98.2 ms)
20 34 48 (2.882 Å, 113.6 ms)

Spatial overlaps only

27 53 79 (1.812 Å, 71.4 ms)
22 43 64 (2.236 Å, 88.2 ms)
18 35 52 (2.752 Å, 108.5 ms)
17 33 49 (2.920 Å, 115.1 ms)
19 37 55 (2.602 Å, 102.6 ms)
15 29 43 (3.327 Å, 131.2 ms)
27 52 77 (1.856 Å, 96.4 ms)
26 50 74 (1.933 Å, 76.2 ms)
24 46 68 (2.103 Å, 82.9 ms)
22 42 62 (2.306 Å, 90.9 ms)
21 40 59 (2.424 Å, 95.6 ms)
20 38 56 (2.553 Å, 100.7 ms)
28 53 78 (1.833 Å, 72.3 ms)

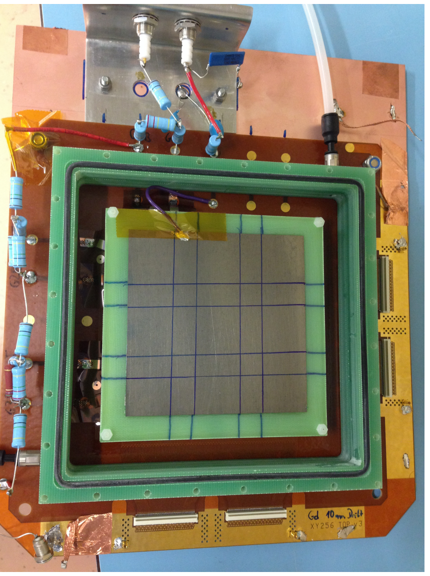
● 1.800 to 2.019 Angstroms
● 2.019 to 2.237 Angstroms
● 2.237 to 2.456 Angstroms
● 2.456 to 2.675 Angstroms
● 2.675 to 2.894 Angstroms
● 2.894 to 3.112 Angstroms
● 3.112 to 3.331 Angstroms
● 3.331 to 3.550 Angstroms

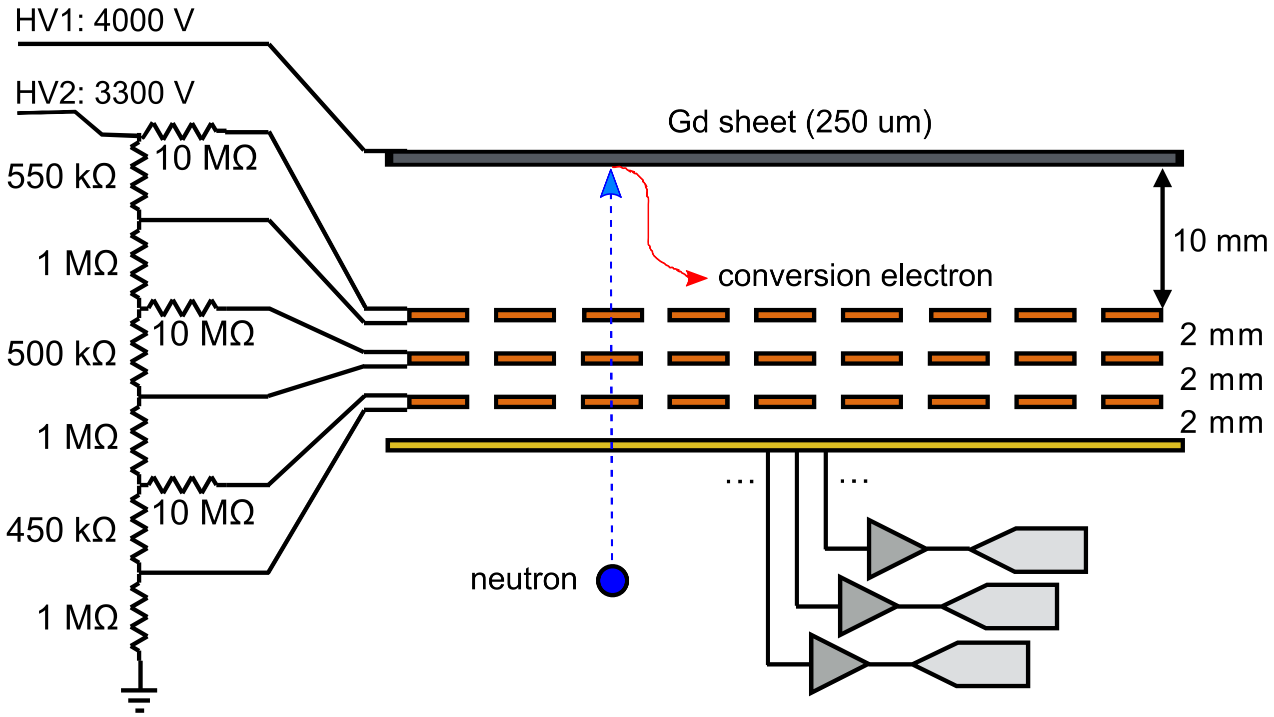
Generated using the Daresbury Laue Suite

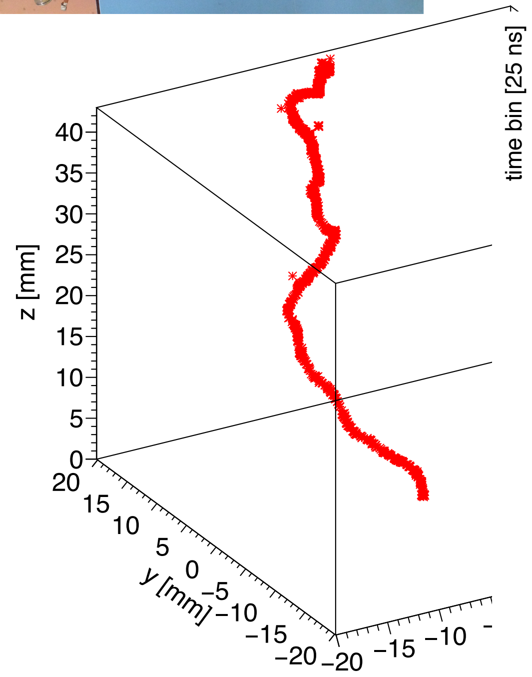
Campbell et al. J. Appl. Cryst. (1998). 31, 496-502
Artz et al. J. Appl. Cryst. (1999). 32, 554-562
Helliwell, J.R. et al. J. Appl. Cryst. (1989) 22, 483–497

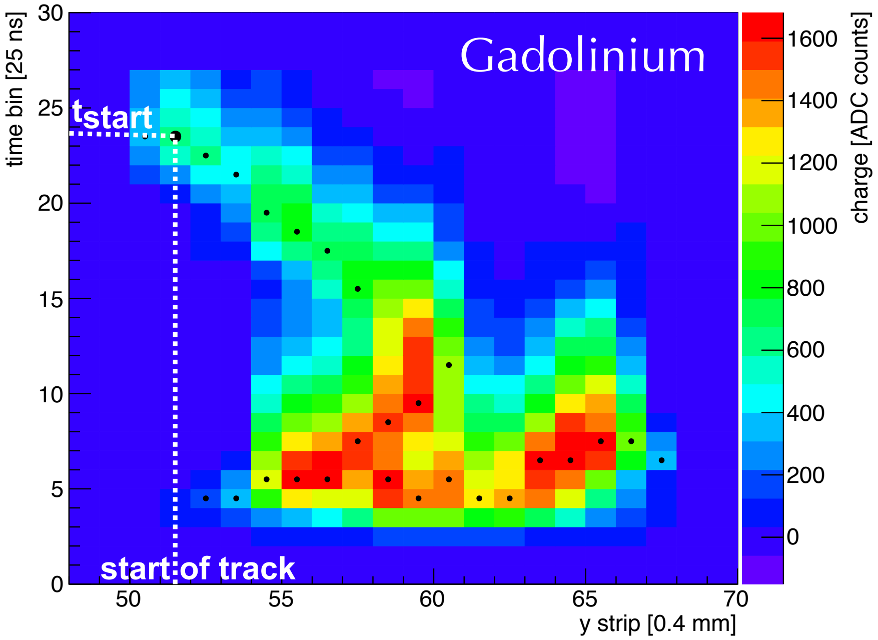
Gd-GEM Detector Design

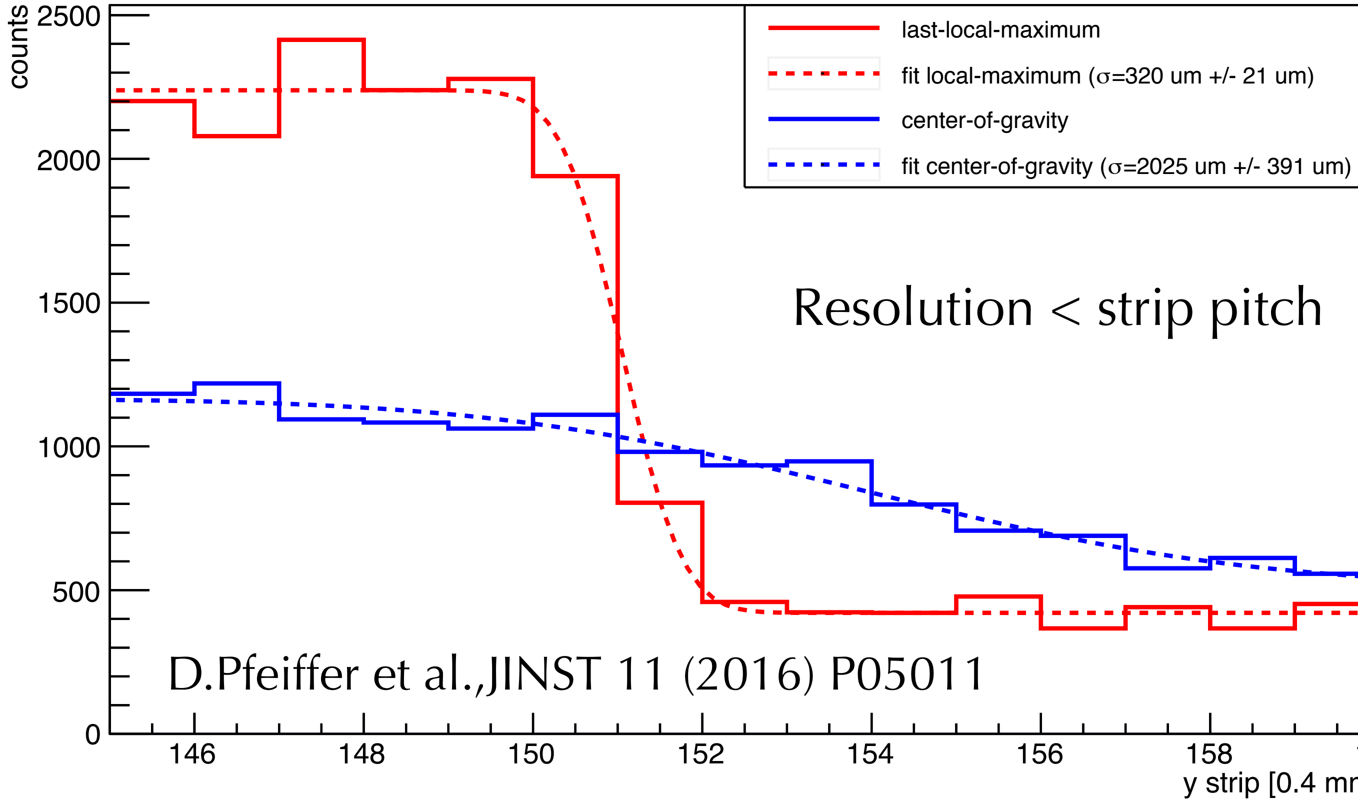
- NMX: <<1mm position resolution requirement, Time Resolved, ca. 1m^2 detector area
- Take Micro Time Projection Chamber concept from ATLAS experiment upgrade
- Resolution: use single layer Gd, look for electrons







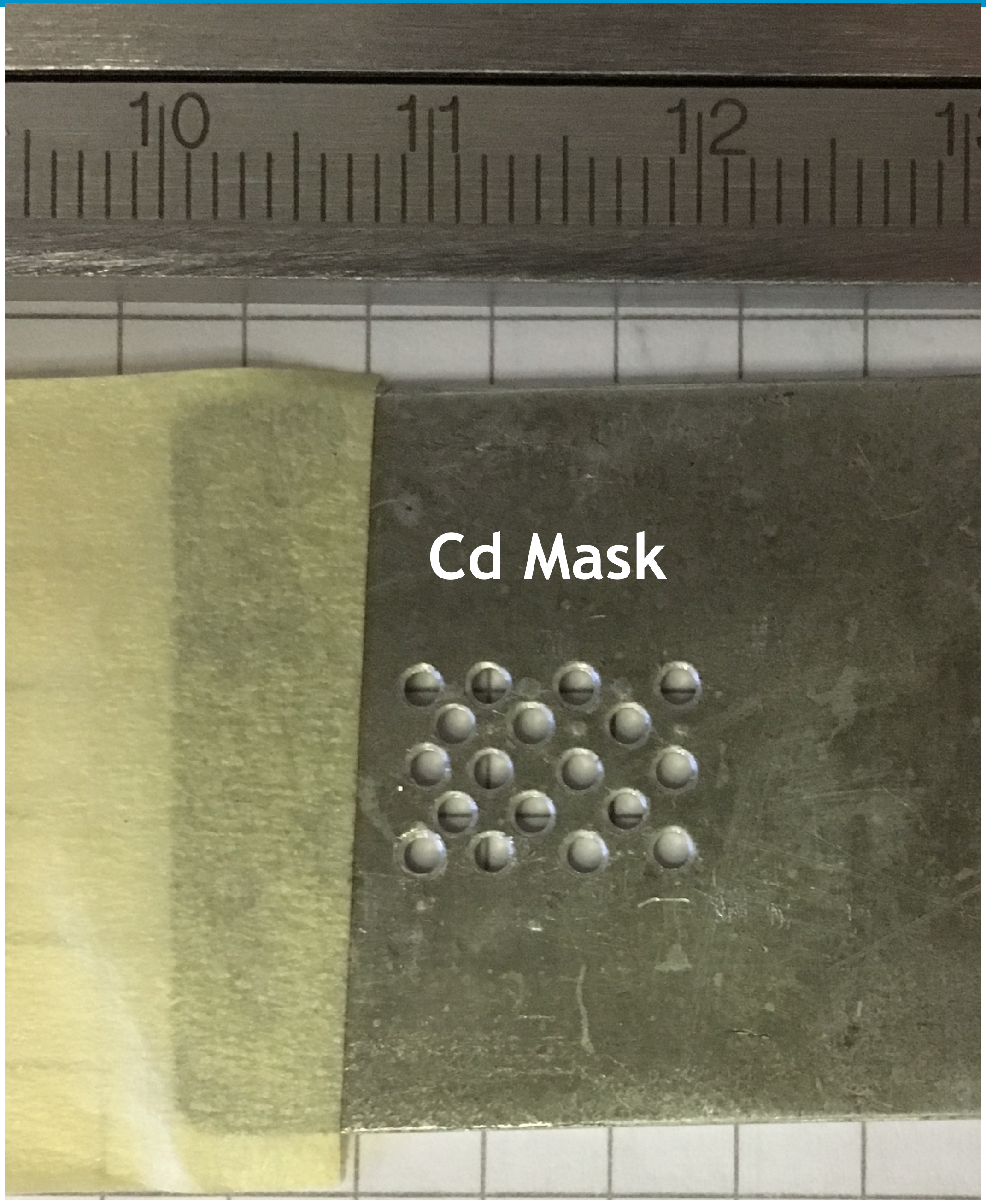


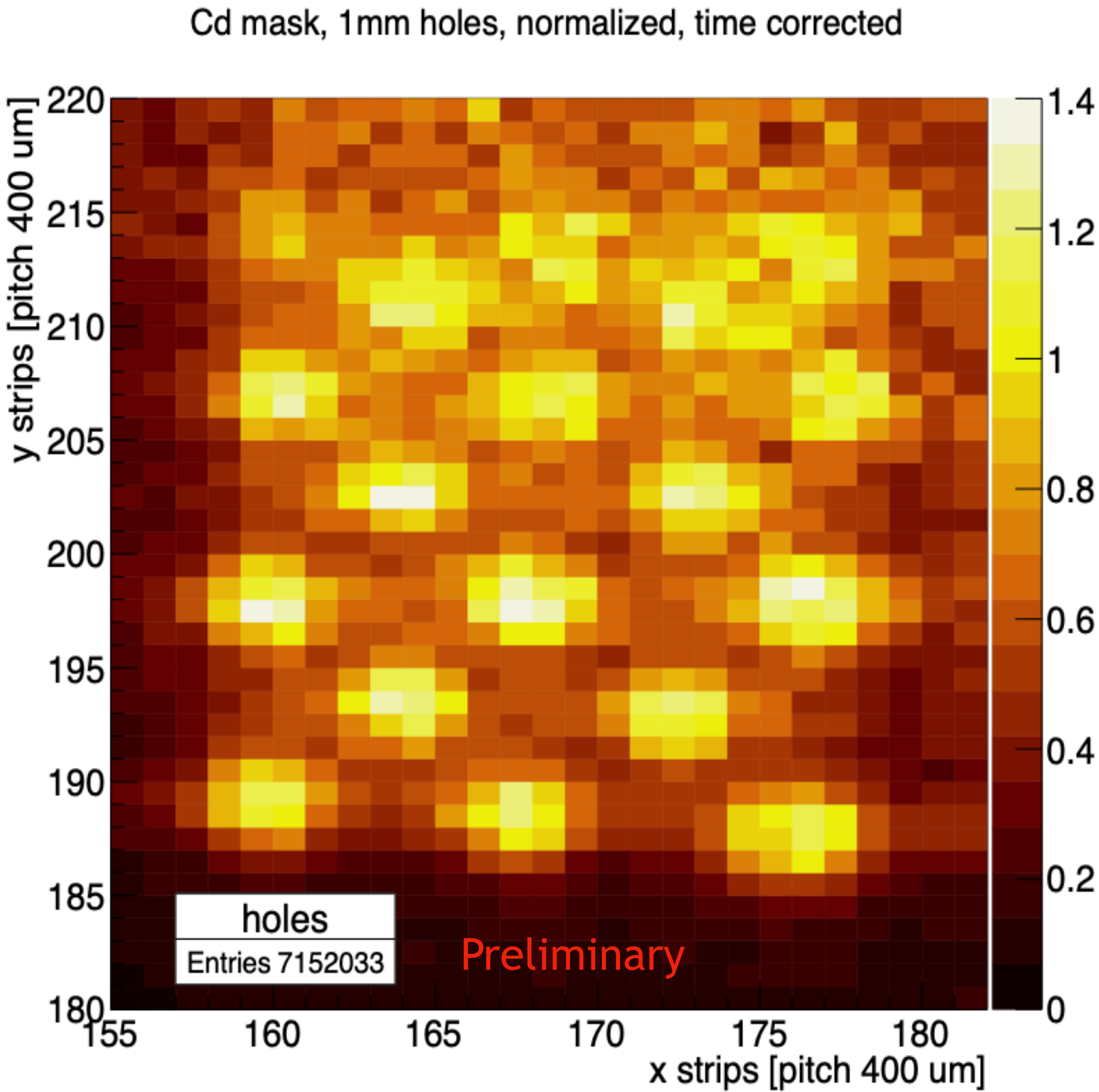


Resolution < strip pitch

D.Pfeiffer et al.,JINST 11 (2016) P05011

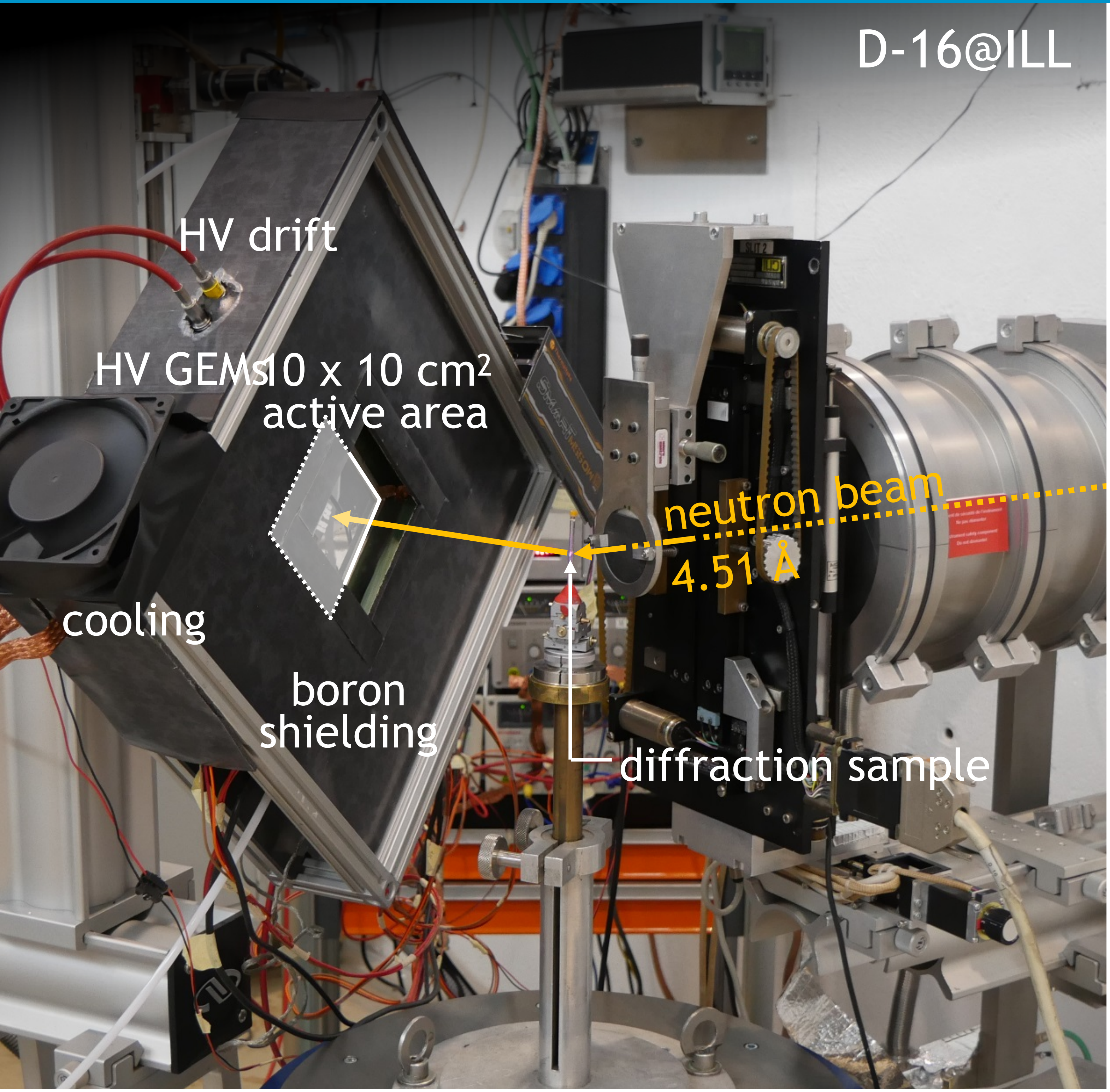
Gd-GEM Detector Demonstrator

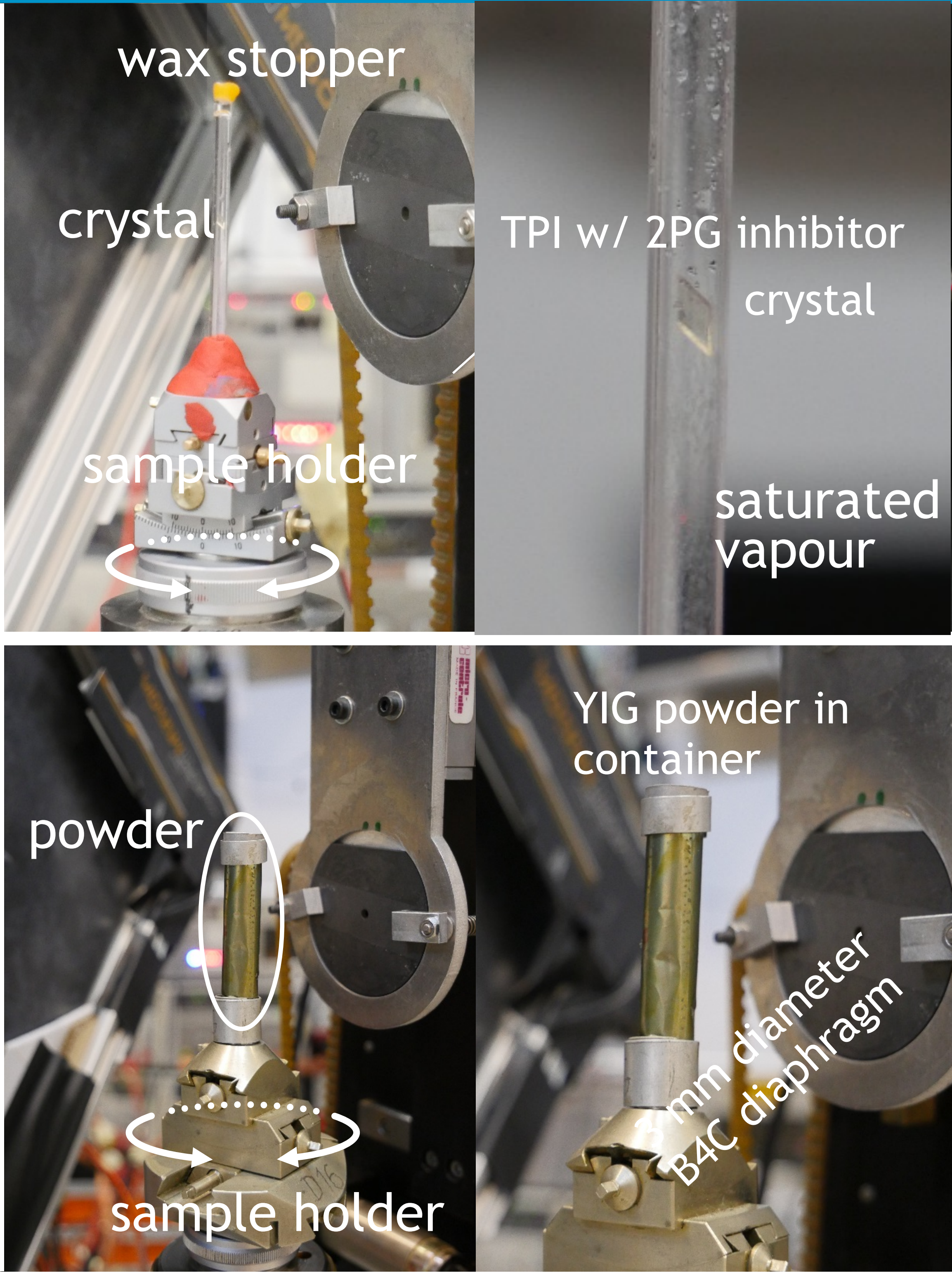




The holes have a minimum separation (centre to centre) of about 2.0 mm horizontally, 1.6 mm vertically, and 1.3 mm diagonally.

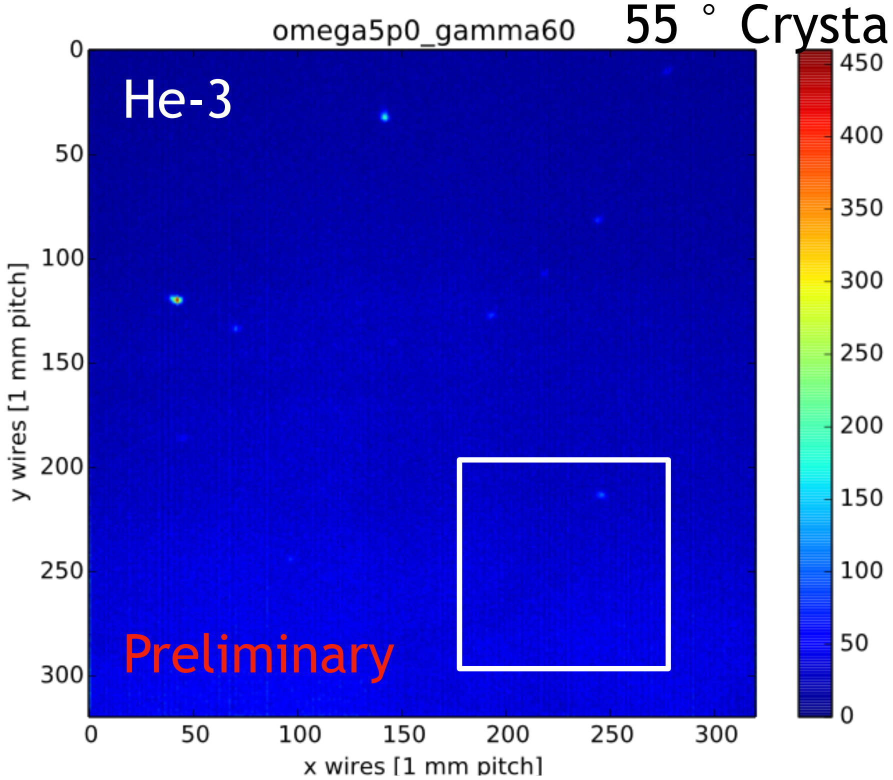
Gd-GEM Detector Demonstrator

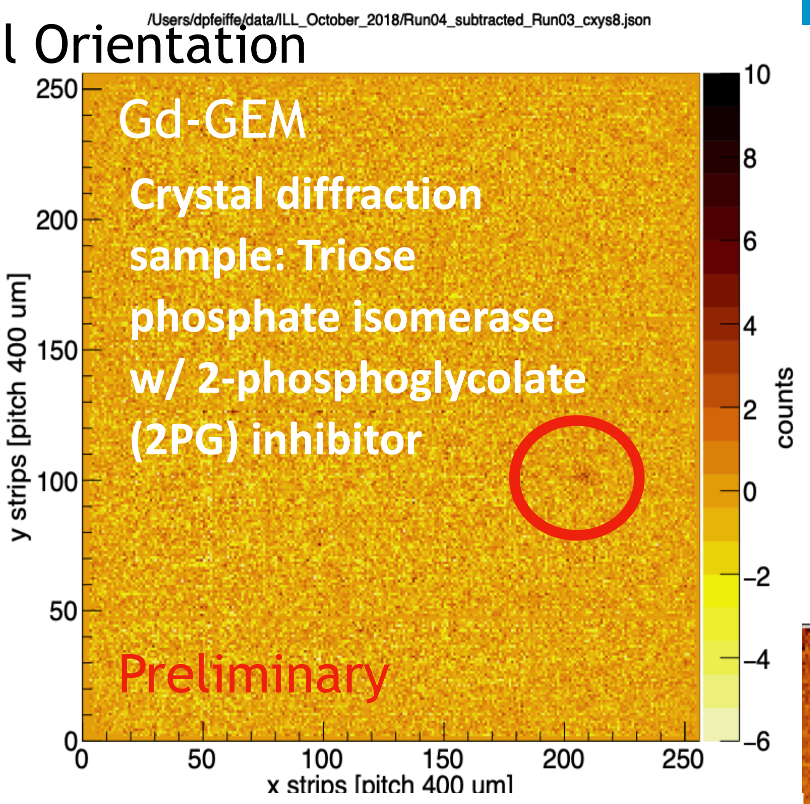




Gd-GEM Detector Demonstrator

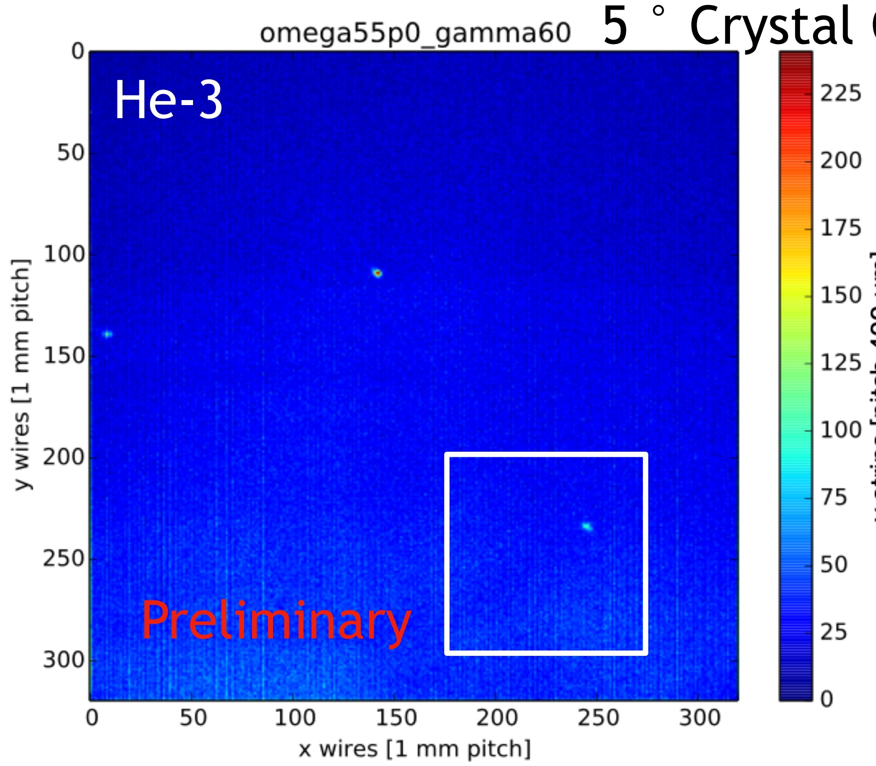
55 ° Crystal Orientation

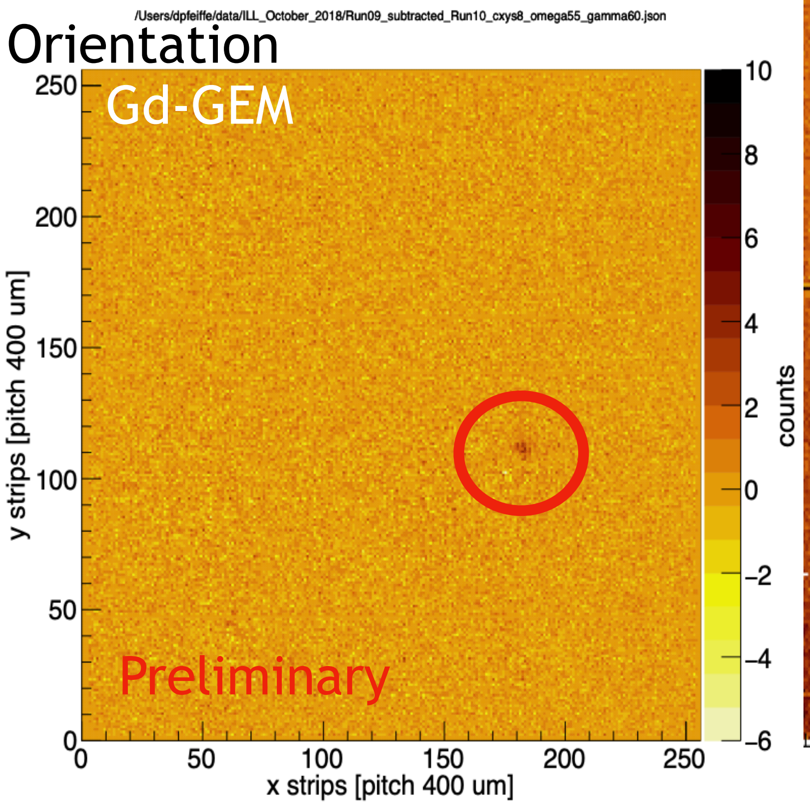




Crystal diffraction sample: Triose phosphate isomerase w/ 2-phosphoglycolate (2PG) inhibitor

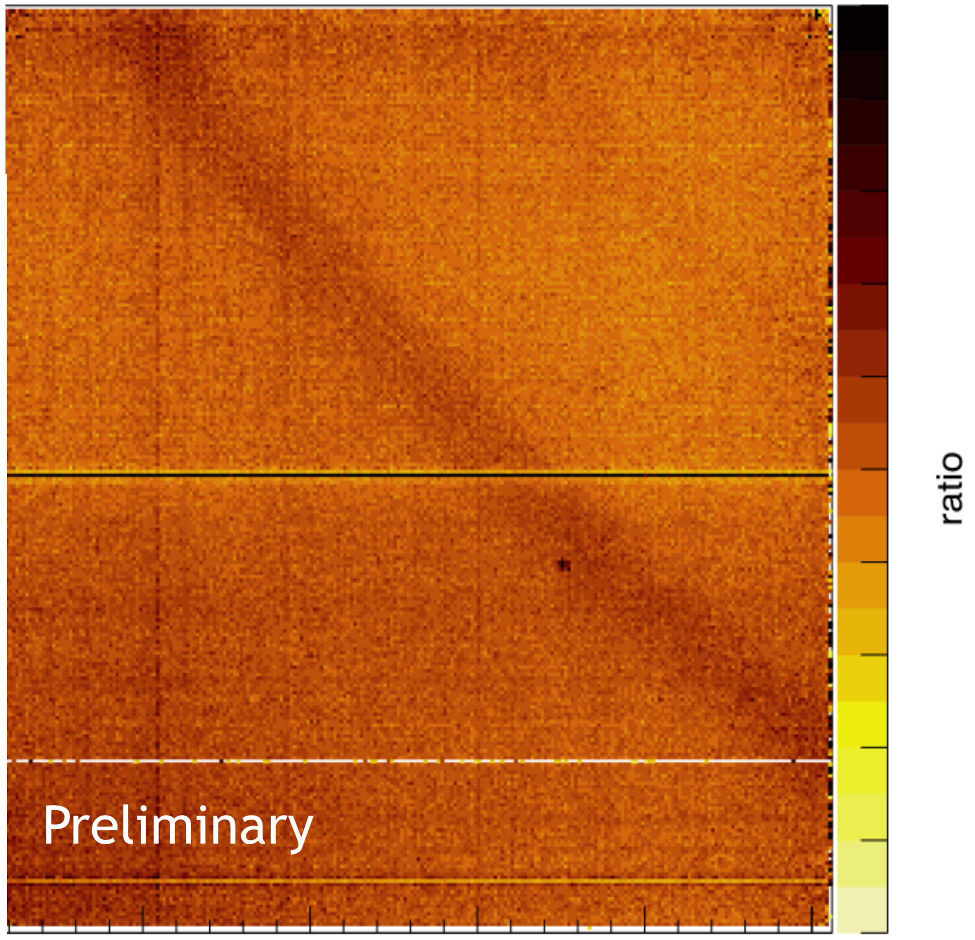
5 ° Crystal Orientation



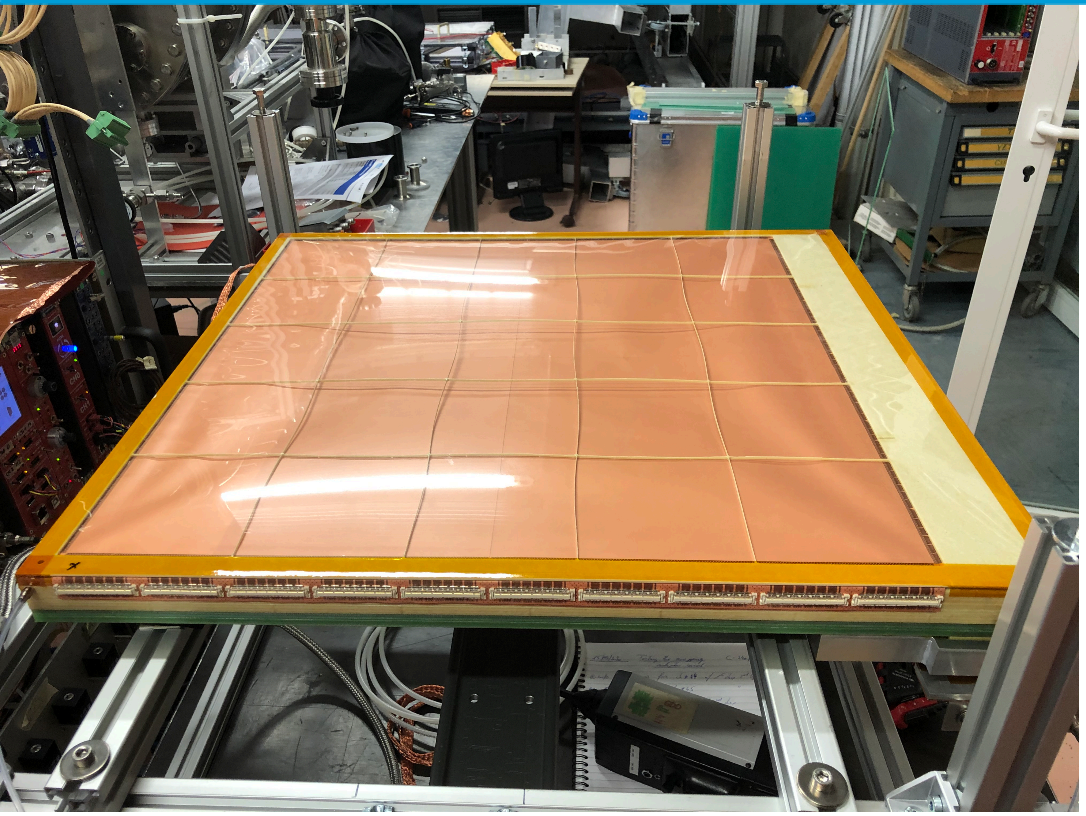


Detector and VMM3a performance sufficient to resolve weak reflections

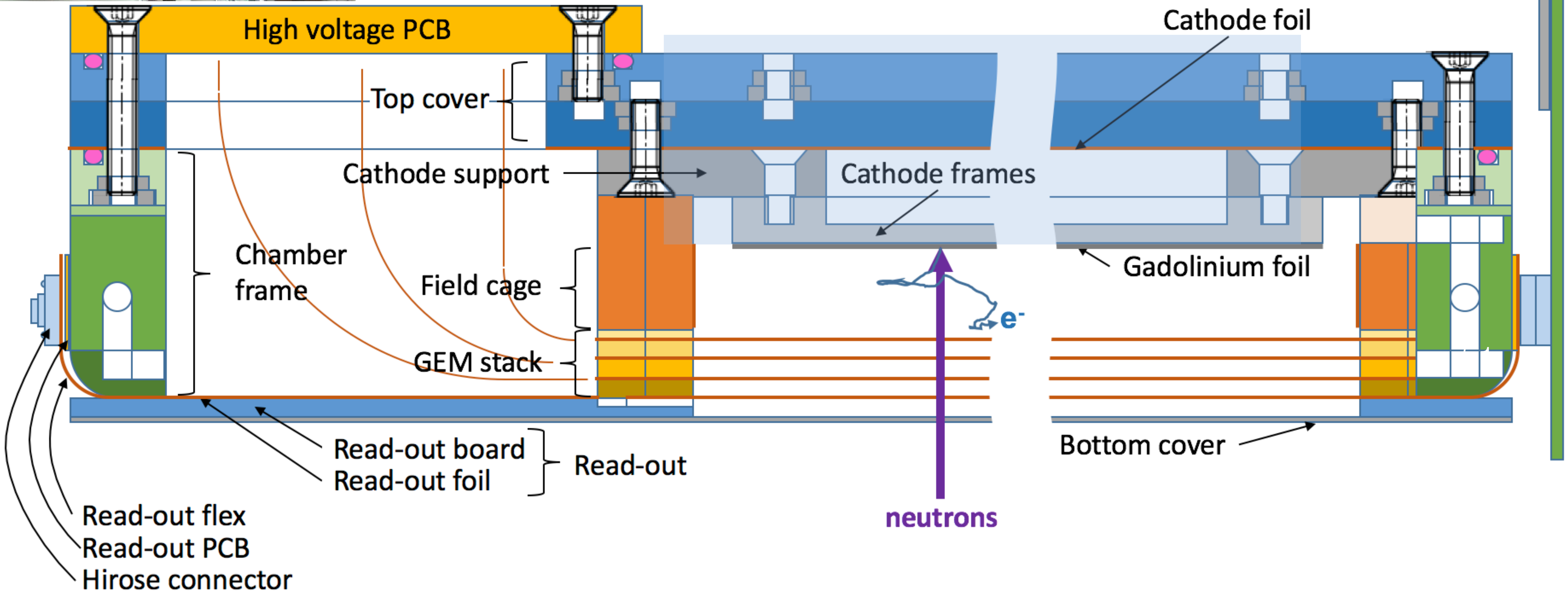
Powder diffraction with YIG powder in container



Gd-GEM Detector for NMX



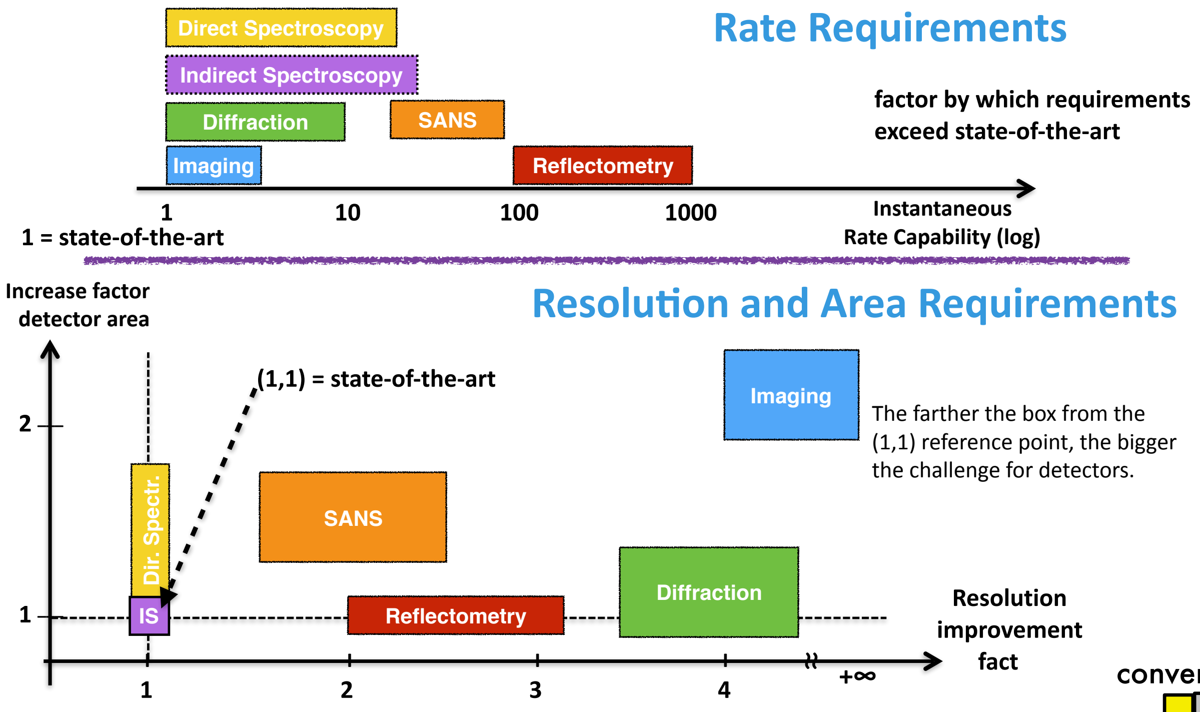
- Full size detector demonstrator Zita (51.2 × 51.2 cm² active area) developed during BrightnESS grant
- 80 VMM3 (40 hybrids) per detector (5120 channels per detector)
- To be tested soon … waiting for beam lines to become available



Thoughts …

- Detector development takes time
- Very difficult to go from concept to beam line in less than a decade
- e.g. Multi Grid started 2009/10. On ESS instrument ca. 22/23
- Detector development time >> Instrument construction time

- This should be our aspiration level for a decade … :

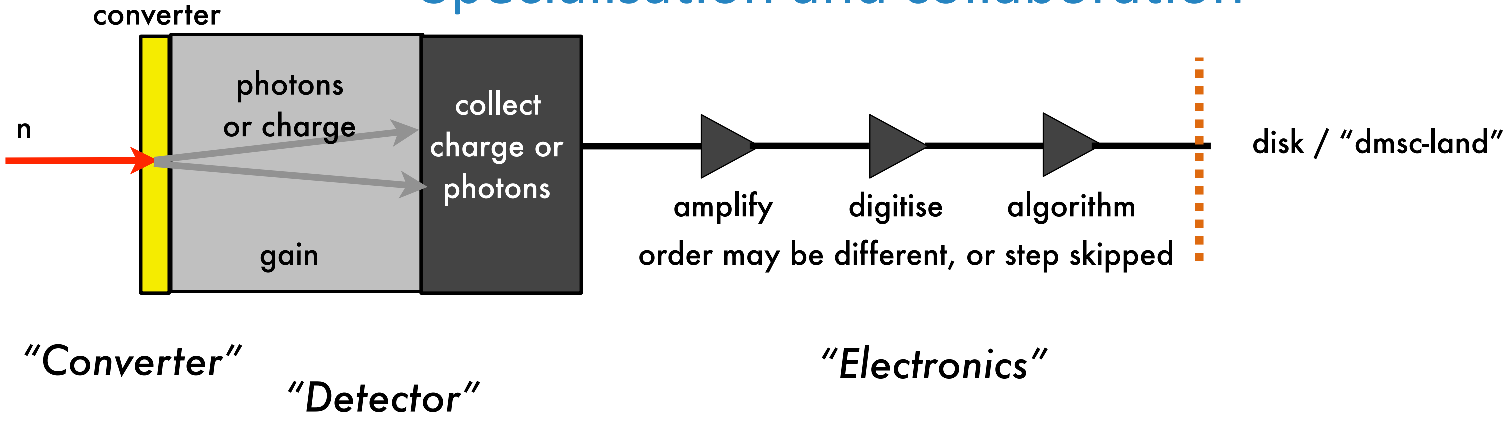


…and cost improvement of a factor of few …

- Computing and electronics have become ubiquitous and very cheap
- Future detectors will be much more designed around electronics
- Processing done in computing where possible

- Simulation will play a much bigger role in design

- Specialisation and collaboration



ESS Partners on Detectors

EUROPEAN
SPALLATION
SOURCE

ill

CERN

SNS
SPALLATION NEUTRON SOURCE

li.u
LINKÖPING UNIVERSITY

THE SPANISH CONTRIBUTION TO EUROPEAN RESEARCH EXCELLENCE
ESS bilbao

SIGILLUM UNIVERSITATIS GOTHORUM CAROLINAE 1666
LUNDS UNIVERSITET

UNIVERSITAS BERGENSIS

Science & Technology Facilities Council

Science & Technology Facilities Council
ISIS

UNIVERSITA' DEGLI STUDI DI MILANO
BICOCCA

BNC
Budapest Neutron Centre

wigner

Consiglio Nazionale Ricerche

IFP

INFN
Istituto Nazionale di Fisica Nucleare

JCNS
Jülich Centre for Neutron Science

DENEX

Detektoren für Neutronen GmbH
Stöteroggestraße 71 | 21339 Lüneburg
Tel.: +49 (0) 4131/248932

IEAP

CDT GmbH
CASCADE
Detector
Technologies

ujf

FZÚ

Helmholtz-Zentrum
Geesthacht
Zentrum für Material- und Küstenforschung

University of Glasgow

Risø DTU
National Laboratory for Sustainable Energy

ideas

COSYLAB

IFE
Institute for Energy Technology

JÜLICH
FORSCHUNGSZENTRUM

Mittuniversitetet
MID SWEDEN UNIVERSITY

icnd.org {

ill NEUTRONS FOR SCIENCE
ess
FRM II Forschungs-Neutronenquelle Heinz Maier-Leibnitz
HZB Helmholtz Zentrum Berlin
ISIS
J-PARC
JCNS
NEUTRON SCIENCES

}

INTERNATIONAL COLLABORATION FOR THE DEVELOPMENT OF NEUTRON DETECTORS

Summary

- 4 major new neutron sources coming online in next decade
- ESS is ca. 80% complete

- Brightness and science goals mean that the requirements for detectors cannot be met with todays state-of-the-art detectors
- Helium-3 crisis means that the “gold standard” for neutron detection is no longer default option

- Helium-3 replacement technologies and the large amount of new instrumentation is driving the detector development: hot topic!
- Talks on novel scintillator and semiconductor detector in this session

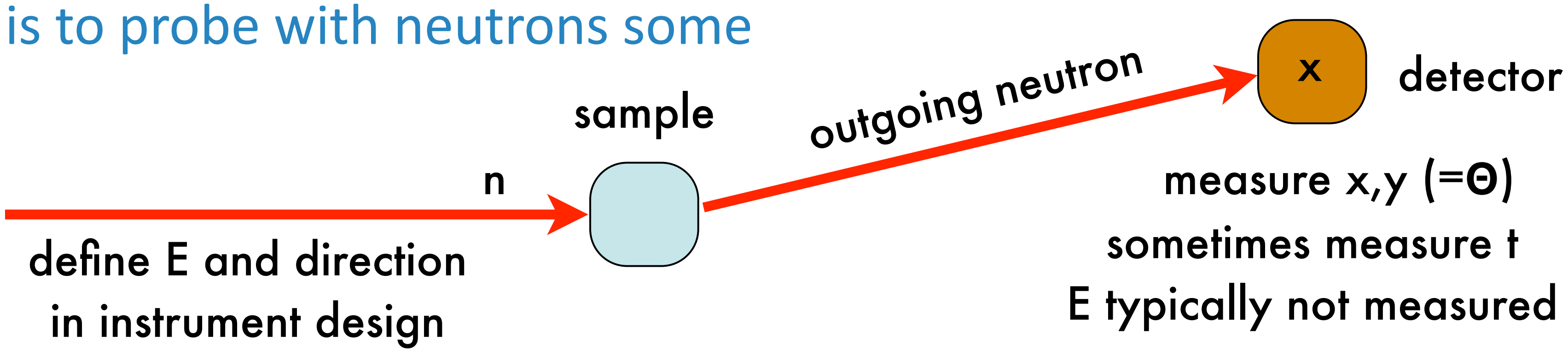
- Now under construction: **yes there is post-helium-3 neutron science!**
- Neutron detectors for future instruments are going to look very different …

- Very much a positive collaborative effort

brightness CRISP The Cluster of Research Infrastructures for Synergies in Physics SINE 2020 SoNDe Solid-State Neutron Detector Cremlin Connecting Russian and European Measures for Large-scale Research Infrastructures CREMLIN PLUS Connecting Russian and European Measures for Large-scale Research Infrastructures HighNESS

Neutrons as a probe

- The purpose of the instruments is to probe with neutrons some property of a sample



n

define E and direction
in instrument design

sample

outgoing neutron

detector

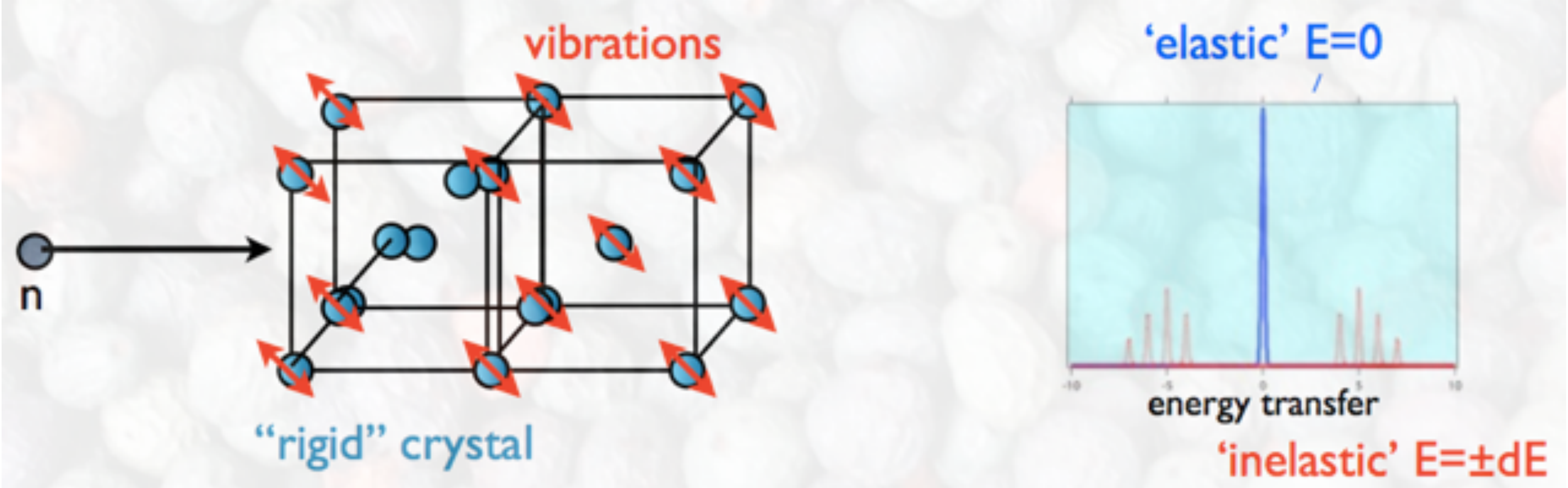
measure x,y (=Θ)
sometimes measure t
E typically not measured

- Very generically, this can be divided into elastic and inelastic categories
  - elastic: gives information on where atoms are
  - inelastic: gives information on what atoms do (i.e., move)

elastic $$\frac{d\sigma}{d\Omega}(\lambda, 2\theta, \psi)$$

inelastic $$\frac{d^2\sigma}{d\Omega dE}(\lambda_{in}, \lambda_{sc}, 2\theta, \psi)$$

Elastic vs Inelastic



Detectors for ESS: baseline for selected instruments

Instrument class	Instrument sub-class	Instrument	Key requirements for detectors	Preferred detector technology	Ongoing developments (funding source)
Large-scale structures	Small Angle Scattering	SKADI	Pixel size, count-rate, area	Pixellated Scintillator	SonDe (EU SonDe)
		LOKI		10B-based	Boron Coated Straws
	Reflectometry	FREIA	Pixel size, count-rate	10B-based	MultiBlade (EU BrightnESS)
		ESTIA			
Diffraction	Powder diffraction	DREAM	Pixel size, count-rate	10B-based	Jalousie
		HEIMDAL		10B-based	Jalousie
	Single-crystal diffraction	MAGIC	Pixel size, count-rate	10B-based	Jalousie
		NMX	Pixel size, large area	Gd-based	GdGEMuTPC(EU)
Engineering	Strain scanning	BEER	Pixel size, count-rate	10B-based	AmCLD, A1CLD (HZG)
	Imaging and tomography	ODIN	Pixel size	Scintillators, MCP, wire chambers	
Spectroscopy	Direct geometry	C-SPEC	Large area (^{3}He-gas unaffordable)	10B-based	MultiGrid (EU BrightnESS)
		T-REX			
		VOR			
	Indirect geometry	BIFROST	Count-rate	3He-based	He-3 PSD Tubes
		MIRACLES			He-3 PSD Tubes
		VESPA	Count-rate	3He-based	He-3 PSD Tubes
SPIN-ECHO	Spin-echo	tbd	tbd	3He-based/10B-based	

arXiv:1411.6194

Good dialogue and close collaboration needed for successful delivery and integration

The Intensity Frontier: The Multi-Blade Detector Design

The Multi-Blade project

High counting rate capability

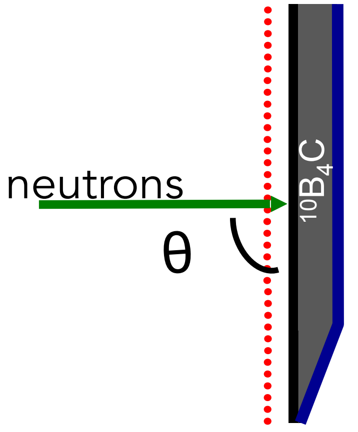
High spatial resolution

A single Boron layer inclined at 5 degrees

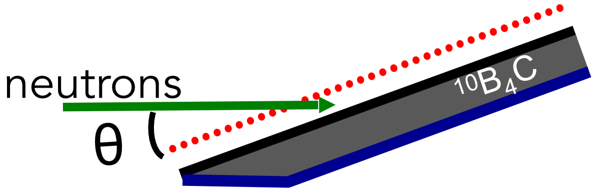
Efficiency <5% at 2.5Å

Efficiency 45% at 2.5Å

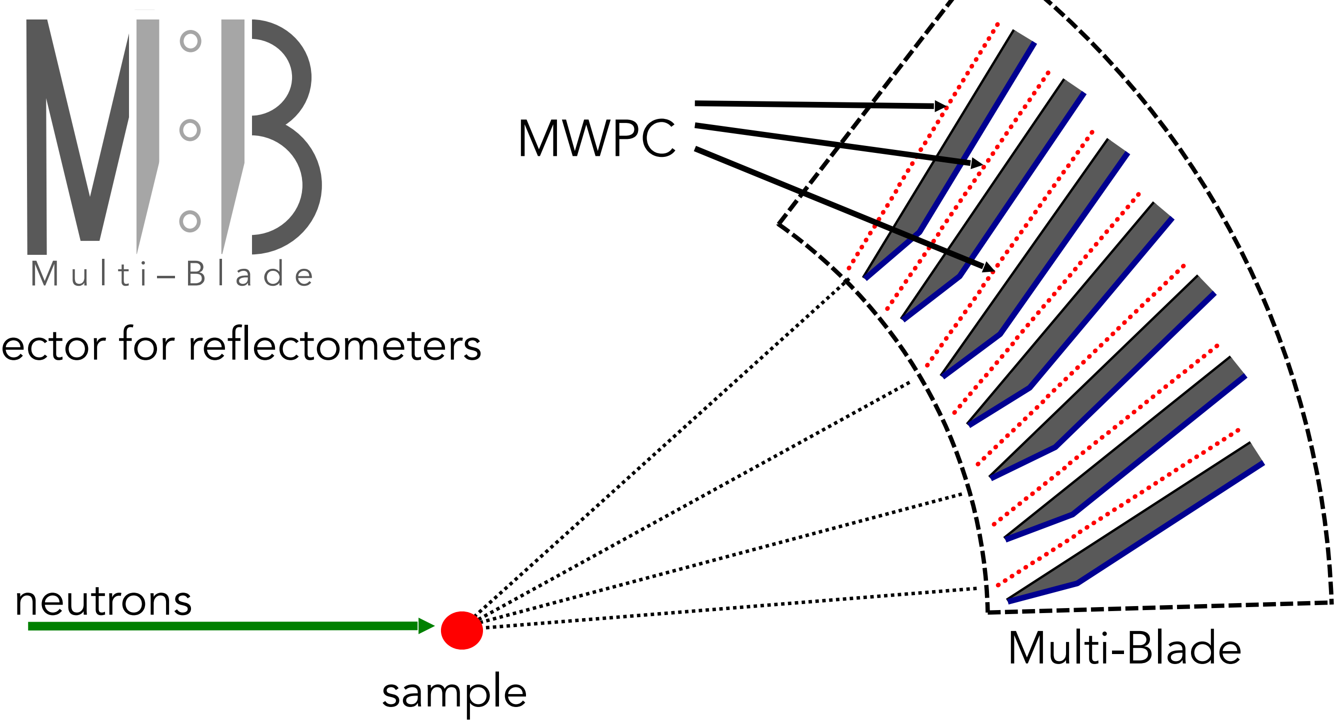
^{10}B-detector for reflectometers

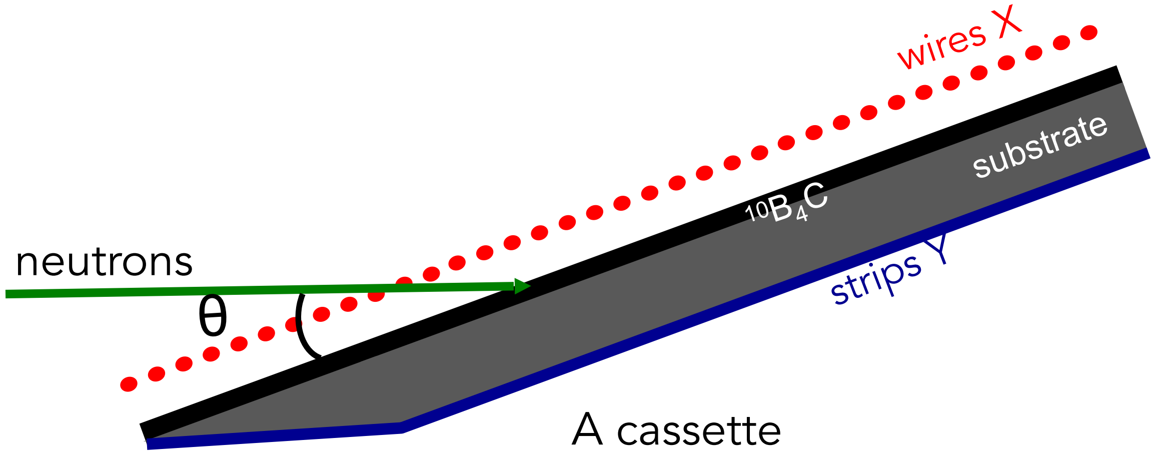


θ = 90 degrees



θ = 5 degrees





A cassette (unit)

θ = 5 degrees

F. Piscitelli et al, Journal of Instrumentation 12, P03013 (2017) - doi: 10.1088/1748-0221/12/03/P03013 , arXiv:1701.07623

BrightnESS is funded by the European Union’s Horizon 2020 research and innovation programme under grant agreement No. 676548

Demonstrator Multi-Blade Detector on the CRISP reflectometer at ISIS, UK

EUROPEAN
SPALLATION
SOURCE

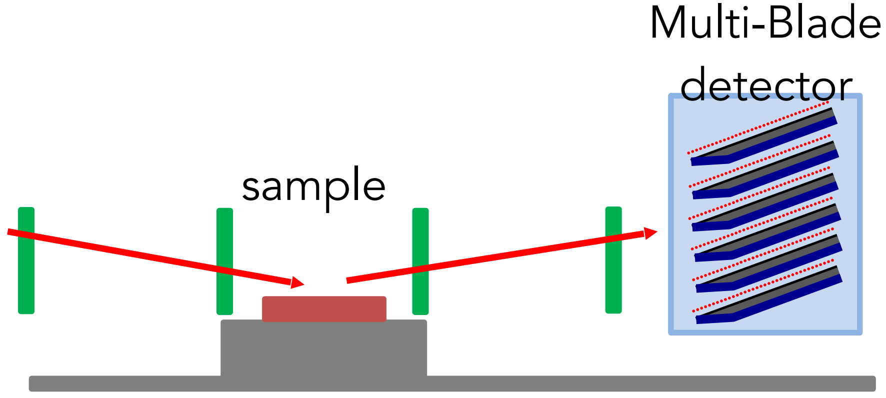
LUND UNIVERSITY

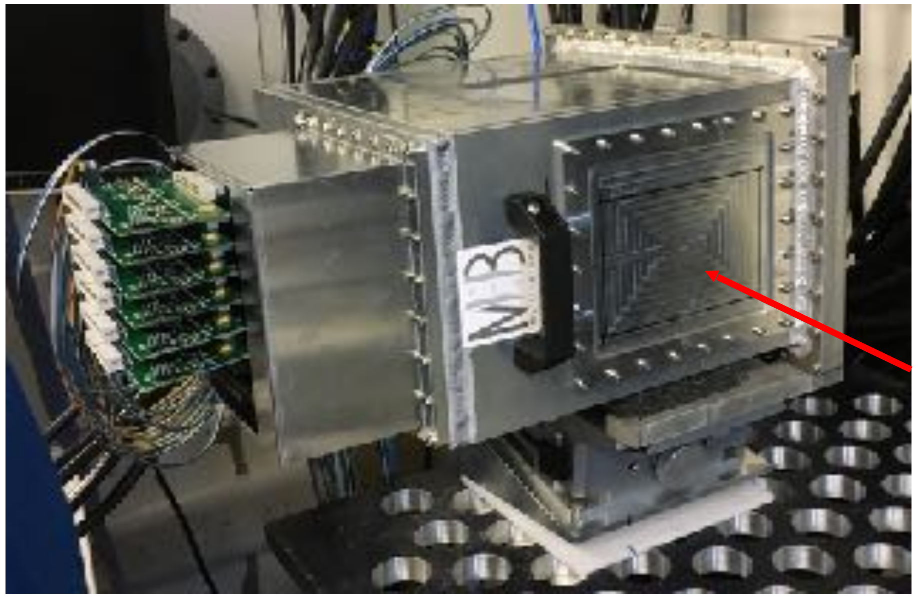
Science & Technology Facilities Council
ISIS

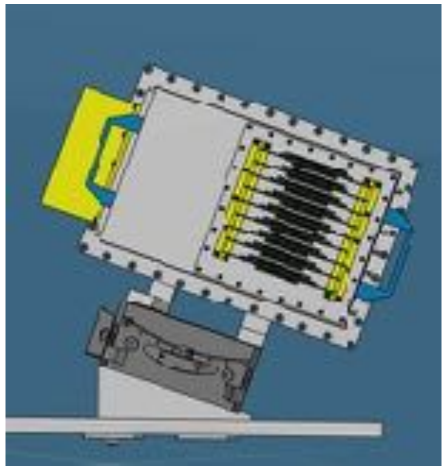
UNIVERSITÀ DEGLI STUDI DI PERUGIA

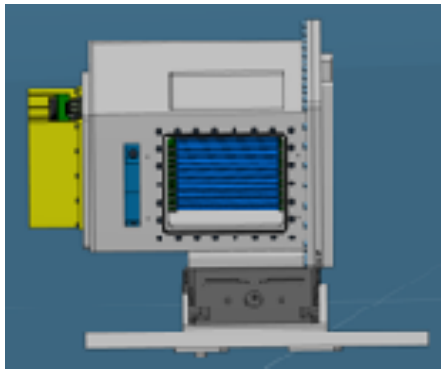
LINKÖPINGS UNIVERSITET

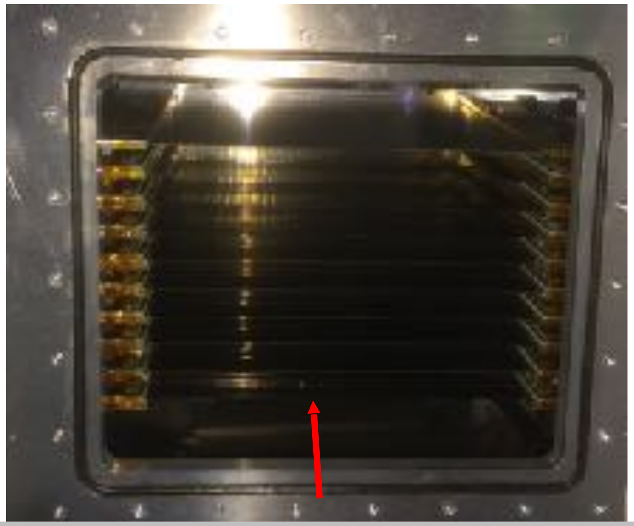
CRISP reflectometer at ISIS

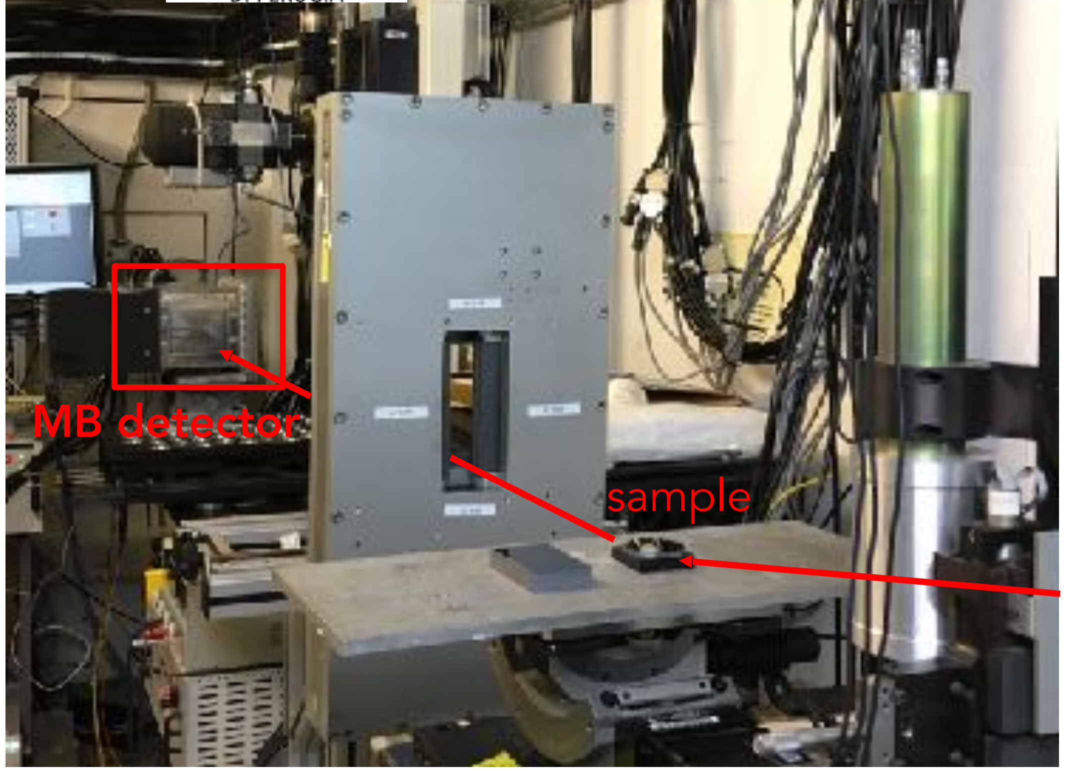


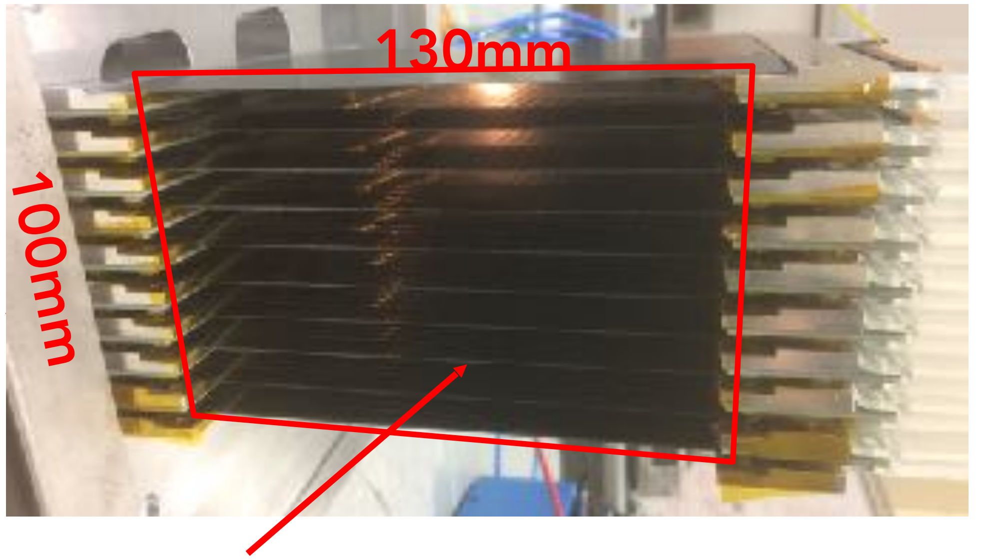












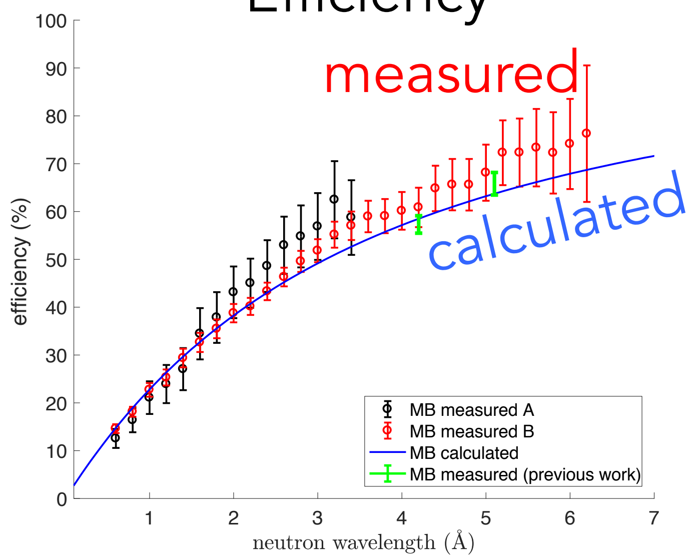
BrightnESS is funded by the European Union’s Horizon 2020 research and innovation programme under grant agreement No. 676548

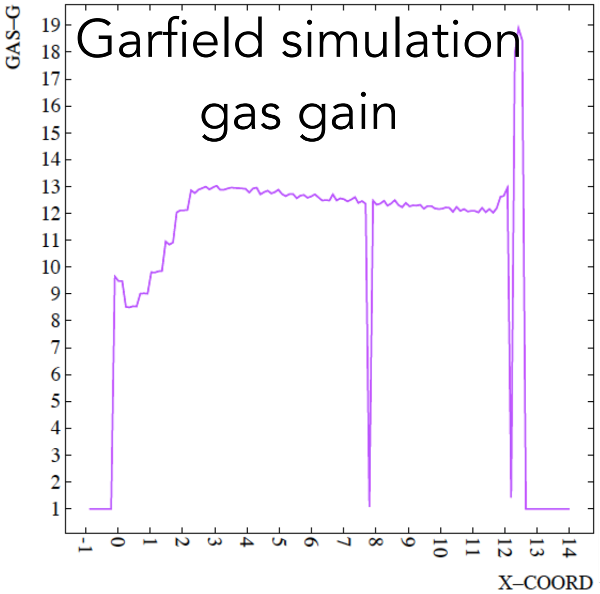
Technical Characterisation on CRISP

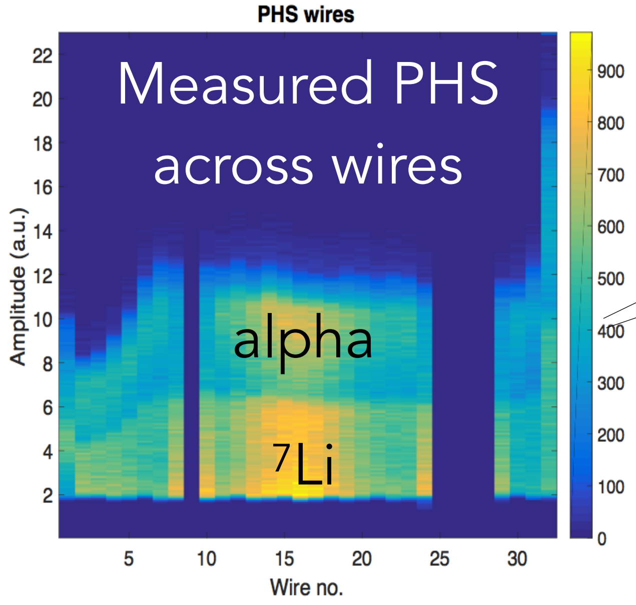
EUROPEAN
SPALLATION
SOURCE

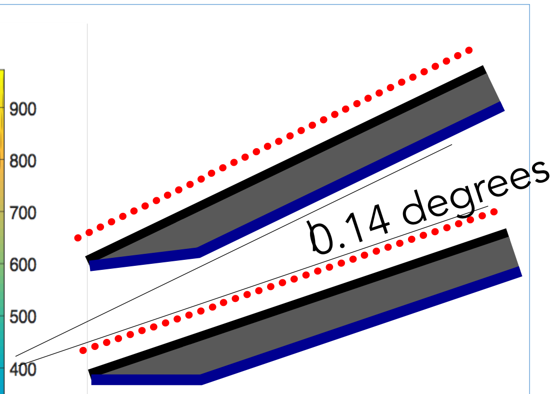
F. Piscitelli et al., Characterization of the Multi-Blade 10B-based detector at the CRISP reflectometer, JINST 13 P05009 (2018).

Efficiency



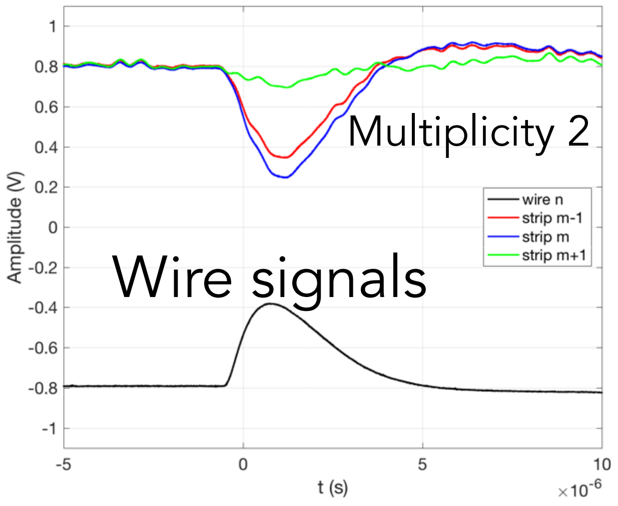




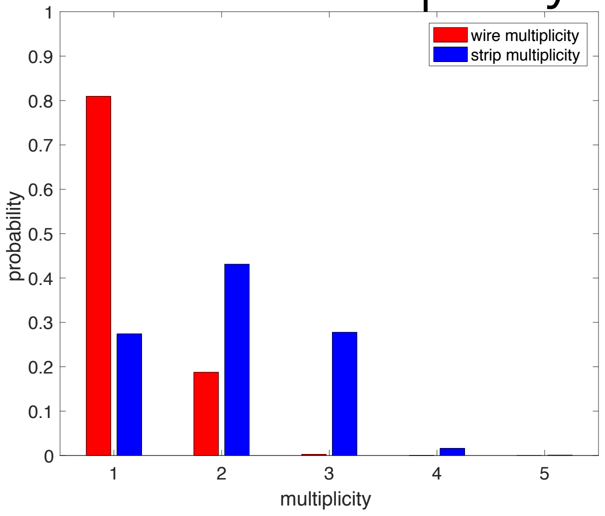


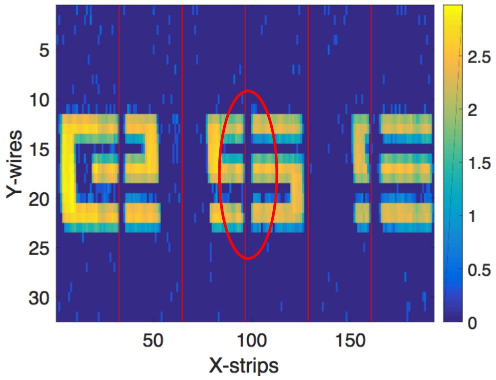
Gain compensation
by HV in final detector

Strip signals

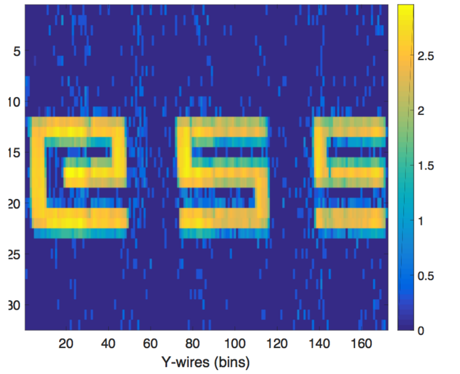


Cluster Multiplicity

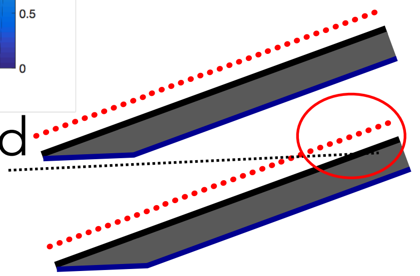




Cassette shadowing
due to overlap
(not a dead area)

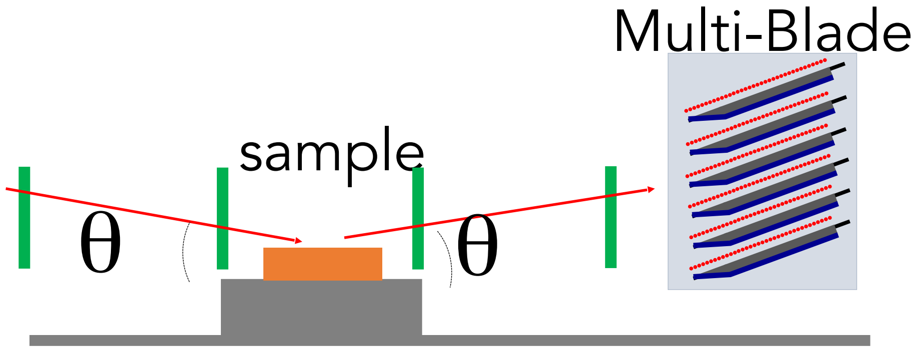


Shadows removed

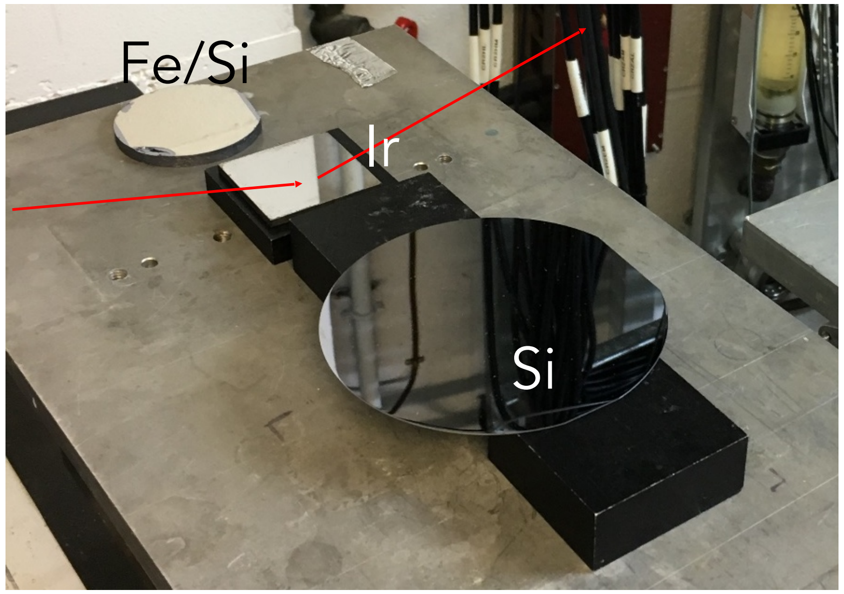


Scientific Results from Multi-Blade detector demonstrator on CRISP instrument

G. Mauri et al., Neutron reflectometry with the Multi-Blade 10B-based detector, Proc. Royal Society A474 (2018) 20180266 arXiv 1804.03962



Ir sample	Si sample	Fe/Si sample
🟧	🟦	🟩



- Iridium

  ↓

  Dependance of the q-resolution on detector spatial resolution

- Silicon

  ↓

  Collimated vs divergent mode (uniformity & spatial resolution)

- Fe/Si supermirror

  ↓

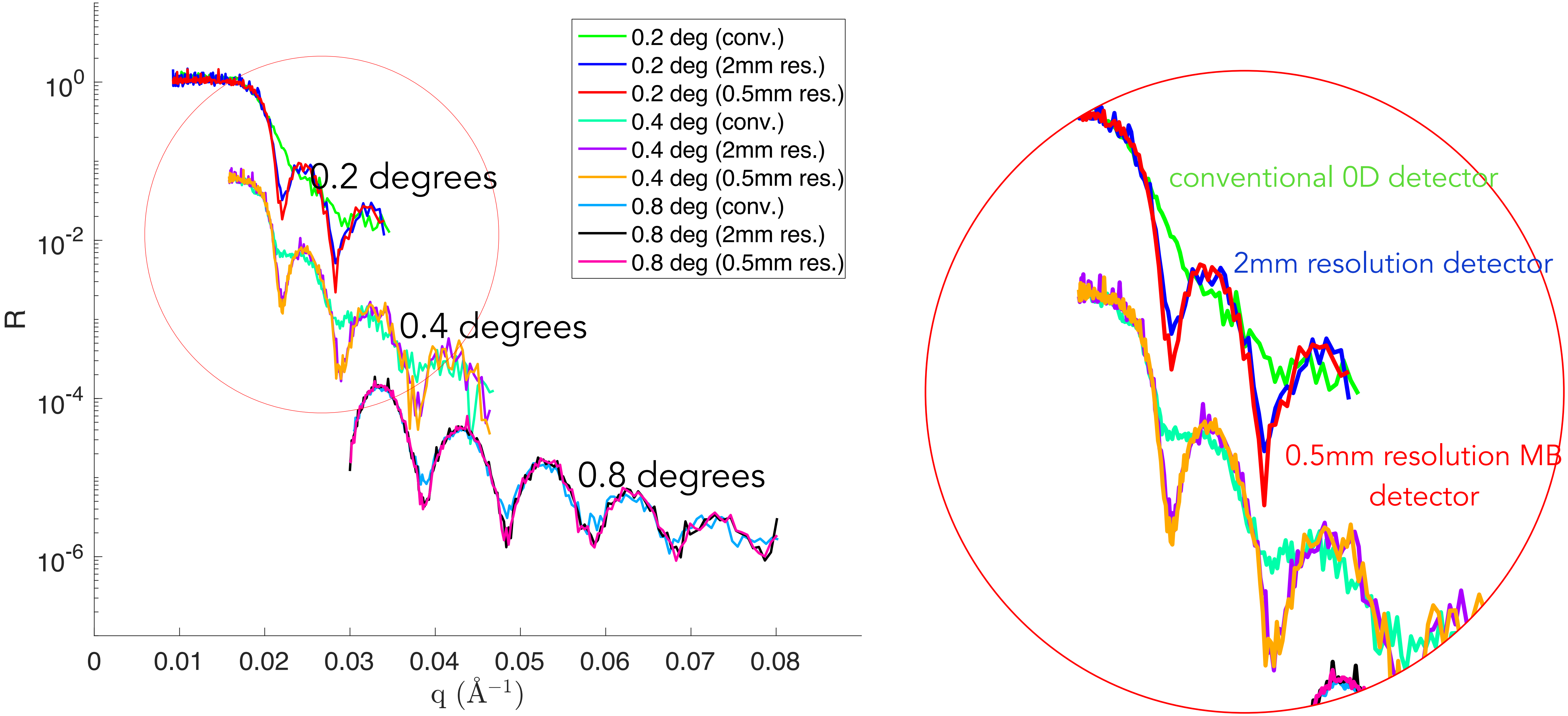
  Off-specular (counting rate & uniformity & spatial resolution)

Scientific results from CRISP: Iridium

EUROPEAN
SPALLATION
SOURCE

G. Mauri et al., Neutron reflectometry with the Multi-Blade 10B-based detector, Proc. Royal Society A474 (2018) 20180266 arXiv 1804.03962

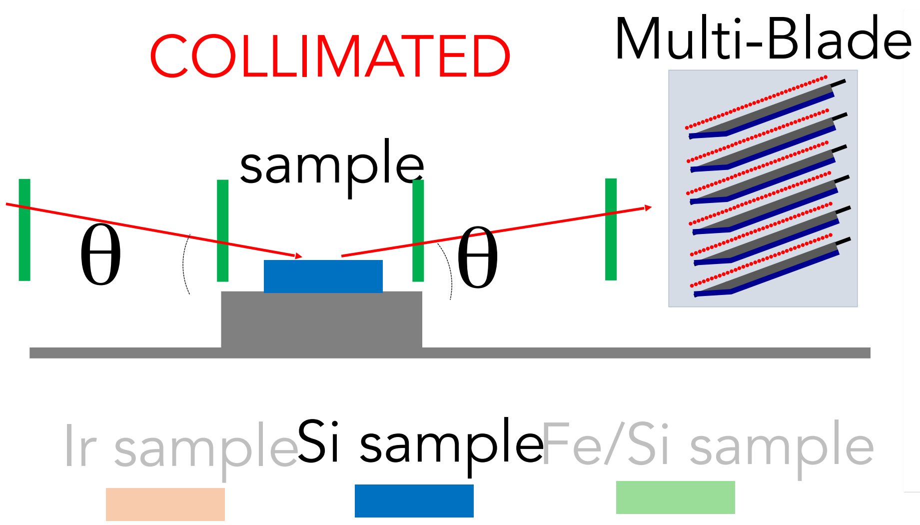
Dependence of the q-resolution on detector spatial resolution



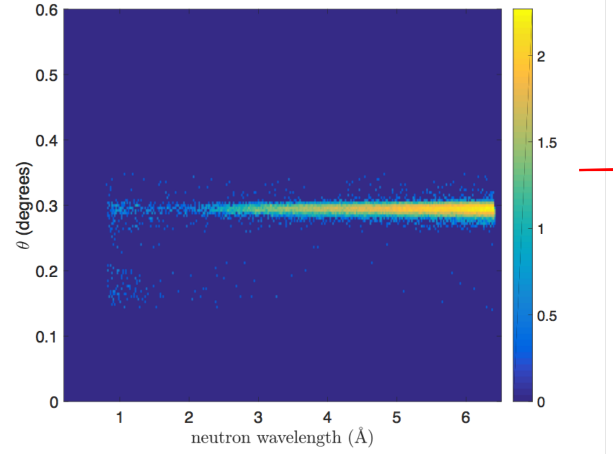
Scientific results from CRISP: Silicon

G. Mauri et al., Neutron reflectometry with the Multi-Blade 10B-based detector, Proc. Royal Society A474 (2018) 20180266 arXiv 1804.03962

COLLIMATED

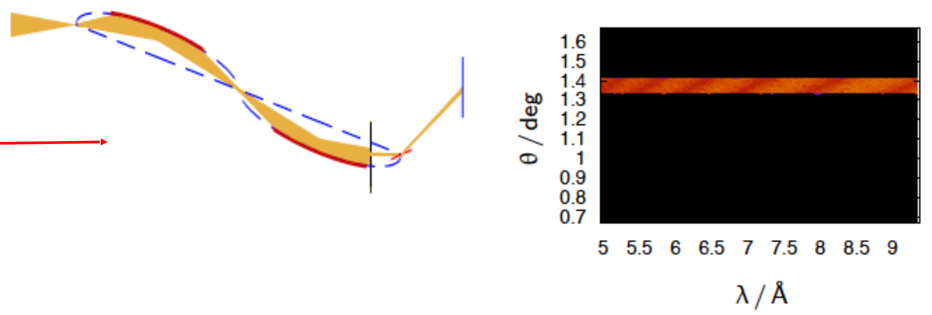


LOWER RATE

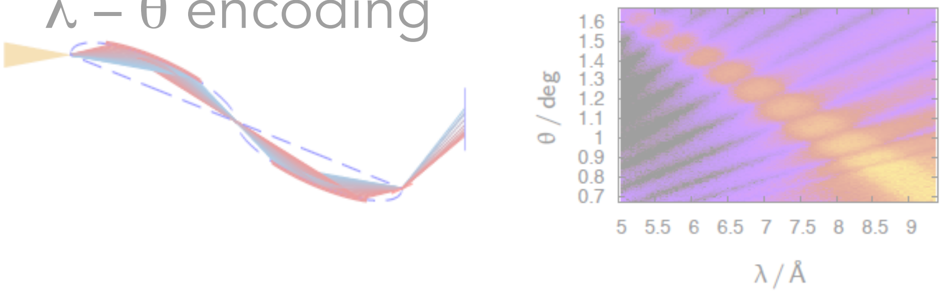


conventional

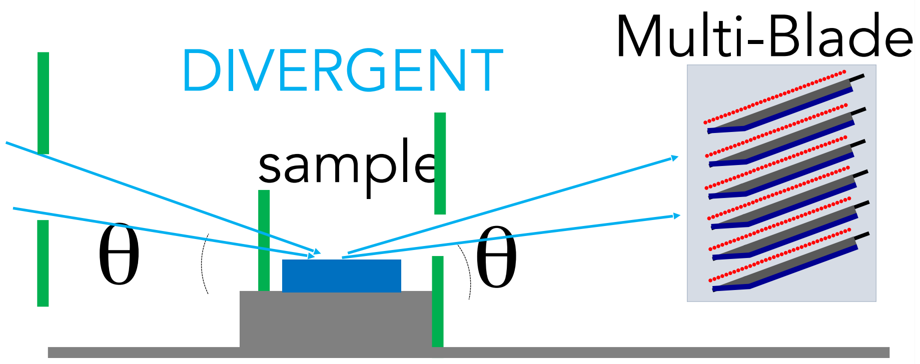
Estia



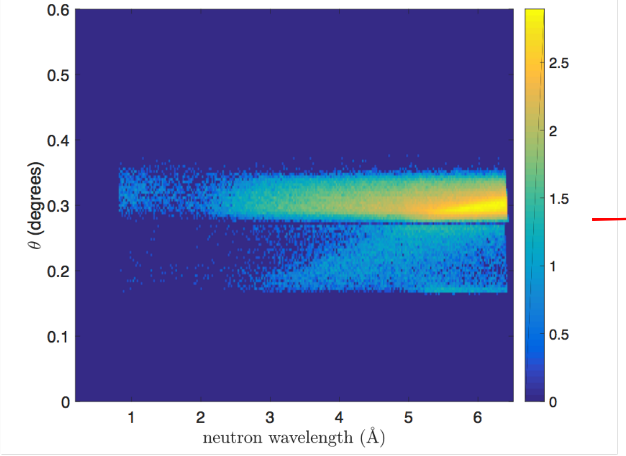
λ – θ encoding



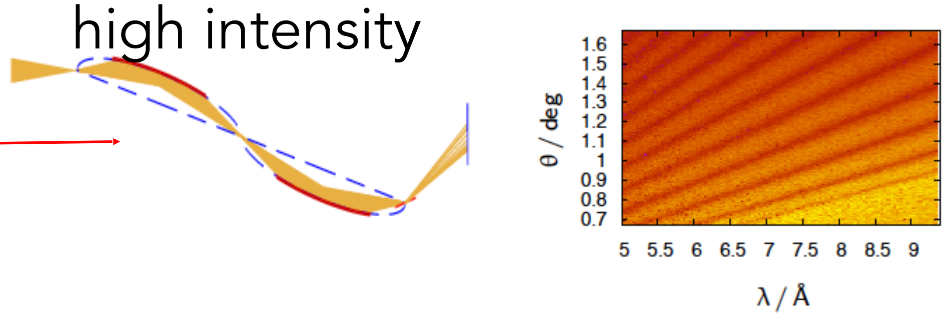
DIVERGENT



HIGHER RATE



high intensity



Scientific Results from CRISP: Scattering from Fe/Si Supermirror

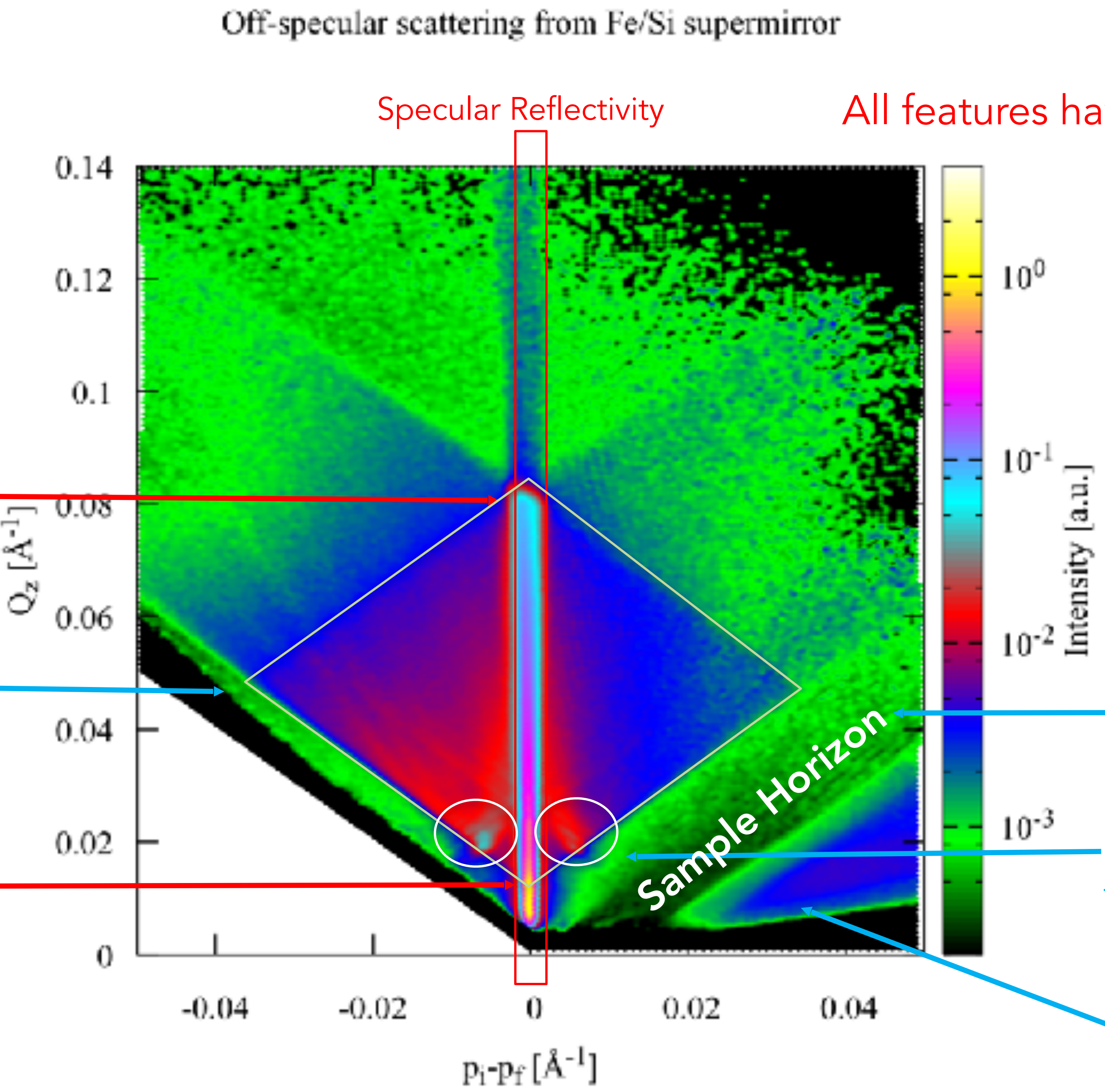
Results

F. Piscitelli et al, Journal of Instrumentation13 P05009 (2018)
arXiv:1803.09589

G. Mauri et al., Proc. Royal Society A474 (2018) 20180266
arXiv 1804.03962

All features have been clearly identified

Specular Reflectivity



Supermirror edge (m=3.8)

Correlated roughness domains from the layers

Si edge

No Transmitted beam, total reflection

Spin-flip scattering signal, from the layers

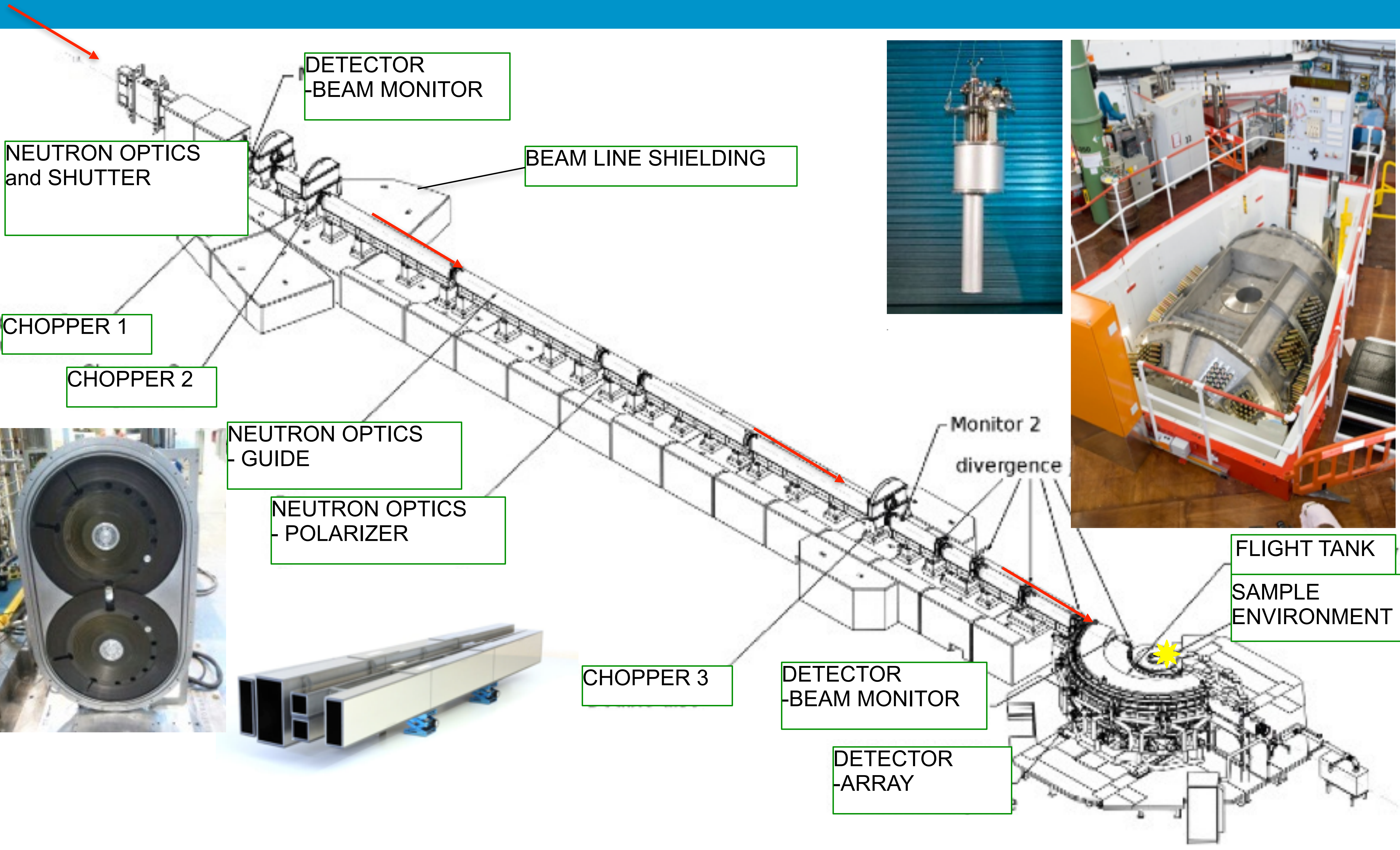
Transmitted beam through the sample

Technology demonstrated, ready for deployment

BrightnESS is funded by the European Union's Horizon 2020 research and innovation programme under grant agreement No. 676548

Layout of a Neutron Instrument

EUROPEAN
SPALLATION
SOURCE



DETECTOR
-BEAM MONITOR

NEUTRON OPTICS
and SHUTTER

BEAM LINE SHIELDING

CHOPPER 1

CHOPPER 2

NEUTRON OPTICS
- GUIDE

NEUTRON OPTICS
- POLARIZER

FLIGHT TANK

SAMPLE
ENVIRONMENT

CHOPPER 3

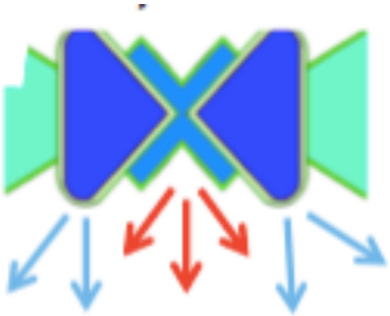
DETECTOR
-BEAM MONITOR

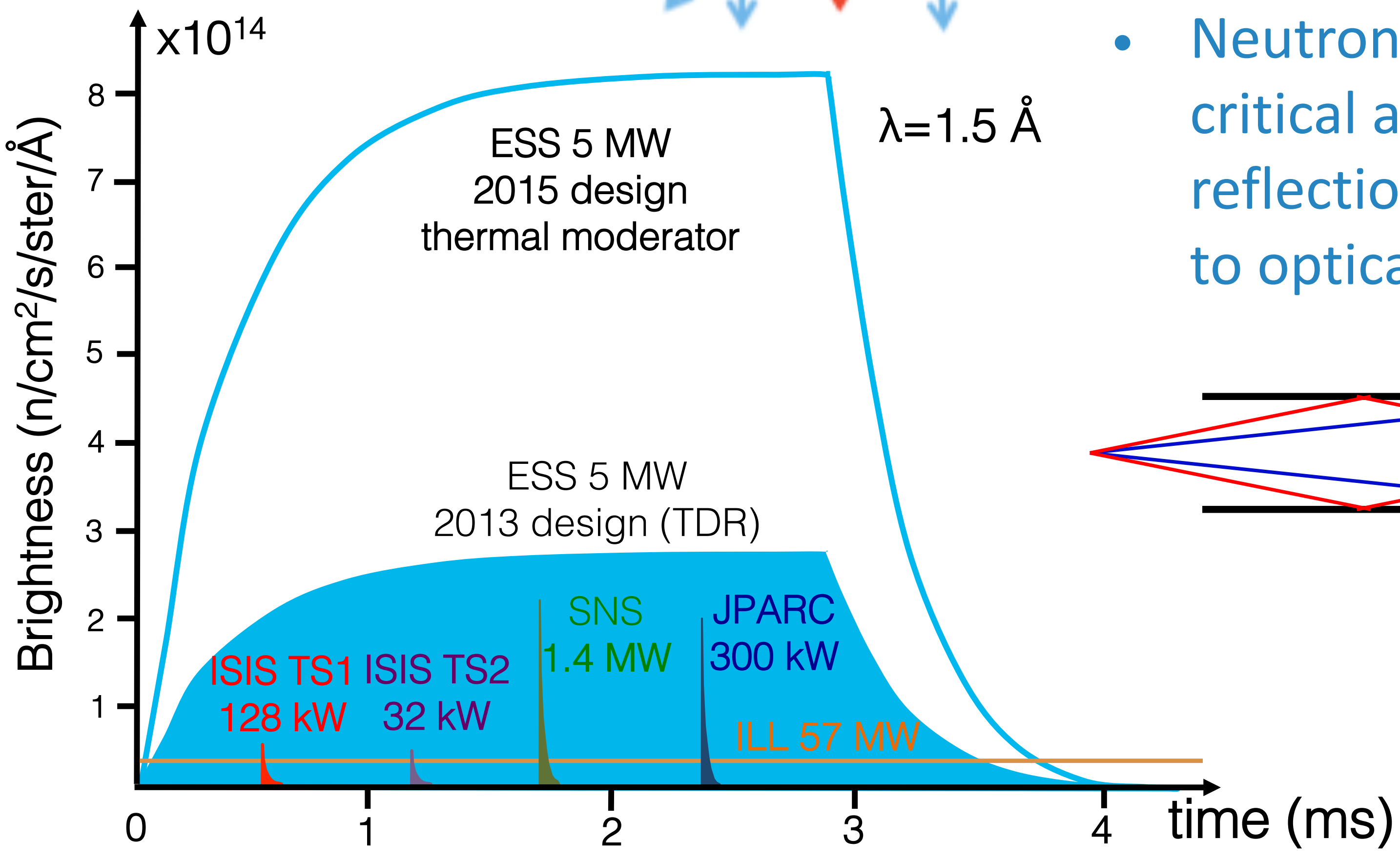
DETECTOR
-ARRAY

Neutron Instrumentation Technology

- ESS will be more powerful and several times brighter than existing facilities.
- However, over the past decades the major order of magnitude gains have been in the instrumentation design

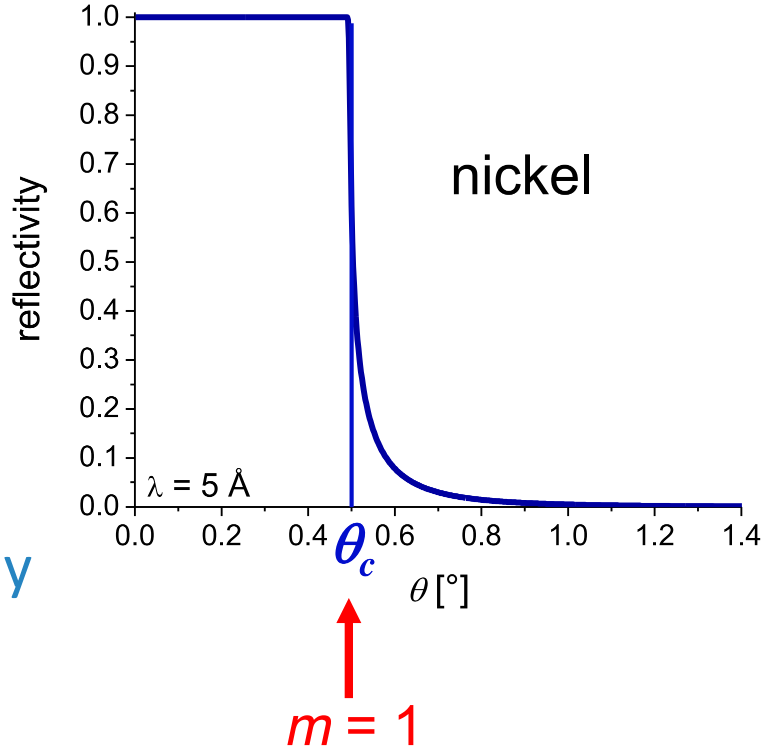
eg neutron moderators

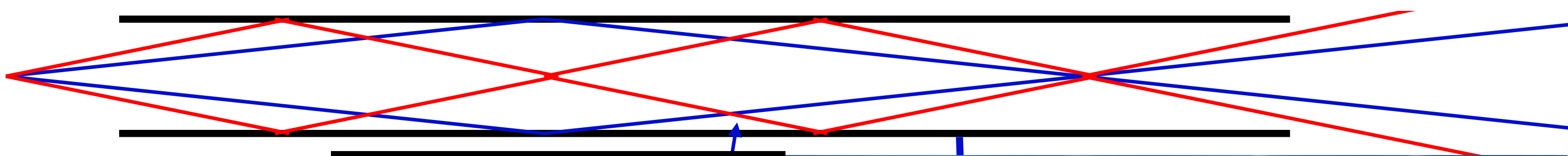




eg neutron transport "neutron optics"

- Neutron guides use this critical angle for internal reflection, in a similar way to optical fibres





- The advances in neutron detection have been more modest, until recently …

What can be done with this brightness?

Instrument Design	Implications for Detectors
Smaller samples	Better Resolution (position and time) Channel count
Higher flux, shorter experiments	Rate capability and data volume
More detailed studies	Lower background, lower S:B Larger dynamic range
Multiple methods on 1 instrument Larger solid angle coverage	Larger area coverage Lower cost of detectors

Also: scarcity of Helium-3 …

Developments required for detectors for new Instruments

What can be done with this brightness?

What does a factor 10 improvement imply for the detectors?

Implications for Detectors	Implications for Detectors
Better Resolution (position and time)	sqrt(10)
Channel count	pixelated: factor 10 x-y coincidence:sqrt(10)
Rate capability and data volume	factor 10
Lower background, lower S:B Larger dynamic range	Keep constant implies: factor 10 smaller B per neutron
Larger area coverage Lower cost of detectors	Factor of a few

Developments required for detectors for new Instruments