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brightness

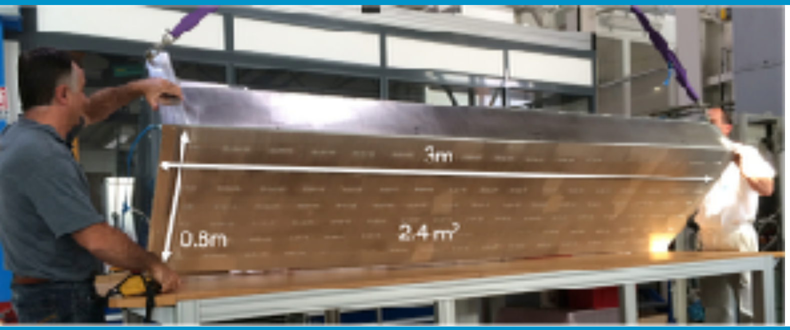
EUROPEAN SPALLATION SOURCE

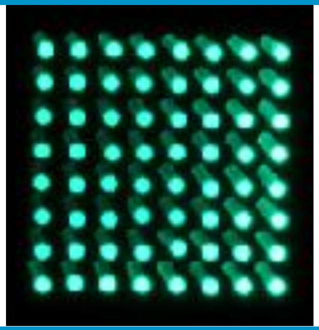
(A new generation of) Neutron Detectors for Neutron Scattering Science

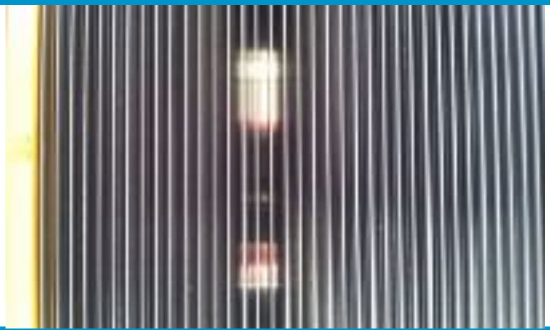
Richard Hall-Wilton
Leader of Detector Group
Deputy Division Head of Instrument Technologies

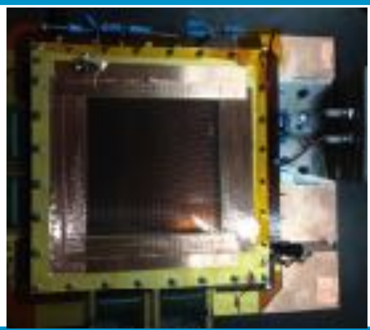
IAEA Technical Meeting on Modern Neutron Detection
4-8 Sep 2017

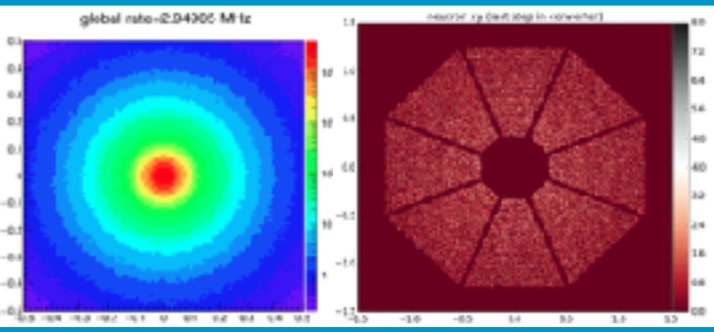
www.europeanspallationsource.se

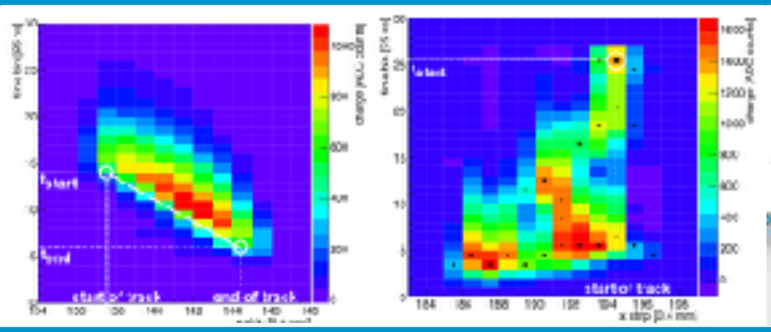


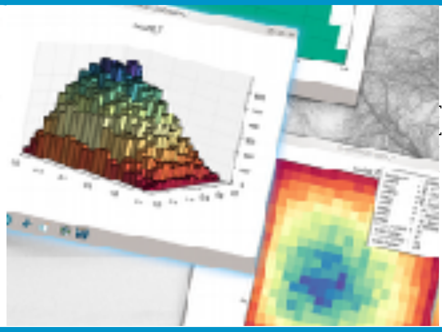


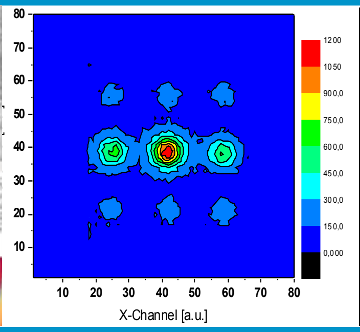


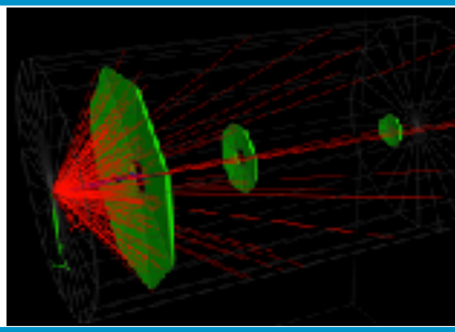






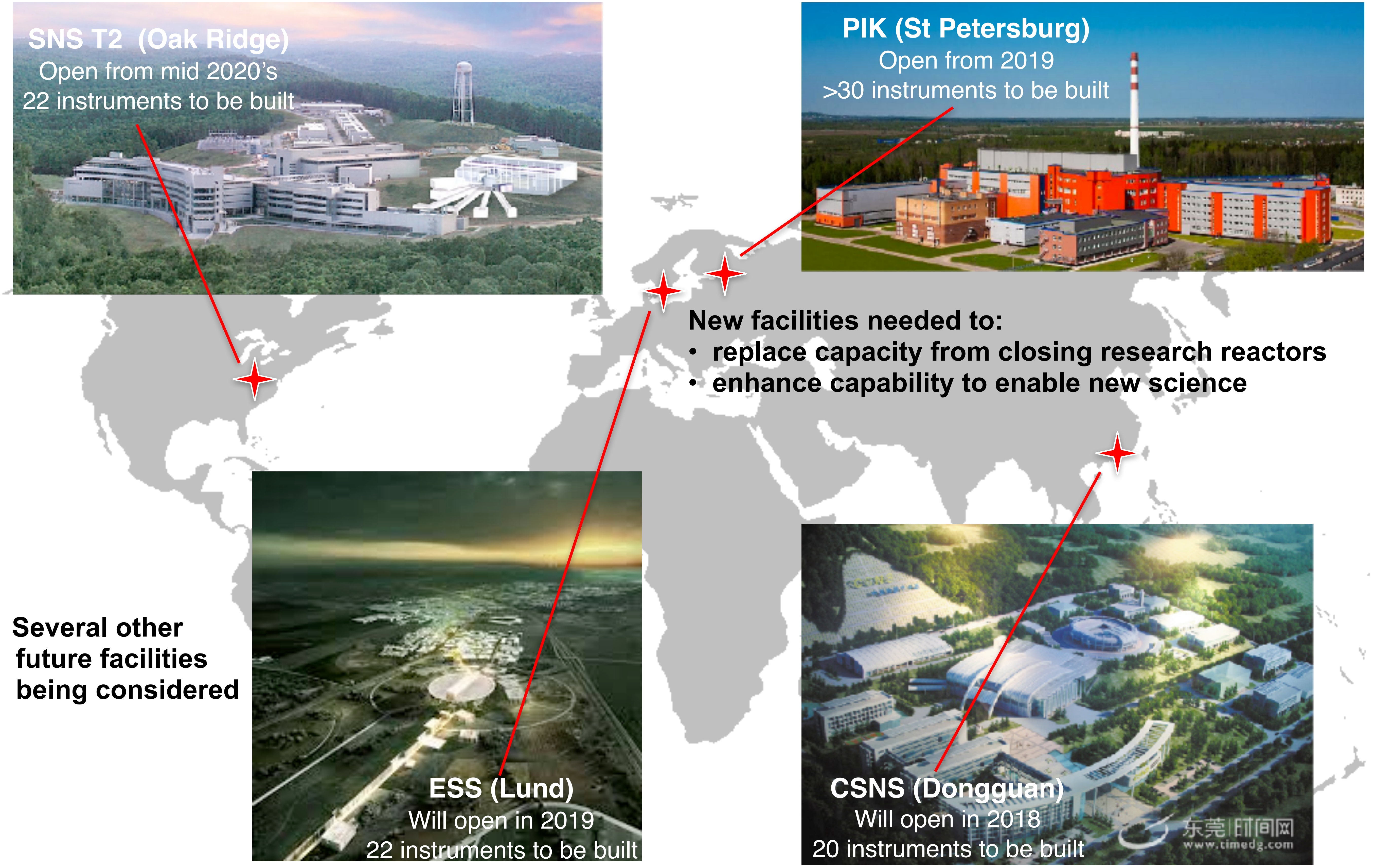







Lighting
New materials
Solar energy
Food
Medicine
Tailor made materials
Pacemakers
Mobile phones
Cosmetics
Bio fuels
Implants
Transportation
Geo science
ESS

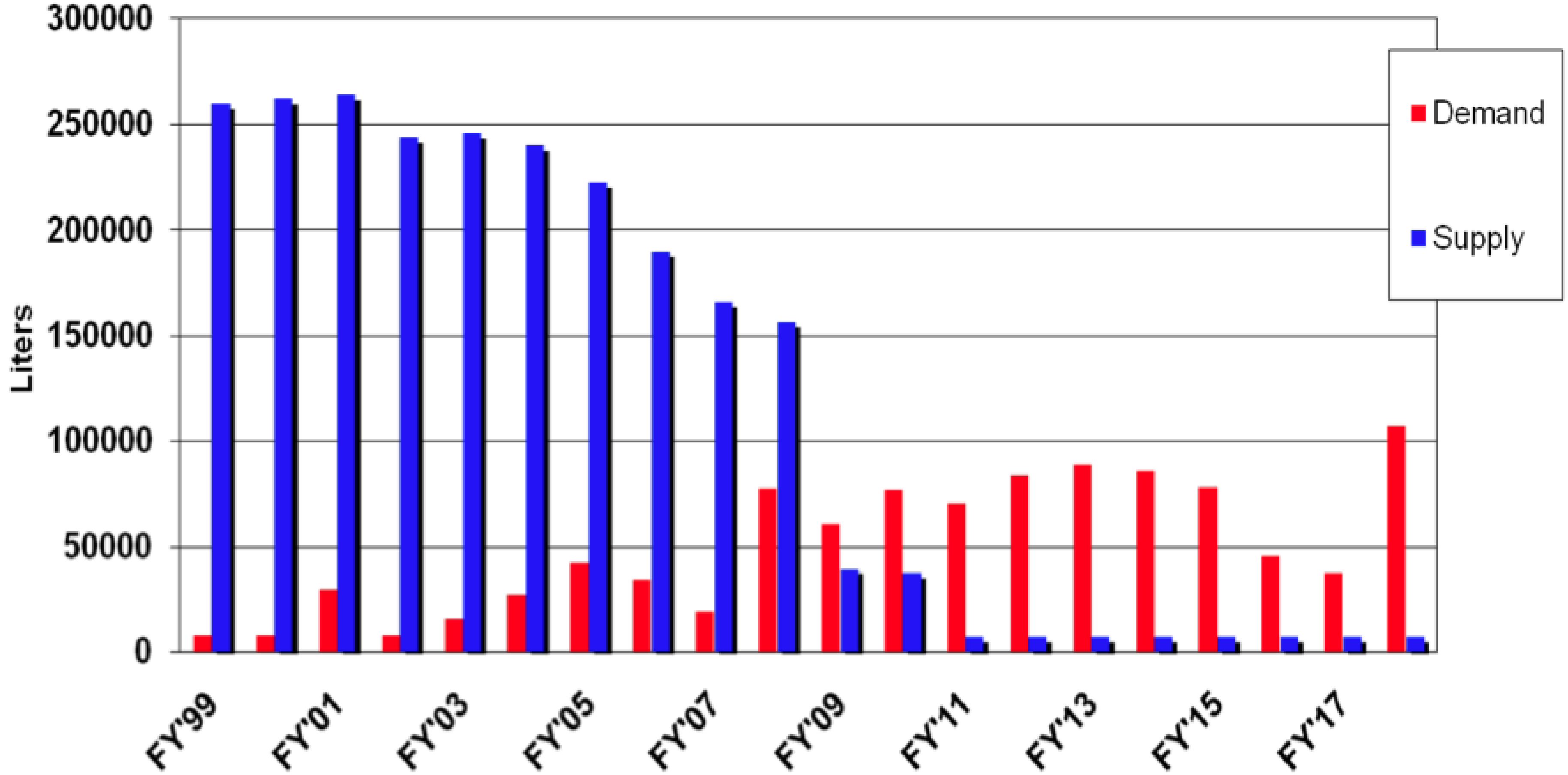
Upcoming Research Facilities

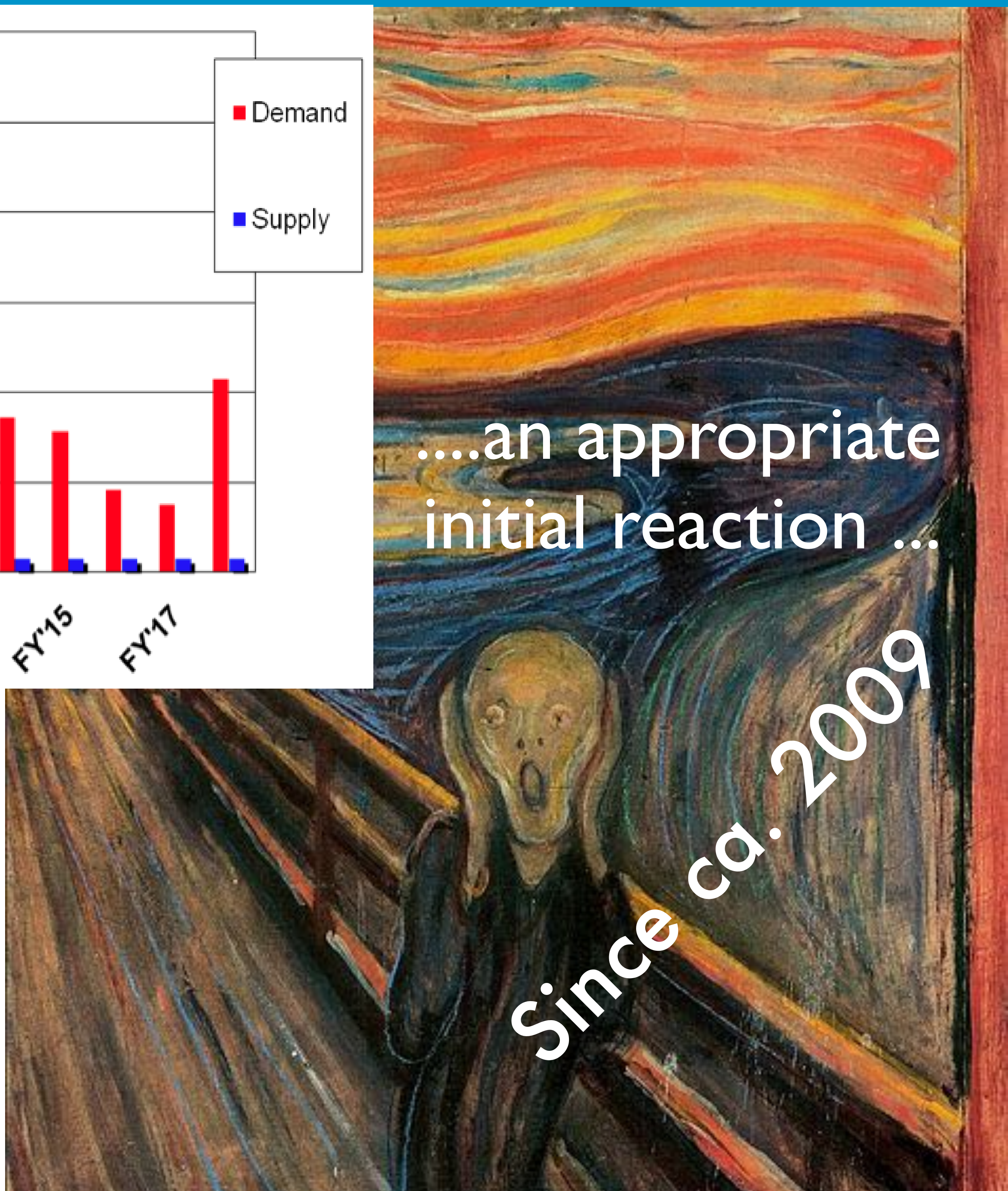


New facilities needed to:
- **replace capacity from closing research reactors**
- **enhance capability to enable new science**

Several other future facilities being considered

Helium-3 Crisis





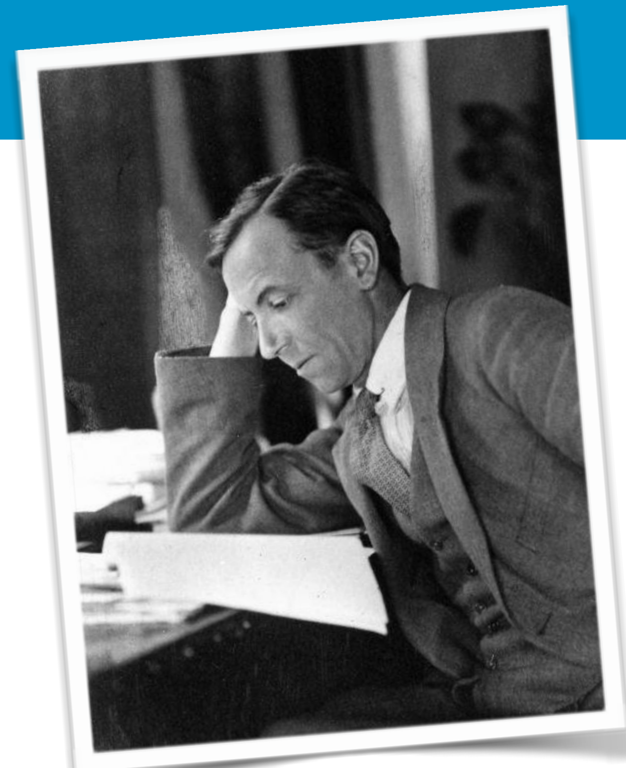
Comment: seems to be some naivety at the moment as stocks are being emptied rapidly

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

Crisis or opportunity ... ?

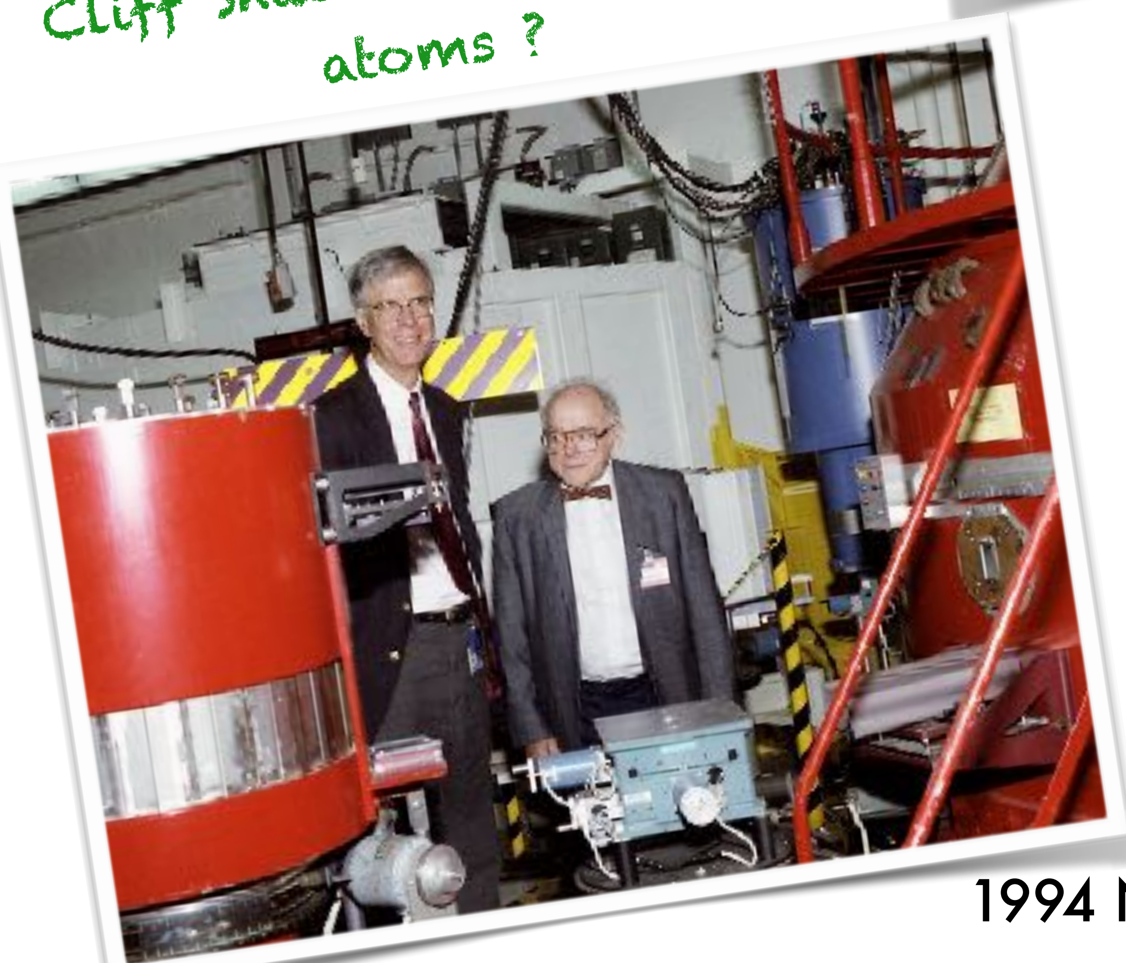
What is Neutron Scattering Science?

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

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Applications of Neutron Science

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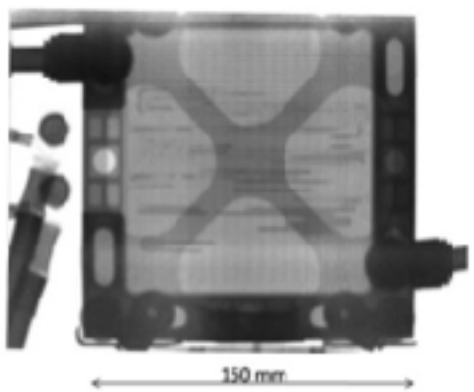
Charge neutral

Deeply penetrating

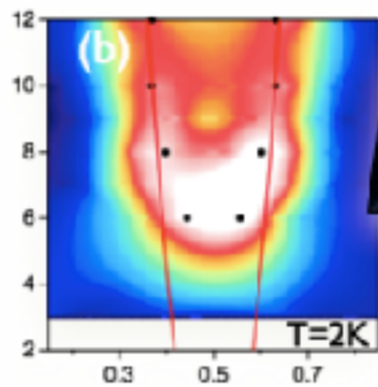


Li motion in fuel cells

Help build electric cars

S=1/2 spin

Directly probe magnetism

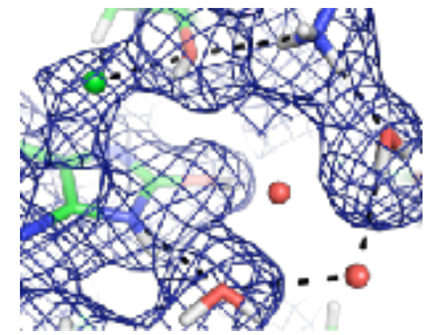


Solve the puzzle of High-Tc superconductivity

Efficient high speed trains

Nuclear scattering

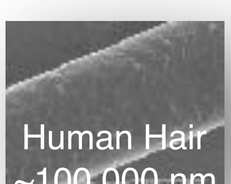
Sensitive to light elements and isotopes

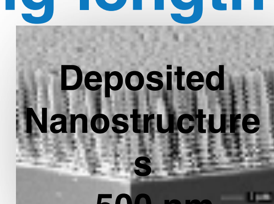


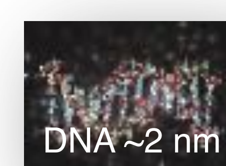
Active sites in proteins

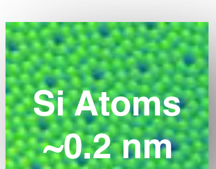
Better drugs

Probing length scales and dynamics

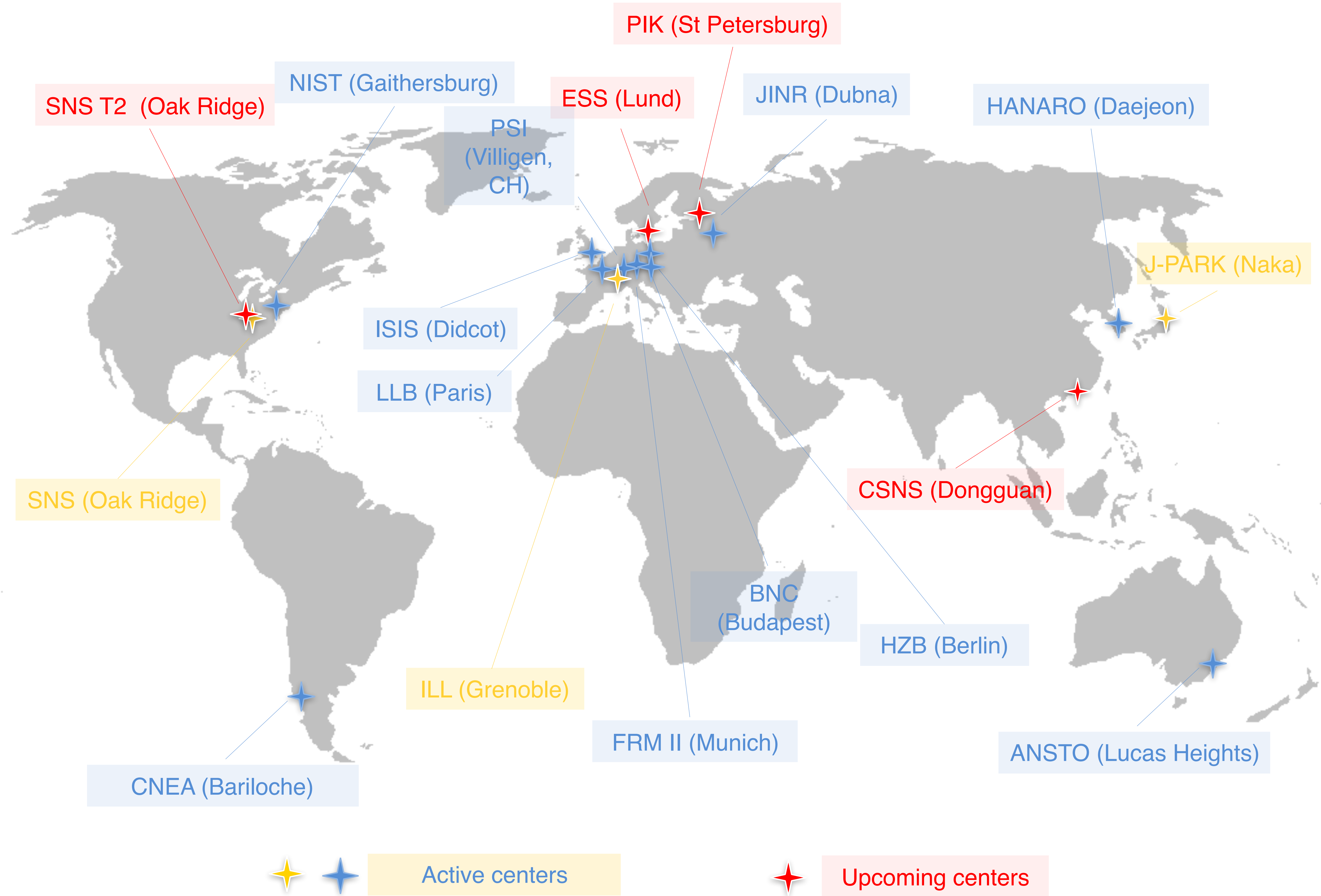






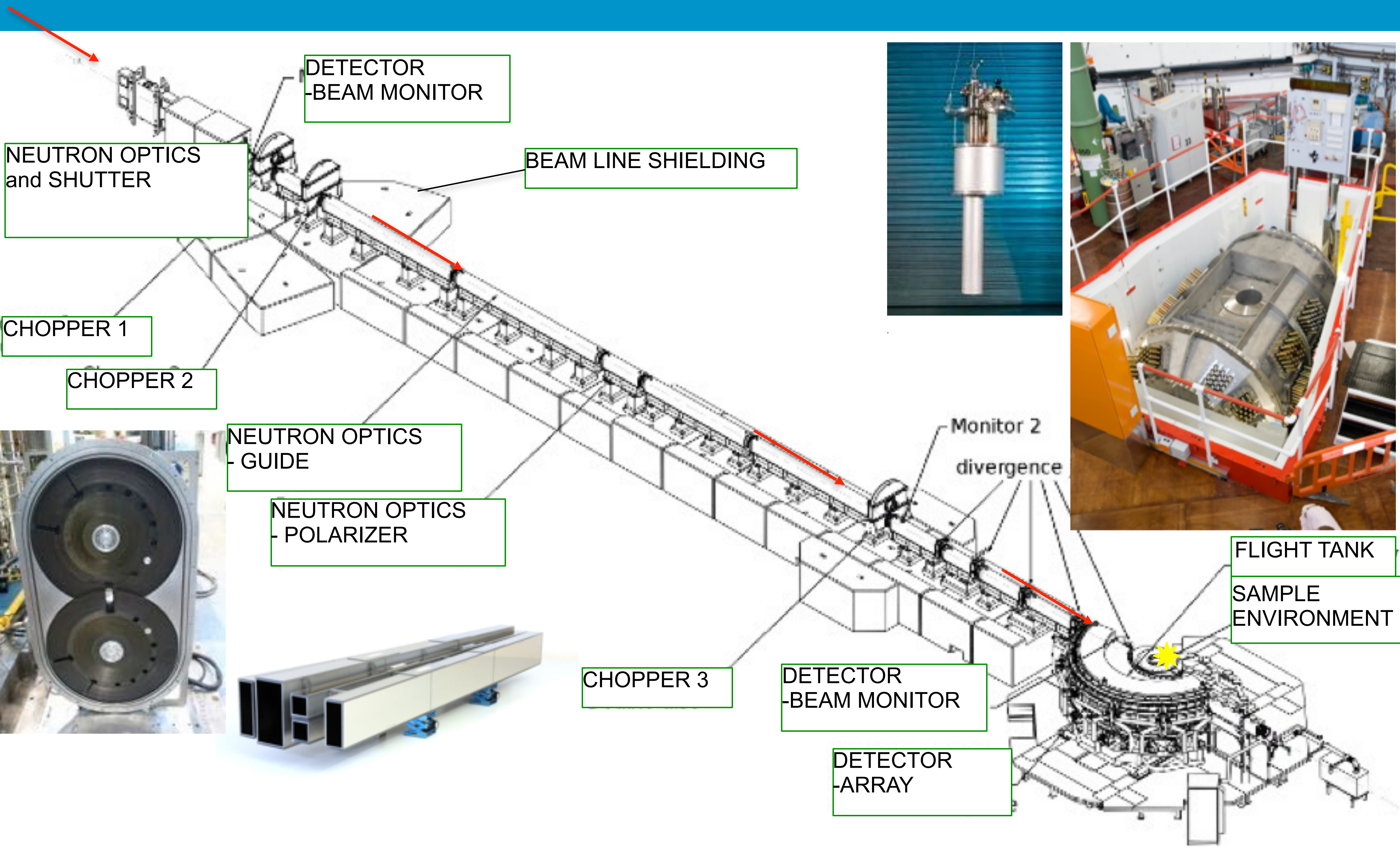


Present and Future of Neutron Research Facilities



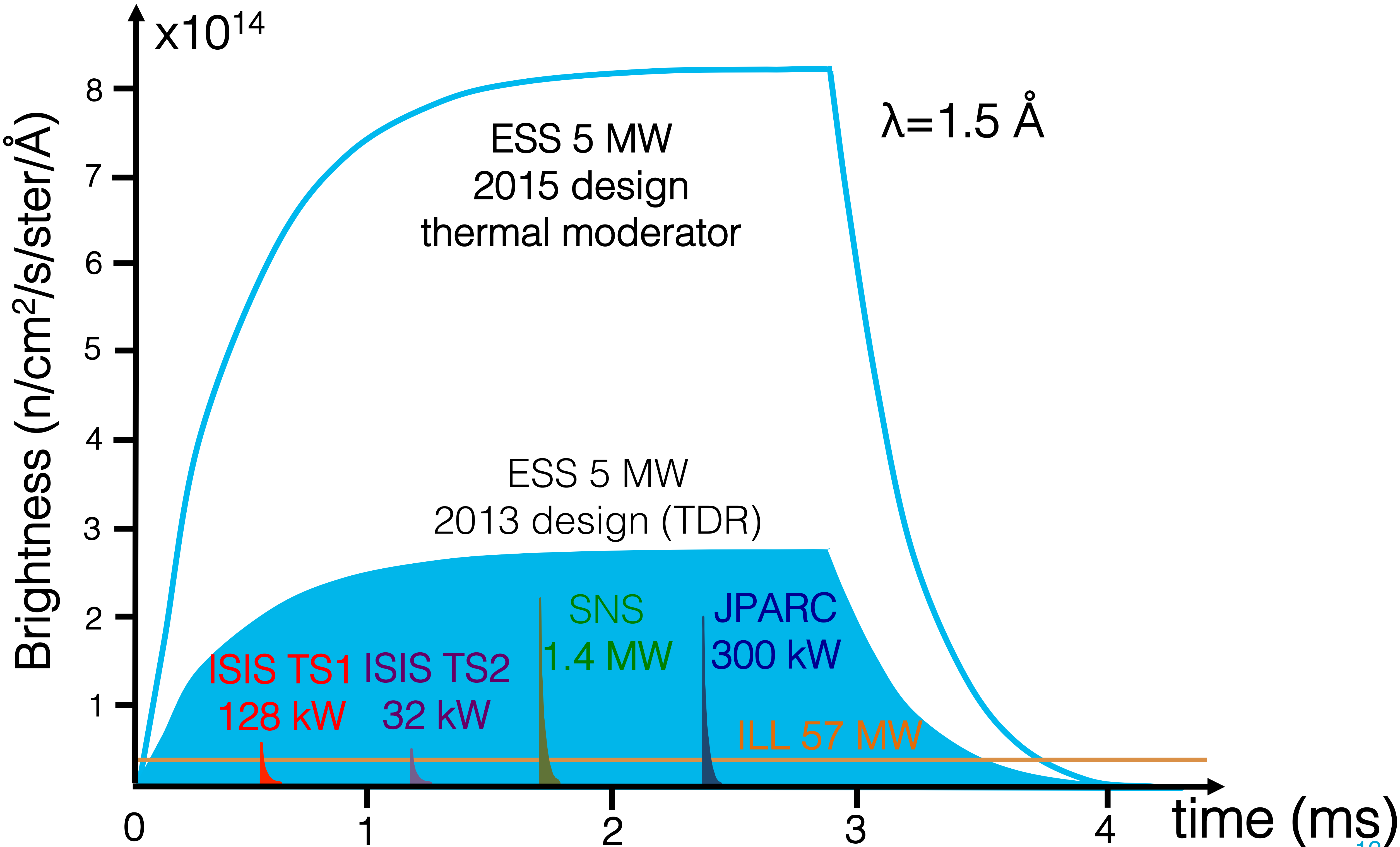
… AND THESE ARE ONLY 18 OF THE ALMOST 50 NEUTRON RESEARCH FACILITIES WORLDWIDE

Layout of a Neutron Instrument



Challenges

Challenge for Rate



What can be done with this brightness

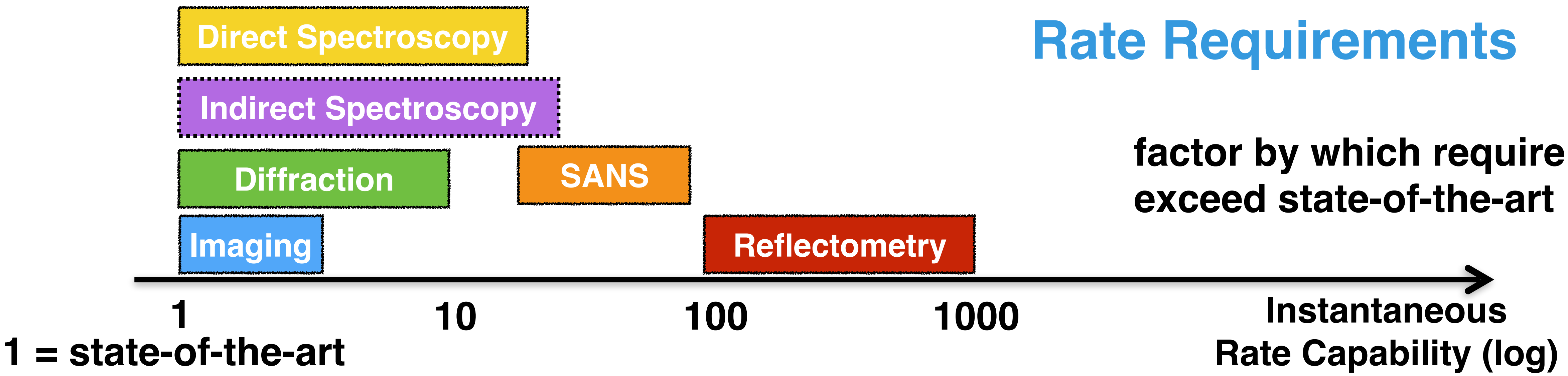
Instrument Design	Implications for Detectors
Smaller samples	Better Resolution (position and time) Channel count
Higher flux, shorter experiments	Rate capability and data volume
More detailed studies	Lower background, lower S:B Larger dynamic range
Multiple methods on 1 instrument Larger solid angle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

Also: scarcity of Helium-3 ….

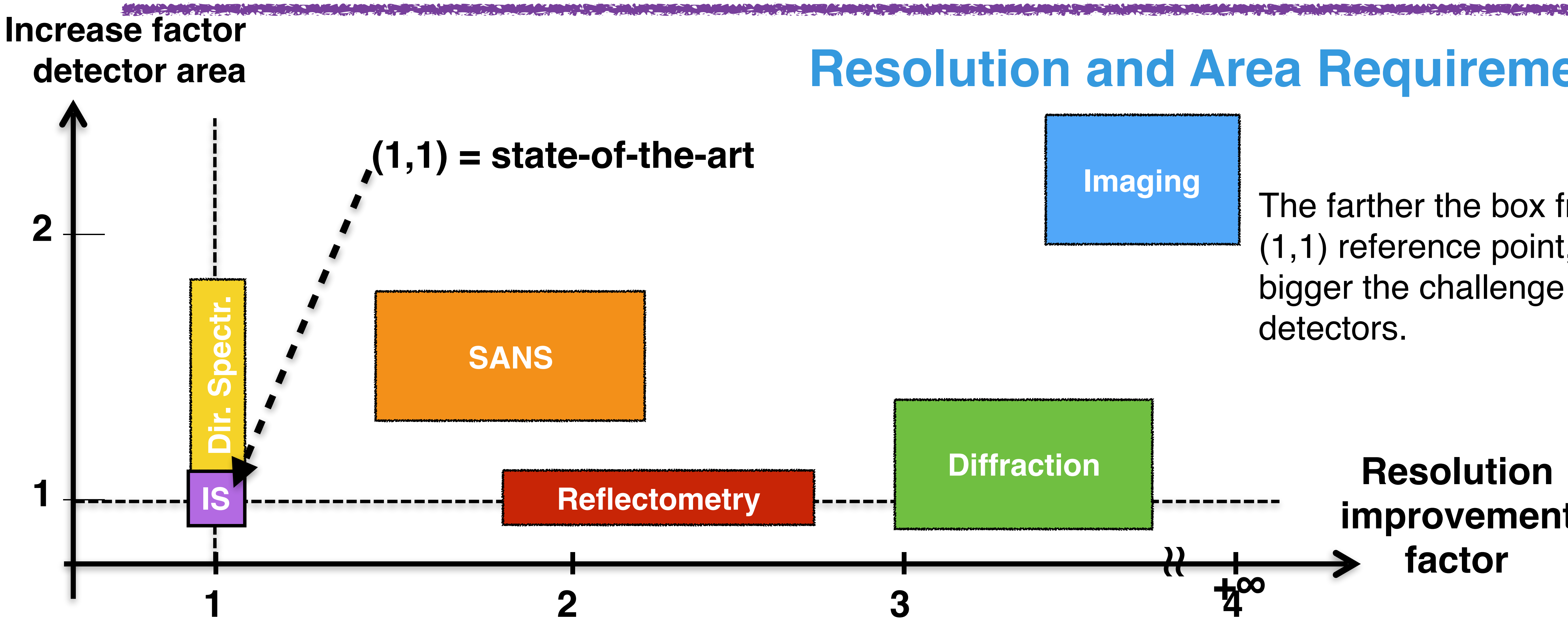
Developments required for detectors for new Instruments

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

Rate Requirements



Resolution and Area Requirements

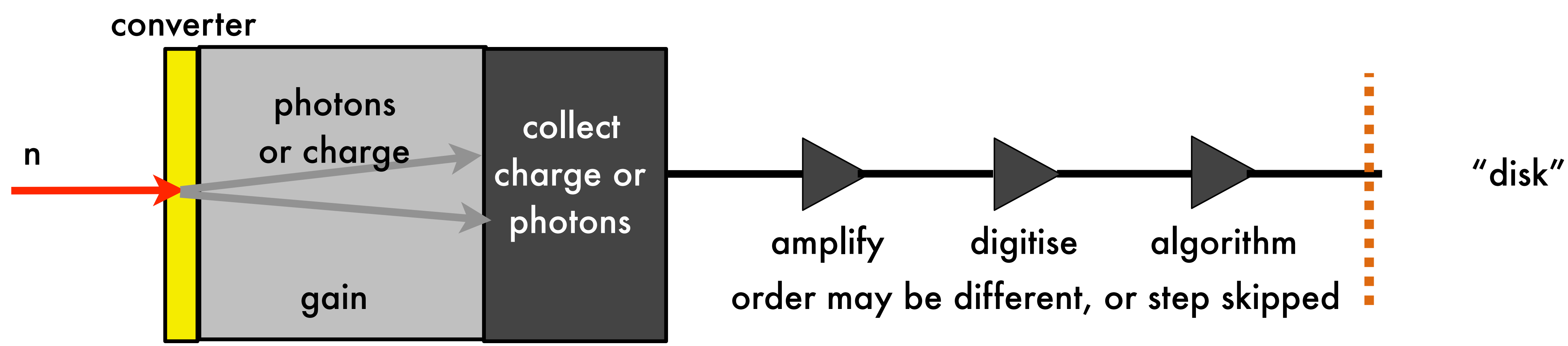


The farther the box from the (1,1) reference point, the bigger the challenge for detectors.

Detectors

Neutron Detectors

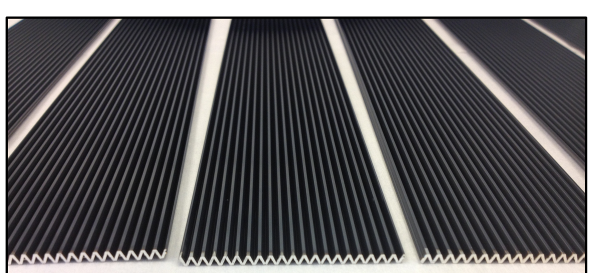
Efficient neutron converters a key component for neutron detectors



"Converter"

"Detector"

"Electronics"



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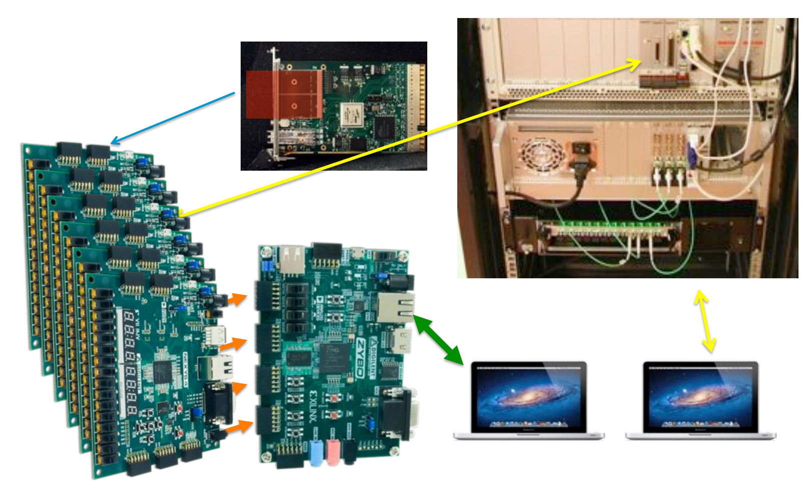


Isotopes Suitable as Cold and Thermal Neutron Convertors

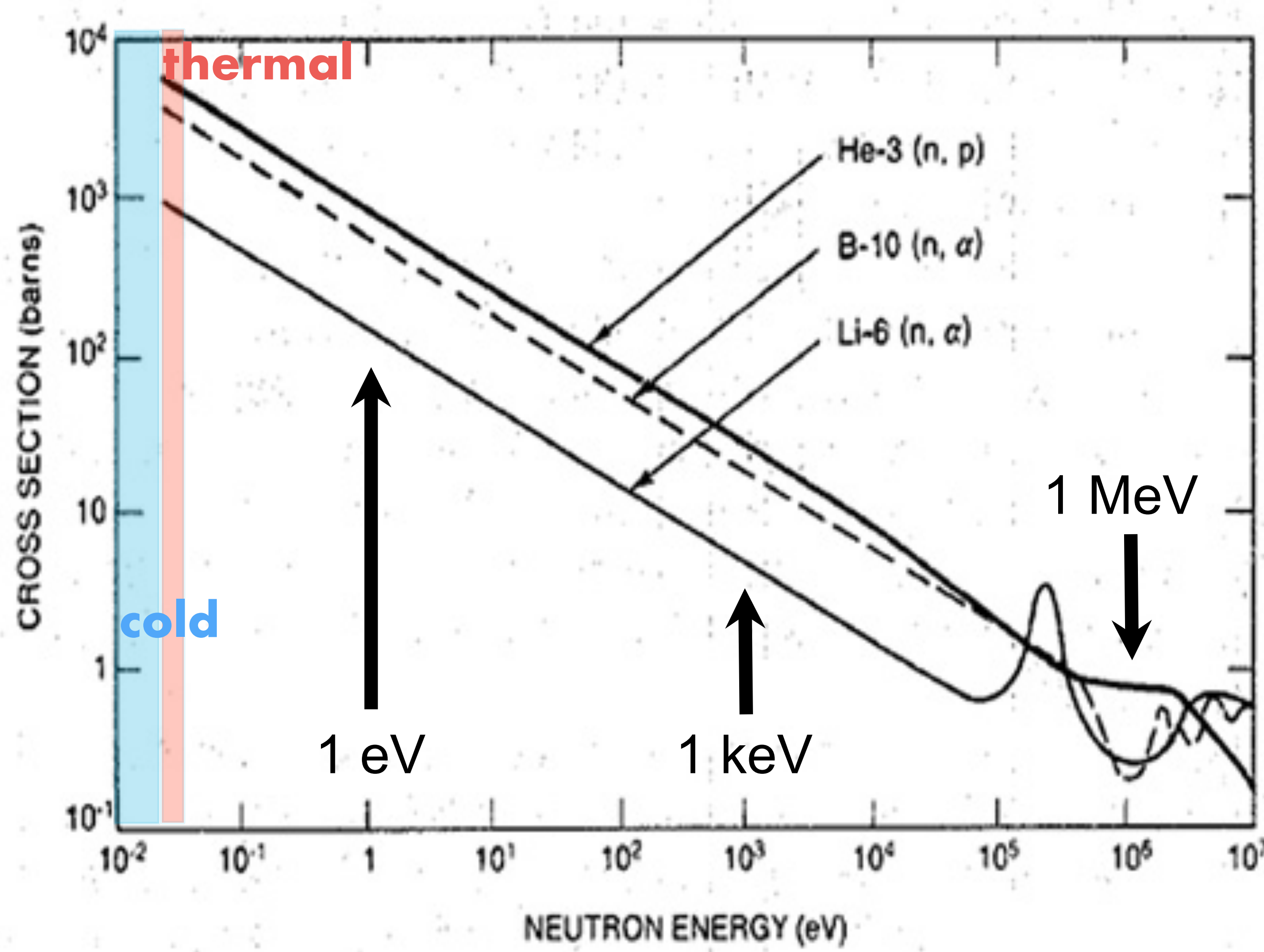
reaction	energy	particle	energy	particle	energy
n (^{3}He, p) ^{3}H	+0.77 MeV	p	0.57 MeV	^{3}H	0.19 MeV
n (^{6}Li, α) ^{3}H	+4.79 MeV	α	2.05 MeV	^{3}H	2.74 MeV
93 % n (^{10}B, α)^{7}Li +2.3 MeV + γ (0.48MeV)		α	1.47 MeV	^{7}Li	0.83 MeV
7 % n (^{10}B, α) ^{7}Li	+2.79 MeV	α	1.77 MeV	^{7}Li	1.01 MeV
n (^{235}U, 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.

- 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



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State of the Art of Neutron Detectors

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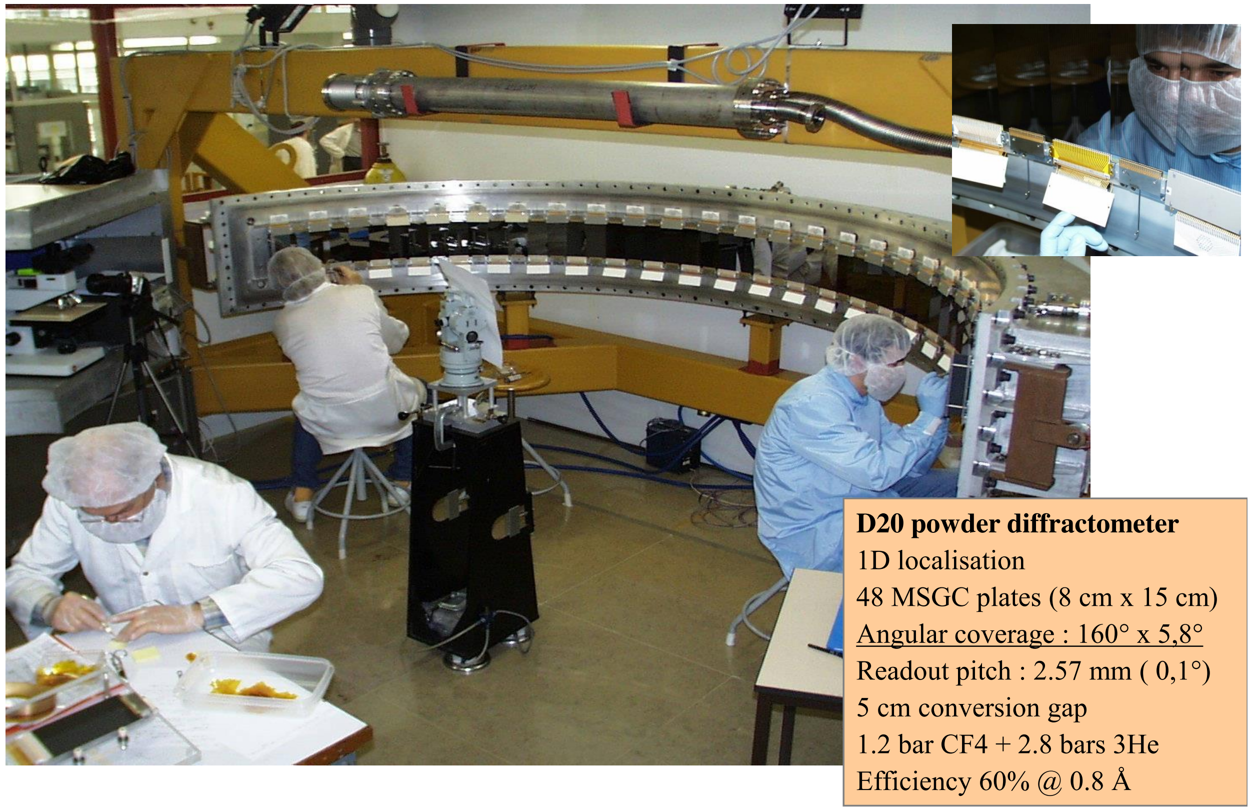
- Helium-3 Tubes most common
- Typically 3-20 bar Helium-3
- 8mm-50mm diameter common
- Using a resistive wire, position resolution along the wire of ca. 1% possible

NEUTRONS FOR SCIENCE

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



- 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

^{10}Boron-based Thin Film Gaseous Detectors

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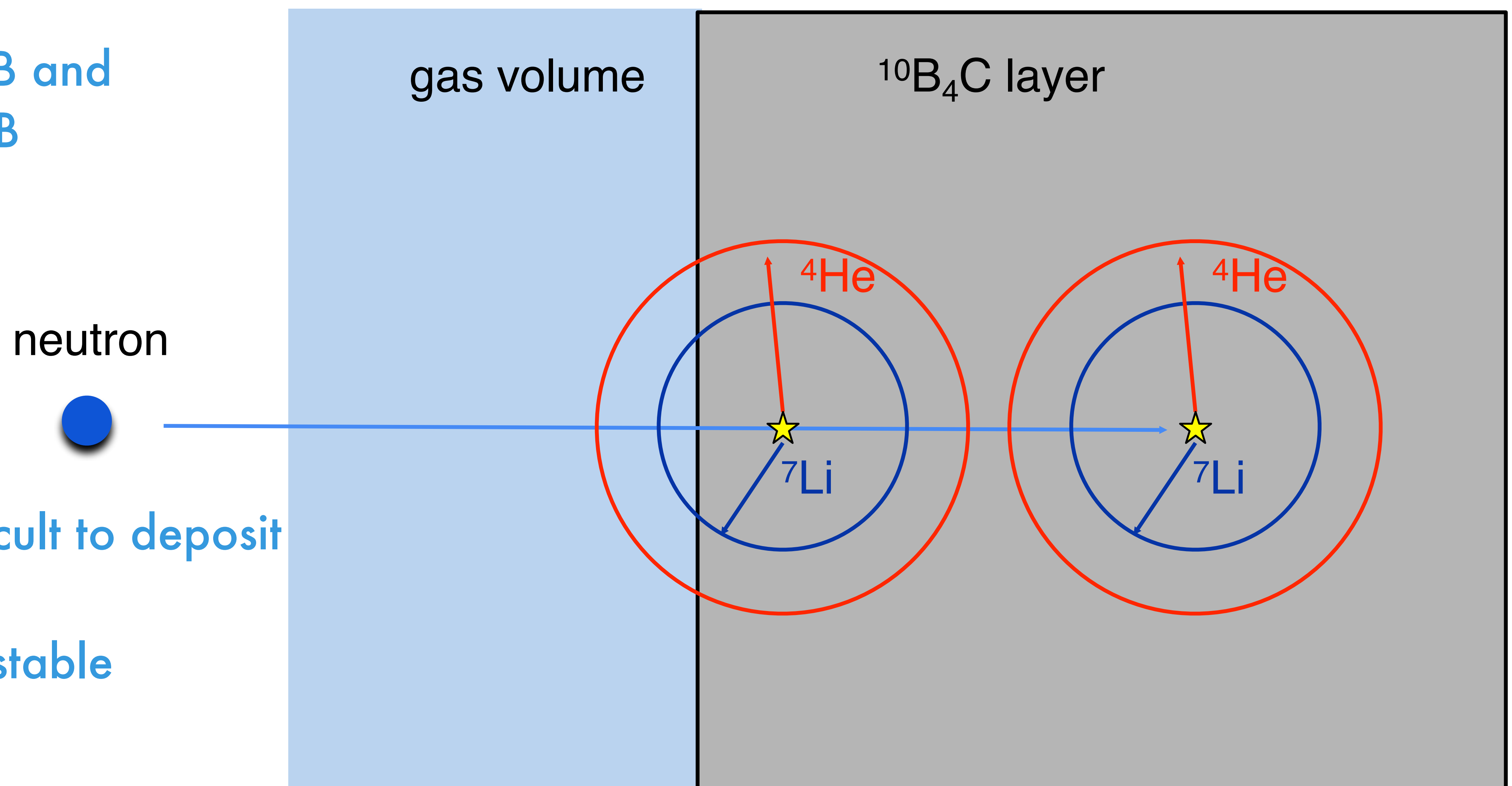
European Spallation Source (ess)

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

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

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$^{10}B_4C$ Thin Film Coatings

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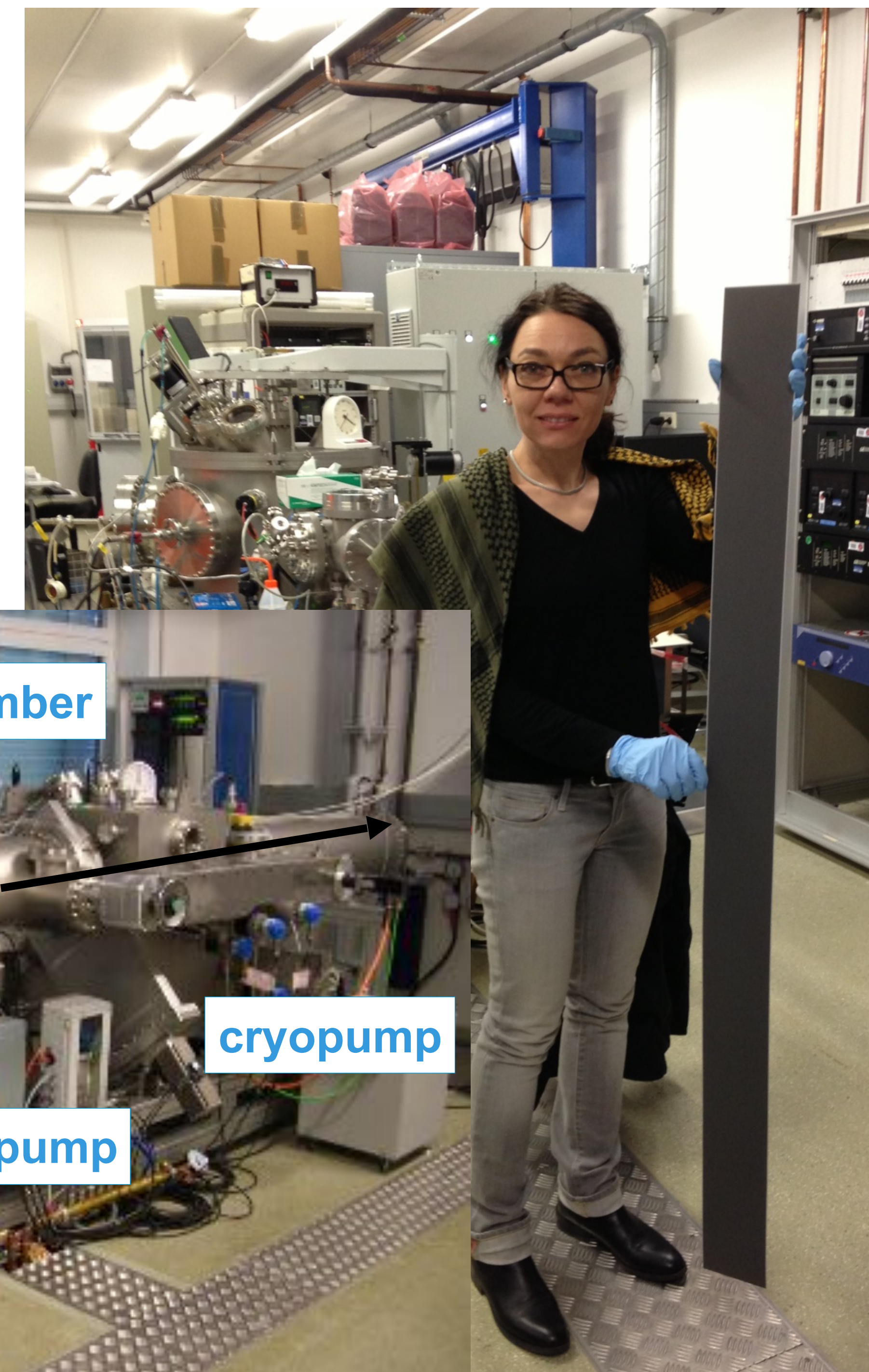
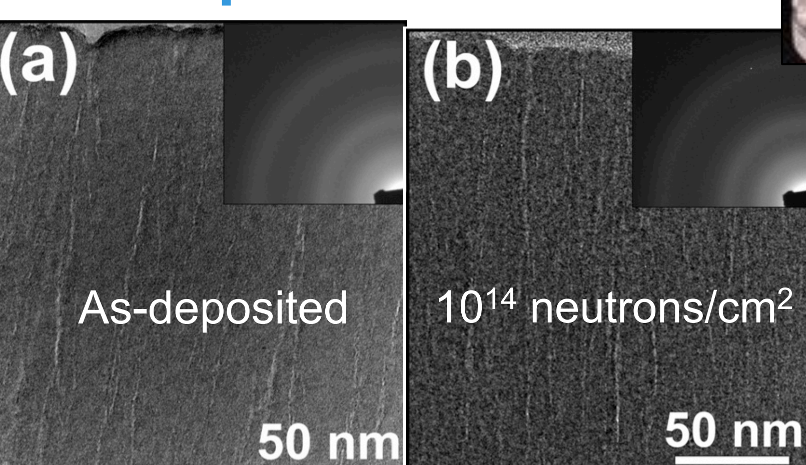
SOLVED

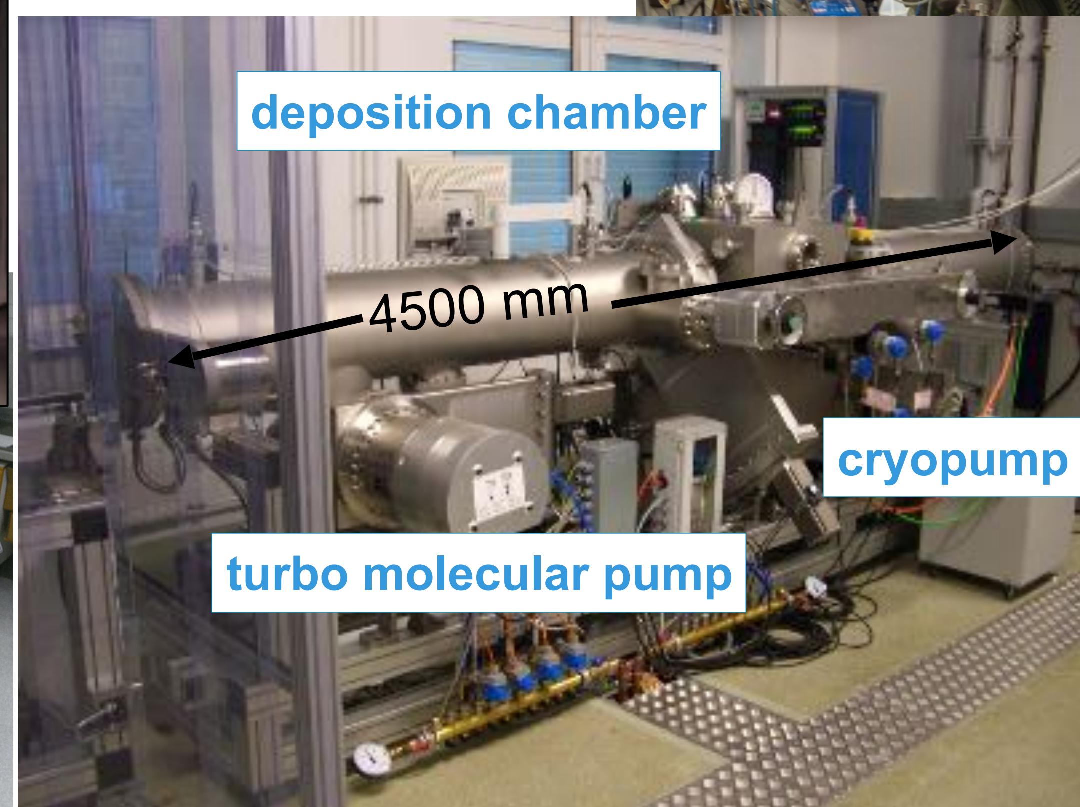
- A number of groups have shown it is possible to deposit large areas of high quality Boron Carbide cheaply
- PVD Magnetron Sputtering
- Deposition parameters highly adaptable
- A very interdisciplinary effort

Helmholtz-Zentrum Geesthacht
Centre for Materials and Coastal Research



- ESS-Linkoping Deposition Facility
- Industrial Coating Machine
- Capacity: >1000m²/year coated with $^{10}B_4C$
- **Cheap**





ESS Thin Films Workshop

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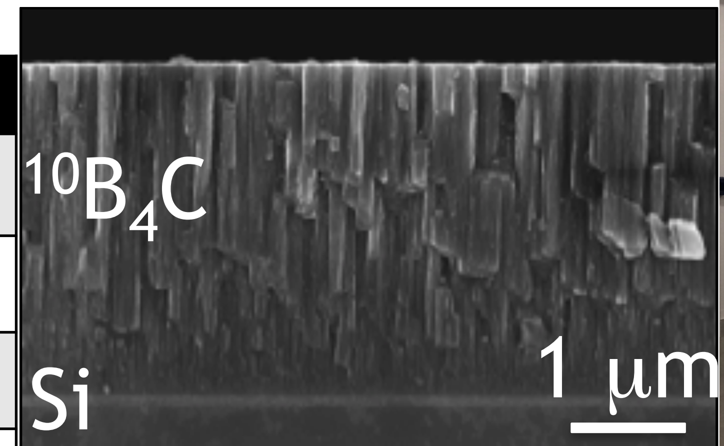
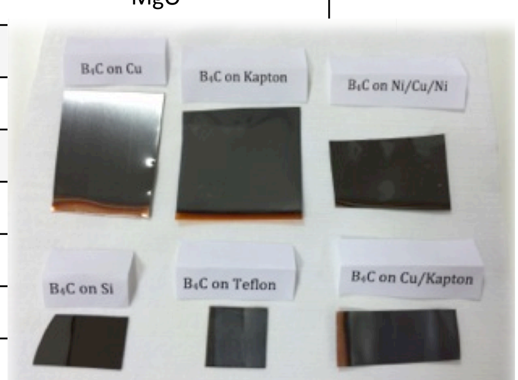
- Co-located w/ Linkoping University for synergies: expertise&facilities
- Industrial coatings machine and production line setup
- Capacity: several times ESS needs
- If interested in coatings: contact us

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	☺



- 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

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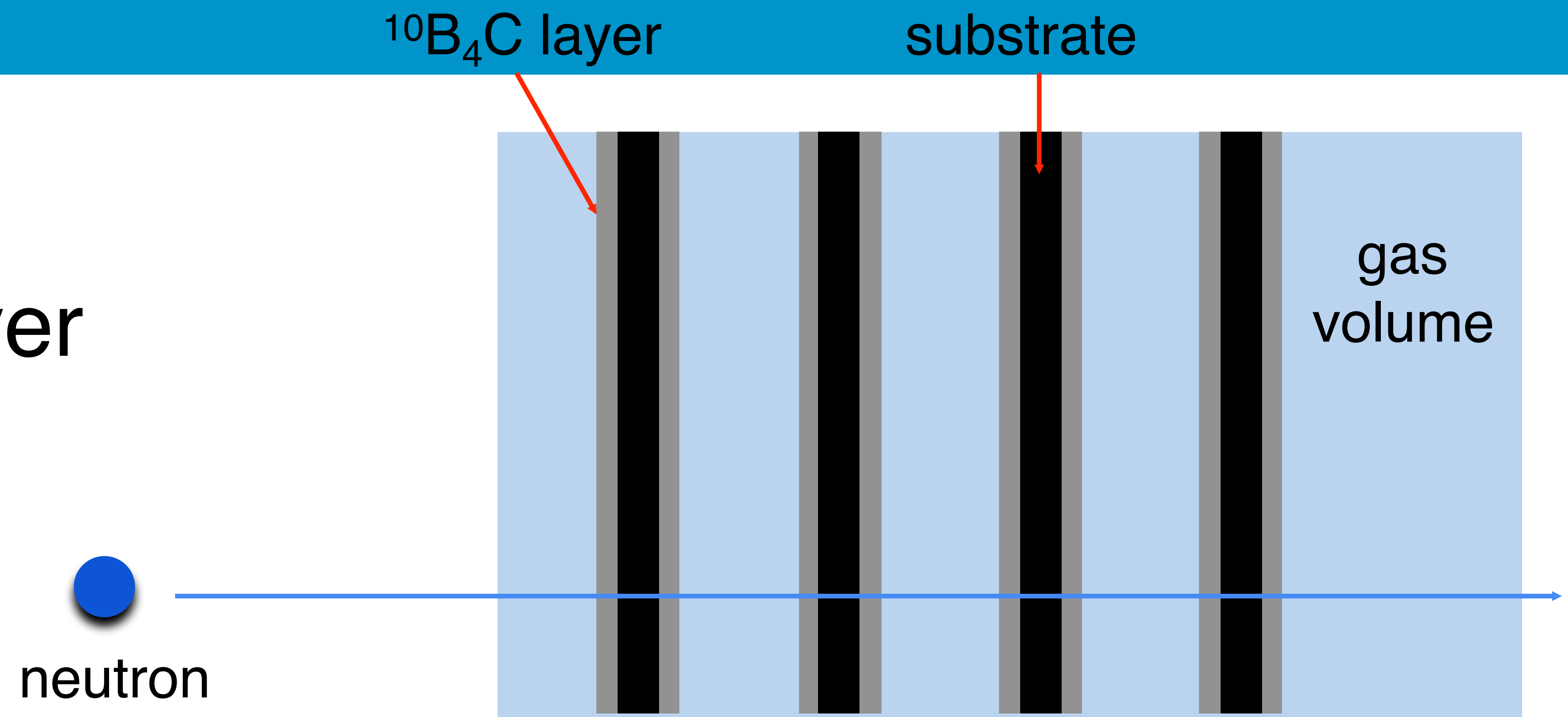
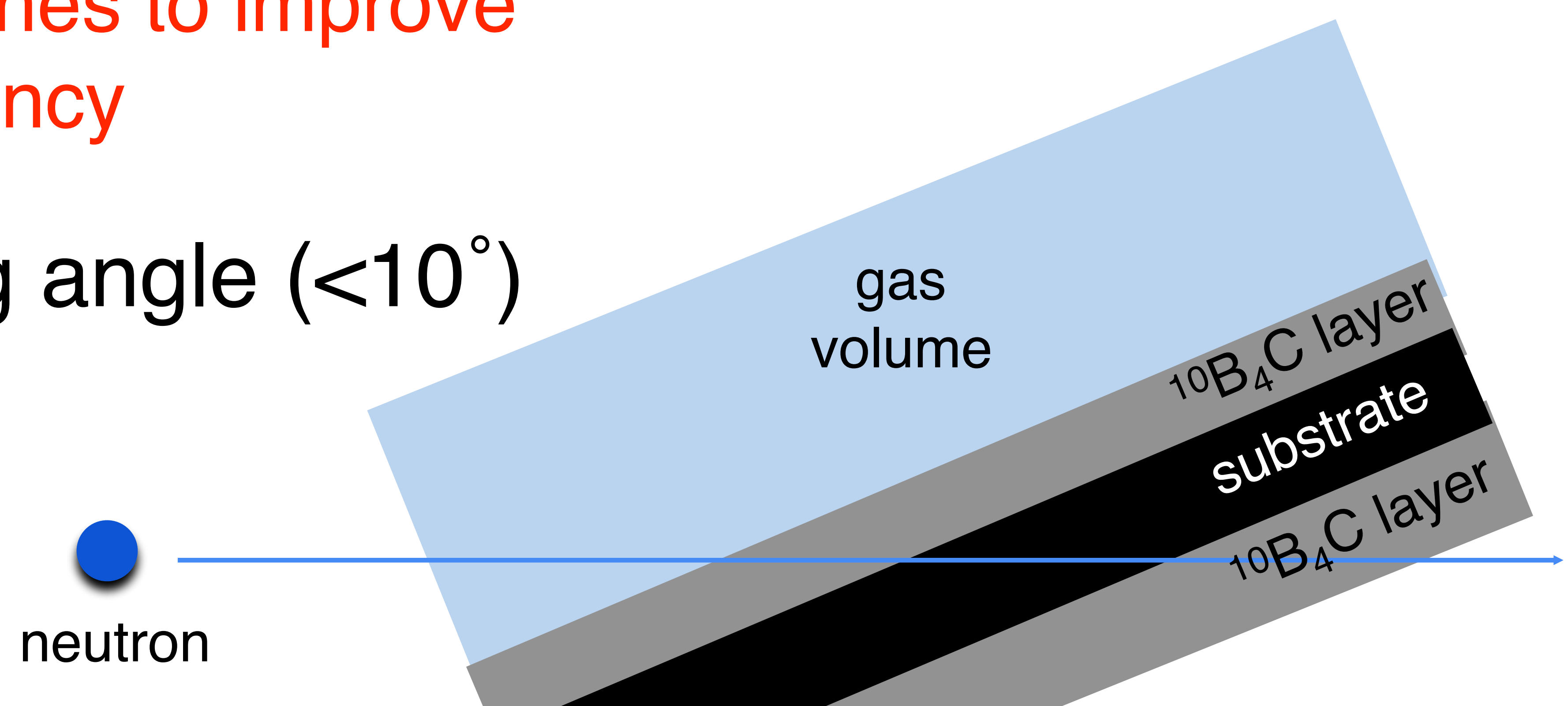
European Spallation Source

Generic approaches to improve efficiency

1. Multi layer



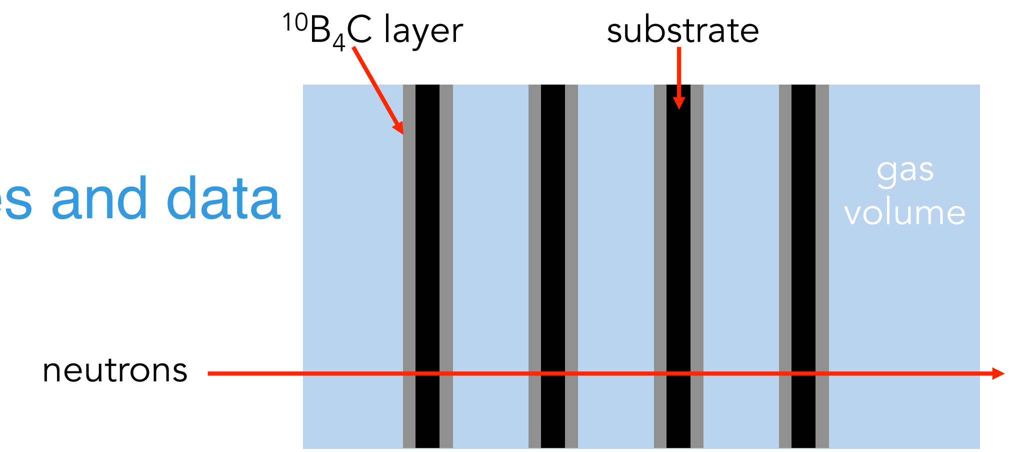
2. Grazing angle (<10˚)



Efficiency of ^{10}B Detectors: Perpendicular Geometry

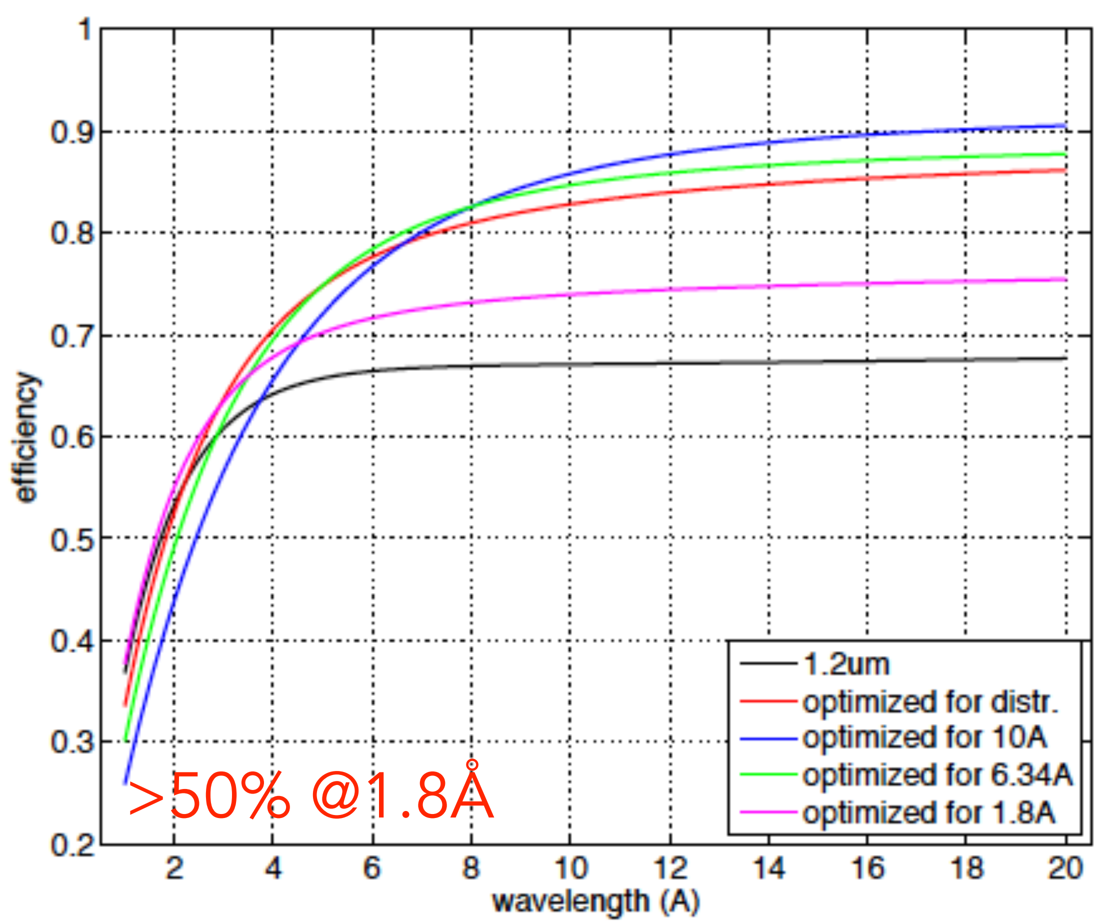
- Single layer is only ca.5%
- Calculations done by many groups
- Analytical calculations extensively verified with prototypes and data
- Details matter: just like for ^{3}He

- Multilayer configuration (example):

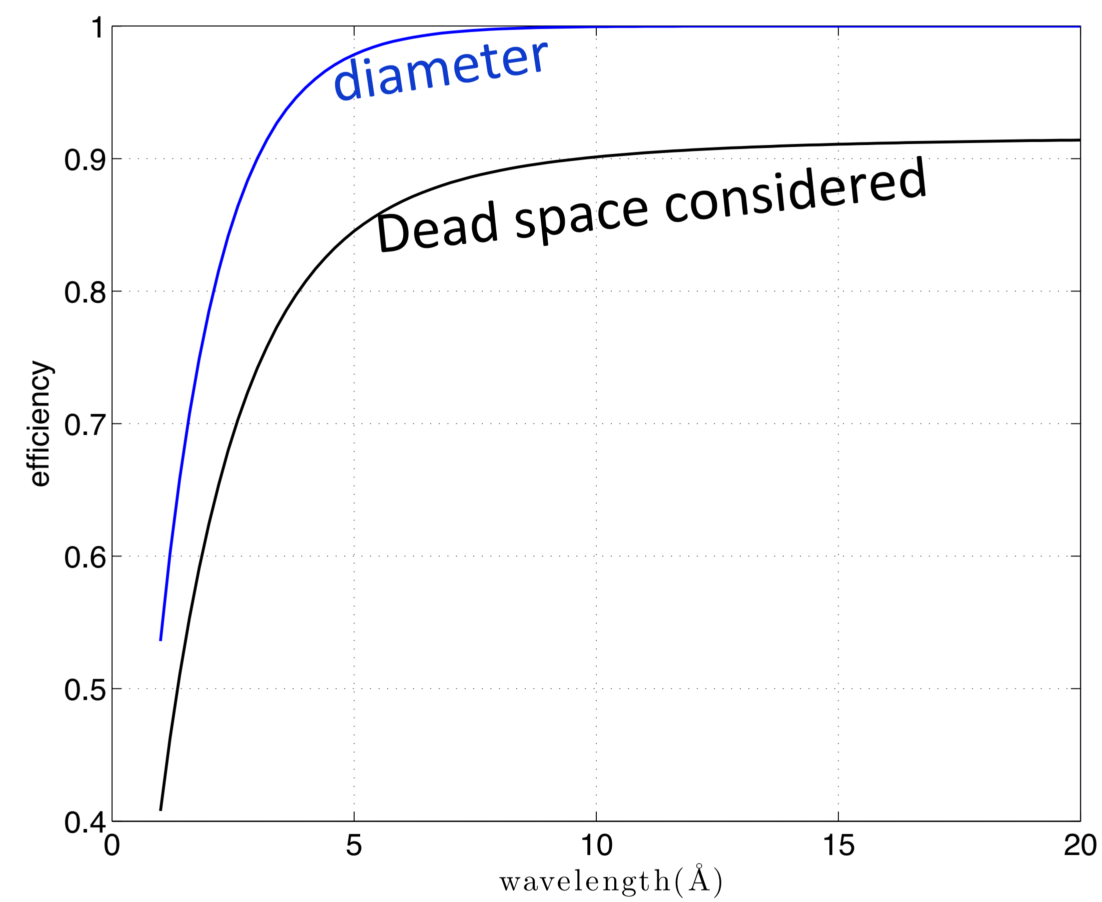


JINST 8 (2013) P04020

Multi-Grid

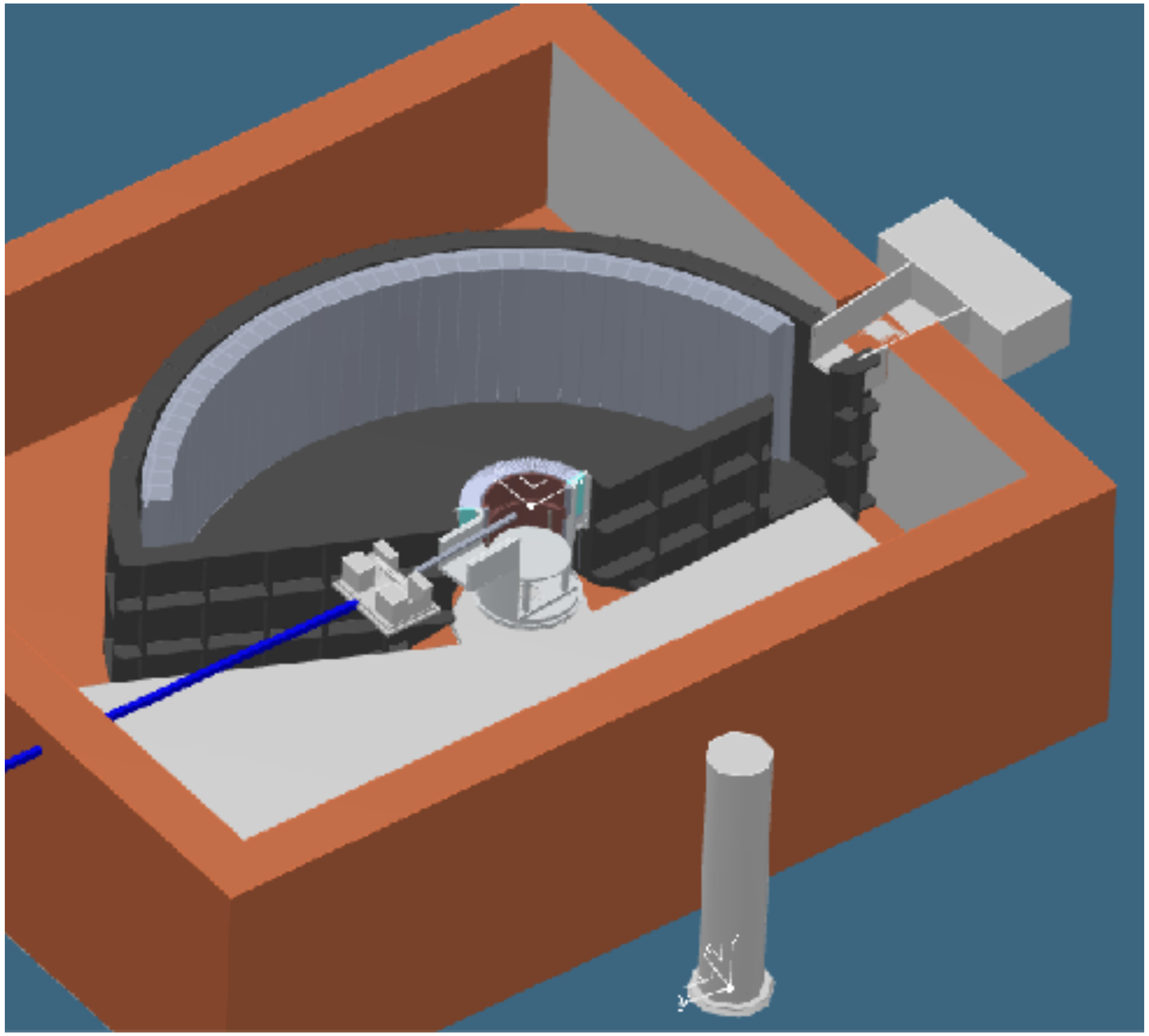


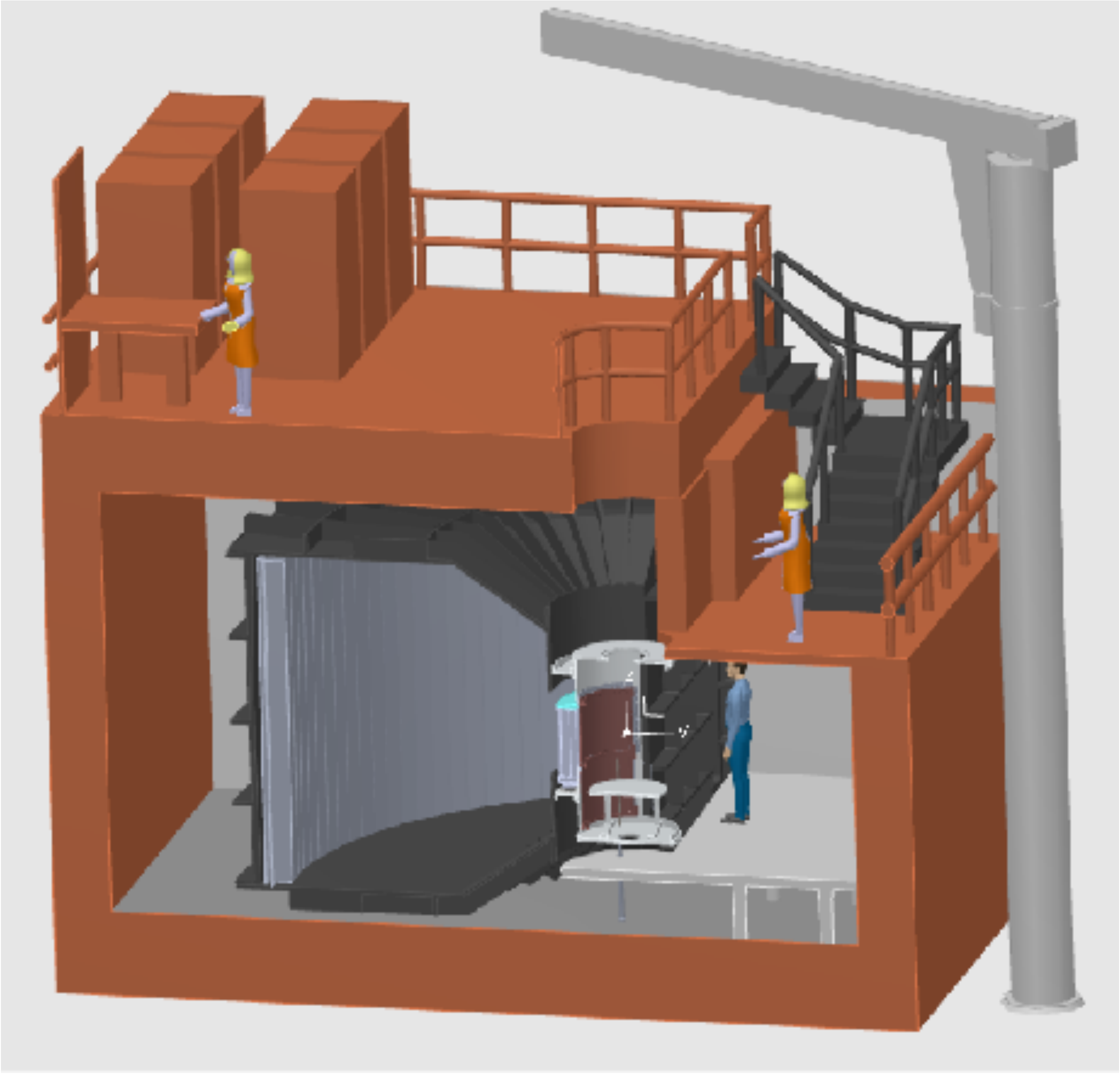
^{3}He tubes – 1 inch – 4.75 bar



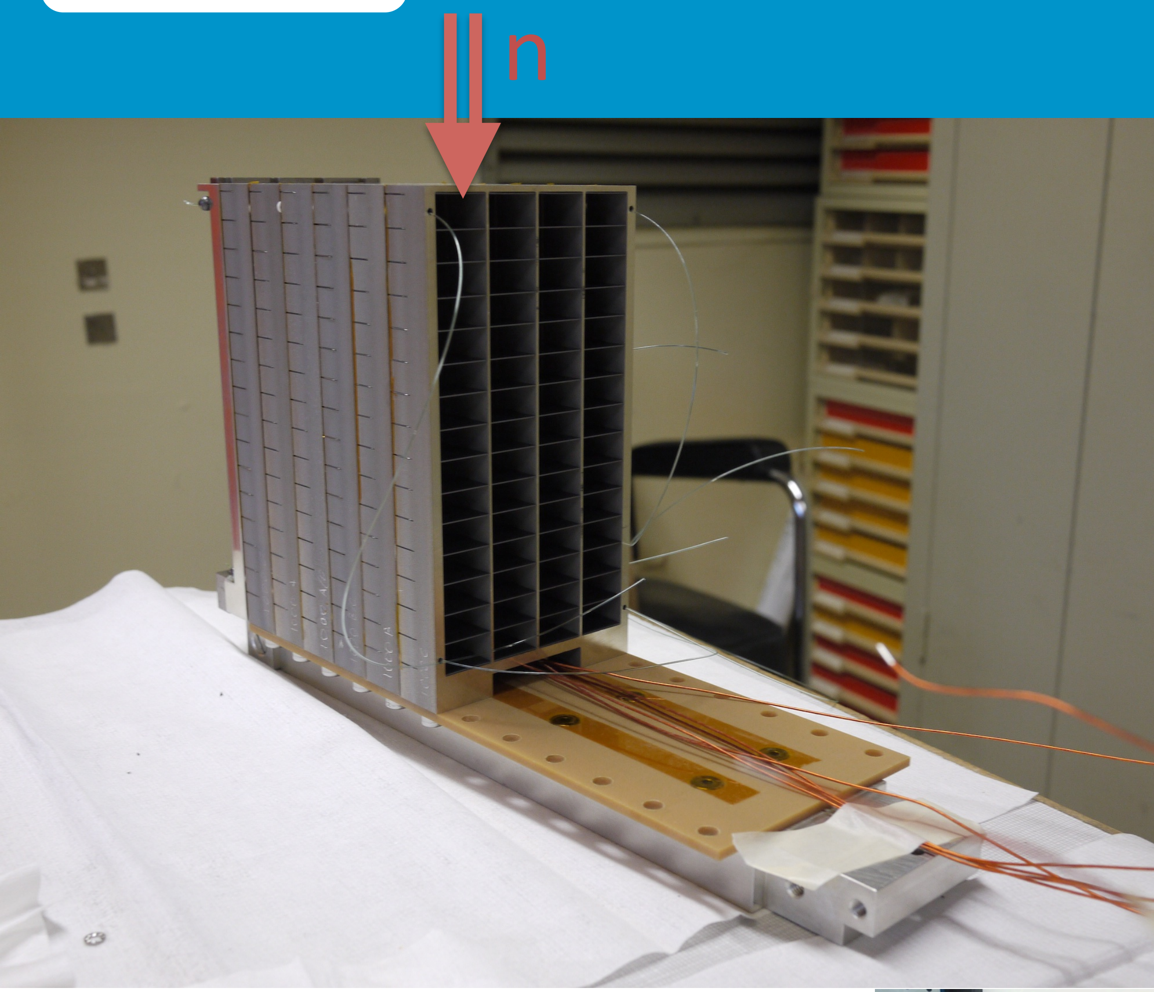
CSPEC at ESS

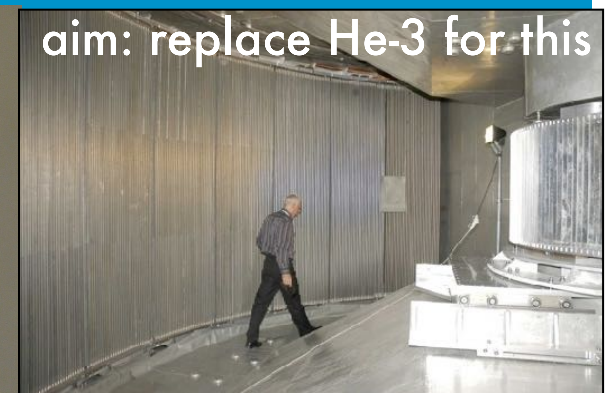
Cold direct geometry chopper spectrometer
0.2 meV < E_i < 20 meV
29m² detector
Horizontal coverage 5° to 135°
Vertical coverage -25° to 25°



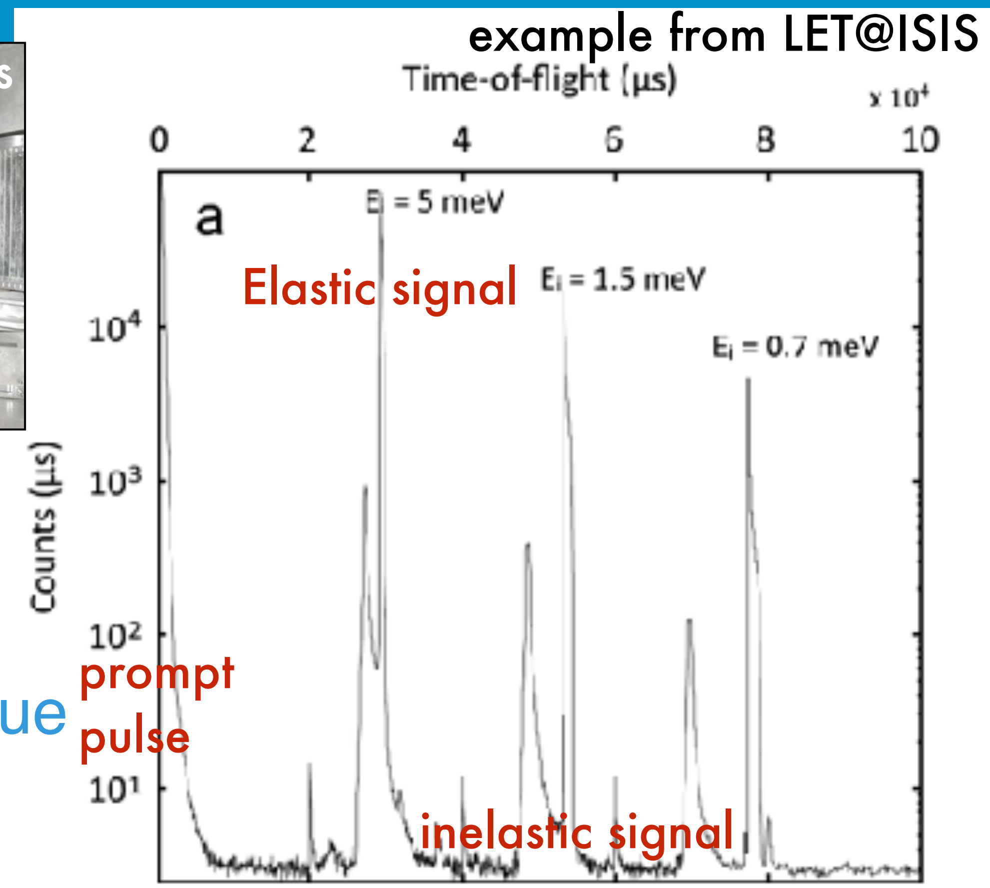


Multi-Grid Detector Design

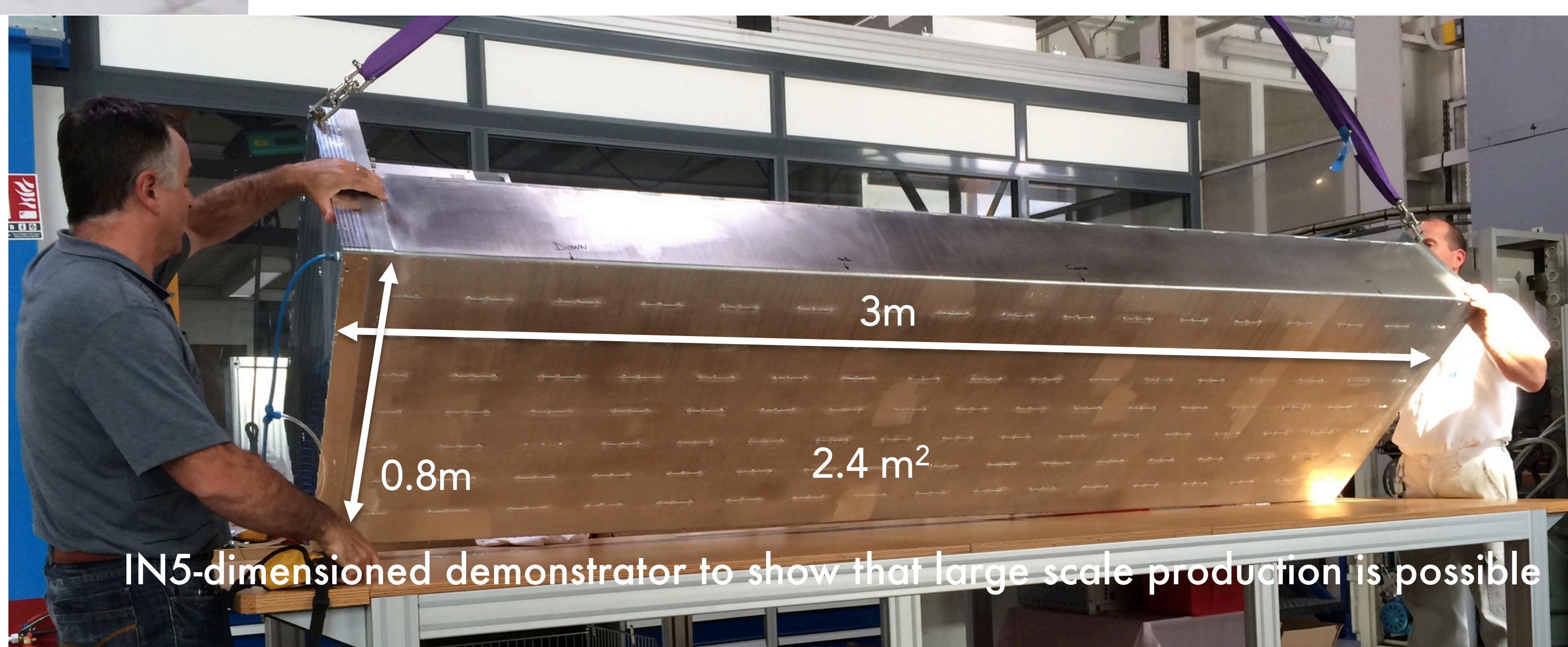




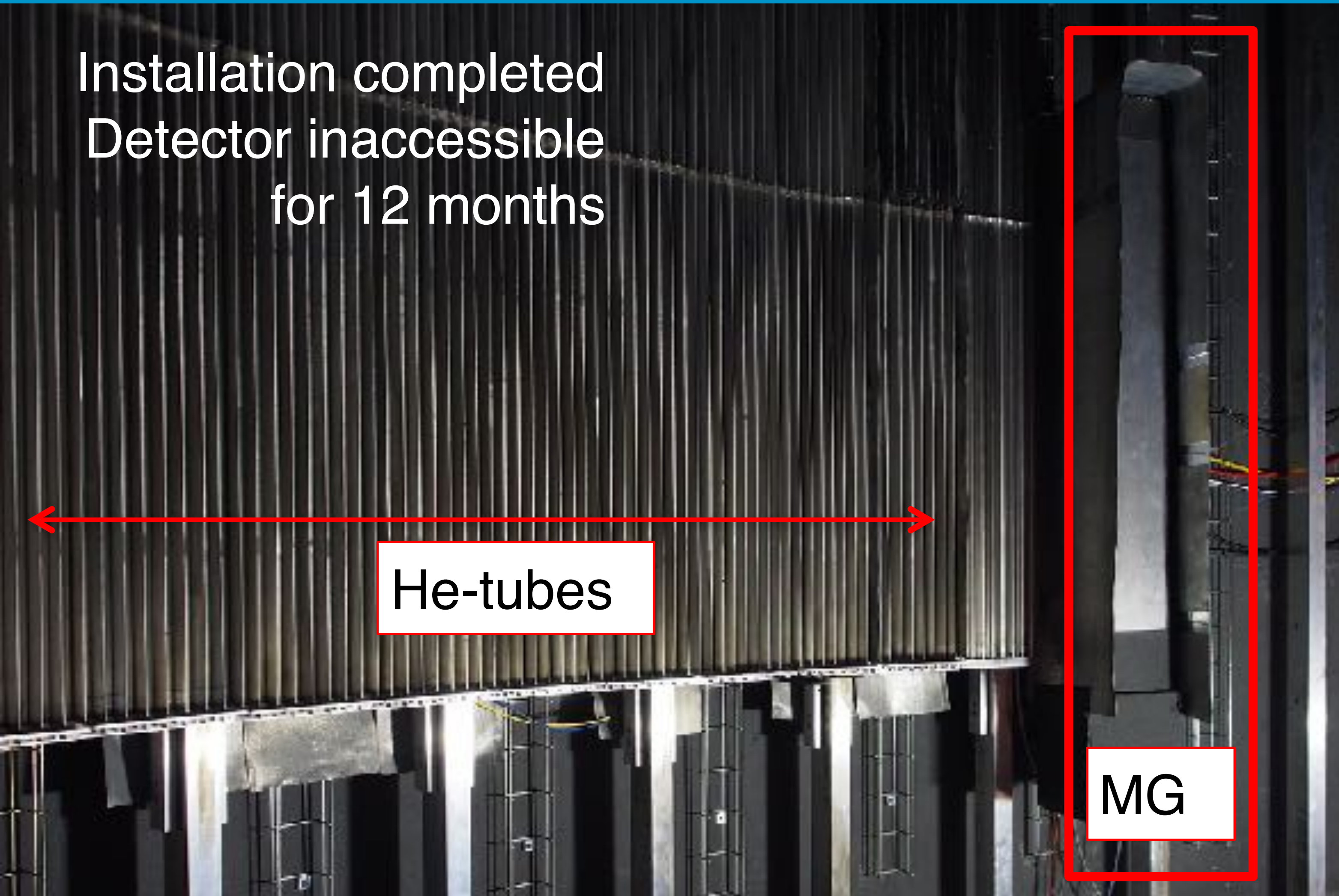
- Very background sensitive technique



- Designed as replacement for He-3 tubes for largest area detectors
- Cheap and modular design
- Possible to build large area detectors again
- 20-50m² envisaged for ESS



Multi-Grid test at CNCS



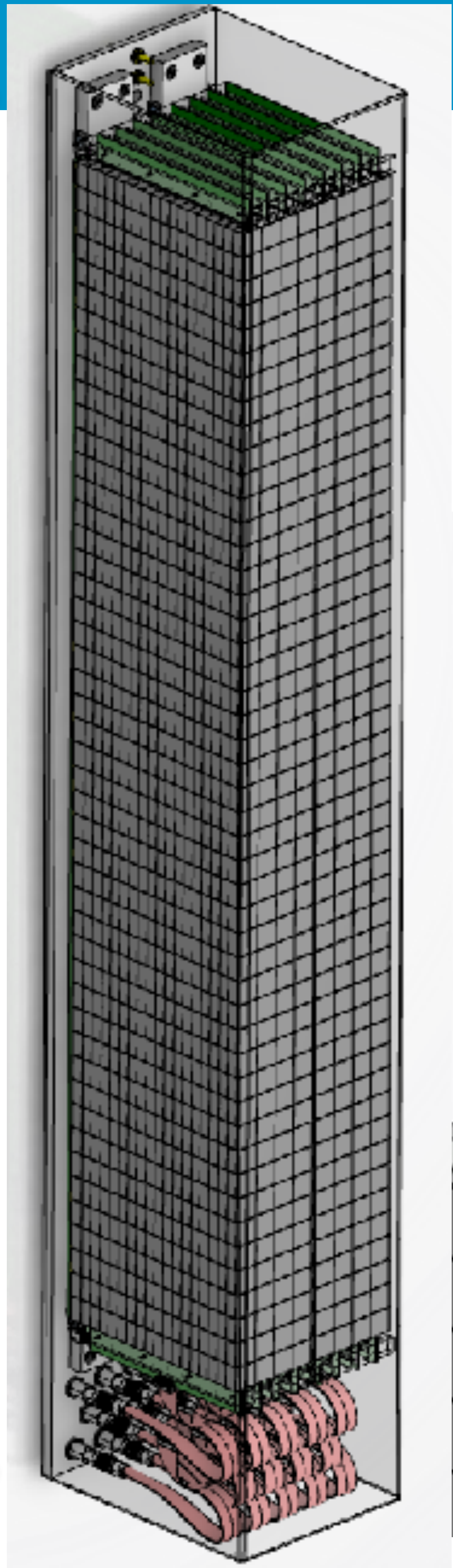
B10 Multi-Grid Detector
Performance is equivalent
to that of He-3 detectors

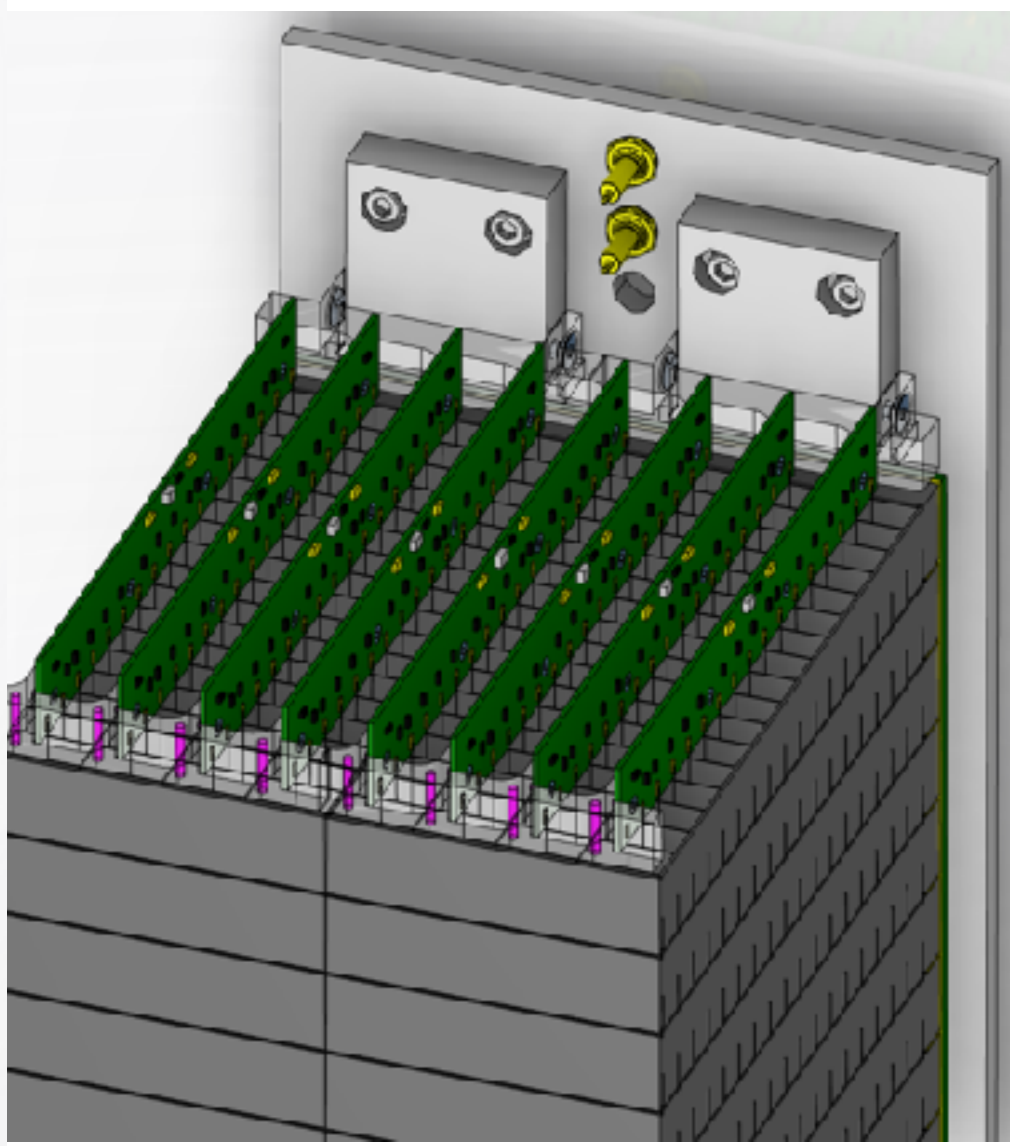
A.Khaplanov et al. *"Multi-Grid Detector for Neutron Spectroscopy: Results Obtained on Time-of-Flight Spectrometer CNCS"* https://arxiv.org/abs/1703.03626
2017 JINST 12 P04030

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

Construction of MG.CNCS in Lund

1.1m





Operation since 2016-07-14

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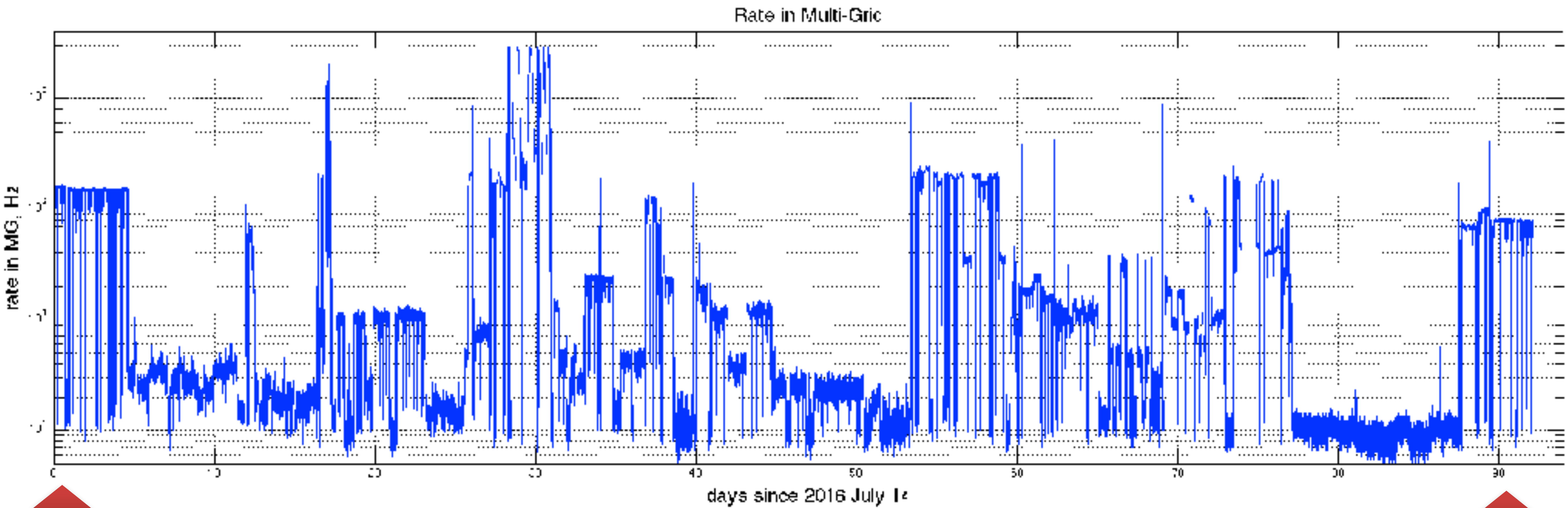
Operation between July 2016 - June 2017



First day

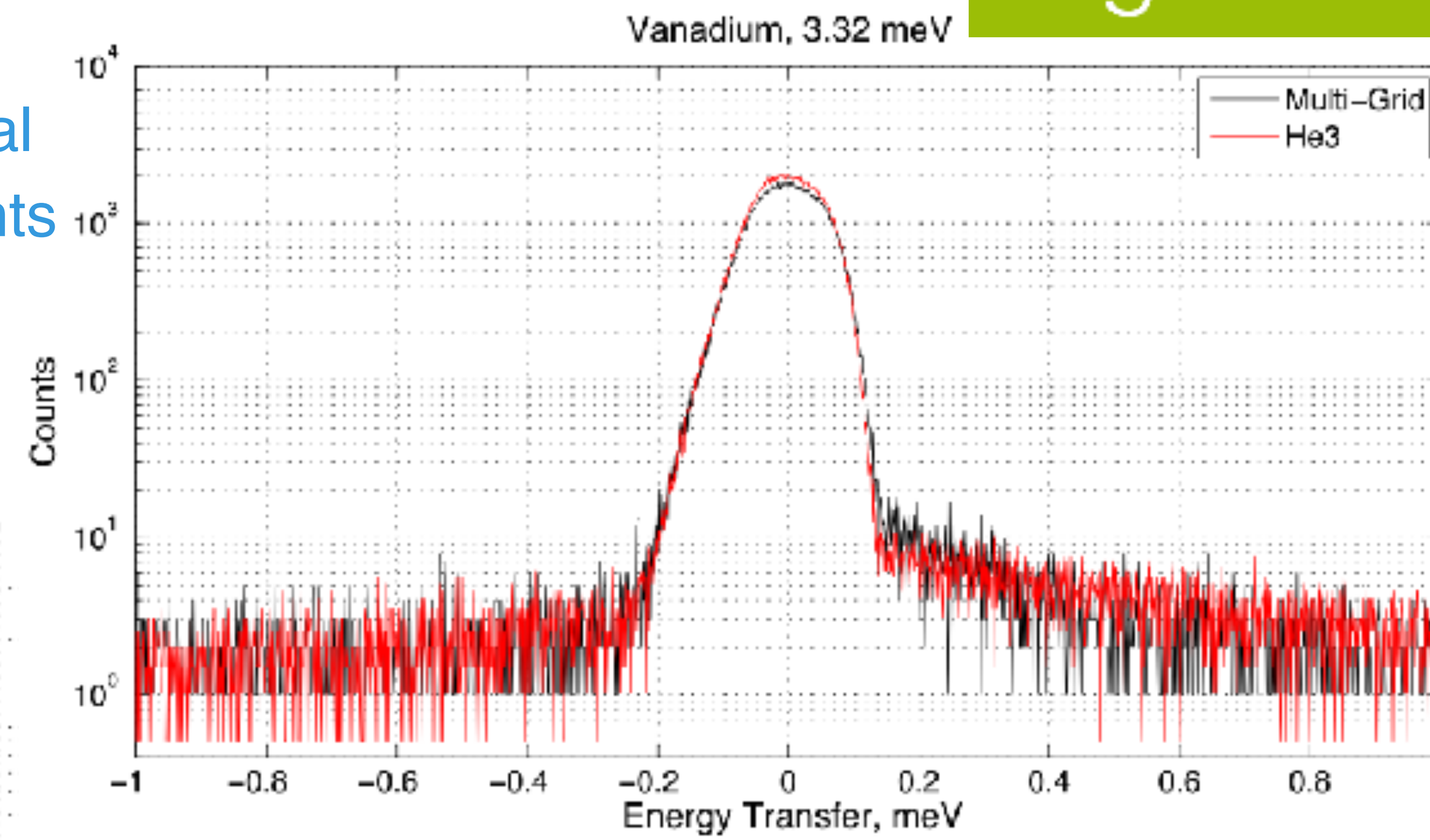
90 days

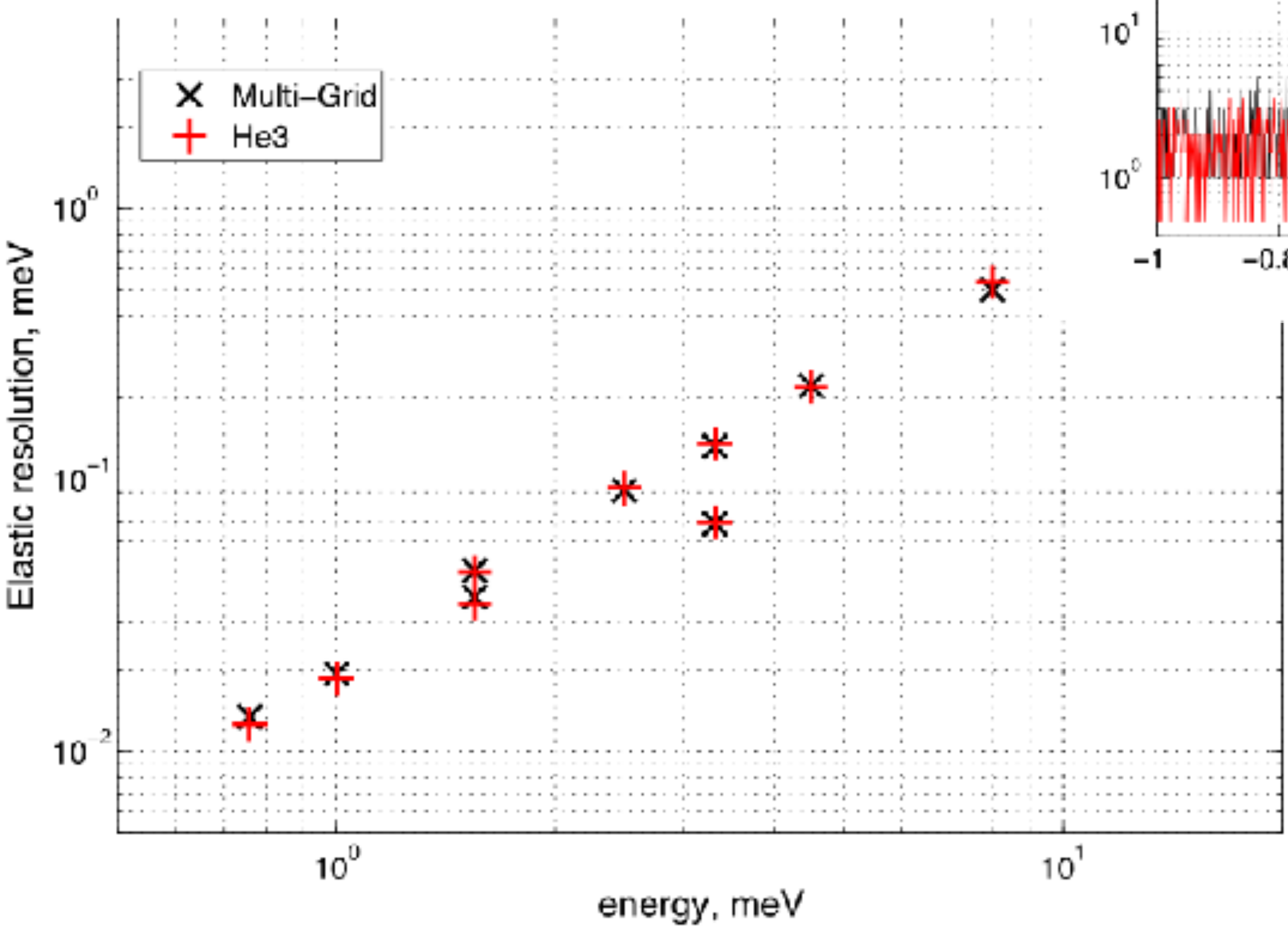
Operating without possibility of access since installation

Count rate stable to within 1-2% for a constant setting

Multi-Grid test at CNCS

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

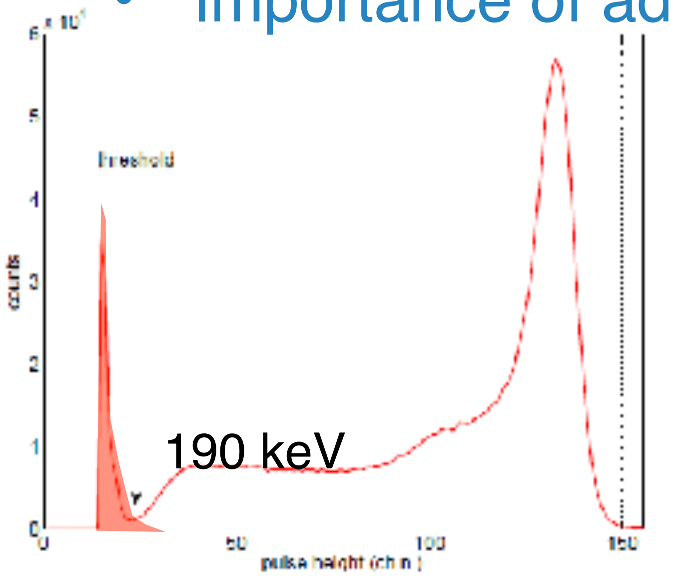




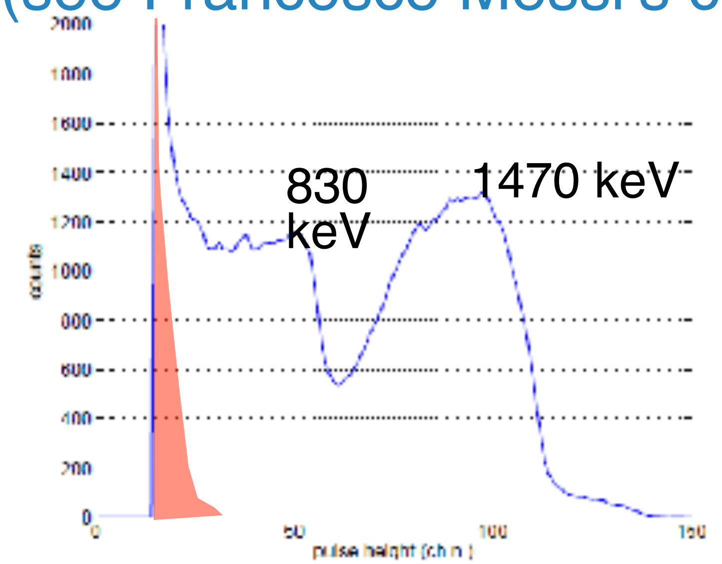
- Advantages over He3 tubes:
  - rate performance
  - fast neutron sensitivity

Background - Gamma Sensitivity

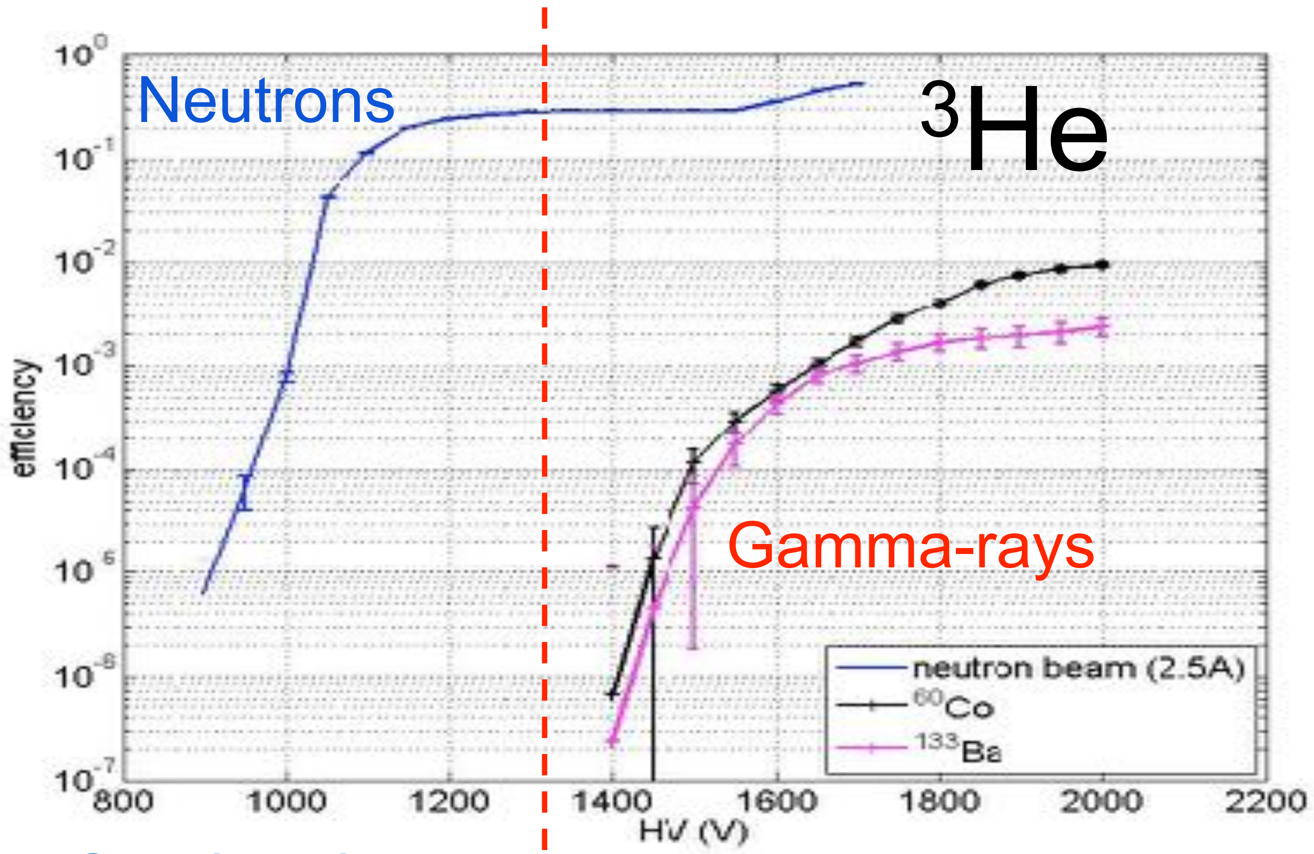
- Importance of advanced testing facilities (see Francesco Messi's contribution)



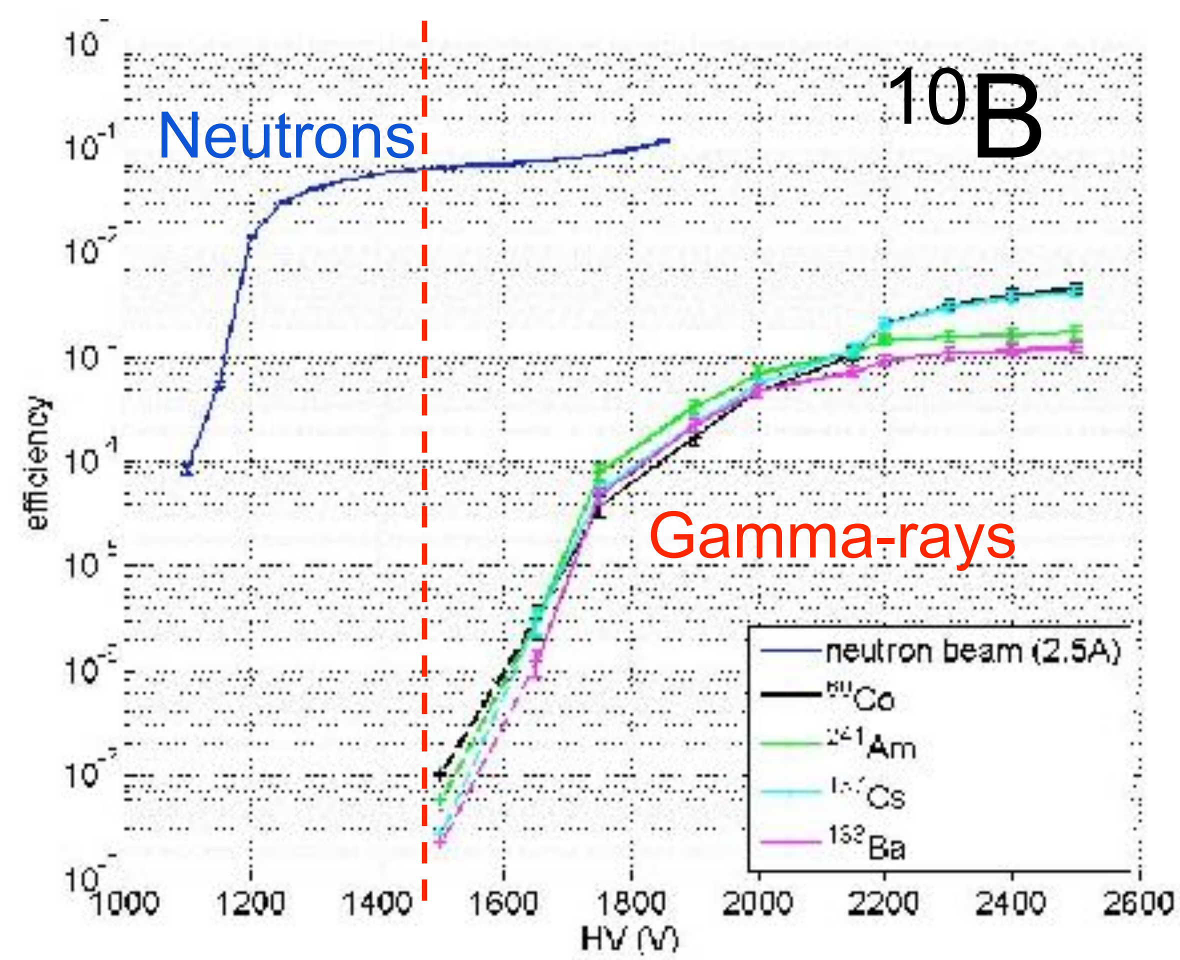
$<10^{-6}$



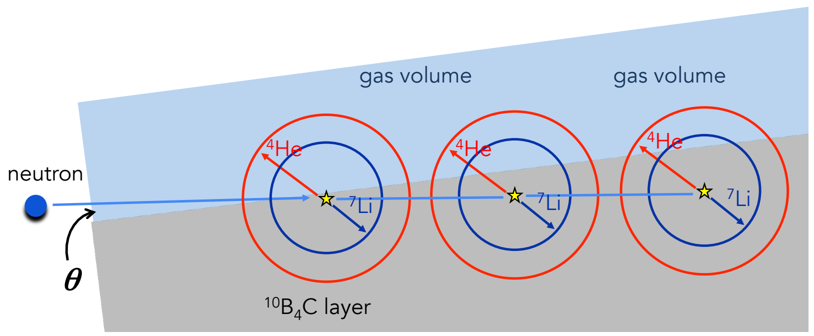
$<10^{-6}$

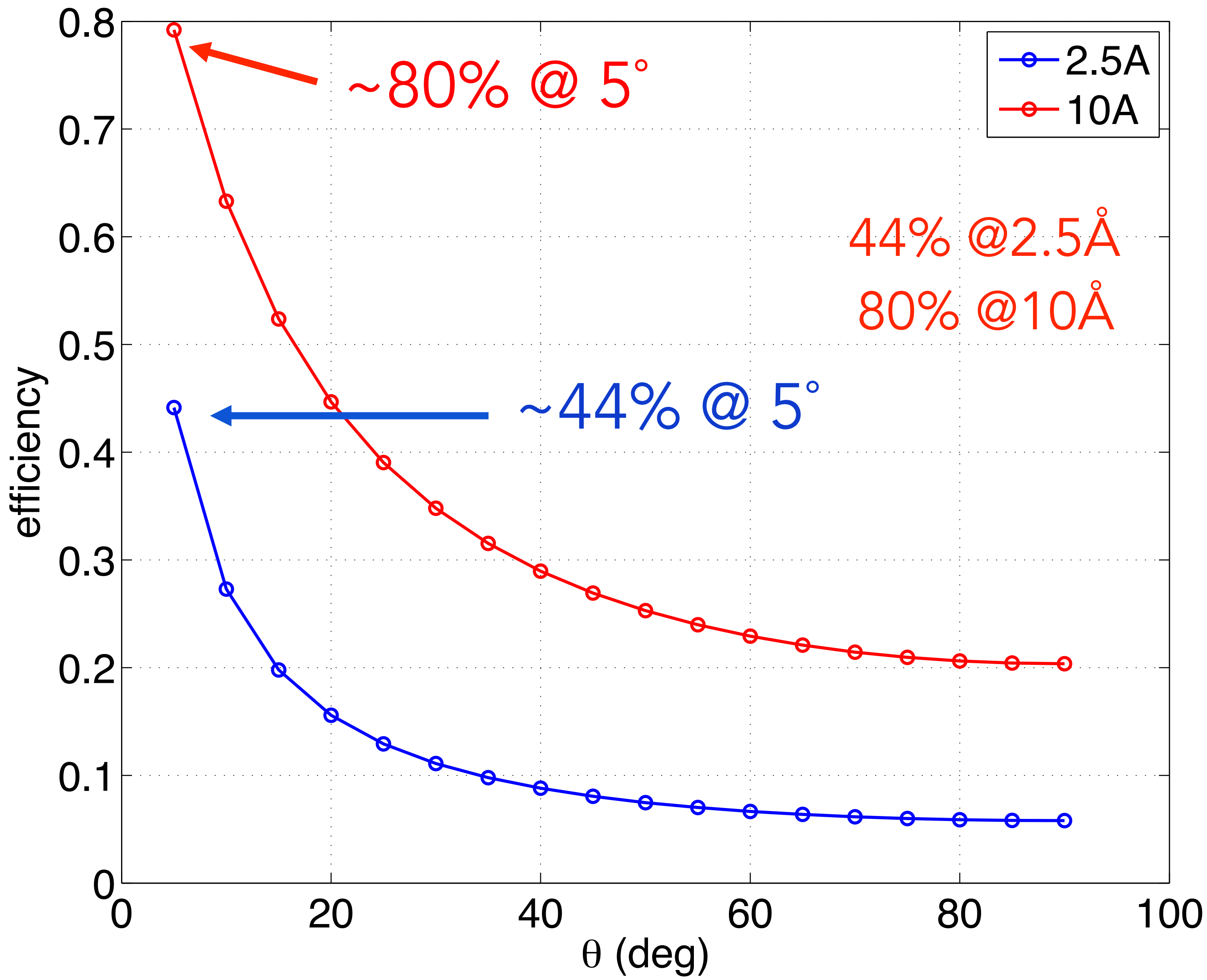


JINST 8 (2013) 10025



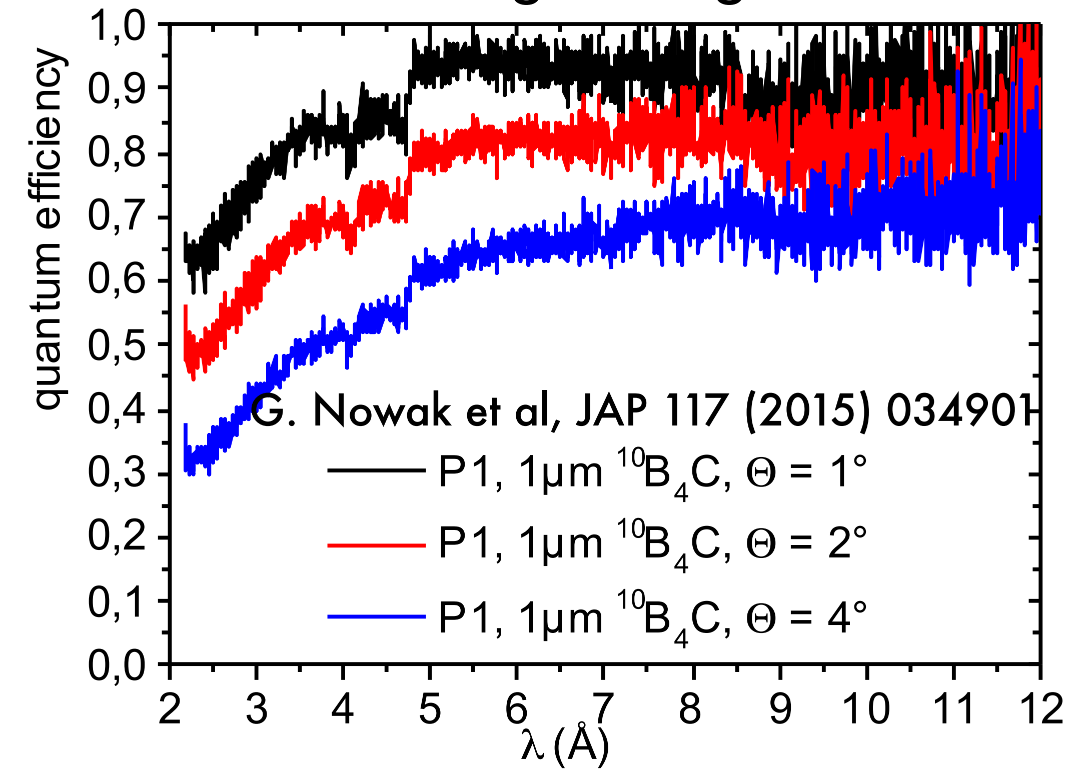
Efficiency of ^{10}Boron Detectors: Inclined Configuration

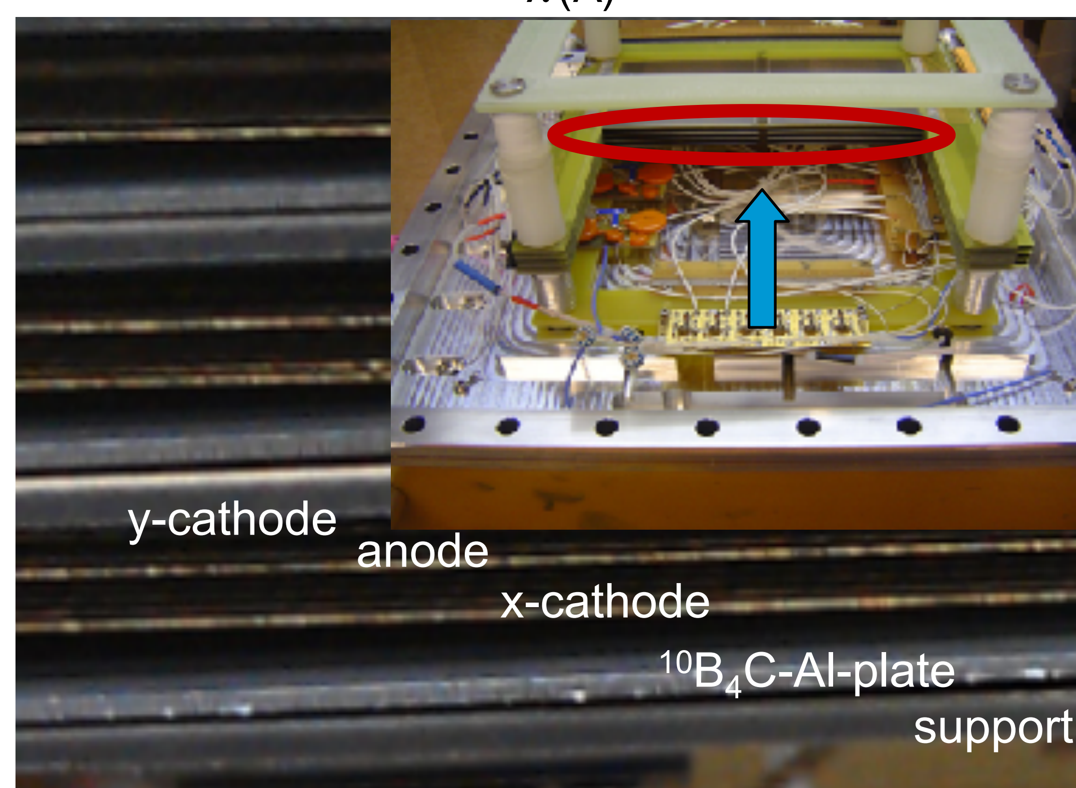




F. Piscitelli, PhD Thesis, U.Perugia (2014)

smaller inclined angles: higher efficienc

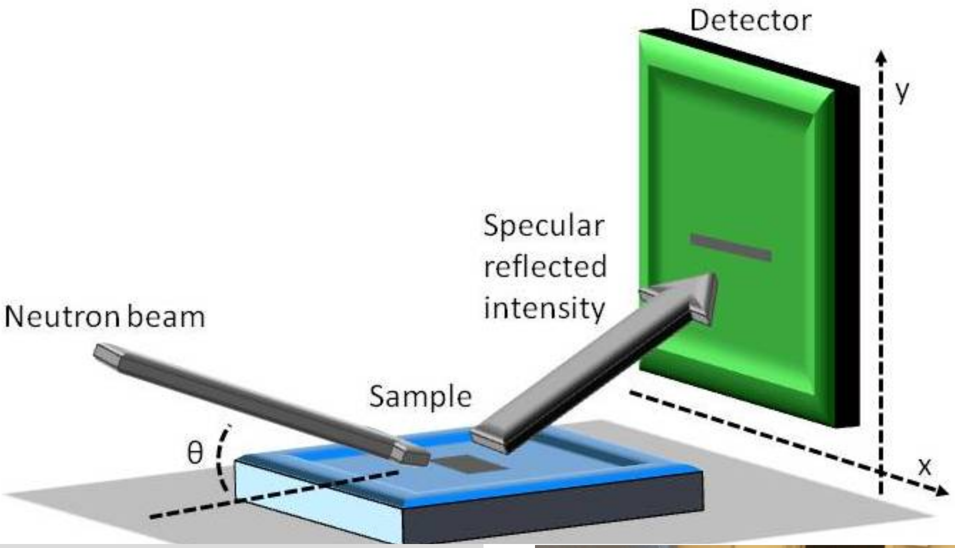


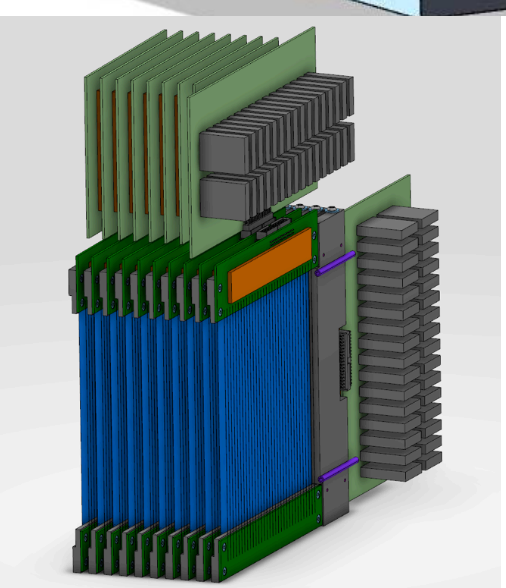


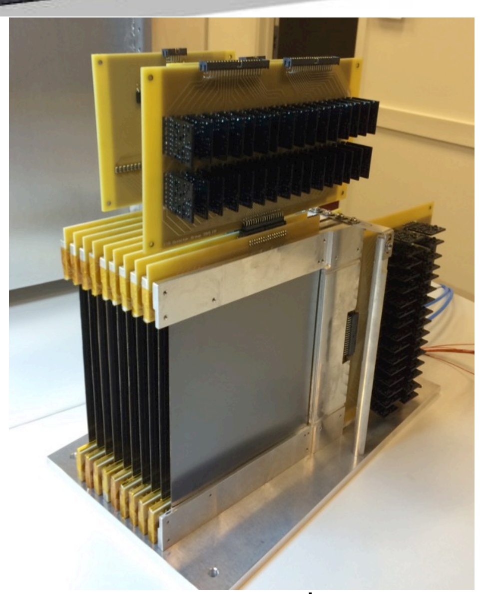
Neutron Reflectometry: A Rate Challenge

brightness

- Rate requirements is high:
  - Intensity of new sources
  - Time structure of pulse
  - Advanced design instruments







Simple, modular, cheap

ESS requirements

area $(mm \times mm)$	spatial resolution $(mm \times mm)$	global rate (s^{-1})	local rate $(s^{-1}mm^{-2})$
500×500	$[\leq 0.5, 2] \times 2$	$[5, 100] \cdot 10^5$	$[5, 300] \cdot 10^2$

x10 x100 -1000

The state of the art

area $(mm \times mm)$	spatial resolution $(mm \times mm)$	global rate (s^{-1})	local rate $(s^{-1}mm^{-2})$
500×500	1×2	$100 \cdot 10^5$	300

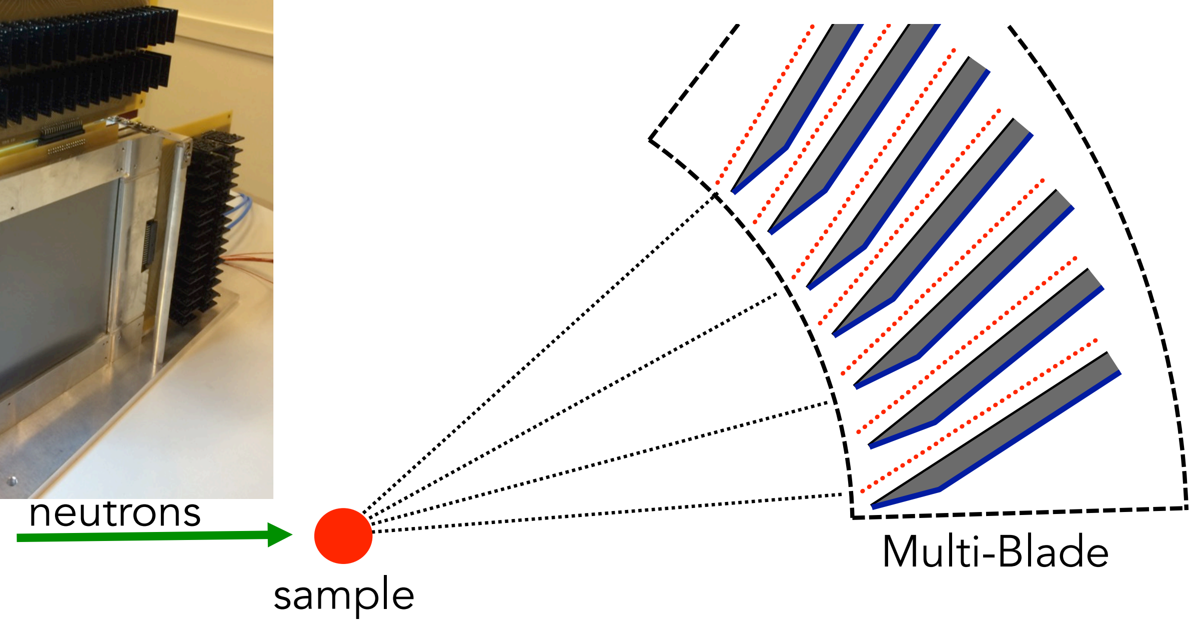
^3He technology

x1 x10

Multi-Blade

area $(mm \times mm)$	spatial resolution $(mm \times mm)$	global rate (s^{-1})	local rate $(s^{-1}mm^{-2})$
	0.3 x 4		>1000

^{10}B technology

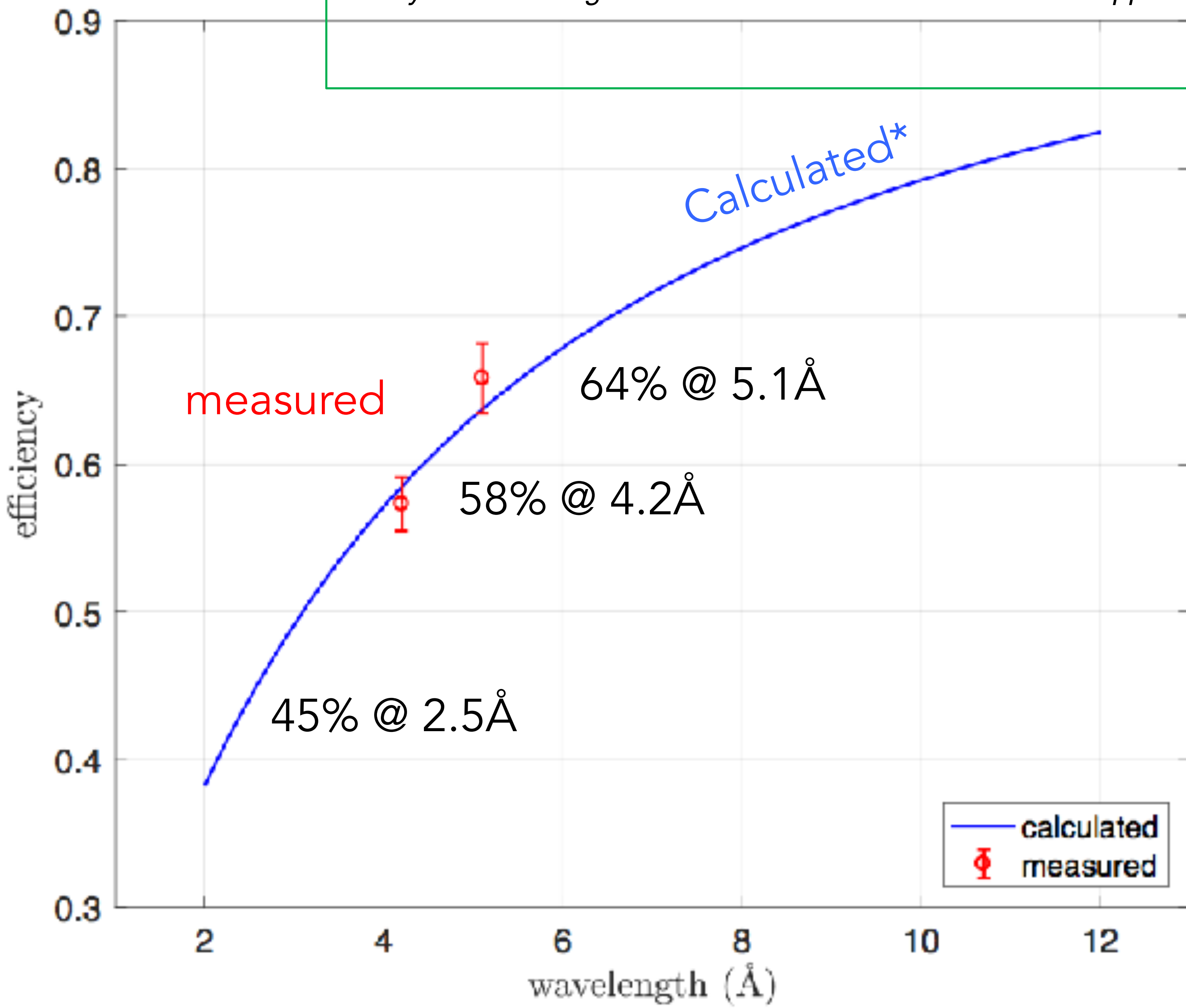


Multi-blade design:
- High rate capability
- Sum-mm resolution

Multi-Blade Results

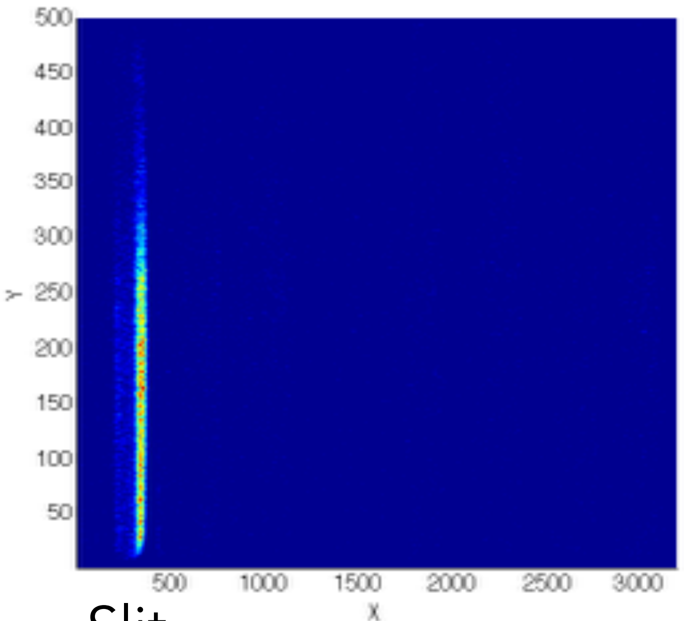
BrightnESS
EUROPEAN SPALLATION SOURCE
Lund University
Wigner Research Institute
Budapest Neutron Centre

*F. Piscitelli and P. van Esch,
Analytical modeling of thin film neutron converters and its application to thermal neutron gas detectors
J. Instrum. 8, P04020 (2013)
arXiv:1302.3153

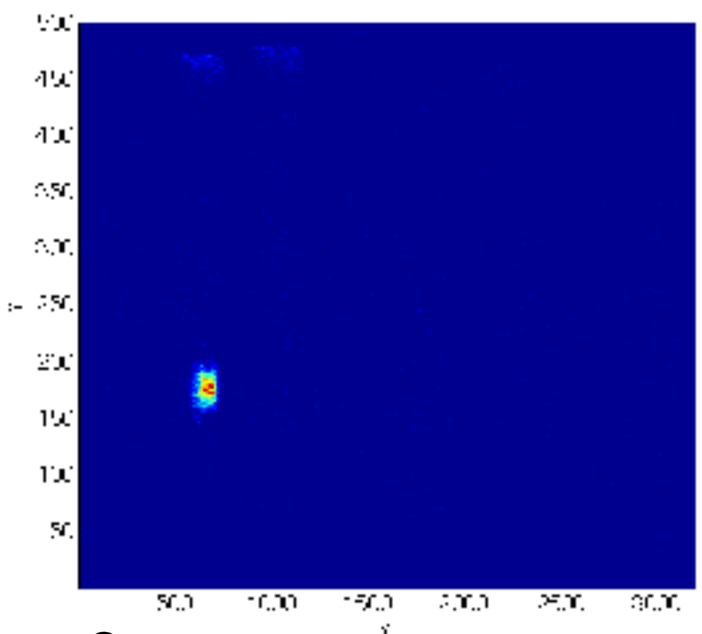


F. Piscitelli et al., The Multi-Blade Boron-10-based Neutron Detector for high intensity Neutron Reflectometry at ESS, JINST 12 (3) P03013 (2017).

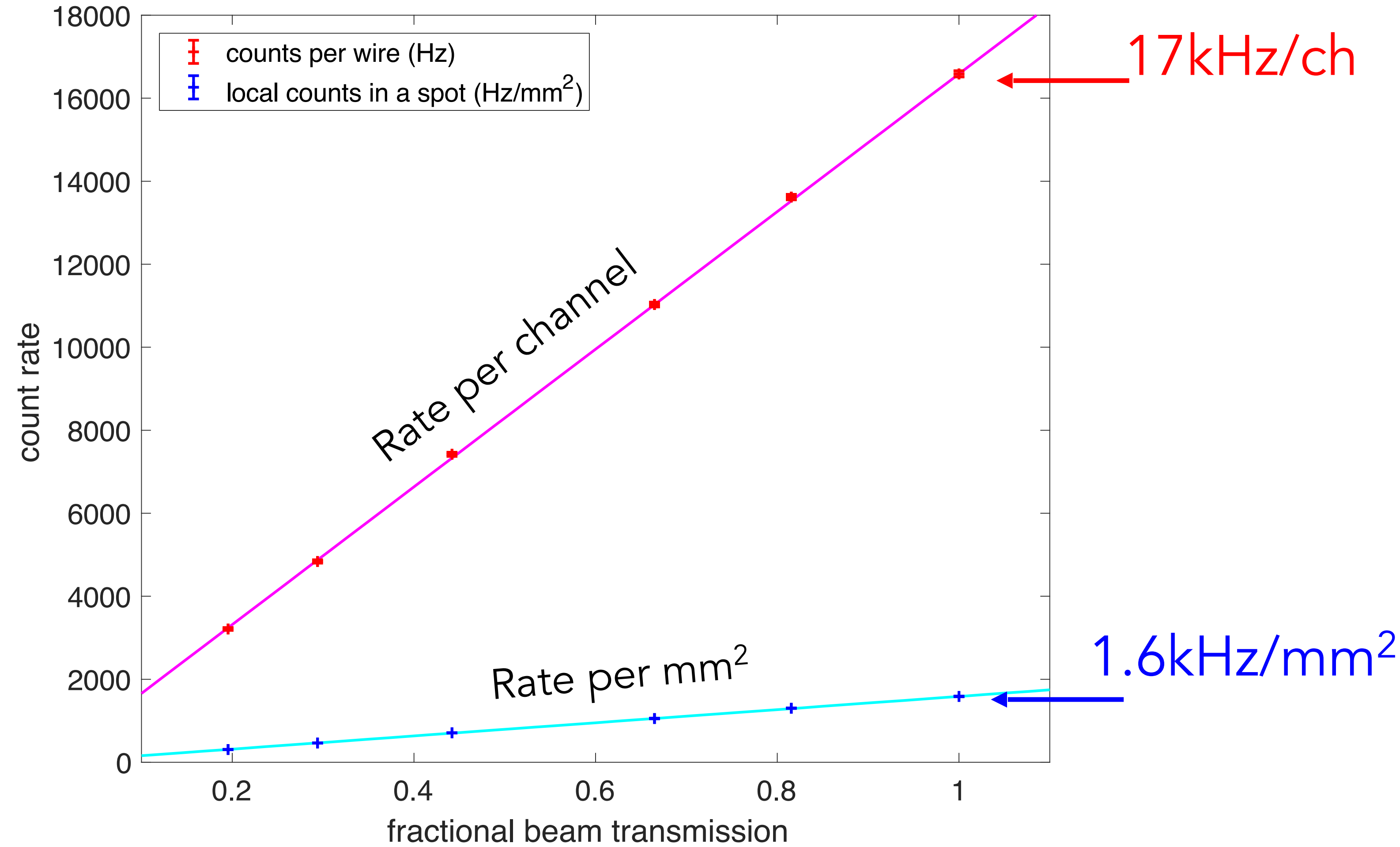
Counting rate capability



Slit



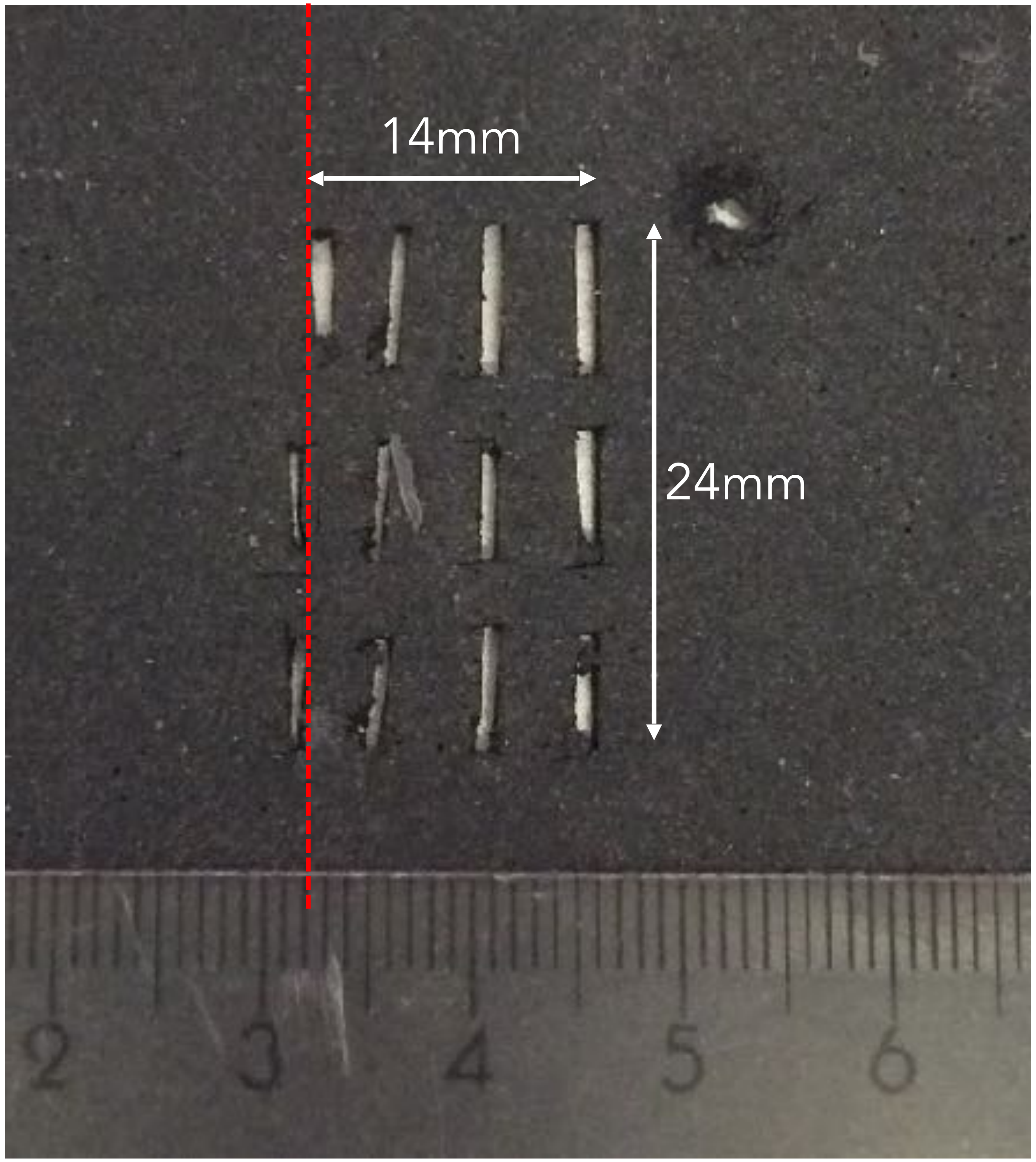
Spot



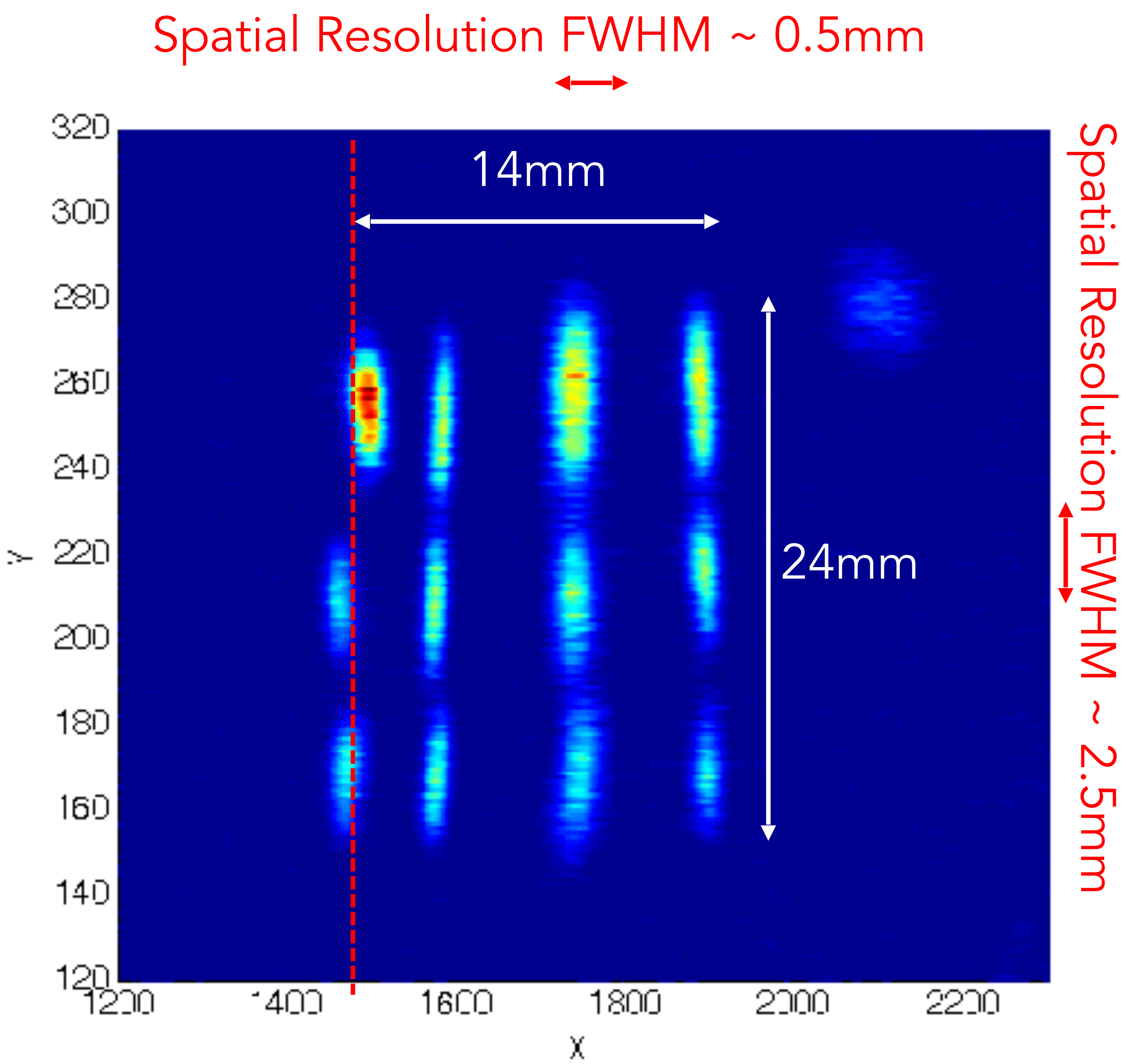
No saturation observed!

F. Piscitelli et al., The Multi-Blade Boron-10-based Neutron Detector for high intensity Neutron Reflectometry at ESS, JINST 12 (3) P03013 (2017).

Images



Mask



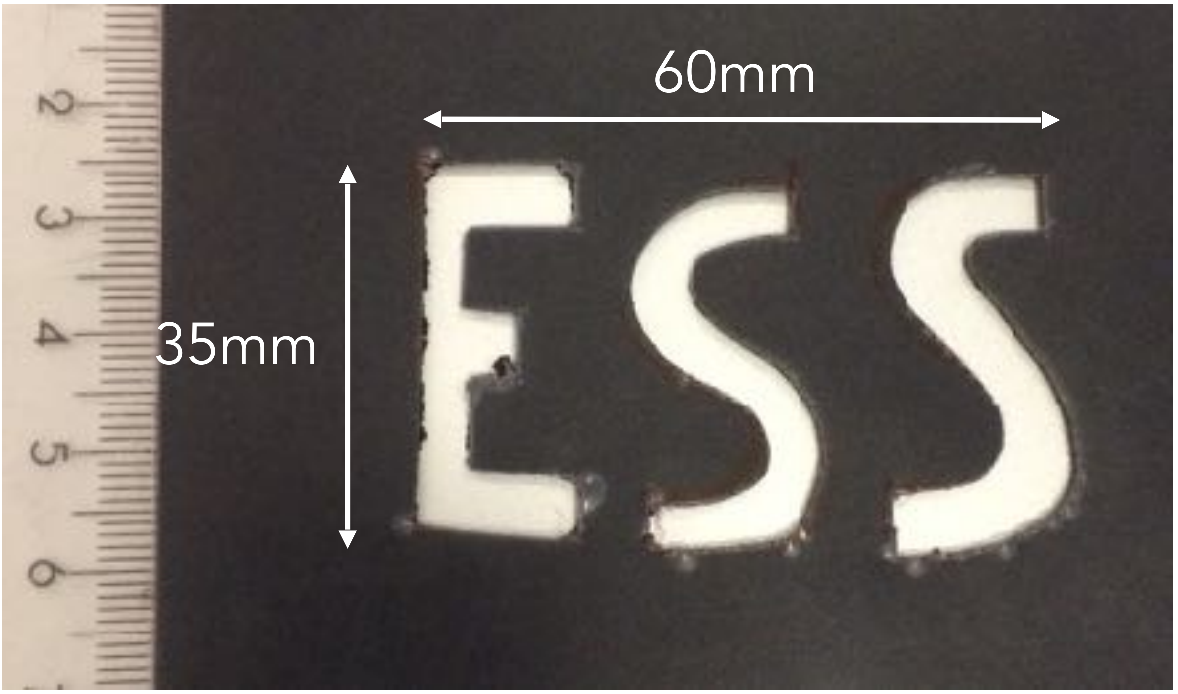
Raw image from the detector

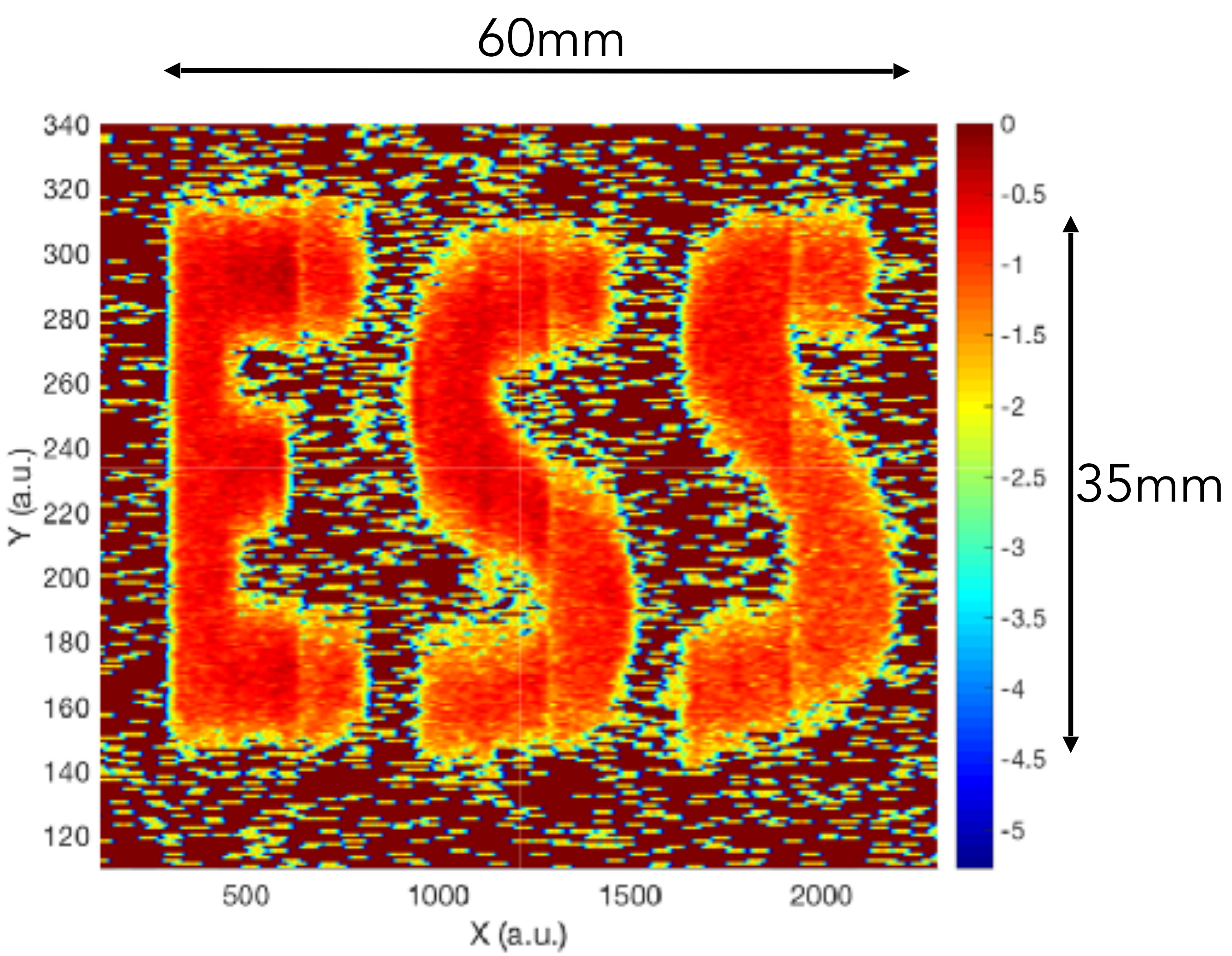
Resolution as designed

Some possibility to push lower if needed …

F. Piscitelli et al., The Multi-Blade Boron-10-based Neutron Detector for high intensity Neutron Reflectometry at ESS, JINST 12 (3) P03013 (2017).

Images



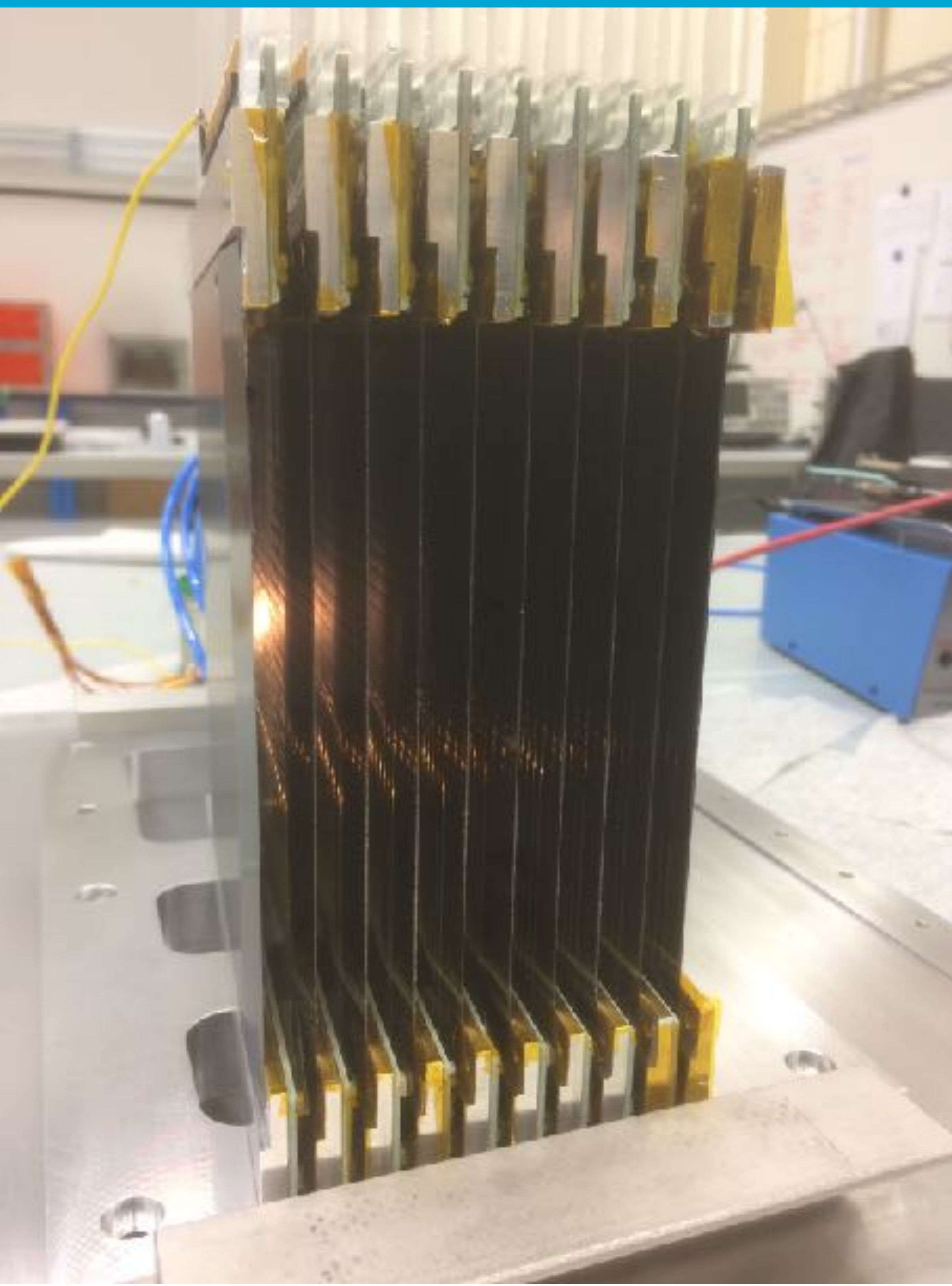


Mask

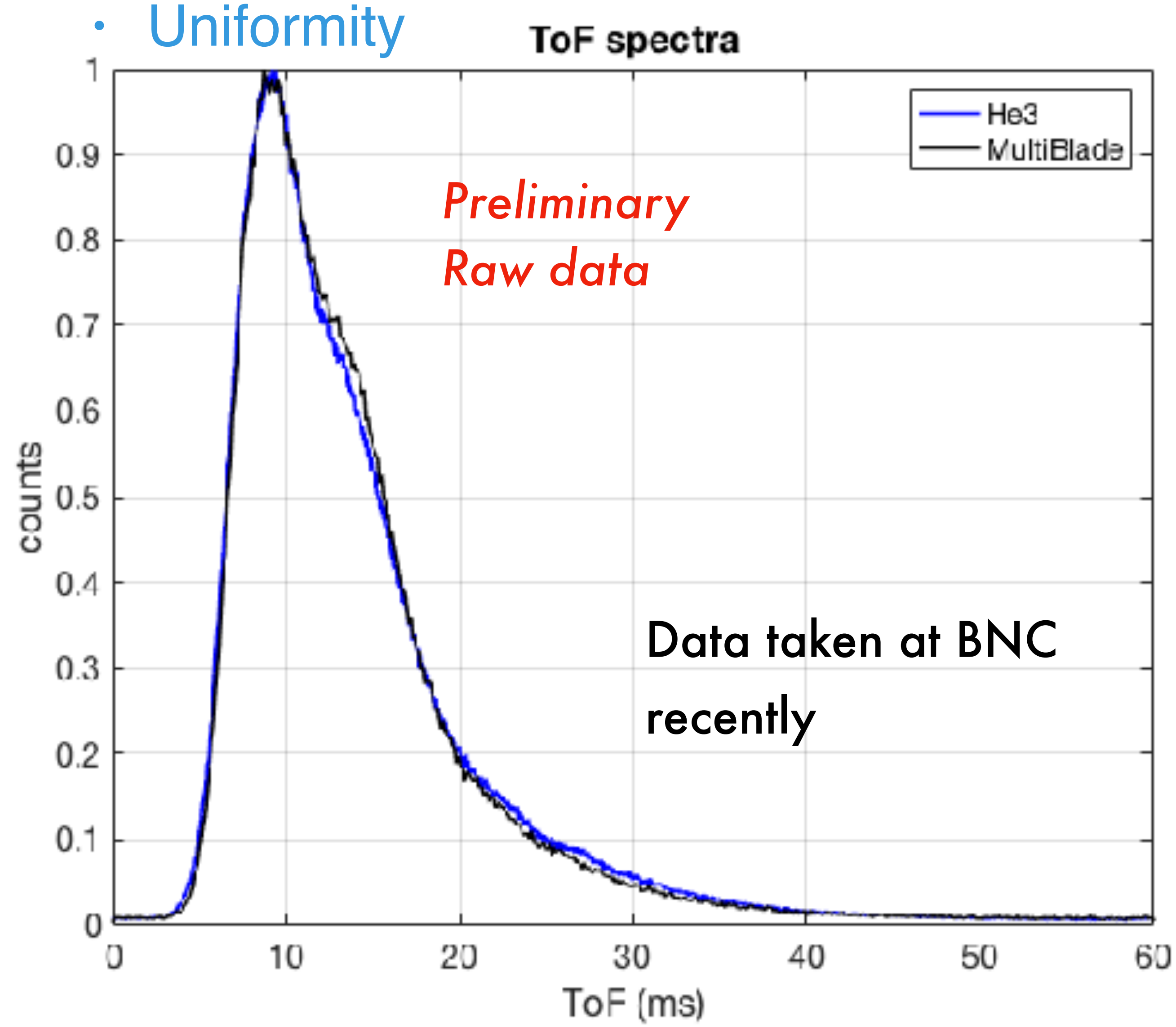
Raw image from the detector (log scale)

F. Piscitelli et al., The Multi-Blade Boron-10-based Neutron Detector for high intensity Neutron Reflectometry at ESS, JINST 12 (3) P03013 (2017).

Multi Blade Demonstrator



- Blade substrate changed from Al to Ti and SS
  - Absolute understanding of alignment
- 2 copies built
- Individual readout for every wire and strip
  - Uniformity

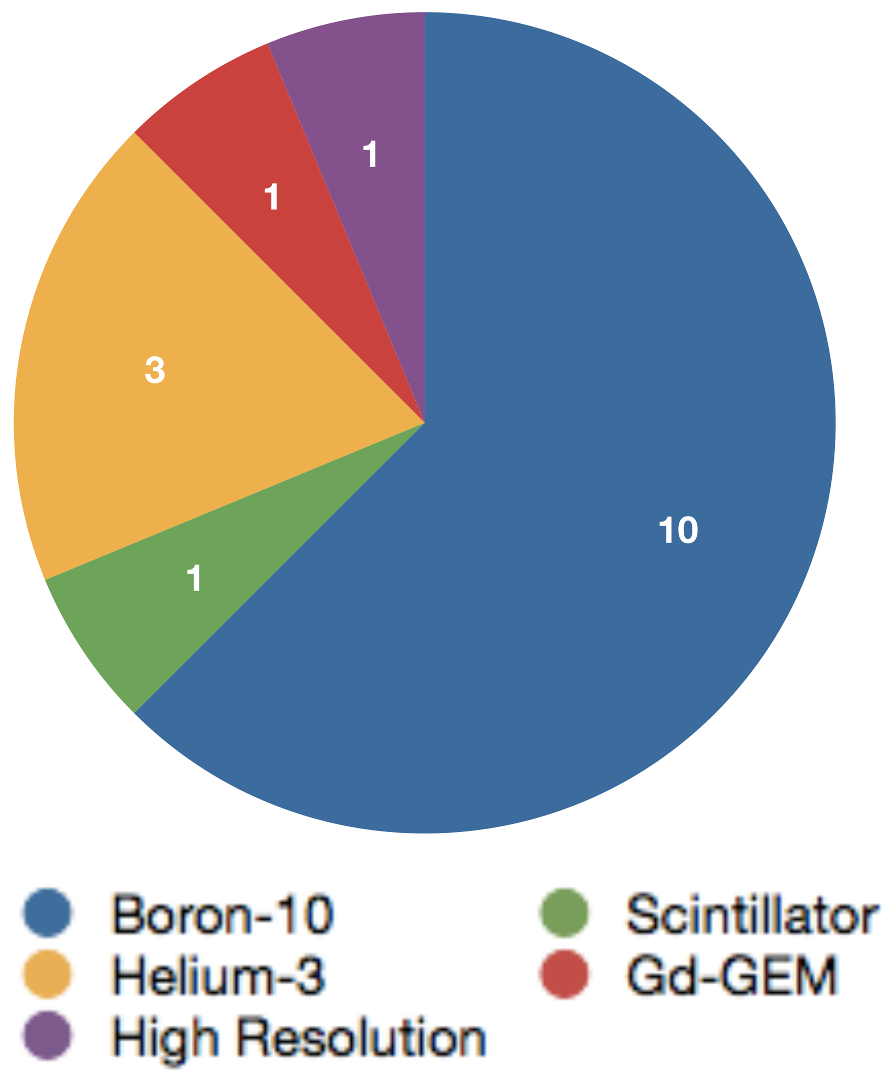


- Next step: demonstration on beam line at ISIS, UK

Preferred Detector Technologies for Baseline Suite

Detectors for ESS will comprise many different technologies

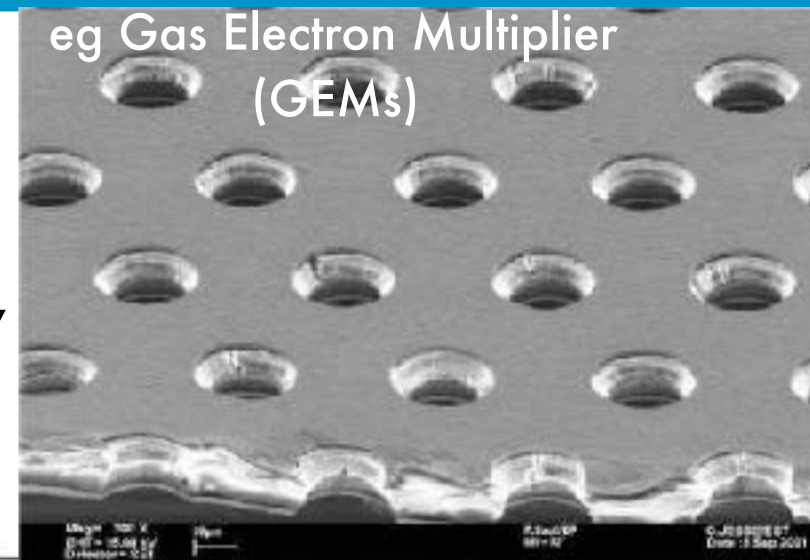
Detector Technologies for 16 Instruments:

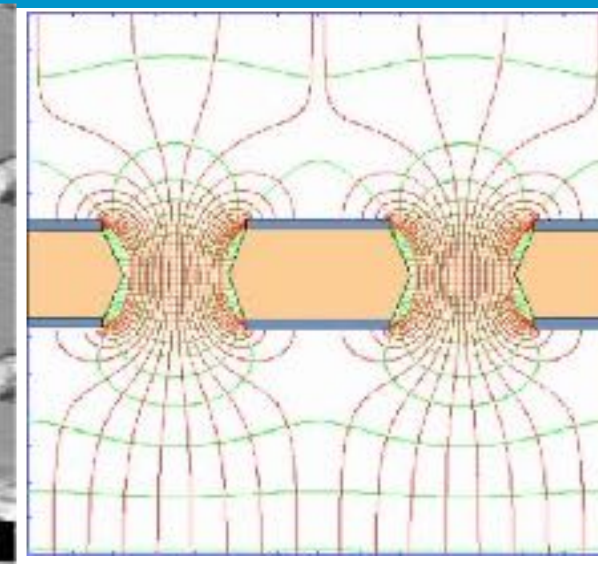


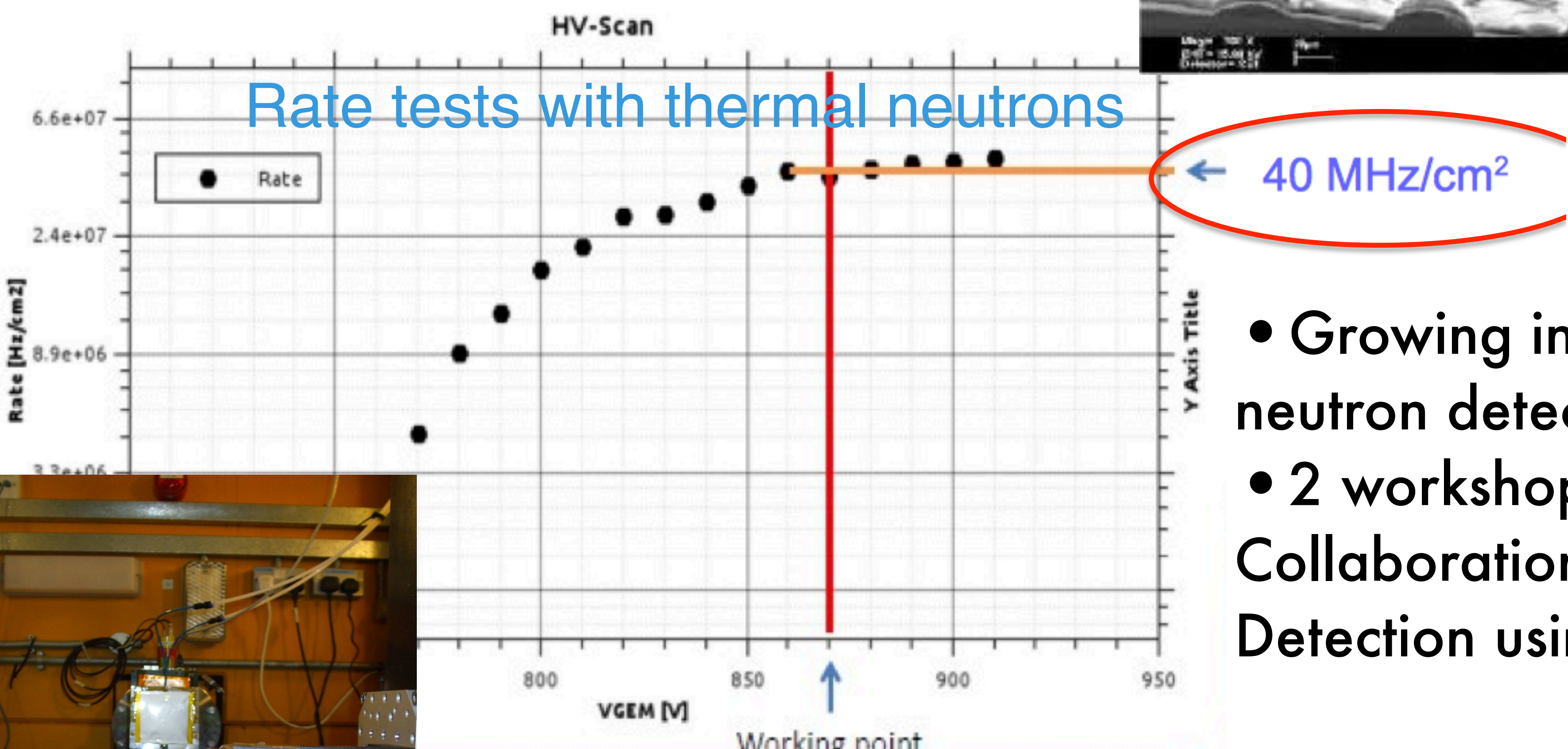
Trends

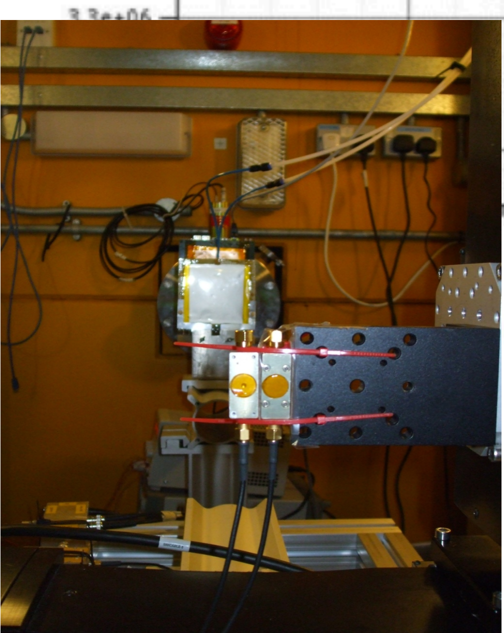
Micropattern Gaseous Detectors

- Field started by A Oed at the ILL with the micro-strip gas chamber (MSGC) in 1988
- Now widespread: many variants
- Potentially very good resolution and very high rate capability









- Growing interest for applications for neutron detection
- 2 workshops organised by CERN RD51 Collaboration (with HEPTECH) on Neutron Detection using MPGDs

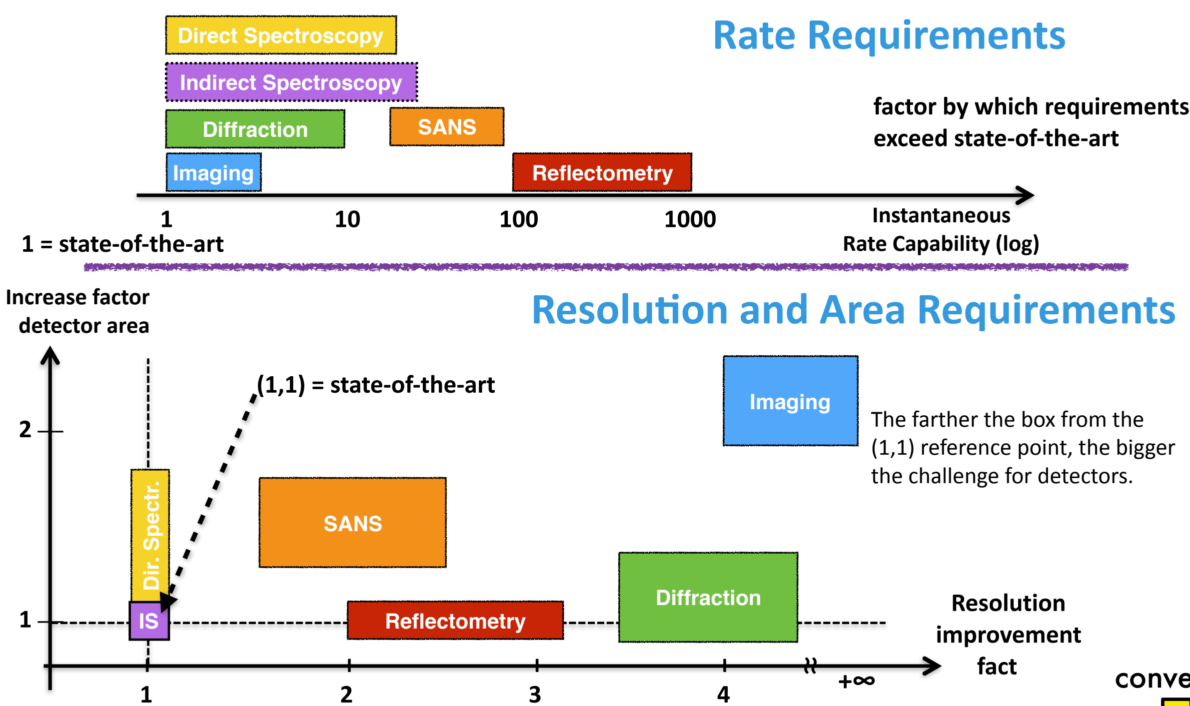
Summary of 1st workshop for MPGDs for neutron detection: arXiv:1410.0107

2nd Workshop: https://indico.cern.ch/event/365380/ arXiv:1601.01534

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. 2021/22
- Detector development time >> Instrument construction time

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

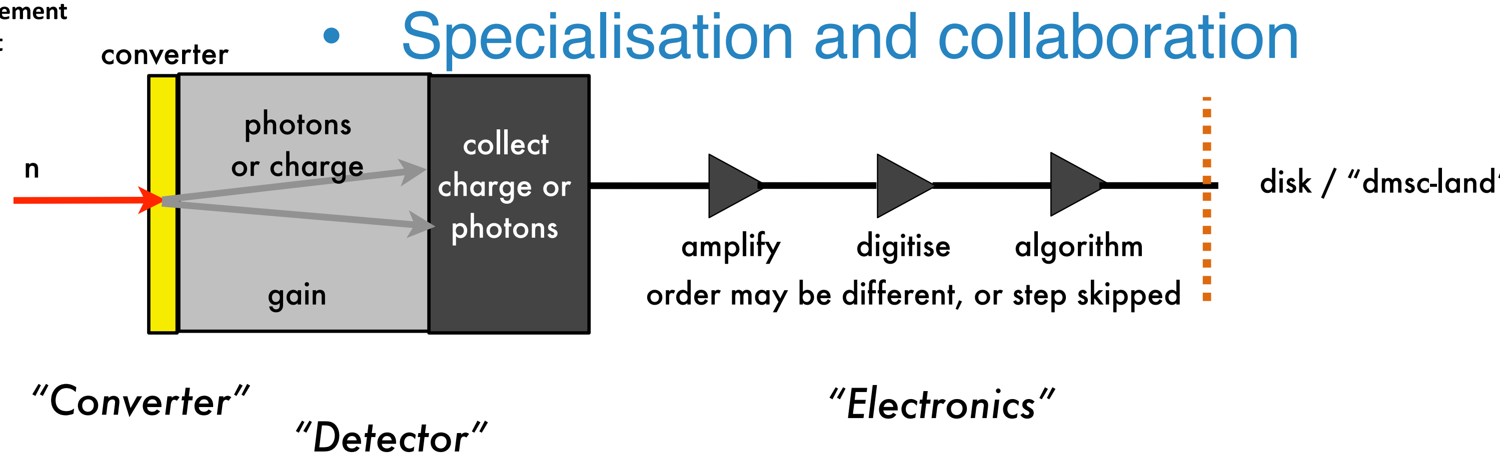


…and cost improvement of a factor of few …

- Computing and electronics have become ubiquitous and very cheap
- Future detectors will be much more designed around electronics

- Simulation will play a much bigger role in design (see Xiao-Xiao Cai's talk)

- Specialisation and collaboration



Summary

- 4 major new neutron sources coming online in next decade

- 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.
- Boron-10 Gaseous detectors becoming mature
- This is a very active topic

- First developments are coming to realisation: **yes there is post-helium-3 neutron science!**
- Neutron detectors for future instruments are going to look very different ...

brightness grant agreement 676548
SoNDe Solid-State Neutron Detector