An efficient camera for fast neutrons

Alan Hewat, ILL and NeutronOptics Grenoble

Fast Neutron imaging is IMPOSSIBLE…

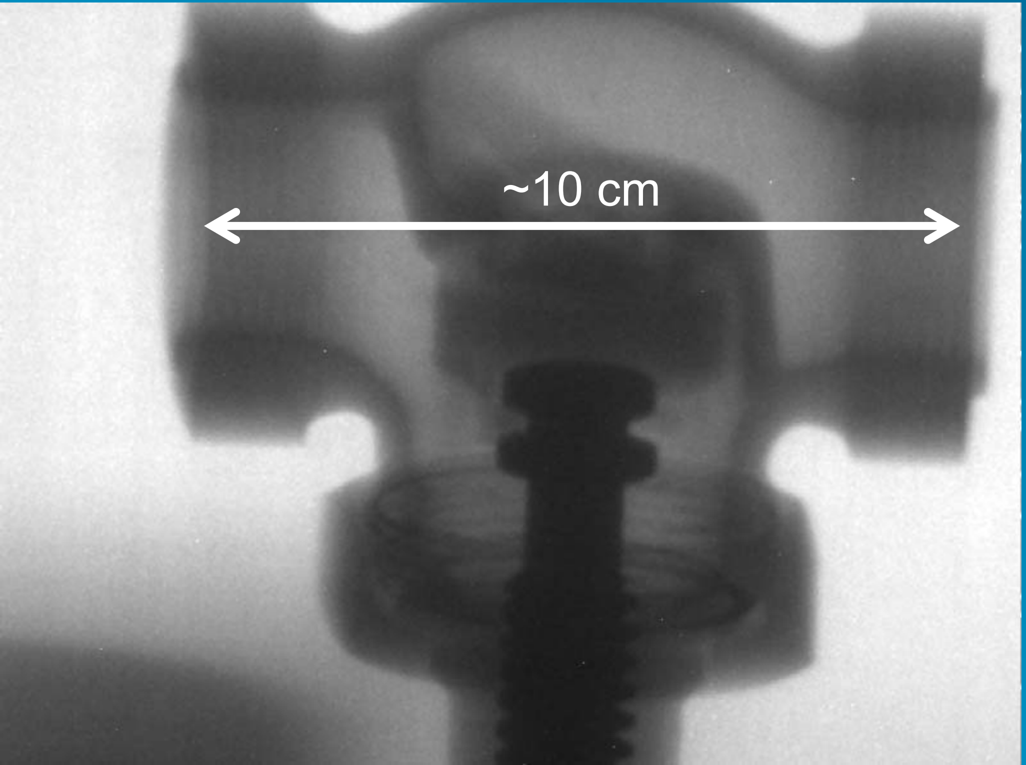
The impossible takes a little longer

An efficient camera for fast neutrons

Alan Hewat, ILL and NeutronOptics Grenoble

2015 - First experience with “fast neutron imaging”

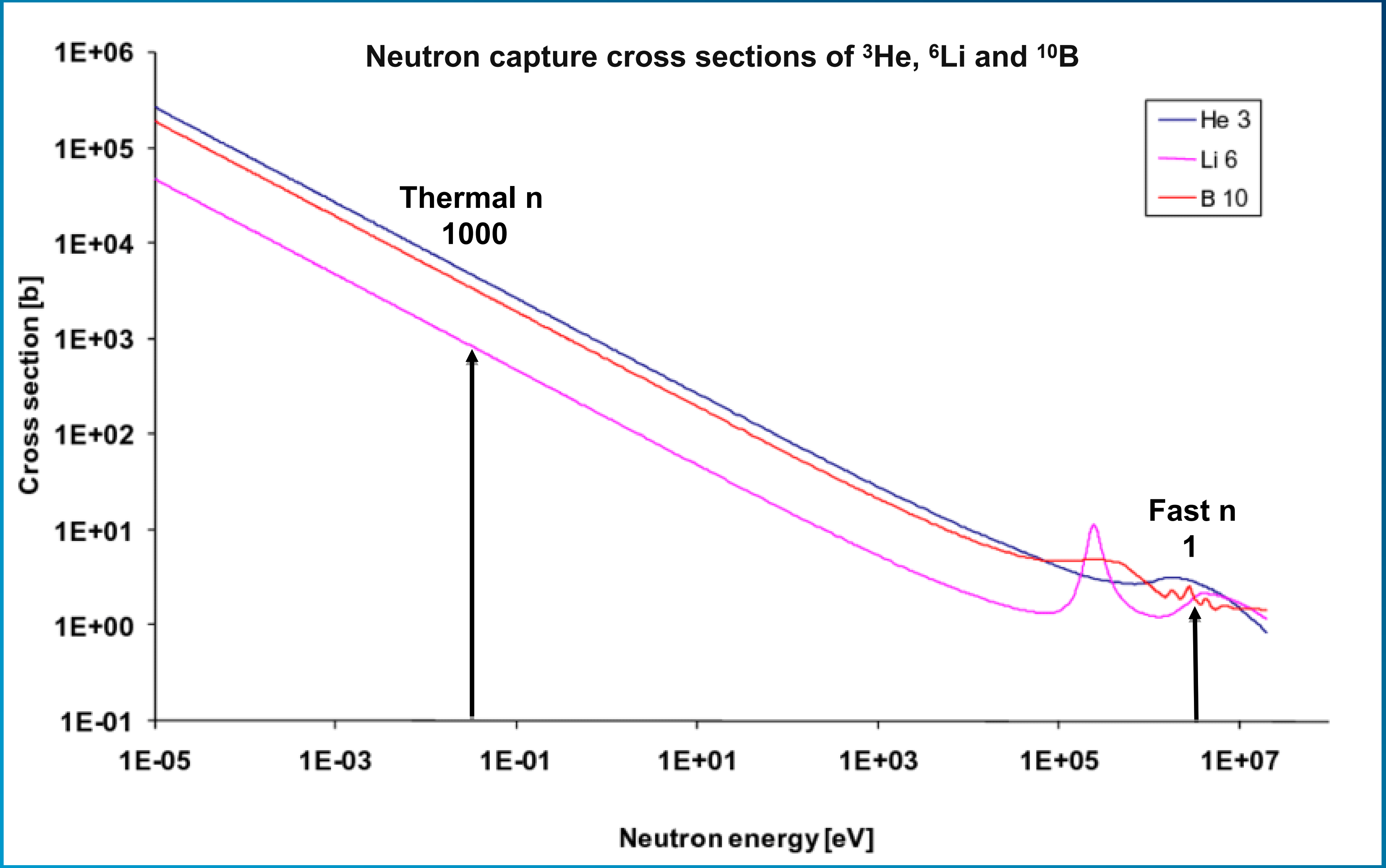
- Florida Uni. purchased our 200x200mm camera for their 1 MW Triga Reactor
- A student also tried our camera on an Adelphi D-T generator ($3x10^9$ n/s)
- He didn’t know that fast neutron imaging was impossible
- He sent me the following astonishing image of a 100mm iron valve !



Unfortunately…

- This is an excellent image
- But with gammas, not neutrons !
- No image with a Pb filter

Fast Neutron imaging is IMPOSSIBLE…



An efficient camera for fast neutrons

Alan Hewat, ILL and NeutronOptics Grenoble

Fast Neutron imaging is IMPOSSIBLE…

The impossible takes a little longer

Availability of small D-D and D-T fast neutron generators

- 10^{10} D-D $n.sec^{-1}$ Ted Cremer, Michael Taylor & Robert Adams presentations Tuesday morning
- 10^{7} thermalised D-D $n.sec^{-1}$ Moderated Adelphi DD110M thermal neutron generator

  BUT at 100cm we divide by $4\pi .10^4$ (Note: THERMAL neutron imaging needs ~10^3 $n.sec^{-1}.cm^{-2}$)

And the Efficiency of fast neutron scintillators is very low

- Use “knock-on protons” from hydrogenous polypropylene PP/ZnS scintillators
- Low probability of proton creation, thick scintillators and low proton-photon yield from ZnS
- While thermal neutron scintillators produce ~160,000 photons for every neutron captured by ^6Li !

Finally, there is a huge gamma background

- Gamma contrast is similar to fast neutron contrast
- And Gamma radiation from D-T generators can destroy electronic detectors
- So we try to use optically coupled CCDs (periscope camera) that can be shielded

Can we optimise a CCD camera for fast neutrons ?

An efficient camera for fast neutrons

Alan Hewat, ILL and NeutronOptics Grenoble

A modern Sony 1" CCD can cover much of neutron imaging

CCD	PCO.edge gold 4.2	NOptics VS60	NOptics 11002	iKon L-936
Type	Scientific sCMOS CIS2020	Sony Interline ICX694ALG	"Kodak" Interline KAI-11002	e2V Full Frame CCD42-40
Resolution pixel	2048 x 2048	2759 x 2200	4008 x 2672	2048x2048
Image diag. mm	18.8 (4/3")	16 (1")	43.3 (35mm)	38 (35mm)
Image area mm	13.3x13.3	12.53x9.99	37.25 x 25.70	27.6 x 27.6
Pixel size µm*	6.5 x 6.5	4.54 x 4.54	9.0 x 9.0	13.5 x 13.5
Quantum Effic*	>70%	75%	50%	90%
Fullwell e- **	~30,000	~30,000	~60,000	~100,000
Read noise e- **	1	6	13	12
Dark c. e-/pix/s	<0.02@-30°C	0.002@-10 °C	0.03@-20 °C	0.01@-50 °C
Peltier Cooling	Δ -30 °C	Δ -35 °C	Δ -38 °C	Δ -80 °C
Read time (s)***	0.01 to 0.02	1	12 to 22	2 to 10
A/D Readout**	16-bits	16-bits	16-bits	16-bits
Interface	USB 3.0	USB 2.0	USB 2.0	USB 2.0
Relative Cost	**16**	**4**	**6**	**50**

…for a more modest price - WCNR11 2018

An efficient camera for fast neutrons

Alan Hewat, ILL and NeutronOptics Grenoble

Is a large CCD an advantage ?

35mm CCD + Nikon f/1.2 (2016)

An efficient camera for fast neutrons

Alan Hewat, ILL and NeutronOptics Grenoble

Is a large CCD an advantage ?

Efficiency ~ CCD/FOV area.

Field-Of-View (FOV)

A large CCD implies a large FOV

35mm CCD + Nikon 50mm f/1.2 – min. focal dist. 500mm – min. FOV 315mm
Area CCD/FOV ~ 1.2%

12.5mm SONY + Fuji. 35mm f/1.4 – min. focal dist. 200mm – min. FOV 60mm
Area CCD/FOV ~ 2.7%

So a smaller CCD can actually be more efficient for a small Field-of-View
BECAUSE the lens can focus closer

We need a large aperture lens with a short focussing distance
Or a longer focal length, but 100mm lenses are at best f/2.8 (25% as bright)

An efficient camera for fast neutrons

Alan Hewat, ILL and NeutronOptics Grenoble

Is a large CCD an advantage ?

Field-Of-View (FOV)

Efficiency ~ CCD/FOV area.

W need a large Lens Aperture (f-number)

f/1.0 is twice as bright as f/1.4

Old x-ray lenses 50mm f/0.7
De Oud Delft RAYXAR
Rodenstock HELIGON
Currently being tested

Current Nikon 50mm f/1.2
Minimum focal dist. 500mm
35mm minimum FOV 315mm
Area CCD/FOV ~ 1.2%

Current Zeiss 25mm f/1.4
Min. focal dist. 252mm
35mm min. FOV 327mm
Area CCD/FOV ~ 1.2%
But also a little less bright

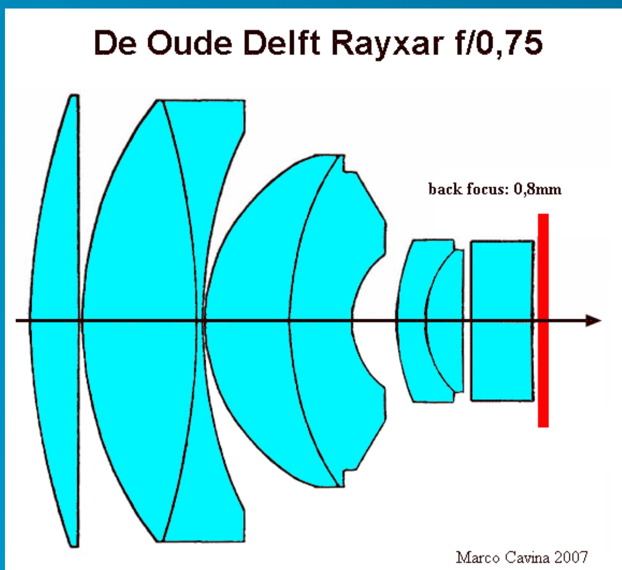
An efficient camera for fast neutrons

Alan Hewat, ILL and NeutronOptics Grenoble

Is a large CCD an advantage ? Field-Of-View (FOV)

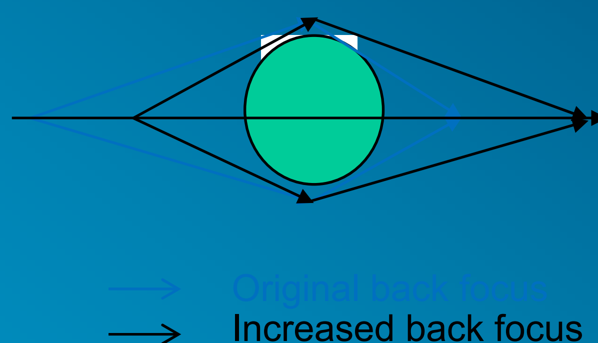
Efficiency ~ CCD/FOV area. Reduce min. focus -> reduce FOV = increase effic

Macro-spacers increase back focus & reduce min. focus & FOV – but also reduce angular aperture



Old x-ray lenses 50mm f/0.7
-> f/1.4 ?
Back focus very small
Currently being tested

Increase back focus ->
Reduces minimum focus & FOV
but also reduces angular aperture

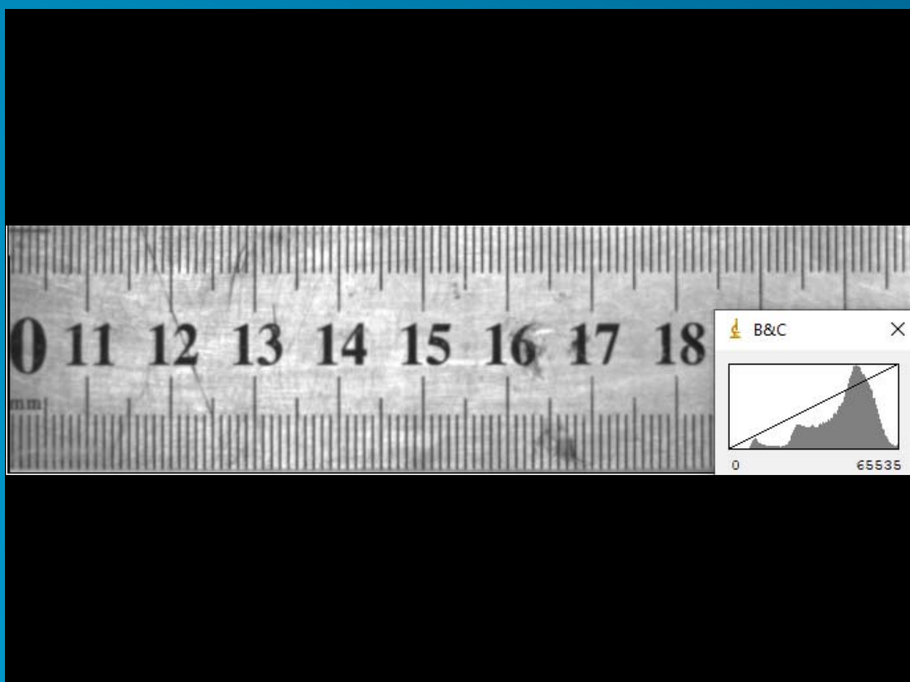


Current Nikon 50mm f/1.2
-> f/1.4 ?
Works well
New Nikon f/0.95 cf Nikon f/1.2
Minimum focus is still 500mm
Cost x12 … for gain x1.6

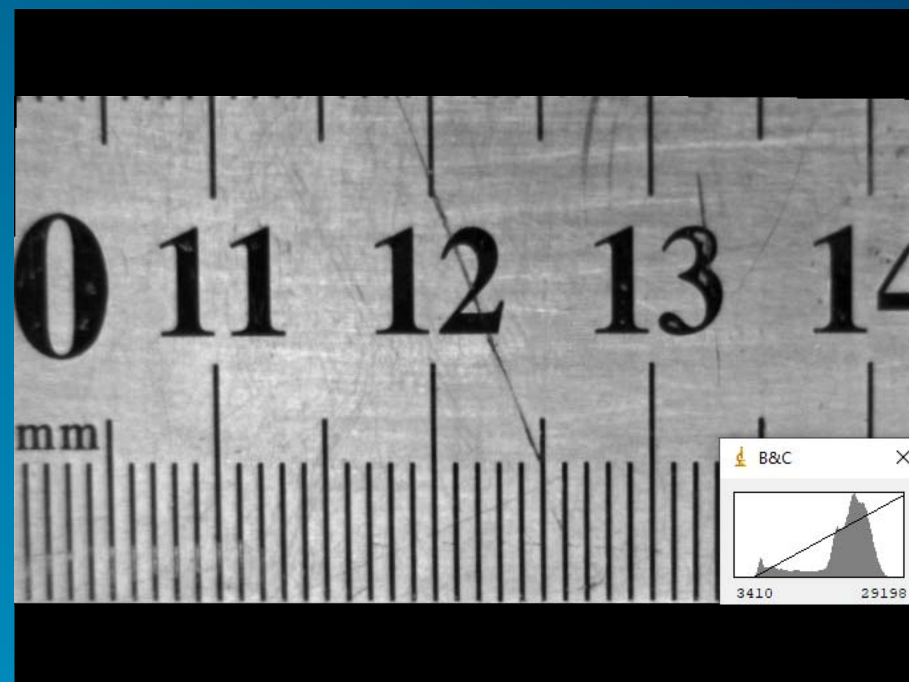
Is a large CCD an advantage ? Field-Of-View (FOV)

Efficiency ~ CCD/FOV area. Macro-spacers -> reduce FOV ≠ increase effic

Macro-spacers to increase back focus & reduce FOV – but also reduce angular aperture f/1.2 ->>



Nikon 50mm at ~500mm



Nikon 50mm at ~250mm

Use of macro-spacer reduces FOV but image brightness not increased because f/1.2 ->>

A large CCD only advantage for large FOV (what other advantages?)

CCD	PCO.edge gold 4.2	NOptics VS60	NOptics 11002	iKon L-936
Type	Scientific sCMOS CIS2020	Sony Interline ICX694ALG	"Kodak" Interline KAI-11002	e2V Full Frame CCD42-40
Resolution pixel	2048 x 2048	2759 x 2200	4008 x 2672	2048x2048
Image diag. mm	18.8 (4/3")	16 (1")	43.3 (35mm)	38 (35mm)
Image area mm	13.3x13.3	12.53x9.99	37.25 x 25.70	27.6 x 27.6
Pixel size μm*	6.5 x 6.5	4.54 x 4.54	9.0 x 9.0	13.5 x 13.5
Quantum Effic*	>70%	75%	50%	90%
Fullwell e- **	~30,000	~30,000	~60,000	~100,000
Read noise e- **	1	6	13	12
Dark c. e-/pix/s	<0.02@-30°C	0.002@-10 °C	0.03@-20 °C	0.01@-50 °C
Peltier Cooling	Δ -30 °C	Δ -35 °C	Δ -38 °C	Δ -80 °C
Read time (s)***	0.01 to 0.02	1	12 to 22	2 to 10
A/D Readout**	16-bits	16-bits	16-bits	16-bits
Interface	USB 3.0	USB 2.0	USB 2.0	USB 2.0
Relative Cost	**16**	**4**	**6**	**50**

Quantum efficiency, Well depth, Read noise, Dark current, Extreme cooling…?

An efficient camera for fast neutrons

Alan Hewat, ILL and NeutronOptics Grenoble

- **IKON quantum efficiency of 90% compared to Sony 75%**

+15% is of no real advantage (except for astronomy)

- **Is IKON greater well depth a big advantage ?**

Well depth = number of electrons stored / pixel (i.e. greater for larger e2v pixels)
Dynamic range = Well Depth / Total Noise (but e2v chip noise is higher)
Well depth reduces electron overflow (e2V has no "anti-blooming" structure)
Importance of Well Depth exaggerated (cf well depth in sCMOS)
I wish we had enough fast neutrons to fill the well ☺

- **Is IKON extreme cooling -100°C a big advantage ?**

In fact, the Sony CCD has **lower dark noise** at higher temperature
The Sony camera also has **lower read noise**
No need for extreme cooling

- **IKON specs for ideal conditions. Hot neutrons are not ideal**

Extreme cooling doesn't help with radiation background noise

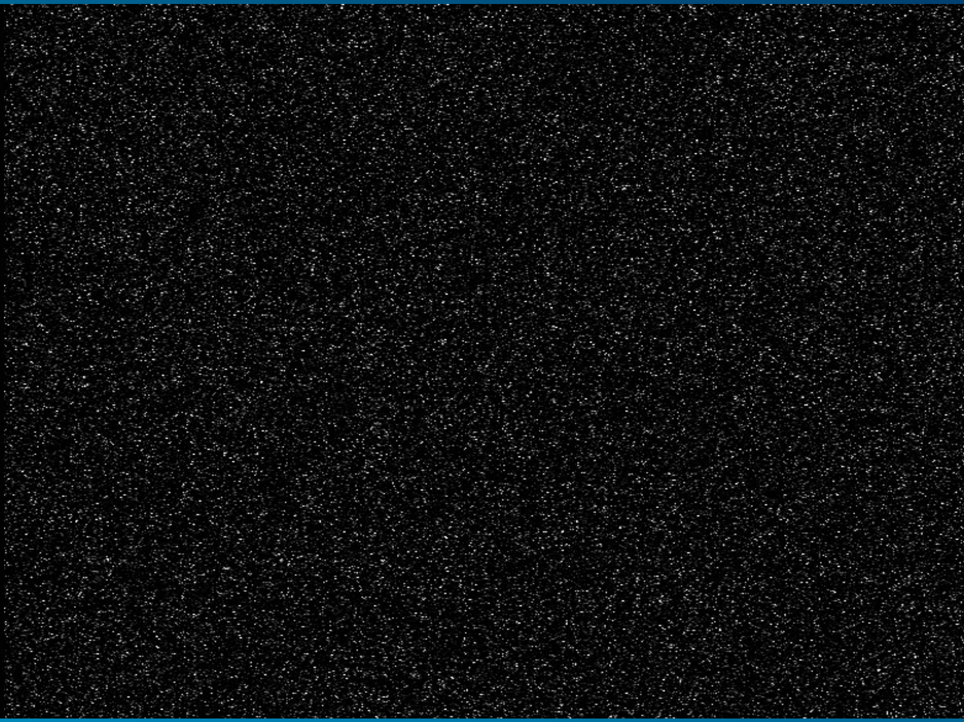
An efficient camera for fast neutrons

Alan Hewat, ILL and NeutronOptics Grenoble

- **N-generators eventually destroy CCDs – replacement cost?**

Sony camera ~10% of IKON cost, easily repaired and less expensive to replace

a) New CCD, 3 hot pixels



b) CCD after use on fast neutron source
"Noise" much greater than specifications

Can't be reduced by extreme cooling ☺

An efficient camera for fast neutrons

Alan Hewat, ILL and NeutronOptics Grenoble

A large CCD is only an advantage for a large FOV
Optics optimisation is much more important

- IKON is a good camera in an ideal environment, but expensive
- Can use cheaper 36x25mm CCDs (NOG-11002, PCO.4000)
- BUT a 1” CCD + 1” lens – is at least as bright for a small FOV
  A small FOV can do 97% of experiments (Burkhard Schillinger)
- AND small CCD is lot less expensive to replace when damaged

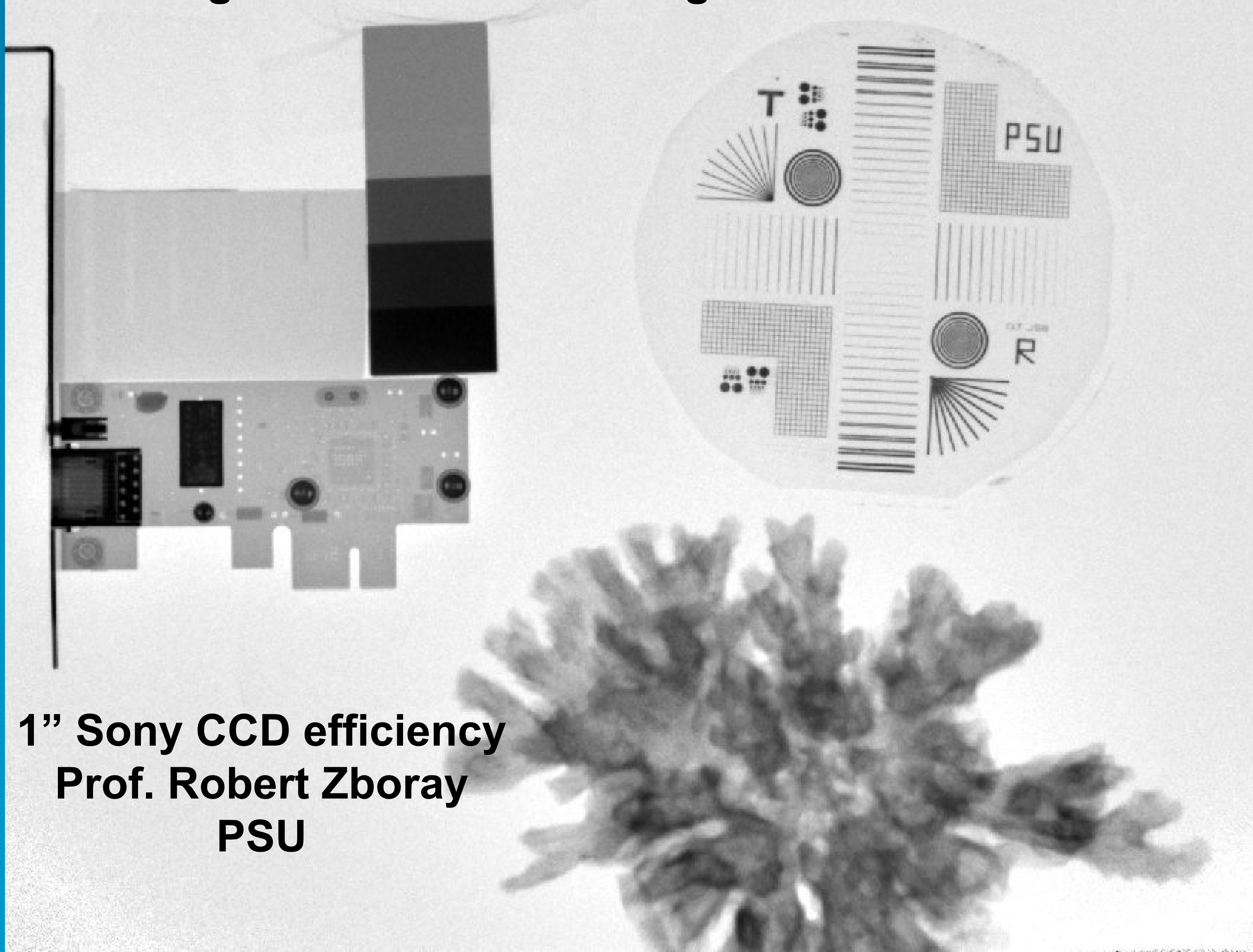
EXAMPLE of 1” CCD camera efficiency and low noise

Robert Zboray at Penn. State University with low flux TRIGA reactor
250 x 200mm camera with THERMAL neutrons

An efficient camera for fast neutrons

Alan Hewat, ILL and NeutronOptics Grenoble

100kW Triga reactor neutron image from our 1” CCD camera

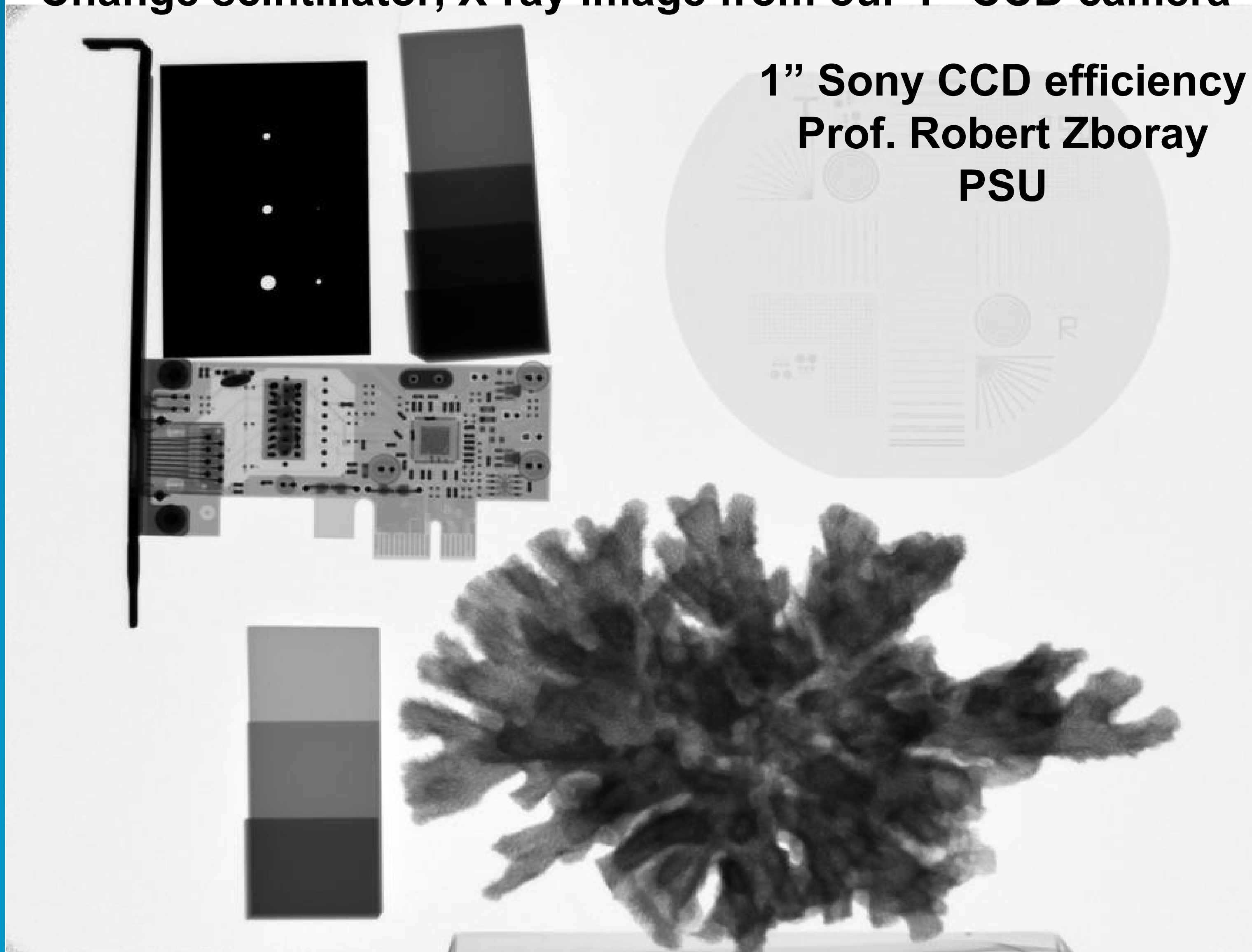


1” Sony CCD efficiency
Prof. Robert Zboray
PSU

An efficient camera for fast neutrons

Alan Hewat, ILL and NeutronOptics Grenoble

Change scintillator, X-ray image from our 1” CCD camera



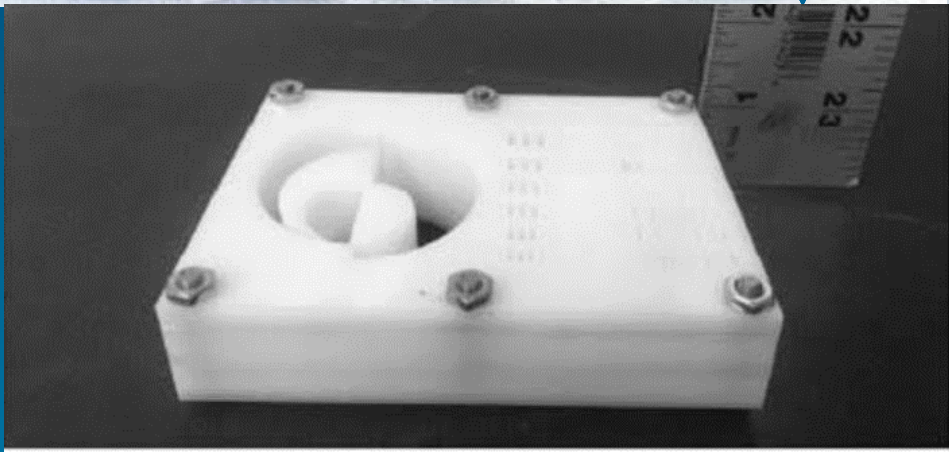
1” Sony CCD efficiency
Prof. Robert Zboray
PSU

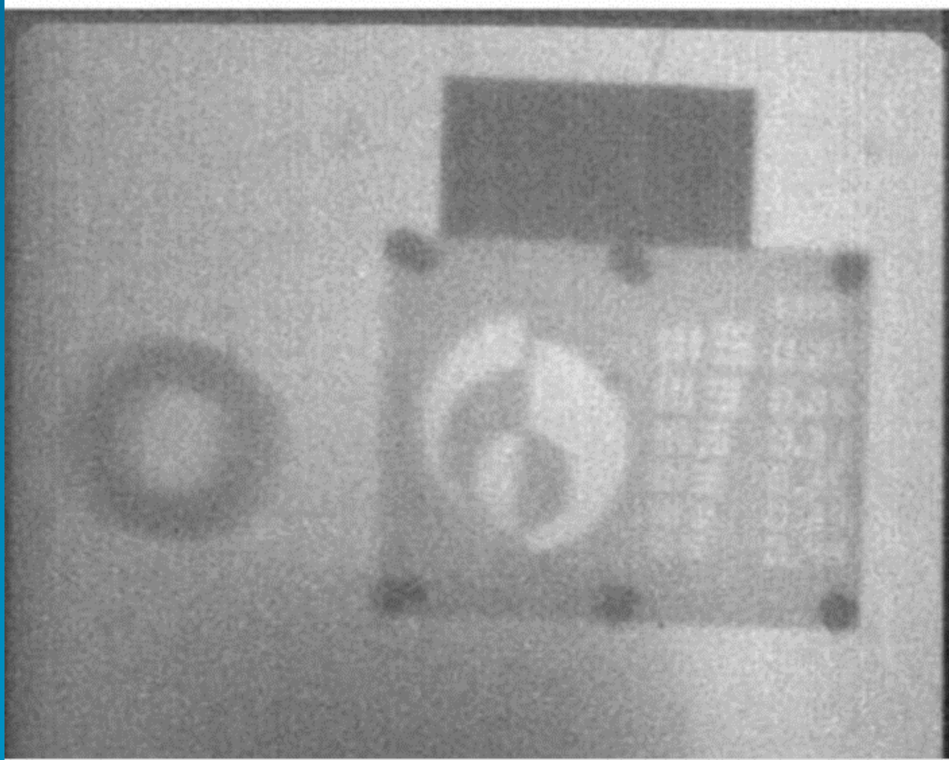
An efficient camera for fast neutrons

Alan Hewat, ILL and NeutronOptics Grenoble

ADELPHI Fast Neutron image

- D.Williams, C. Brown, Ch. Gary, T. Cremer
- Our 200x200mm camera, PP scintillator
- Adelphi DT109-110 DT neutron generator
- 3x10^9 n/s of 14 MeV neutrons
- 25 mm Delrin (-CH2O-)n block
- 25 mm Pb gamma filter
- 10 min exposure, 1.4m from 2mm aperture
- Largest lines 2 mm thick, 2mm spacing





Impossible takes a little longer

We can reduce exposure to ~2 minutes with a more compact camera

An efficient camera for fast neutrons

Alan Hewat, ILL and NeutronOptics Grenoble

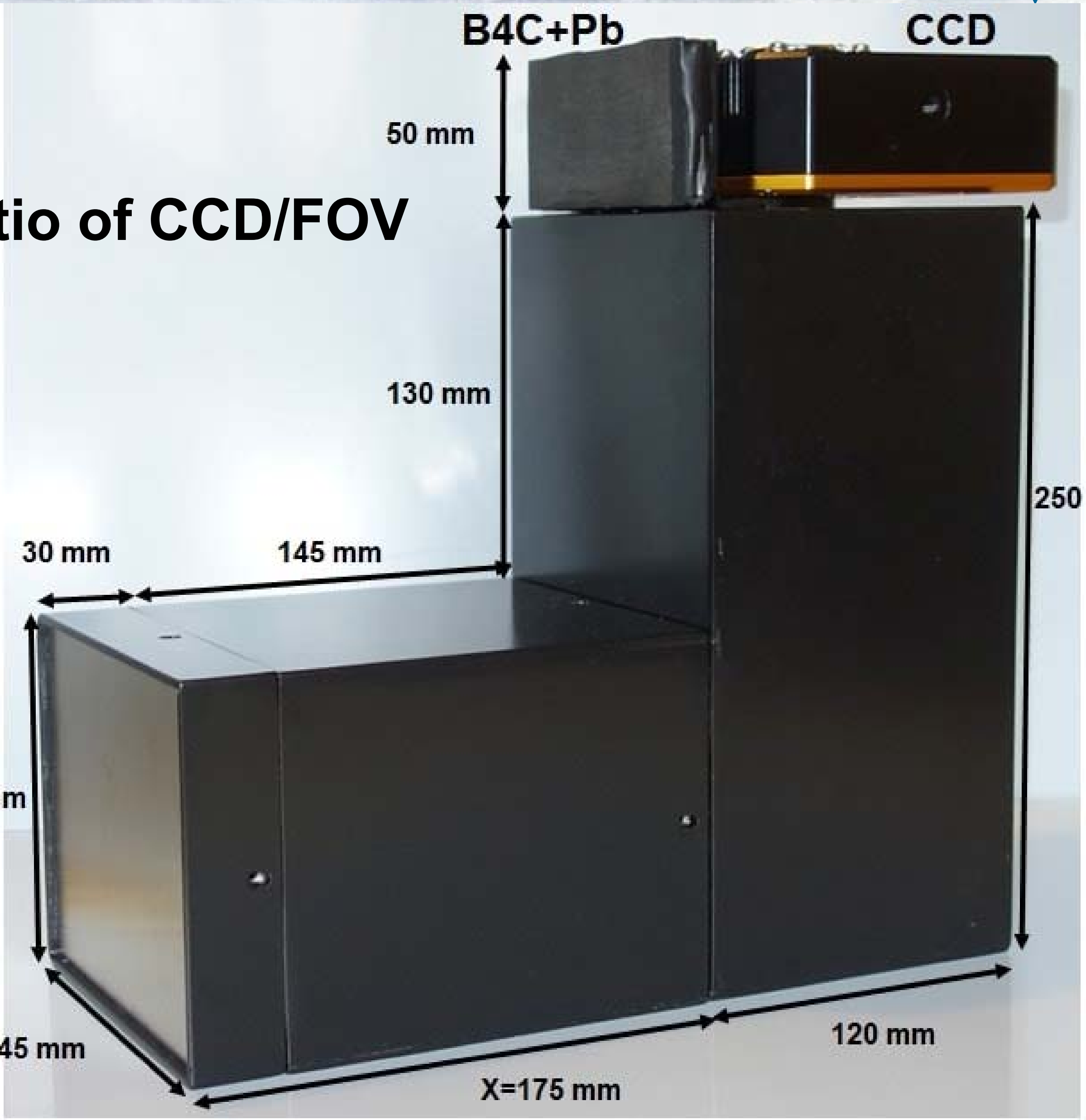
Why Compact?

- **Efficiency ~ Ratio of CCD/FOV**

So x4 faster than our

250x200 mm camera

But no magic solution

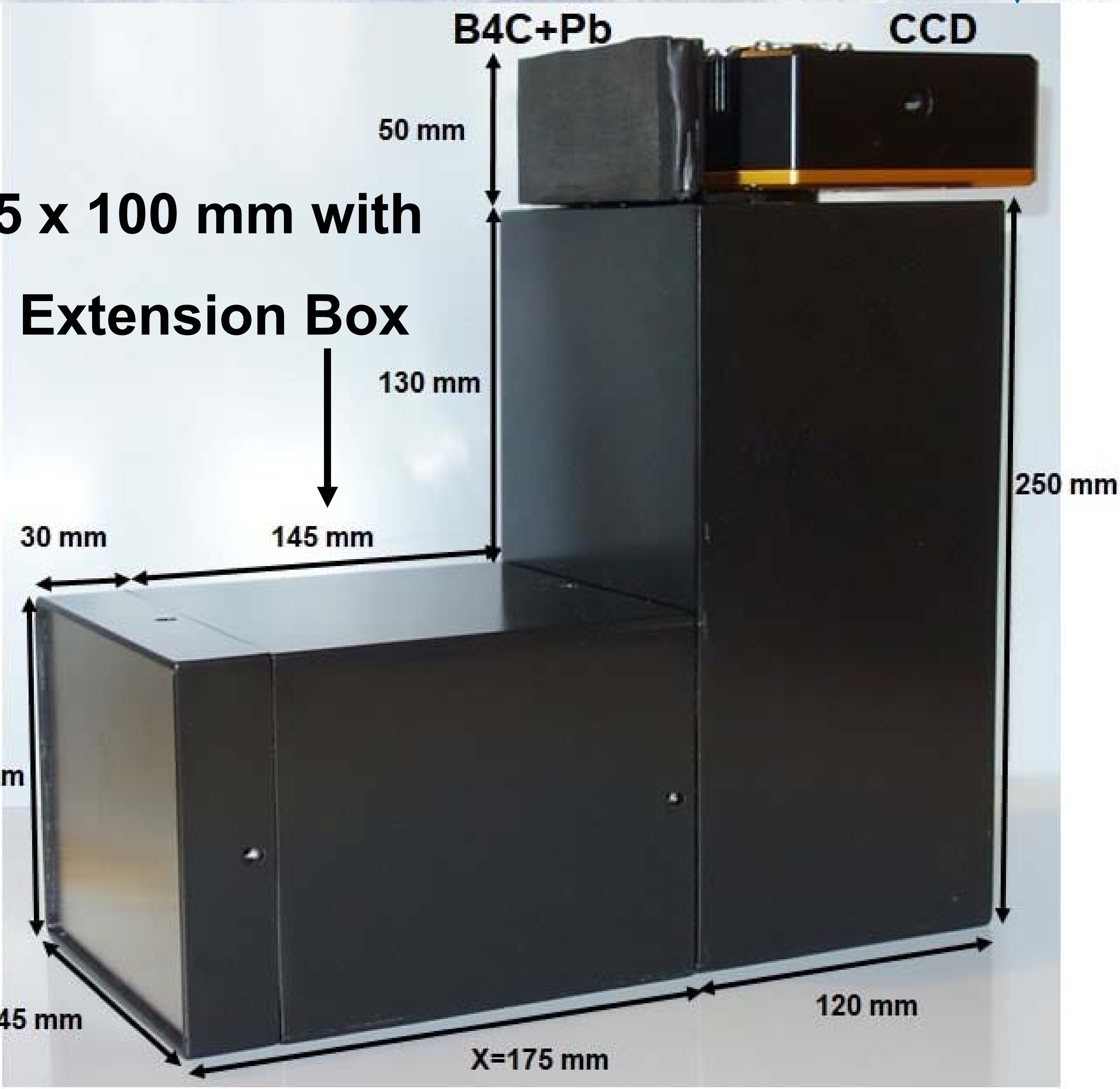


An efficient camera for fast neutrons

Alan Hewat, ILL and NeutronOptics Grenoble

Field-Of-View?

• 85 x 70 mm or 125 x 100 mm with an Extension Box

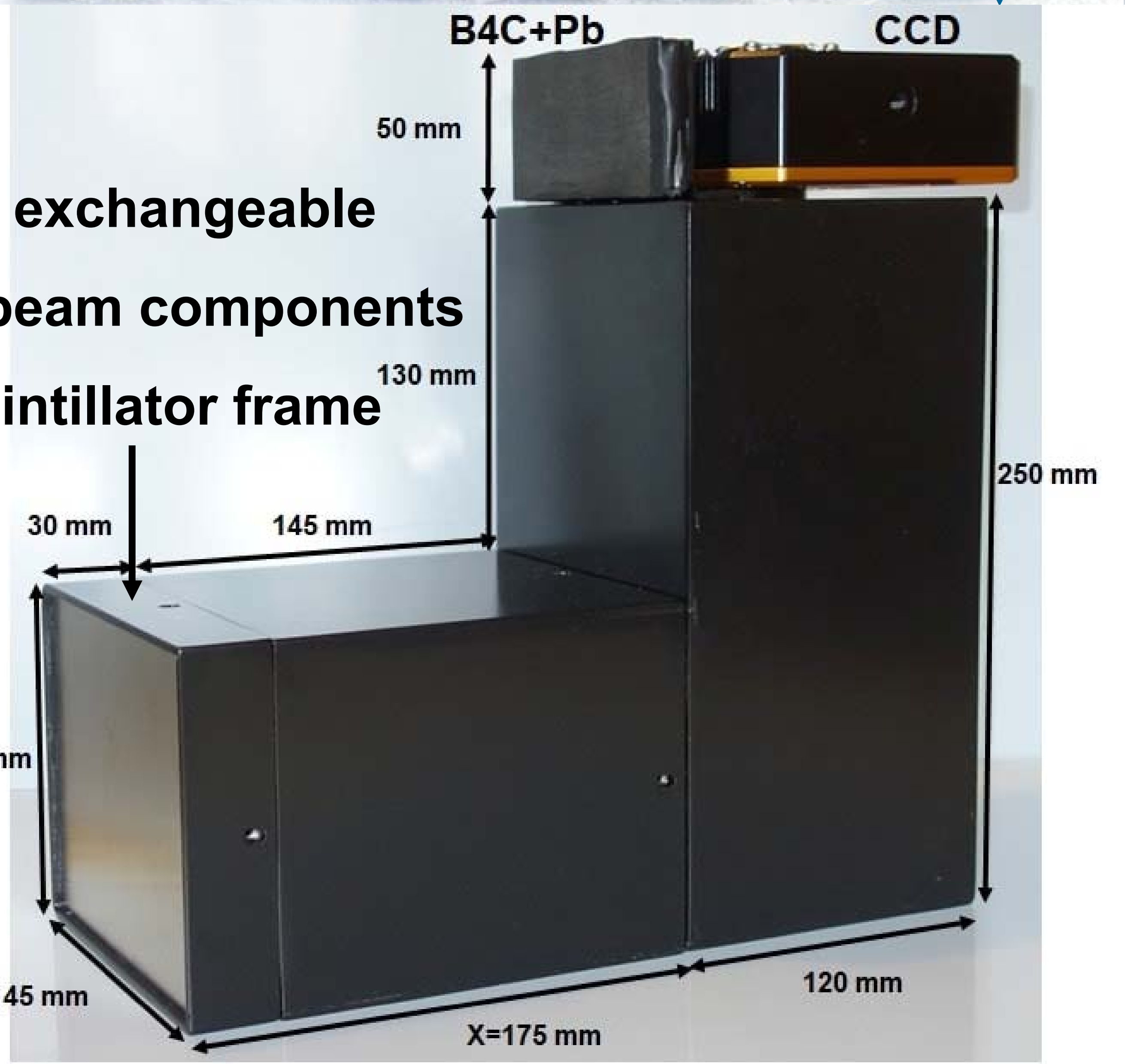


An efficient camera for fast neutrons

Alan Hewat, ILL and NeutronOptics Grenoble

Scintillator ?

- PSI/RC-TriTec PP exchangeable
- X-ray or thermal beam components



An efficient camera for fast neutrons

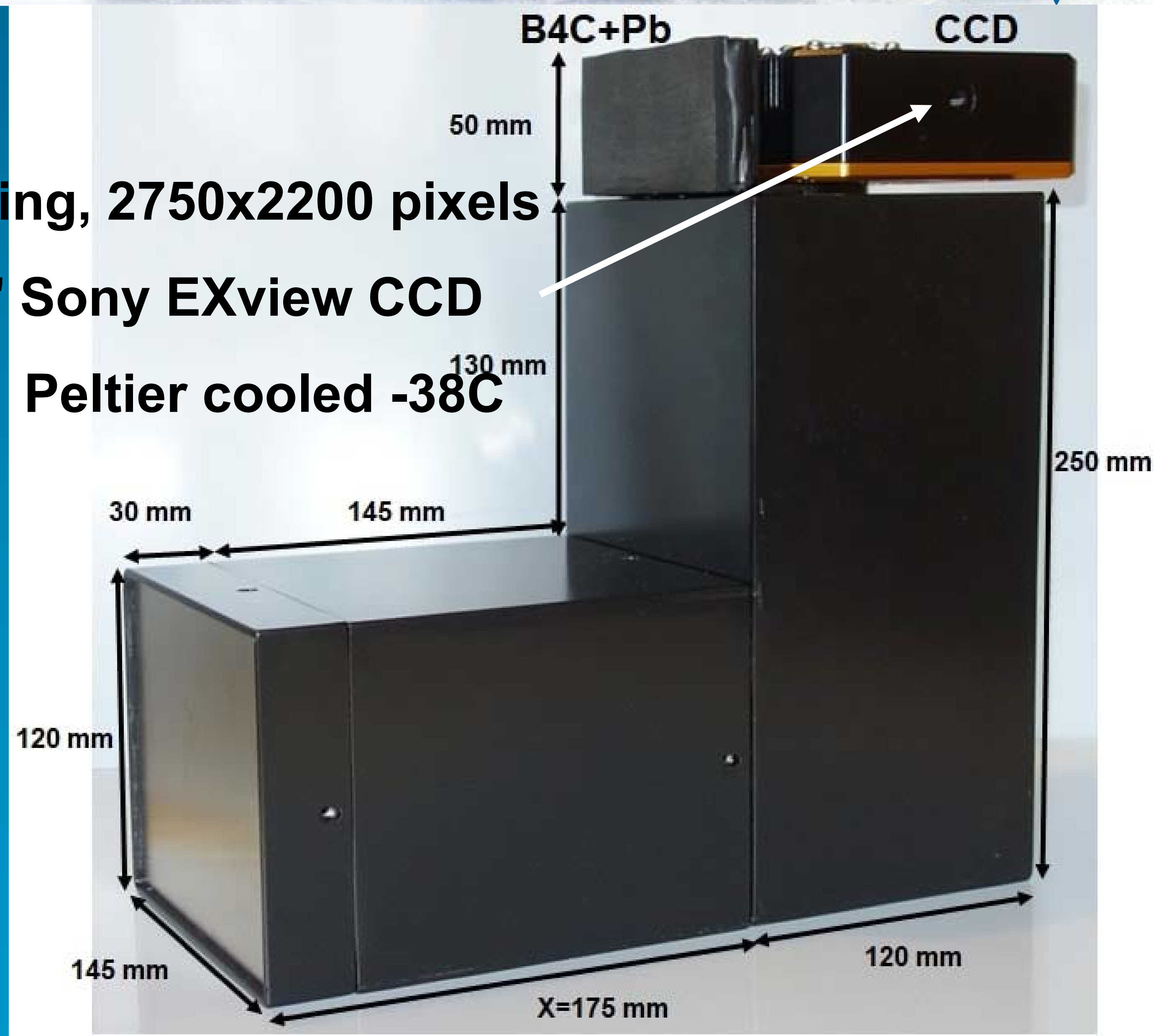
Alan Hewat, ILL and NeutronOptics Grenoble

Cold Sony CCD

- Up to 8x8 binning, 2750x2200 pixels

1" Sony EXview CCD

Peltier cooled -38C

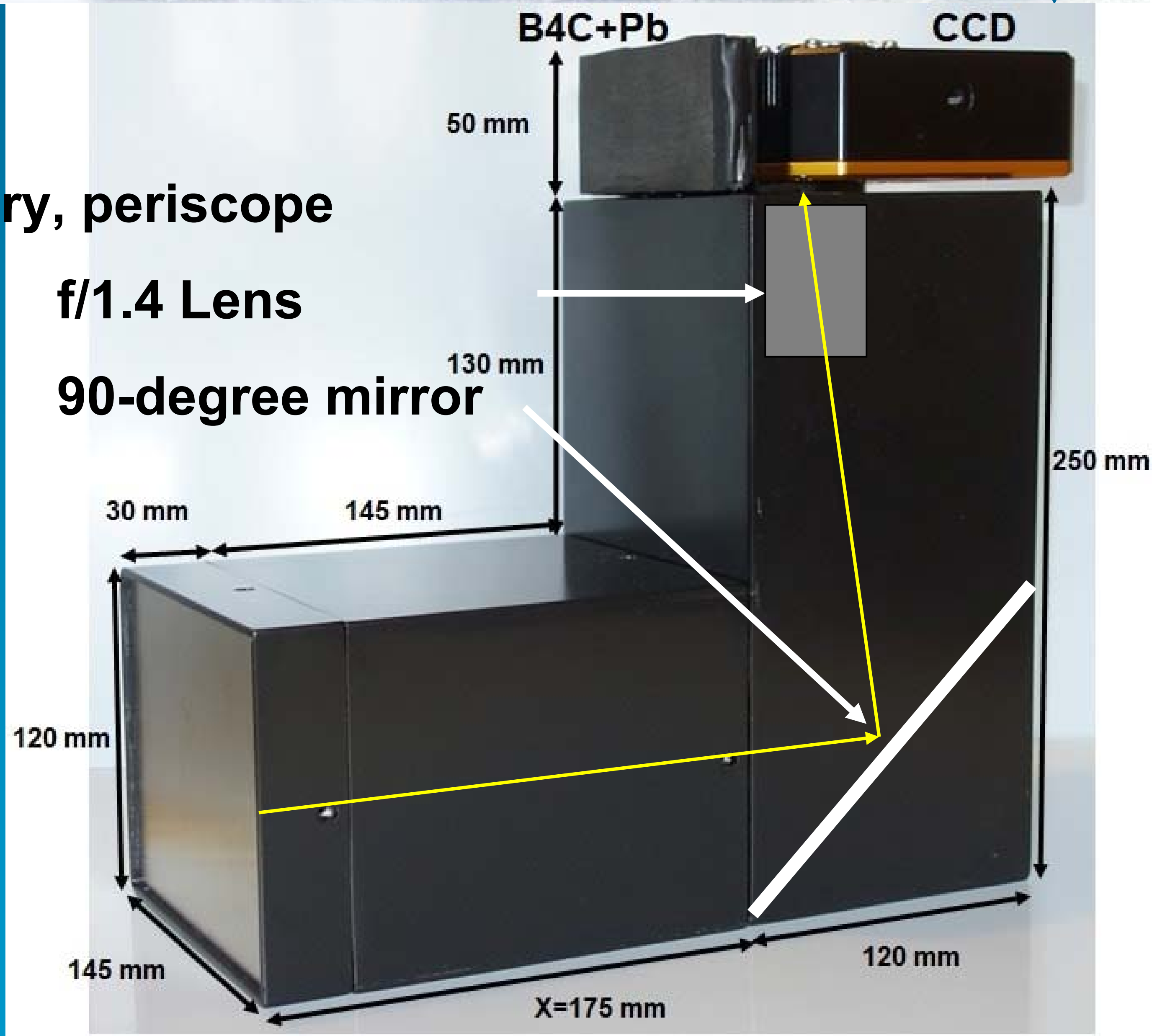


An efficient camera for fast neutrons

Alan Hewat, ILL and NeutronOptics Grenoble

Shielding

- Fixed Geometry, periscope

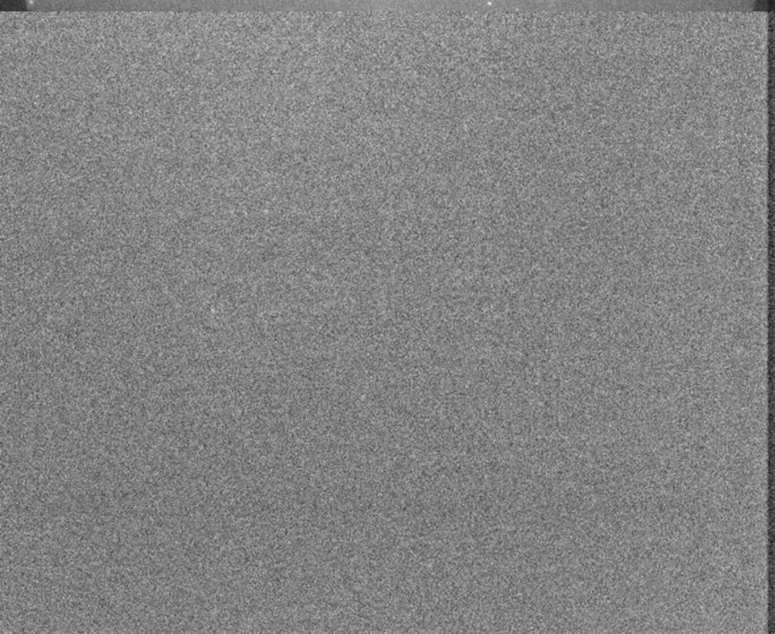


- Shielding
- Simplicity
- Repair cost

A Small Problem…

PP/ZnS afterglow spots (ZnS clusters)

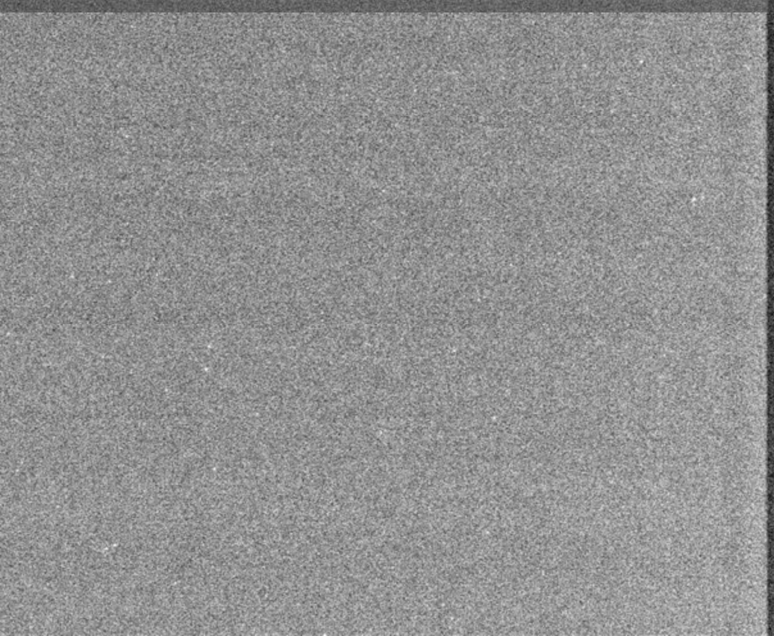
10 minute exposure after >1hr in darkness
Confirmed by PSI, but not noticed earlier



10 minute exposure after >1 day in darkness
No spots seen in 600s exposure

An efficient camera for fast neutrons

Alan Hewat, ILL and NeutronOptics Grenoble



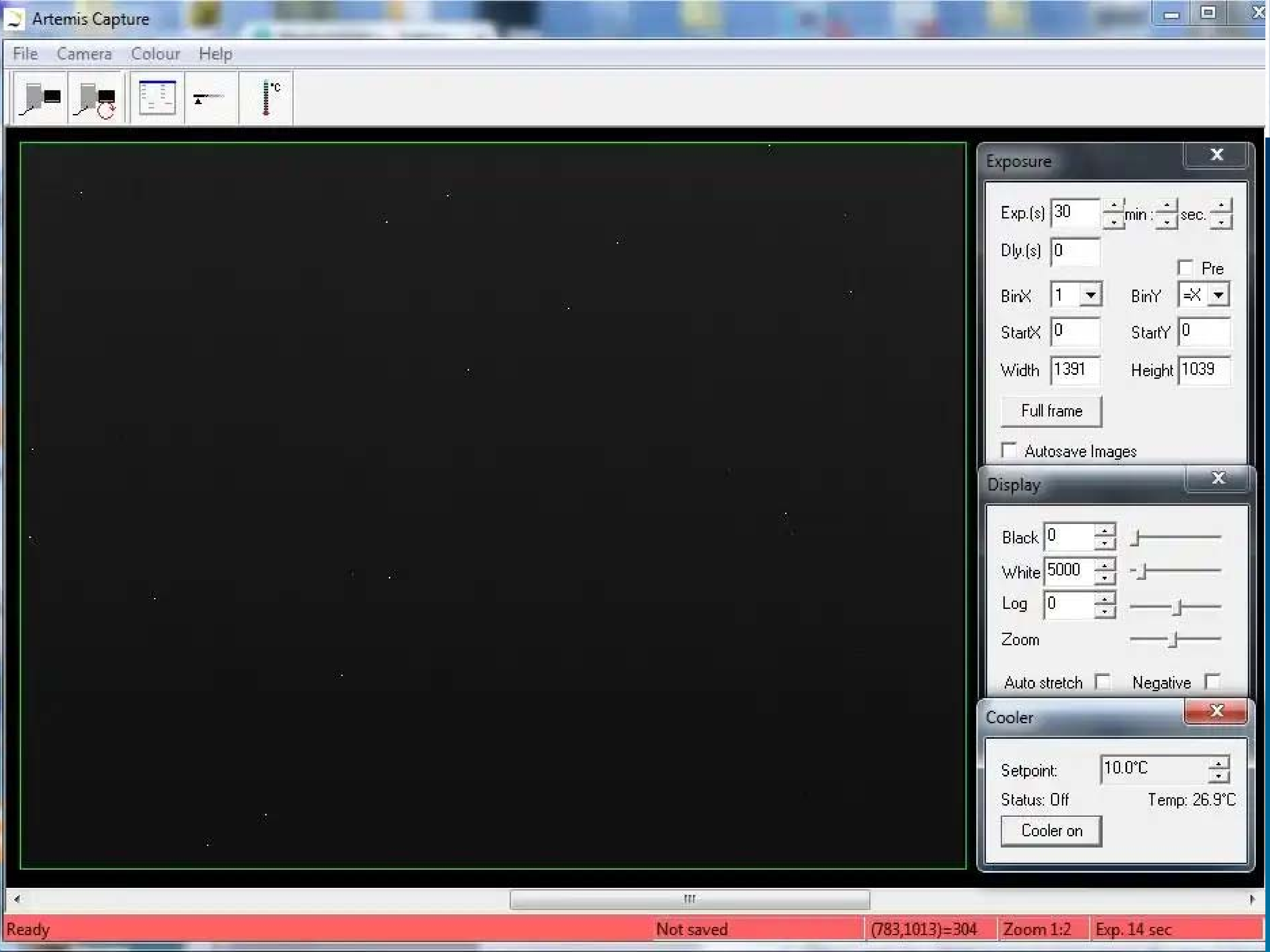
PP/ZnS afterglow spots (ZnS clusters)

1 hour exposure after >2 days in darkness
Camera sensitivity can still see faint spots
Amplifier glow at top with 1 hour exposure

Demonstrates high sensitivity and very low noise of Sony camera

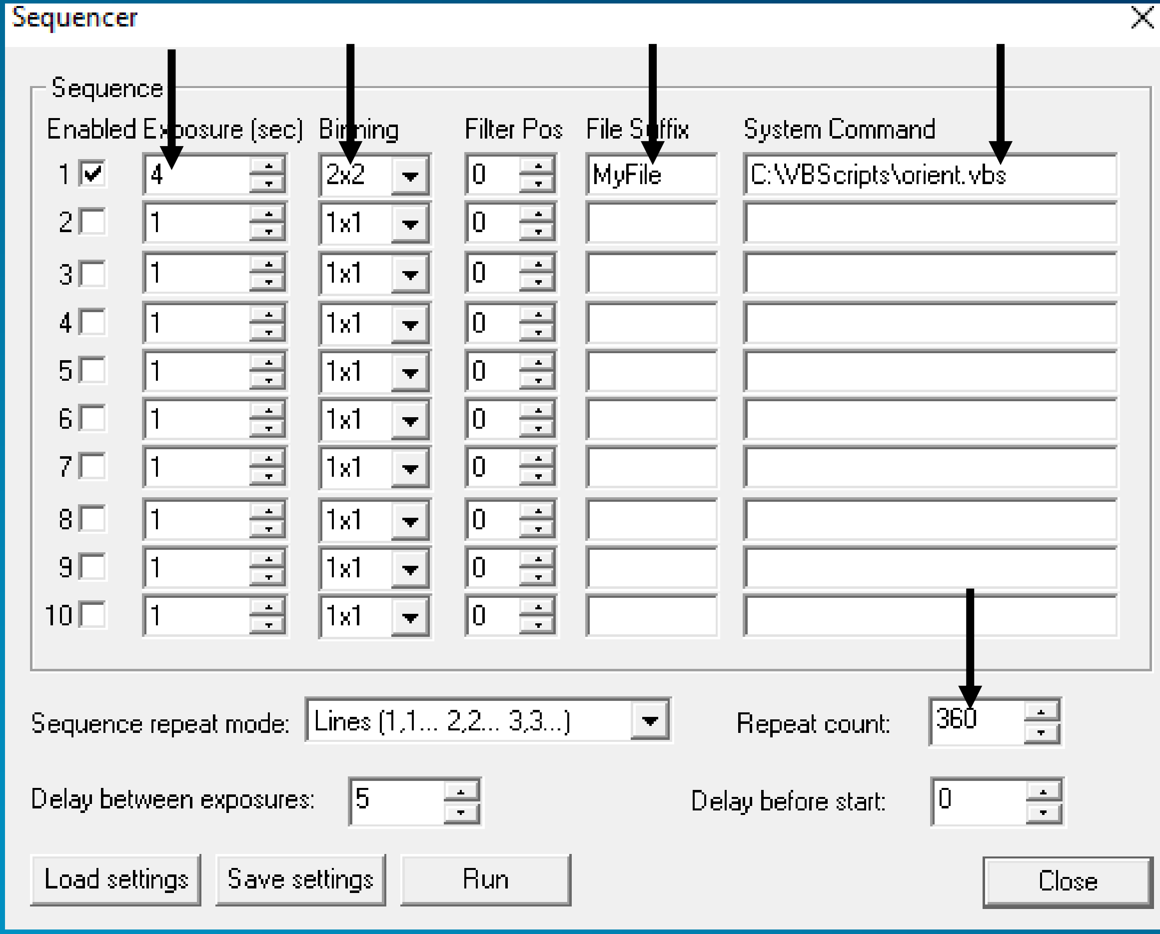
New PP/ZnS scintillator 250x200mm

10 minute exposure after 8 hours in darkness


Artemis Capture
File
Camera
Colour
Help
Exposure
Exp.(s) 30
min :
sec.
Dly.(s) 0
Pre
BinX 1
BinY =X
StartX 0
StartY 0
Width 1391
Height 1039
Full frame
Autosave Images
Display
Black 0
White 5000
Log 0
Zoom
Auto stretch
Negative
Cooler
Setpoint: 10.0°C
Status: Off
Temp: 26.9°C
Cooler on
Ready
Not saved
(783,1013)=304
Zoom 1:2
Exp. 14 sec

Camera Acquistion and Synchronisation software

- Expose 4 seconds
- Bin 2x2
- Readout to “MyFile”
- Execute stepping VBS script
- Repeat 360 times
- Execute another sequence



An efficient camera for fast neutrons

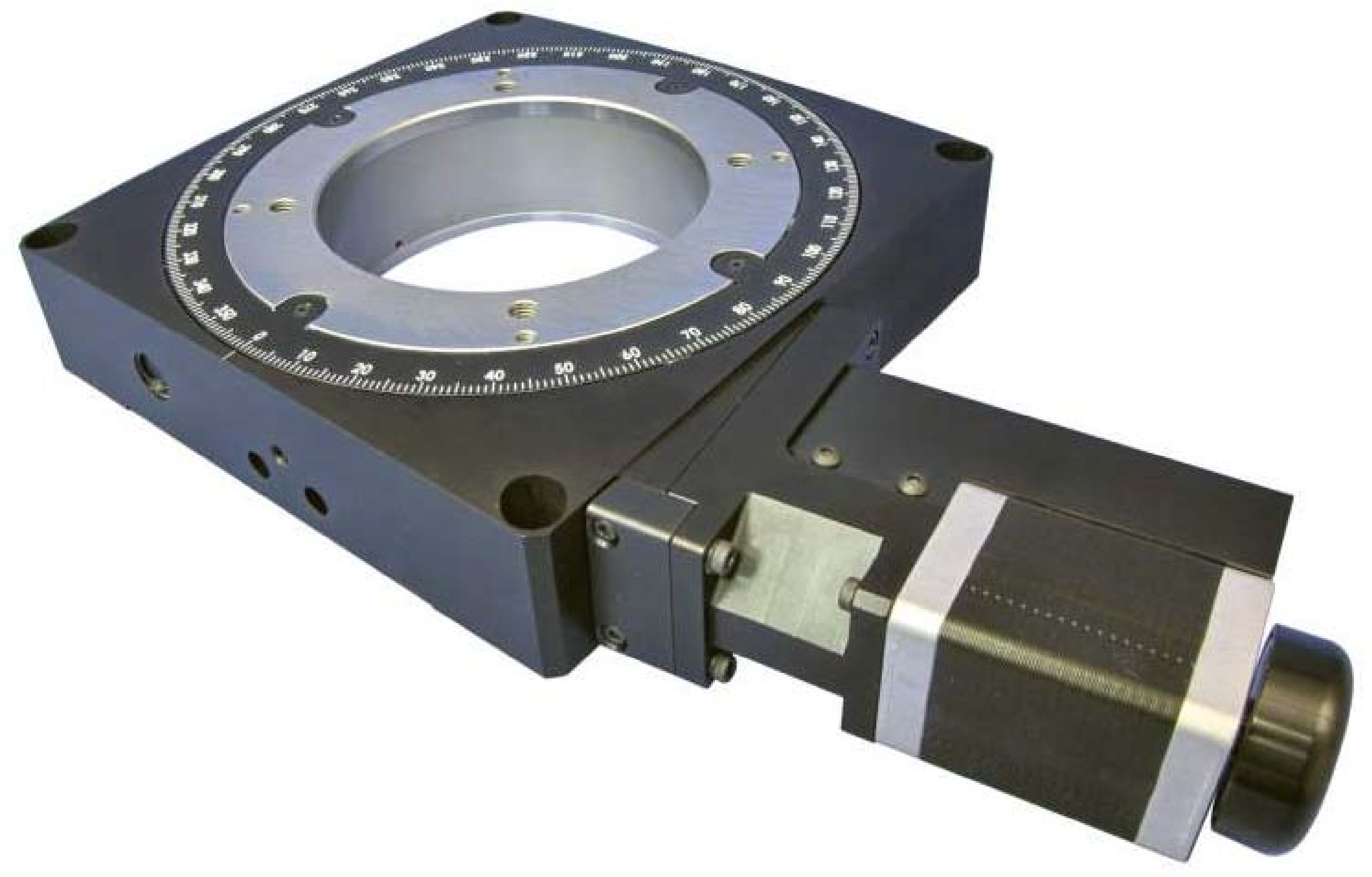
Alan Hewat, ILL and NeutronOptics Grenoble

Newport USA

Tomography

Mechanics

Made in France



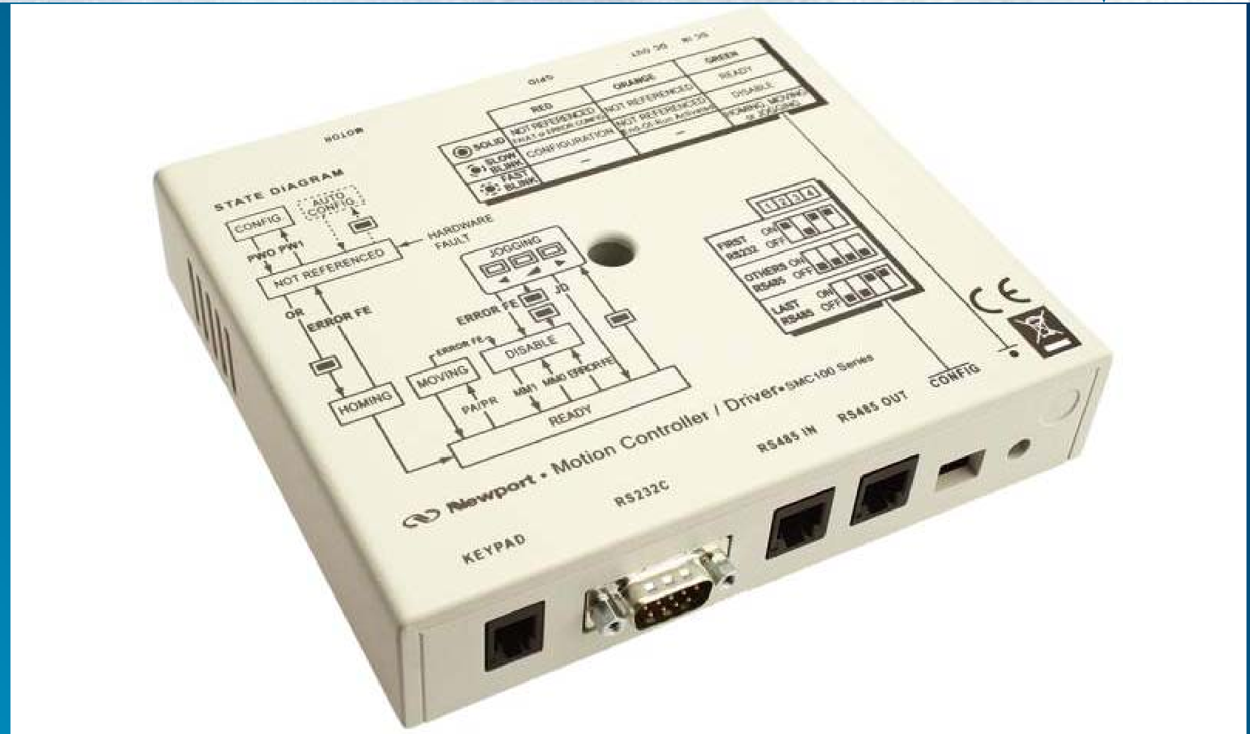
Micro-Controle France Motorized 360° stepping stage, URS150
Aperture 90mm, 30kg load, 40°/s, ±0.35 mdeg, wobble ±12 μrad

An efficient camera for fast neutrons

Alan Hewat, ILL and NeutronOptics Grenoble

Micro-Controle France
360° stepping controller

USB connect to Windows,
Control with *.BAT scripts
Or remote manual control



C:\commands.bat | Plink -v -serial COM4 -sercfg 57600,8,n,1,N   Port #4 Link Plink

This pipes the following Commands.bat script to execute stepping commands:

echo 1PR0.5	Position motor #1 Relative 0.5^o
timeout /t 1 /nobreak >nul 2>&1	Timeout eventually in 1 second
taskkill /f /IM Plink.exe	Kill port link Plink when finished
exit	**SIMPLICITY**

An efficient camera for fast neutrons

Alan Hewat, ILL and NeutronOptics Grenoble

Sample Alignment

Translation stages

Sample plate

Elevation stage

Manual alignment

An efficient camera for fast neutrons

Alan Hewat, ILL and NeutronOptics Grenoble

Promote the wider use of Neutron & X-ray Imaging…

… with technically competitive yet inexpensive cameras

Thank you for your attention…

An efficient camera for fast neutrons

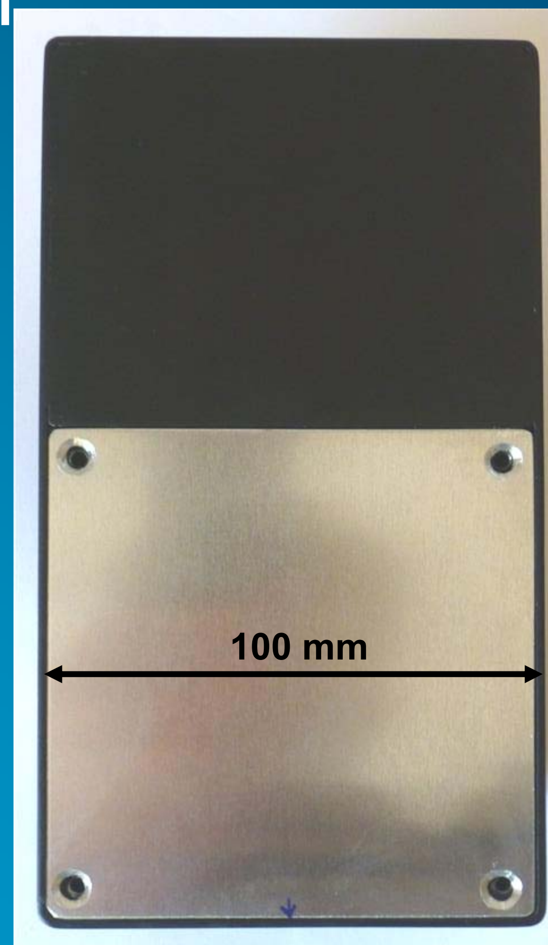
Alan Hewat, ILL and NeutronOptics Grenoble

Is a larger CCD a big advantage ? Field-Of-View (FOV)

Efficiency ~ CCD/FOV area. But a large CCD implies large FOV, low efficiency?

25 mm f/0.95 Voigtlander MFT
2013 NeutronOptics Saclay

- Image area 17.3x13.0 mm MFT
- Min. Focus Distance=175 mm
- FOV at MFD = 100x78 mm
- Area CCD/FOV ~ 2.66%



Alan Hewat, ILL and NeutronOptics Grenoble

A compact neutron camera for fast neutron tomography

Support from an International Agency, using PSI / RC-Tritec PP scintillators

- The scintillator can be exchanged in-situ for thermal neutron or gamma scintillators to test beam components
- The FOV with a cooled 16-bit 1” Sony CCD is 125x100 mm or 85x70 mm with 2750x2200 pixels and up to 8x8 binning
- The L-shaped periscope design allows good radiation protection, simplicity and low repair cost
- Newport Micro-Controle (France) mechanics for tomography are synchronised with imaging using *.bat Windows scripts

An efficient camera for fast neutrons

Alan Hewat, ILL and NeutronOptics Grenoble

Is a larger CCD a big advantage ? Field-Of-View (FOV)

Efficiency ~ CCD/FOV area. Reduce min. focus -> reduce FOV = increase effic

25 mm f/1.4 Zeiss Interlock

- Imaging area 24x36 mm
- Min. Focus Distance=252 mm
- FOV at MFD = 327x218 mm
- Area CCD/FOV ~ 1.2%

35 mm f/1.4 Zeiss Interlock

Imaging area 24x36 mm
Min. Focus Distance=300 mm
FOV at MFD = 273x182 mm
Area CCD/FOV ~ 1.7%

- **So a larger CCD is not more efficient**
- But f/0.95 is x2 as bright as Zeiss f/1.4

And Voigtlander cannot image 35mm

ZEISS Interlock 1.4/25

ZEISS Interlock 1.4/35

Ikon-L936 (e2V CCD42-40) is a good camera, BUT…

Specifications Summary[3]

Active pixels	2048 x 2048
Sensor size	27.6 x 27.6 mm
Pixel size (W x H)	13.5 µm x 13.5 µm
Active area pixel well depth	100,000 e^- (150,000 e^- for BR-DD model)
Maximum readout rate	5 MHz
Read noise	2.9 e^-
Maximum cooling	-100°C
Frame rate	0.95 fps (full frame)

Not really true

Specifications are NOT all obtained SIMULTANEOUSLY

An efficient camera for fast neutrons

Alan Hewat, ILL and NeutronOptics Grenoble

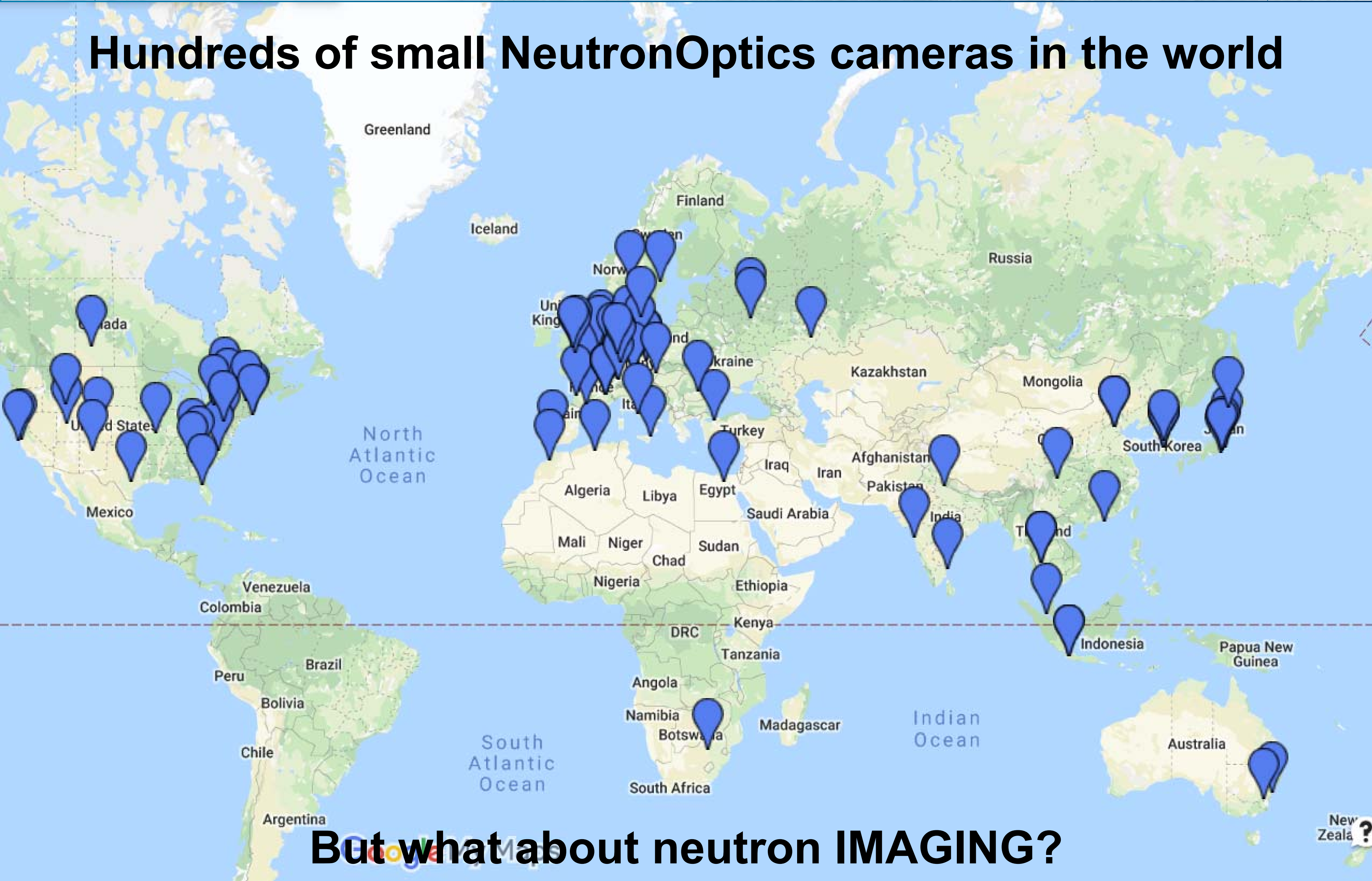
Starting in 2005 – simple cameras for sample alignment

We sold such cameras to many labs - including to Japan, and PSI Switzerland !

An efficient camera for fast neutrons

Alan Hewat, ILL and NeutronOptics Grenoble

Hundreds of small NeutronOptics cameras in the world



But what about neutron IMAGING?

Advanced Imaging Cameras – Our Clients include...

- Egyptian Atomic Energy Authority EAEA, Egypt (via an international Agency)
- Laboratoire Leon Brillouin (LLB) Saclay, Paris France
- NTEC New Technology Engineering Center Academy of Sciences, Samara, Russia.
- Joint Institute for Nuclear Research Dubna near Moscow, Russia.
- Thailand Institute of Nuclear Technology (TINT) Bangkok, Thailand
- Centre de Recherche Nucleaire de Birine (CRNB) Algeria
- Colorado School of Mines Physics Department, Golden, Colorado, USA.
- Laboratory for Thermal-Hydraulics Paul Scherrer Institute, Switzerland.
- UF Training Reactor University of Florida, USA.
- Malaysian Institute of Nuclear Technology (MINT) Malaysia
- Sandia National Laboratories, Livermore, California, USA.
- Indira Gandhi Centre for Atomic Research (IGAR) Kalpakkam, Tamil Nadu, India
- NFRI National Fusion Research Institute Daejeon, Korea.
- TechValley Korea X-ray inspection, Seoul, Korea.
- BARC Bhabha Atomic Research Centre, India
- Idaho National Laboratory Materials and Fuels, Idaho Falls, USA.
- CNESTEN Center for Nuclear Techniques, Morocco (via an international Agency)
- İTÜ Energy Institute Istanbul Technical University, Turkey
- University of Texas at Austin Nuclear and Radiation Engineering, Texas, USA.
- Hokkaido University Graduate School of Engineering, Japan.
- Penn. State University Mechanical & Nuclear Engineering, USA.
- National Nuclear Energy Agency BATAN, Indonesia (via an international Agency)
- Adelphi Technology Neutron Sources, Redwood City, California, USA.
- Nuclear and Radiological Engineering Georgia Institute of Technology, USA.
- Czech Technical University (CTU) Prague, Czech Republic