

Alan Hewat, ILL and Neutron Optics Grenoble



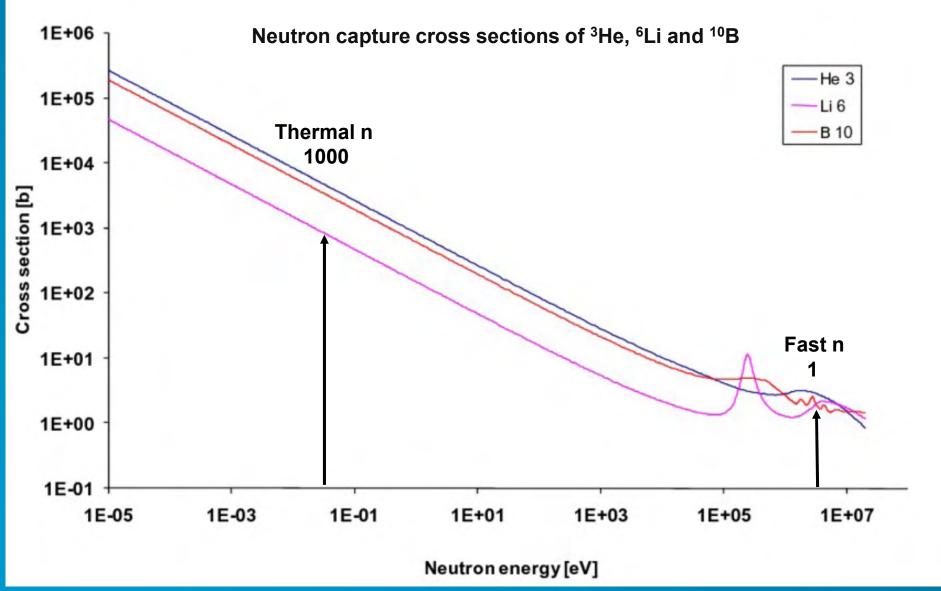




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Fast Neutron imaging is IMPOSSIBLE...



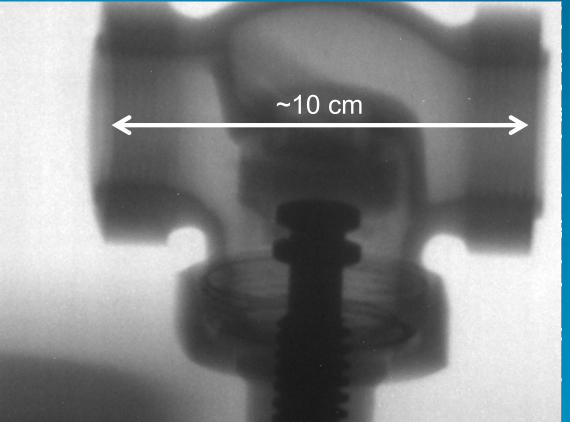


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2015 - First experience with "fast neutron imaging"

- Florida Uni. purchased our 200x200mm camera for their 1 MW Triga Reactor
- A student also tried our camera on an Adelphi D-T generator (3x10⁹ 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
- CCD chip was soon destroyed



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Fast Neutron imaging is IMPOSSIBLE...

The impossible takes a little longer

Availability of high flux D-D and D-T fast neutron generators

- 10¹⁰ D-D n.sec⁻¹ Ted Cremer, Michael Taylor & Robert Adams presentations Tuesday morning
- 10⁷ thermalised D-D n.sec⁻¹ Moderated Adelphi DD110M thermal neutron generator (Note: we can do THERMAL neutron imaging with <10³ n.sec⁻¹.cm⁻²)

But the Efficiency of fast neutron scintillators is very low

- Hot neutrons cannot be captured thermalisation (moderators) in reactors, accelerator sources
- Otherwise 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!
- Bernhard Walfort presentation 13:30 today

Direct imaging with large flat panels would be interesting

- But Gamma radiation from generators can destroy electronic detectors
- So we try to use less efficient optically coupled CCDs that can be shielded

Can we optimise a CCD camera for fast neutrons?







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

CCD	PCO.edge gold 4.2	NOptics VS60	NOptics 11002	iKon L-936
Туре	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



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Is a large CCD an advantage? 35mm CCD + Nikon f/1.2 (2016)











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

Efficiency ~ CCD/FOV area. But a large CCD implies 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

Large CCDs 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)



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

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

Also need a large 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%

Works well with macro-spacers To reduce focal dist. to 250mm



Current Zeiss 25mm f/1.4

Min. focal dist. 252mm 35mm min. FOV 327mm Area CCD/FOV ~ 1.2%

Alan Hewat, MLZ Experts 23 Oct 2019



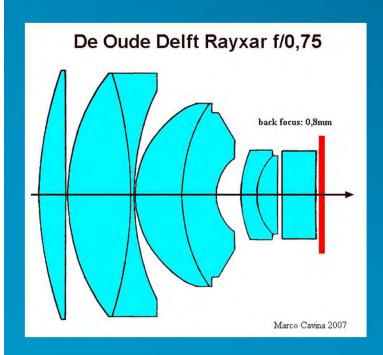
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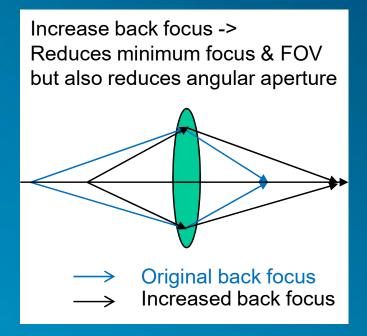
Is a large CCD an advantage? Field-Of-View (FOV)

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 ?
Currently being tested



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





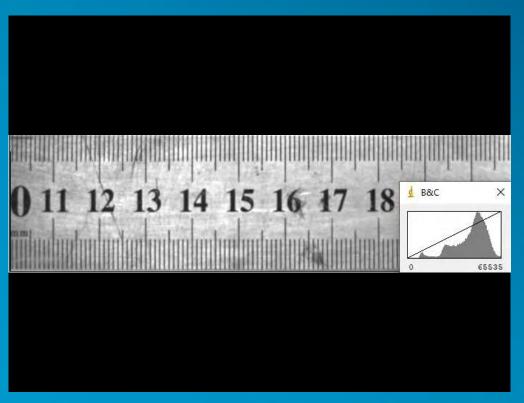
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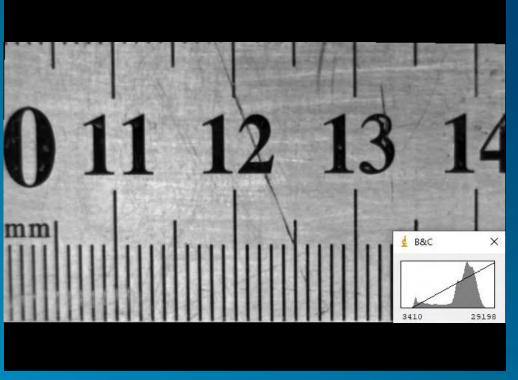


Is a large CCD an advantage? Field-Of-View (FOV)

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 ->>



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

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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...?



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- ICON quantum efficiency of 90% compared to 75%
- +15% is no big advantage (except for astronomy)
- Is ICON greater well depth a big advantage?

Well depth = number of electrons stored / pixel (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 ICON 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
- ICON specs for ideal conditions. Hot neutrons are not ideal Extreme cooling doesn't help with radiation background noise

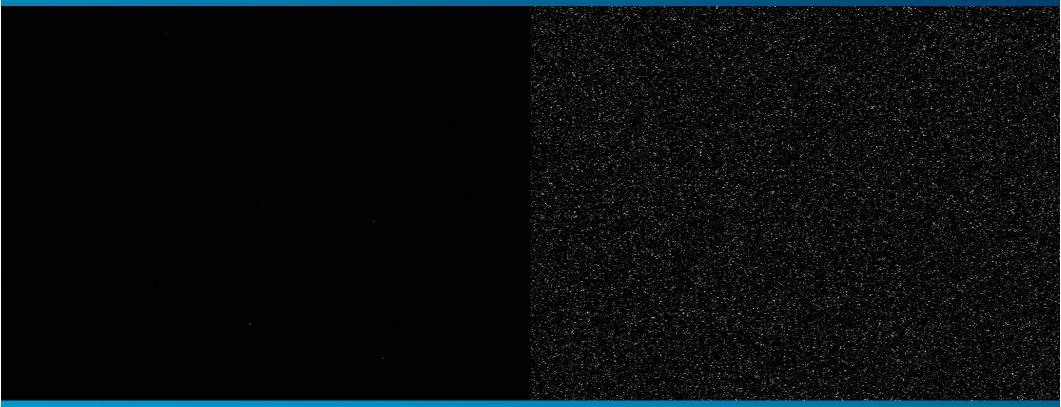


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N-generators eventually destroy CCDs – replacement cost?

Sony camera ~10% of ICON 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 ©

Alan Hewat, MLZ Experts 23 Oct 2019



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A large CCD is only an advantage for a large FOV

- ICON 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
- AND a lot less expensive to replace when damaged

EXAMPLE of 1" CCD camera efficiency and low noise

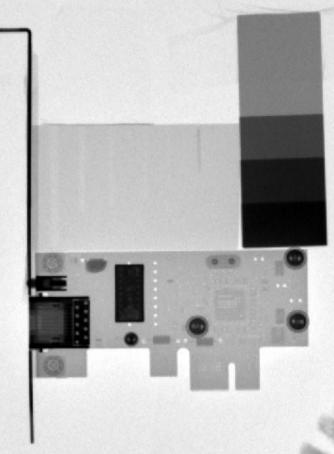
Robert Zboray at Penn. State University with low flux TRIGA reactor 250 x 200mm camera with THERMAL neutrons



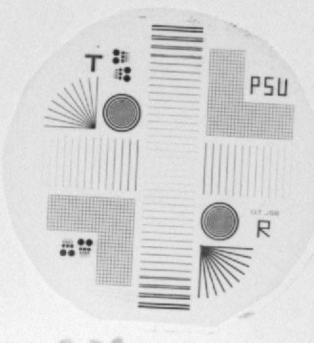
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100kW Triga reactor neutron image from our 1" CCD camera



1" Sony CCD efficiency Prof. Robert Zboray PSU





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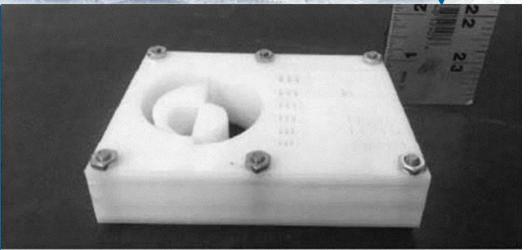


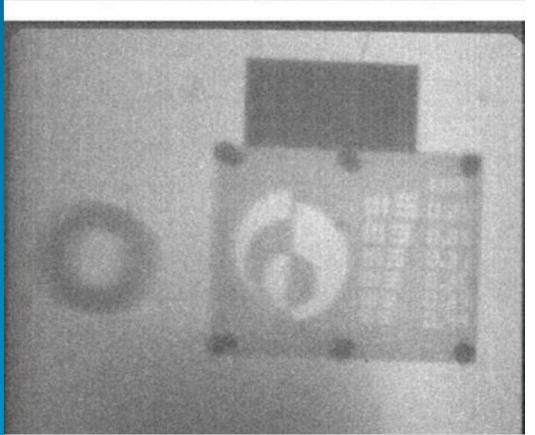
ADELPHI Fast Neutron image

- D.Williams, C. Brown, Ch. Gary, T. Kremer
- Our 200x200mm camera, PP scintillator
- Adelphi DT109-110 DT neutron generator
- 3x10⁹ n/s of 14 MeV neutrons
- 1" thick 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







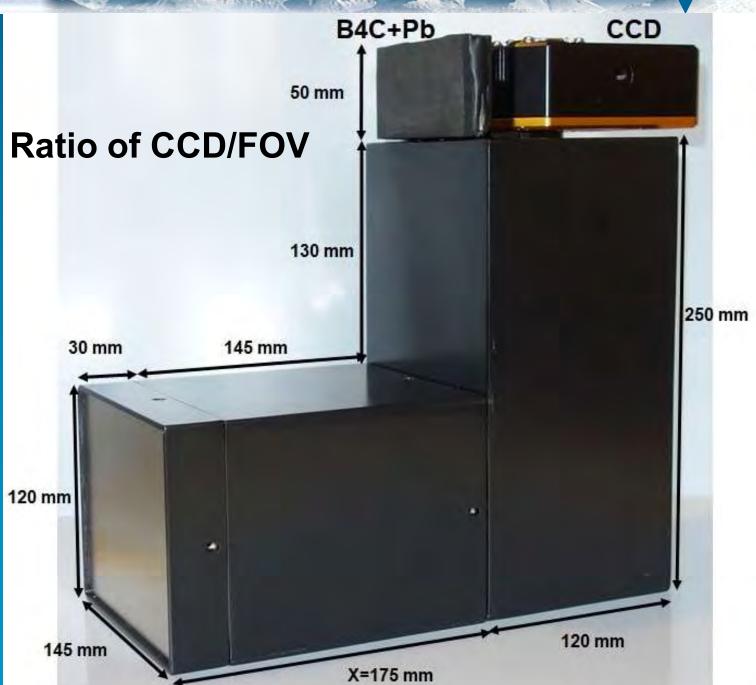
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Why Compact?

Efficiency ~

So x4 faster than our 250x200 mm camera But no magic solution

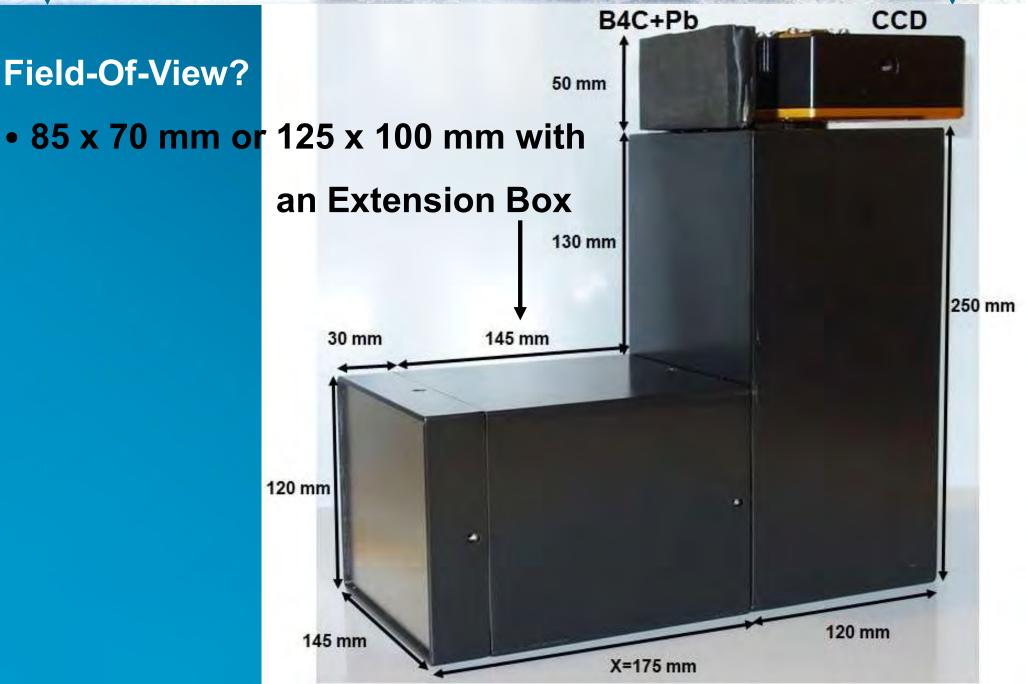




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Field-Of-View?





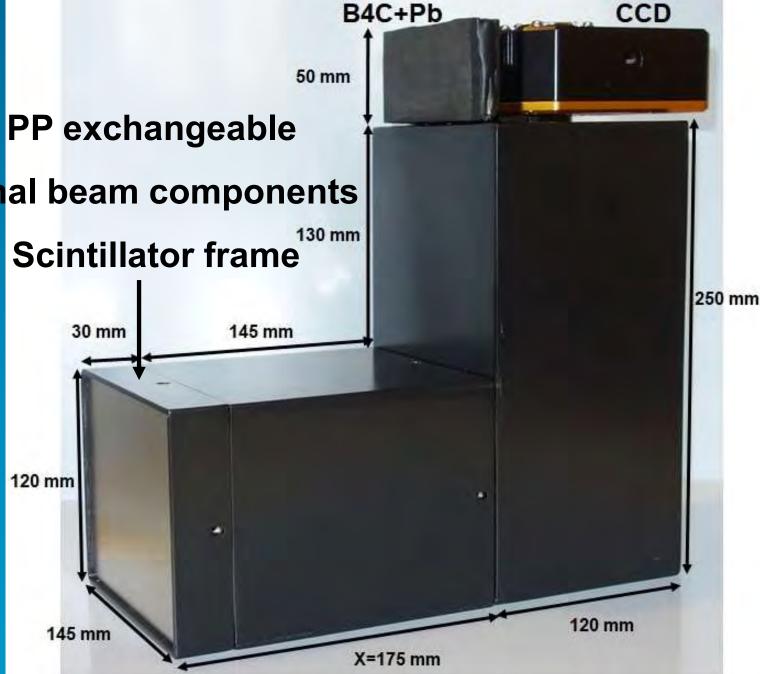
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Scintillator?

PSI/RC-TriTec PP exchangeable

X-ray or thermal beam components





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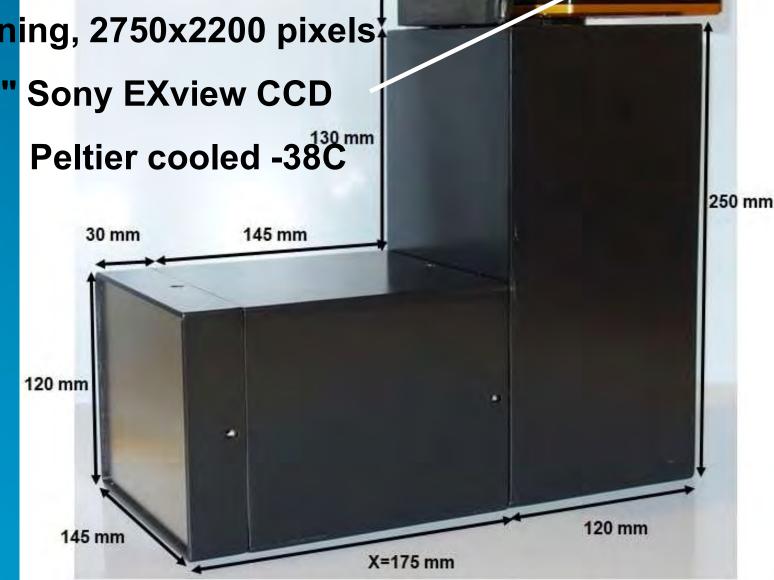


CCD

Cold Sony CCD

Up to 8x8 binning, 2750x2200 pixels

1" Sony EXview CCD



B4C+Pb

50 mm



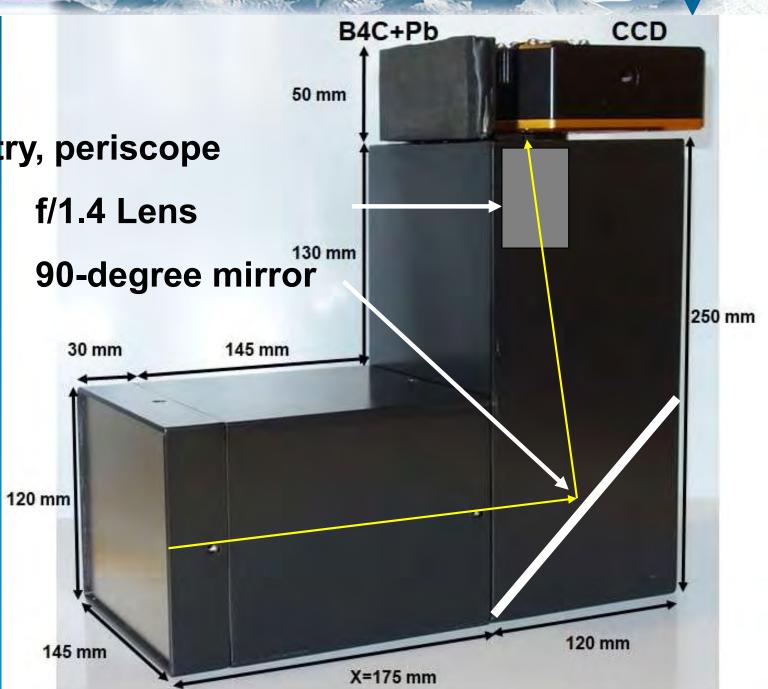
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Shielding

Fixed Geometry, periscope

- Shielding
- Simplicity
- Repair cost





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A Small Problem...

PP/ZnS afterglow spots (ZnS clusters)

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

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



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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

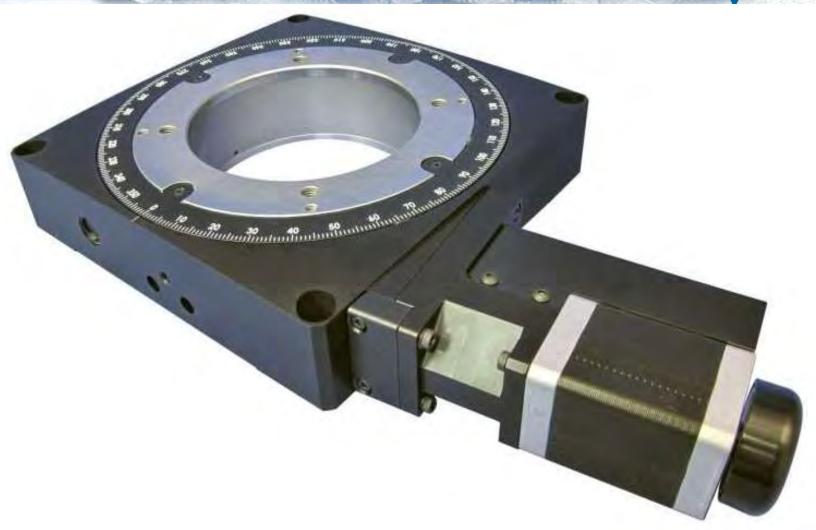


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Newport USA

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



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

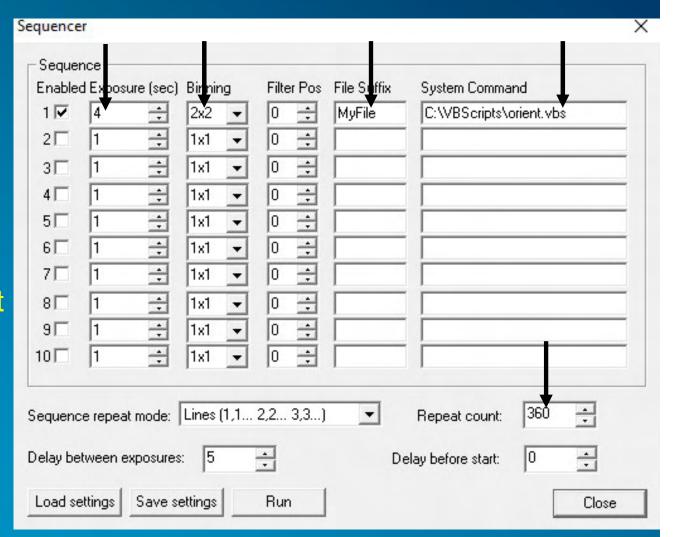






Camera Acquistion and Synchronisation software

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





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Translation stages

Sample plate

Elevation stage

Manual alignment









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