Electron Detectors, Old and New

John Matheson Feb 2013

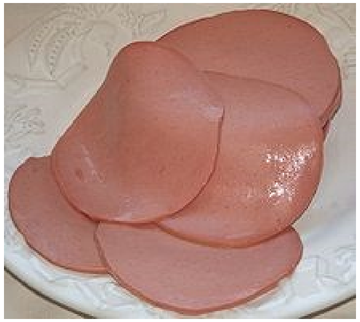
- I shall mostly talk about (imaging) detectors for XPEEM
- An application example: Warning, contains shellfish
- The XPEEM technique and instrumentation
- Introducing old and new detectors (MCP vs MAPS)
- Characterisation metrics for imaging detectors
- The RAL electron detector test system
- Some detector test results – imaging
- Some detector test results – counting
- Why have MAPS detectors not been adopted (yet) ?
- Summary and Conclusions

XPEEM application example – Abalone shell

See: *Architecture of Columnar Nacre, and Implications for Its Formation Mechanism*
Metzler at al, Phys Rev Lett 98, 268102 (2007)

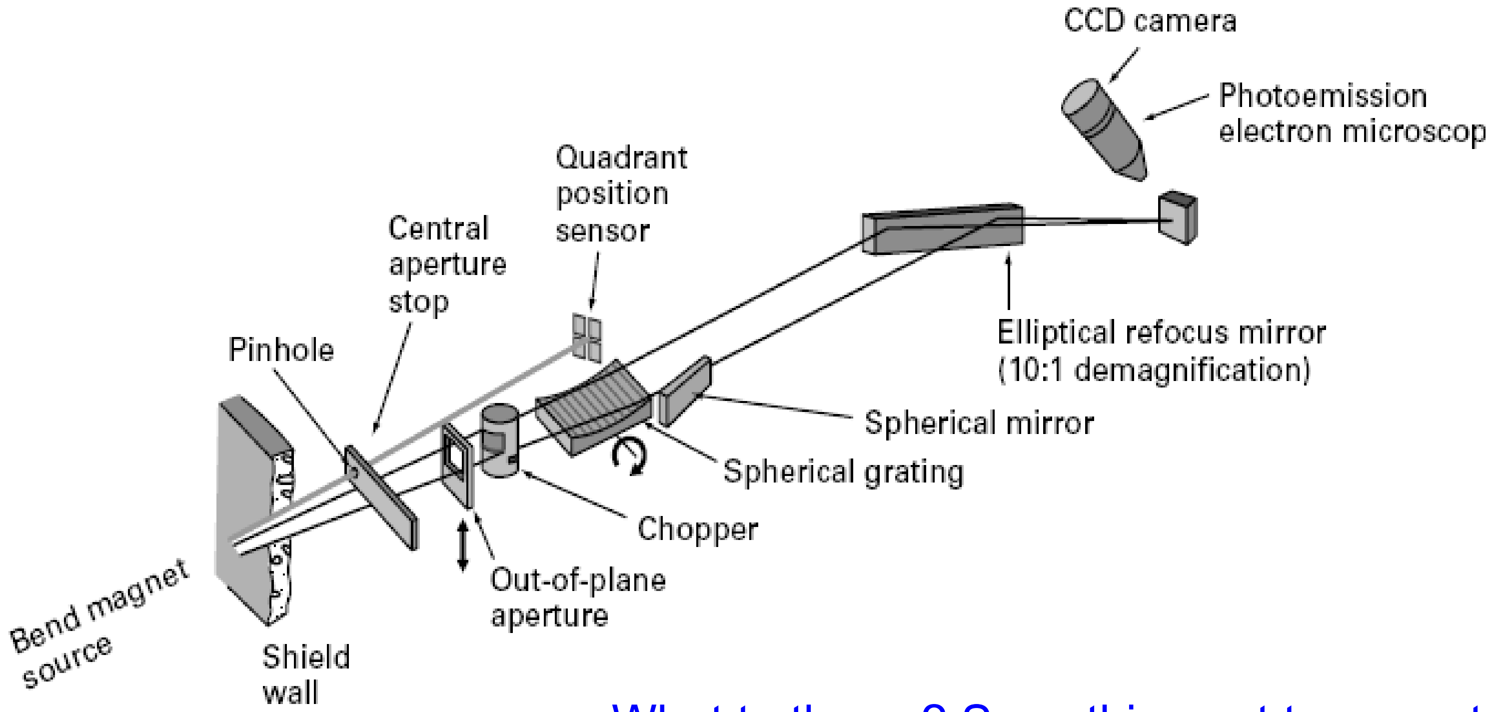
- Abalone shell has beautiful metallic sheen
- Mostly made of chalk !
- How does the organism build up the shell ?
- The excitement happens at a *surface*

- What techniques might we use to understand ?
- Time-honoured method: throw something at it and see what bounces back….
- (cf. Rutherford 1908)



- Not to be confused with a Baloney

XPEEM: a technique for studying surfaces



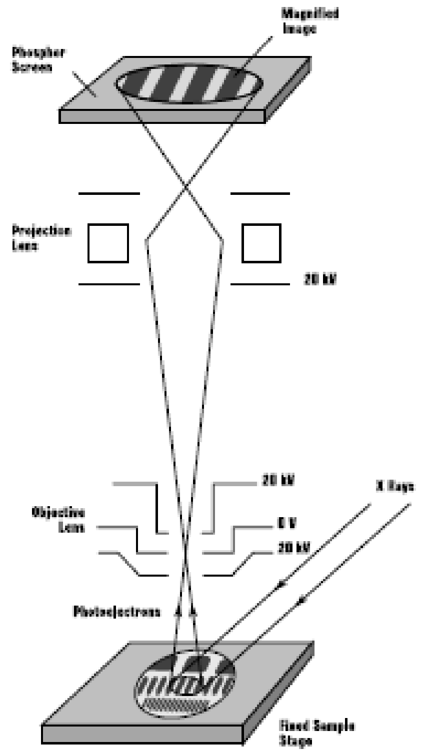
Schematic layout of Branchline 7.3.1.1.

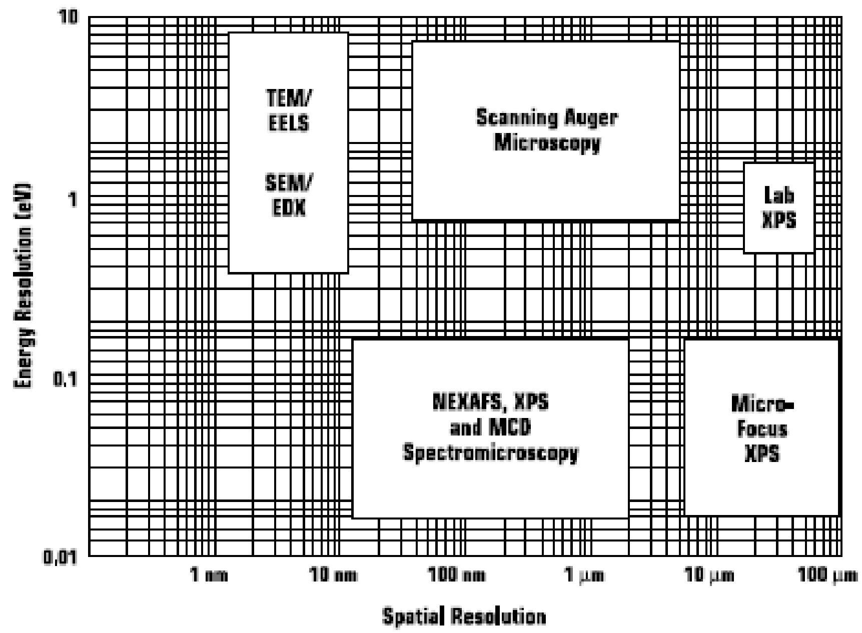
Advanced Light source (ALS)
Lawrence Berkeley Lab

What to throw ? Something not too penetrating
VUV photons
Soft X-ray photons
Low energy electrons

XPEEM: X-rays in, photoelectrons out

XPEEM: a technique for studying surfaces





XPEEM is a spectromicroscopy – spatial and energy resolution
ID of elements from electron binding energies
Energy filtering of electrons in some instruments
Electrons accelerated to 20keV

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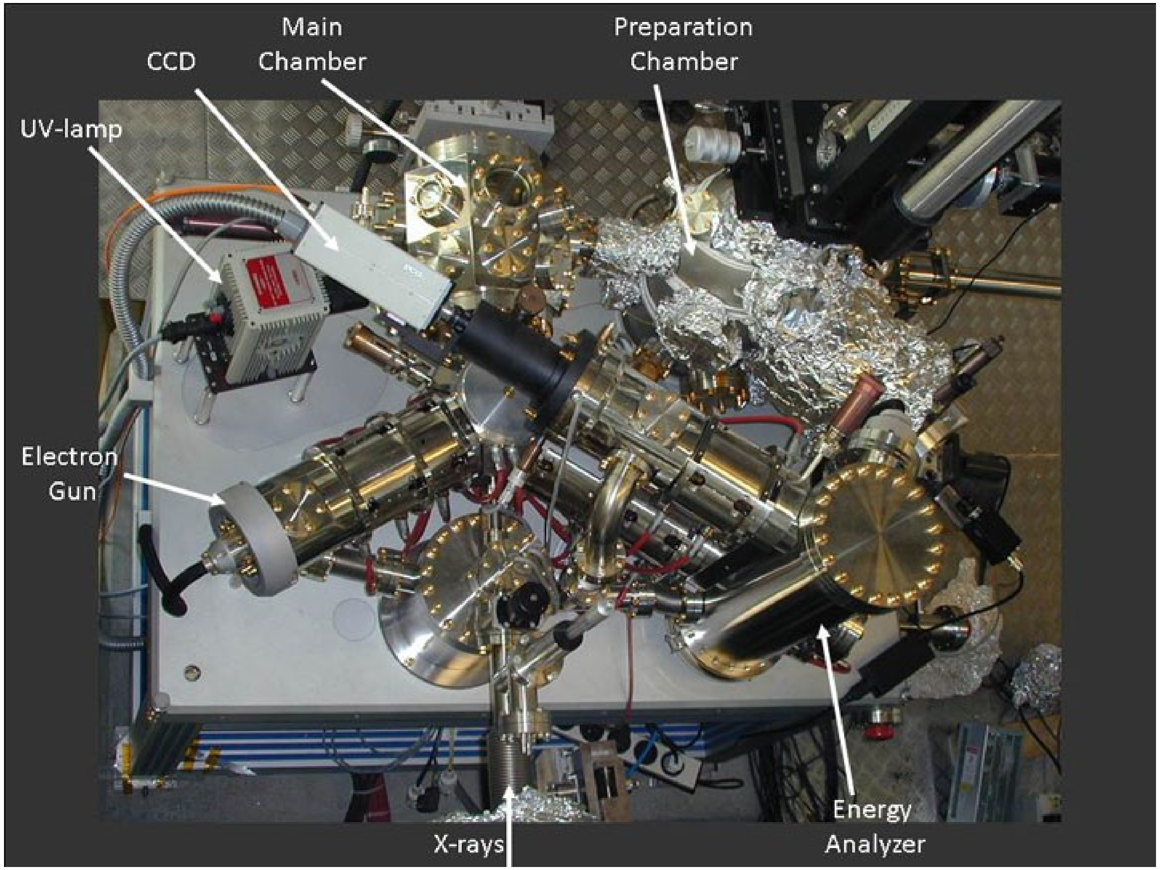
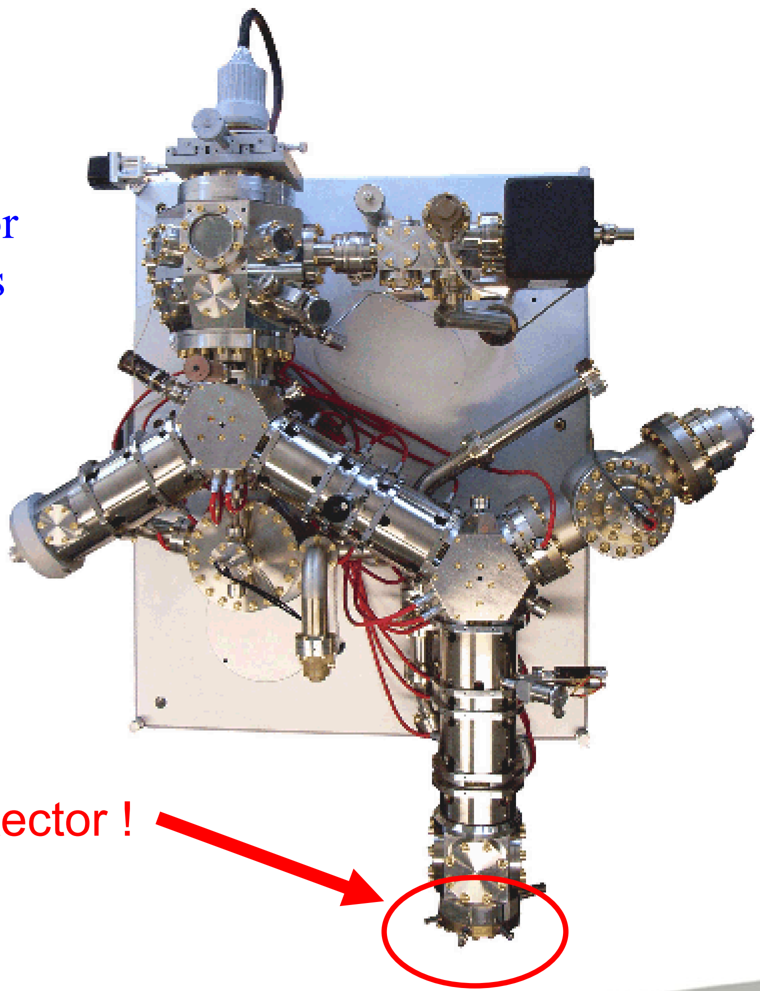
The Elmitec SPELEEM3 (at Elettra)



- excite electrons from sample: X-rays, UV, electron beam
- electron optics gives x20000 magnification, 8nm resolution (claimed)
- imaging energy filter improves resolution

The most recent development: aberration correction

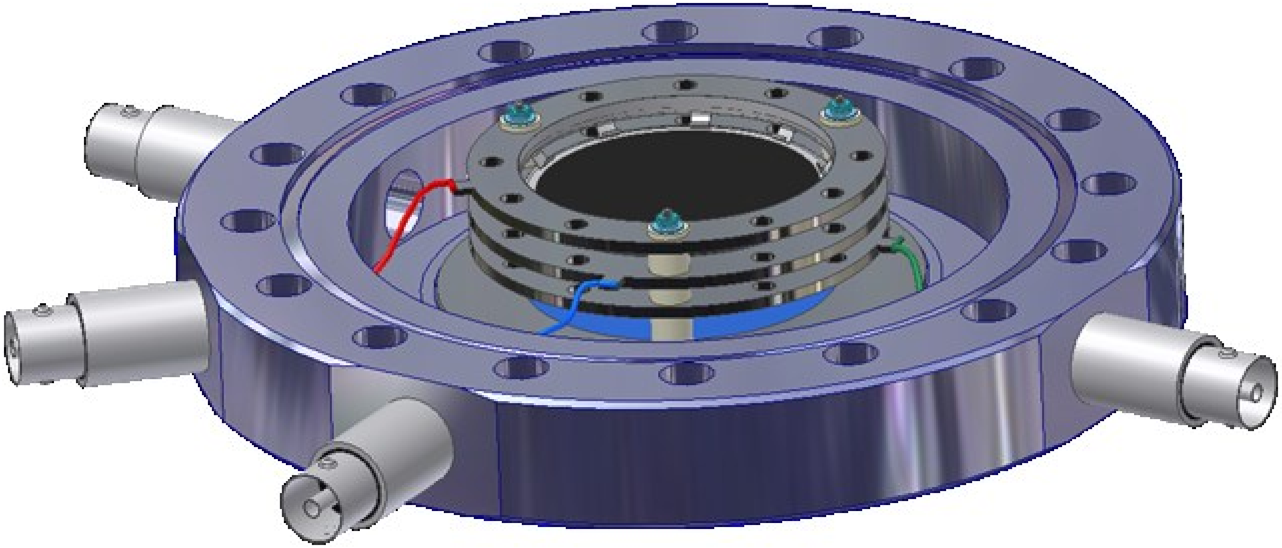
- aberration correction by electrostatic mirror
- mirror can be tuned to generate aberrations compensating those of the objective lens
- 3nm resolution (calculated)
- factor of 8 increase in flux at the detector (calculated)



Same old detector !

See e.g. Wichtendal et al., "*SMART: An aberration-corrected XPEEM/LEEM with energy filter*",
Surf Rev & Lett Vol.5 Iss.6 P.1249 (1998)

Microchannel plate detector: the current standard



- standard on Elmitec instruments
- uses Burle MCPs, phosphor screen, FO feedthrough
- Sensicam cooled CCD camera, lens coupling
- also used: MCP + delay line anode
- also used: scintillator + CCD
- Is it any good ?

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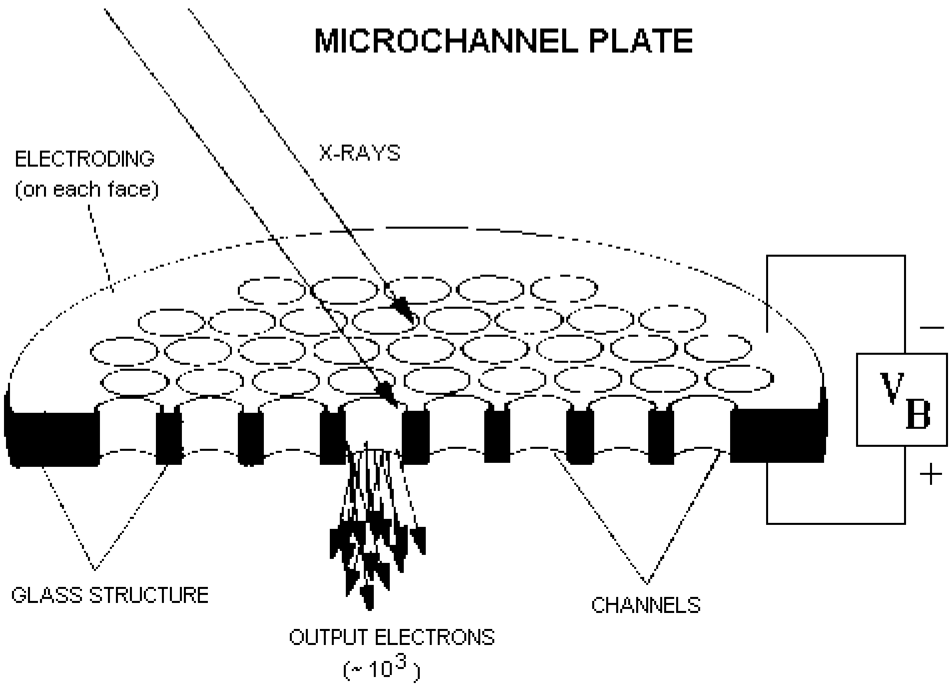
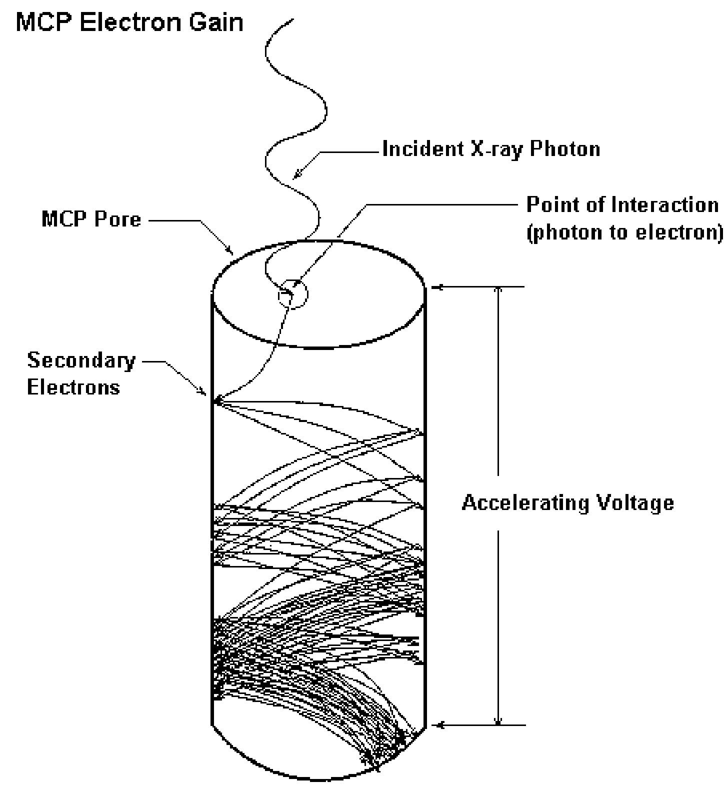
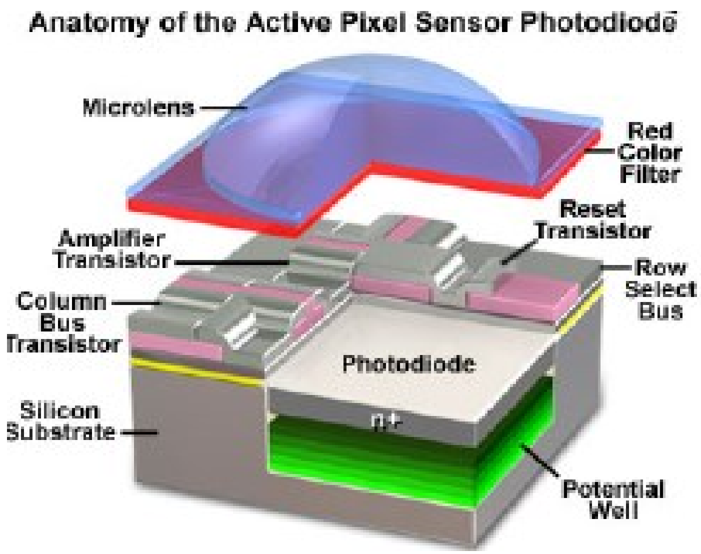
Quick refresher on MCPs



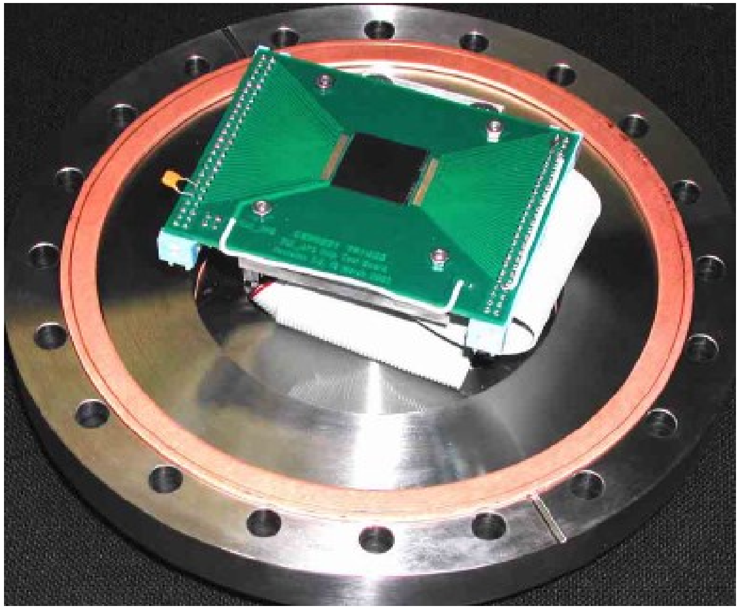


- “our” detector uses 2 MCPs (chevron)
- output electrons impinge on phosphor screen
- FO feedthrough to outside world
- Sensicam cooled CCD camera, lens coupling
- MCPs not very user friendly….

Candidate technology for a new detector – MAPS



• sensor and readout electronics integrated in CMOS process
• must be back illuminated for 20keV electrons (4 micron range)



• StarTracker MAPS previously backthinned and tested at RAL and LMB Cambridge
• accuracy of thinning is critical at this electron energy
• We used a "Vanilla" MAPS developed by the MI3 Consortium

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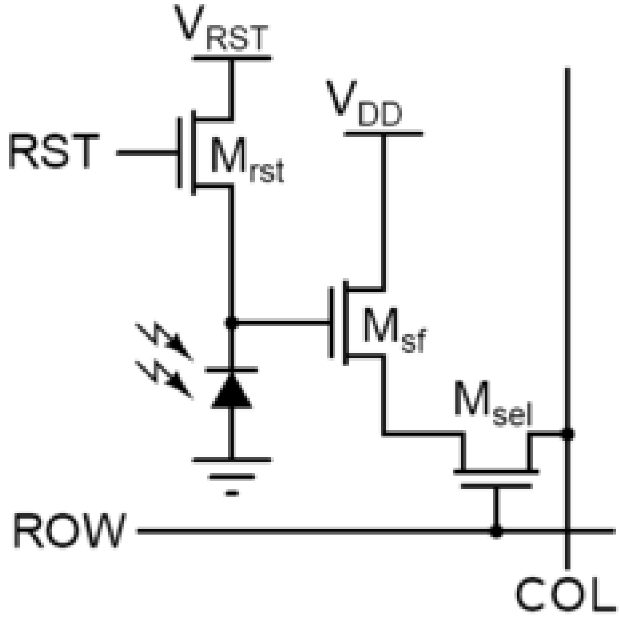
Some more details about MAPS

Generic 3T MAPS Pixel



MI3 Vanilla/PEAPS
Made in 350 nm CMOS
25 µm x 25 µm pixels
520 x 520 pixel array
=> 13mm by 13mm
2 sides buttable => 26mm by 26mm
25 e- rms readout noise
100000 electrons full well capacity
Novel "flushed" mode reset

We used a backthinned version
Thinned to epilayer, estimate 15-20 micron epitaxial Si remaining
Operated in analogue mode with external 12-bit ADC

Characterisation of Vanilla – A novel active pixel sensor for radiation detection
A.Blue et al., NIM A581 287 (2007)

Metrics for imaging detectors

Metrics for imaging very different to figures of merit usually encountered for HEP detectors

Seminal early work, first use of DQE:
Albert Rose, *A unified approach to the performance of photographic film, television pickup tubes and the human eye*, Journal of the Society of Motion Picture Engineers Vol.47 No.4 P.273 (1946)

Terms to conjure with:

Modulation transfer function (MTF)
Noise power spectrum (NPS) (Wiener* spectrum)
Detective quantum efficiency (DQE)

* Not to be confused with the sausage known as a Wiener in Frankfurt and a Frankfurter in Vienna….

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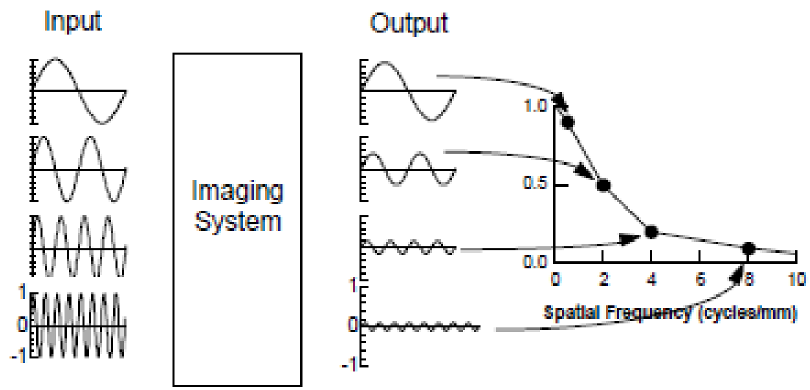
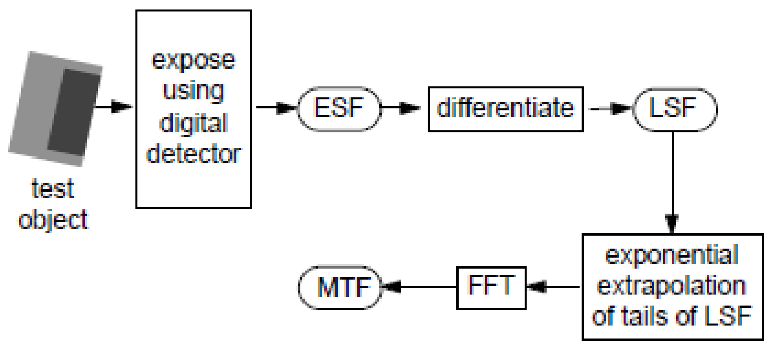
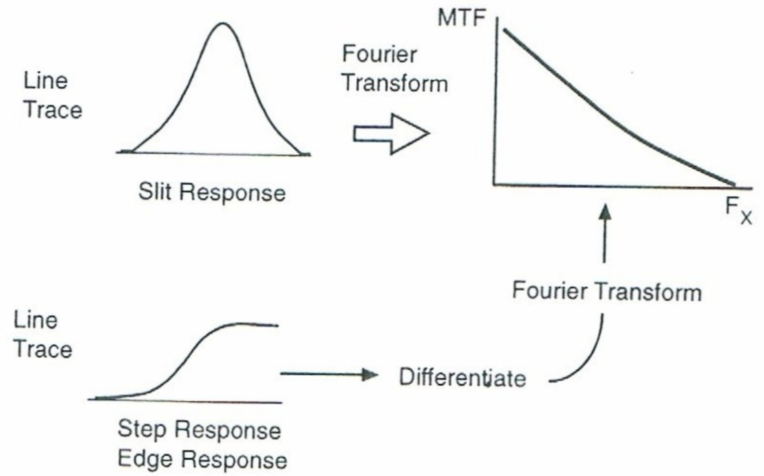
Imaging metrics: Modulation transfer function

Ratio of output to input modulation as a function of spatial frequency



measures change in the amplitude of sine waves



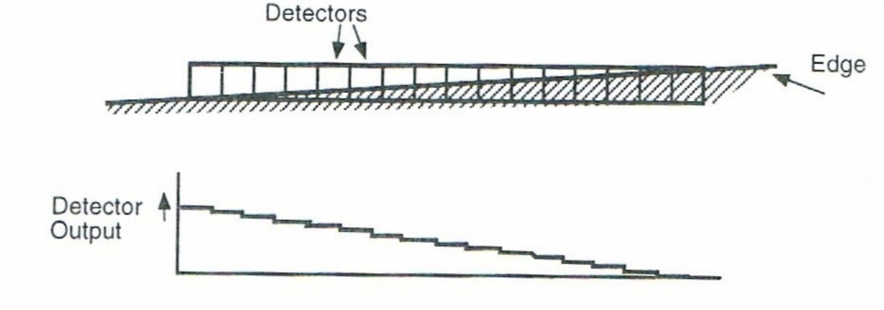


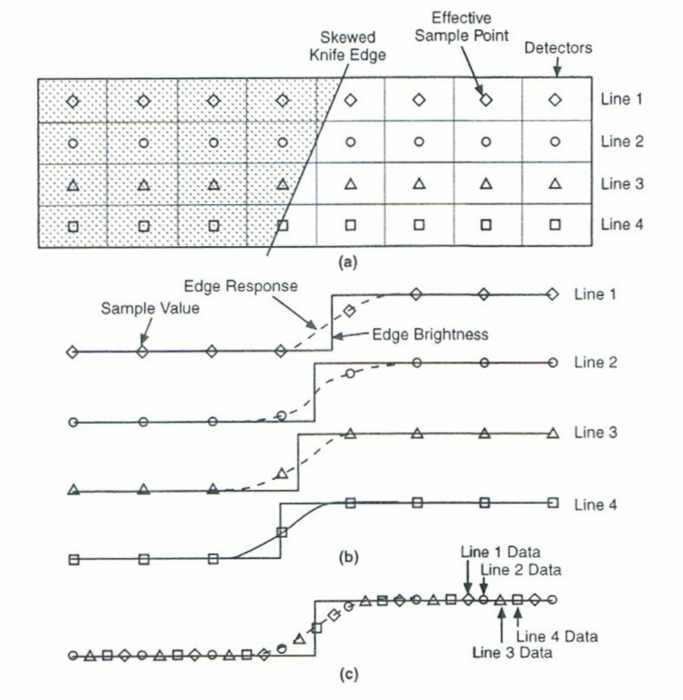
See e.g Gerald C. Holst, *Testing and Evaluation of IR Imaging Systems*, SPIE, 1998 .

Measuring the edge spread function

ESF can be measured using a test edge skewed relative to the pixels

Allows oversampling to << pixel size

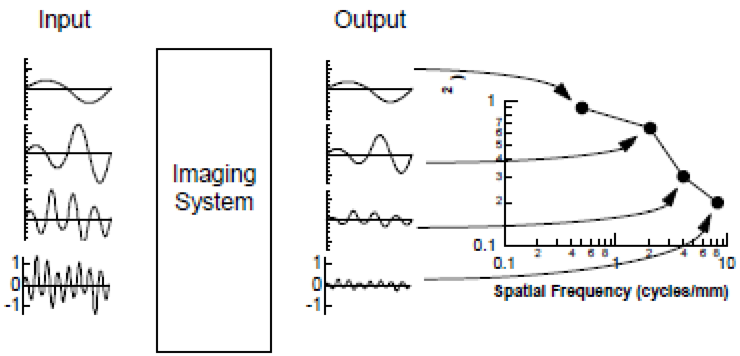




Fujita et al. *A simple method for determining the modulation transfer function in digital radiography.*
IEEE Trans Med Imaging. 1992;11(1):34-9

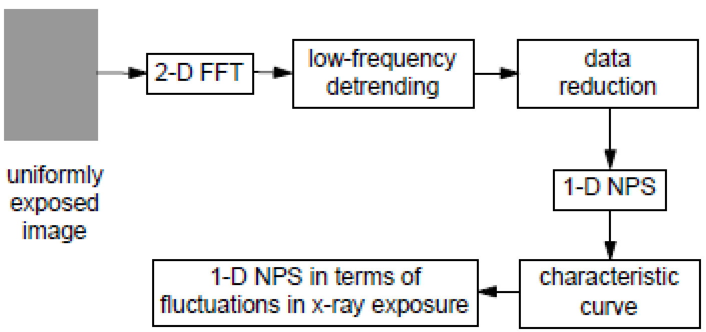
Imaging metrics: Noise power spectrum

Measuring NPS (conceptually)



Measure change in the variation in the amplitude of sine waves

Measuring NPS (experimentally) Digital Detector

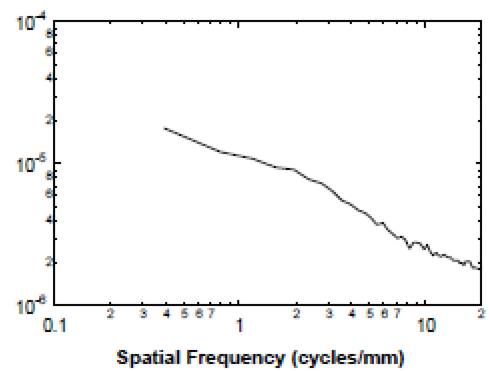


Noise

noise can be characterized by standard deviation in the output image

a more complete description is given by the noise power spectrum

Typical NPS



See e.g. Robert M Nishikawa, "*The Fundamentals of MTF, Wiener Spectra, and DQE*" University of Chicago

Imaging metrics: Detective Quantum Efficiency

- any image has an inherent signal to noise ratio, before viewing by a detector, due to the statistical nature of the illumination
- this SNR is a function of spatial frequency
- DQE is a measure of how the available signal to noise ratio is degraded by an imaging system

$$DQE(\omega) = \frac{SNR^2_{out}(\omega)}{SNR^2_{in}(\omega)}$$

$SNR_{out}(\omega)$ = SNR in the output image

$SNR_{in}(\omega)$ = SNR incident on the detector

$$DQE(\omega) = \frac{Q\ MTF^2(\omega)}{W(\omega)} \left(\frac{dO}{dQ}\right)^2$$

where $MTF(\omega)$ = MTF of detector

$W(\omega)$ = noise power spectrum of image

$\frac{dO}{dQ}$ = gain of the system

To get DQE, need MTF, NPS and incident flux
To get MTF, use a knife edge
To get NPS, use flood illumination

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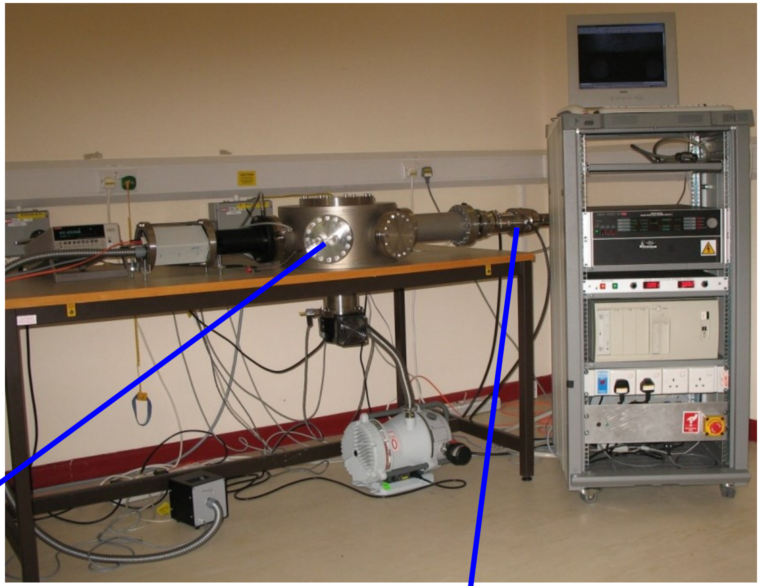
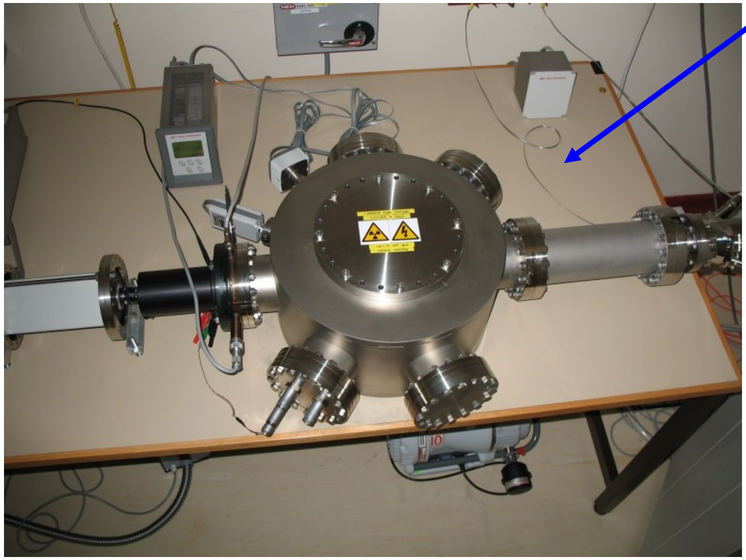
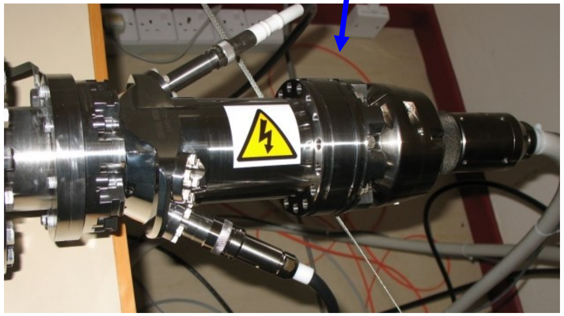
Electron detector test system overview

- Kimball Physics 20 keV electron gun
- IRD thin window diodes and Keithley 6517A electrometer for beam current measurement
- Turbomolecular pump and scroll pump







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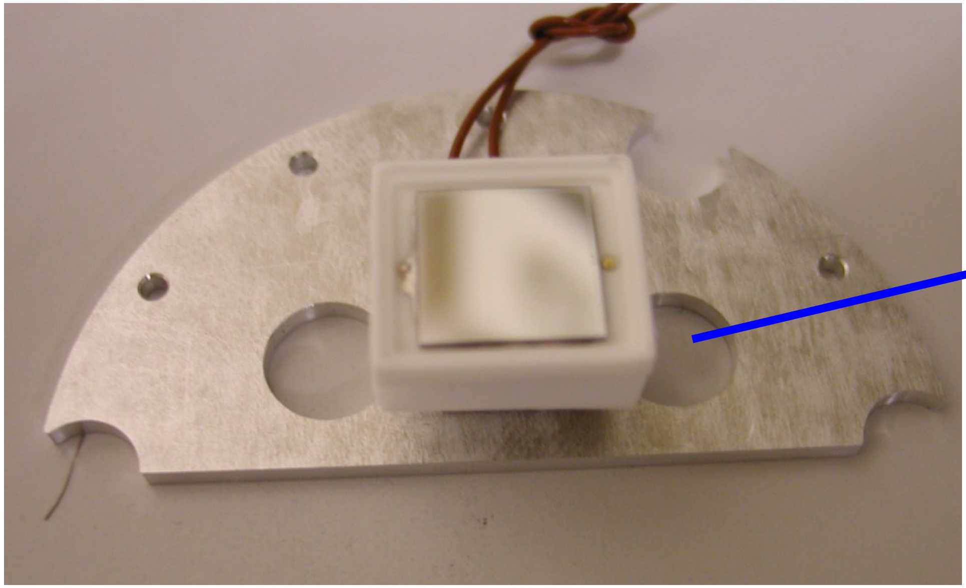
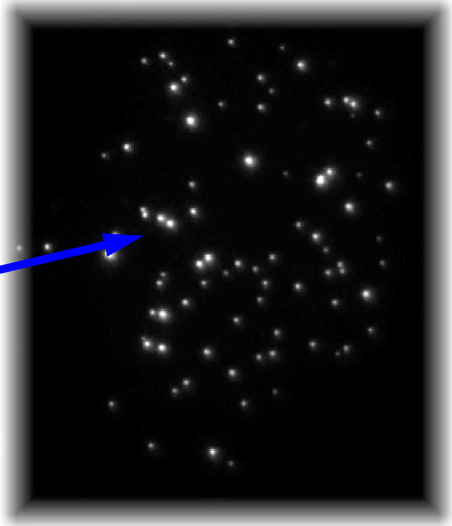
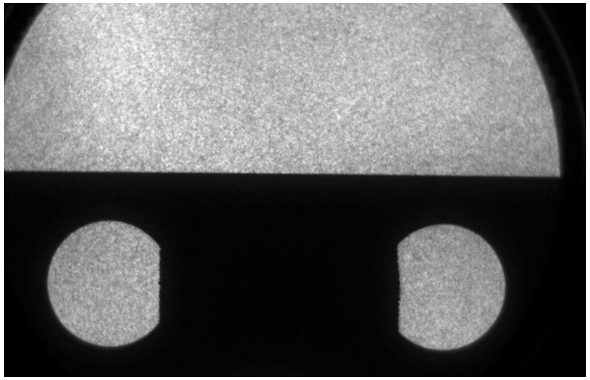
Test system – MCP detector specific



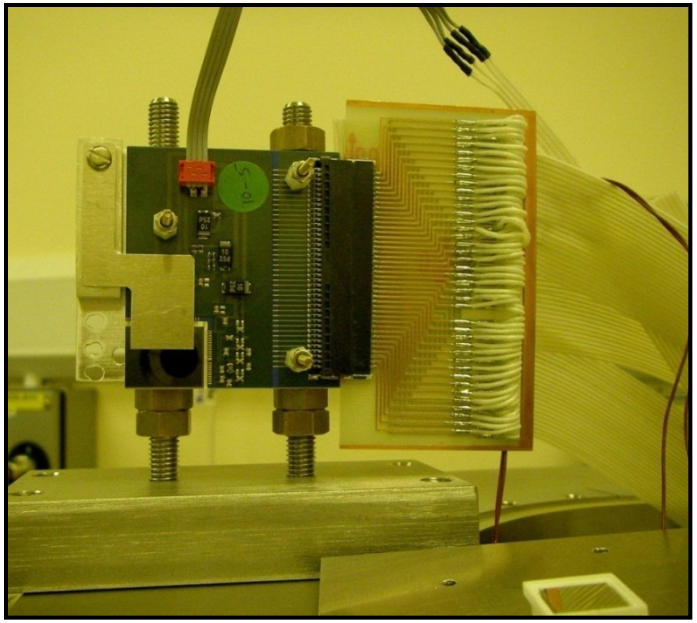


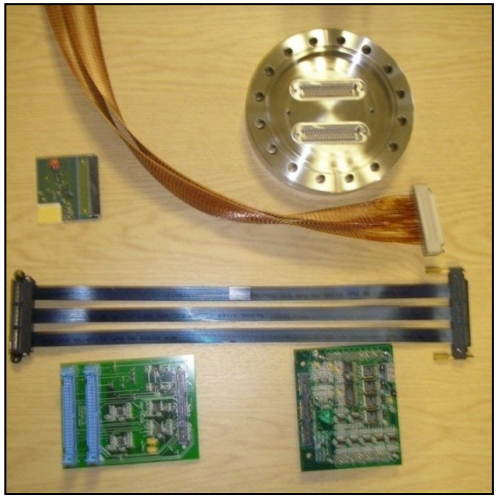


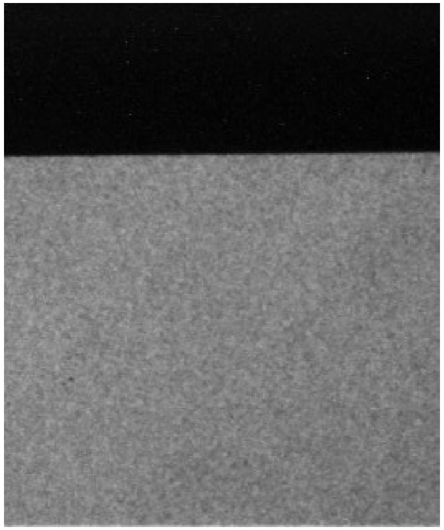
- mounts in front of MCP detector
- knife edge to allow MTF calculation
- apertures for defining counts/s in known area
- IRD diode for beam current *
- 150nm Al filter deposited on diode
- diode requires calibration

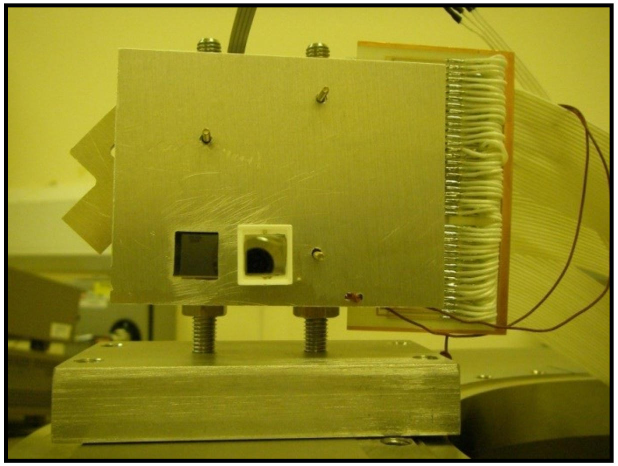
* www.ird-inc.com

Test system – MAPS detector specific



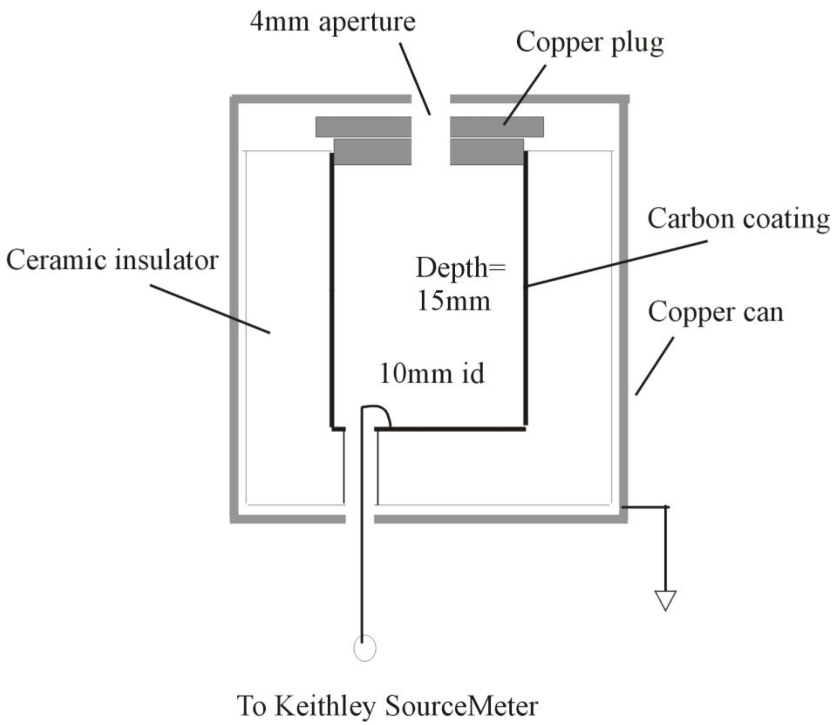


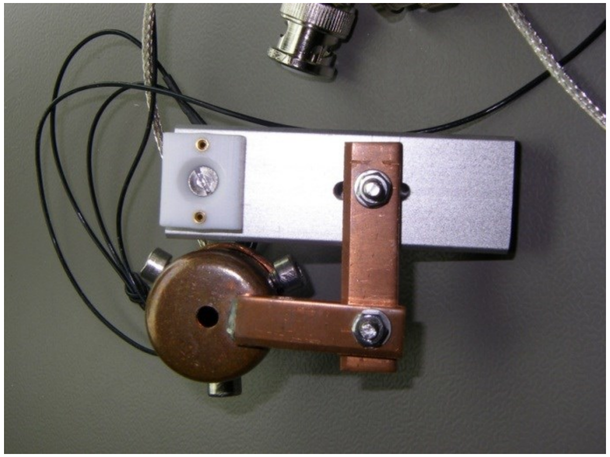


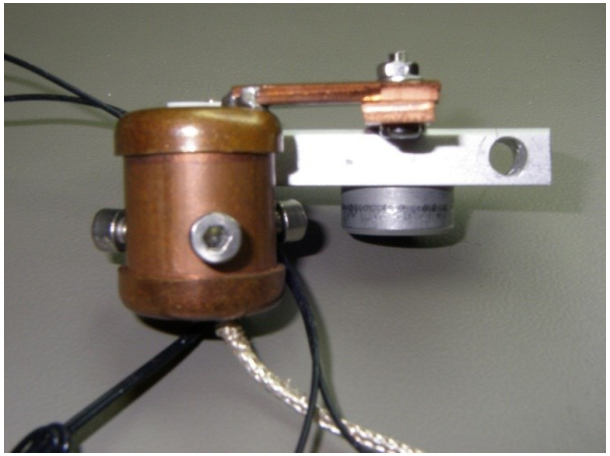


- UHV compatible cables
- UHV compatible PCBs
- 100 way CF100 feedthrough
- York/Brunel design

Calibrating the beam current (1)







Al filter makes diode blind to stray light
IRD only supply calibration for bare diode
Custom Faraday cup made for calibration

D.T.Grubb *The calibration of beam measurement devices in various electron microscopes, using an efficient Faraday cup* 1971 J. Phys. E: Sci. Instrum. 4 222

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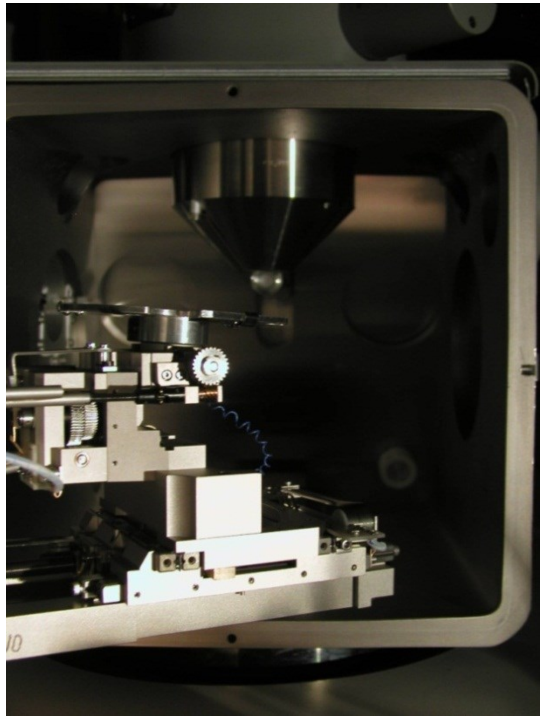
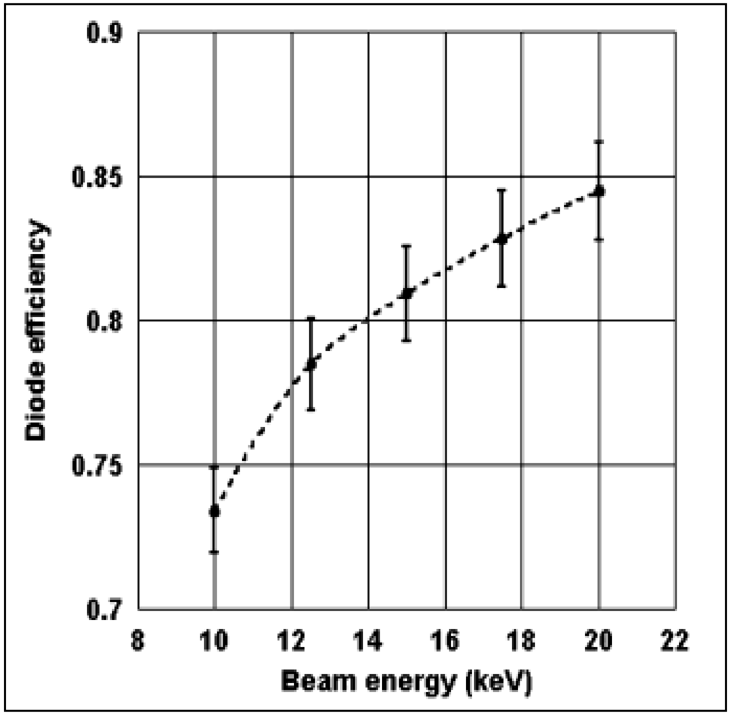
Calibrating the beam current (2)





Venerable Leica SEM in CMF
Equipped with feedthroughs, motorised X-Y stage

Set beam spot size, current
Move the diode or cup under the beam
Calibrate diode relative to cup

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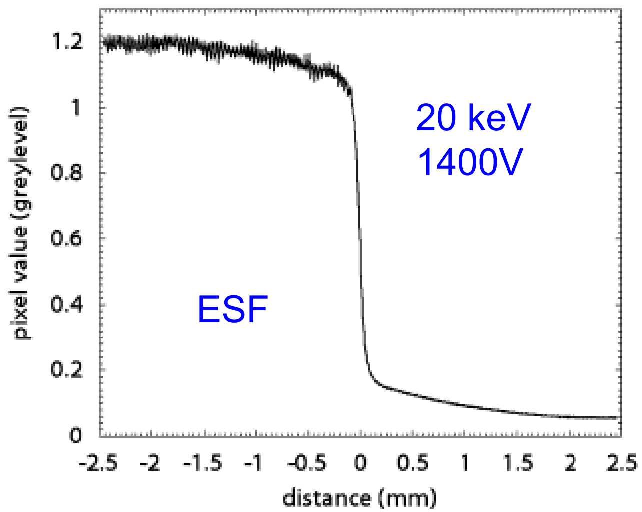
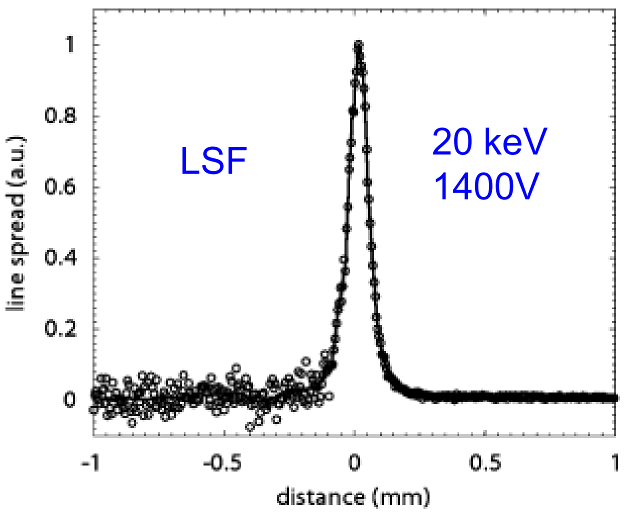
Experimental Details, Data Analysis

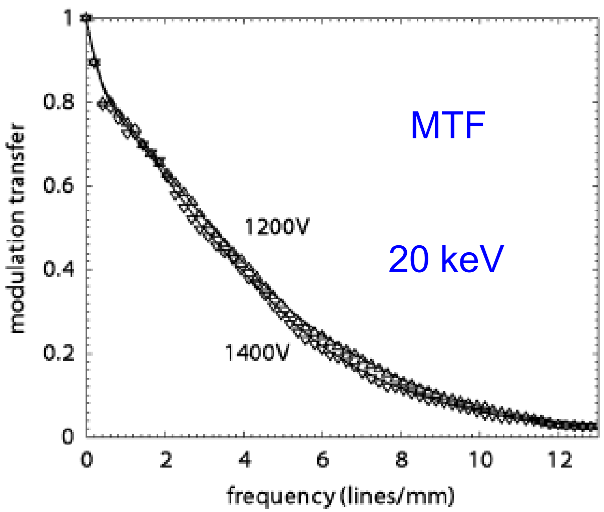
- acquire multiple image frames ("stack") with the DUT
- IRD diode current recorded at the same time => incident fluence
- acquire stacks with knife edge => MTF
- acquire stacks without knife edge => NPS
- each time a stack is recorded with illumination, an equivalent stack is recorded without illumination => dark field subtraction
- separate flood images used to correct pixel-to-pixel gain variation
- data analysis performed in Image-J*, using macros written by Greg Moldovan (Dept of Materials, Oxford University, now at Oxford Instruments Nanoanalysis)

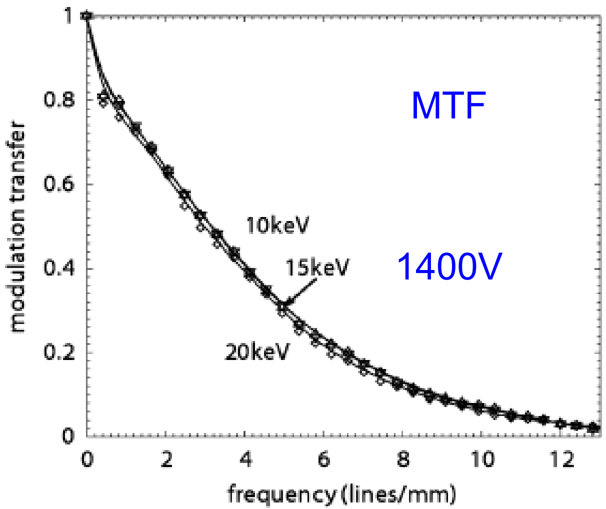
*Abramoff, M.D., Magalhaes, P.J., Ram, S.J. *"Image Processing with ImageJ"*. Biophotonics International, volume 11, issue 7, pp. 36-42, 2004

MCP results 1



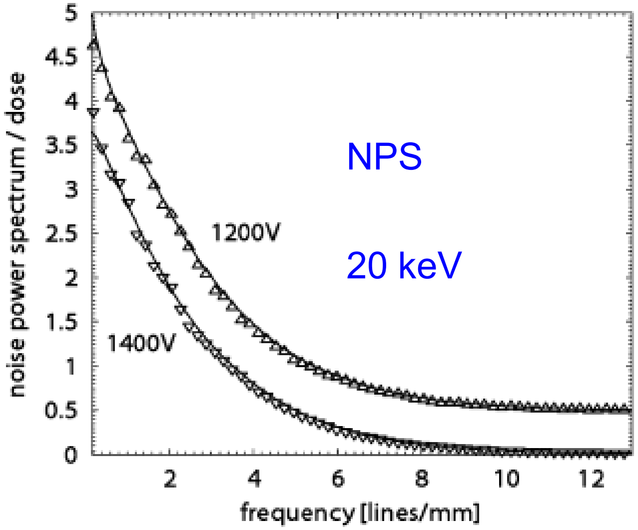


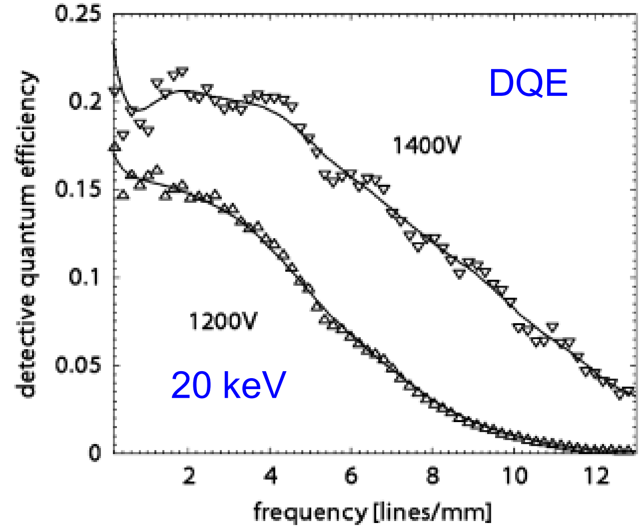


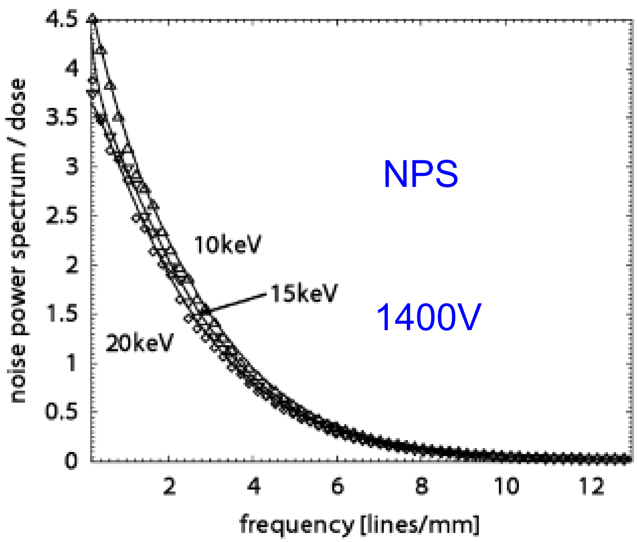


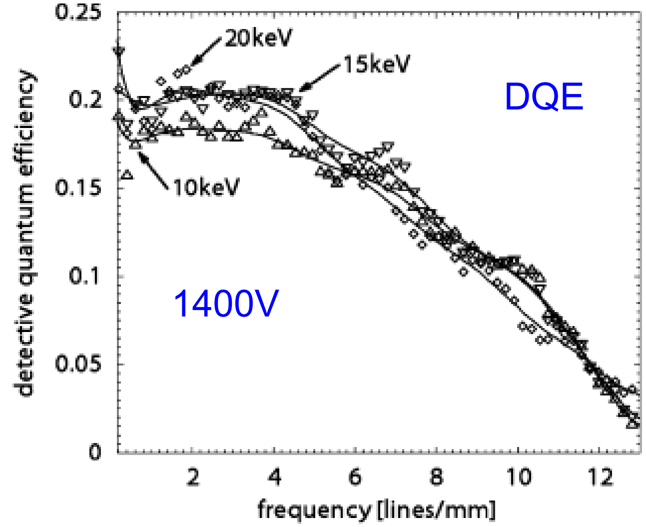
"spatial resolution" ~ 120 μm

MCP results 2









DQE(at resolution limit) ~ 0.02 (1200V) - 0.11 (1400V)
DQE(0) ~ 0.15 (1200 V) – 0.2 (1400 V)

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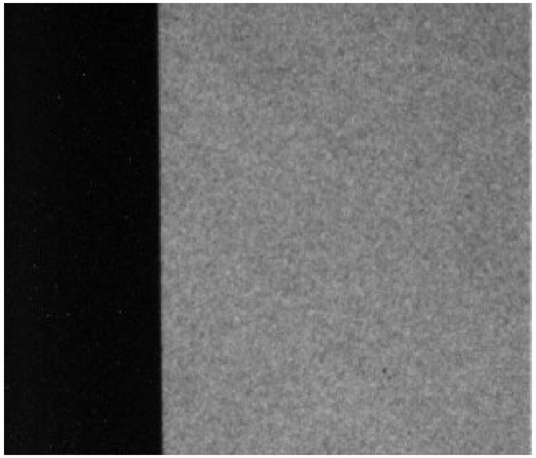
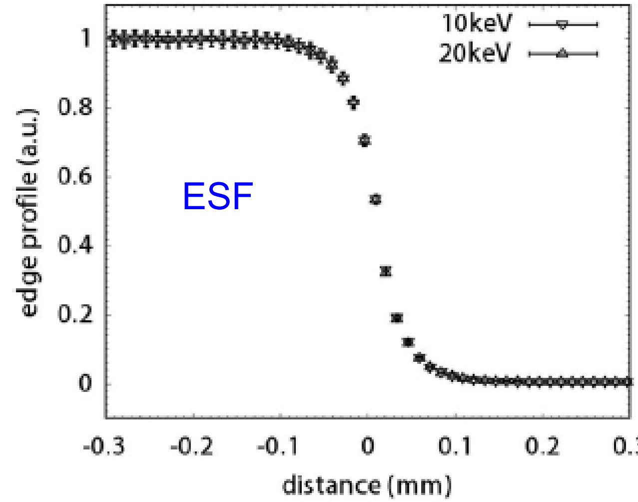
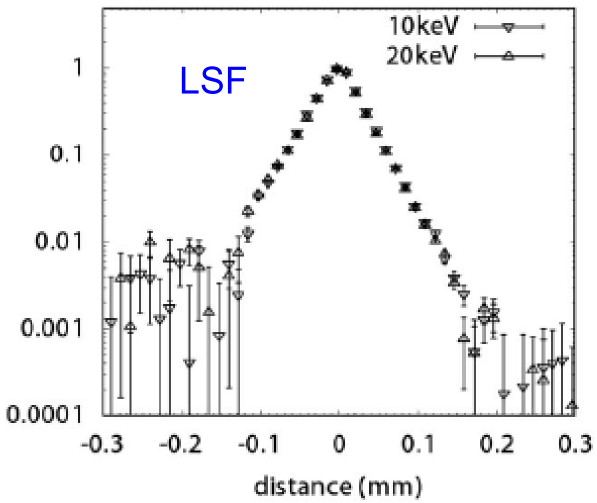
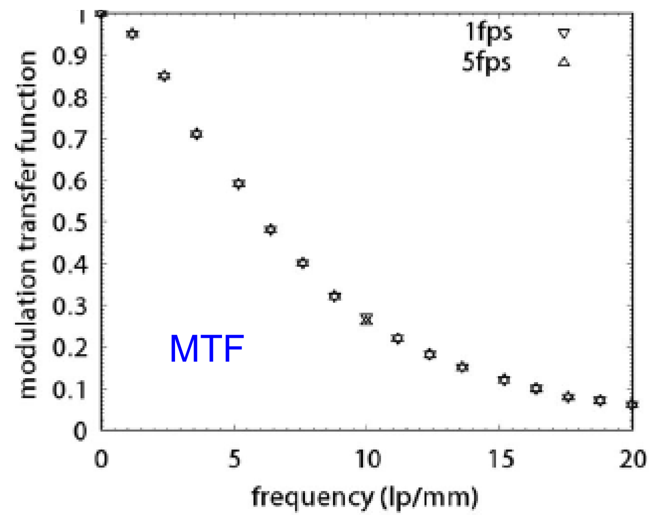
MAPS results 1



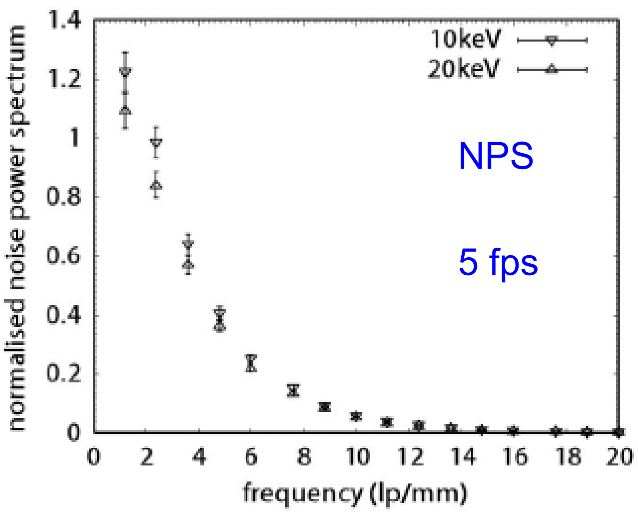


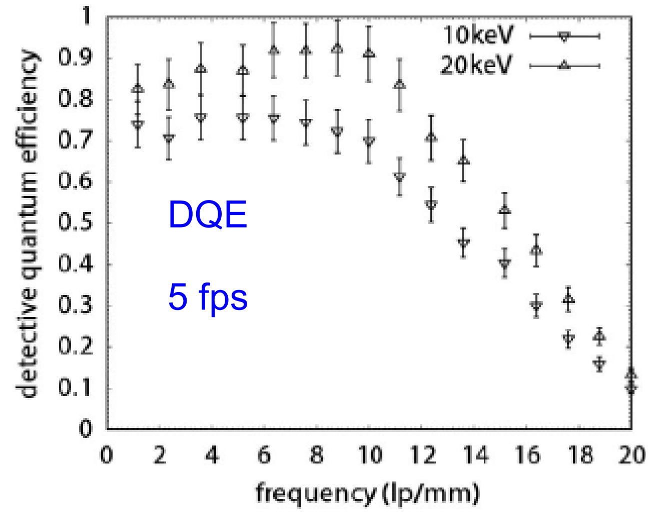


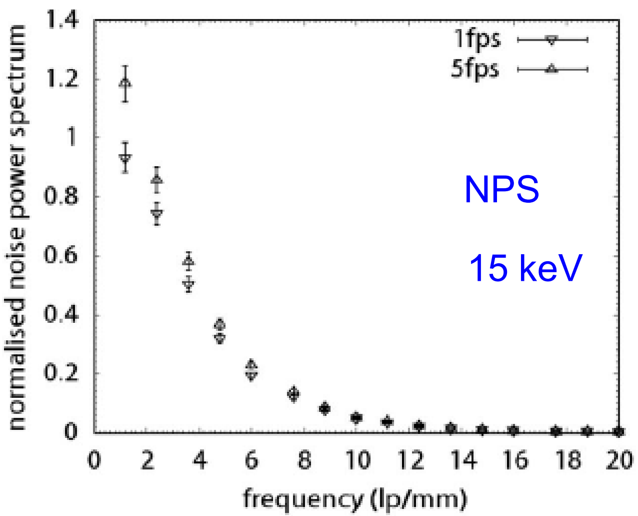


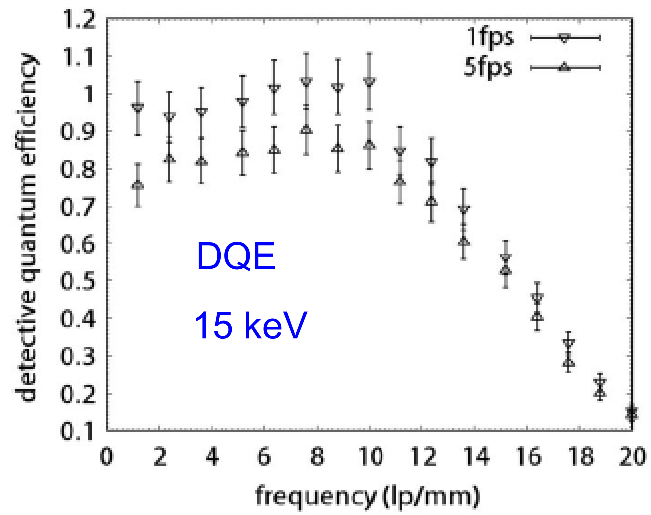
“spatial resolution” ~ 33 μm

MAPS results 2









DQE(0) ~ 0.9 (5 fps) – 1 (1fps)
DQE at limit of spatial resolution ~ 0.54
DQE at 100 μm spatial resolution ~ 0.85

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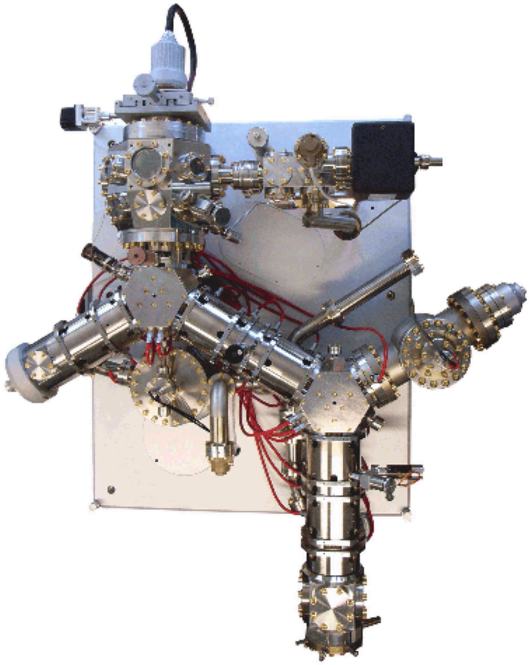
Why doesn't everybody switch to MAPS ?

1) It's too expensive
2) The money is better spent on aberration correction
3) It is no good for time-resolved studies

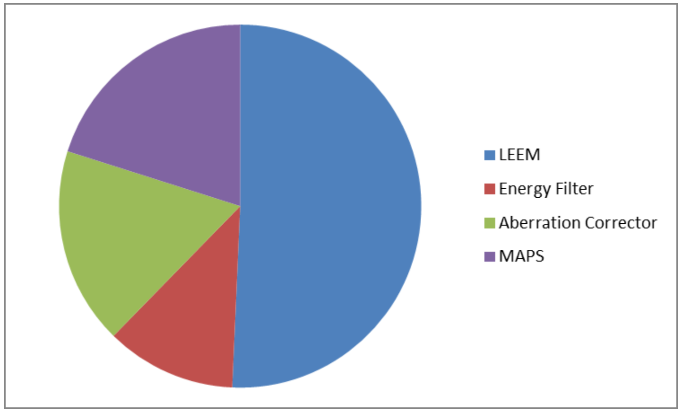
1) How does the cost compare ?



<u>Shopping list</u>

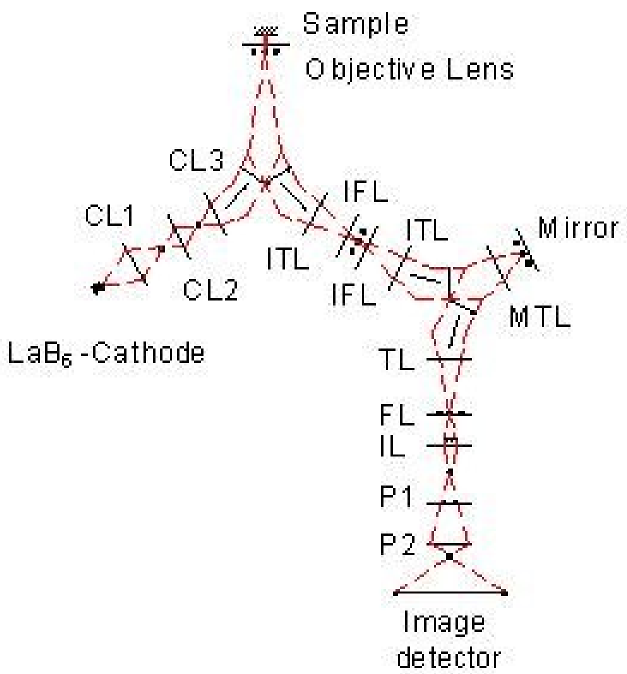
<u>Instrument</u>
LEEM £580 K
Energy analyser £133 K
Aberration corrector £ 201 K

<u>Detector</u>
Chip Design £35 -100 K
Mask set and wafers £63 K
Backthinning ??
Guess £ 230 K total
(we would get many chips !)

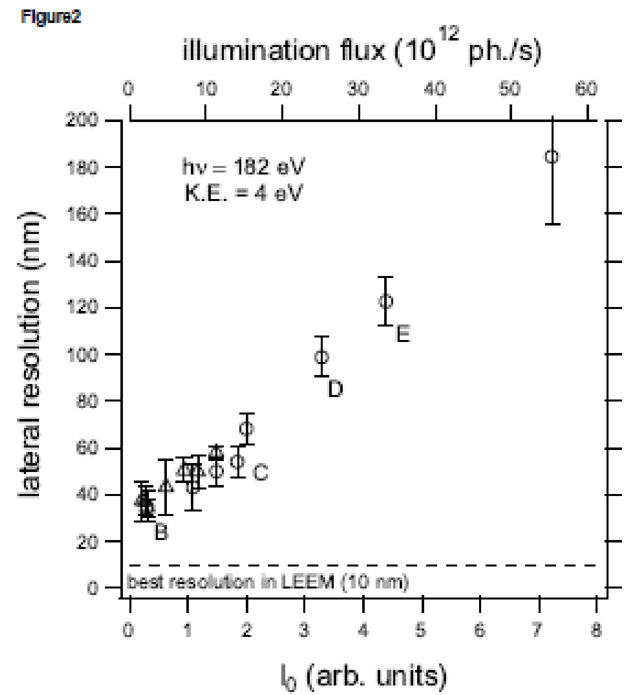


Why doesn't everybody switch to MAPS ? (2) – AC is more useful

"*Electrons are not photons*" – La Palisse



Locatelli et al.,*"Image blur and energy broadening effects in XPEEM"*, ULTRAMICROSCOPY Vol.111 No.8 P.1447-1454 (2011)

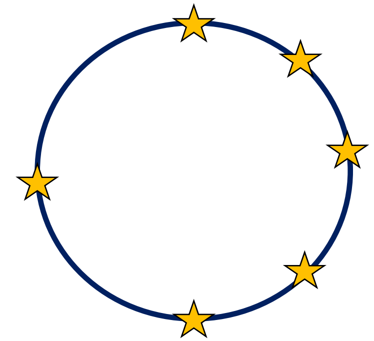


You still need a the most efficient detector you can get !!
Plus at x20000 and 3nm resolution, detector resolution needs to be < 60 μm

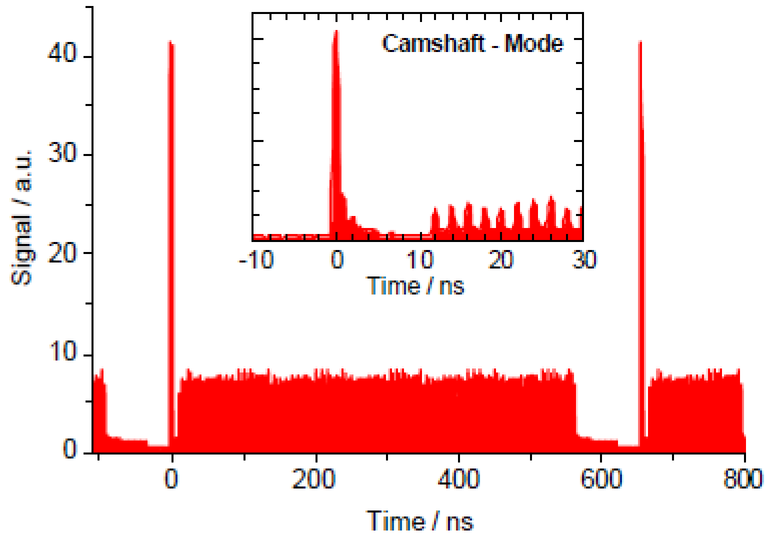
Why doesn't everybody switch to MAPS ? (3) – no good for timing

Timing properties:
MAPS frame rate limitation
MAPS charge collection by diffusion (~100ns)
MCP + electronic readout 10s of ps*

MCP + phosphor – limited by afterglow, but often use pump-probe technique at synchrotrons
Detector is gated, with timing derived from ring
Only need a fast pulsed power supply



"Camshaft mode" of filling RF buckets



This is the *technica*l stumbling block to the adoption of MAPS

It is expected to be soluble by adding a kicker to the electron optics in the XPEEM

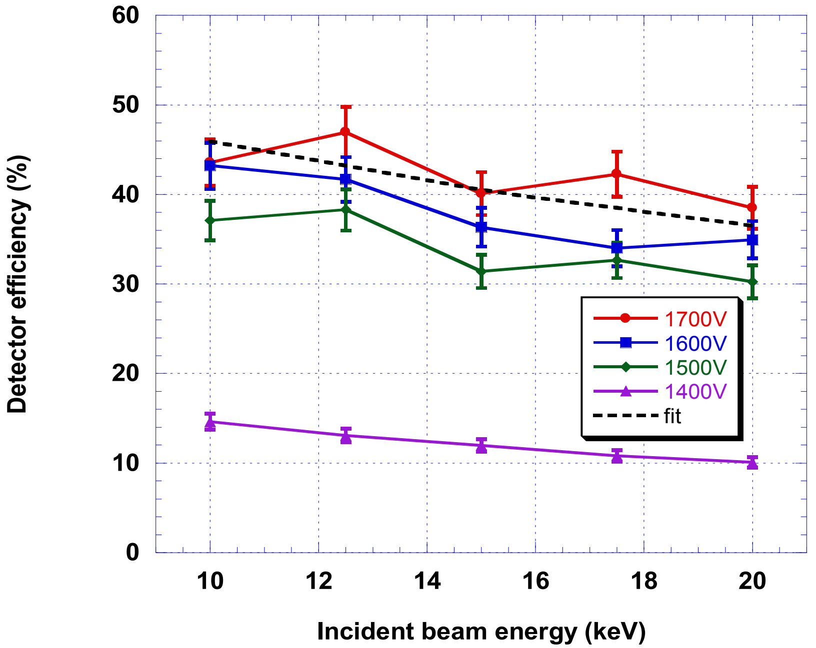
If not, can swap detectors mechanically without breaking vacuum (BESSY)

*Akatsu et al., *"MCP-PMT timing property for single photons"*, NIM A528 763 (2004)

Science & Technology Facilities Council

Single electron detection (MCP)

- *See if we can detect single electron hits*
- Important for ToF applications such as COLTRIMS*
- Turn down the beam current, increase the detector frame rate
- Apply a threshold to the image in Image-J
- Use the Image-J (cell ?) counting function to count the hits

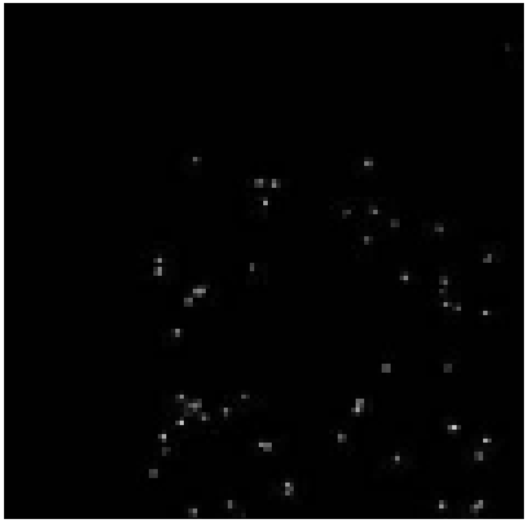


- Can see individual hits with fair efficiency
- Consistent with efficiency reported for MCP with delay line readout**
- Need to turn the bias up high….
- Efficiency *falls* as incident electron energy *increases*
- Theoretical efficiency limited by open area ratio
    - Add CsI coating ? Suppressor grid ?
- Bright spots in phosphor are not symmetrical !
    - Mount CCD direct on FO ?

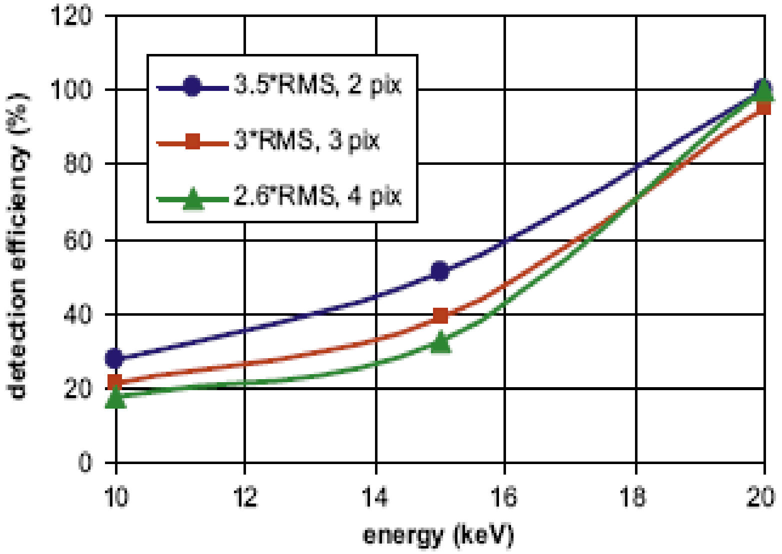
* J. Ullrich et al., "*Recoil-Ion and Electron Momentum Spectroscopy: Reaction-Microscopes*", Rep. Prog. Phys. 66,1463 (2003)

** *Absolute quantum efficiencies of micro-channelplates for 8-28 keV electrons* R W Wijnaendts van Resandt J. Phys. E: Sci. Instrum. 13 1162 (1980)

Single electron detection (MAPS)



- *See if we can detect single electron hits*
- Turn down the beam current, increase the detector frame rate
- Acquire stacks with beam on and off
- Data analysis in Matlab
- For each pixel, loop through dark frames and get mean, RMS
- Make threshold cuts and size cuts on clusters



- Can see individual hits
- Value measured for efficiency depends on cuts chosen

- Fair estimate:
    - 95% at 20 keV
    - 40% at 15 keV
    - 20% at 10 keV

- Efficiency *falls* rapidly as incident energy *falls*
- *Implies existence of a dead layer*
    - Might be improved by delta-doping*

*Shouleh Nikzad et al. *Direct detection and imaging of low-energy electrons with delta-doped charge-coupled devices* APPL. PHYS. LETT. VOL. 73, No. 23, 3417 (1998)

Conclusions

We have the technology….. to characterise electron detectors !
Electron detectors are ubiquitous and there is a need to evaluate quantitatively.
I have mainly focused on one application, but there are many more.

Below 15 keV, MCP beats MAPS for single electron detection efficiency

MCP great for gating, timing. Fast timing remains the domain of MCPs for now.
Gating is a soluble electron optics problem for MAPS.

MCP spatial resolution just adequate for current XPEEM, MAPS better.
Spatial resolution will become limiting factor with AC XPEEM.
Better spatial resolution allows bigger FOV.
MCP DQE depends on detector bias, MAPS better.
MCP is fragile, MAPS is not.

Direct detection is the future for XPEEM, most likely technology is MAPS.

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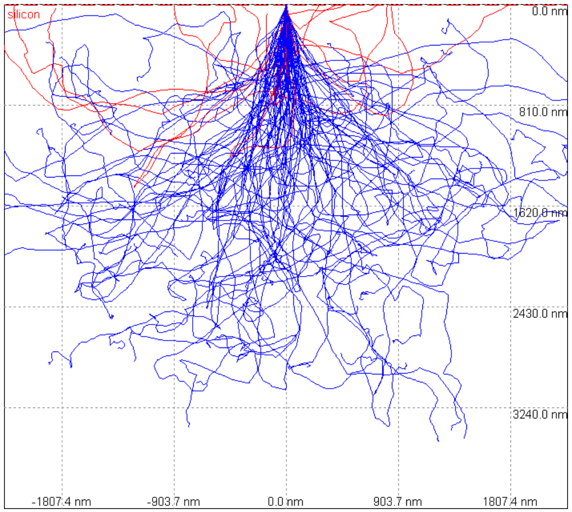
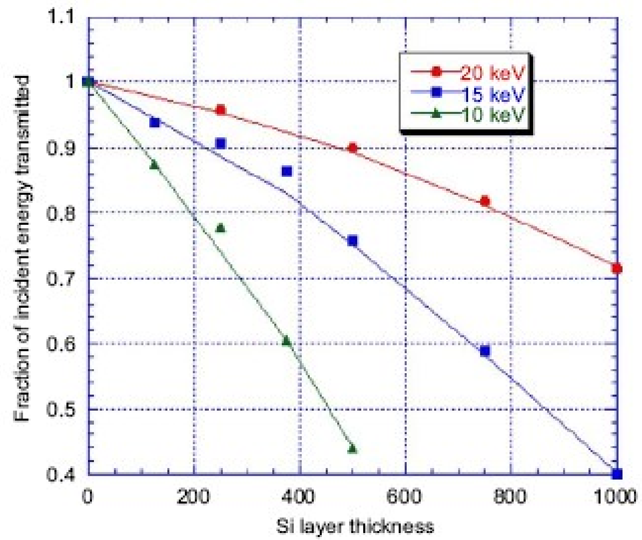
Ray Cochrane *Burle*
Howard Padmore, James Glossinger, Andrew Doran *Advanced Light Source*

Spare Slides

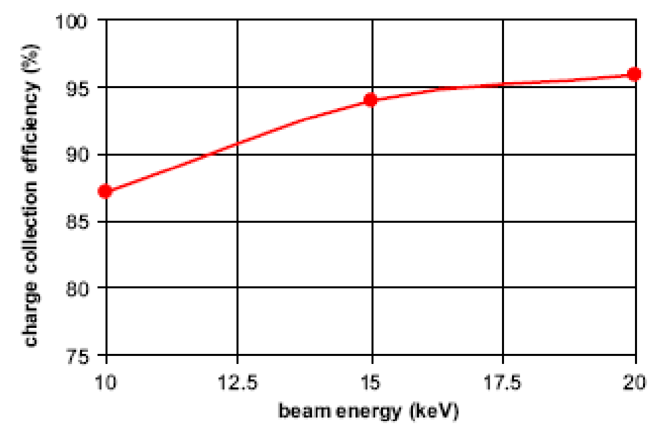
Charge collection efficiency (MAPS)





Dead layer
125 nm at 10 keV
150 nm at 15 keV
200 nm at 20 keV

- Calibration of system in ADC Units/signal electron obtained using a front illuminated MAPS and light illumination
- Flood images recorded with beam current set to give an image near the centre of the ADC range
- IRD diode current used to calculate the expected charge collection in the MAPS
- CASINO* simulations performed to estimate signal loss in a dead layer
- Apparent increase of layer thickness with beam energy indicates some charge is still collected from the "dead" layer

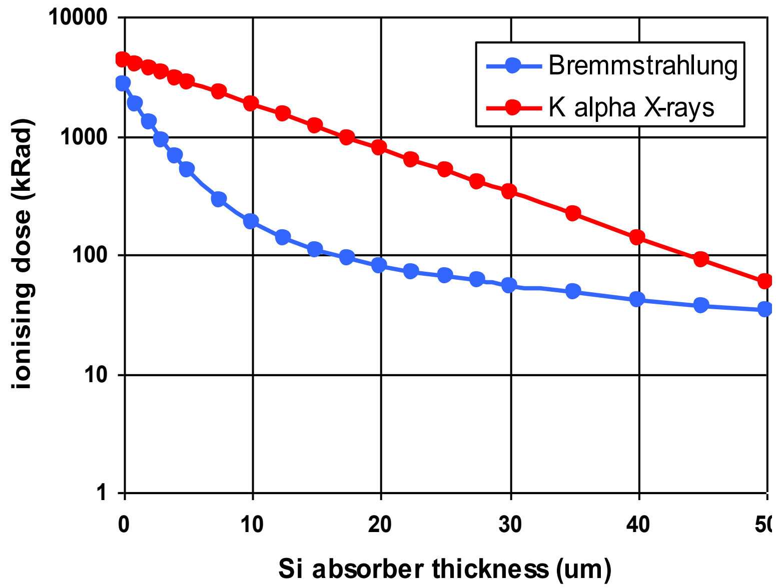


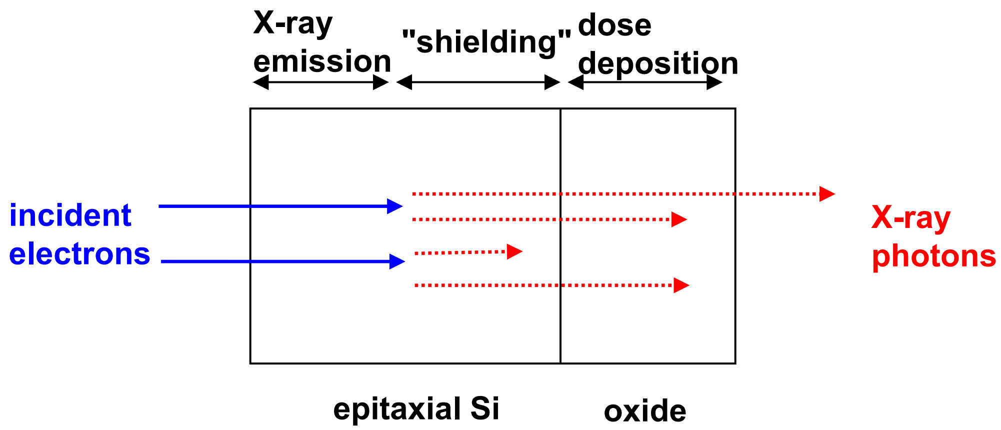
* See http://www.gel.usherbrooke.ca/casino/index.html, D.Drouin et al., Scanning Vol 29 No 3 P 92 (2007)

Shouleh Nikzad et al. *Direct detection and imaging of low-energy electrons with delta-doped charge-coupled devices* APPL. PHYS. LETT. VOL. 73, No. 23, 3417 (1998)

Radiation hardness

- front illuminated detector - dose rate up to 7 Mrad p.a. for E filtered PEEM, 60 Mrad p.a. with aberration correction !
- back thinned detector - no direct dose
- secondary dose from Si K X-rays 1.8keV
- secondary dose from Bremmstrahlung 0-20keV
- based on Green and Cosslett, McCall papers





- dose p.a. unfiltered
- few krad p.a. looks realistic
- other modes worse than XPEEM
- calculation is a fudge….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