Synchrotron / X-ray Applications Detectors Make the Big Difference

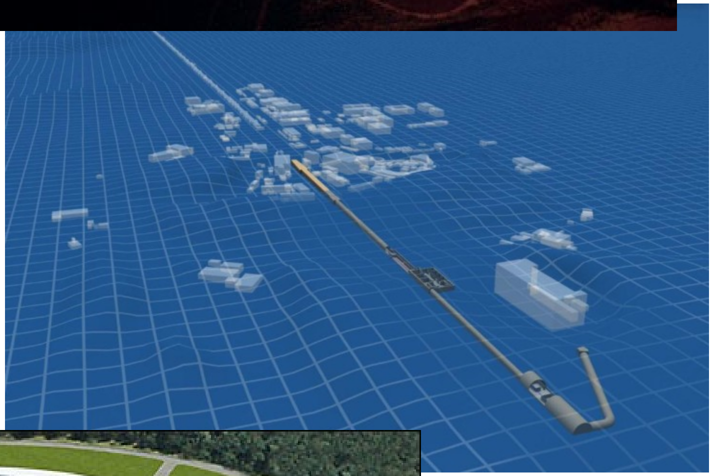
Klaus Attenkofer[1]

And many users of APS, companies …….

[1]Argonne National Laboratory

X-ray Sciences Division / High Energy Physics Division

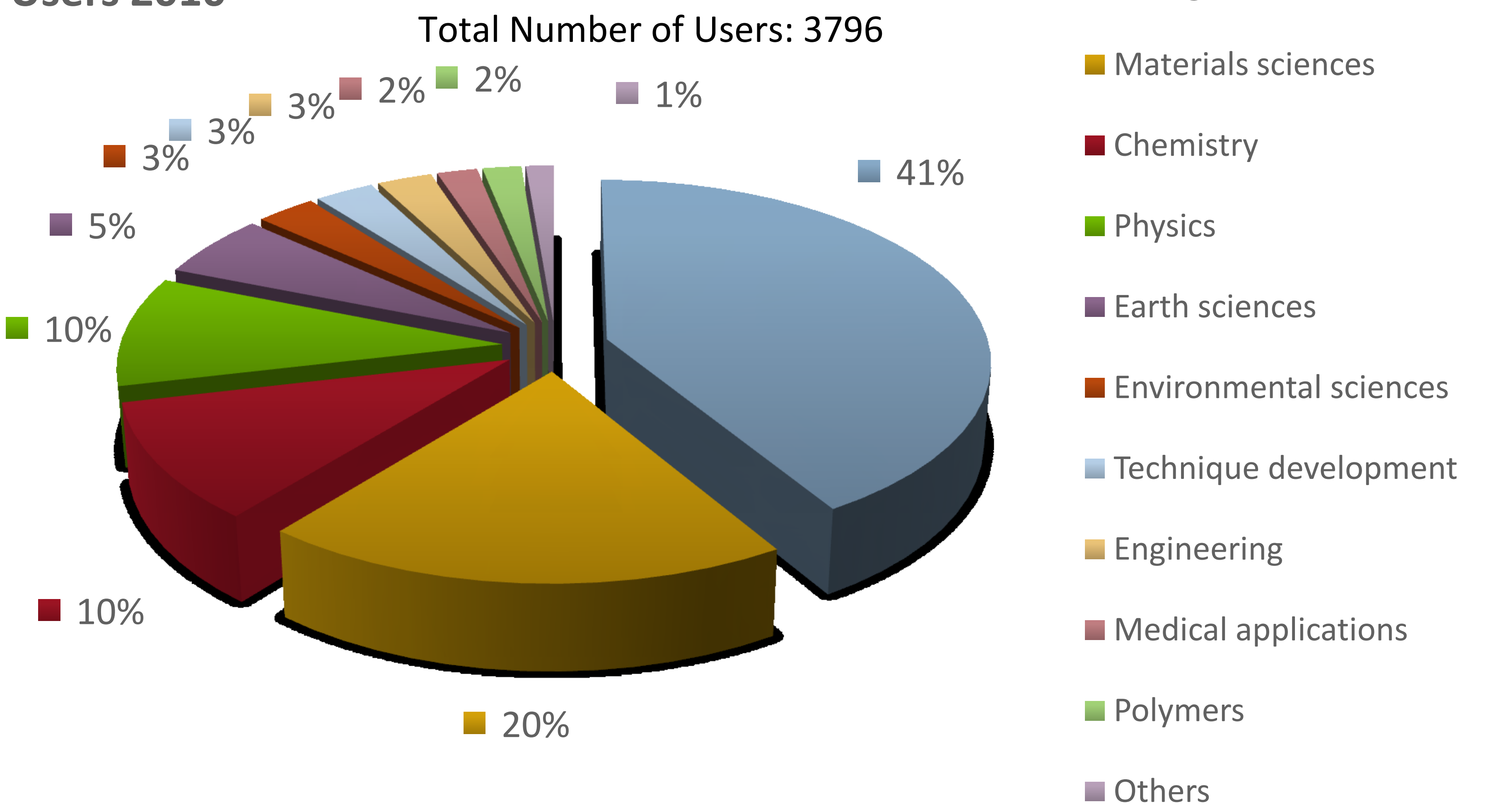
Overview



- The synchrotron community and experiments
- Lessons learned from the past
  - The detection requirements
  - Existing Detection Systems which changed the game
  - Lessons to be learned
- The next big challenges
- Conclusions

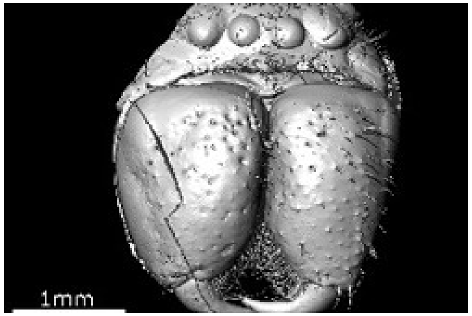
The Community
The Advanced Photon Source as Example

Users 2010



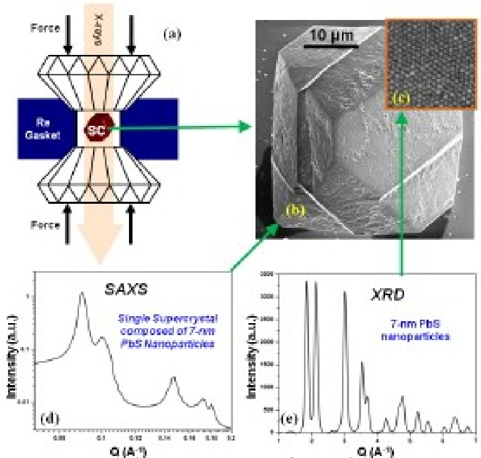
The Community Same Examples

Palaeozoology



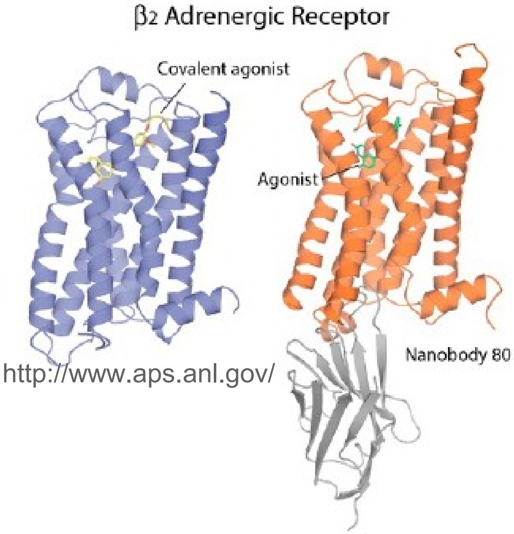
http://www.xradia.com/

Geo sciences



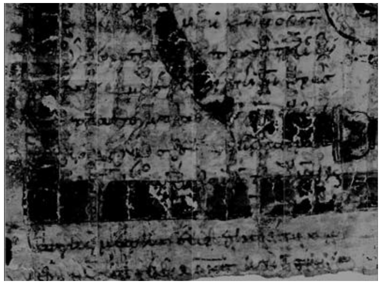
http://www.aps.anl.gov/

Structural biology



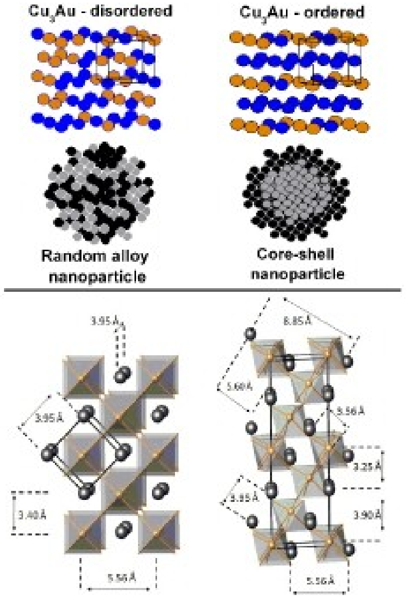
http://www.aps.anl.gov/

Archaeology



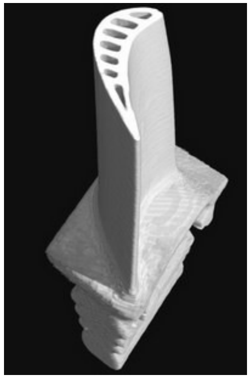
http://www2.slac.stanford.edu/tip/2005/may20/archimedes.htm

Nano sciences



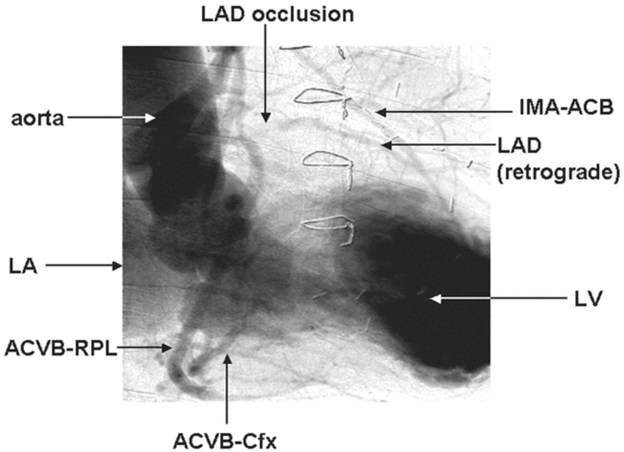
http://www.aps.anl.gov/

Engineering



www.nikonmetrology.com/ct_turbine_blades

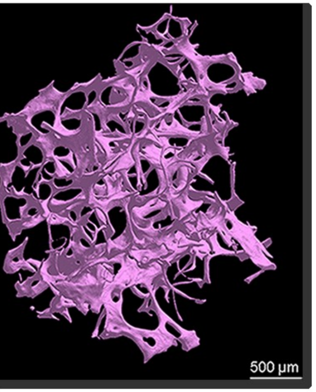
Clinical imaging

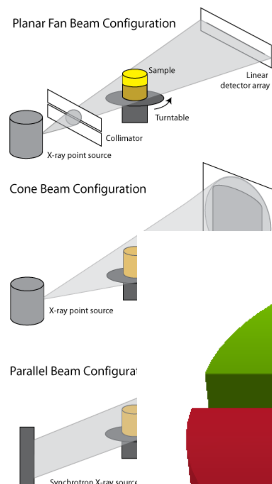


J. Synchrotron Rad. (2003). ***10, 219-227***

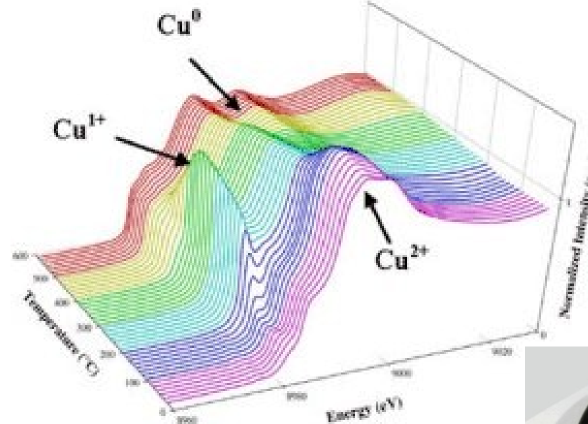
The Applied Techniques and Detection Requirements

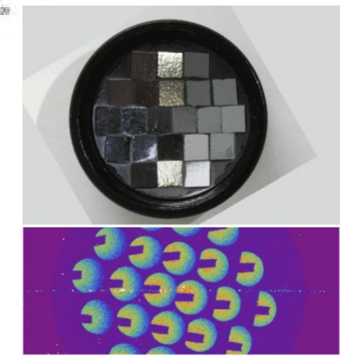
3D-Imaging

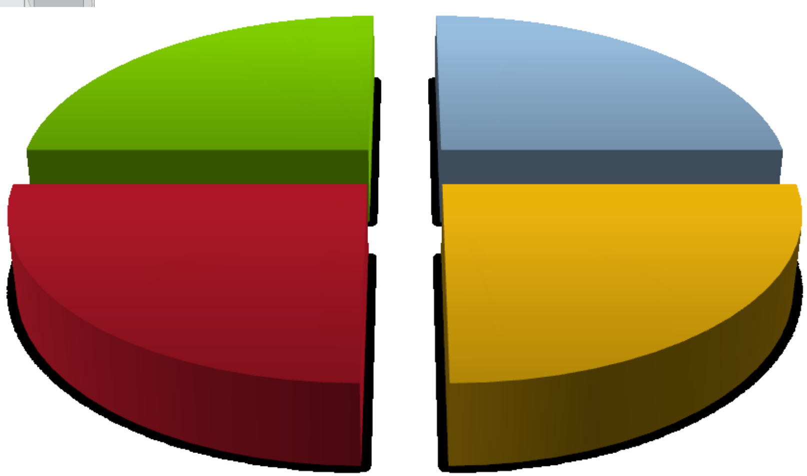




X-ray Spectroscopy







2D-Imaging

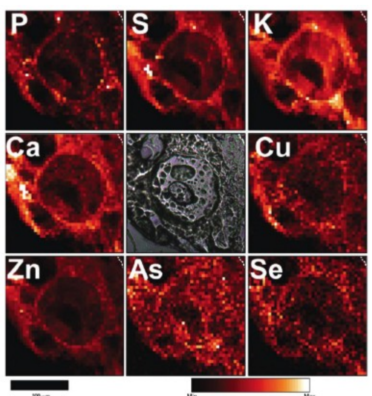
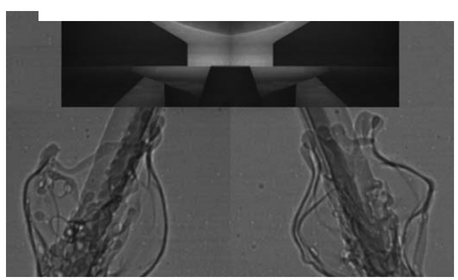
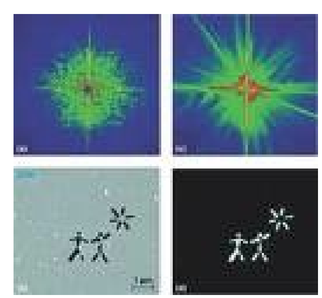
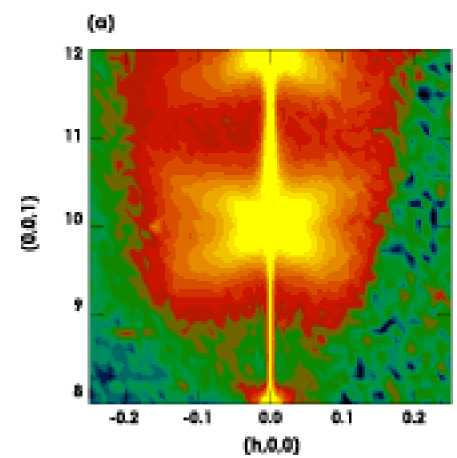


Figure 1. Micro-XRF element maps of hyperplastic epidermis taken from the skin of a mouse exposed to UVR and As(III) for 182 days. Dashed lines in upper right corners demarcate the boundary between epidermis and a tiny amount of dermis. Abbreviations: Max, maximum; Min, minimum. A phase-contrast image in the central panel shows a large, circular nucleus containing a large nucleolus. Other pocklike structures are artifacts of desiccation. The giant cell is a typical "sunburn" cell with a huge nucleus and a barely perceptible cytoplasm. The nucleolus, being mostly RNA, contains little, if any, of the sampled elements. Near the large cell are several normal-sized epidermal cells. The elements sulfur, phosphorus, potassium, calcium, copper, zinc, and Se are generally concentrated in the membrane regions at the peripheries of the cells.



X-ray Scattering





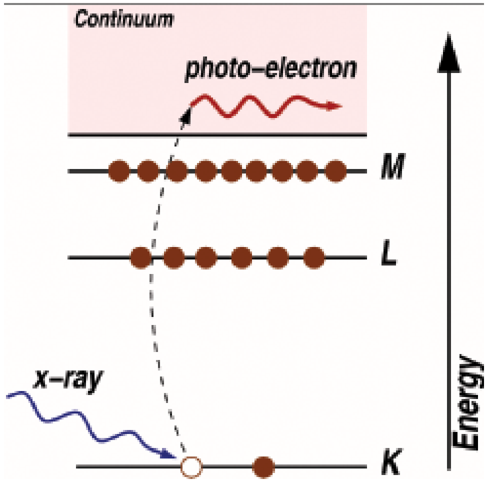
Typical Beam Conditions

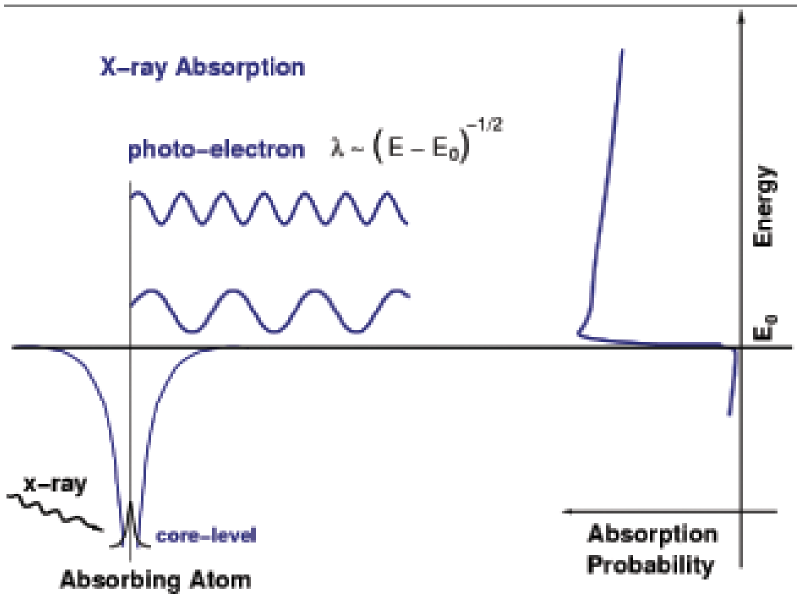
- Primary beam
  - Flux: ~ 10^{10}-10^{16} Photons/s
  - Beam size: ~ 1x1mm^2 - 30x30nm^2; typical: 100x300μm^2
  - Photon energy: 1 eV -150keV typical: ~10keV
  - Bandwidth: 10^{-4} (monochromatic), 10^{-2} (polychromatic)
  - Time-structure:
    - High energy synchrotrons (4-5 world-wide): typically 5-10MHz rep-rate with 100ps pulse width (about 10^3-10^9 photons/pulse)
    - "Modern" 2-3GeV rings (large number): typically 100MHz-500MHz with 100ps-50ps pulse width (about 10^2-10^8 photons/pulse)

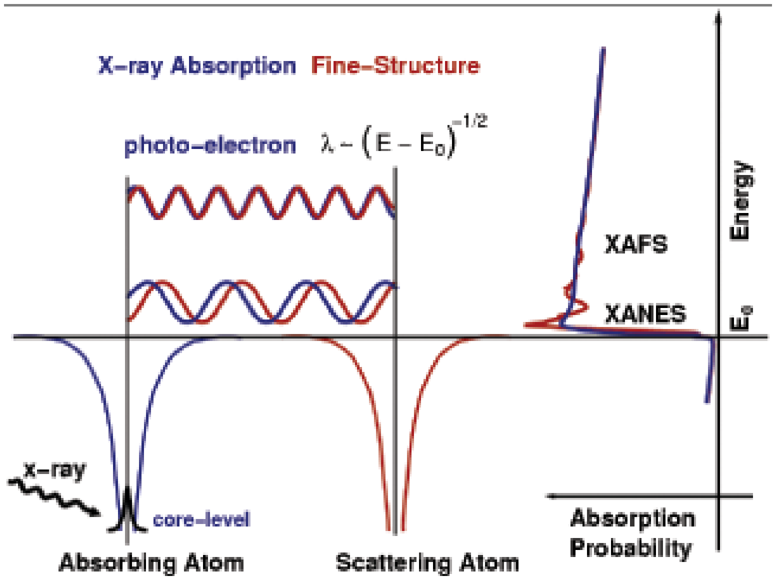
Spectroscopy: XAFS
What is X-ray Absorption?

- NEXAFS probes electronic states – EXAFS next neighbors
- "Principle" difference: photo-electron in bonded (NEXAFS) are non-bonded (EXAFS) state

Initial absorption process

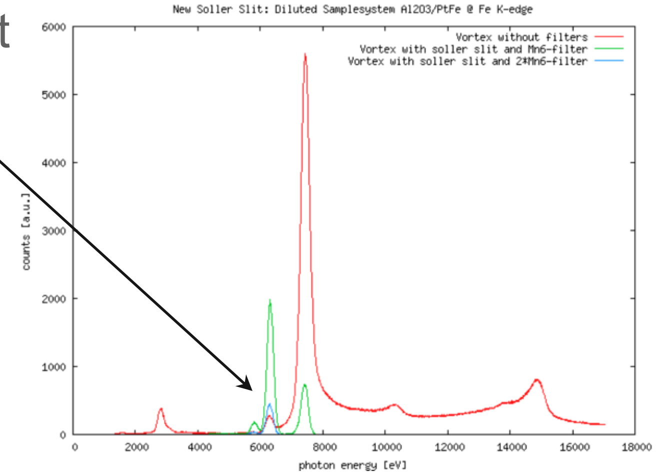


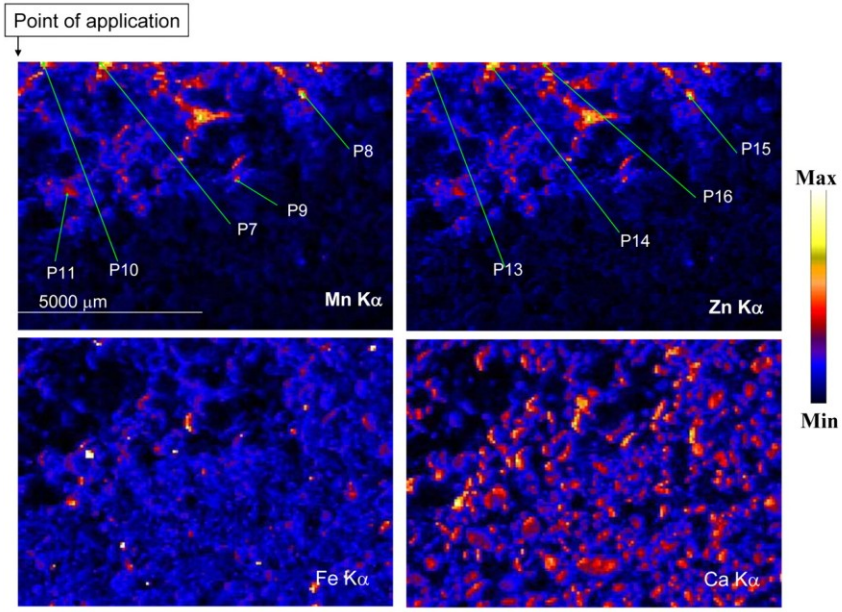




Spectroscopy
The Task

- Main detector properties:
  - Many “bad” photons and only few “good” ones
  - Signal to back-ground depends on the concentration and composition
  - Fluorescence emission is isotropic (emission in 4π)
  - Total number of photons up to 10^{10} Photons/s
- Two detector solutions:
  - Single photon detection & electronic energy resolution (pulse height distribution)
  - Current type detection system combined with energy filters:
    - Z-1-filters with soller slit system
    - Crystal optics (sometimes using spatially resolving detectors)





Spectroscopy
Short History of XAFS Detectors

Physics

Catalysis
Material Sciences

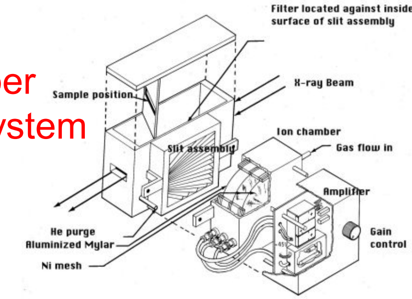
- Bio, Geo,
- Nuclear
  Engineering
- Chemistry ...

Development of combined techniques Microscopes

Real material under real conditions

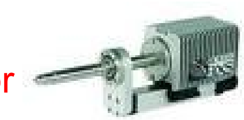
- Lytle Detection system (mid 70's)
  - Enabler technology (allowed new filed: catalysis)
  - Cheap (a few $K) and easy to install
  - Diluted samples with dominating elastic background (~1mmol-samples)
- Ge-multi-element detector (mid 90's)
  - Records full emission energy spectrum
  - Maximal count rate per element typically: ~100-200Kcps. (about 10-30 elements)
  - Diluted samples down to (~1μmol-samples)
- Si-Drift diodes (starting ~2000)
  - Increased count rate and smaller fill-factor
  - Simple air cooling makes it easy to integrate
  - First "multi" element systems available
- Crystal optics (~ 2008-.....)
  - Unprecedented energy resolution allows new spectroscopy techniques
  - Typically very complex instruments

Ionization chamber with filter & slit system

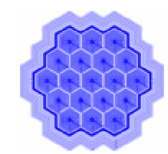


Multi-element Ge-detector (LN2)

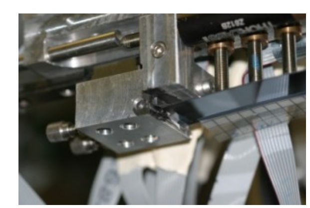
Single element Silicon Drift Detector



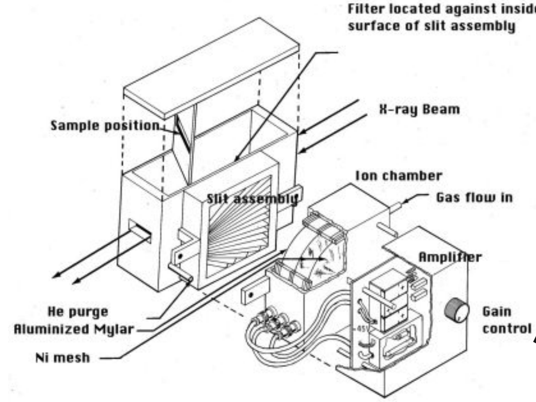
Multi element Silicon Drift Detector



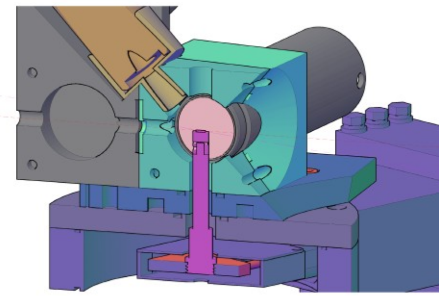
Modern Crystal Optics combined with area detectors



Spectroscopy
The Big Detector Challenges

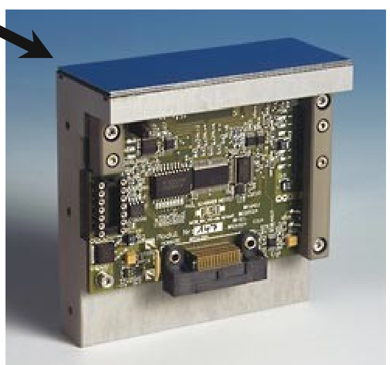


Modern fabrication technology



- Packaging
  - Large solid angle at least 1π perhaps 2-3π
  - Small footprint
  - Modular system?
  - Modules must be compatible with harsh environment
    - Temperature
    - Pressure
    - Chemical environment (solvents, oxidizers, fuels….)
- Detection capabilities (of system)
  - 10^9-10^{10}cps (at 100-5MHz rep rate)
  - Energy resolution 50-150eV at 10KeV
  - High detection efficiency between 3KeV-30KeV
  - Bunch to bunch resolution capability?
- Economics:
  - Typical cost for spectroscopy systems ~$250K
  - Moderate number of systems: ~20-40 per year (dependent on prize)

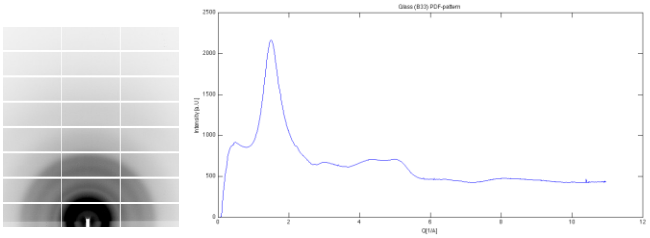
Integration and monolithic



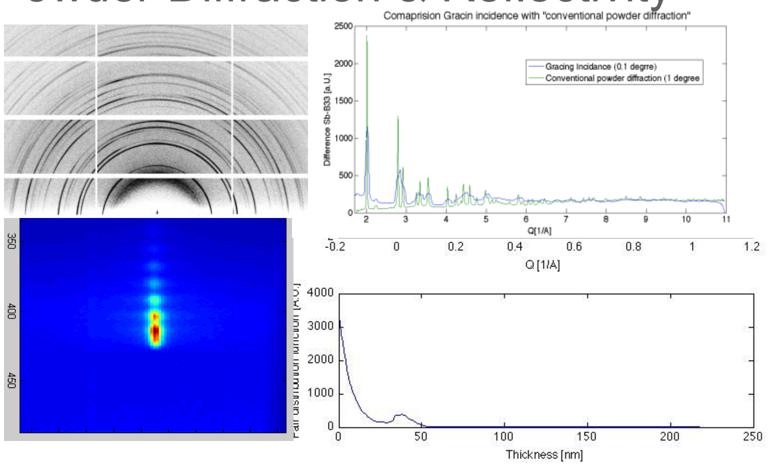
X-ray Scattering and Diffraction
What is Scattering ?

- Small angle scattering probes:
  Shape and Size of particles
- Wide angle scattering:
  - PDF: amorphous and systems with low ordering
  - Powder diffraction: small crystallites (orientation, size, strain ….)
  - Single crystal diffraction:
    - Protein crystallography
    - Diffuse Scattering
    - Crystal truncation rod (CTR)
- Grazing incidence experiments:
  - Reflectivity
  - Small and wide angle techniques

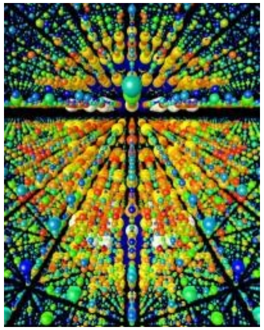
PDF (pair distribution function)

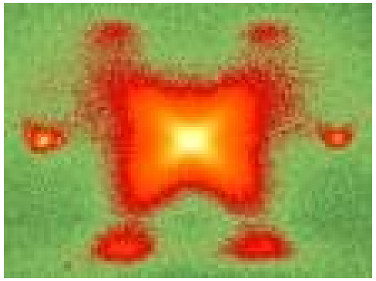


Powder Diffraction & Reflectivity



Single Crystal Techniques



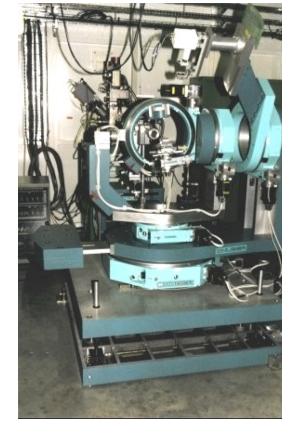


X-ray Scattering and Diffraction
Short History of Scattering Detectors

Required Time*:

1-2 weeks

- Point detector & complex goniometer (70's)
  - Technique development
  - Fully detector limited:
    maximal count rate about 30Kcps
  - Low back-ground

8 hours

- Image plate detectors (mid 90's)
  - Integrating detector
  - Relative good signal-to-background
  - Much higher maximal count rate
  - 2-D detection efficiency

1-30 minutes

- CCD with fiber or lens coupled phosphor (early 2000's)
  - Much faster readout (~2s)
  - Better fill factor
  - Issues with low count rate applications

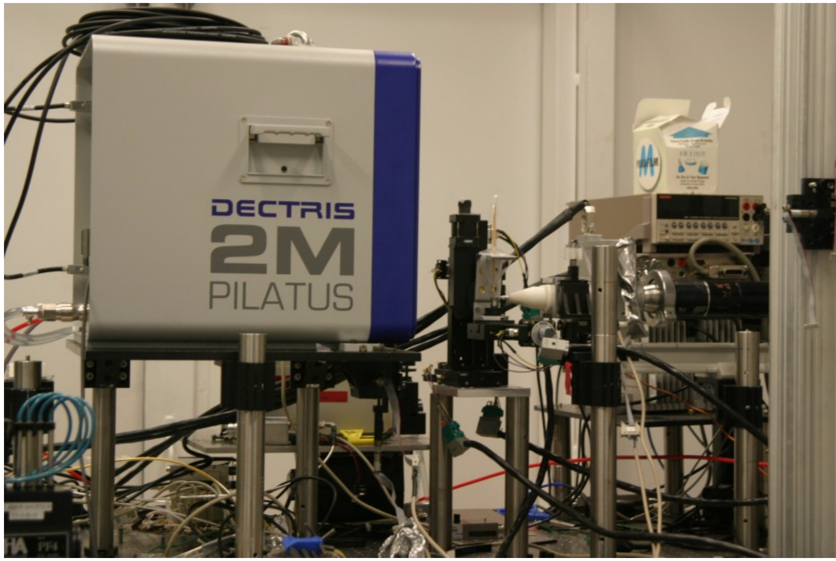
1 second

- PAD detectors (2008…..)
  - Bunch-to-bunch gateable
  - Excellent low count rate capability
  - Relative low spatial resolution

*: full Q-information

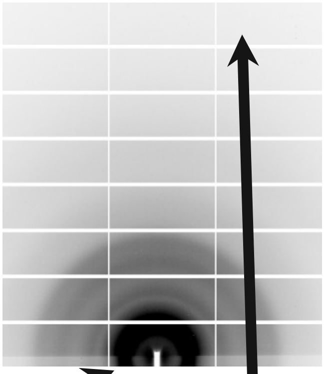
X-ray Scattering and Diffraction
The Task

- Main detector properties:
  - Large detection area
  - Moderate energy resolution to suppress background (500eV @ 10KeV)
  - Good spatial resolution (10-50μm)
  - Large dynamic range (10^{-3}counts -10^{10}counts)
  - Count rates
    - Up to: 10^4 Photons/(100μm^2 x bunch) (5MHz rep rate)
    - Typical maximal count rate: 10^{-2} Photons/(100μm^2 x bunch) (100MHz rep rate)
  - Energy range: 8-120KeV
- Two detector solutions:
  - Single photon detection & electronic energy resolution (pulse height distribution)
  - Integrating (bunch-bunch resolution)



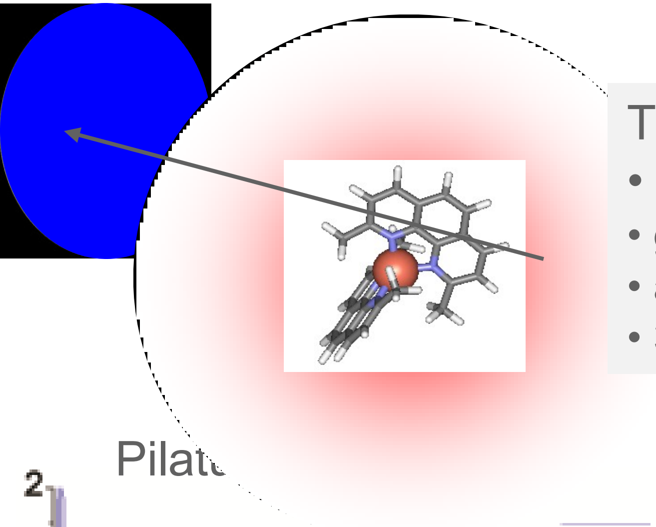
X-ray Scattering and Diffraction
Some Remarks to Single Photon Counting

Raw data:



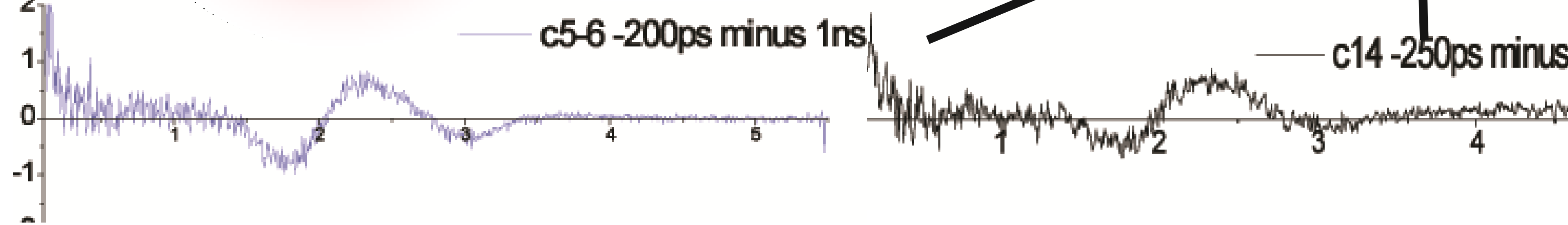
Time resolved liquid scattering:

- 10^7 photons/Bunch at 12KeV
- gated signal: 1KHz rep rate
- about 4min total accumulation time
- 3mmol sample and 20mmol sample



Pilat

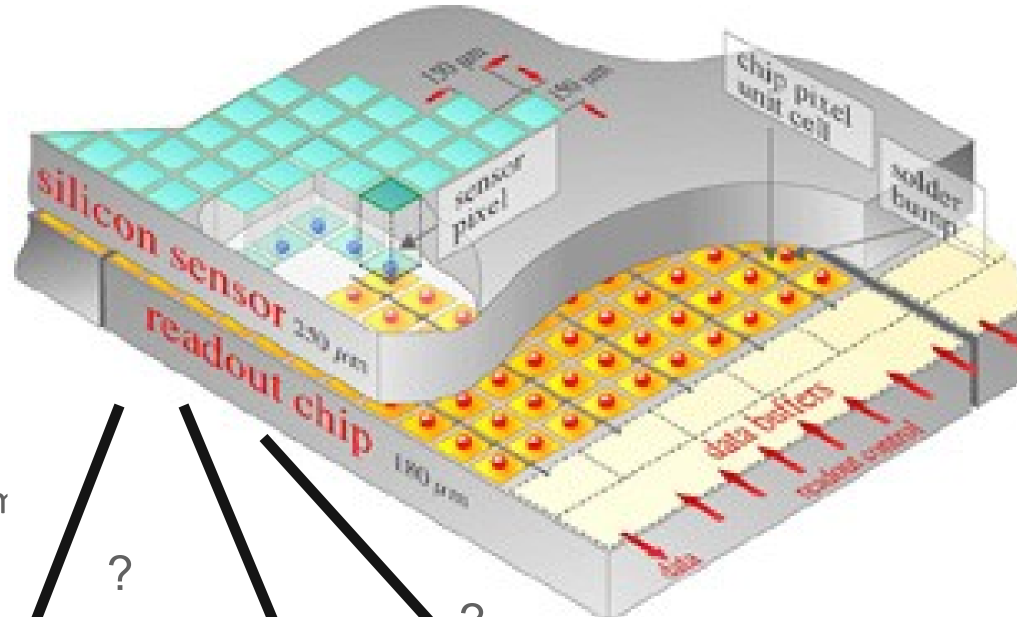
MAR 165:



- Single photon counting: Significant better in low count rate application!
- Current pixel size is too large!
- Single photon counting allows energy discrimination -> background!

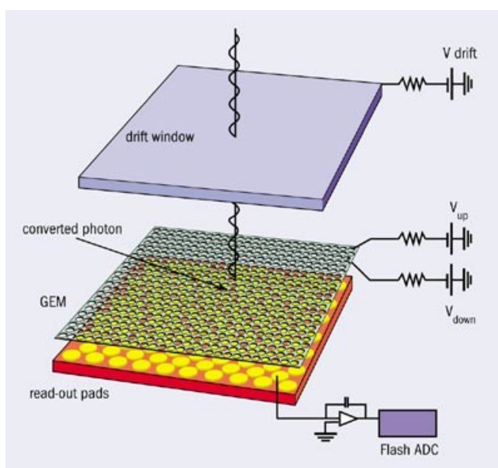
X-ray Scattering and Diffraction
The Big Detector Challenges

- Main detector challenges:
  - Higher spatial resolution: ~5-10µm
  - Large areas
  - Price < $1M ?
  - Storage of Multiple frames?
  - Count rate up to: 10^4 Photons/(100µm bunch)
  - Energy range: 5KeV-120KeV
- Detector solutions:
  - ?????????



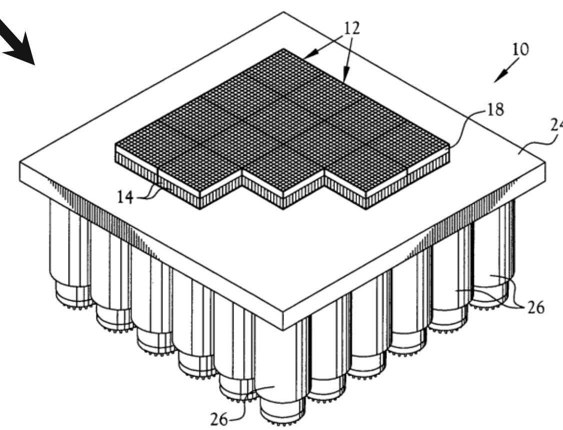
?

?

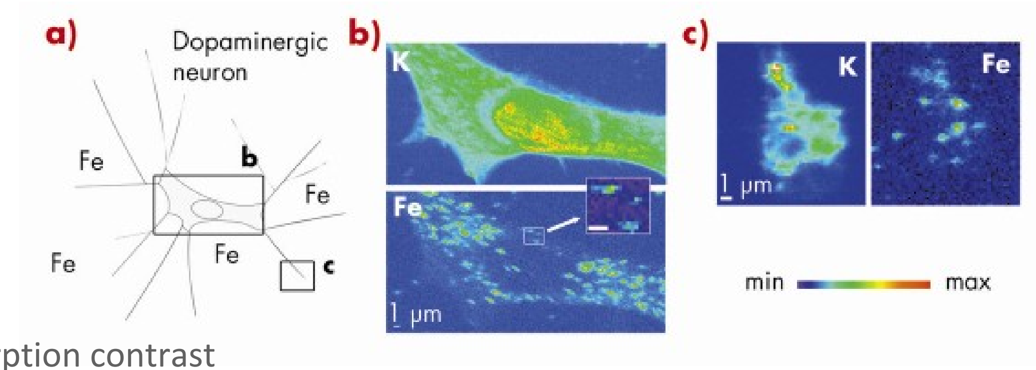


?

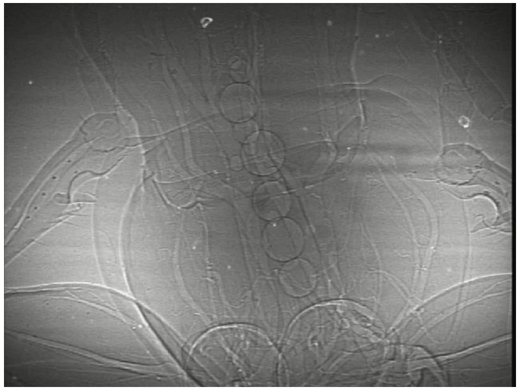
Si-PMT based?

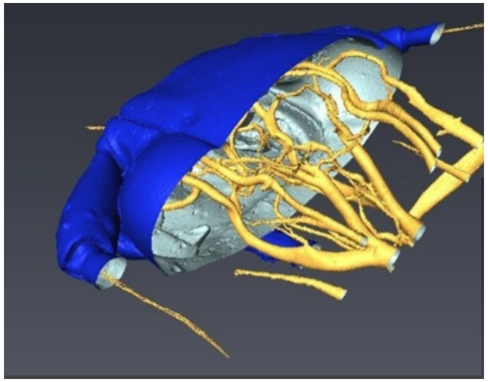


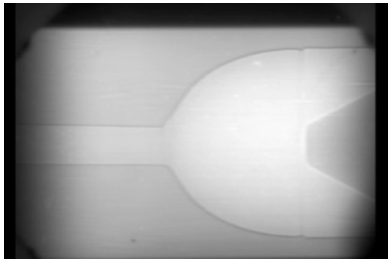
Imaging
What is Imaging ?



- Full field imaging
  - Phase contrast
    - Mainly for materials with low absorption contrast
    - Biological but also materials science problems
  - Time resolved
    - Slow resolution in milisecond range
    - High resolution down to ns-frame rate
- Scanning probe
  - Extreme high resolution (down to 10nm)
  - Elemental maps
- 3-D reconstruction (tomography)
  - Absorption
  - Phase-contrast
  - Diffraction contrast



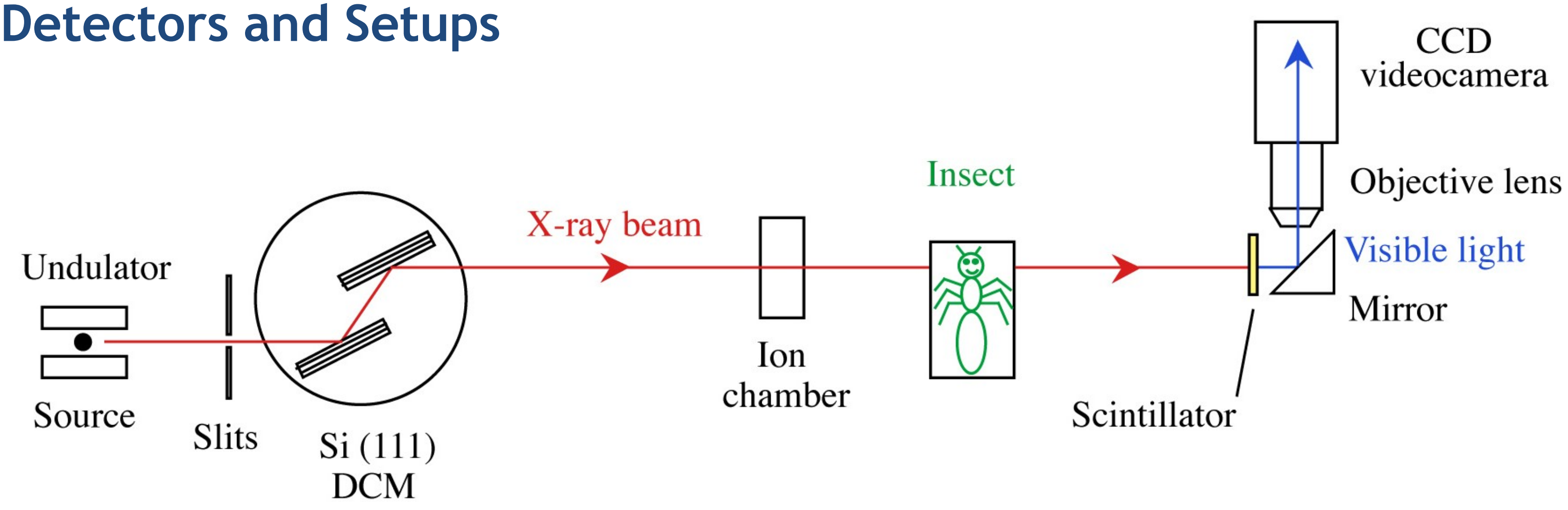


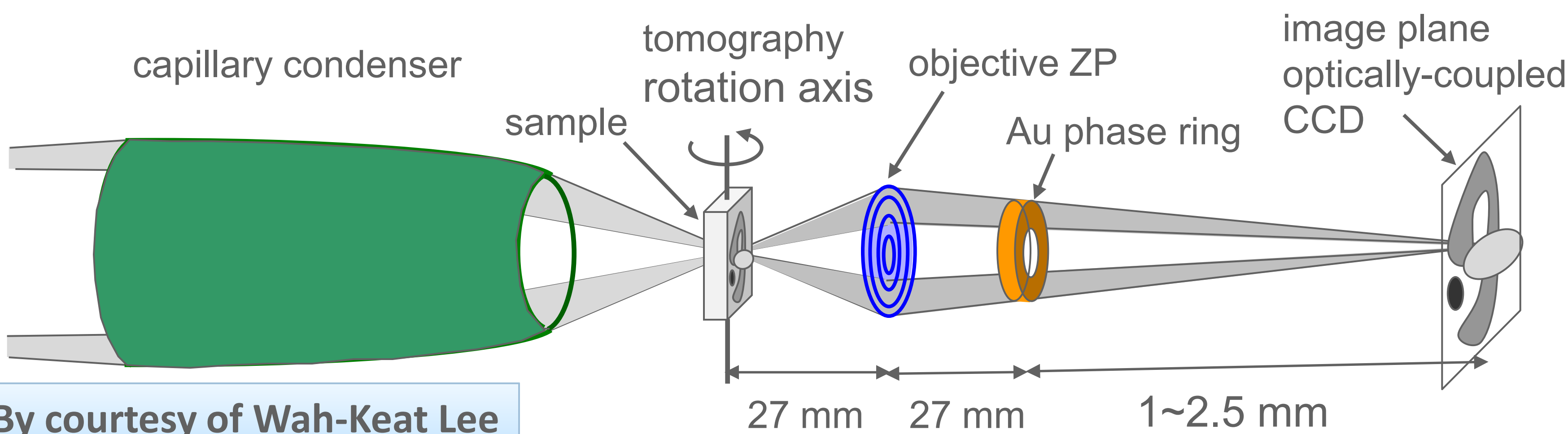


By courtesy of Wah-Keat Lee

Imaging

Detectors and Setups

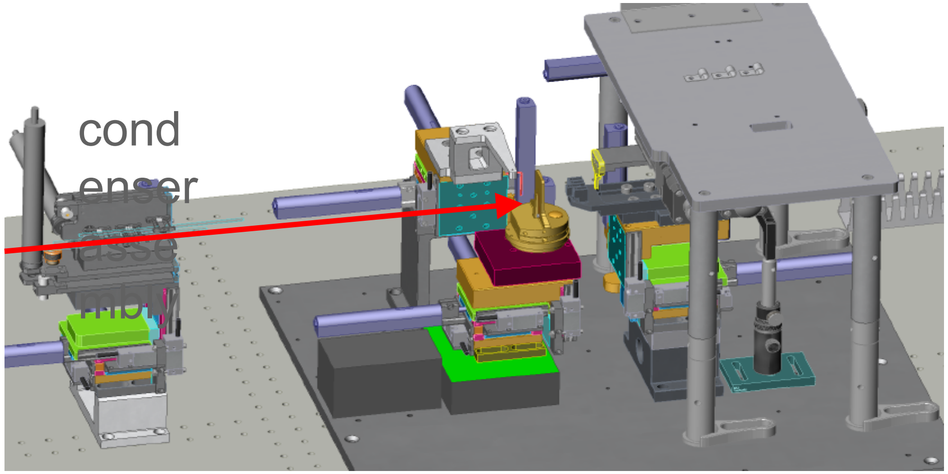




By courtesy of Wah-Keat Lee

Imaging
The Task

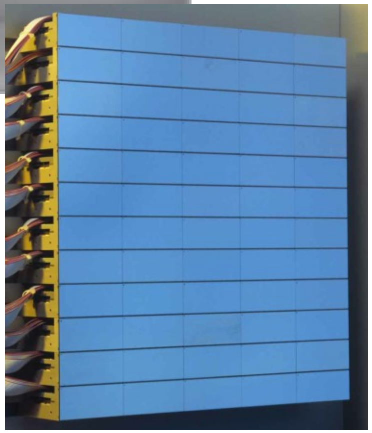
- Main detector properties:
  - Medium size detection area (1mm^2-1cm^2)
  - No energy resolution
  - Good spatial resolution (100nm-5μm)
  - Medium dynamic range (10^{-1}counts -10^{4}counts)
  - Count rates
    - Up to: 10^4 Photons/(100μm^2 x bunch) (5MHz rep rate)
    - Typical maximal count rate: 10^{-2} Photons/(100μm^2 x bunch) (100MHz rep rate)
  - Energy range: 8-30KeV
  - In some cases Bunch-to-Bunch resolution
  - Fast read-out: 100Hz-10KHz
- Two detector solutions:
  - Scintillator-PAD detector
  - Direct illuminated fast CCD
  - MCP-units?

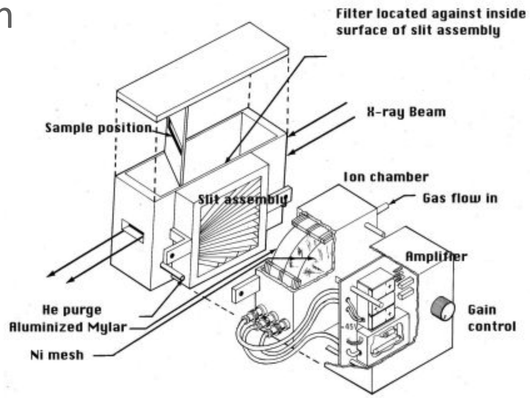


By courtesy of Wah-Keat Lee

Lessons learned from the past

- Every detector which had large impact
  - Relative easy to handle
  - Was developed over multiple product generations
  - Comes as a complete system (detector, electronics, software, and implementation in beamline architecture)
  - Availability due to industrial production
  - Addresses a general detector property applicable to many experiments
- Examples for collaborations between HEP and synchrotron community
  - Ge-detectors
  - All current PAD-detectors: Pilatus, Eiger, Medipix
  - Si-Drift detectors





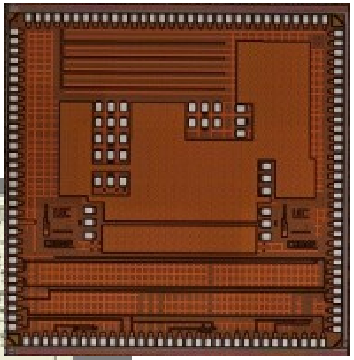
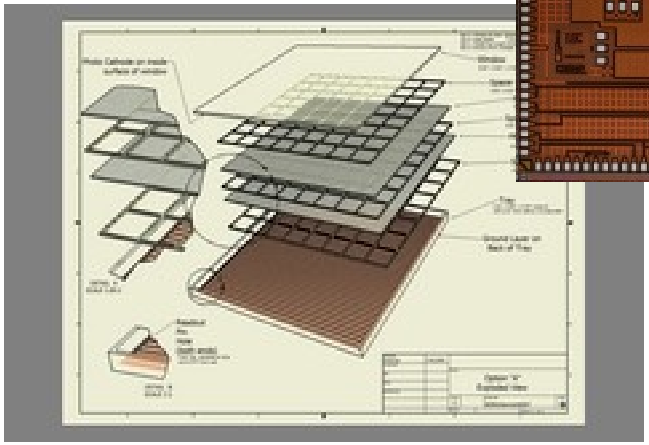
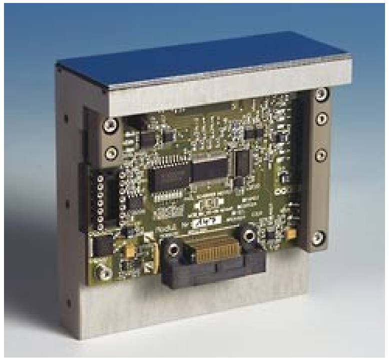
Where We are Now?
The Big Detector Challenges at Synchrotrons

Count-rate limitation (pixelated detector)	• Either by charge integrating systems or by smaller pixel size
Limited spatial resolution (pixelated detector)	• 50µm pixel size is next generation of pixelated x-ray detectors • The challenge will be to create 1-10µm resolution (comparable to optical systems and following the trend for smaller beam sizes)
Fast readout to follow non reversible processes	• Mainly driven by insitu-community (like battery-community) • Currently integrating memory on pixel • Alternative bunch-to-bunch analysis and flexible “intelligence”
Large solid angle fluorescence/scattering detection system for insitu-work	• Currently only little effort is done • Utilizing optimized sample-environment and detection systems are possible (currently used in timing community)

Where We are Now?
State of the Art

Property	Charge Integrating Detectors	Single Photon Counting Detector	Fast Readout
Advantage	Large Dynamic range for high count-rate application	Large dynamic range for low count rates (maximal ~600Kcps)	Following fast changes in the micro-milli-second
Disadvantage	"bad" signal-to-background ratio for low count rates	maximal count-rate per pixel ~600Kcps	Requires relative sophisticated electronics
Current activities	Cornell BNL/KETEK/Fermi German collaboration	Pilatus/Eiger (50x50mum^2) Collaboration MEDIPIX-collaboration	Eiger (10 KHz)
State-Of-The-Art	None existing device commercially available	172mumx172mum available	Next year commercially available (10KHz)
Next Big Challenge	? Demonstration of working system?	5-10mum pixel size	Bunch to bunch "read-out"

Where We are Now?
HEP and Other Communities can Contribute!

- Advantages
  - Long tradition of building detectors
    - Strong electronics programs
    - ASIC and sensor chip development
    - Large innovative power
- Challenges
  - Very different culture
    - Dedicated instrumentation versus changing setups
    - Homogeneous versus very divers community
    - Different “language”
    - Single experiment versus large collaborations
  - Different funding channels and agencies
  - Different sciences
    - “coming in contact problem”

However: A very powerful combination (and it is already successfully done)

Conclusion

- Synchrotron community is highly divers
  (scientific background and experimental approaches)
- Most impact can be achieved by providing “better” detectors
  (Detector developments had been THE enabler in the past)
- Development of industrial partners is essential (availability)
- HEP-synchrotron connection was very fruitful

Let’s start to work together!