Challenges for Future Detector Development for Current and Future Light Source Experiments

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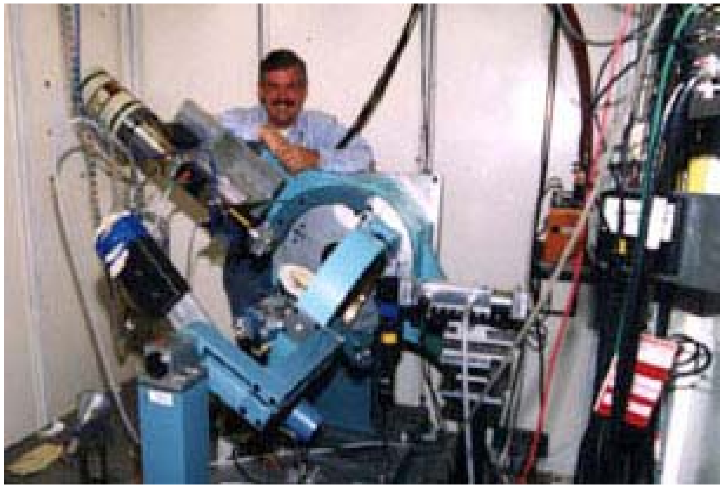
Outline

- SR: the “Photon Superprobe”
- Philosophy & culture
- Detector challenges
  - SRSs
  - FELs
- Solutions
  - At least, ways forward

Synchrotron Radiation: the Photon Superprobe

- Covers Infrared to Gamma-like energies: 10^9 range
  - Unique source in regions not covered by tunable lasers
- Different energy ranges need different instrumentation and different detector technologies
  - IR
  - VUV
  - Soft X-ray
  - Hard X-ray
  - High-energy



(From left) Peter Johnson (BNL), Tonica Valla (BNL), Zikri Yusof (Universoty of Connecticut), Barry Wells (University of Connecticut).

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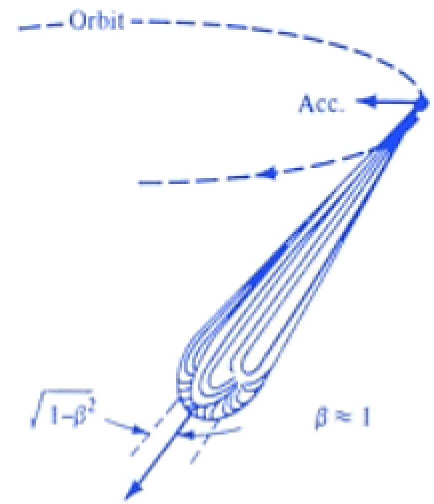
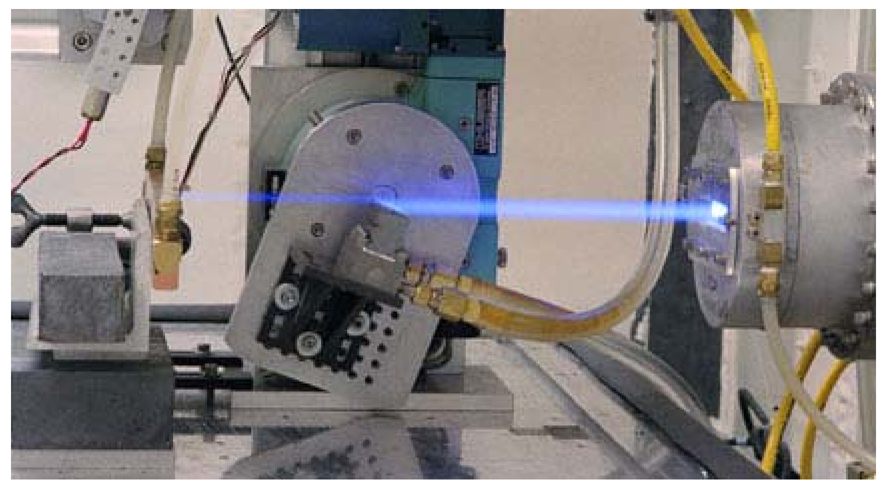
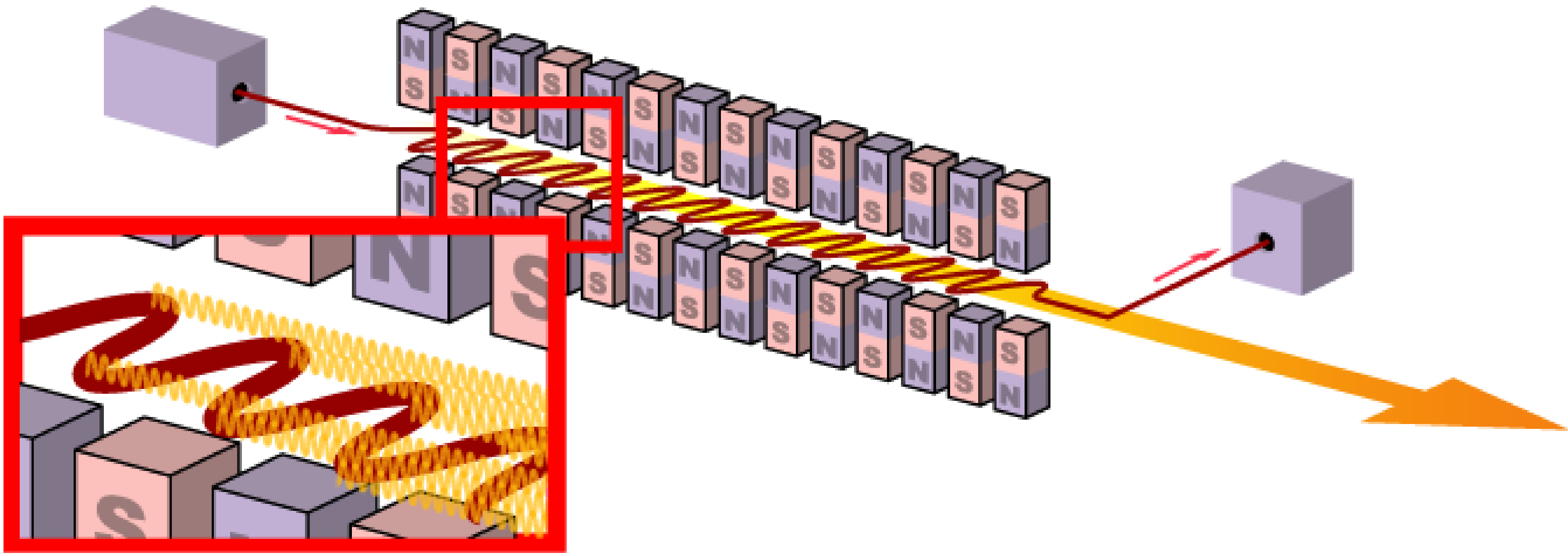
SR contd: Unique properties

- Very bright:
  - Very intense
  - Highly collimated
  - Large coherent fraction
- Polarized
  - spin-sensitivity
  - anisotropy sensitive
- Pulsed
  - time-resolved studies
- Has application in most scientific fields.





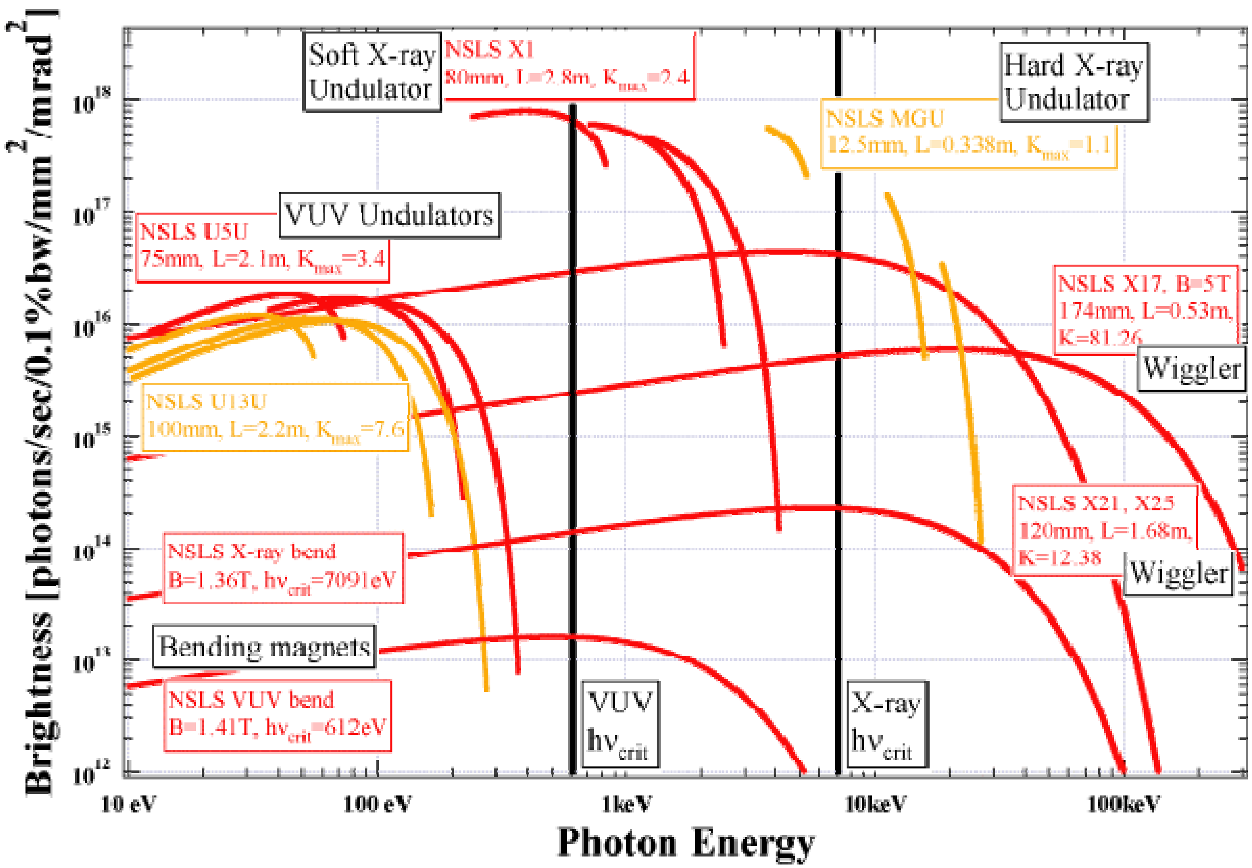
Wigglers, Undulators and FELs



- Wiggler is series of strong bends alternating in sign
- Undulator is series of weak bends, so light emitted from successive bends has some coherence.
- FEL is very long undulator so radiation field is strong enough to introduce periodic microbunches inside bunch and hence a resonance with undulator.

SR contd: Typical SR source spectra

- Wide variety of sources:
  - dipole magnets
  - wigglers
  - undulators
- Each have advantages and disadvantages

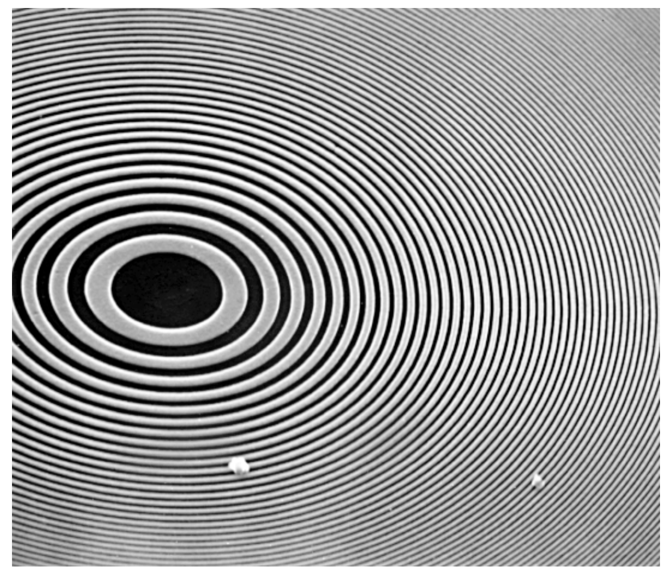


SRSs worldwide

- 16 in USA
- 23 in Europe
- 25 in Asia
- 1 in Australia
- 1 in South America

Why is brightness important

- Emittance: δl x δθ (hor. and vert.)
  - Comes from electron beam emittance and SR emission process
  - Is conserved
- Brightness in units of ph/s/mm^2/mr^2/0.1% δE/E
  - spatial, angular and spectral components.
- Energy resolution of crystal monochromator
  - $|\delta E/E| = \tau + \cot(\theta)\delta\theta$
  - δθ is dominant if >~10^{-5}rad
- Louiville's theorem:
  - What is the smallest focal spot we can make?



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Microfocus

- Assume 10um source size:
  - 1nm -> demagnification by 10,000
    - 100m long beamline -> 10mm working distance!
  - > increase in angular divergence by x 10,000
  - > for < 1 radian convergence angle on sample, source divergence must be < 100uradian
  - 1 radian is a big number, impractical for x-ray focusing elements so we'd rather have a smaller source size AND lower divergence, i.e.
  - HIGH BRIGHTNESS
- 1um, 10uradian -> 1:1000, 10mradian convergence.

Culture

- SR and HEP are cultural opposites
  - HEP: teams of hundreds for one experiment, complex detector system
  - SR: teams of <10 usually, simple apparatus.
  - HEP: Experiment takes years
  - SR: Experiment takes hours or days
  - HEP: Detector IS experiment
    - Scientists closely involved in design
  - SR: SAMPLE is experiment: SR and detector a necessary evil
    - Scientists just want the result

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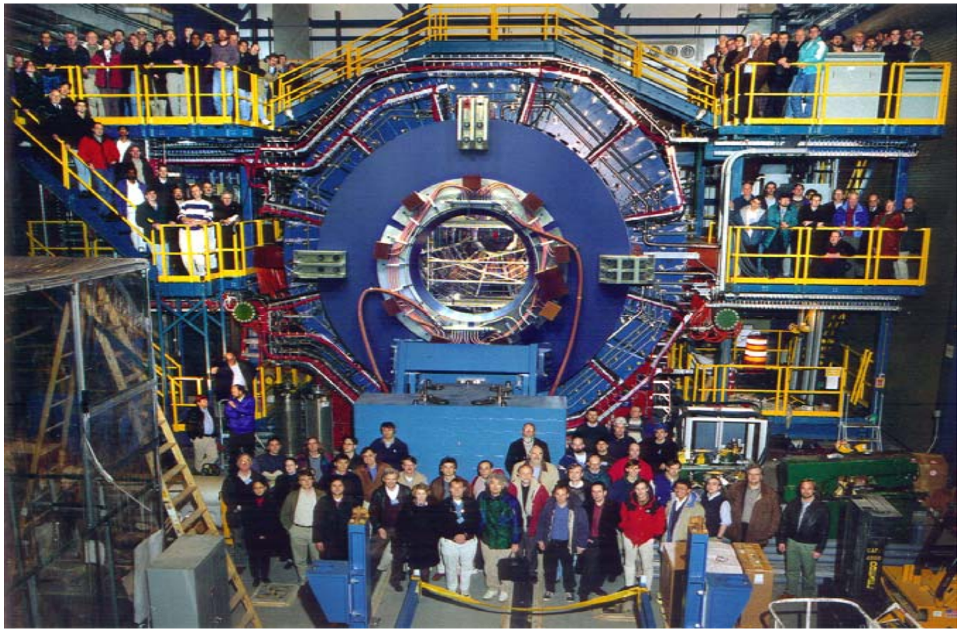

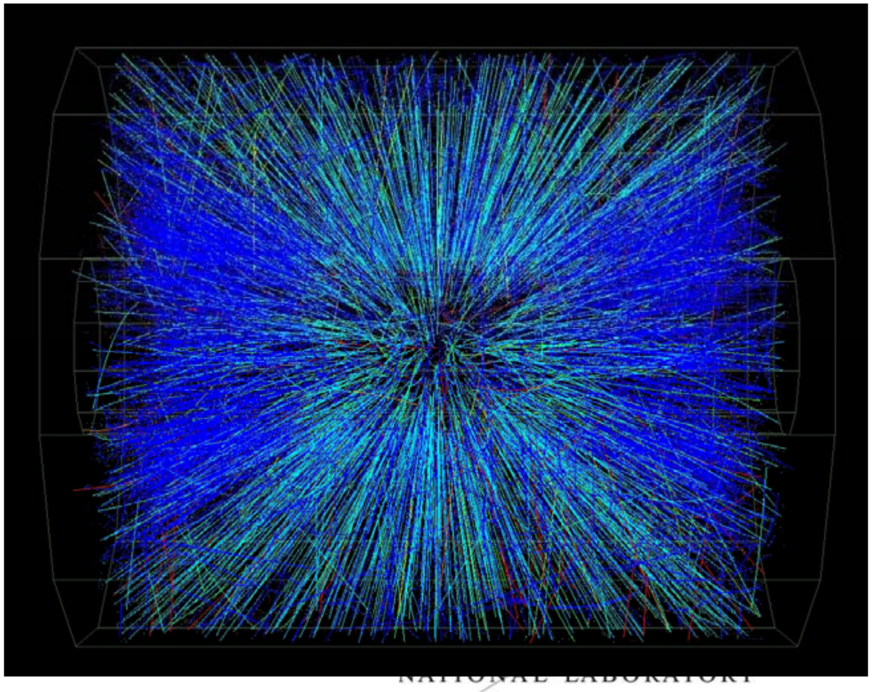

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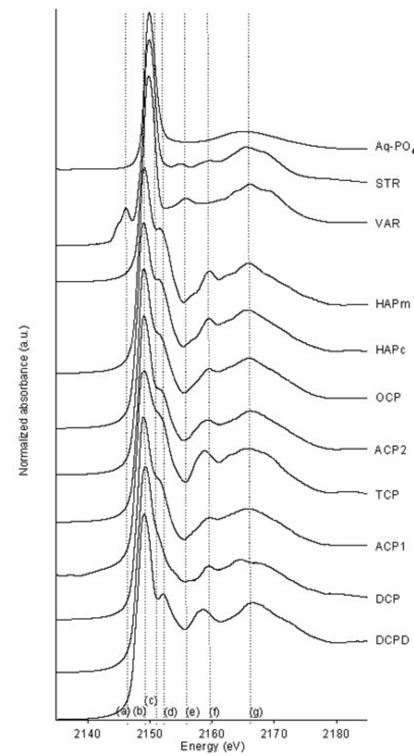

SRSs and FELs

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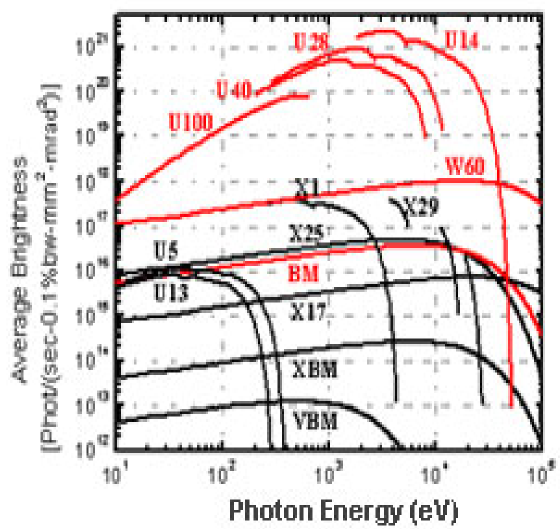
  - Electron or positron storage ring
  - No trigger, no 'free time' to dump data.
  - High average brightness, high stability
  - low peak brightness
  - fairly broadband source (~1% best case without filtering)
- FEL is pulsed source (~10ms bunch spacing)
  - Driven by LINAC / photocathode electron gun (low repetition rate)
  - Pulse width < 1ps
  - Low average brightness
  - Very high peak brightness
  - quasi-monochromatic (10^-3 SASE, 10^-4 Seeded)

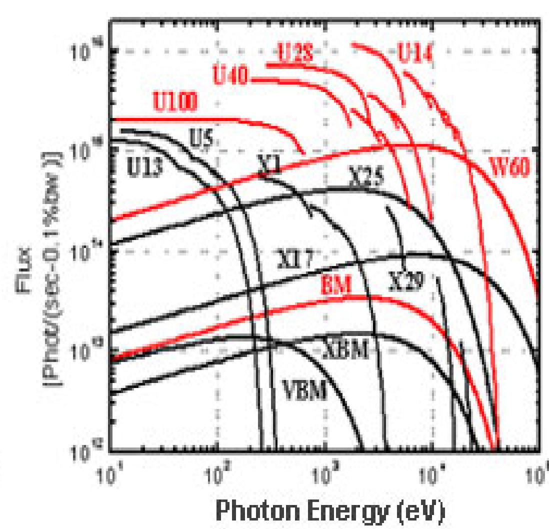
Diamond Light Source (UK)

- Electron Beam Energy 3 GeV
- Circumference 561.6 m
- Number of cells 24 double-bend achromatic
- Straight sections 4 x 8 m, 18 x 5 m
- Beam current 300 mA (500 mA)
- Emittance 2.74 nm rad (horizontal) 0.0274 nm rad (vertical)
- Life time >10 h (20h)
- Max beamline length 40 m
- End-station capacity 30-40
- Phase I beamlines 7 for operation in January 2007

NSLS-II

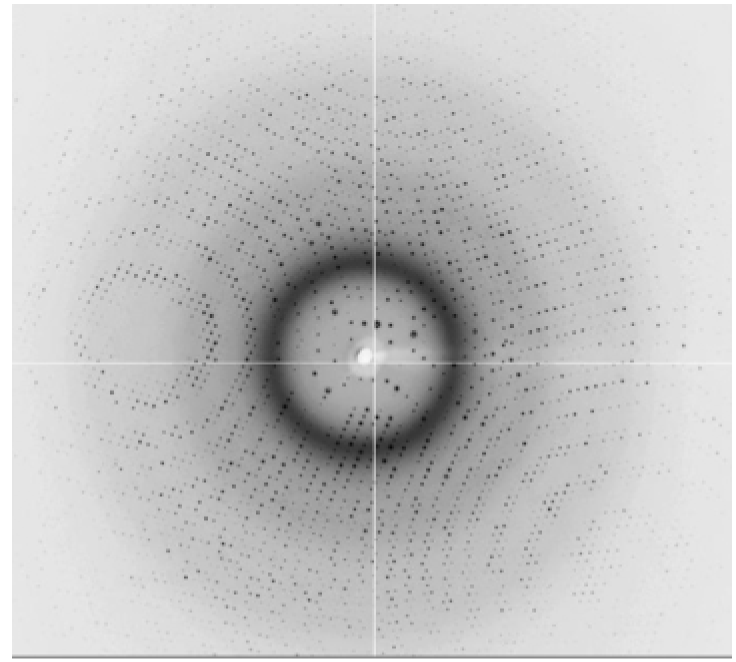
- A new 3rd-generation source at BNL
- 3GeV, 600m circumference.
- 24 TBA cells
- 5m straights
- 1.5nm-rad/0.008nm-rad
- Green-field site adjacent to NSLS
- 2012 ops.

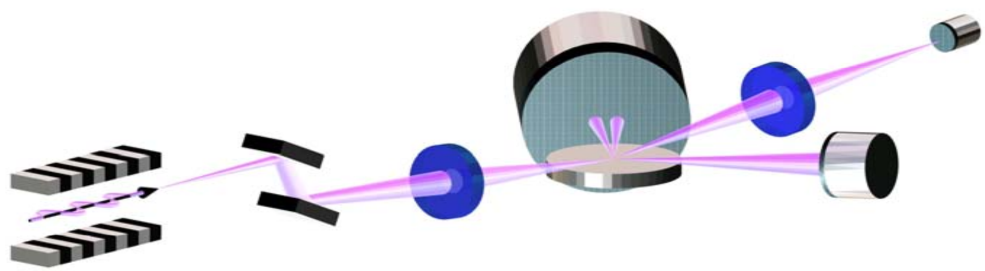




Detector challenges: SR

- Dynamic range
  - Photon counting
    - Energy range
    - Rate
    - Energy resolution
- Coverage
  - Area & spatial resolution, Fast readout of 2D detectors
- Multi-dimensionality
  - Space, Energy, Time, Temp., Press.
- Multiple concurrent methodologies





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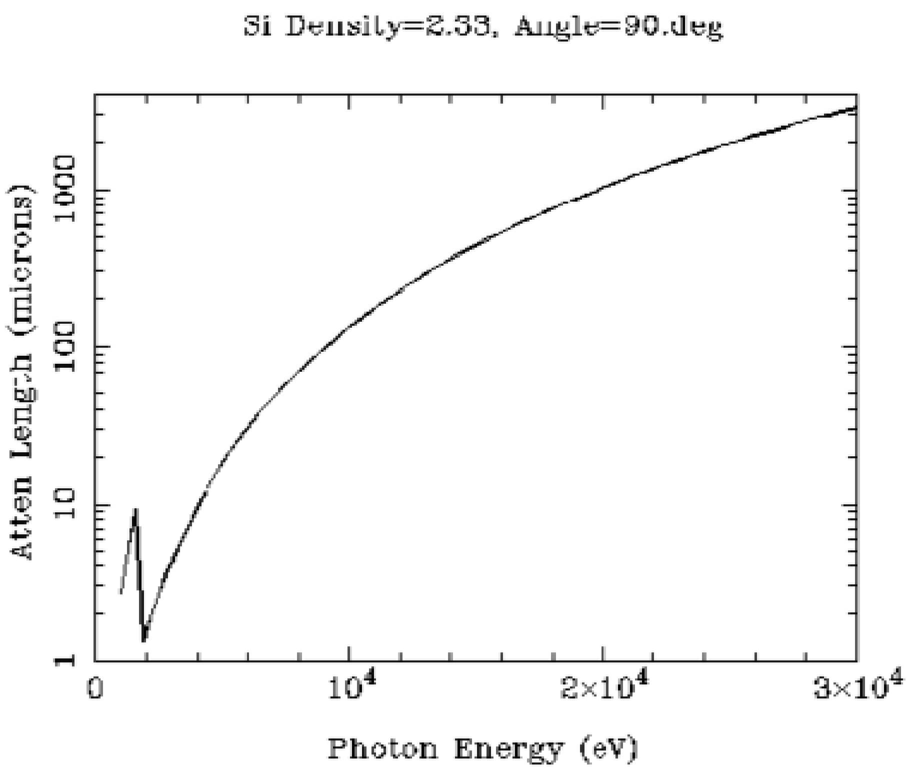
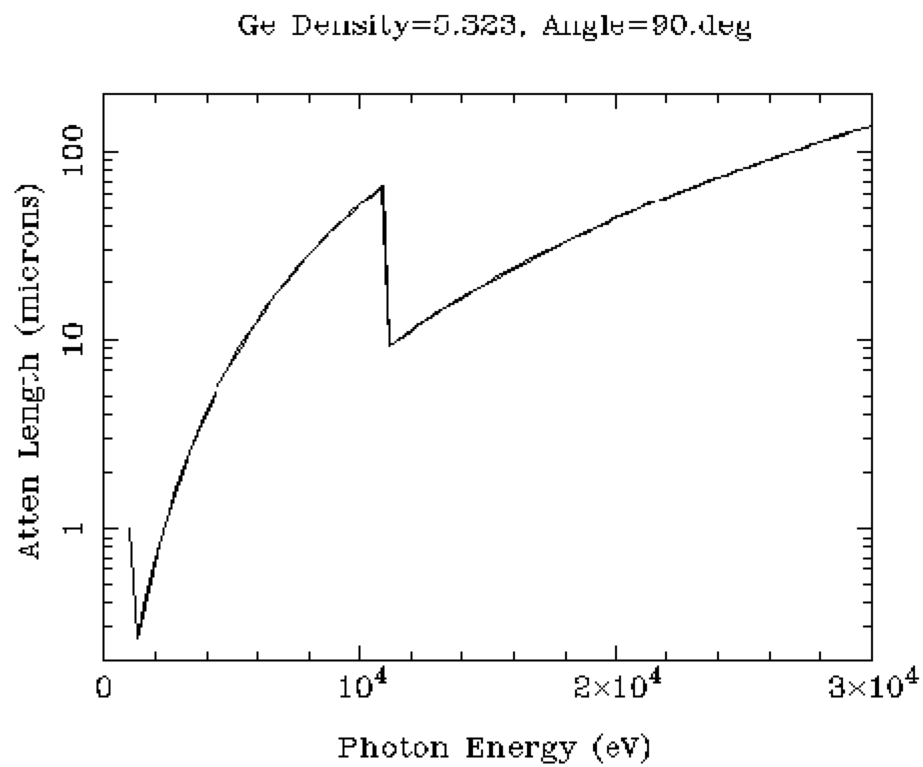
Absorption length for Si & Ge



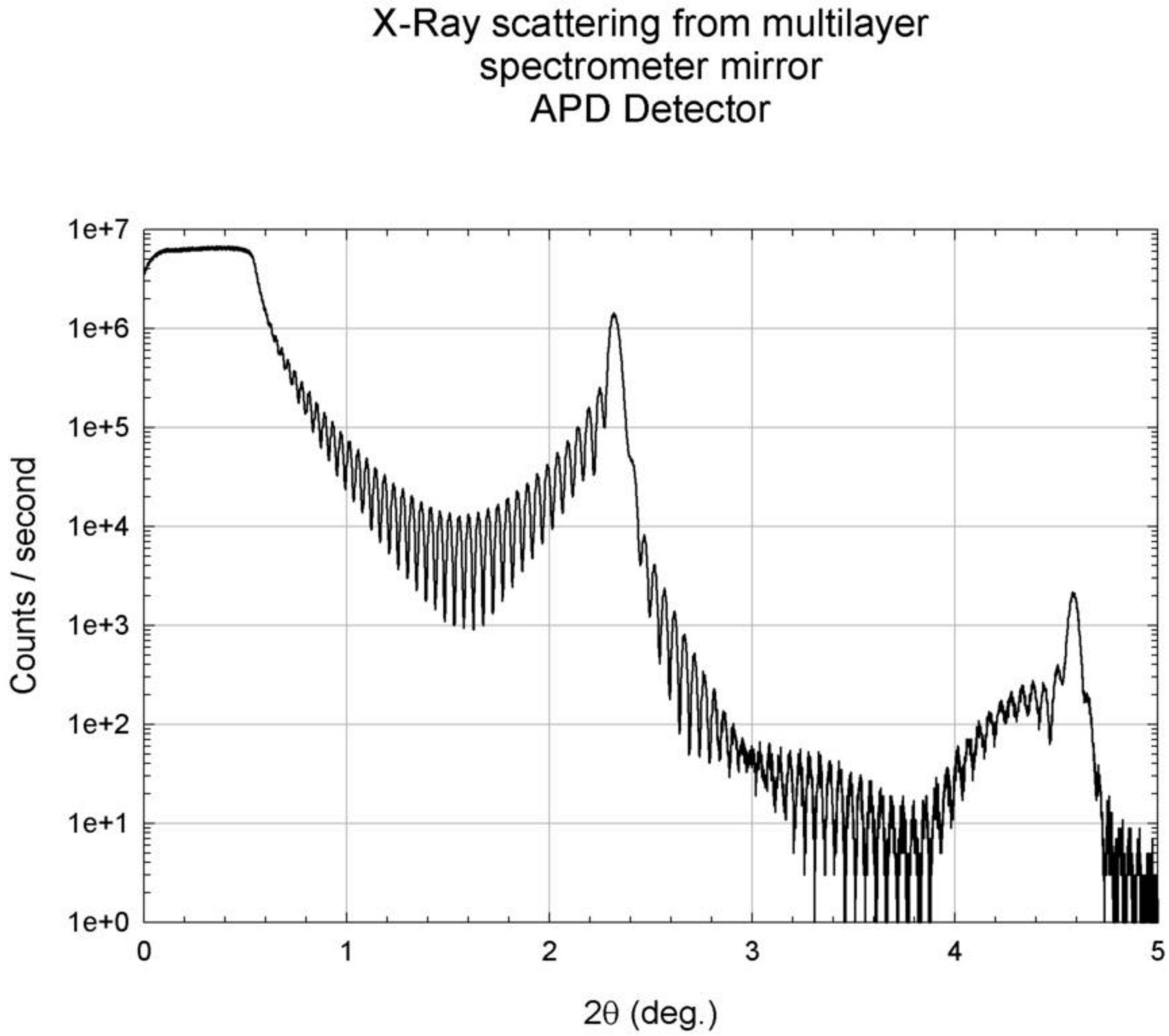


- Materials science needs E > 20keV to penetrate dense materials (alloys, ceramics etc.)

- Biology needs higher E to reduce radiation damage

Basic dynamic range example

- Reflectivity is simplest scattering experiment.
- Near zero degrees, reflectivity is ~1, so intensity can easily hit 10^10, even on an old source.
- Lowest count rate is detector noise limited



A more complex dynamic range example

- Scanning fluorescence microprobe
  - Microfocus x-ray spot rastered across a sample
  - Fluorescence emission spectrum recorded as a function of spot position
  - Spectra analyzed to provide elemental composition at each point on the sample
  - Geology, mineralogy, environmental science, catalysis, metallurgy
  - Requires photon-counting system for energy analysis
  - Requires high count rate to enable acquisition of images with large pixel count in finite time.

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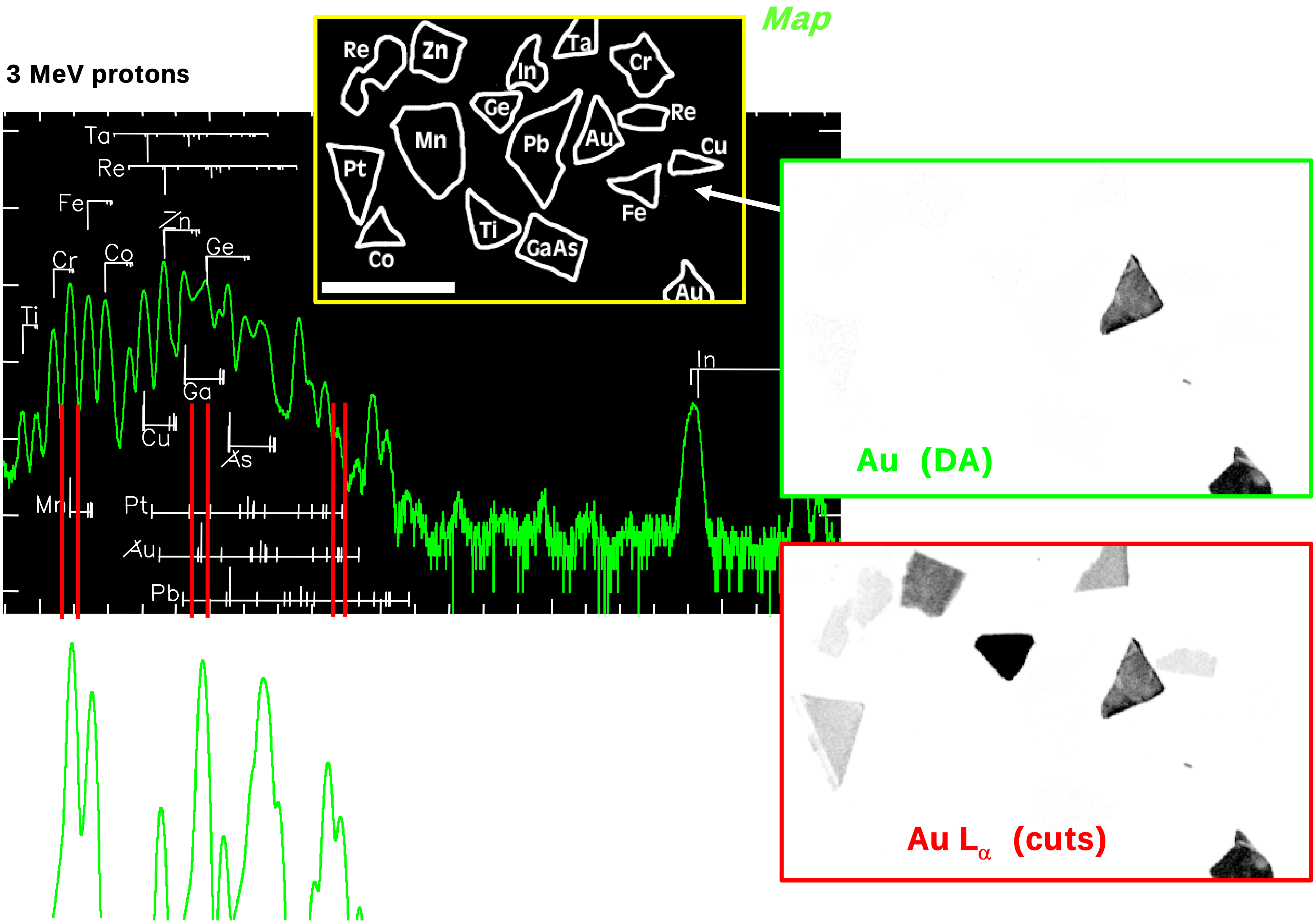
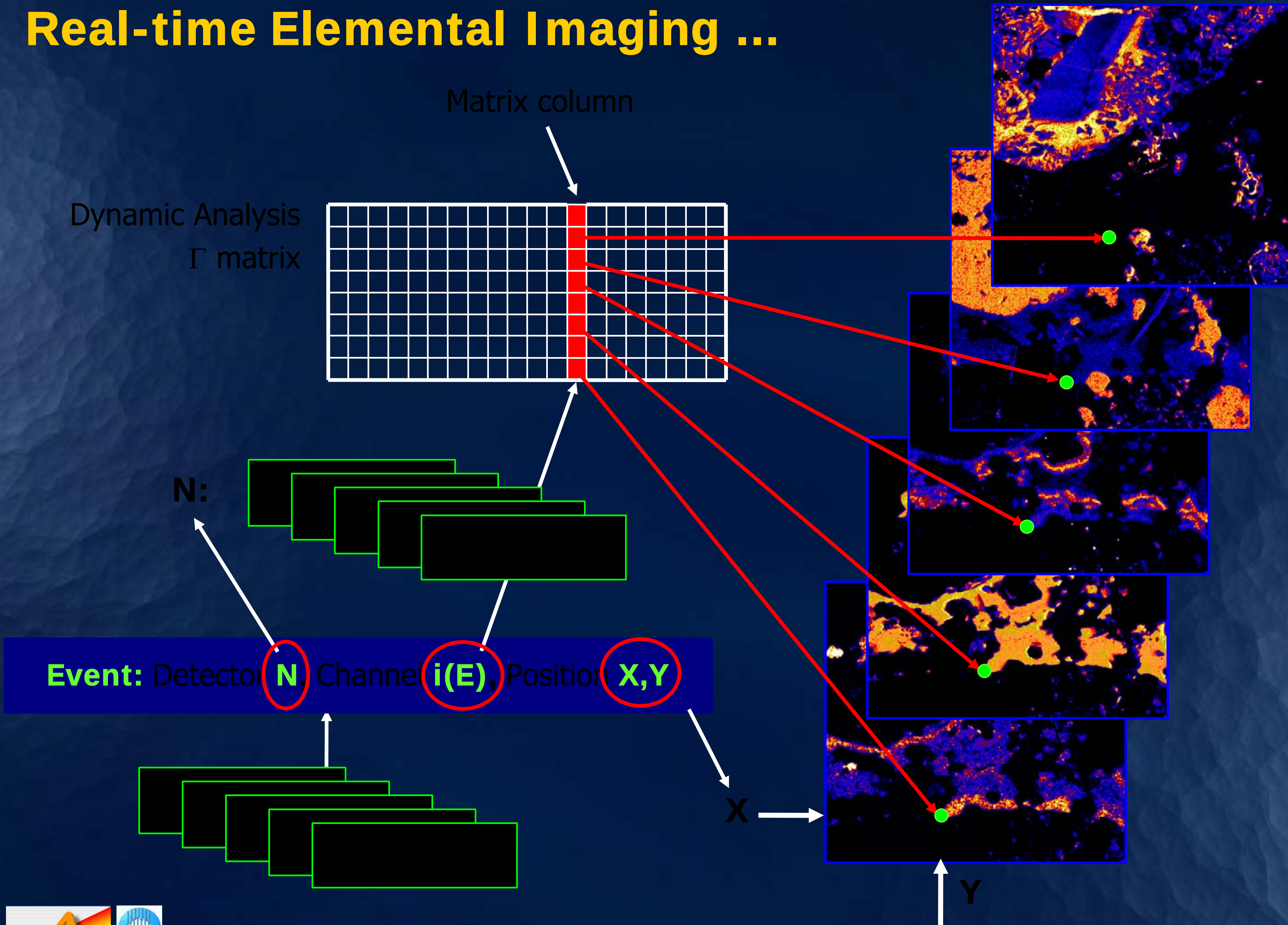
Illustration of Dynamic Analysis using PIXE

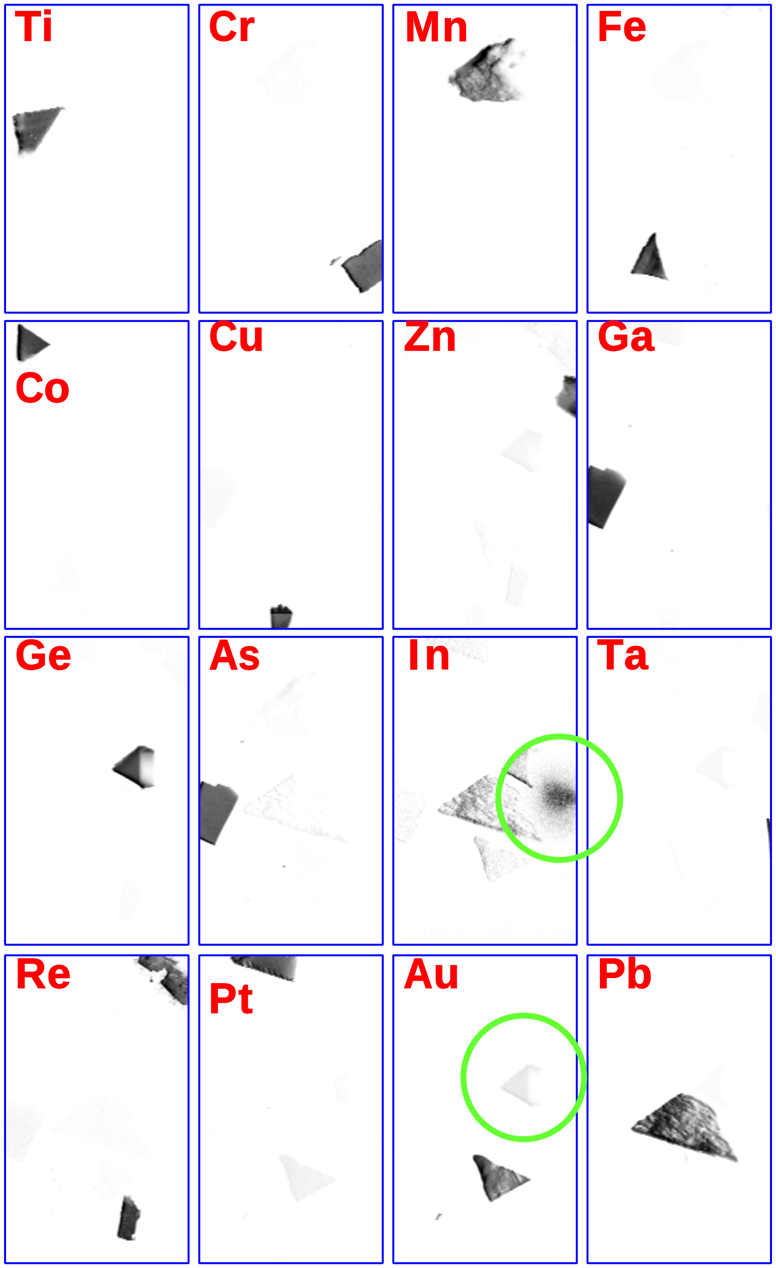


Real-time Elemental Imaging …

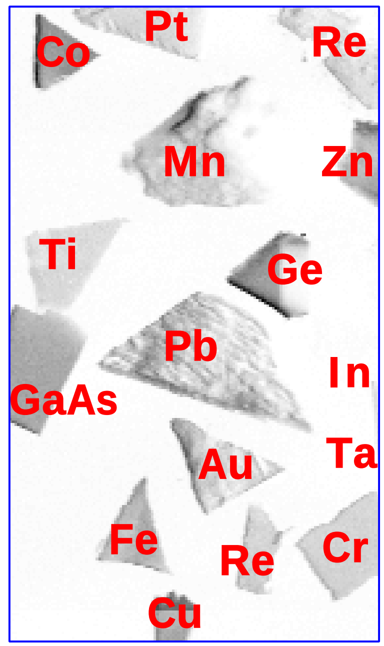


Test of Dynamic Analysis using SXRF

Dynamic Analysis

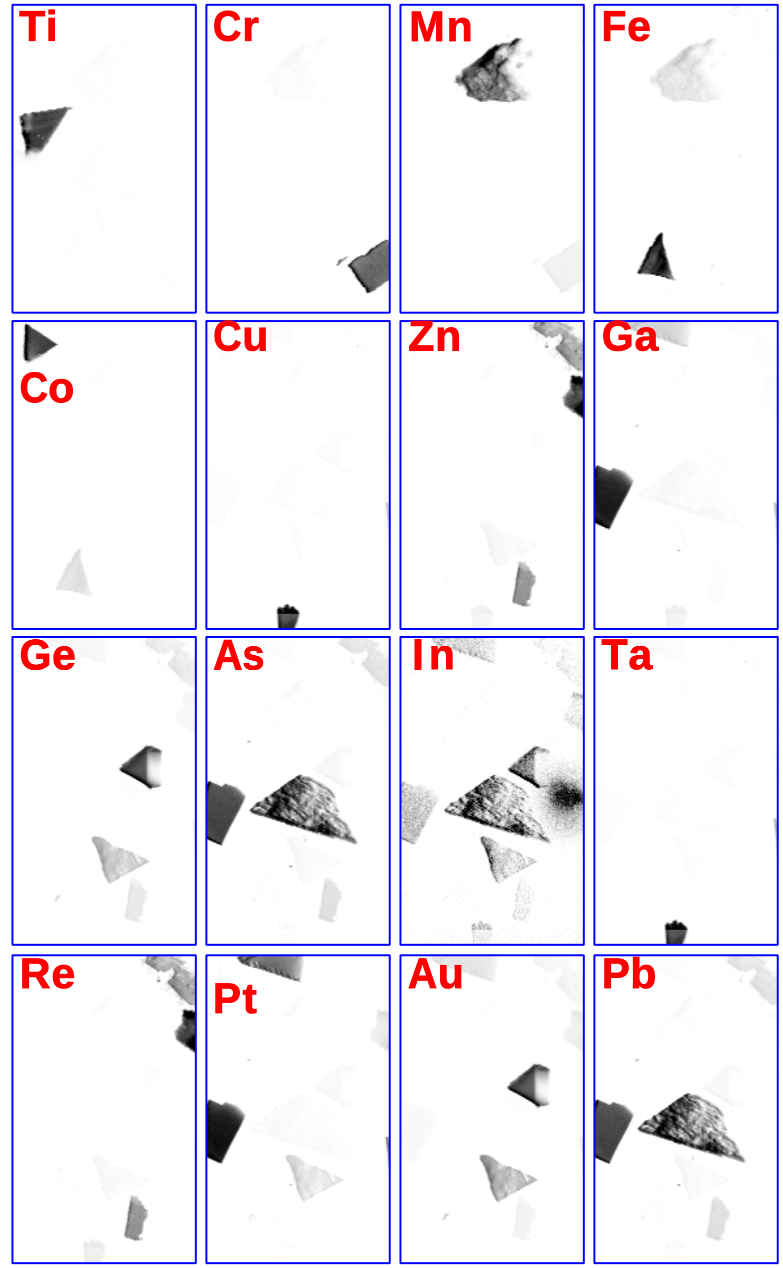


Map

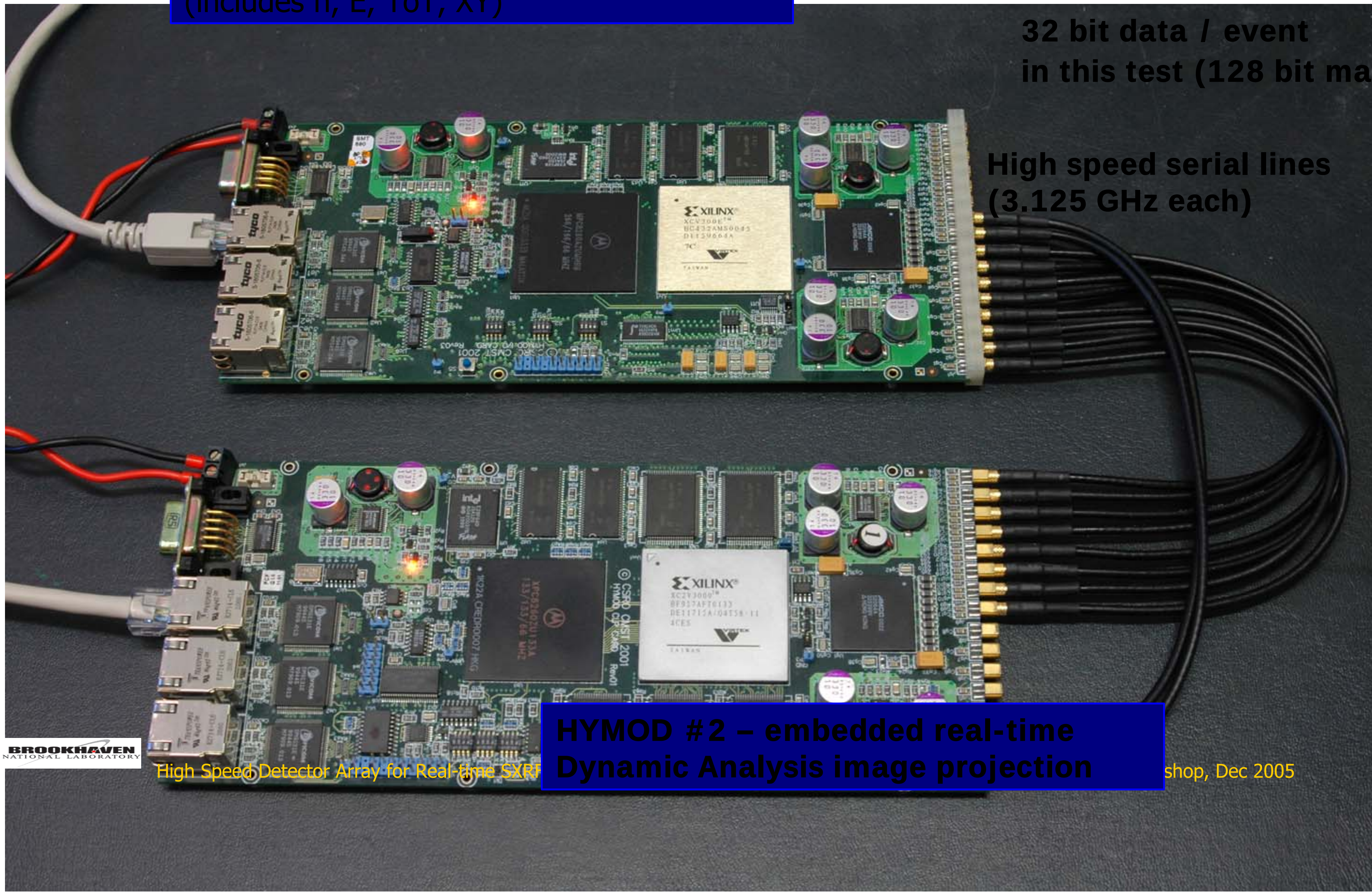


16.1 keV photons

Simple Energy Cuts

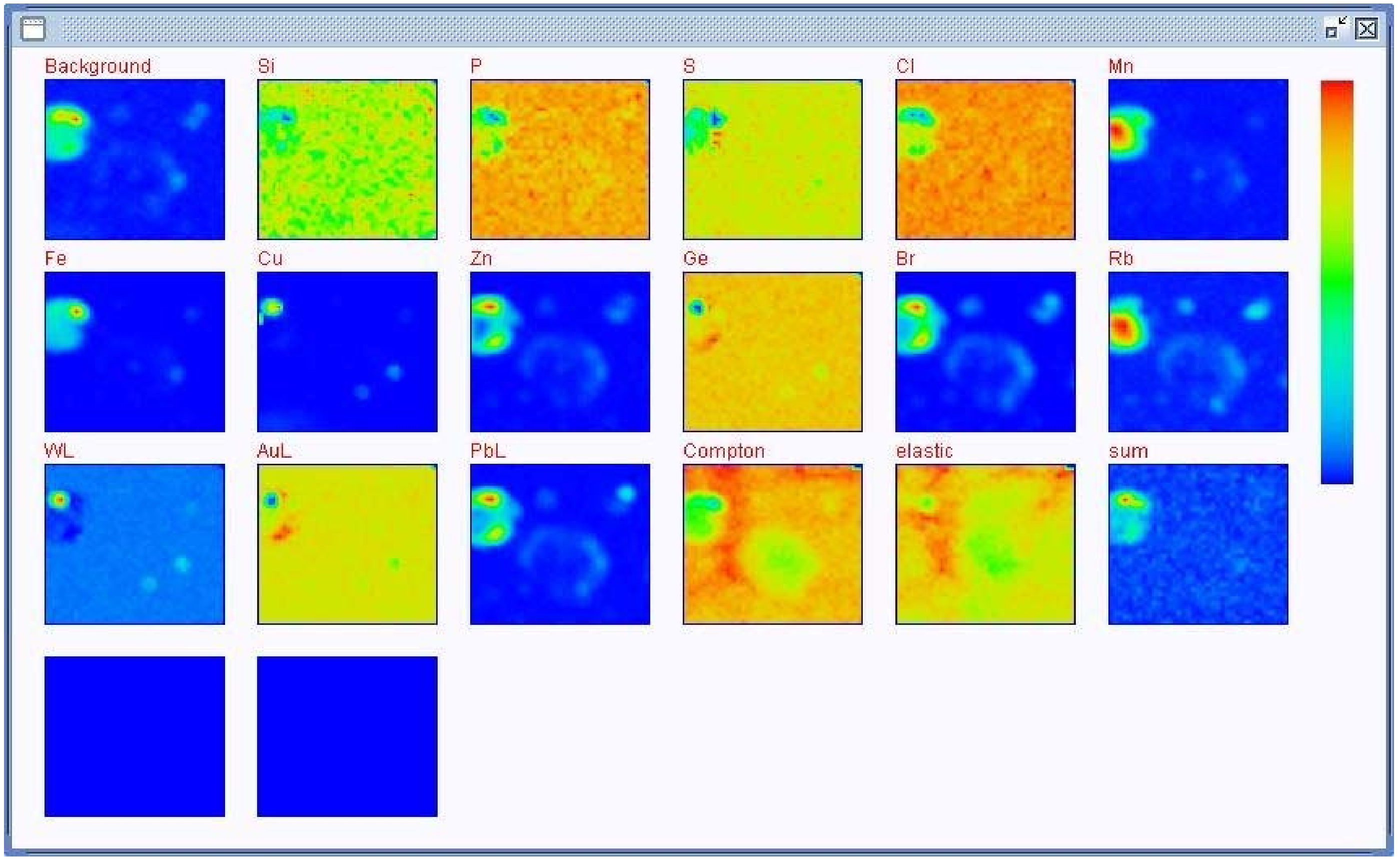


Test of Real Time SXRF Imaging using Hymod



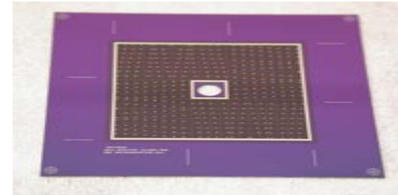
Test of Real Time SXRF Imaging using HYMOD

25 M events in test data-set (fluid inclusions; APS 2-ID-E; simulate ToT) ...



... processed in HYMOD #2 using Dynamic Analysis into elemental images in 250 ms, at 100 M events per second (400 Mbytes/s).

Progress



BNL 384 element Si detector array development:

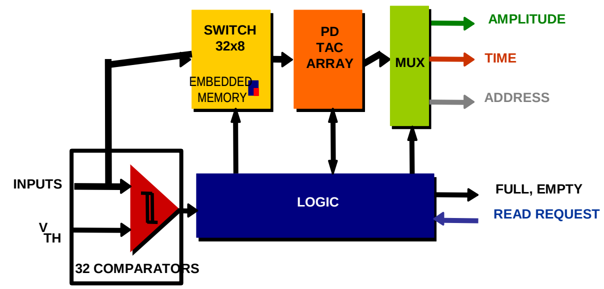
32-channel Pre-amp/pulse shaper ASIC.

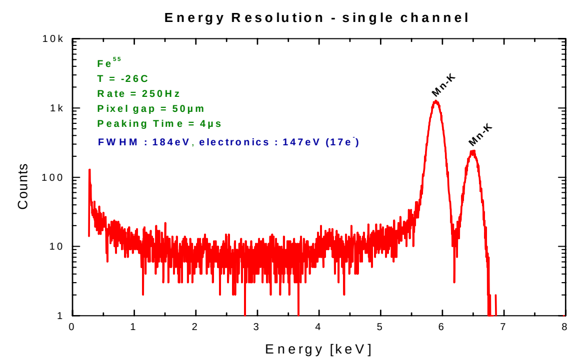
Achieves 184 eV resolution (Mn Kα).

New ASIC demonstrates peak-detecting de-randomizer, 32:1 multiplexer and ADC.

Time-over-threshold demonstrated for pile-up rejection.

Metal absorption mask demonstrated to control charge-sharing between detectors.





Real-time quantitative SXRF imaging:

Concept developed for real-time processing using CSIRO HYMOD pipelined, parallel processor.

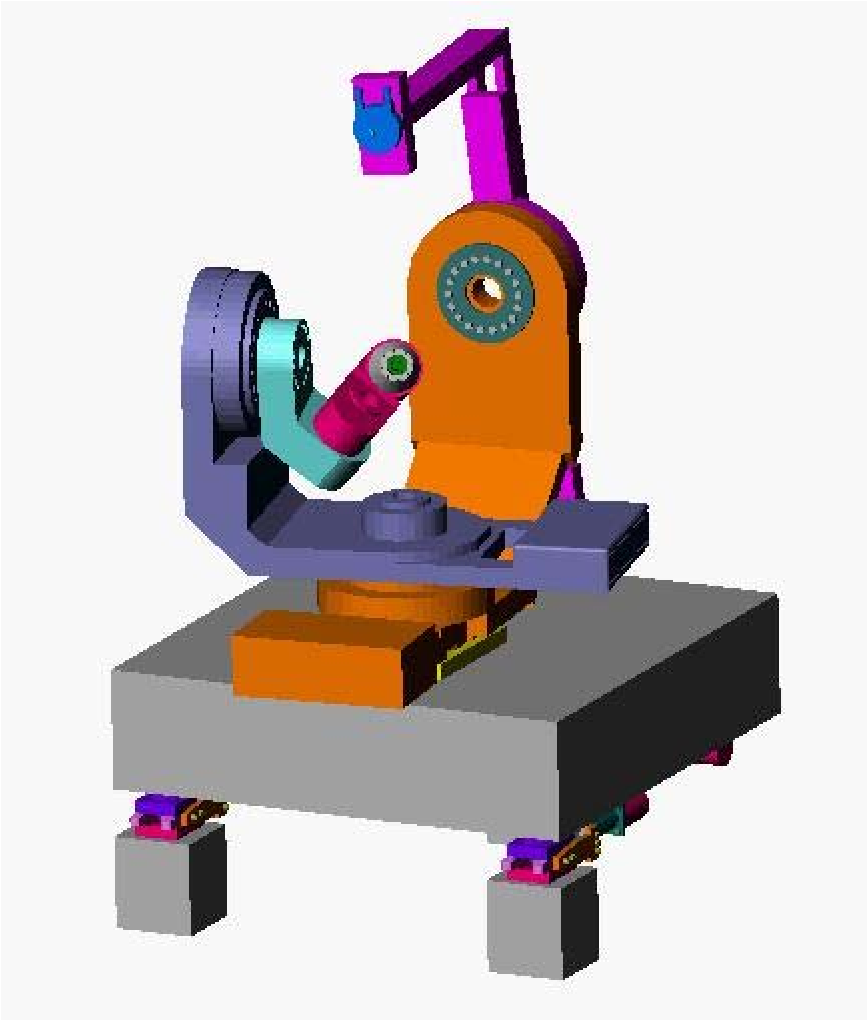
De-coupling of data acquisition from stage control for fast scanning (XY sampled into data stream).

Dynamic Analysis method demonstrated for imaging of SXRF data off-line (APS sector 2; PNC-CAT, sector 20).

DA real-time deconvolution demonstrated at **10^8 events/second** using HYMOD.

Coverage, traditional method

- Complex goniometry
  - to allow single-point simple detector (or, more recently, a small 2-D detector) to access any point on sphere around sample
  - to allow sample to have an arbitrary orientation w.r.t. the incident x-ray beam, with minimum blind regions.

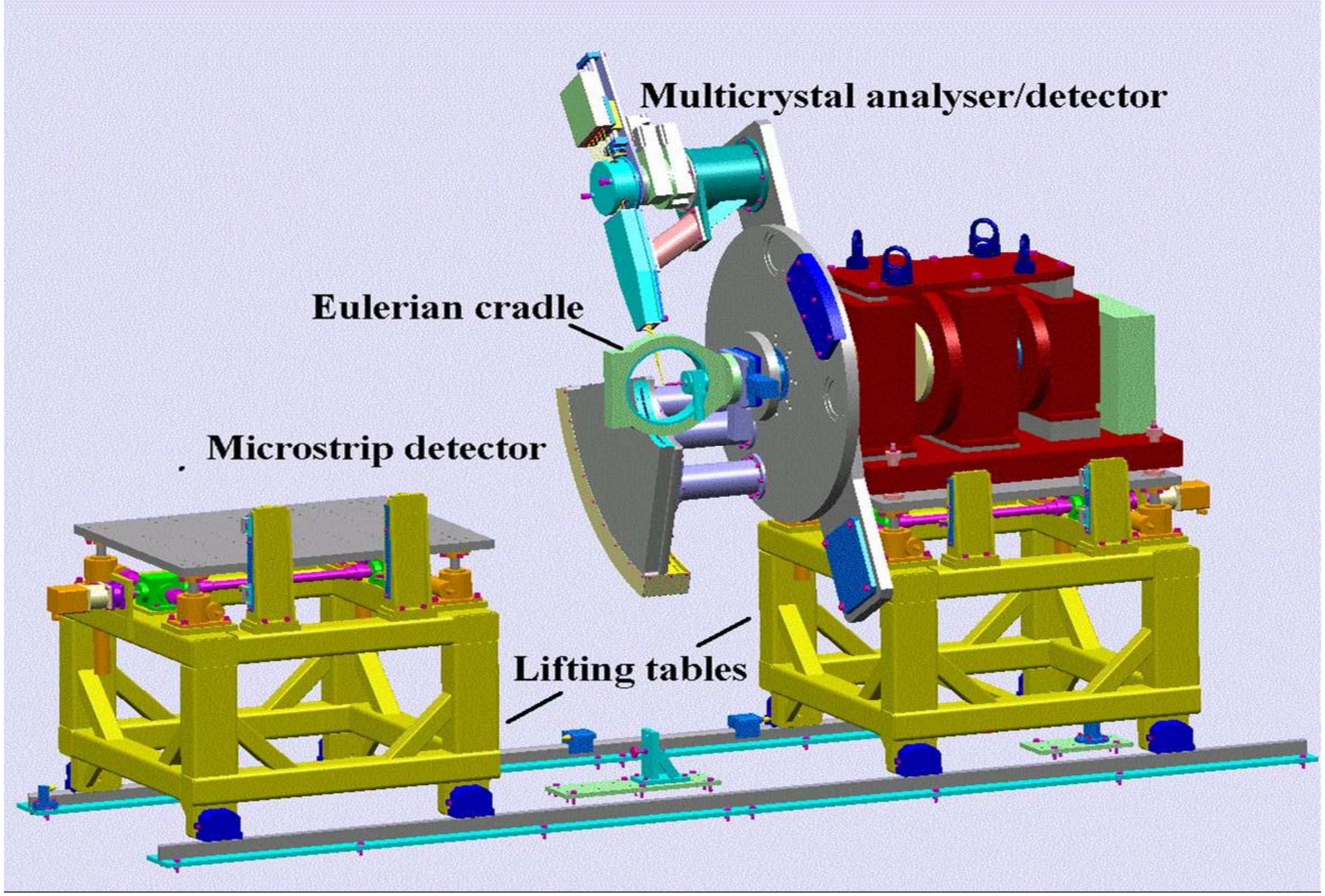


SLS powder diffractometer

Uses MYTHEN strip detector plus crystal array

A similar instrument is being designed at Diamond

Diamond instrument will use HERMES initially, and an optimized version as an upgrade.



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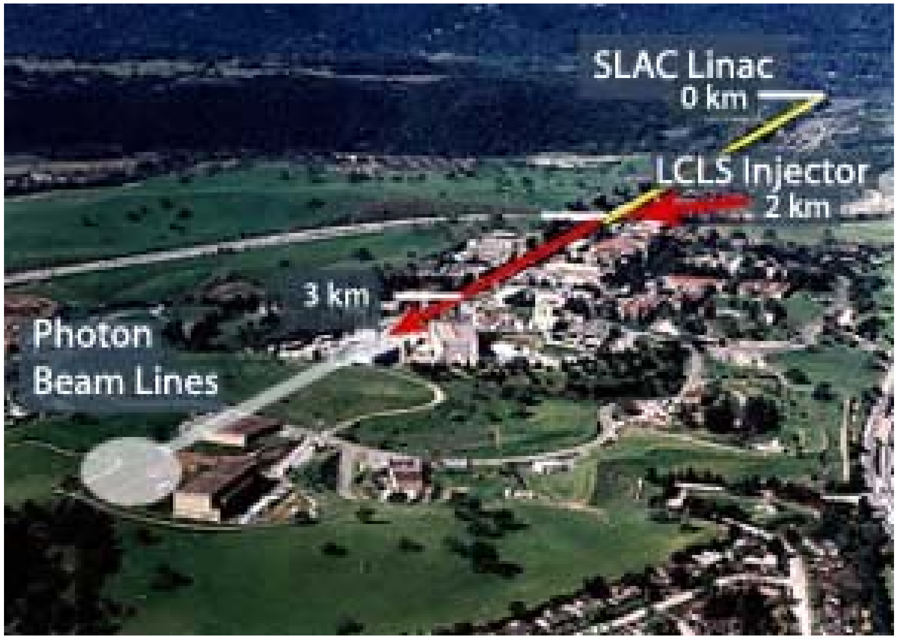
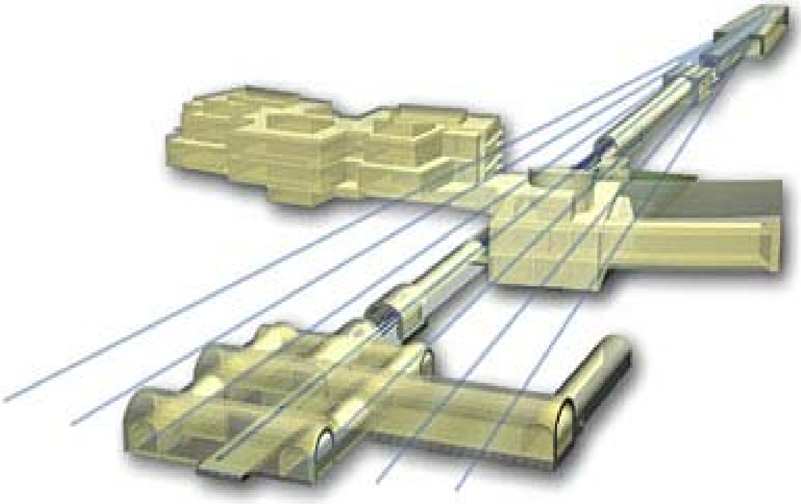
LCLS

- 16GeV electrons from 1/3 of SLAC
- 1.5 - 15 Angstrom radiation
- 5-6 end stations
- Operational 2009





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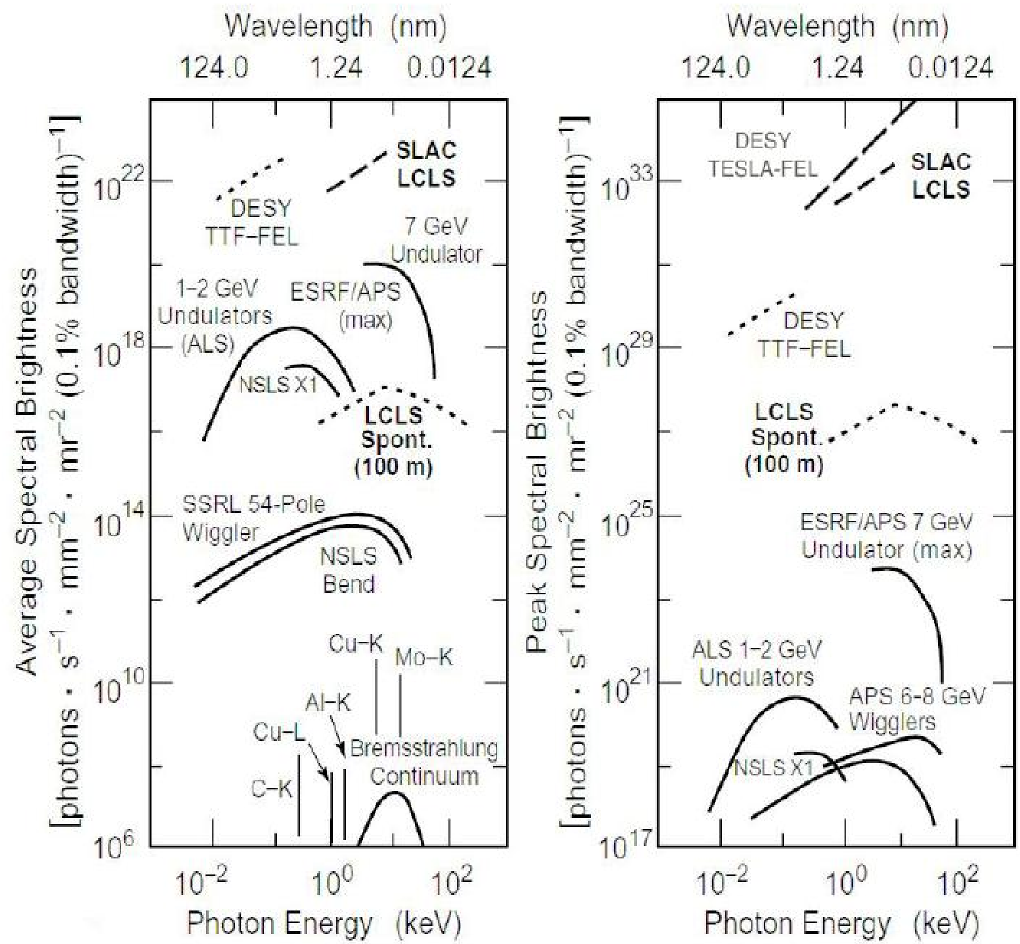

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The XFEL project (DESY)

- 20GeV LINAC
- Remote green field site for end-stations
- Very intense
- 10Hz rep. rate (~1ms macropulse with 200ns sub-period)
- Based on TESLA technology

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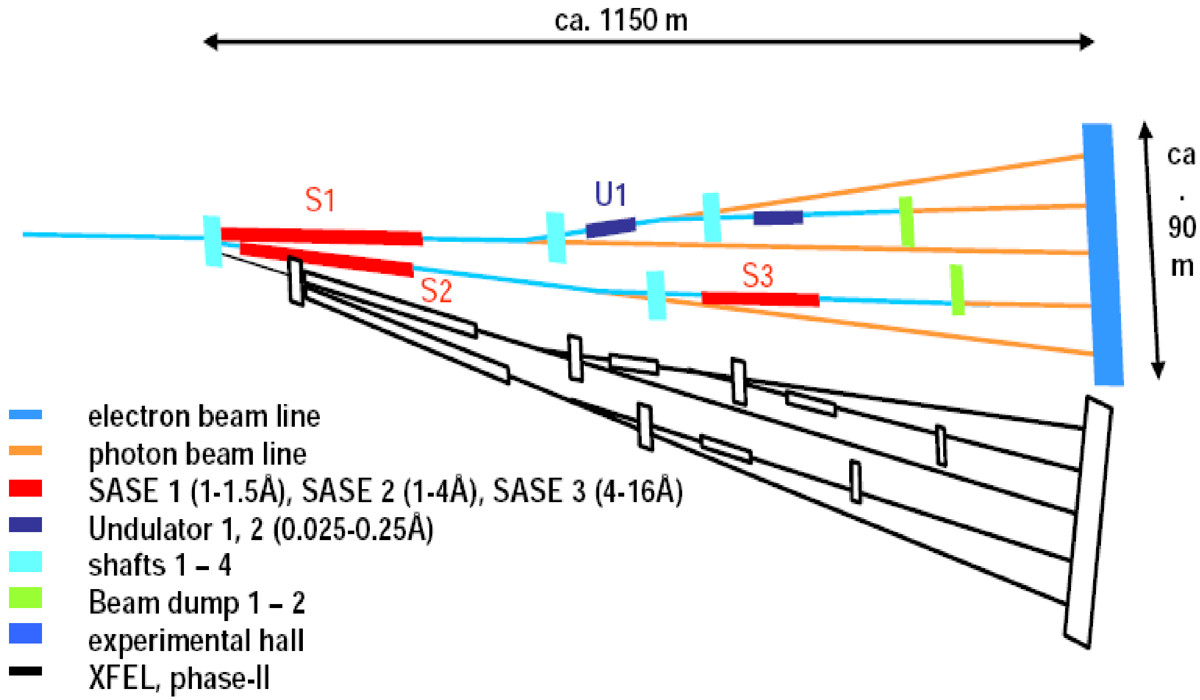

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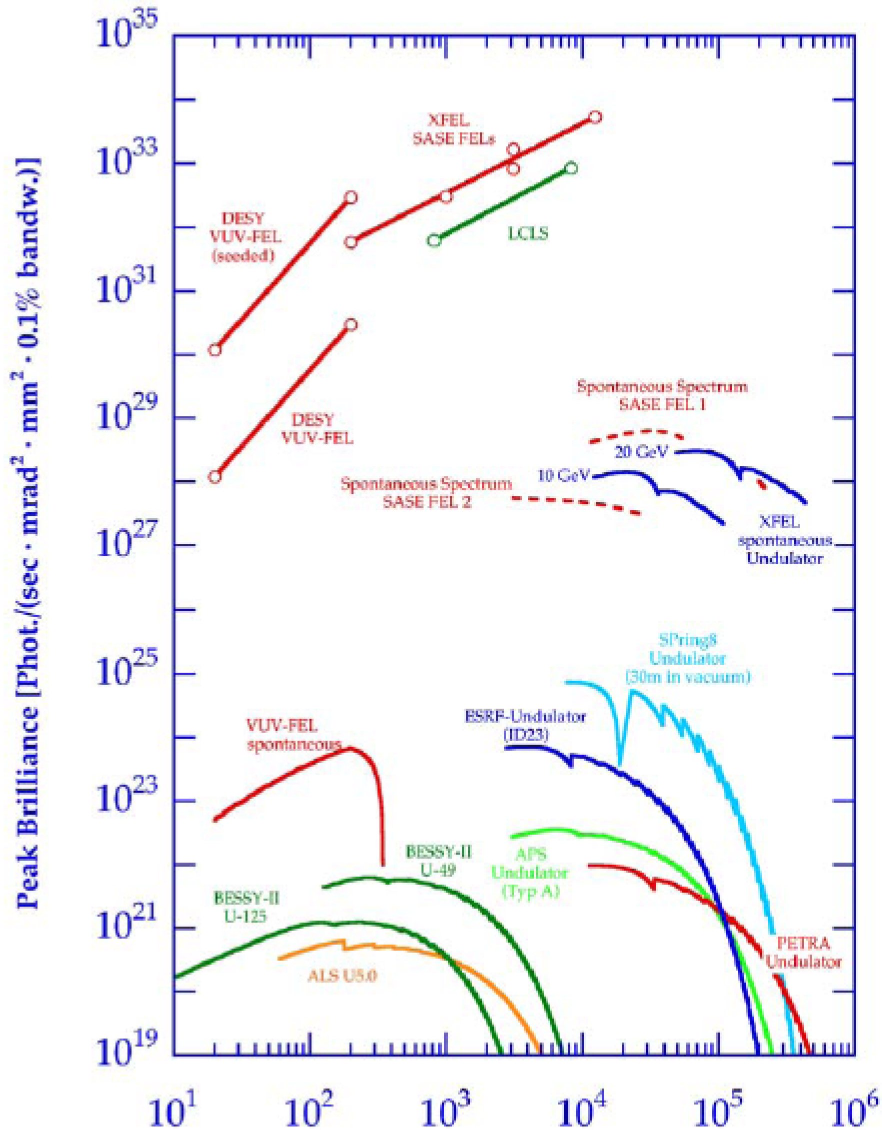
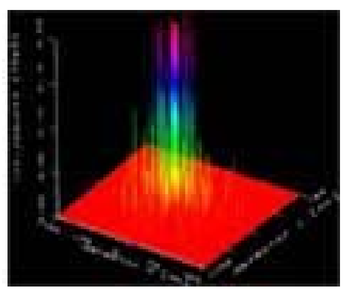
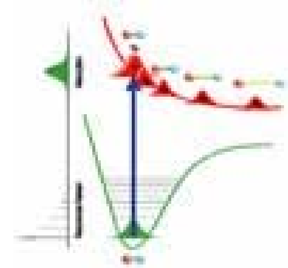


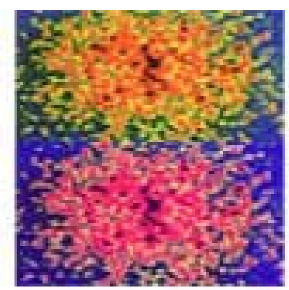
LCLS main thrust areas

- Atomic Physics
- Femtochemistry
- Nanoscale Dynamics
- Single Particles & Biomolecules
- Warm Dense Matter
- Soft X-ray scattering

LUSI

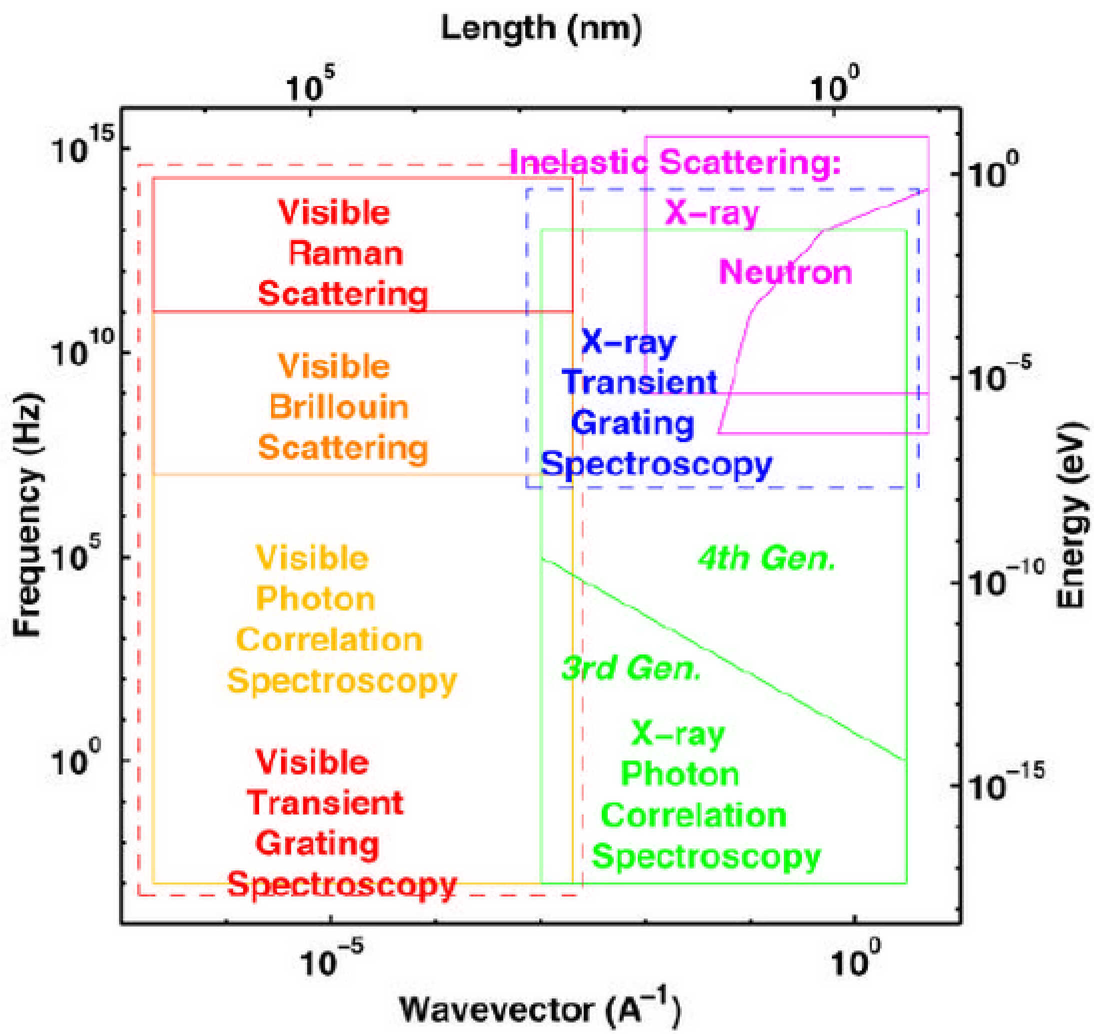






Nanoscale Dynamics

- Fully-coherent beam gives far-field 'speckle' pattern
  - Speckle fluctuations are a measure of system dynamics (Brownian motion in colloids, reptation in polymers, phase changes in alloys etc.)
- Transient Grating Spectroscopy
  - Atomic-scale relaxation phenomena using FEL or Laser pulse as alignment field and delayed x-rays as probe (magnetism, ferroelectrics etc).



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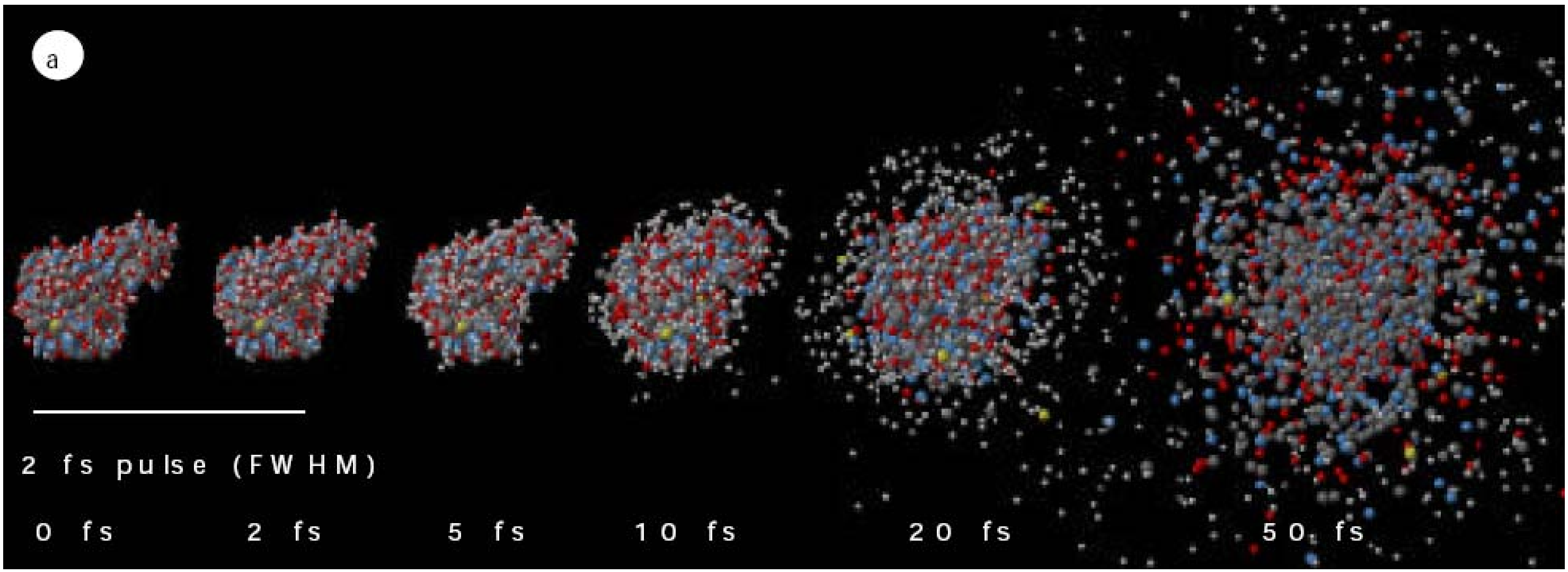
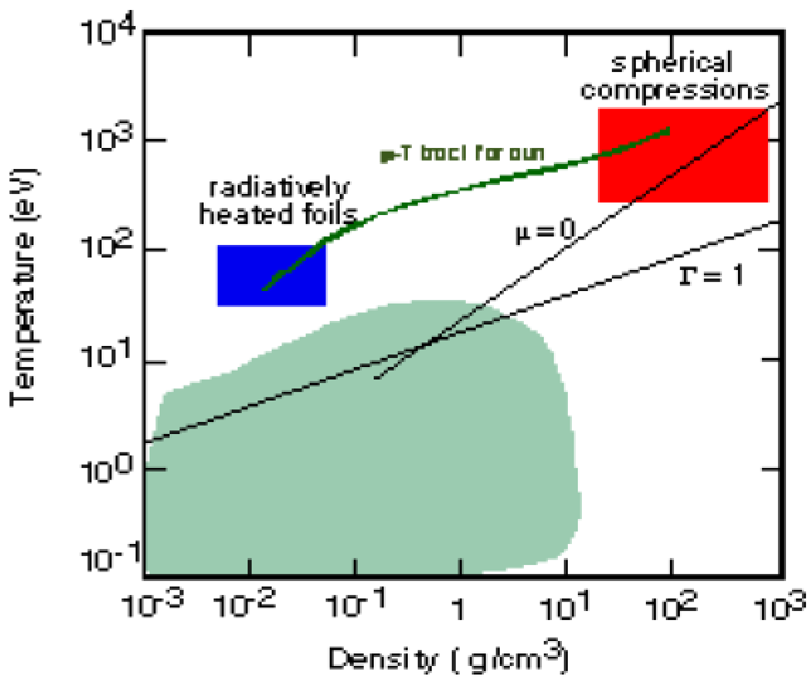
Single particles & Biomolecules

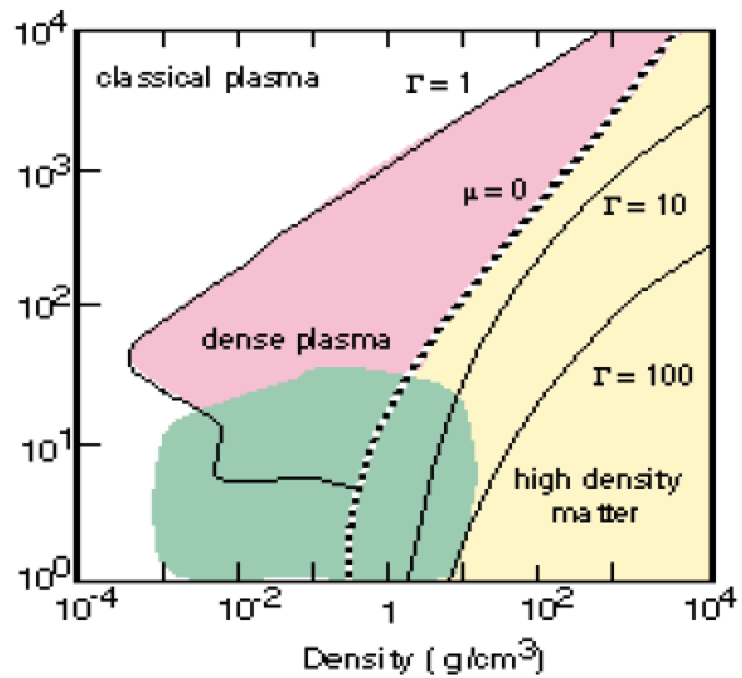
- Catch it if you can!
  - Needs lots of photons /shot to record diffraction pattern
  - Make photon pulse short compared to explosion time
  - Make many shots to sample all rotation views of molecule



Warm dense matter

- Region of temperature-density phase diagram which is poorly understood (green region)
  - Not a plasma
  - Not a conventional solid
  - FEL pulse can prepare and probe it





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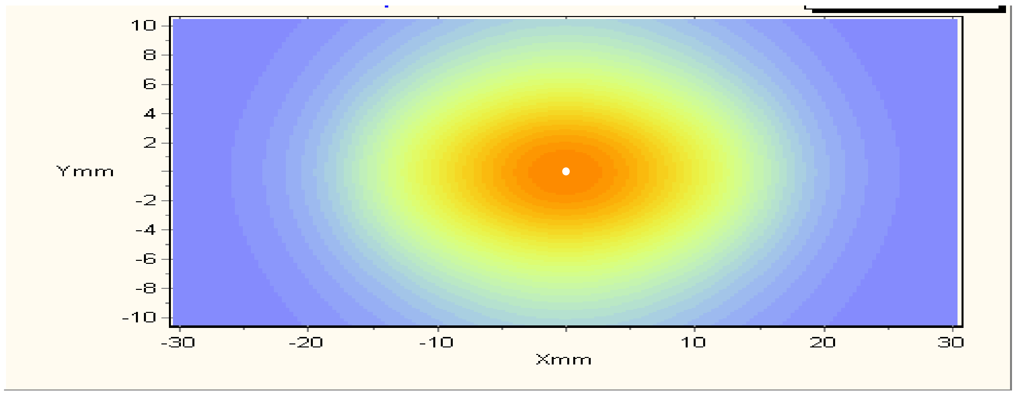
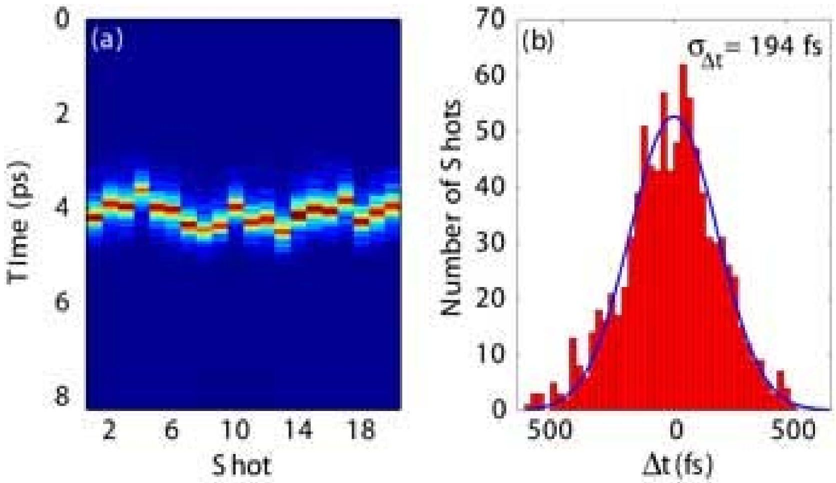
Detector challenges: FEL

- Shot-Shot fluctuations
- No photon-counting
  - detector dynamic range
  - spectral purity
    - 24keV photon looks like 3 8keV photons to detector, but not to atom!
- Radiation damage?
  - Certainly for sample
  - probably for detector
- Time jitter





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Non-destructive Monitoring of Pulse-by-Pulse variations

- Intensity
  - Non-invasive incident beam intensity monitor
- Energy
  - Not an easy one!
- Time
  - At least of electron beam arrival at undulator output (demonstrated at SPPS).
- Position
  - Hopefully can be combined with intensity monitor
  - 5um diamond film with Be 4-quadrant electrodes as photoconductive monitor ? (~2% absorbing, microcoulombs of photocharge)

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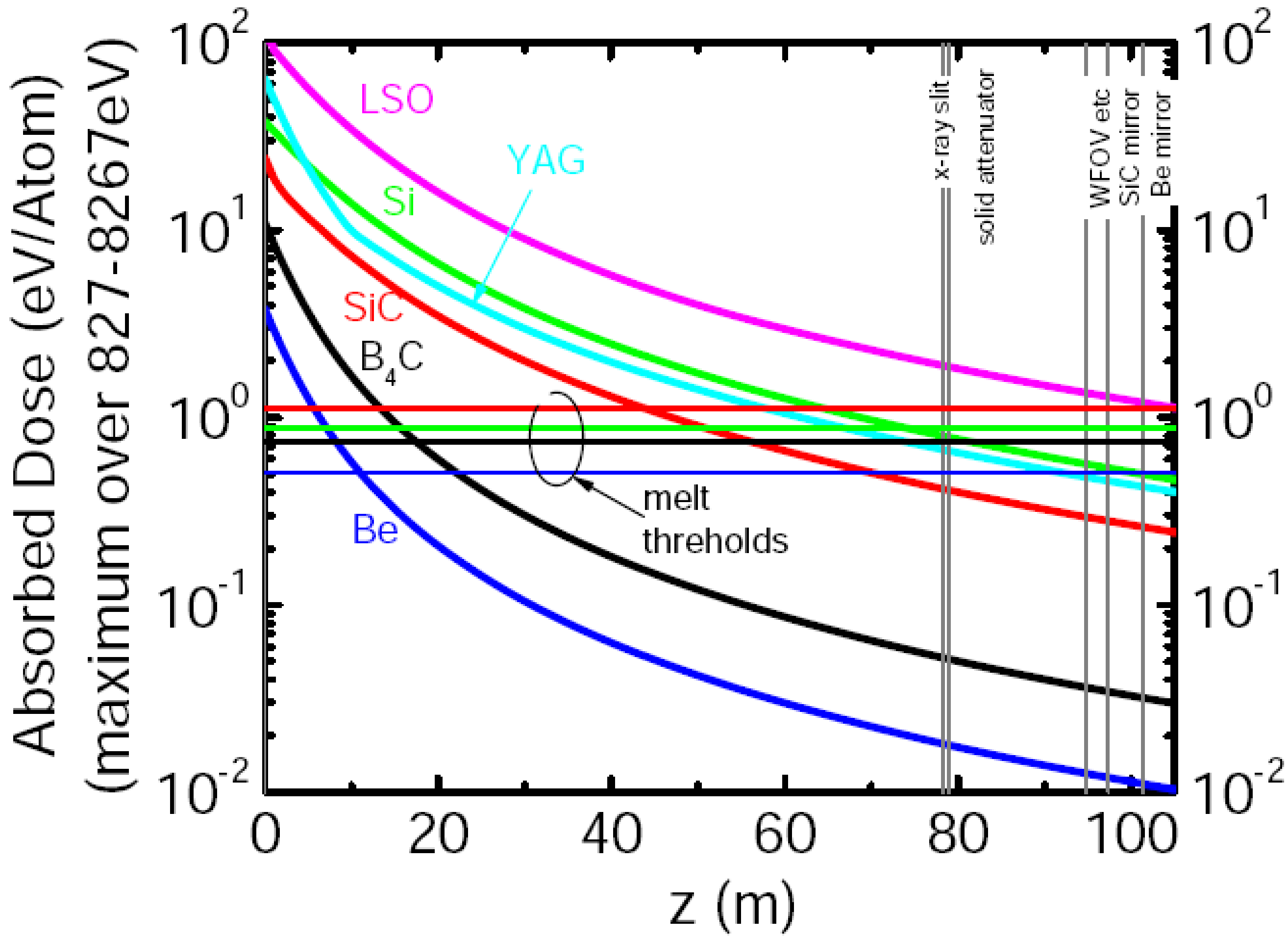
Dynamic range

- No photon counting is very limiting
  - Simple integrate/ADC is difficult to push beyond 10^4 true S/N ratio
    - Need to adopt more sophisticated ranging techniques
  - Experiment can generate dynamic range of >10^6 in a single image (?)
  - No spectral information from a simple integrating device
    - High-order FEL and spontaneous emission
    - Optical dispersion + integrating PSD

Radiation damage

- Normal-incidence dose levels beyond melt threshold for high-Z materials



1ms readout active-matrix area detector

- Fully pixellated detectors are complicated
- Hybrid (bump-bonded) devices add fabrication difficulties
- Monolithic devices built on high-resistivity silicon provide simplest structure
  - No bump-bonding
  - Simplest structure is active-matrix type
    - Small pixels in principle possible (no on-pixel amps)
    - row-by-row parallel readout
    - N readout channels instead of N x N
- Need to provide low-resistivity layer to fabricate readout structures

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Pixel structure

- Low-resistivity layer is formed by deep implant.
- JFET switches are fabricated in this layer
- Charge is produced by photoionization
- Electrons collect under pixel (switch is OFF)
- Charge is read out by turning transistor ON, connecting stored charge to a buss-bar, and read out by a charge-sensitive amplifier.

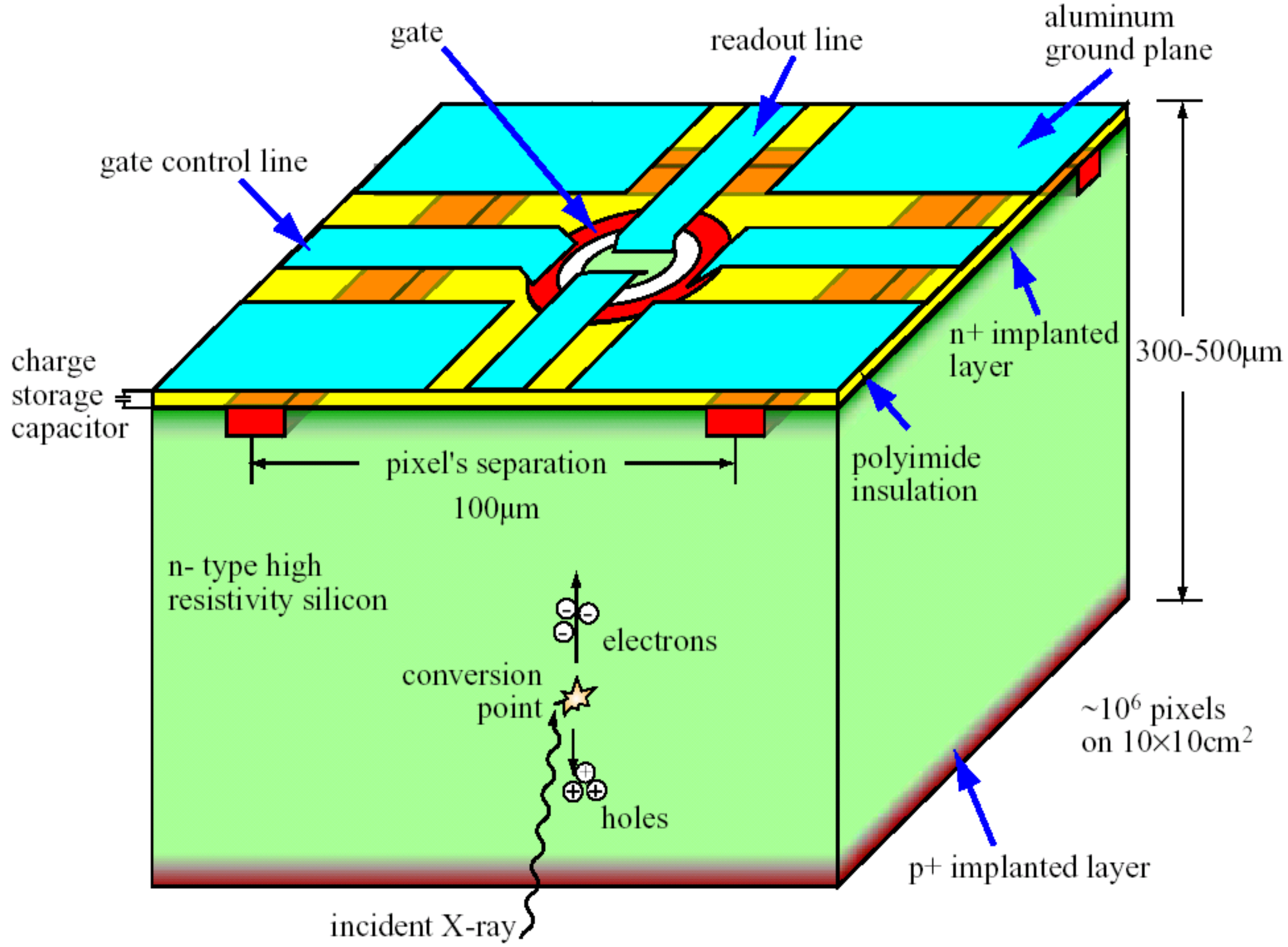

Figure 6. One pixel from an Active Matrix Pixel detector array. The device is fabricated by forming a low-resistivity silicon layer suitable for JFET switching devices on top of high-resistivity silicon optimized for detector fabrication. The JFET transistors formed in this layer are used to row-sequentially switch the collected charge into column output amplifiers.

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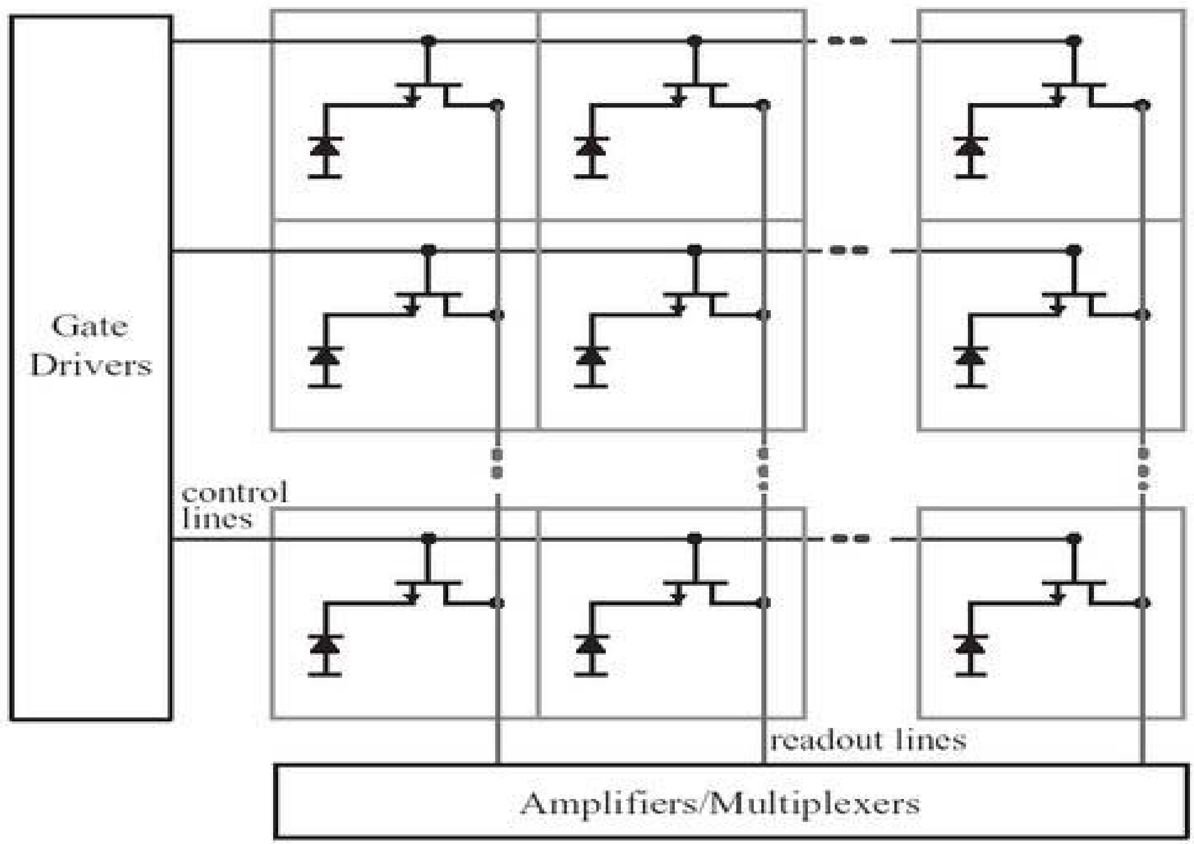
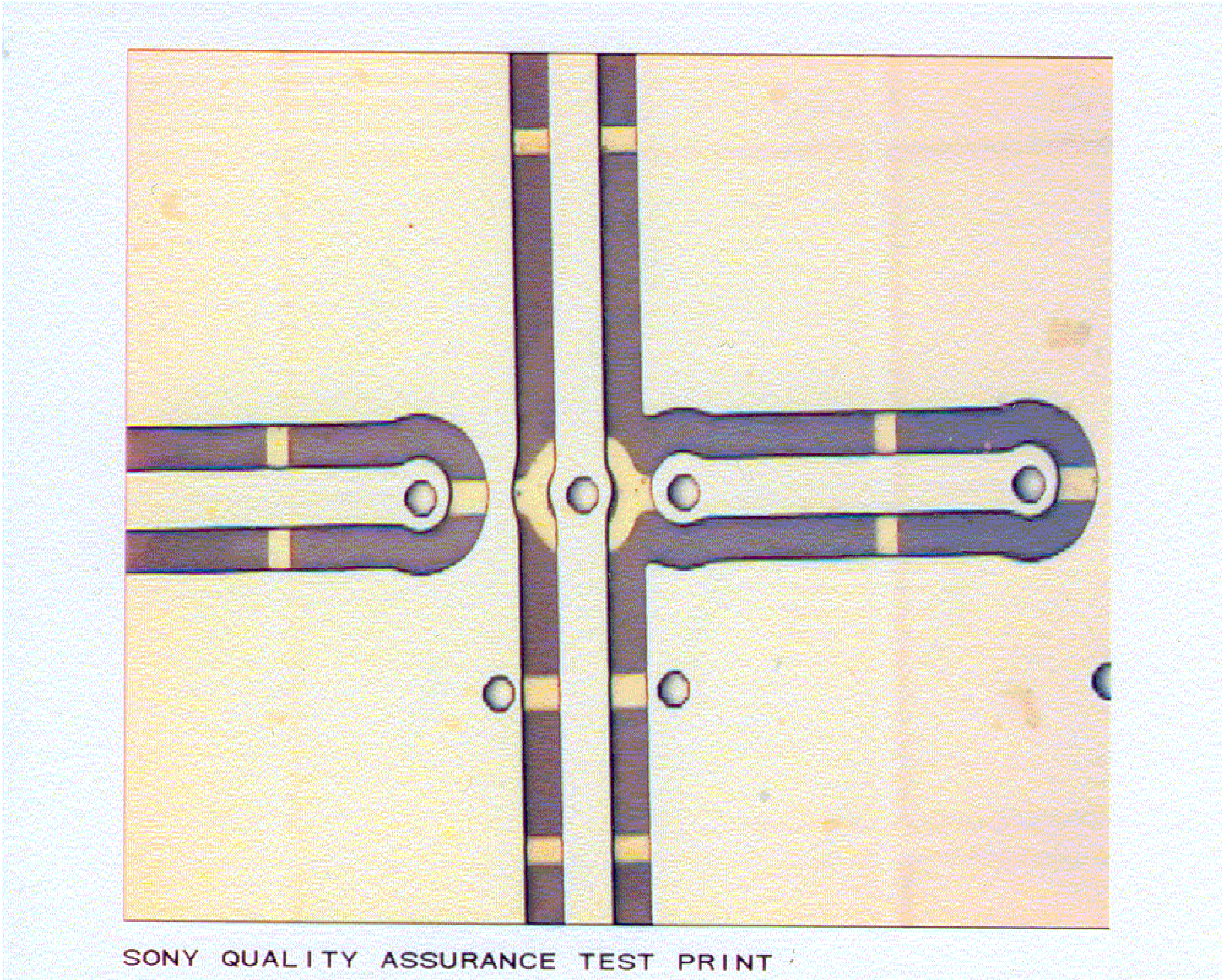
Active matrix readout

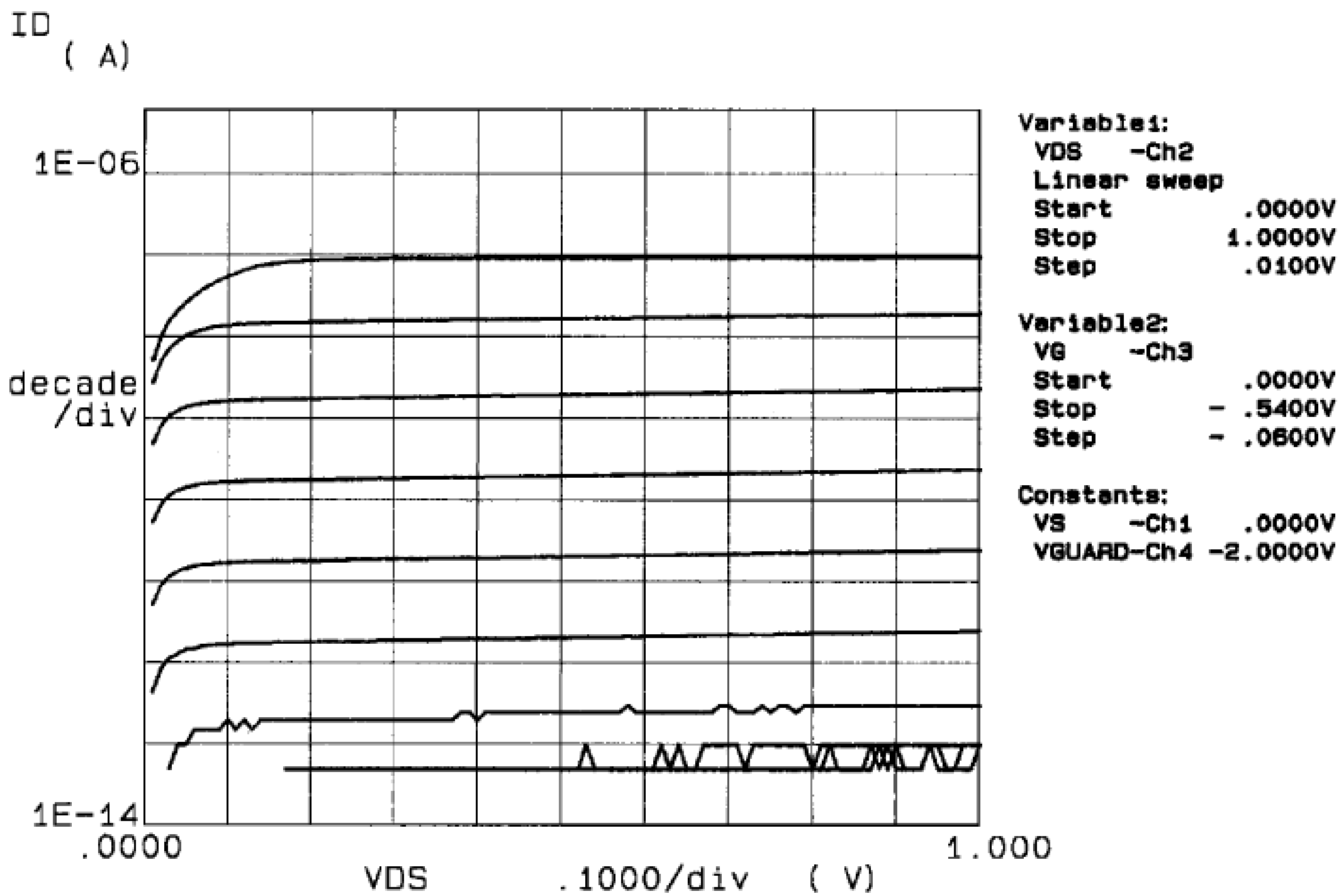
- Charge stored in diode capacitance (switches off)
- Readout amplifier/ADC on each column
- Switches turned on sequentially row-by-row
- Charge read out and digitized
- 1us per row => 1ms for 1000 rows.
  - 8-channel 40MHz/channel ADC chip exists
  - 32 chips, each ADC multiplexed among 4 columns
  - 2Gb/s data rate



Cross-point switch



Lateral JFET characteristics



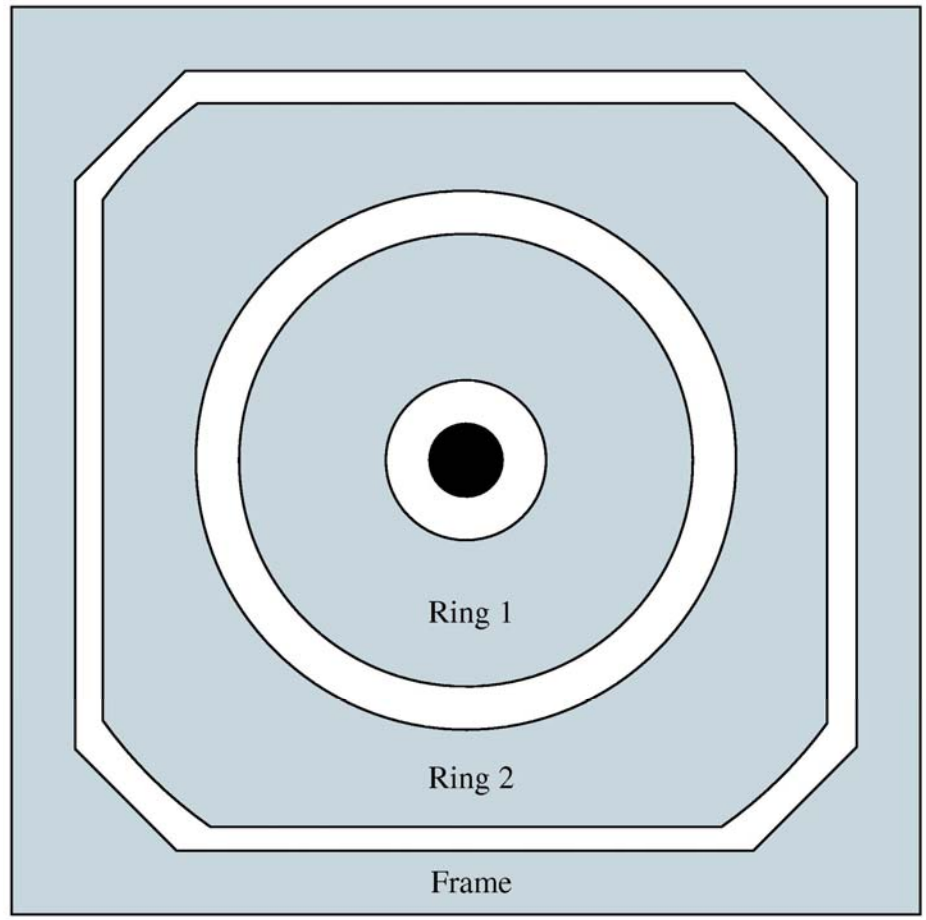
- JFETs of the required quality can be fabricated

Alternative small-pixel structure

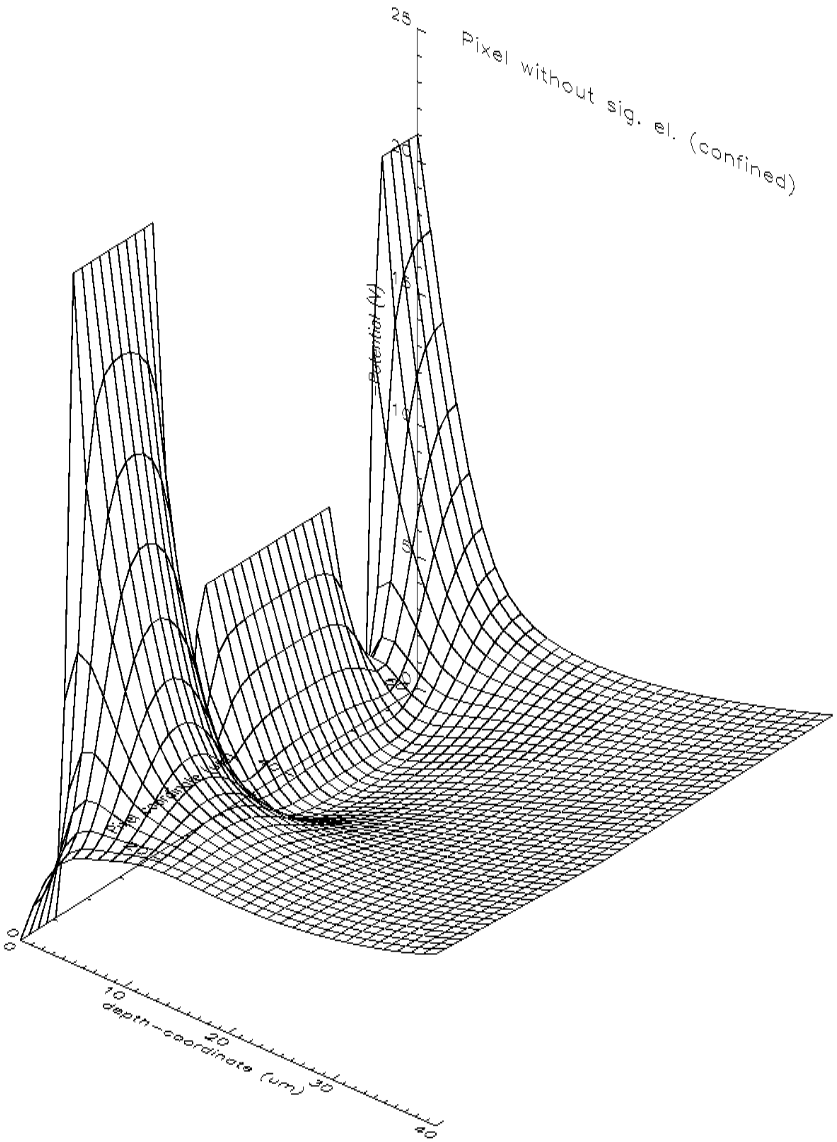
- Small pixels are difficult with transistor switch
- Charge can be stored in potential well and released in a controlled way, similar to drift detectors.
- Single charge transfer step; not a CCD
- This 'charge pump' technology is ideal for speckle applications.
  - No kTC noise

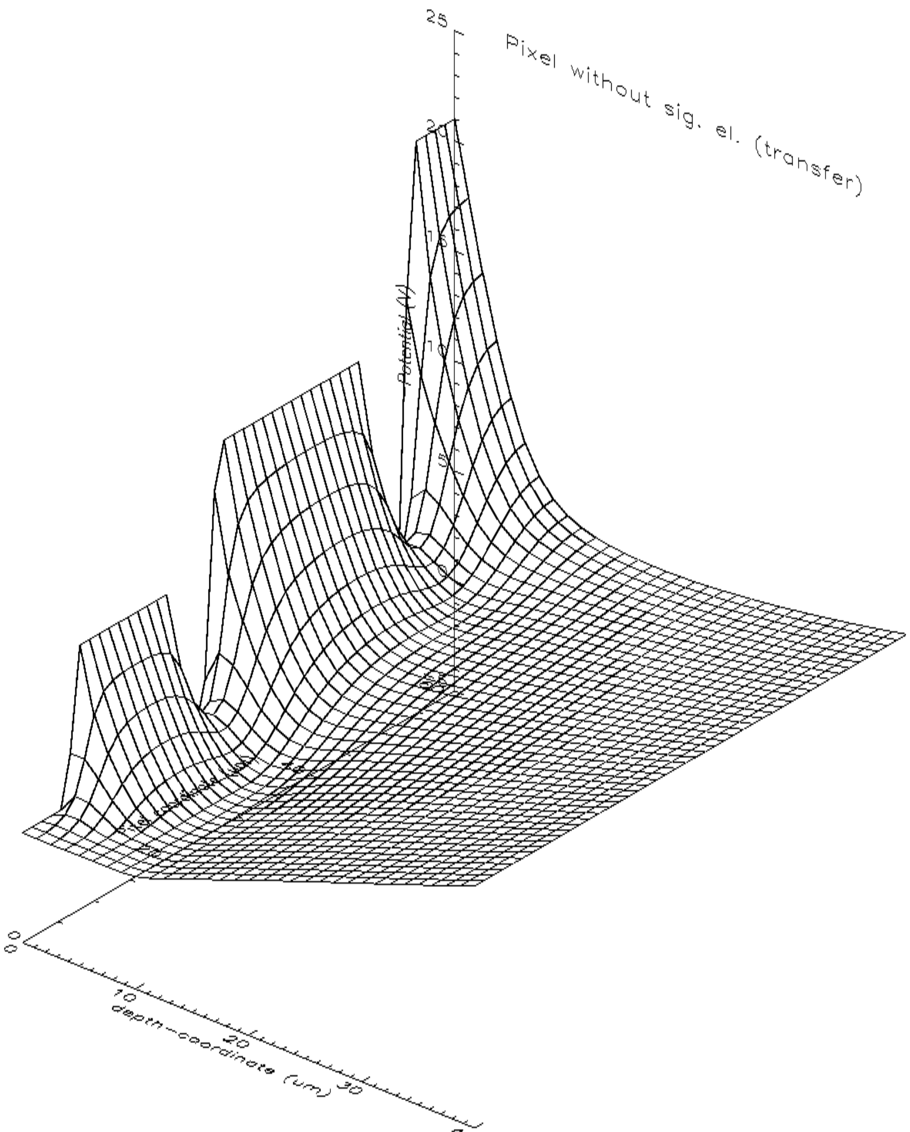
Top view of a pixel with a charge pump single transfer

- Charge-pump pixel has two front-side implants, p+ and n+
- p+ in n-type wafer forms rectifying junction
- n+ forms ohmic contact for charge extraction.
- Back-side has uniform p+ rectifying contact.



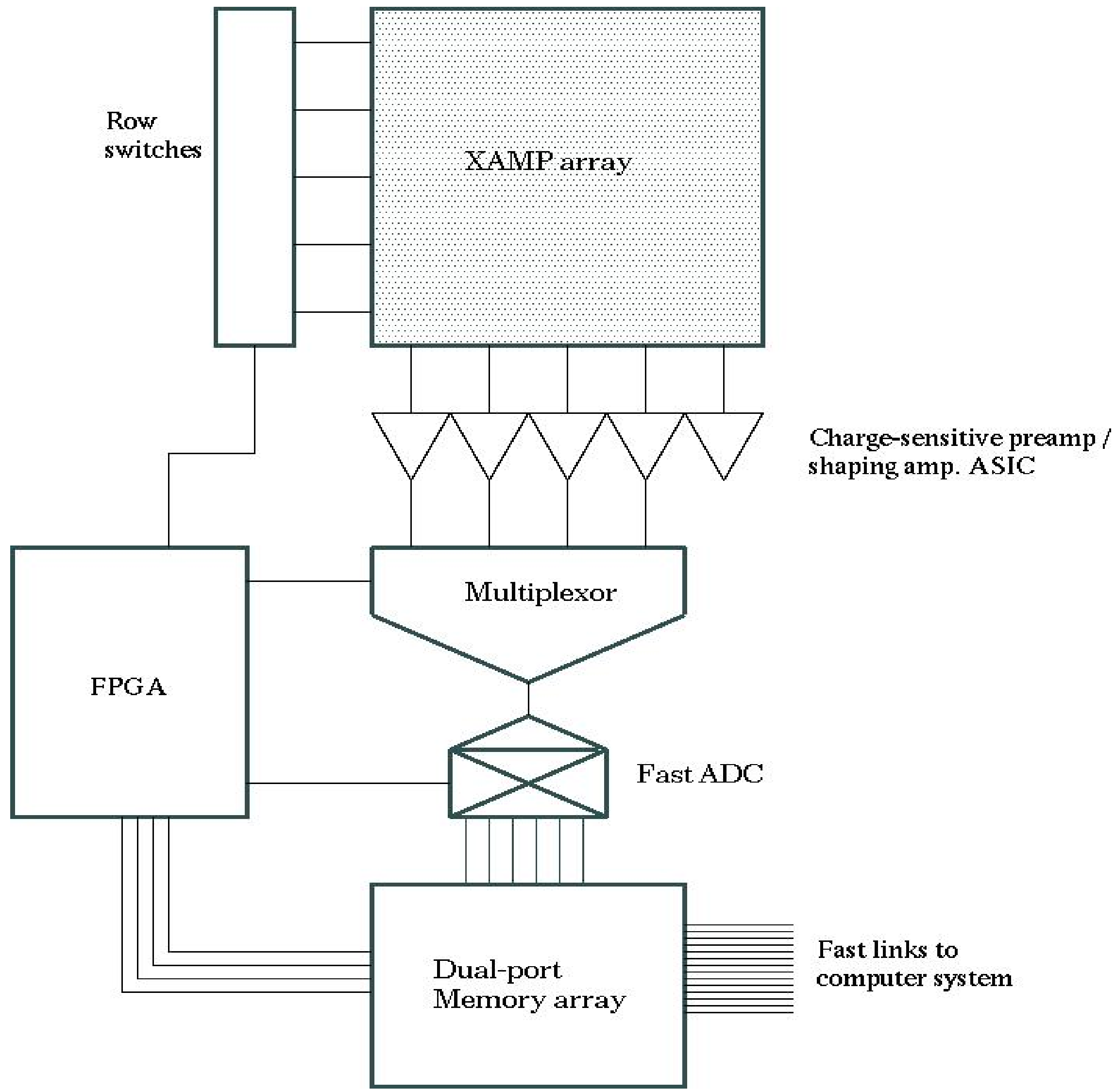
Charge pumping (no transistor)





Readout system

- Row-by-row readout, 1us/row
- 32 Fast (>20MHz) 8-channel ADC's multiplexed e.g. x4 = 1024
- 2GB/s instantaneous
  - raw data from ADCs
- 250MB/s averaged, i.e. to be stored
- Data streamed through FPGA to fast memory and terabyte disk store.
  - FPGA does background correction



Summary

- SR: Huge range of experiments and photon energies, each requiring more sophisticated detector systems
- FEL: All of the above PLUS femtosecond synchronization and exploding optics
- Some serious investment needed in both cases

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