Physics 198

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Introduction to Radiation Detectors and Electronics

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course notes in pdf format at www-physics.LBL.gov/~spieler

WHY?

Radiation is the only observable in processes that occur on a scale that is either too brief or too small to be observed directly.

Originally developed for atomic, nuclear and elementary particle physics, radiation detectors now are applied in many diverse areas of science, engineering and everyday life.

Progress in science is driven not just by the interplay of theory and experiment, but also by breakthroughs in instrumentation.

Types of Radiation:

a) charged particles

electrons, protons, atomic nuclei
+ many elementary particles

b) neutral particles

neutrons
+ many elementary particles

c) photons

light
x-rays
gamma rays

Emphasis of this course:

detection of individual particles or photons

The development of detector systems is an interdisciplinary mix of physics and electronics.

For example, understanding of a modern tracking detector in high-energy physics or a medical imaging system requires knowledge of

- solid state physics
- semiconductor device physics
- semiconductor fabrication technology
- low-noise electronics techniques
- analog and digital microelectronics
- high-speed data transmission
- computer-based data acquisition systems

Some examples as introduction….

- imaging in astronomy
  (thanks to Steve Holland, Engineering Div. LBNL)

- medical imaging –
  positron emission tomography
  (thanks to Bill Moses, Life Sciences Div. LBNL)

- detection of trace elements by x-ray fluorescence
  (thanks to Joe Jaklevic, Engineering Div. LBNL)

- tracking detectors in high-energy physics

- failure analysis in silicon integrated circuits

Astronomical Imaging

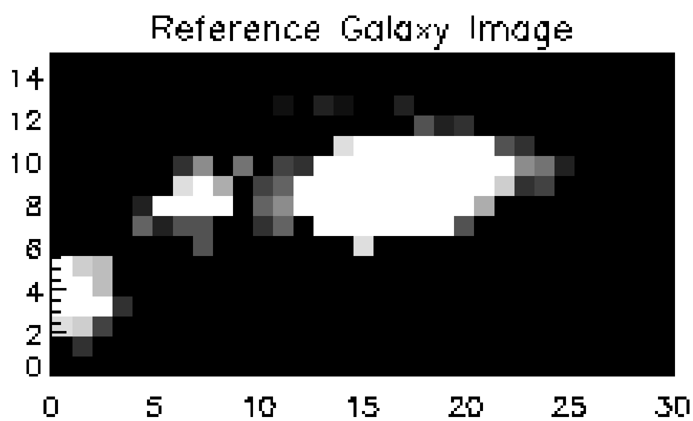
(thanks to Steve Holland, Engineering Div. LBNL)

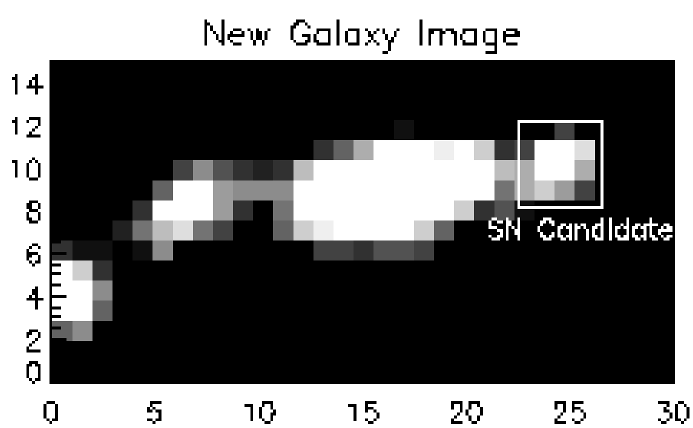
Practically all faint light imaging in astronomy relies on electronic sensors

- visible light
- IR
- UV
- x-rays

Example: Supernova Search

(S. Perlmutter et al., see www-physics.lbl.gov)

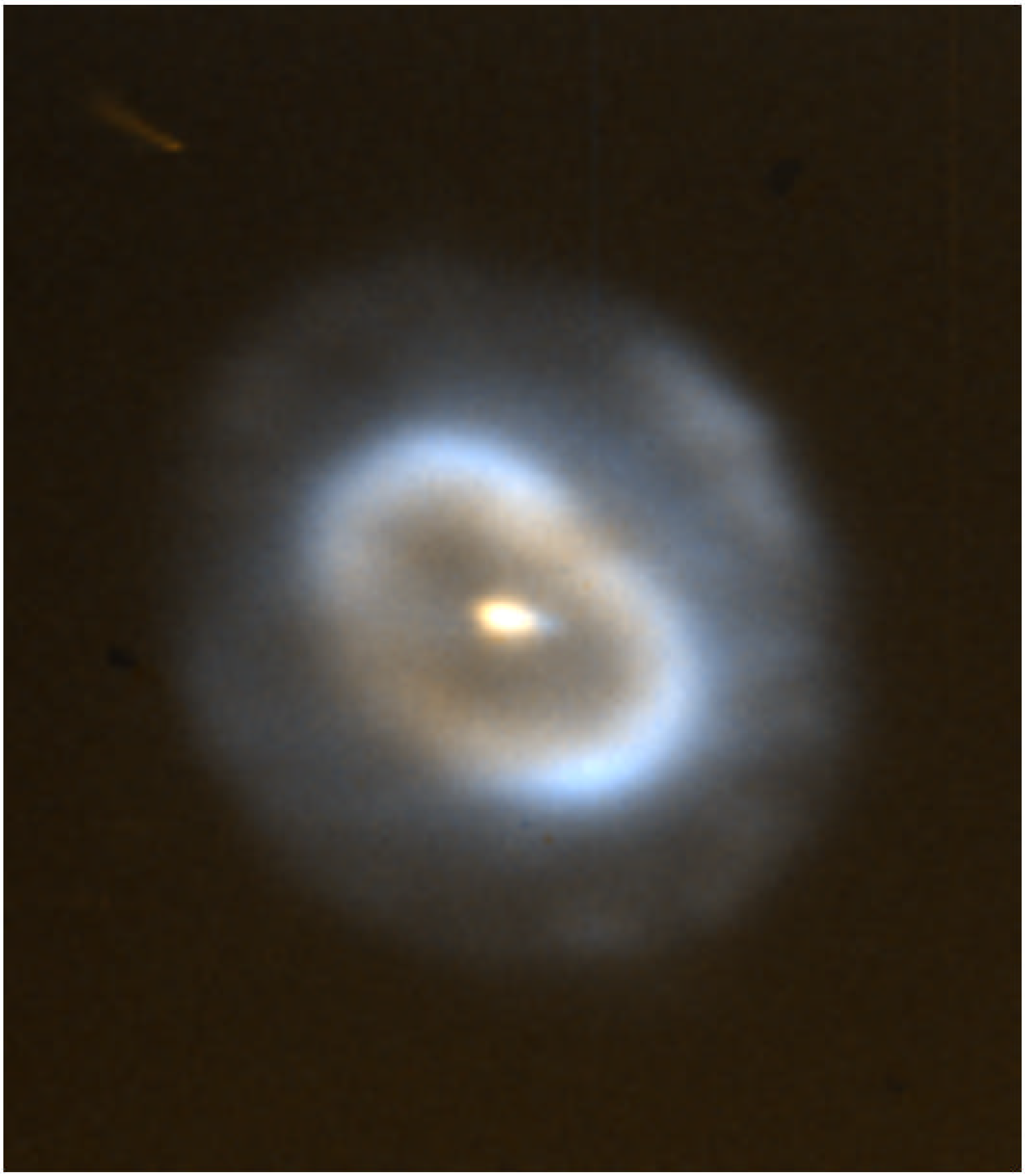




The image sensors are arrays of pixelated semiconductor detectors, called CCDs (charge coupled devices). Pixel size typ. 10 – 30 μm.

Planetary Nebula NGC7662 (CCD at -120°C)

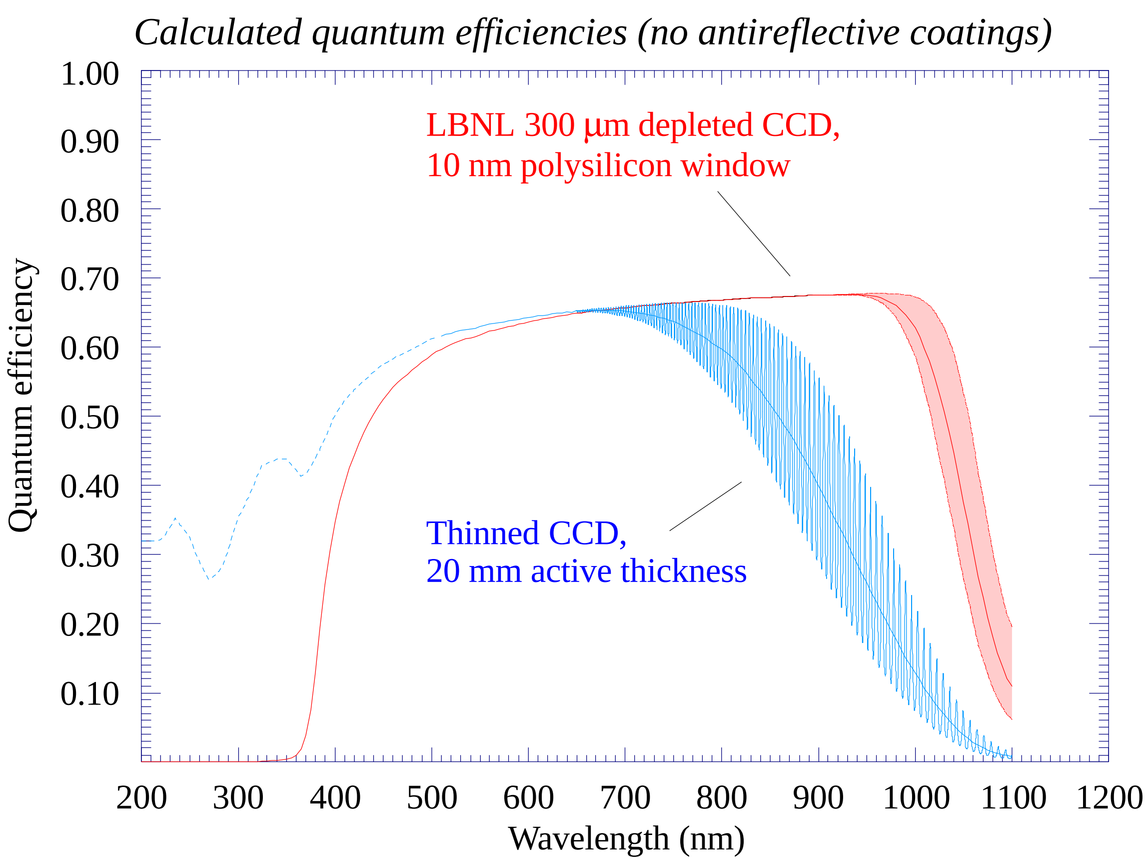
Photon flux in outer halo is ≈ 35 photons/pixel/sec, image generated from 100 sec exposures at different λ, Lick 1-m



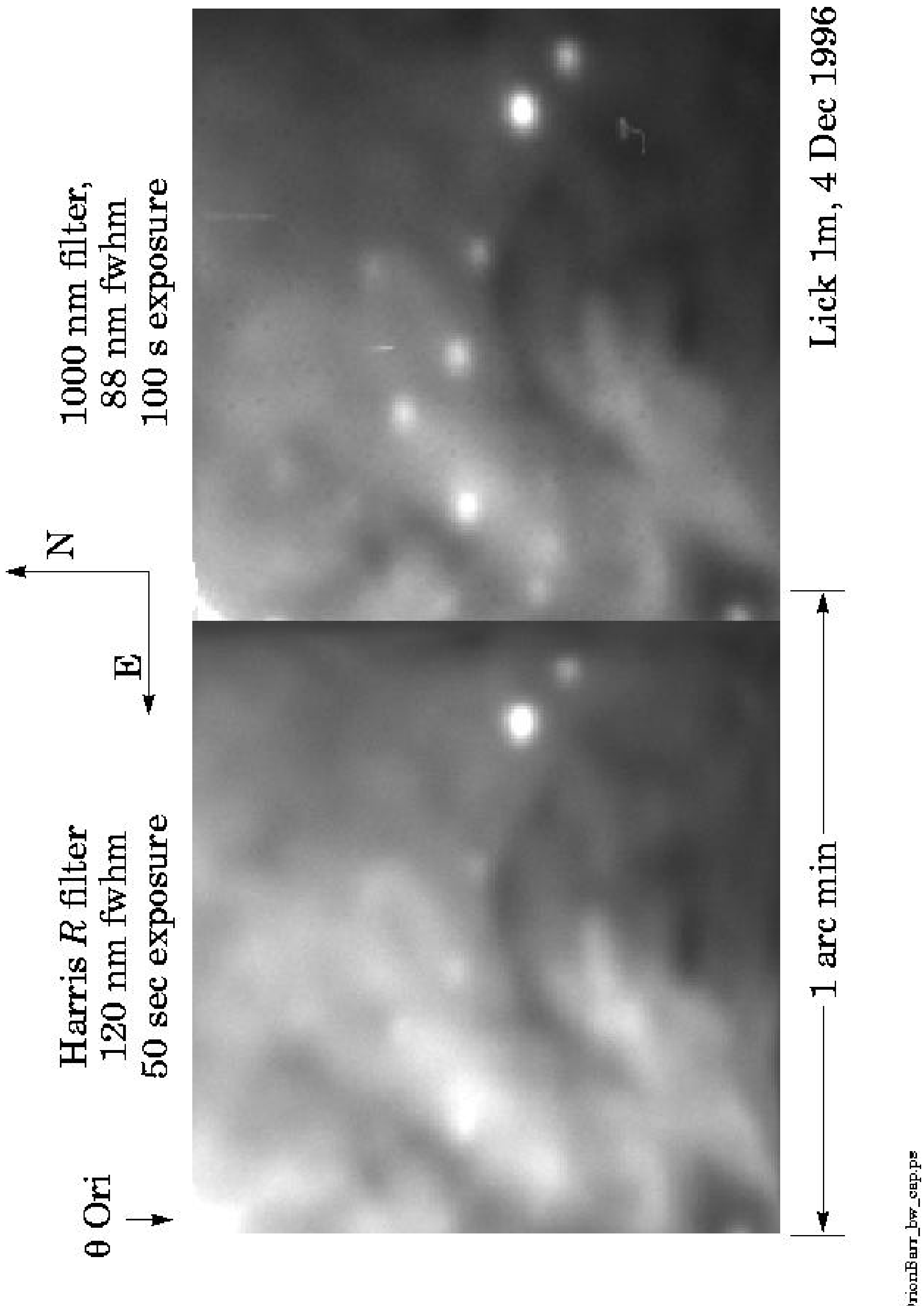
Similar CCDs are widely used in camcorders, but astronomical imaging requires much greater sensitivity and the ability to record *very* small signals (order 1 electron).

At LBNL a novel CCD has been developed in conjunction with the supernova group.

Quantum Efficiency of Fully Depleted LBNL CCD
vs. Conventional Thinned CCD



Comparison between thinned CCD (bottom/left) and deep depletion device. Interstellar dust tend to absorb in the blue, so extended red response of LBNL CCD shows features obscured in thinned CCDs.

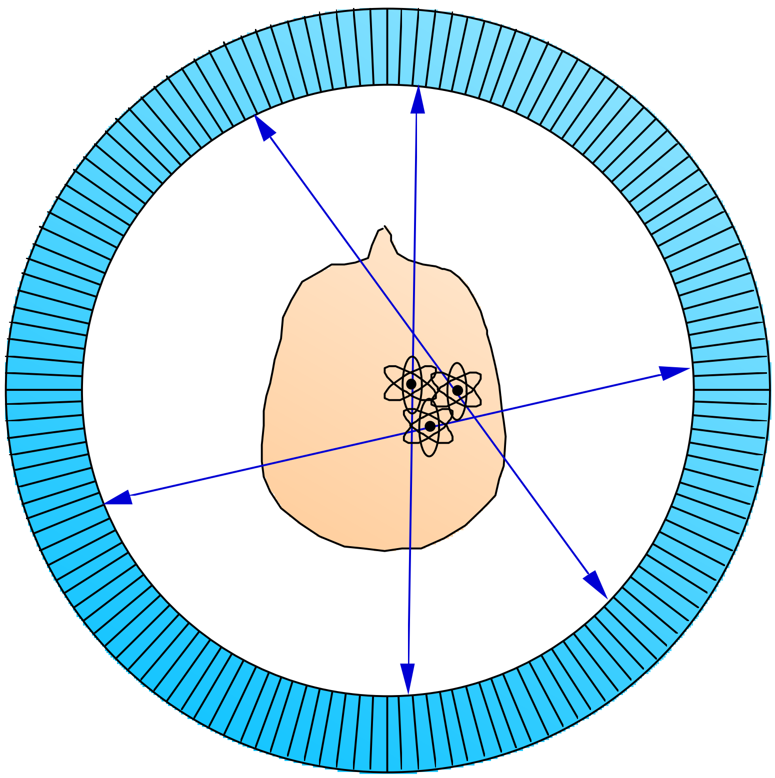


Medical Imaging – Positron Emission Tomography

(thanks to Bill Moses, Life Sciences Div. LBNL)

What is Positron Emission Tomography (PET)?

- Patient injected with drug having β^+ emitting isotope.
- Drug localizes in patient.
- Isotope decays, emitting β^+.
- β^+ annihilates with e^- from tissue, forming back-to-back 511 keV photon pair.



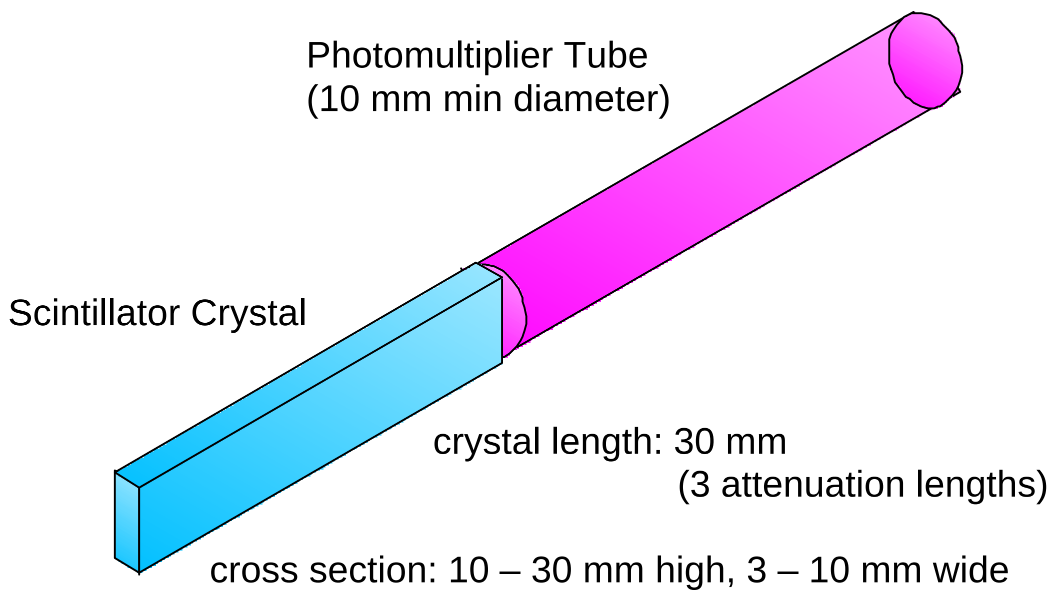
- 511 keV photon pairs detected via time coincidence.
- Positron lies on line defined by detector pair (a *chord*).

Forms planar image of a "slice" through the patient.

Common Tracer Isotopes

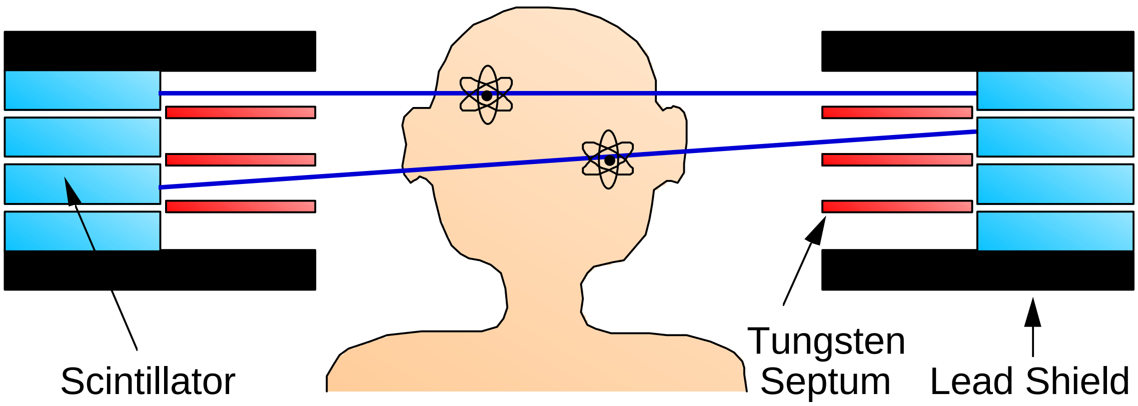
^{18}F	2 hour half life (+) Chemically “so-so” (±) Cyclotron-produced (-)
^{15}O, ^{11}C, ^{13}N	2 to 20 min. half-life (-) Chemically excellent (+) Cyclotron-produced (-)
^{82}Rb	2 min. half-life (-) Chemically boring (-) Generator-produced (+)

Individual Detector Element



Scintillator converts photon energy into light
Photomultiplier tube converts light into electrical signal

Multi-Layer PET Cameras



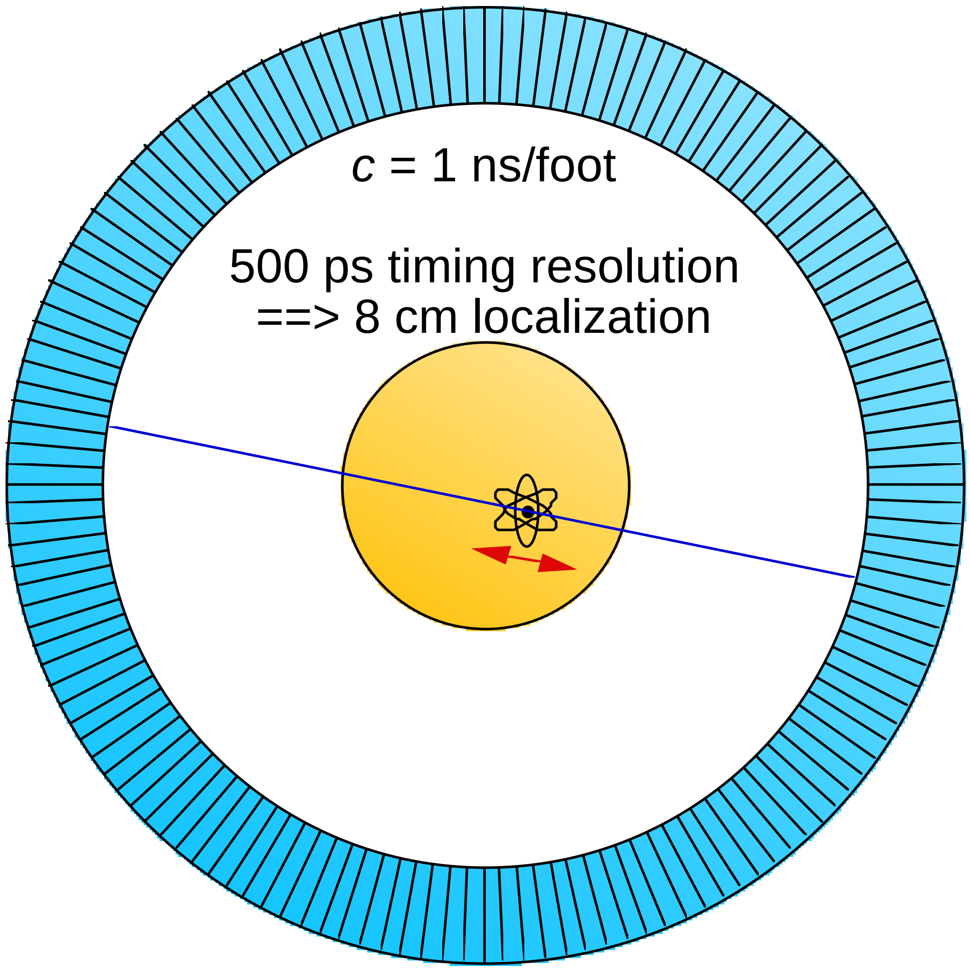
- Can image several slices simultaneously
- Can image cross-plane slices
- Can remove septa to increase efficiency (“3-D PET”)

However,

- More expensive

Planar images are “stacked” to form 3-D image

Time-of-Flight Tomograph



- Utilize difference in time of arrival between the two detectors
- Can localize source along line of flight
- Time-of-flight information reduces noise in images

However,

- Difficult to control timing of all detectors
- More expensive

Typically used to augment “standard” PET to reduce background.

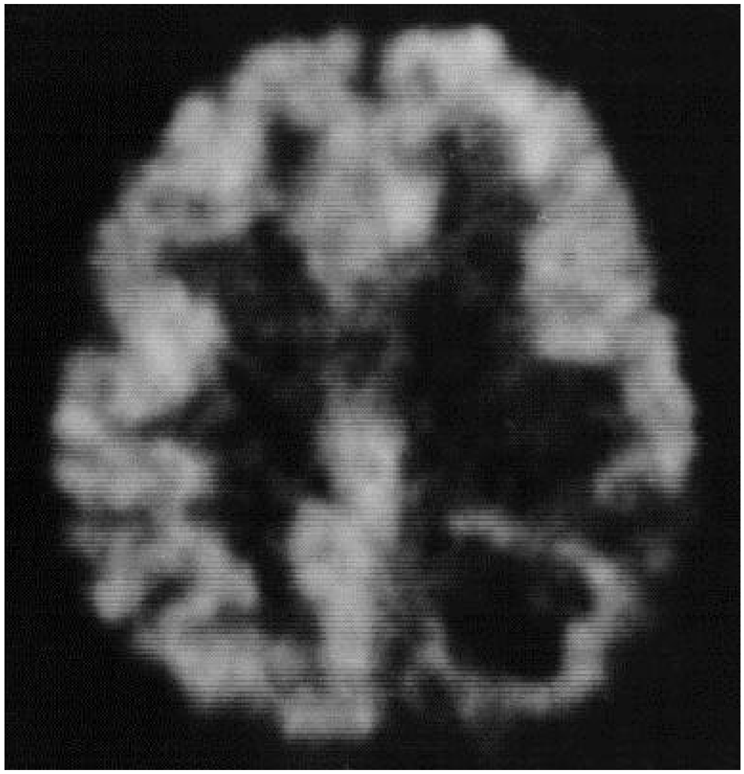
Typical Tomograph Parameters

- Patient port 30 cm diameter (head machine) or 50 cm diameter (body machine).
- 3.5 to 6 mm scintillator crystal width.
- 24 to 48 layers, covering 15 cm axially.
- 8 liters of BGO scintillator crystal.
- 500 photomultiplier tubes.
- "Several" million dollars

    Scintillator is 25% of total parts cost
    PMTs are 25% of total parts cost
    Next component is <5% total parts cost

Applications

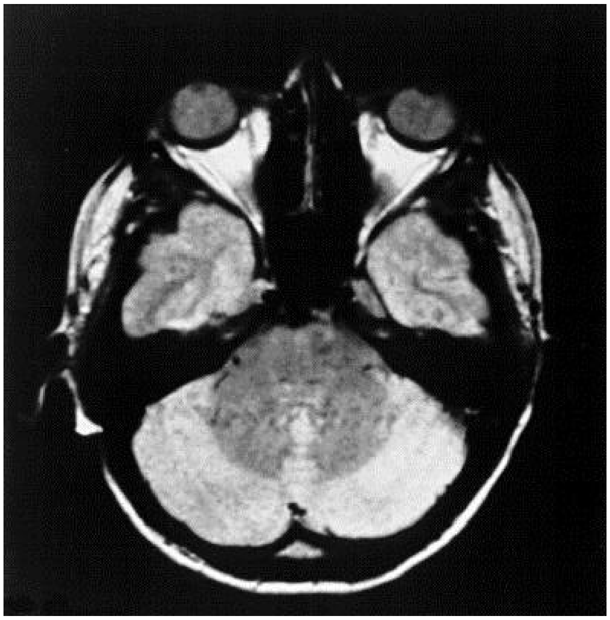
Tumor vs. Necrosis



- Brain tumor treated by radiation therapy.
- Symptoms recur
- Too much or too little radiation
- Check with PET

Too much radiation	⇒	dead area
Too little radiation	⇒	rapid metabolism blood circulation increases tracer concentration

Epilepsy – Comparison of NMR with PET



NMR
(now called MRI)

PET

note bright left
frontal lobe of brain

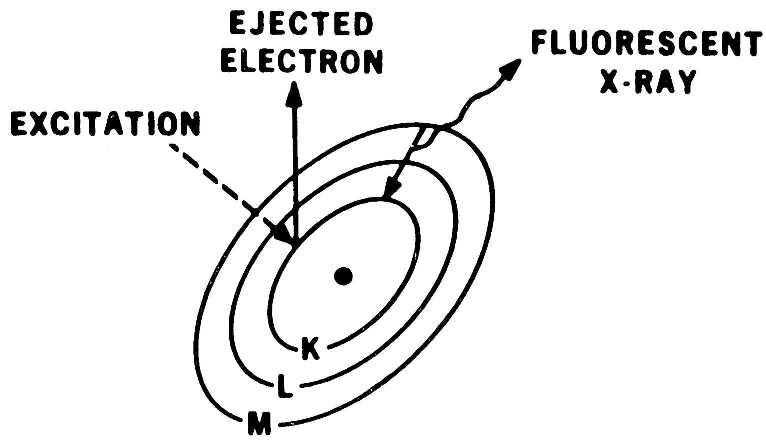
NMR and PET are complementary.

PET depends on rate of metabolism – allows dynamic measurements.

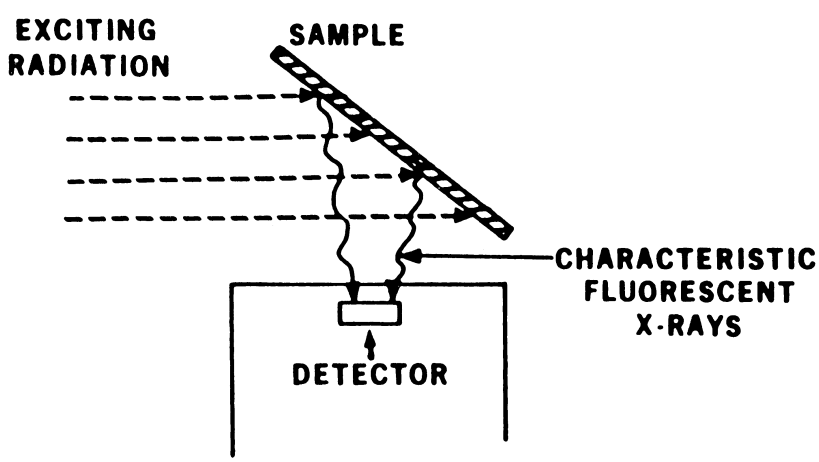
X-Ray Fluorescence

(thanks to Joe Jaklevic, Engineering Div. LBNL)

When excited by radiation of sufficient energy, atoms emit characteristic x-rays that can be used to detect trace contaminants.

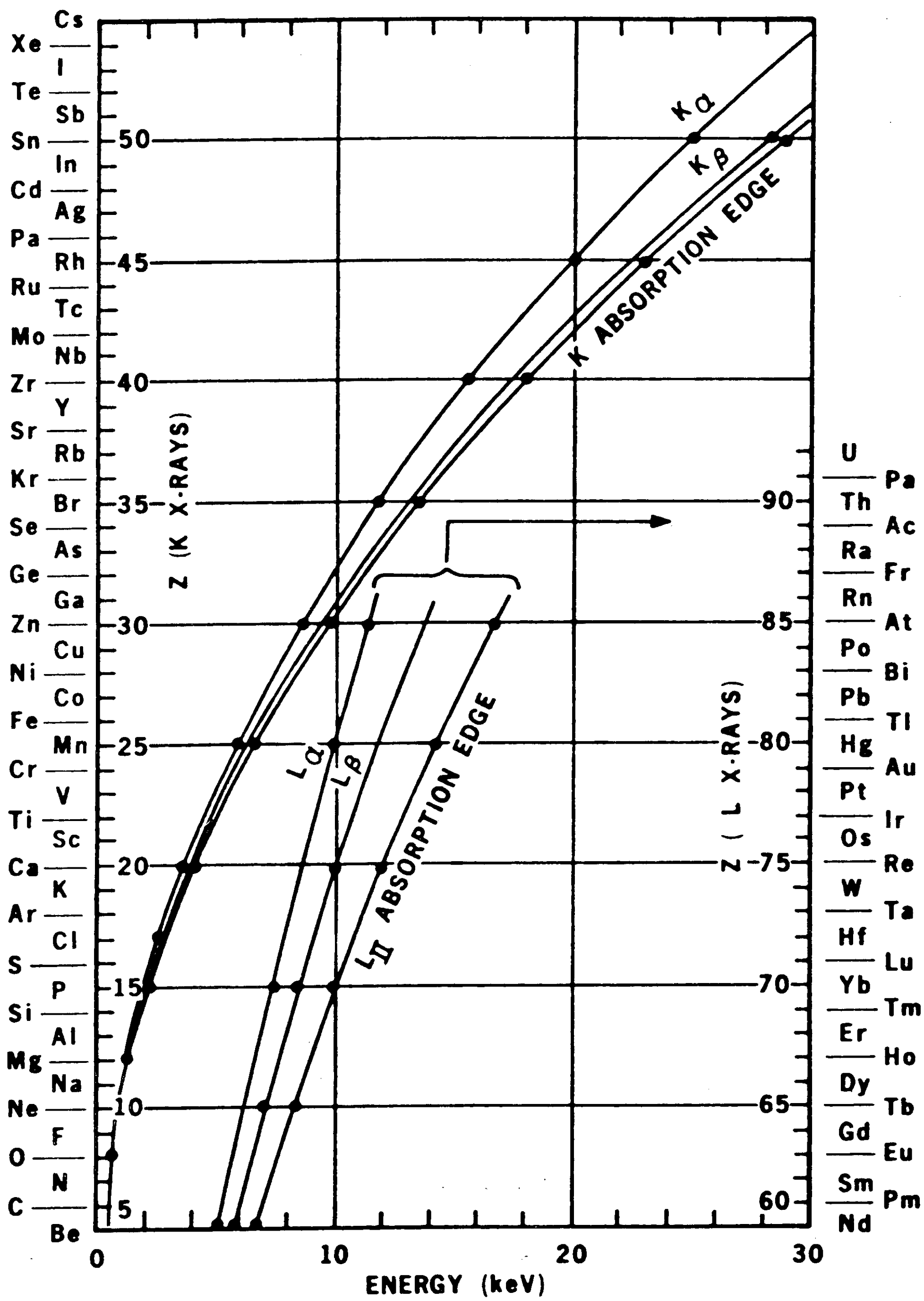


Experimental arrangement



The incident radiation can be broad-band, as long as it contains components of higher energy than the atomic transitions of the atoms to be detected.

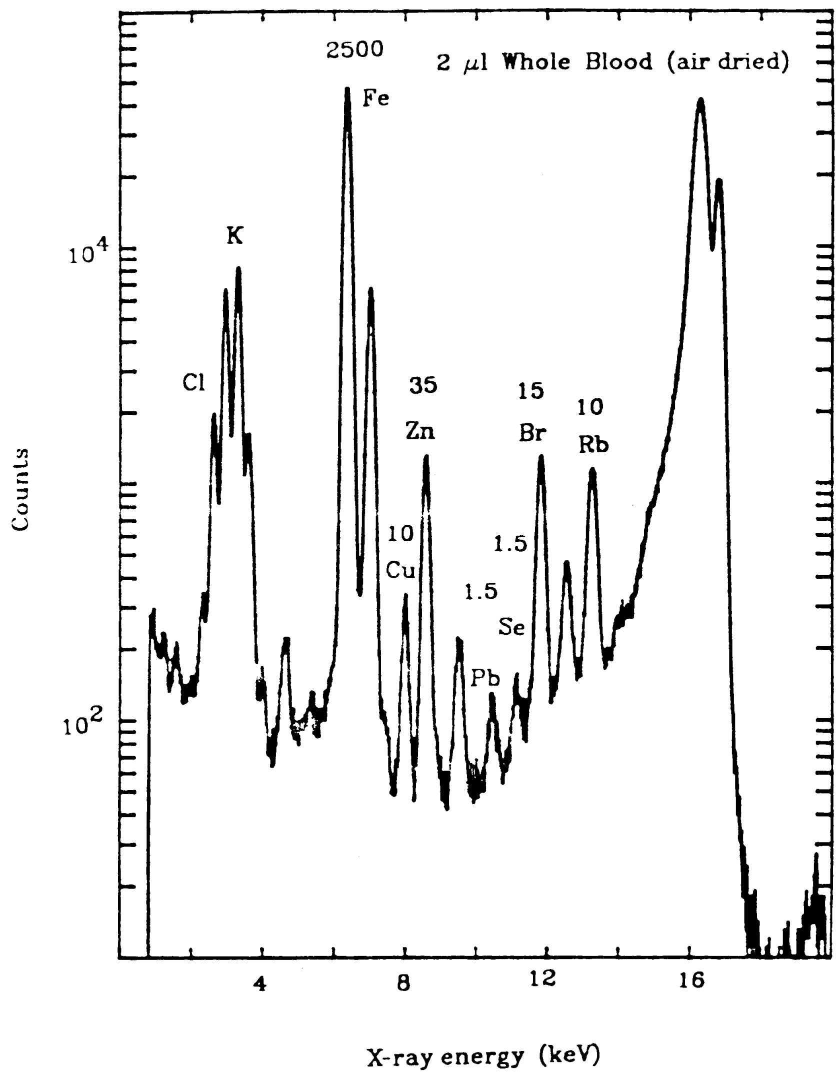
Energy of the K and L absorption edges vs. atomic number Z.



X-ray fluorescence can provide high sensitivity with small samples.

Spectrum taken from 2 μ*l* (1 mm^3) of blood.

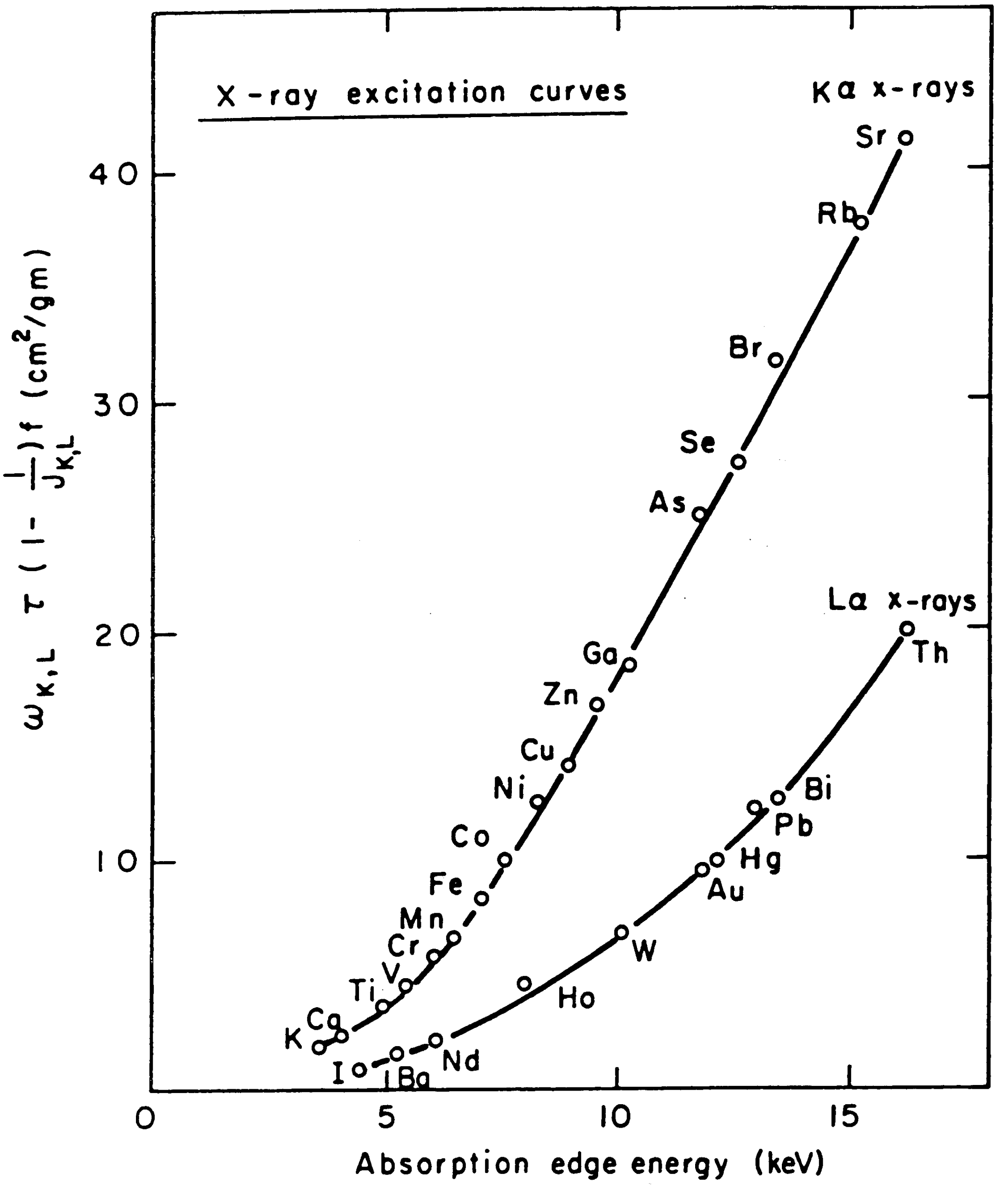
Concentrations are given in parts per million



Note the Pb peak (measurement taken before the introduction of unleaded gasoline).

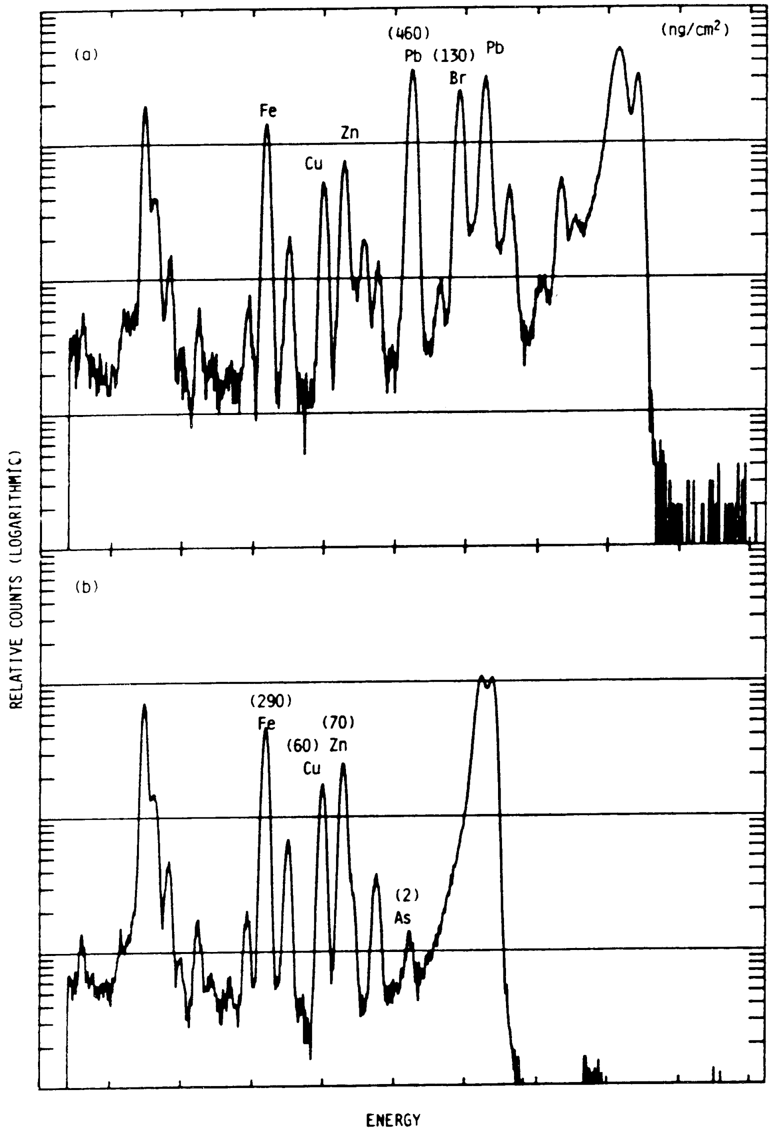
The sensitivity is limited by background.

In part, the signal-to-background ratio can be improved by judicious choice of the excitation energy.



Note the increase in cross section with energy. Using the smallest possible excitation energy for a specific element reduces background from higher energy transitions.

Air sample, particles captured on filter, particle size < 2.5 µm.



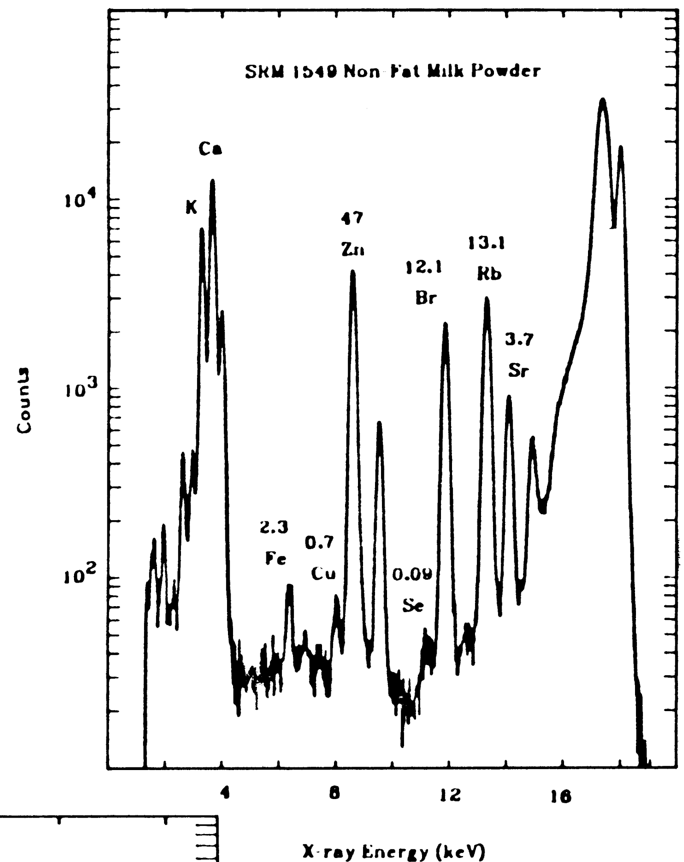
The upper edge of the spectrum indicates the excitation energy.

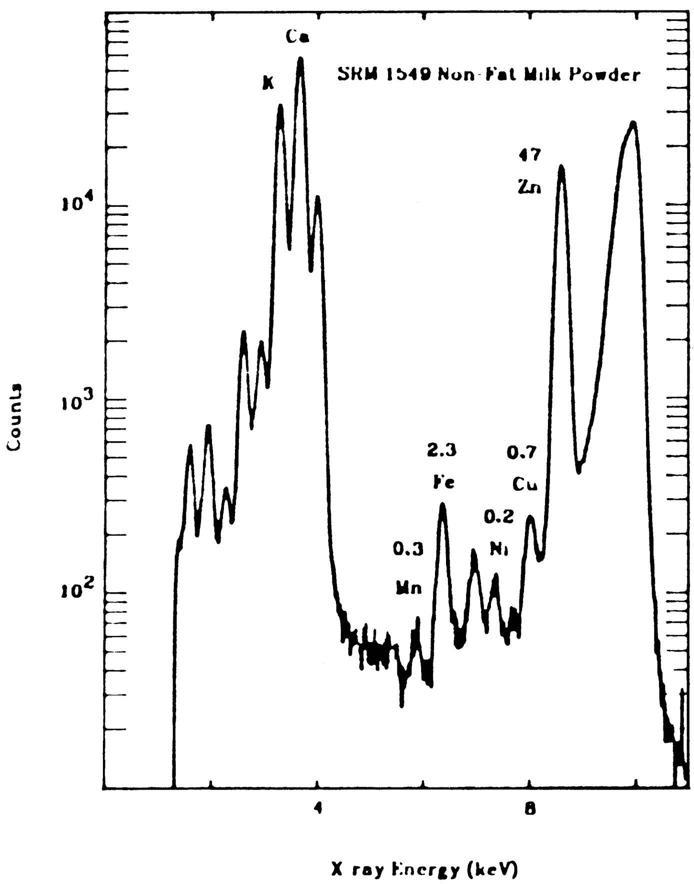
Note the As peak in the lower spectrum, which is obscured by more intense peaks from other elements at higher excitation.

At low excitation energies (<10 keV) emissions from high Z elements and high order transitions are significantly reduced.

Trace contaminants in milk powder, taken at two excitation energies.

Concentrations in ppm.





Reduced excitation energy:

Improved sensitivity for Mn, Ni.

Vertex Detection in High-Energy Physics

Detectors for high-energy physics comprise various subsystems to measure different parameters of the interaction products.

A typical detector at a colliding beam accelerator includes

1. Vertex detection
   to determine the position of the primary interaction and secondary decays
2. Precision tracking in a magnetic field
   momentum measurement
3. Calorimetry (Electromagnetic + Hadronic)
   energy measurement
4. Muon detection

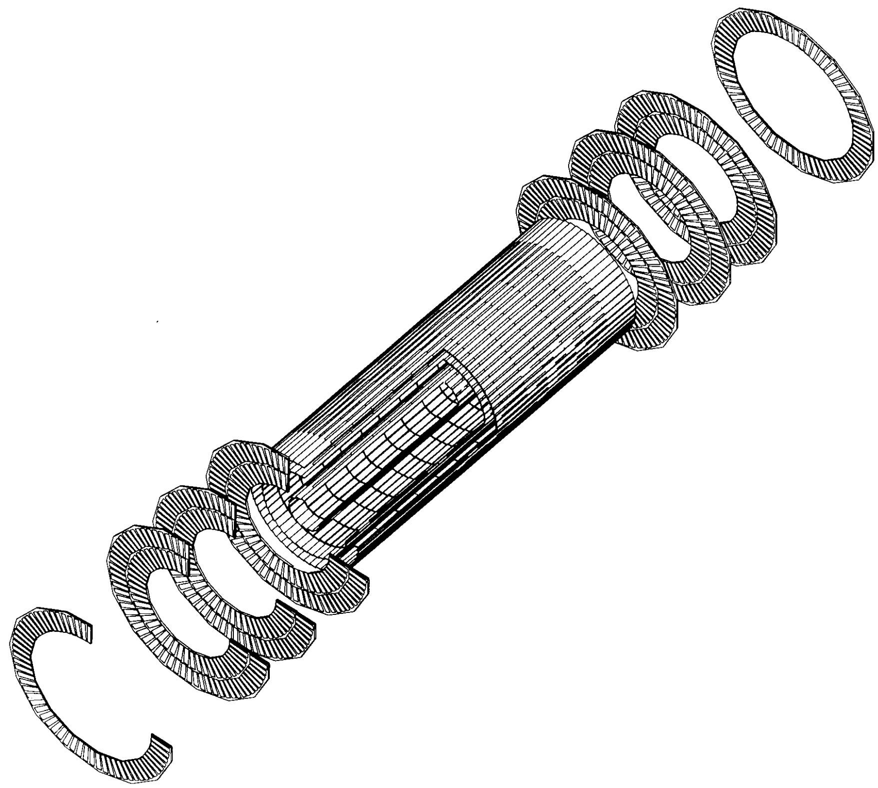
Vertex detectors have become critical components of modern detectors.

These systems rely on silicon sensors with 5 – 10 μm position resolution at radii of ~ 10 cm.

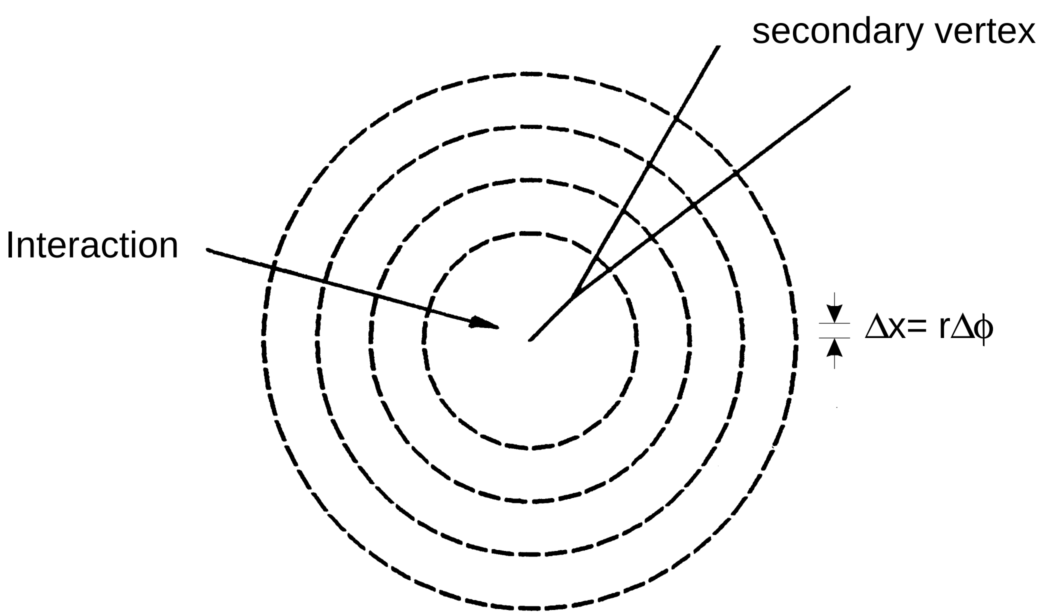
The high density of detector elements requires highly integrated readout electronics, monolithically integrated on silicon chips.

These readout ICs are highly specialized, so they are not available commercially. Determining the architecture and optimum technology, and then designing and system testing these ICs are among the main activities in the construction of large detector systems.

Typical configuration of a modern vertex detector

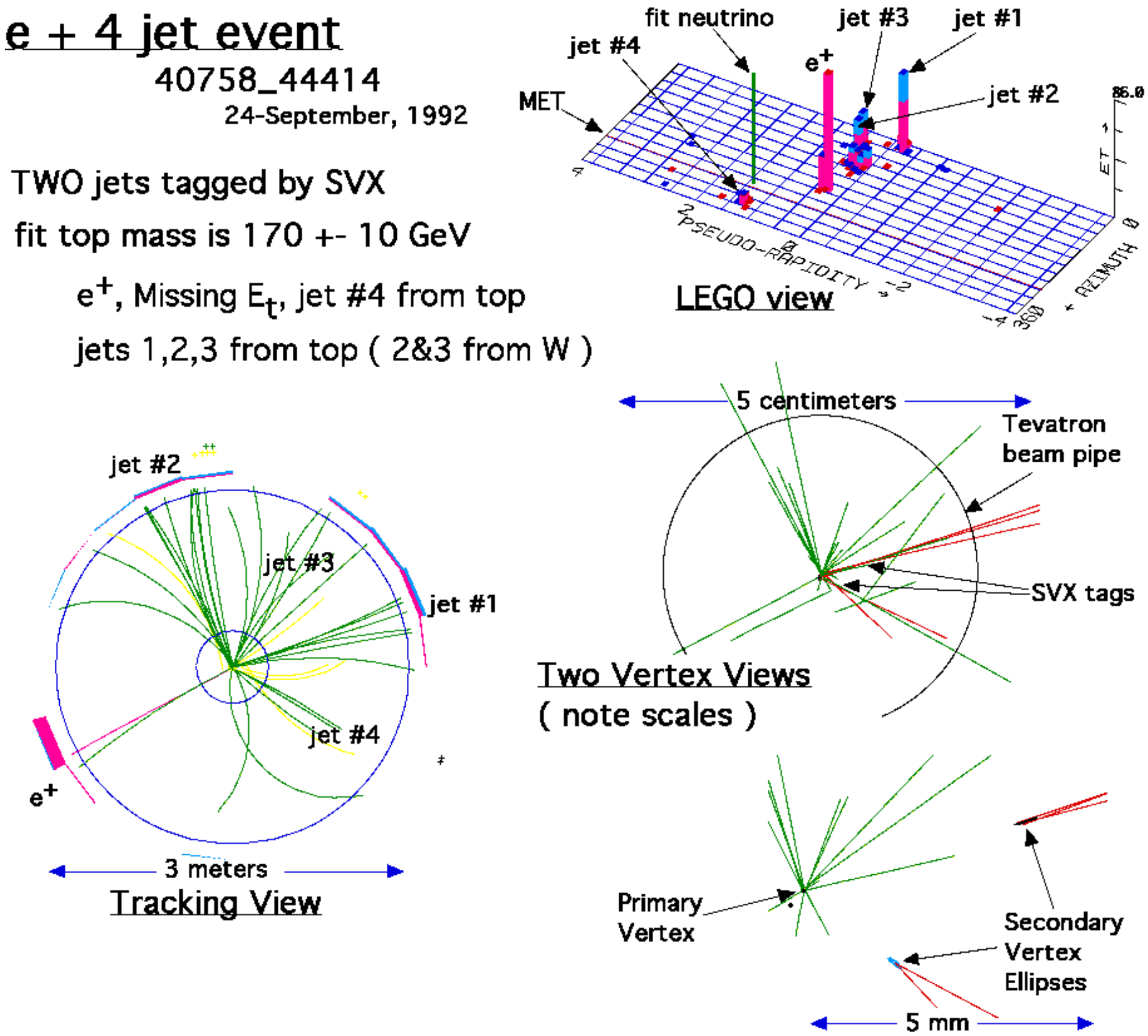


Resolution is provided primarily in azimuth, i.e.
radial electrodes in the disks,
electrodes parallel to the beam axis in the barrel:



Discovery of Top Quark
(CDF data)

Unique identification of the top quark by detecting secondary vertices in a high-resolution silicon vertex detector:



$t\bar{t} \to W\overline{W}b\bar{b}$

W has very short lifetime

$W \to q\bar{q} \to 2$ jets

$\overline{W} \to$ positron + neutrino

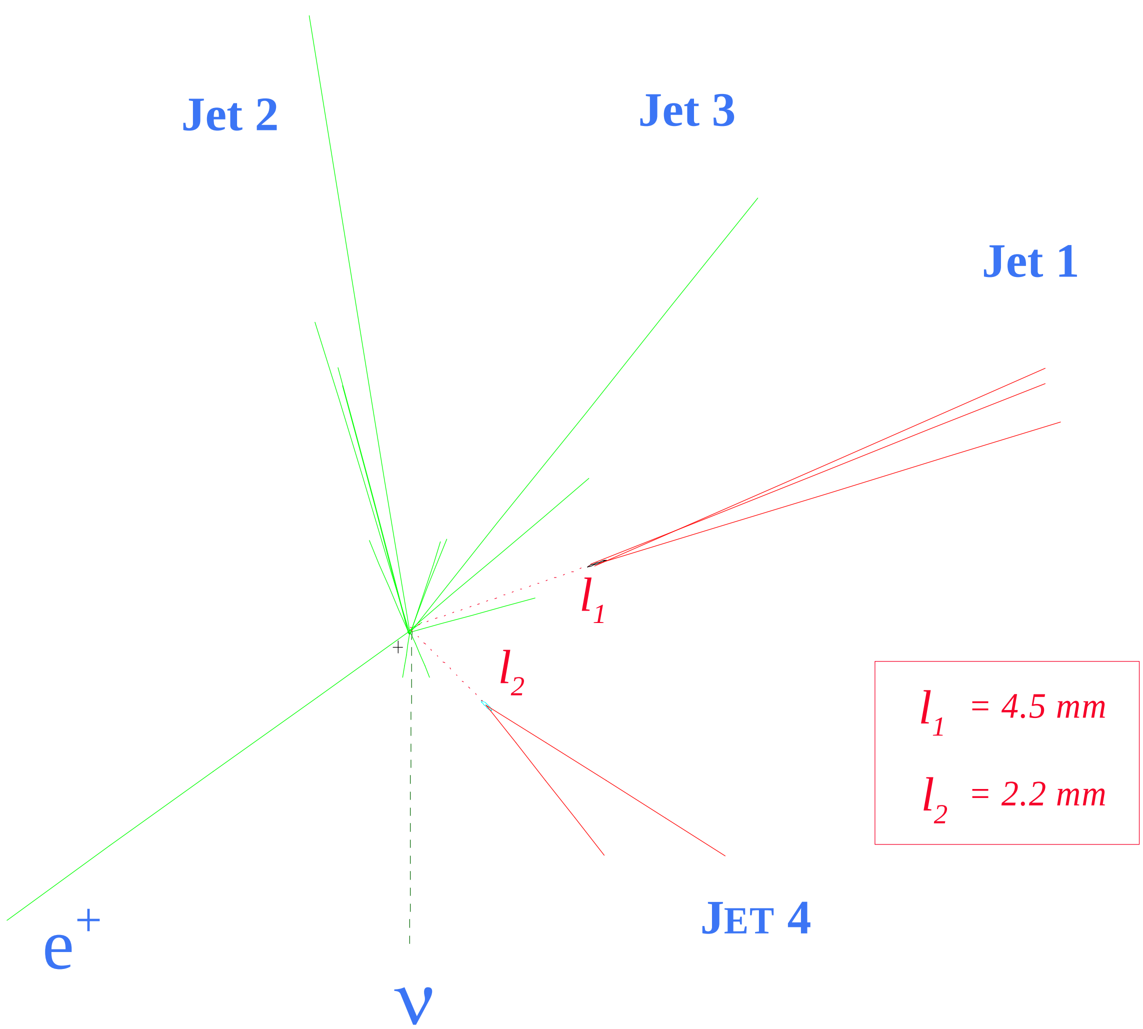
b emitted as B Meson, "long" lifetime

$b, \bar{b} \to$ displaced vertices

↑

zoom in on displaced vertices (next page)

$t\bar{t}$ Event
SVX DISPLAY
CDF

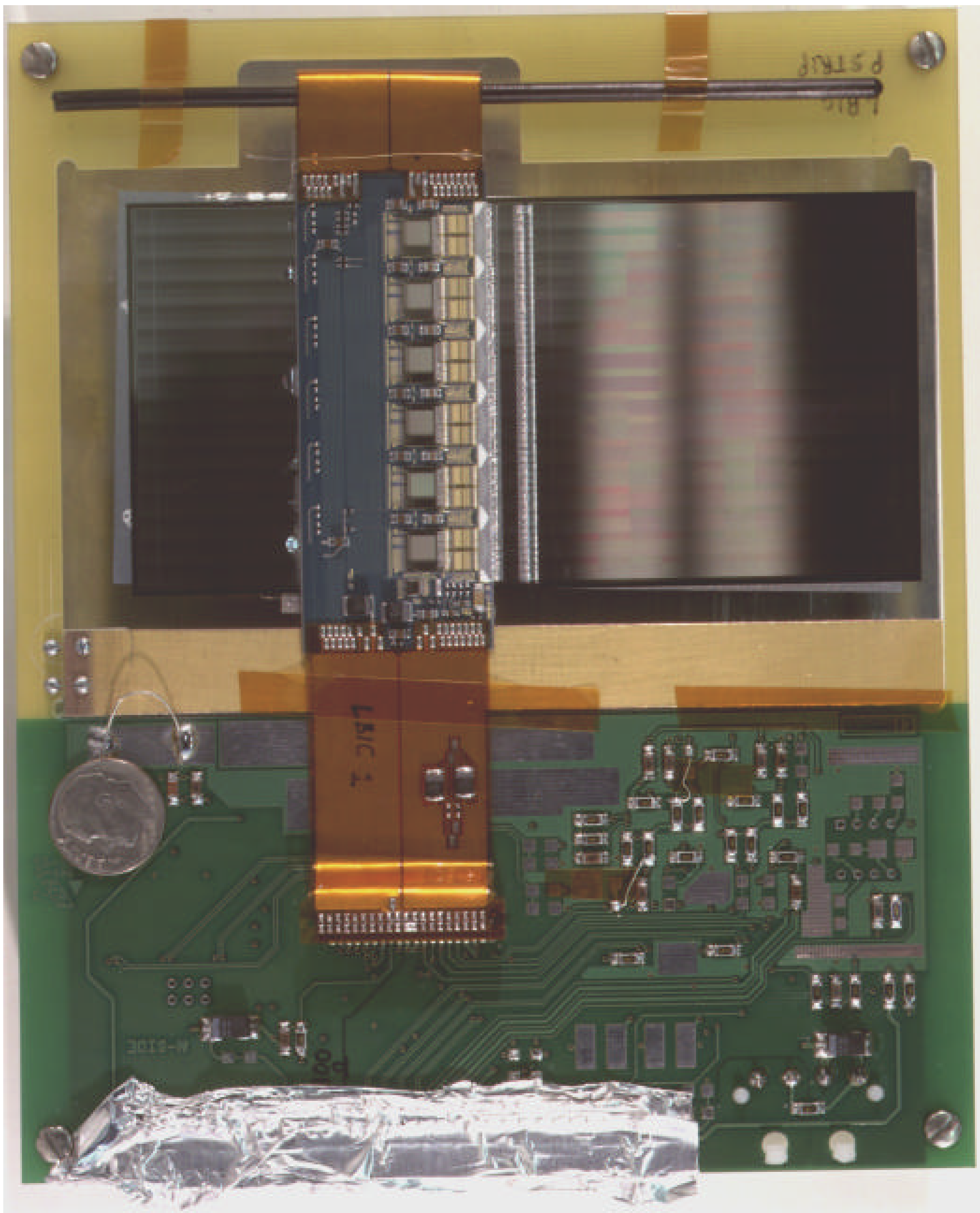


M_{top}^{Fit} = 170 ± 10 GeV/c^2

24 September, 1992
RUN #40758, EVENT #44414

A representative silicon detector module

readout ICs ↓ wire-bonds ↓ silicon detector ↓



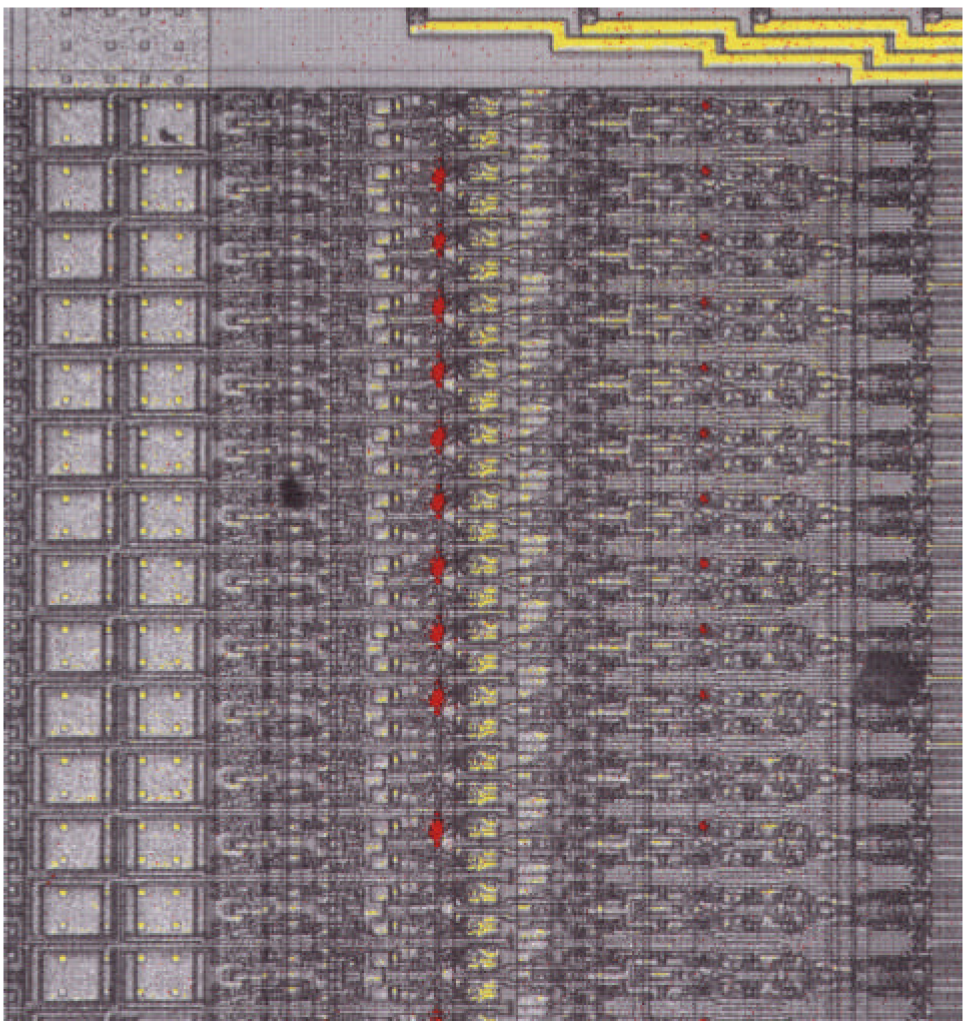
The module is mounted in a pc-board support frame to facilitate handling during test. The module itself is the rectangular object in the upper half of the picture.

In the course of developing the front-end ICs, poor fabrication yields led us to an extensive program of failure analysis.

One tool is to view IR images of chips. Defects can form localized high-field regions that allow electrons to acquire sufficient energy while traversing their mean free path to excite atomic transitions. Emission from these defect sites can be “seen” with appropriate position-sensitive sensors.

Data taken with T. Ohsugi at Hiroshima University.

1.2 x 1.5 mm^2 view of chip
Image at λ= 1 μm (red) superimposed on visual image (gray/yellow)

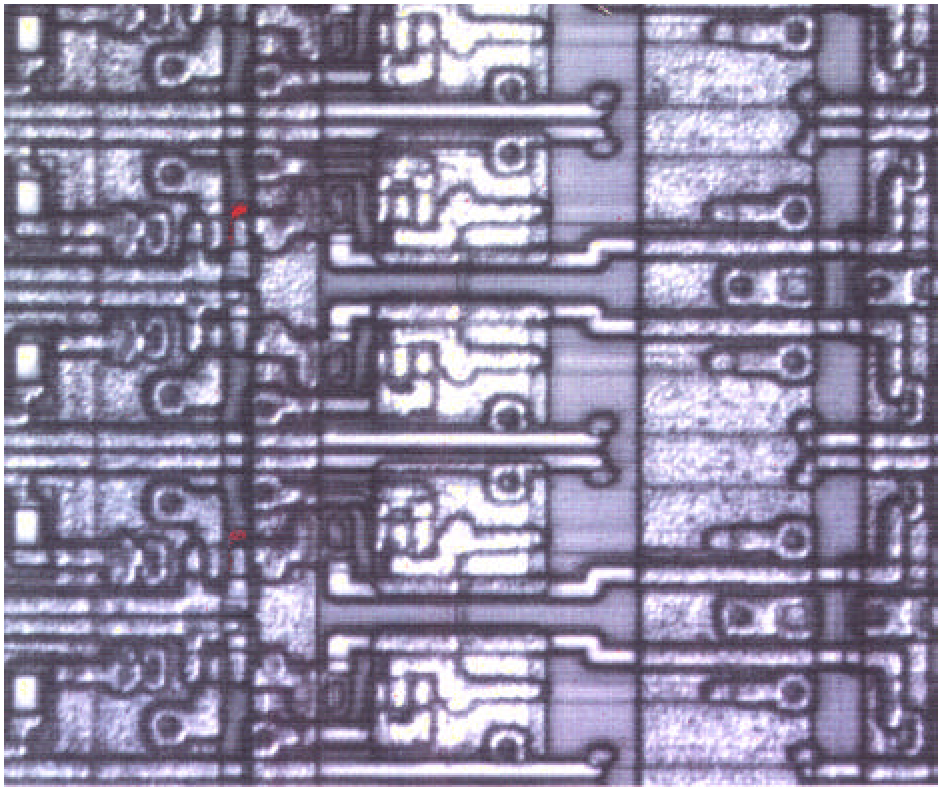


↑ ↑
red spots indicate IR emission

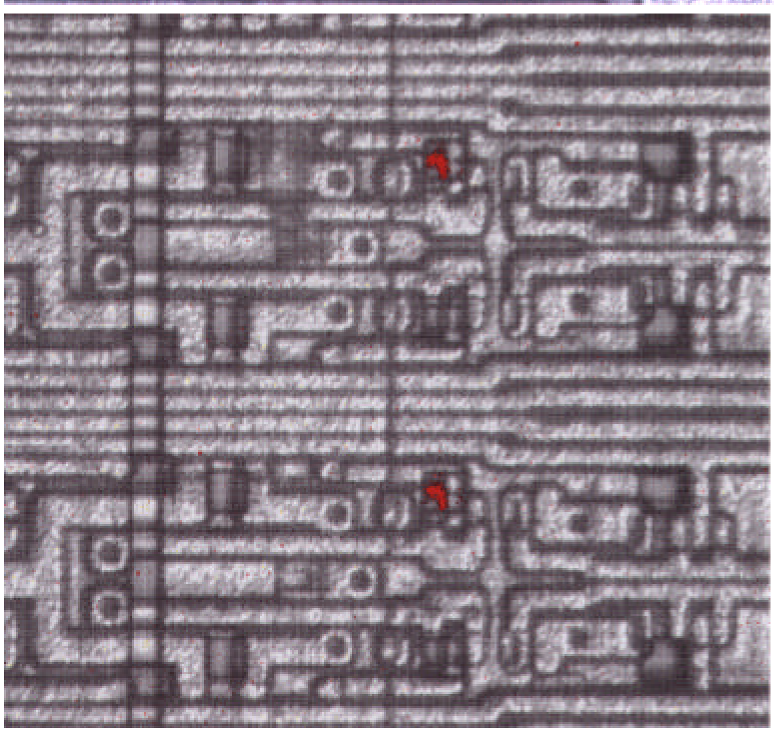
Viewing the emission sites at higher resolution allows the identification of individual transistors.

Left row

~ 30 µm



Right row



Since the aluminum metallization is opaque at 1 mm, the emission appears to “go around the corner”.

Course Content

1. Energy Loss Mechanisms and Spectrum Formation
2. Scintillation Detectors

   Use a “simple” detector system to
   explain basic requirements and functional blocks of
   complete system

3. Semiconductor Detectors (ionization chambers)

   signal formation

   electronic noise

   optimization of signal-to-noise ratio

   pulse processing electronics

      amplification and pulse shaping
      amplitude digitization
      time measurements

4. A Semiconductor Device Primer
5. Photodiodes
6. Gaseous Detectors
7. Position Sensitive Detectors
8. Detectors for Weakly Ionizing Radiation
9. Development of a System Concept
10. Why Things Don’t Always Work

Open to change as required.

The course does not follow a specific text, but a useful book is

Radiation Detection and Measurement
by Glenn F. Knoll, Wiley, 1989,

QC787.C6K56
ISBN 0-471-81504-7

Additional literature will be specified for specific topics.

Course notes and homework problems will be posted on the World Wide Web (www-physics.LBL.gov/~spieler)

Homework will provide basis of pass/fail.

Questions …

Scheduling?

Office hours?

I'll be available after each lecture,

or contact me and we can meet some other time

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