

IV. Detector Systems – Conflicts and Compromises

1. Conflicts

Custom integrated circuits essential for vertex detectors in HEP.

Requirements

1. low mass to reduce scattering
2. low noise
3. fast response
4. low power
5. radiation tolerance

reduction in mass \Rightarrow thin detector

radiation tolerance \Rightarrow thin detector

thin detector \Rightarrow less signal \Rightarrow lower noise required

lower noise \Rightarrow increased power

fast response \Rightarrow increased power

increased power \Rightarrow more mass in cabling + cooling

immunity to external pickup \Rightarrow shielding \Rightarrow mass

+ contain costs

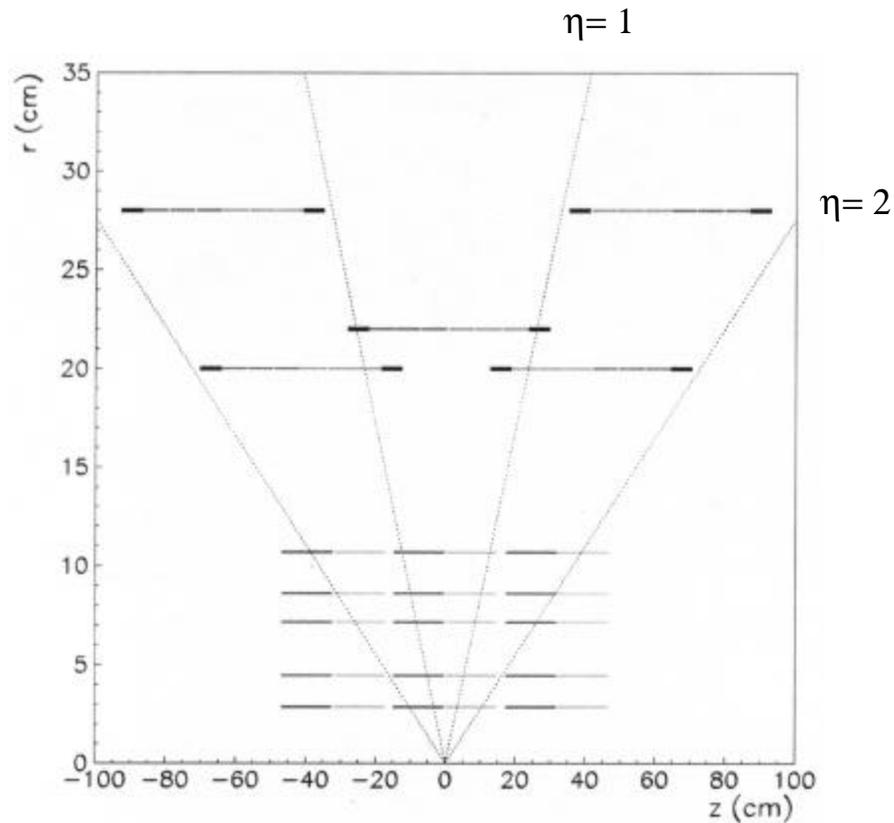
How to deal with these conflicting requirements?

Some examples ...

2. CDF Vertex Detector Upgrade: SVX2

Expand coverage of existing vertex detector

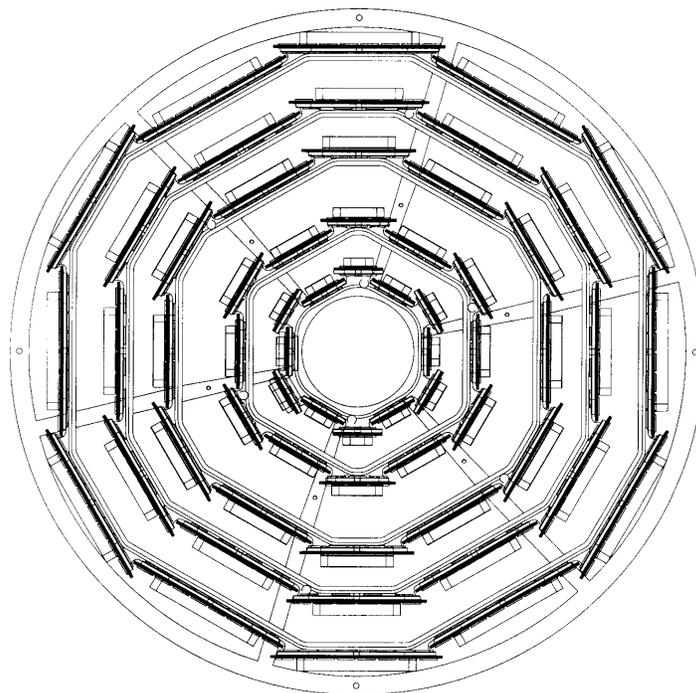
a) side view ($z = \text{beam axis}$)



Inner 5 layers: SVX2

Outer 2 layers: ISL

b) Axial view of vertex detector



Property	Layer 0	Layer 1	Layer 2	Layer 3	Layer 4
Radial distance (cm)	2.45	4.67	7.02	8.72	10.6
Stereo angle (degrees)	90	90	+1.2	90	-1.2
$r\phi/z$ readout channels	256/512	384/576	640/640	768/512	896/896
$r\phi/z$ readout chips	2/2	3/3	5/5	6/4	7/7
$r\phi/z$ strip pitch (μm)	60/141	62/125.5	60/60	60/141	65/65
Total width (mm)	17.14	25.59	40.30	47.86	60.17
Total length (mm)	74.3	74.3	74.3	74.3	74.3

Layers 0, 1 and 3 use 90° stereo angle, whereas layers 4 and 5 use 1.2° stereo angle to reduce ghosting.

Electronic Readout

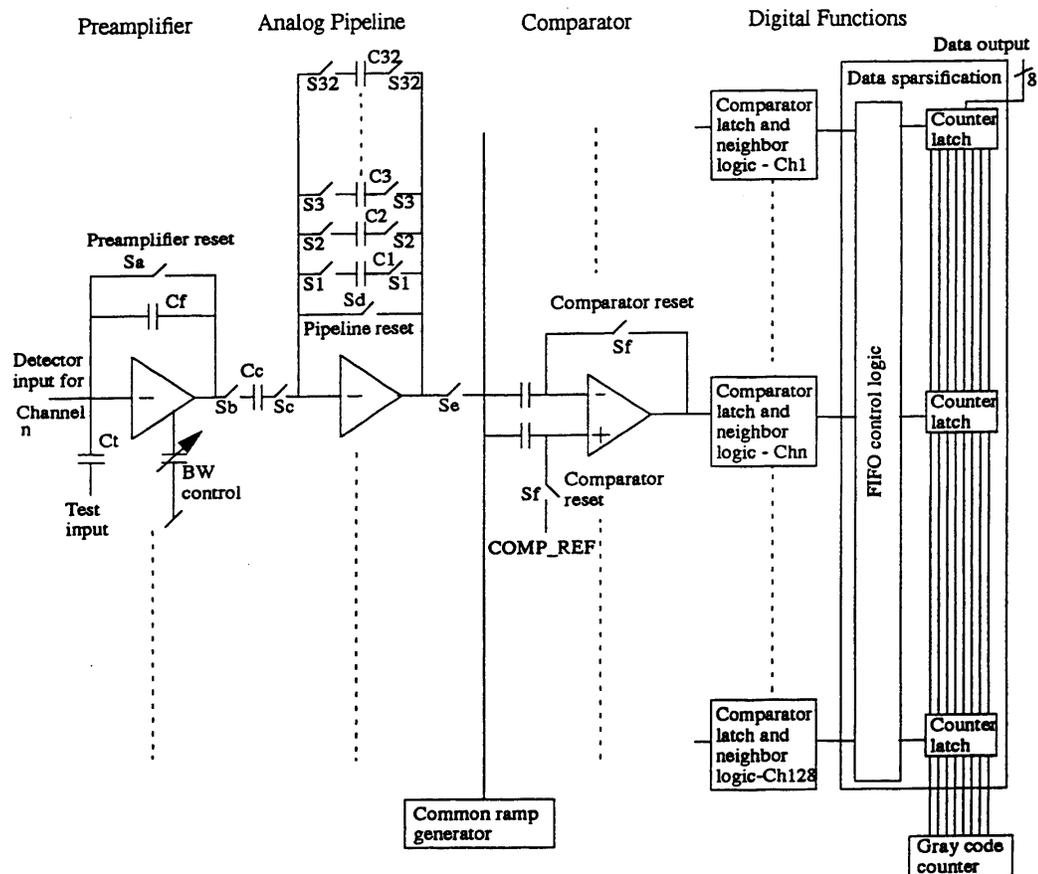
SVX2 uses the SVX3 chip, which is a further development of the SVX2 chip used by DØ.

Include on-chip digitization of analog signal

Threshold, calibration via on-chip DACs

All communication to and from chip via digital bus

Block diagram of SVX2



Wilkinson ADC integrated with pipeline + comparator, which is also used for sparsification. Adds $100 \mu\text{m}$ to length and $300 \mu\text{W}/\text{ch}$ power.

ADC clock runs at 106 MHz in experiment, tested to 400 MHz

Total power: 3 mW/ch

SVX2 die layout

Dimensions: 6.3 x 8.7 mm
0.8 μm , triple-metal rad-hard CMOS

Input Pads

Preamplifiers

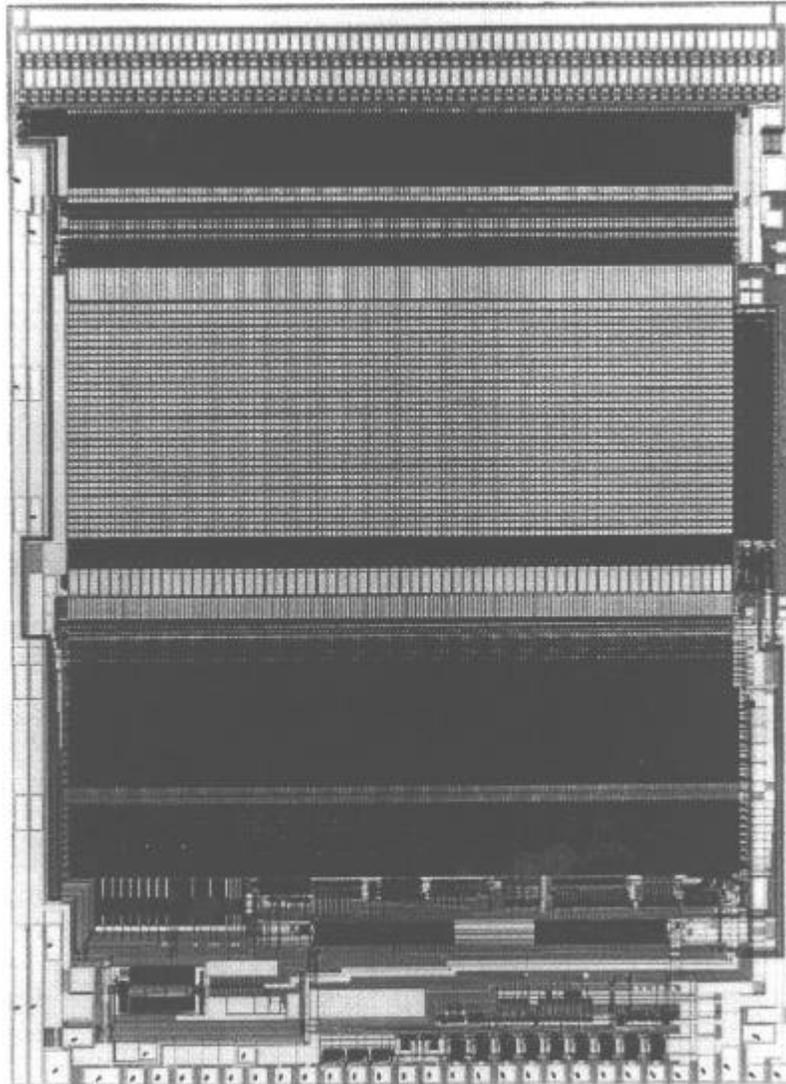
Analog Pipeline

ADC Comparator

Neighbor Logic

Sparsification +
Readout

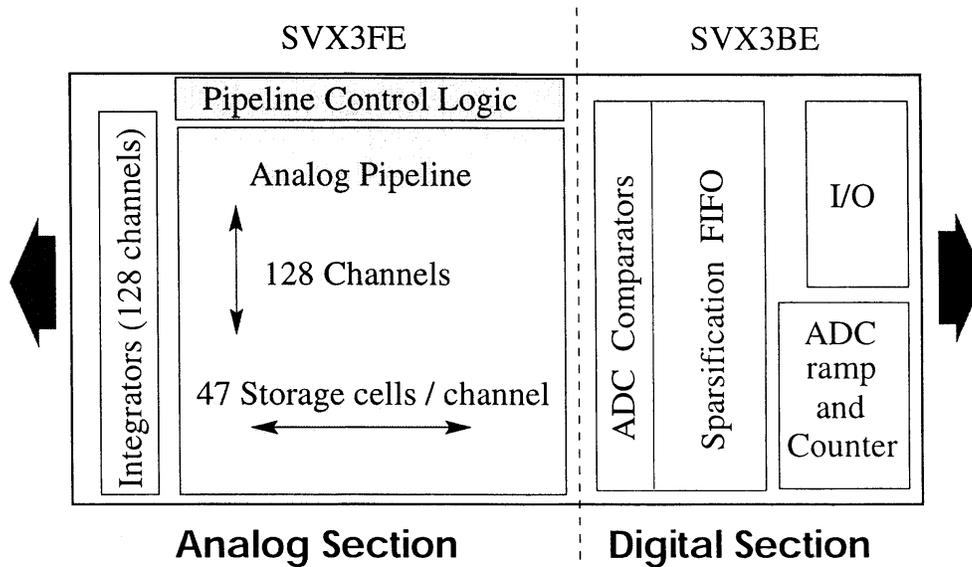
ADC Ramp +
Counter, I/O



SVX2 (used by DØ) is designed for sequential signal acquisition and readout.

SVX3 (used by CDF) allows concurrent read-write, i.e. signal acquisition and readout can proceed concurrently.

SVX3 Floor Plan

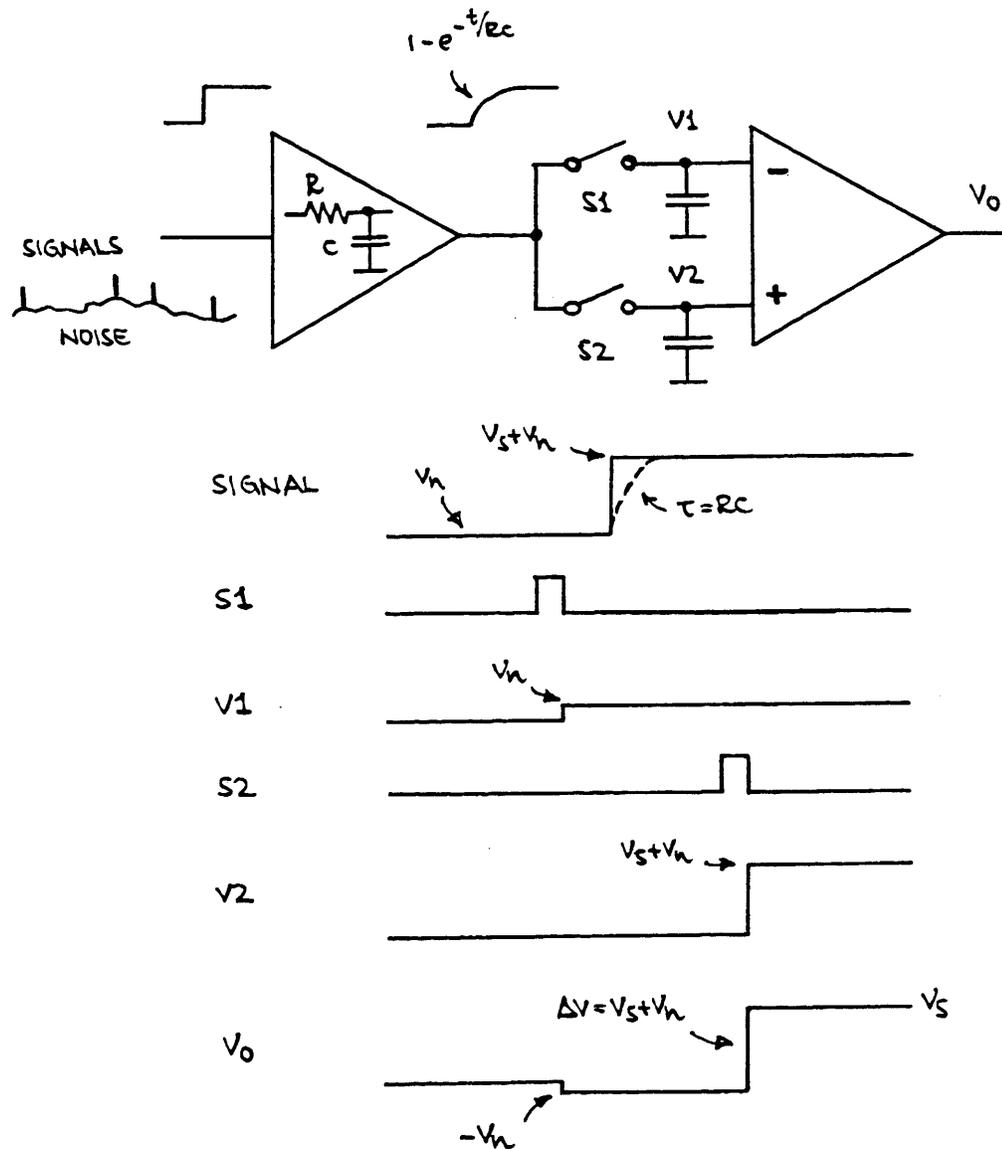


Analog section:	6.26 x 8.06 mm ²
Digital section:	6.26 x 4.97 mm ²
Combined in 1 chip:	6.26 x 12 mm ²

Measured Noise: $Q_n = 500 \text{ el} + 60 \text{ el/pF rms}$

Both chips fabricated in rad-hard CMOS.

SVX2 and SVX3 utilize correlated double sampling for pulse shaping



Correlated double sampling requires prior knowledge of signal arrival.

OK for colliders if $\Delta T_{beam} > T_{shaper}$, but not for random signals.

High luminosity colliders (B Factories, LHC) have much shorter beam crossing intervals

⇒ continuous shaping required

3. BaBar Silicon Vertex Tracker

B mesons from $\Upsilon(4S)$ production have low momentum.

Asymmetry in beam energies (9 GeV e^- on 3.1 GeV e^+) used to provide boost ($\beta\gamma = 0.56$) that allows conventional vertex detectors to cope with short B meson lifetime.

Vertex detector must provide resolution in boost direction, i.e. parallel to beam axis, rather than in $r\phi$.

Resolution requirement not stringent:

Less than 10% loss in precision in the asymmetry measurement if the separation of the B vertices is measured with a resolution of $\frac{1}{2}$ the mean separation (250 μm at PEP-II)

P 80 μm vertex resolution required for both CP eigenstates and tagging final states.

Resolution is multiple-scattering limited

beam pipe: 0.6% X_0

Use crossed strips

z -strips for vertex resolution

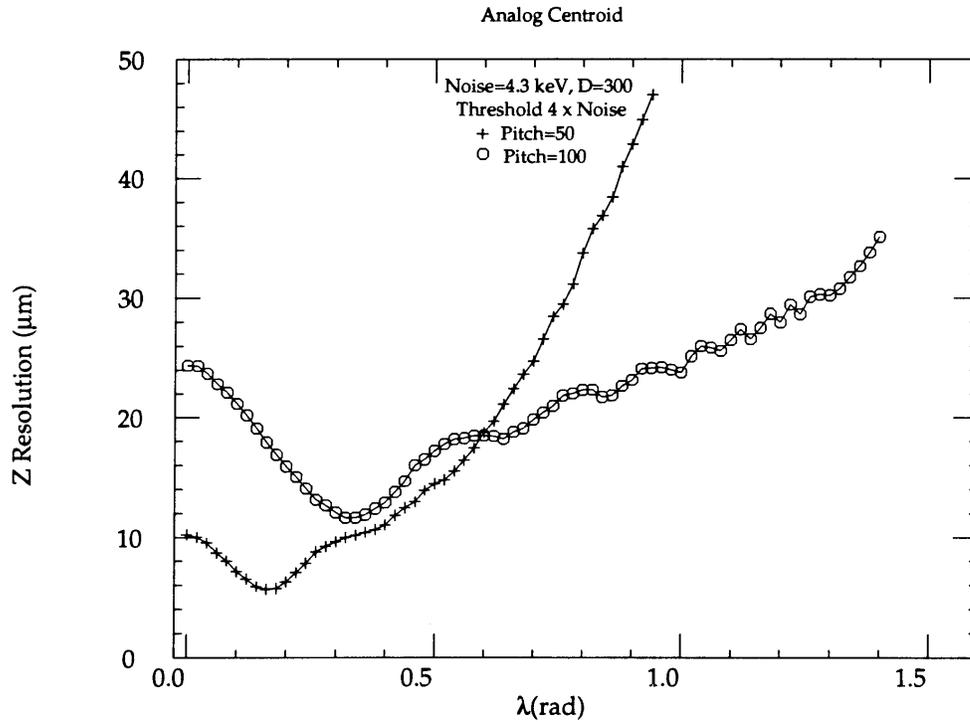
$r\phi$ strips for pattern recognition

Measurement does not require utmost position resolution

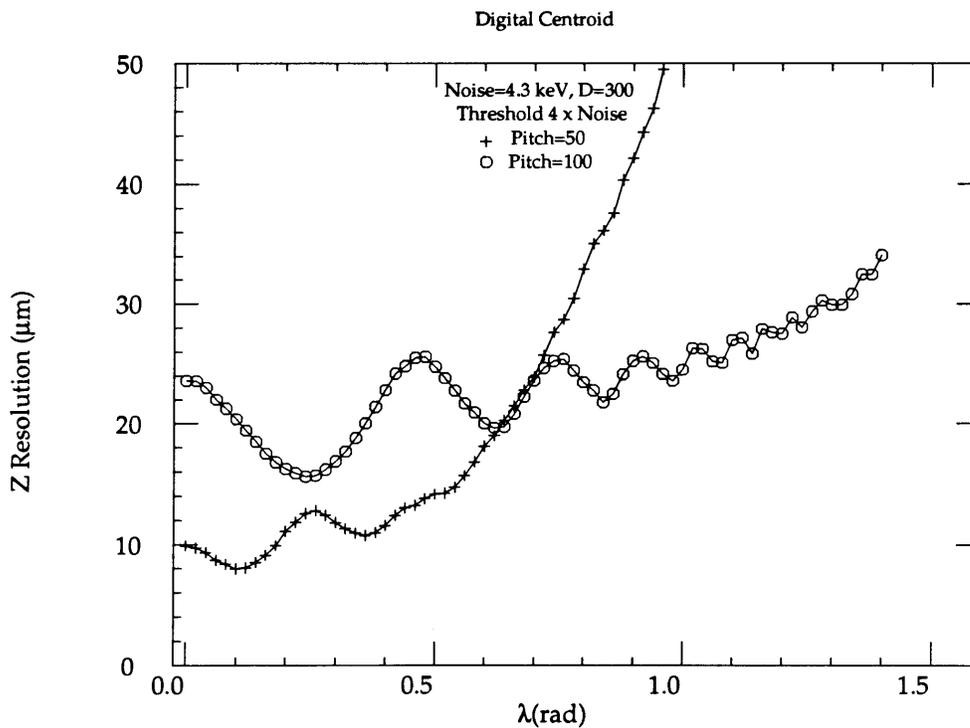
P use binary readout

Position resolution for analog and binary readout vs dip angle λ .

Analog readout (50 and 100 μm pitch)

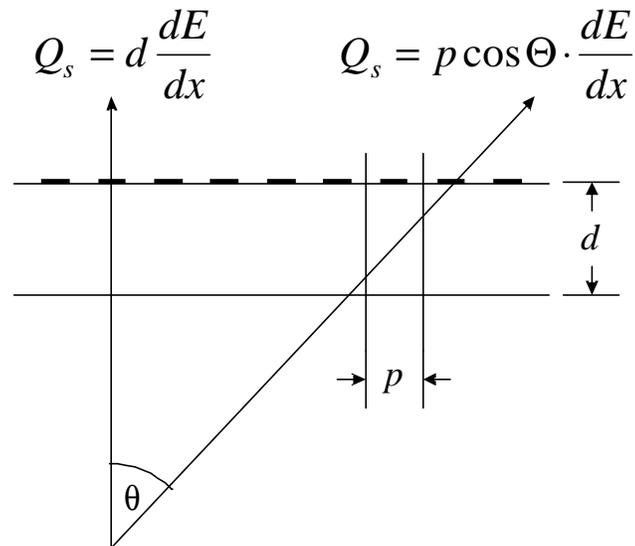


Binary readout (50 and 100 μm pitch)



Why does 100 μm pitch yield better resolution at large dip angles?

Signal in z -strips degrades at large dip angles



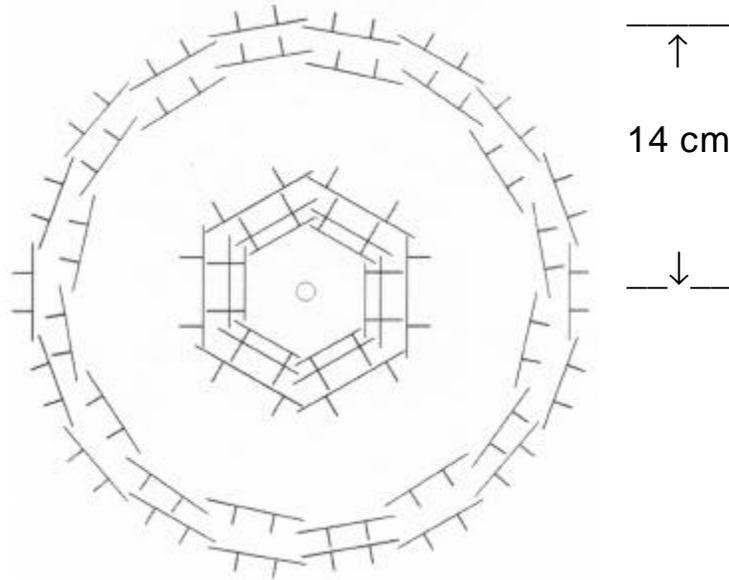
Change strip pitch at $\lambda > 0.7$ radians

Furthermore

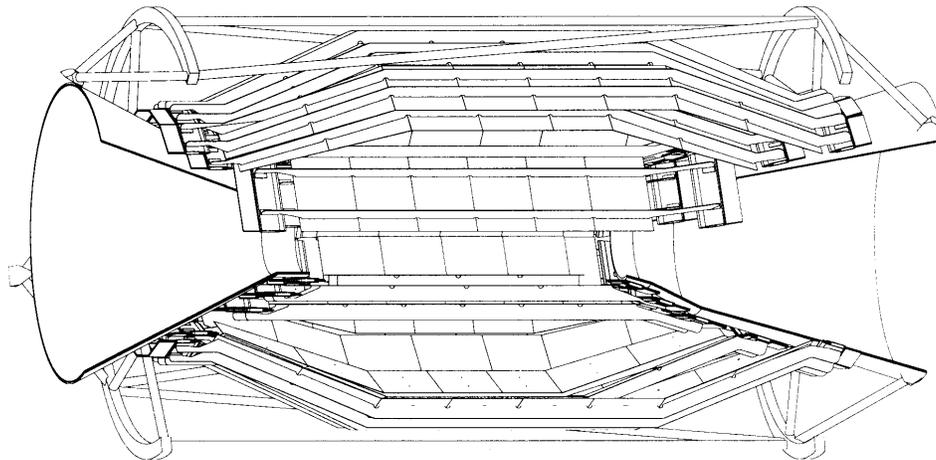
add coarse analog information (3 – 4 bits adequate)

Mechanical arrangement of detector

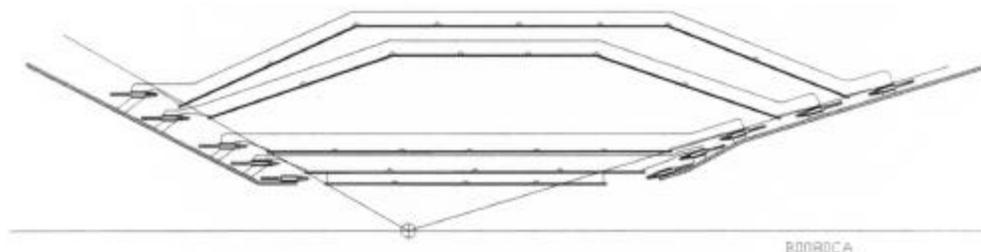
Axial view



Side view



Outer layers use “lampshade” geometry instead of disks



Electronics mounted outside of active region
(connected to detectors by kapton cables)

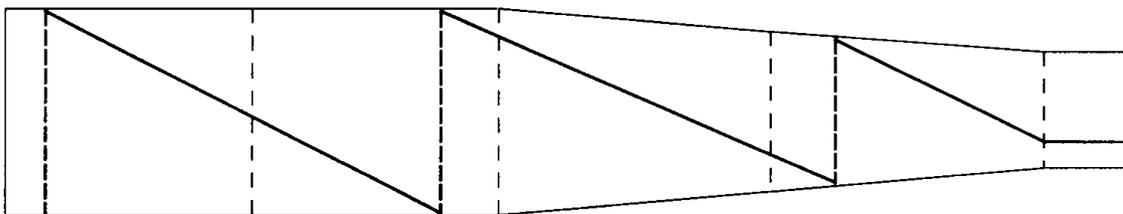
P long strips (high capacitance) in outer layers

Layer	Fanout Type	Length (cm)	Number of Readout		Typical Pitch at		Number of Circuits
			Strips	Channels	Input (μm)	Output (μm)	
1	z , F+B	12.5	950	768	100	50	12
	ϕ , F+B	3.0	768	768	50	50	12
2	z , F+B	14.5	1150	1024	100	50	12
	ϕ , F+B	3.0	960	1024	50	50	12
3	z , F+B	15.6	1360	1280	100	50	12
	ϕ , F+B	2.0	1280	1280	50	50	12
4a	z , F	19.7	885	512	200	50	8
	z , B	24.3	1115	512	200	50	8
	ϕ , F+B	2.0	512	512	65	50	16
4b	z , F	20.6	930	512	200	50	8
	z , B	24.2	1160	512	200	50	8
	ϕ , F+B	2.0	512	512	65	50	16
5a	z , F	25.2	1160	512	200	50	9
	z , B	25.1	1205	512	200	50	9
	ϕ , F+B	2.0	512	512	65	50	18
5b	z , F+B	26.1	1205	512	200	50	18
	ϕ , F+B	2.0	512	512	65	50	18

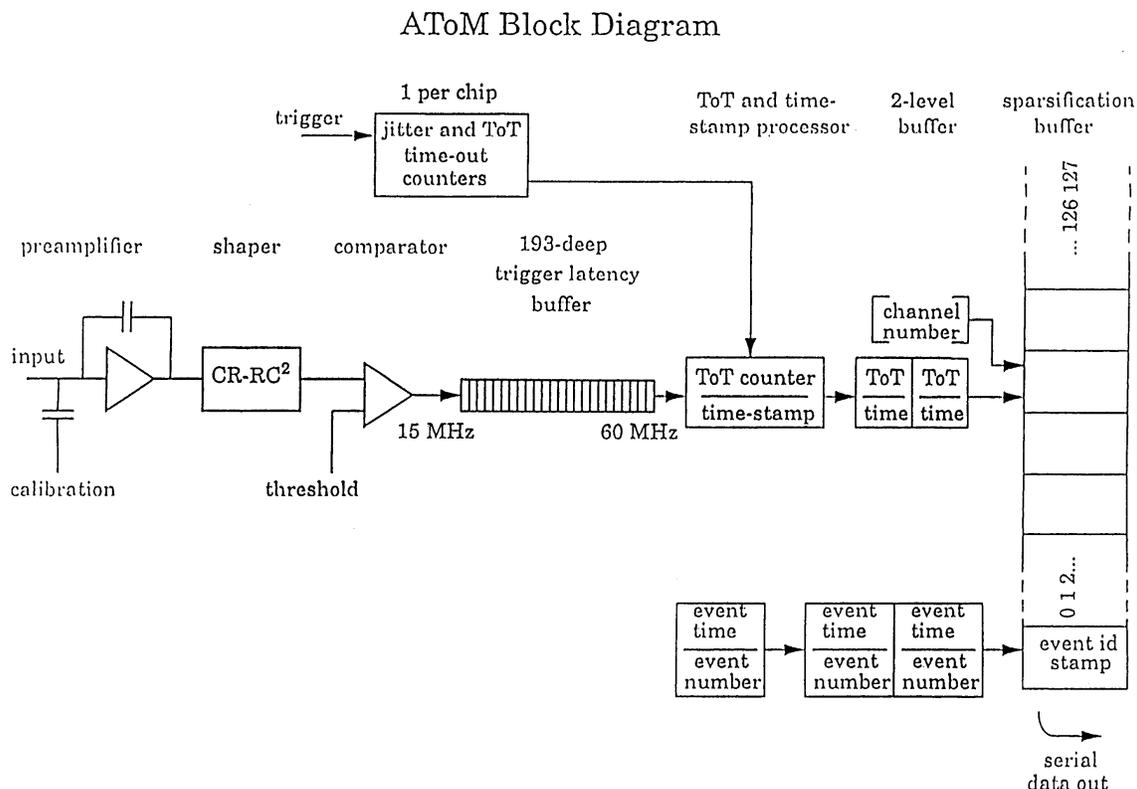
z -strips are connected at ends, to avoid cables in middle of detector.

Kapton connecting cables that connect multiple detector segments
(use $r\phi$ resolution to disentangle ambiguities)

Connections made along diagonals:



AToM – Readout IC for BaBar Vertex Detector (LBNL, Pavia, UCSC)



Preamplifier with continuous reset

CR-RC² shaper with selectable shaping times (100, 200 and 400 ns)

Outer layers of tracker have longer strips (higher capacitance) than inner layers. Lower occupancy allows use of longer shaping time to maintain electronic noise.

Coarse digitization via Time-Over-Threshold
(analog information for position interpolation only requires
3 – 4 bit resolution)

Measured noise (pre-production run) for 3 shaping times

100 ns:	$Q_n = 350 \text{ el} + 42 \text{ el/pF}$
200 ns:	$Q_n = 333 \text{ el} + 35 \text{ el/pF}$
400 ns:	$Q_n = 306 \text{ el} + 28 \text{ el/pF}$

4. Development of a Tracker Concept at the LHC

ATLAS Tracking detector for the LHC

LHC: Colliding proton beams
 7 TeV on 7 TeV (14 TeV center of mass)
 Luminosity: $10^{34} \text{ cm}^{-2}\text{s}^{-1}$
 Bunch crossing frequency: 40 MHz
 Interactions per bunch crossing: 23
 Charged particles per unit of rapidity: 150

$$\Rightarrow \text{hit rate} \quad n' = \frac{2 \cdot 10^9}{r_{\perp}^2} \left[\text{cm}^{-2}\text{s}^{-1} \right]$$

where r_{\perp} = distance from beam axis

If the detector subtends ± 2.5 units of rapidity,
 the total hit rate in the detector is $3 \cdot 10^{10} \text{ s}^{-1}$

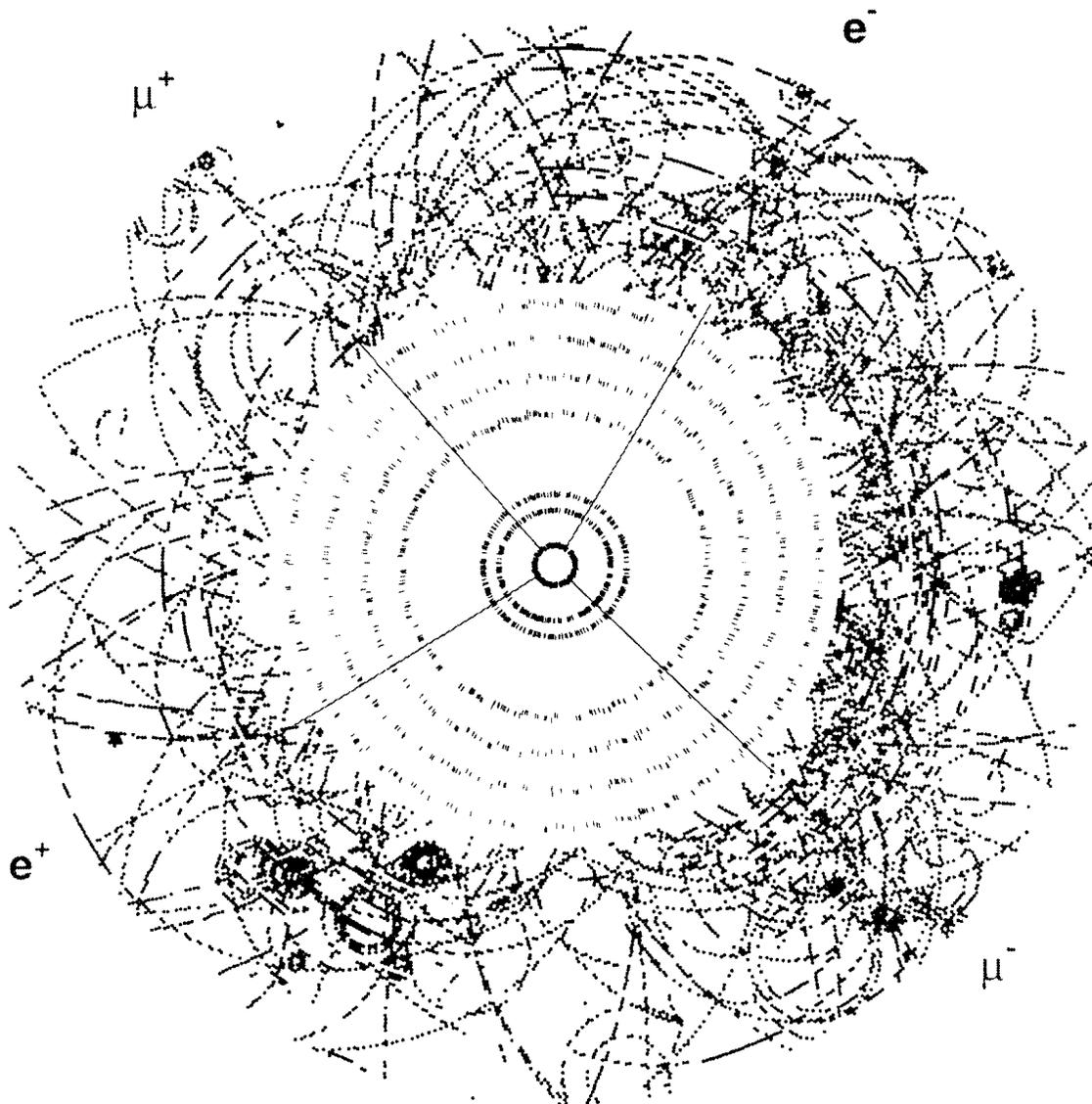
Hit rate at $r_{\perp} = 14 \text{ cm}$: $\sim 10^7 \text{ cm}^{-2}\text{s}^{-1}$

Overall detector to include

1. Vertexing for B-tagging
2. Precision tracking in 2T magnetic field
3. Calorimetry (EM + hadronic)
4. Muon detection

“Typical Event” – Axial View

$$H \rightarrow ZZ^* \rightarrow \mu^+ \mu^- e^+ e^- \quad (m_H = 130 \text{ GeV})$$



Appears worse than it is – tracks spread azimuthally, but high track density at forward angles.

Radiation Damage

Two sources of particles

- a) beam collisions
- b) neutron albedo from calorimeter

Fluences per year (equivalent 1 MeV neutrons)

r ~ 10 cm typ. $5 \cdot 10^{13} \text{ cm}^{-2}$

r ~ 30 cm typ. $2 \cdot 10^{13} \text{ cm}^{-2}$

Ionizing Dose per year

r ~ 10 cm 30 kGy (3 Mrad)

r ~ 30 cm 4 kGy (400 krad)

In reality, complex maps are required of the radiation flux, which is dependent on local material distribution.

How to cope with ...

- High total event rate
 - a) fast electronics
high power required for both noise and speed
 - b) segmentation
reduce rate per detector element

for example, at $r = 30$ cm the hit rate in an area of $5 \cdot 10^{-2} \text{ cm}^2$ is about 10^5 s^{-1} , corresponding to an average time between hits of $10 \mu\text{s}$.
 - P** longer shaping time allowable
 - P** lower power for given noise level
- Large number of events per crossing
 - a) fast electronics (high power)
 - b) segmentation
if a detector element is sufficiently small, the probability of two tracks passing through is negligible
 - c) single-bunch timing
reduce confusion by assigning hits to specific crossing times

P Segmentation is an efficient tool to cope with high rates.

With careful design, power requirements don't increase.

P Fine segmentation feasible with semiconductor detectors

- “ μm -scale” patterning of detectors
- monolithically integrated electronics mounted locally

Large number of front-end channels requires simple circuitry

Single bunch timing **P** collection times $< 25 \text{ ns}$

Radiation damage is a critical problem in semiconductor detectors:

a) detector leakage current

$$I_R = I_{R0} + a\Phi Ad$$

P shot noise

$$Q_{ni}^2 = 2q_e I_R F_i T_S$$

P self-heating of detector

reduce current by cooling

$$I_R(T) \propto T^2 e^{-E/2k_B T}$$

reduce shaping time

reduce area of detector element

b) Increase in depletion voltage

P thin detector

P allow for operation below full depletion

P less signal

Requires lower noise to maintain minimum S/N

P decrease area of detector element
(capacitance)

Note: gas-proportional chambers are also subject to radiation damage

plasma-assisted polymerization in avalanche region

P deposits on electrodes

Use of a highly-developed technology, i.e. Si rather than “exotic” materials, provides performance reserves and design flexibility to cope with radiation damage.

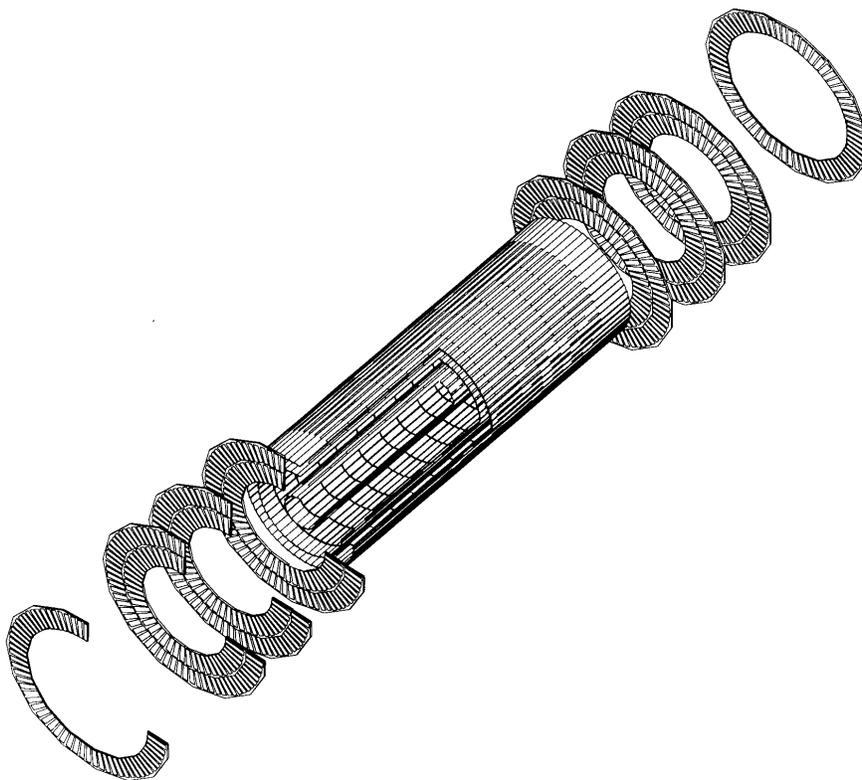
Layout

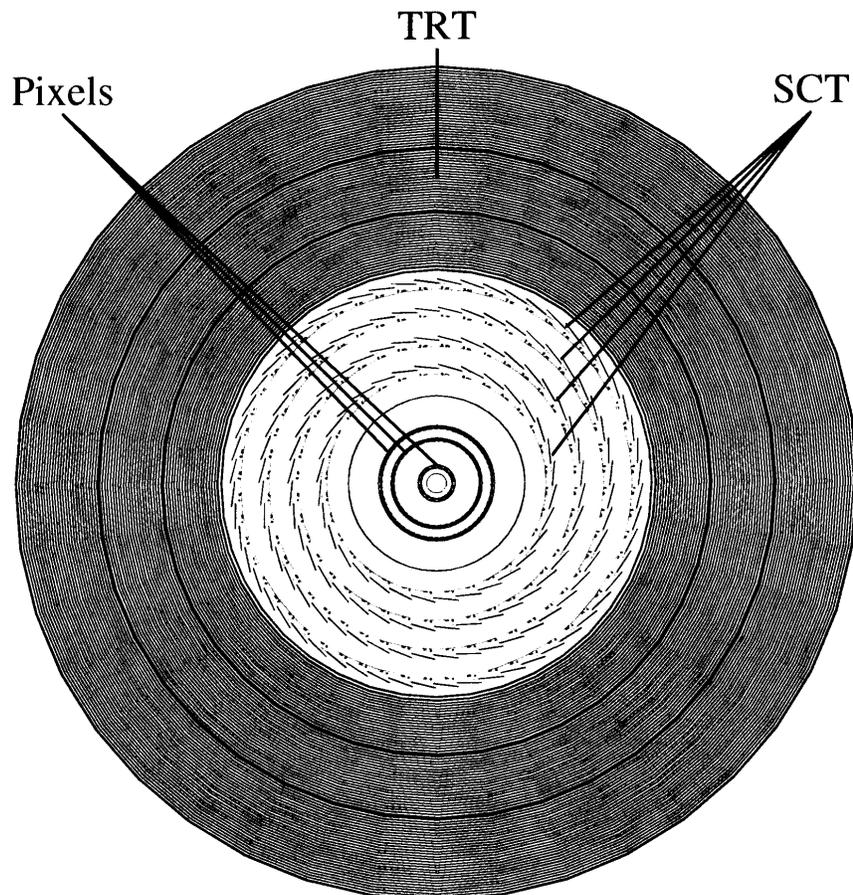
Full coverage provided by a combination of barrel and disk layers.

Coverage provided by

- a) barrel in central region
- b) disks in forward regions

to provide maximum coverage with minimum Si area.





Pixels at small radii (4, 11, 14 cm) to cope with

- high event rate (2D non-projective structure)
- radiation damage

small capacitance ~ 100 fF **P** low noise $Q_n \gg 100$ el

Strips at larger radii (30, 37, 45, 52 cm) - minimize material, cost

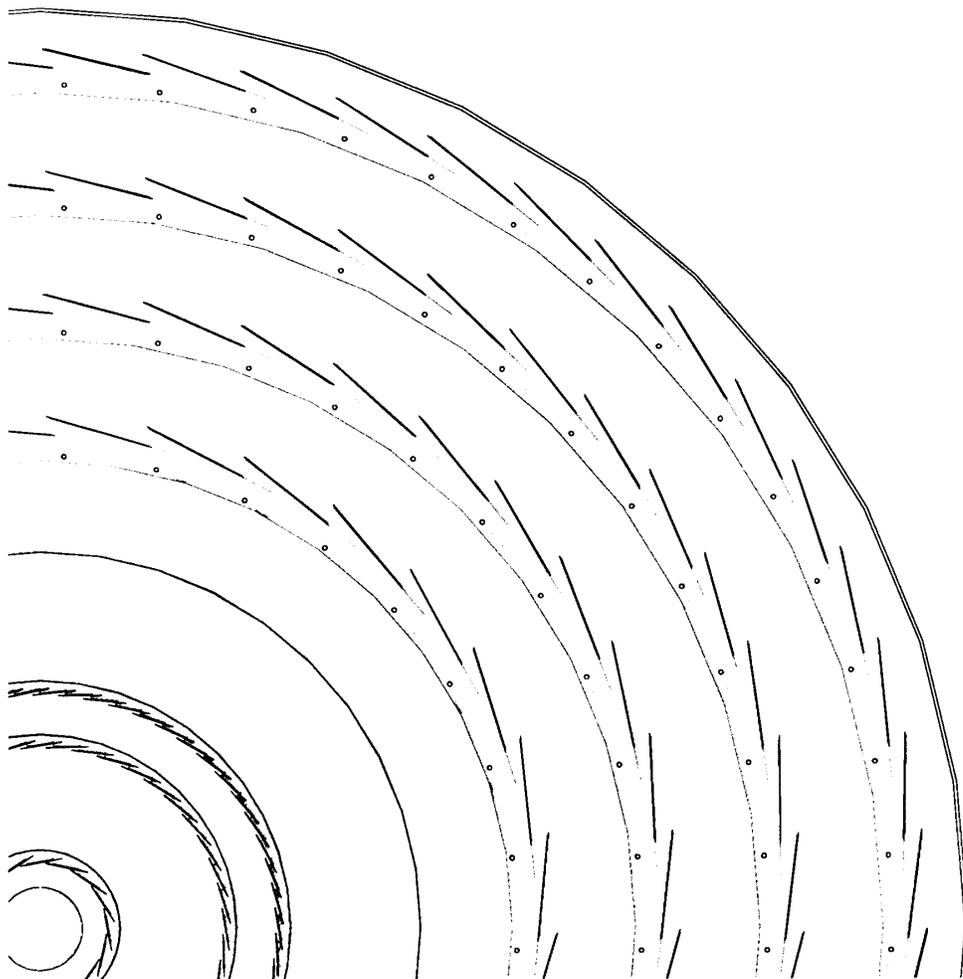
Pixels and strips provide primary pattern recognition capability

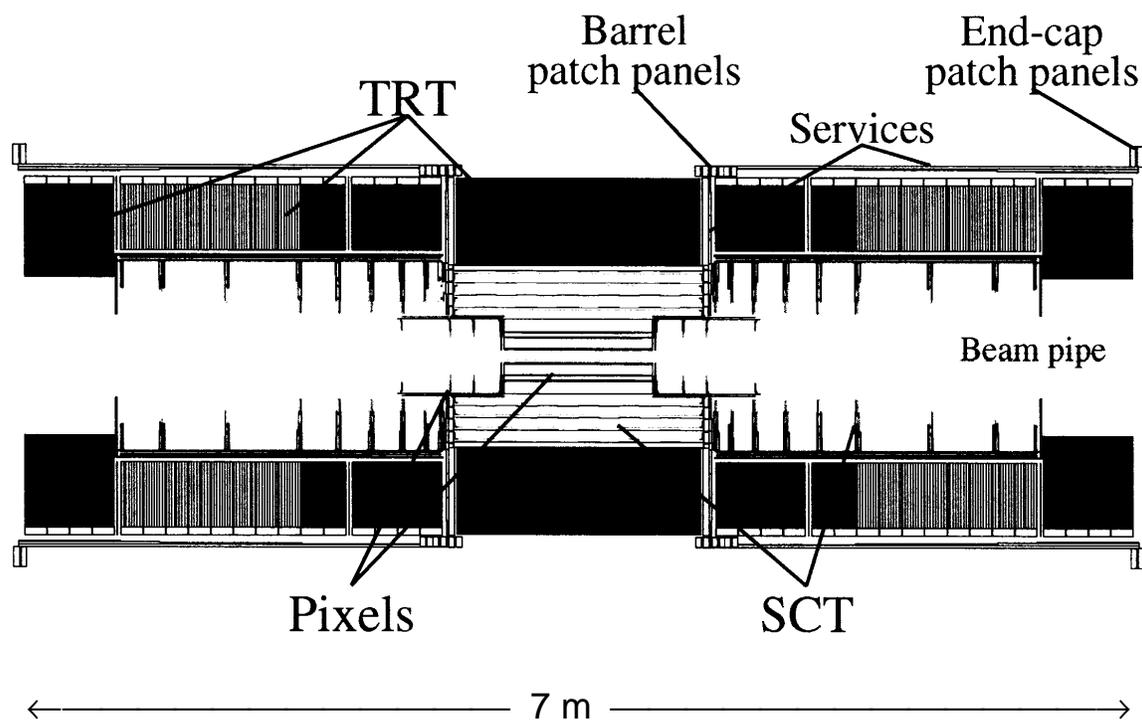
Straw drift chambers at outer radius (56 – 107 cm)

~ 70 layers yield 40 space points at large R and augment pattern recognition by continuous tracking (least expensive solution)

Detector modules arranged in cylindrical shells (barrels).

Modules will be “shingled” to provide full coverage and overlap to facilitate relative position calibration.





Strip modules use back-to-back single-sided detectors with small-angle stereo (40 mrad) to provide z -resolution with negligible “ghosting”.

Resolution provided by 3 detector types in barrel

	R_f	z
Pixels	12 μm	66 μm
Strips	16 μm	580 μm
Straws	170 μm	—

Segmentation **P** Large number of data channels

Total number of channels and area

Pixels	1.4×10^8 channels	2.3 m^2
Strips	6.2×10^6 channels	61 m^2
Straws	4.2×10^5 channels	

But, ...

only a small fraction of these channels are struck in a given crossing

Occupancy for pixels, $50 \mu\text{m} \times 300 \mu\text{m}$:

4 cm Pixel Layer	4.4×10^{-4}
11 cm Pixel Layer	0.6×10^{-4}

Occupancy for strip electrodes with $80 \mu\text{m}$ pitch, 12 cm length:

30 cm Strip Layer	6.1×10^{-3}
52 cm Strip Layer	3.4×10^{-3}

Utilize local sparsification – i.e. on-chip circuitry that recognizes the presence of a hit and only reads out those channels that are struck.

P data readout rate depends on hit rate, not on segmentation

First implemented in SVX chip

S.A. Kleinfelder, W.C. Carrithers, R.P. Ely, C. Haber, F. Kirsten, and H.G. Spieler, A Flexible 128 Channel Silicon Strip Detector Instrumentation Integrated Circuit with Sparse Data Readout, IEEE Trans. Nucl. Sci. **NS-35** (1988) 171

Readout

Strips + Pixels: many channels

Essential to minimize

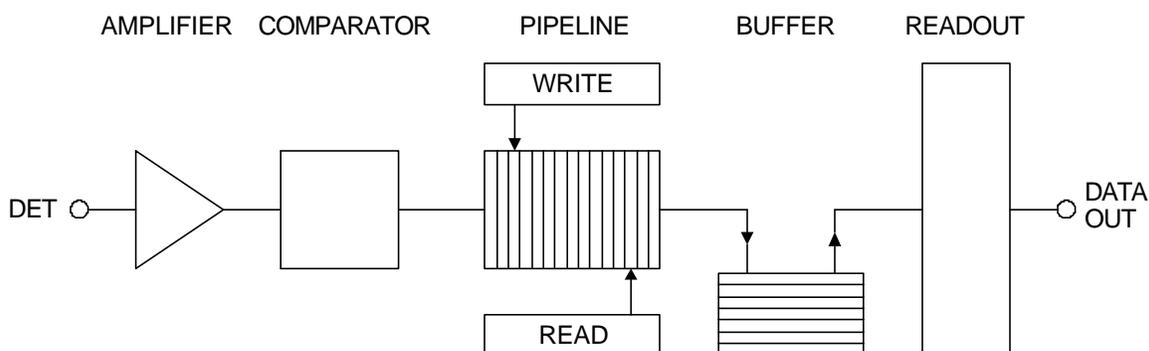
- power
- material (chip size, power cables, readout lines)
- cost (chip size)
- failure rate (use simple, well controlled circuitry)

Goal is to obtain adequate position resolution, rather than the best possible

P Binary Readout

- detect only presence of hits
- identify beam crossing

Architecture of ATLAS strip readout



Unlike LEP detectors ...

Crossing frequency \gg readout rate

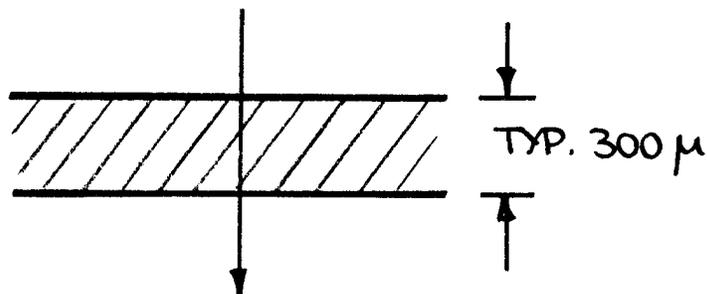
data readout must proceed simultaneously
with signal detection (equivalent to DC beam)

Single 128-channel BiCMOS chip (BJT + CMOS on same chip) in radiation-hard technology.

Required Signal-to-Noise Ratio

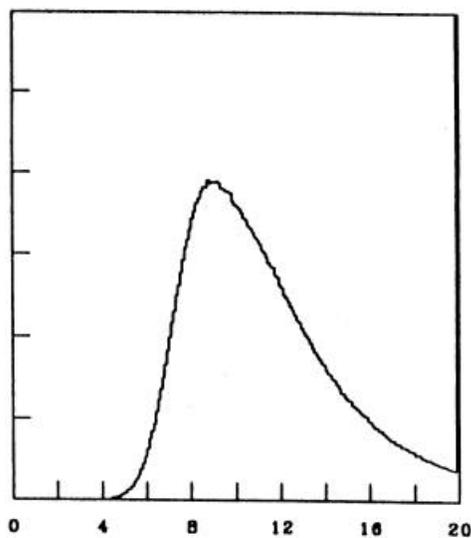
Acceptable noise level established by signal level and noise occupancy

1. Signal Level

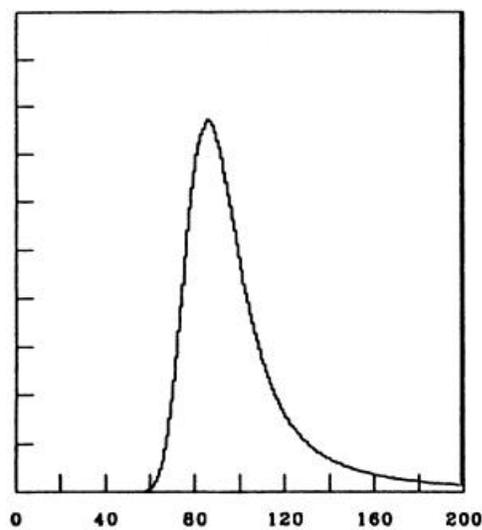


For minimum ionizing particles: $Q_s = 22000 \text{ el}$ (3.5 fC)

Signals vary event-by-event according to Landau distribution
(calculation by G. Lynch)



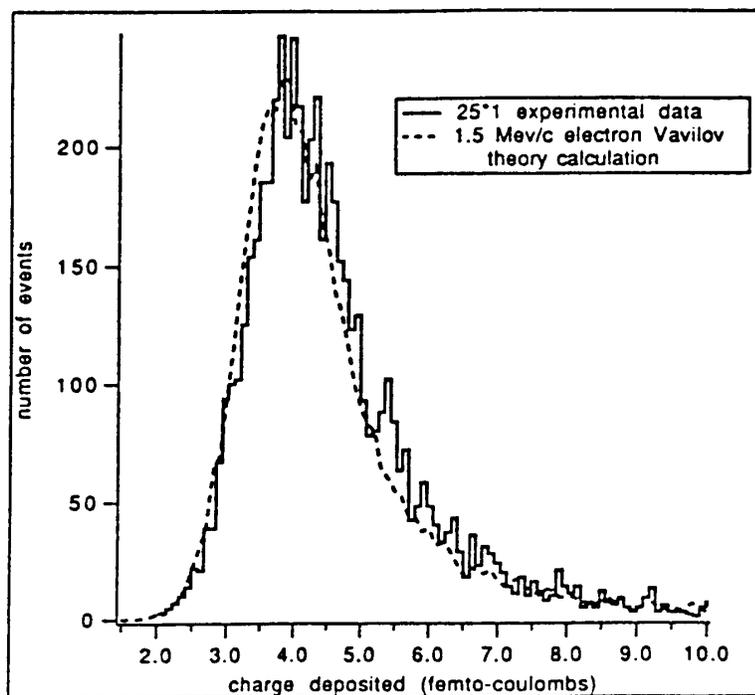
Si : 40 μm thick



Si : 300 μm thick

Relative width of distribution decreases with increasing energy loss.

Measured Landau distribution in a 300 μm thick Si detector
(Wood et al., Univ. Oklahoma)



The Landau distribution peaks at the most probable energy loss Q_0 and extends down to about $0.5 Q_0$ for 99% efficiency.

Assume that the minimum energy is $f_L Q_0$.

Tracks passing between two strips will deposit charge on both strips. If the fraction of the signal to be detected is f_{sh} , the circuit must be sensitive signal as low as

$$Q_{\min} = f_{sh} f_L Q_0$$

2. Threshold Setting

It would be desirable to set the threshold much lower than Q_{min} , to be insensitive to threshold variations across the chip.

A lower limit is set by the need to suppress the noise rate to an acceptable level that still allows efficient pattern recognition.

As discussed in an Appendix, the threshold-to-noise ratio required for a desired noise rate f_n in a system with shaping time T_S is

$$\frac{Q_T}{Q_n} = \sqrt{-2 \log(4\sqrt{3}f_n T_S)}$$

Expressed in terms of occupancy P_n in a time interval Δt

$$\frac{Q_T}{Q_n} = \sqrt{-2 \log\left(4\sqrt{3}T_S \frac{P_n}{\Delta t}\right)}$$

In the strip system the average hit occupancy is about 5×10^{-3} in a time interval of 25 ns. If we allow an occupancy of 10^{-3} at a shaping time of 20 ns, this corresponds to

$$\frac{Q_T}{Q_n} = 3.2$$

The threshold uniformity is not perfect. The relevant measure is the threshold uniformity referred to the noise level. For a threshold variation ΔQ_T , the required threshold-to-noise ratio becomes

$$\frac{Q_T}{Q_n} = \sqrt{-2 \log\left(4\sqrt{3}T_S \frac{P_n}{\Delta t}\right)} + \frac{\Delta Q_T}{Q_n}$$

If $\Delta Q_T/Q_n = 0.5$, the required threshold-to-noise ratio becomes $Q_T/Q_n = 3.7$.

To maintain good timing, the signal must be above threshold by at least Q_n , so $Q_T/Q_n > 4.7$.

Combining the conditions for the threshold

$$\left(\frac{Q_T}{Q_n}\right)_{\min} Q_n \leq Q_{\min}$$

and signal

$$Q_{\min} = f_{sh} f_L Q_0$$

yields the required noise level

$$Q_n \leq \frac{f_{sh} f_L Q_0}{(Q_T / Q_n)_{\min}}$$

If charge sharing is negligible $f_{sh} = 1$, so with $f_L = 0.5$, $Q_0 = 3.5$ fC and $(Q_T / Q_n)_{\min} = 4.7$

$$Q_n \leq 0.37 \text{ fC} \quad \text{or} \quad Q_n \leq 2300 \text{ el}$$

If the system is to operate with optimum position resolution, i.e. equal probability of 1- and 2-hit clusters, then $f_{sh} = 0.5$ and

$$Q_n \leq 0.19 \text{ fC} \quad \text{or} \quad Q_n \leq 1150 \text{ el}$$

ATLAS requires $Q_n \leq 1500 \text{ el}$.

Prototype Results

ATLAS has adopted a single chip implementation (ABCD chip).

- 128 ch, bondable to 50 μm strip pitch
- bipolar transistor technology, rad-hard
 - **P** minimum noise independent of shaping time
- peaking time: ~ 20 ns (equivalent CR-RC⁴)
- double-pulse resolution (4 fC – 4 fC): 50 ns
- noise, timing: following slides
- 1.3 to 1.8 mW/ch (current in input transistor adjustable)
- on-chip DACs to control threshold + operating point
- Trim DACs on each channel to reduce channel-to-channel gain and threshold non-uniformity
- Readout allows defective chips to be bypassed
- Optical fiber readout with redundancy
- die size: 6.4 x 4.5 mm²

For illustration, the following slides show data from a previous prototype IC, the CAFE chip

This was part of an initial 2-chip implementation (BJT analog chip and CMOS digital chip)

ICs now in production with similar results.

CAFE Timing Performance

1. Chips from run 1 measured on test boards

- **irradiated to 10^{14} cm^{-2} (MIP equiv)**

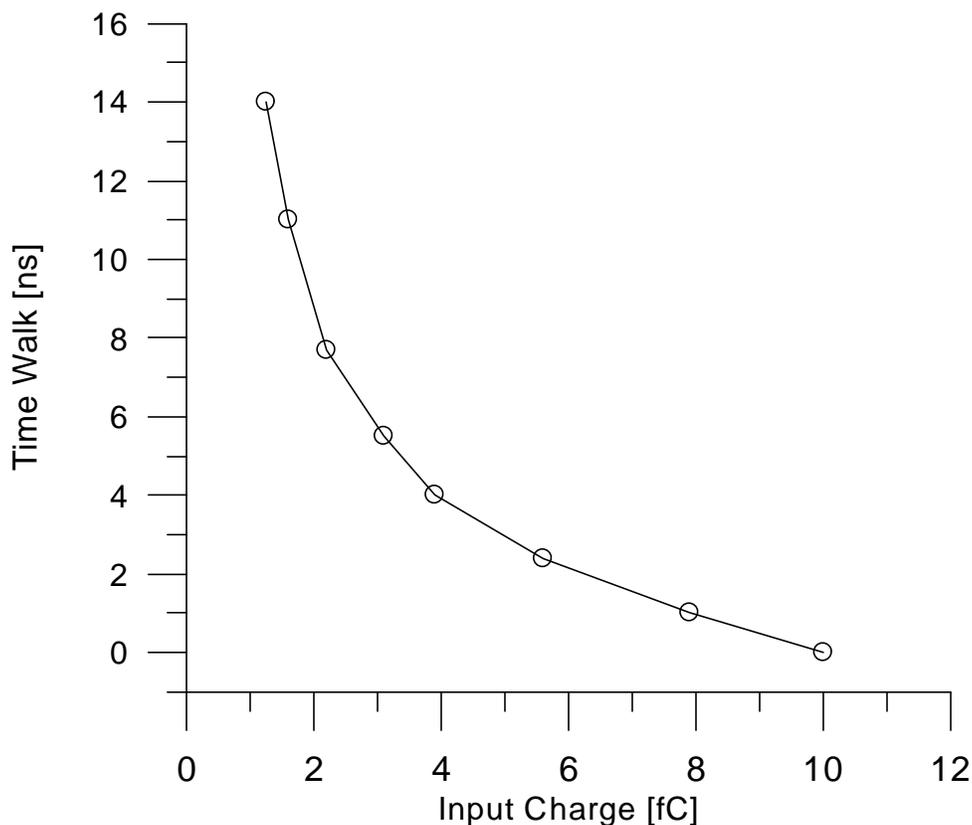
Time Walk 16 ns (1.25 - 10 fC) at 1 fC threshold
 1.25 - 4 fC: 12 ns
 4 fC - 10 fC: 4 ns

Jitter at 1.25 fC \approx 4 ns FWHM

Total time distribution (99% efficiency)
 confined within about 18 ns.

2. Chips from Run 2 measured on test boards (pre-rad)

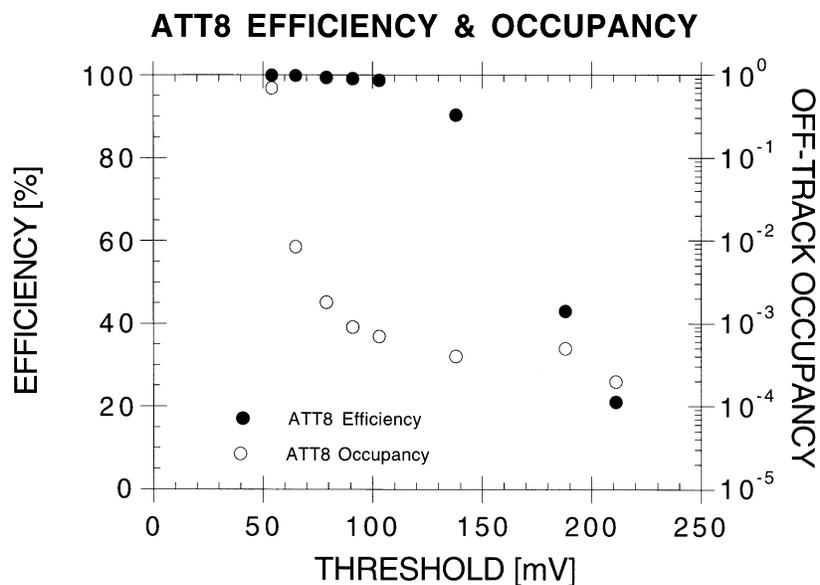
$C_{\text{load}} = 15 \text{ pF}$, 1 fC threshold, jitter as above



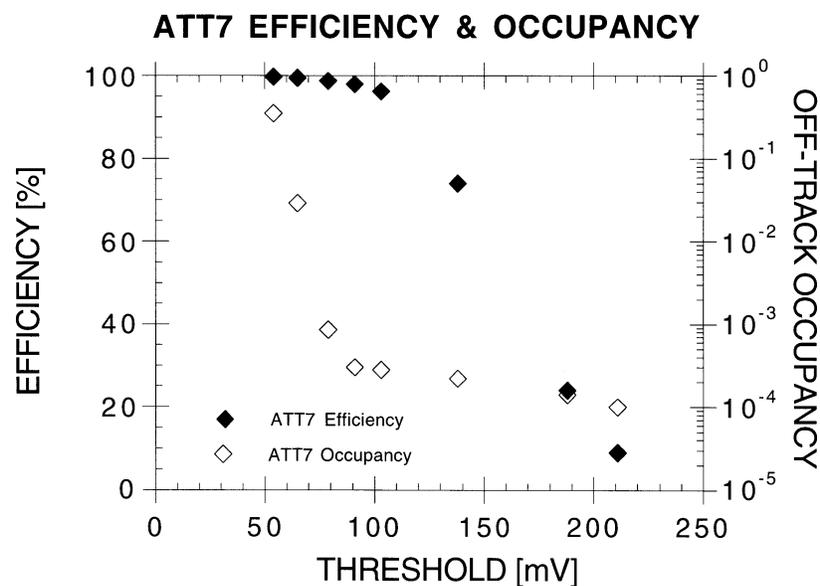
Test Beam Data

Tracking Efficiency vs. Occupancy for Full-Length Modules

non-irradiated module

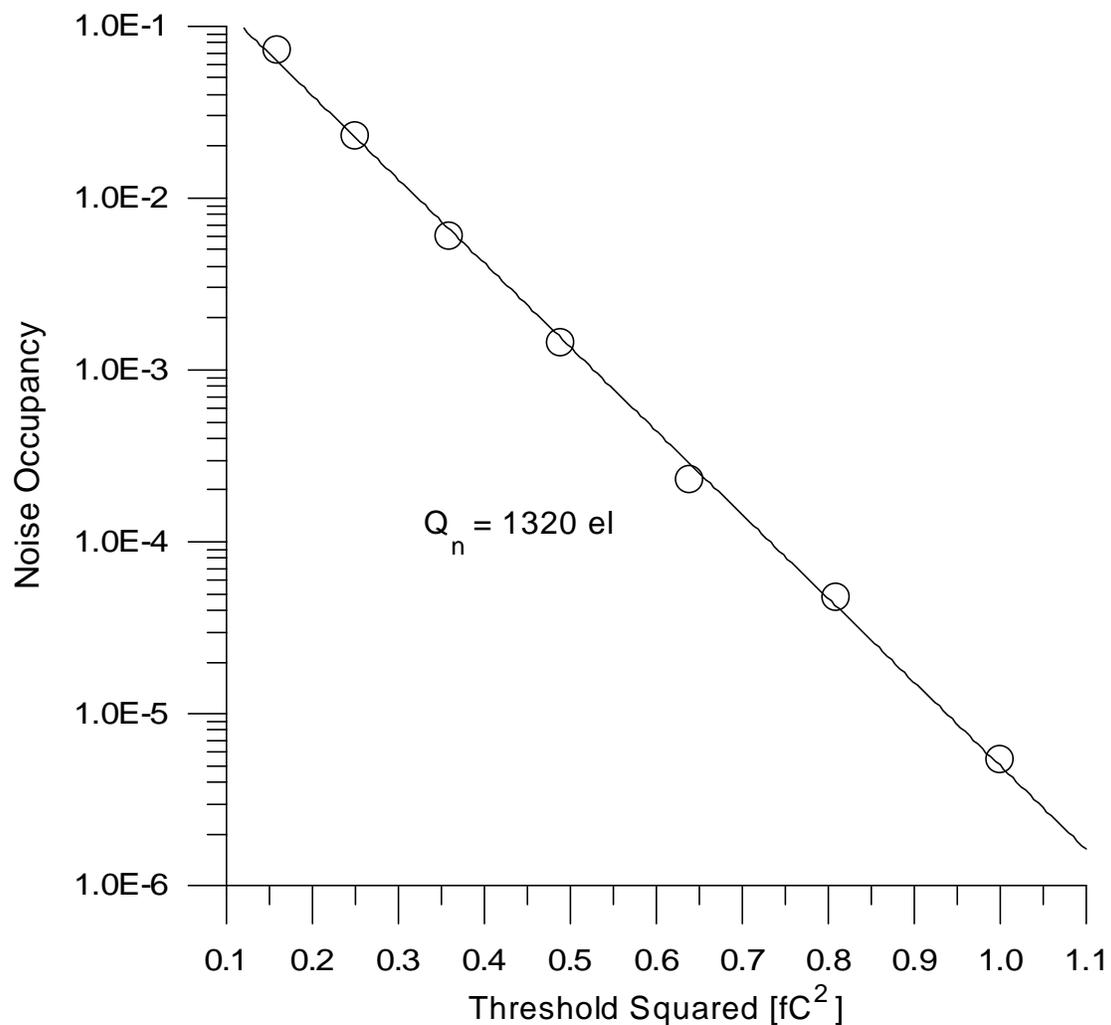


irradiated module ($\Phi = 10^{14} \text{ cm}^{-2}$)



Noise Occupancy vs. Threshold

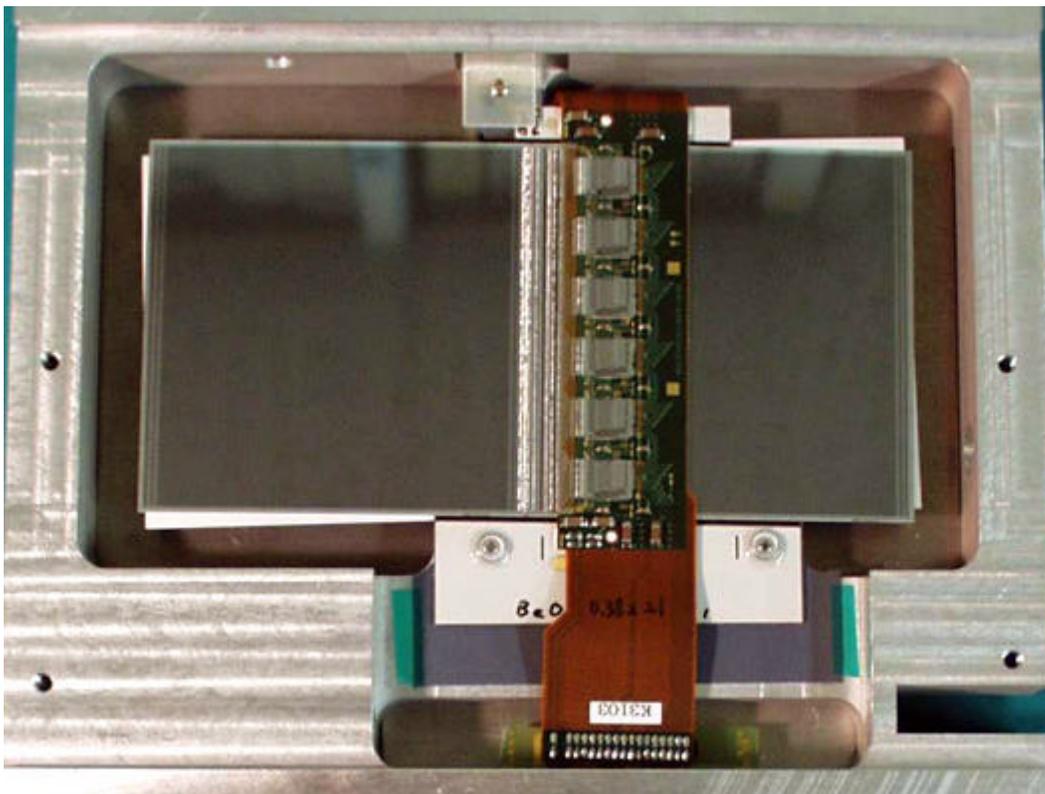
Module with CAFE chip in test beam position at KEK



Baseline fluctuations, digital cross-talk

P deviations from straight line plot
(gaussian noise)

ATLAS Silicon Strip Detector Module (mounted in fabrication fixture)



Two $6 \times 6 \text{ cm}^2$ single-sided Si strip detectors butted edge-to-edge to form 12 cm long detector

Two $6 \times 12 \text{ cm}^2$ detectors glued back-to-back and rotated to one another by 40 mrad to form small-angle stereo

Readout ICs – 128 channels each – mounted on detectors and connected at middle.

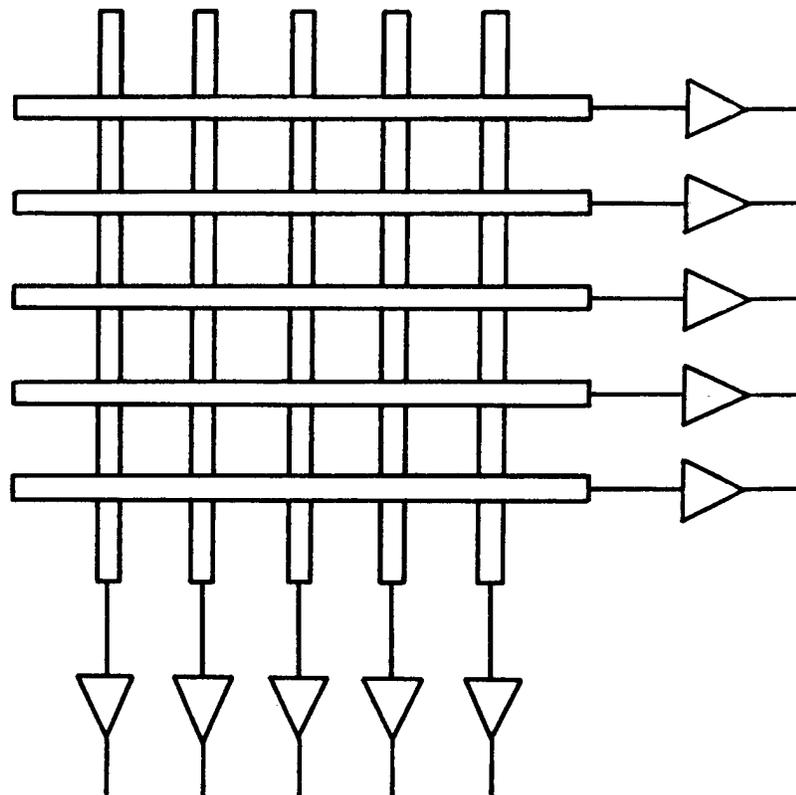
Strip pitch: $80 \mu\text{m}$
no. of channels: 2×768

Binary readout with on-chip pipeline and readout sparsification

Kapton pigtail connects to local opto-module for clock, control, data transmission

Two-Dimensional Detectors

Example: Crossed strips on opposite sides of Si wafer



n readout channels **P** n^2 resolution elements

Problem: ambiguities with multiple hits

n hits in acceptance field **P** n x -coordinates
 n y -coordinates

P n^2 combinations

of which
 $n^2 - n$ are “ghosts”

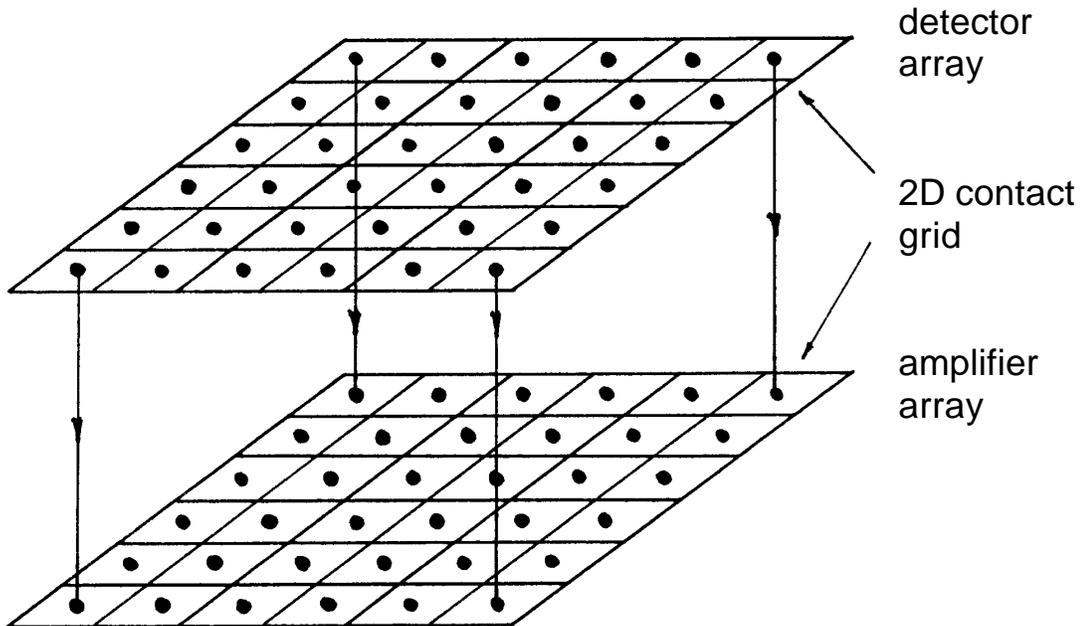
ATLAS strips reduce ambiguities by using small angle stereo (40 mrad).

Not sufficient at small radii – need non-projective 2D detector

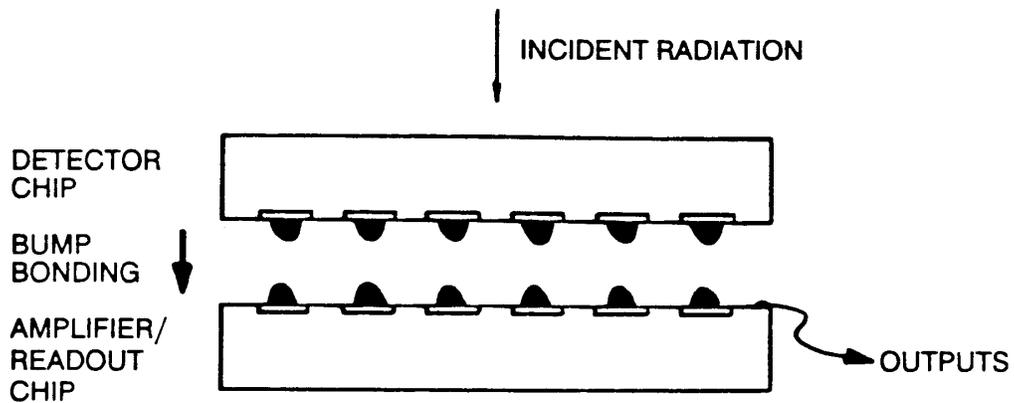
Pixel Detectors with Random Access Readout

Amplifier per pixel

Address + signal lines read out individually addressed,
i.e. single, pixels

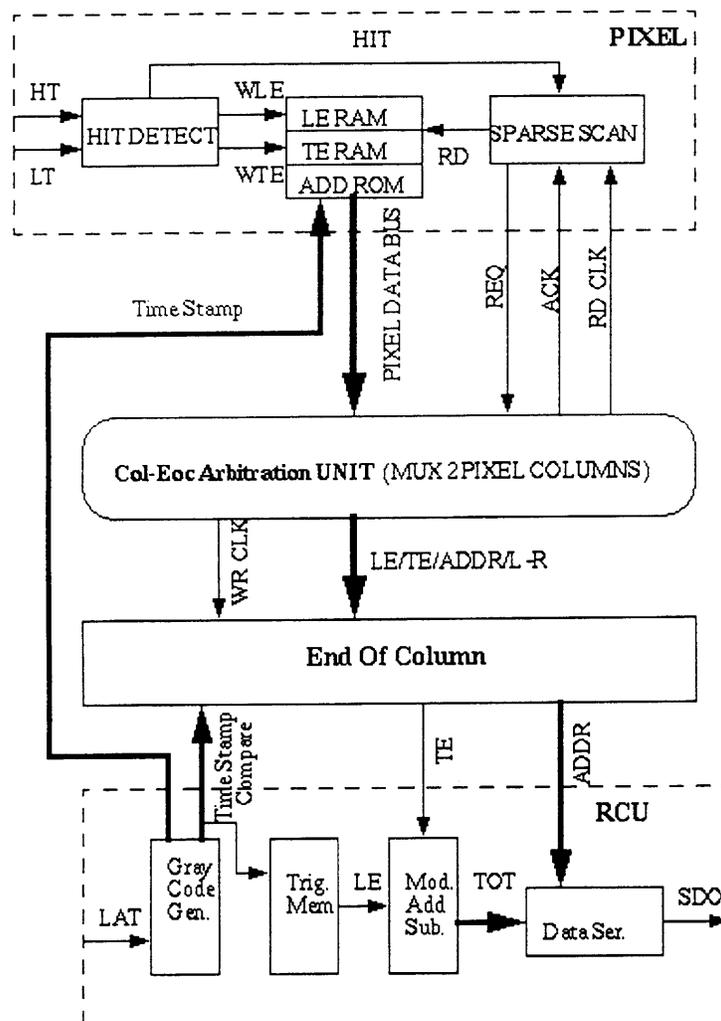


2D contact via "bump bonds"



ATLAS Pixel System

Fast Pixel Readout for ATLAS

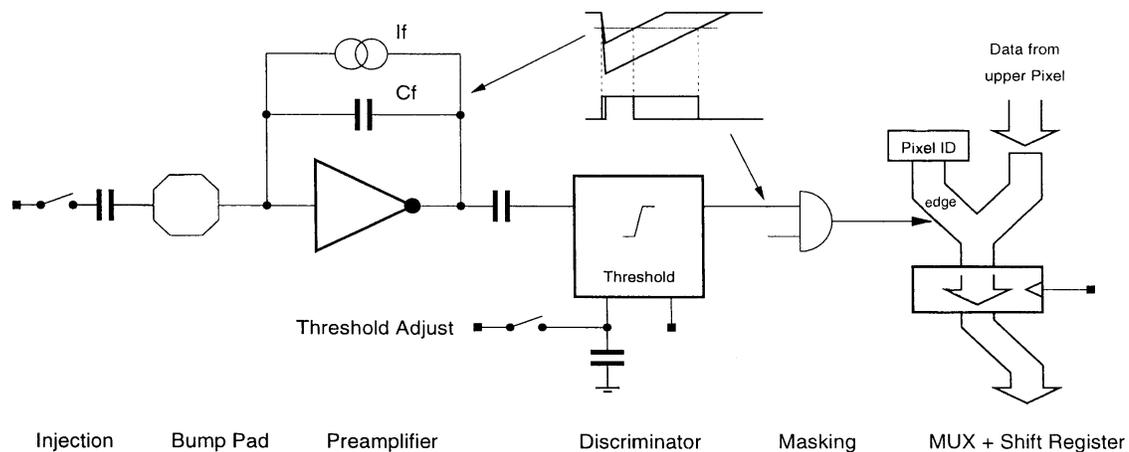


Quiescent state: no clocks or switching in pixel array

When pixel is struck: pixel address is sent to column buffer at chip periphery and time stamped

Receipt of trigger: check to see which addresses are in selected time bin and selectively read out pixels.

Block Diagram of Pixel Cell



Linear discharge of preamplifier feedback capacitor provides linear time-over-threshold digitization for readout of analog information.

Pixel size: $50 \mu\text{m} \times 400 \mu\text{m}$

Power per pixel: $< 40 \mu\text{W}$

Final chip: 24 columns x 160 pixels (3840 pixels)

Module size: $16.4 \times 60.4 \text{ mm}^2$

16 front-end chips per module

61440 pixels per module

fabricated in $0.25 \mu\text{m}$ CMOS

$\sim 2.5 \cdot 10^6$ transistors

functional to $> 100 \text{ Mrad}$

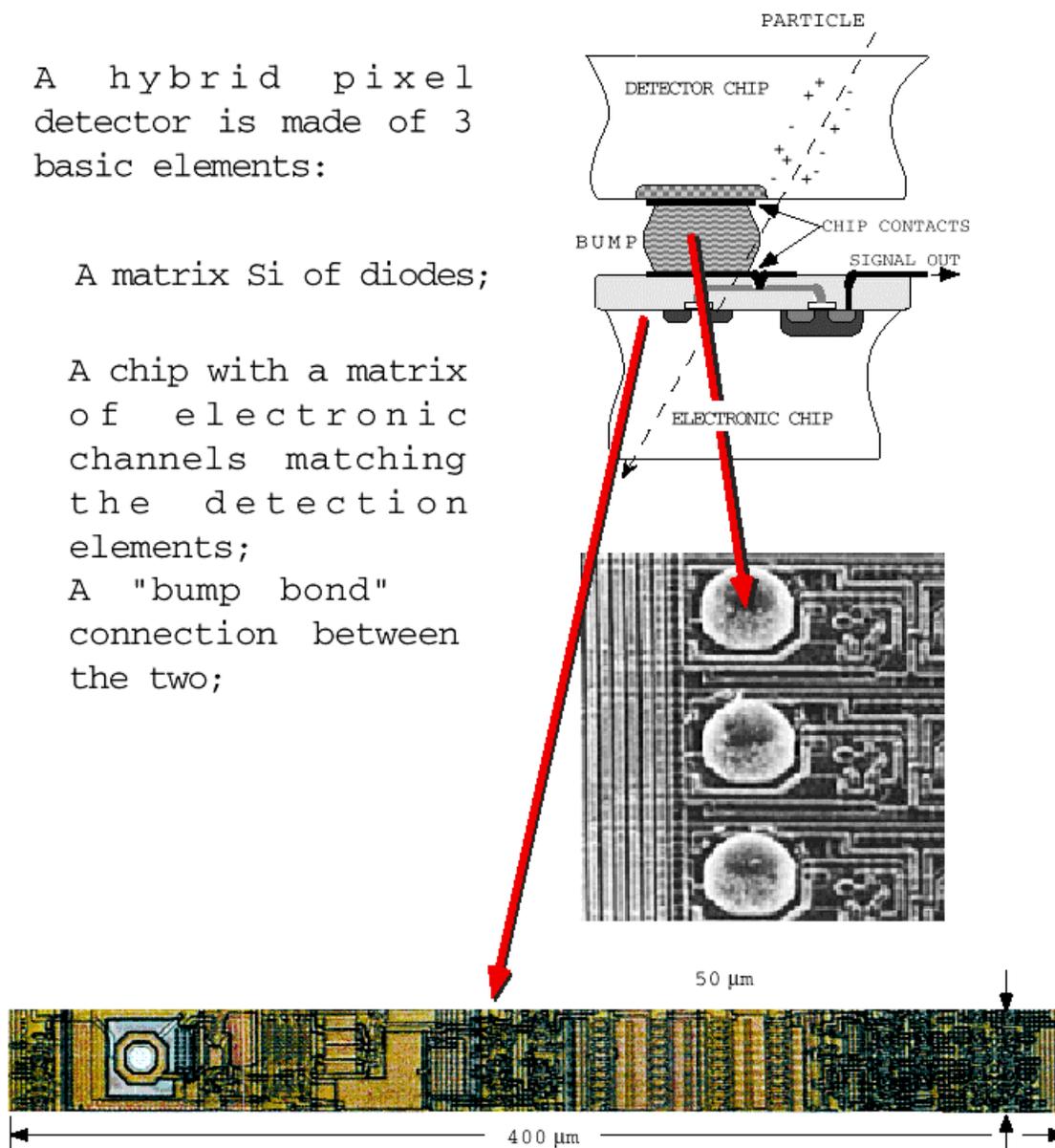
Detail of bump bonding with layout of single pixel

A hybrid pixel detector is made of 3 basic elements:

A matrix Si of diodes;

A chip with a matrix of electronic channels matching the detection elements;

A "bump bond" connection between the two;



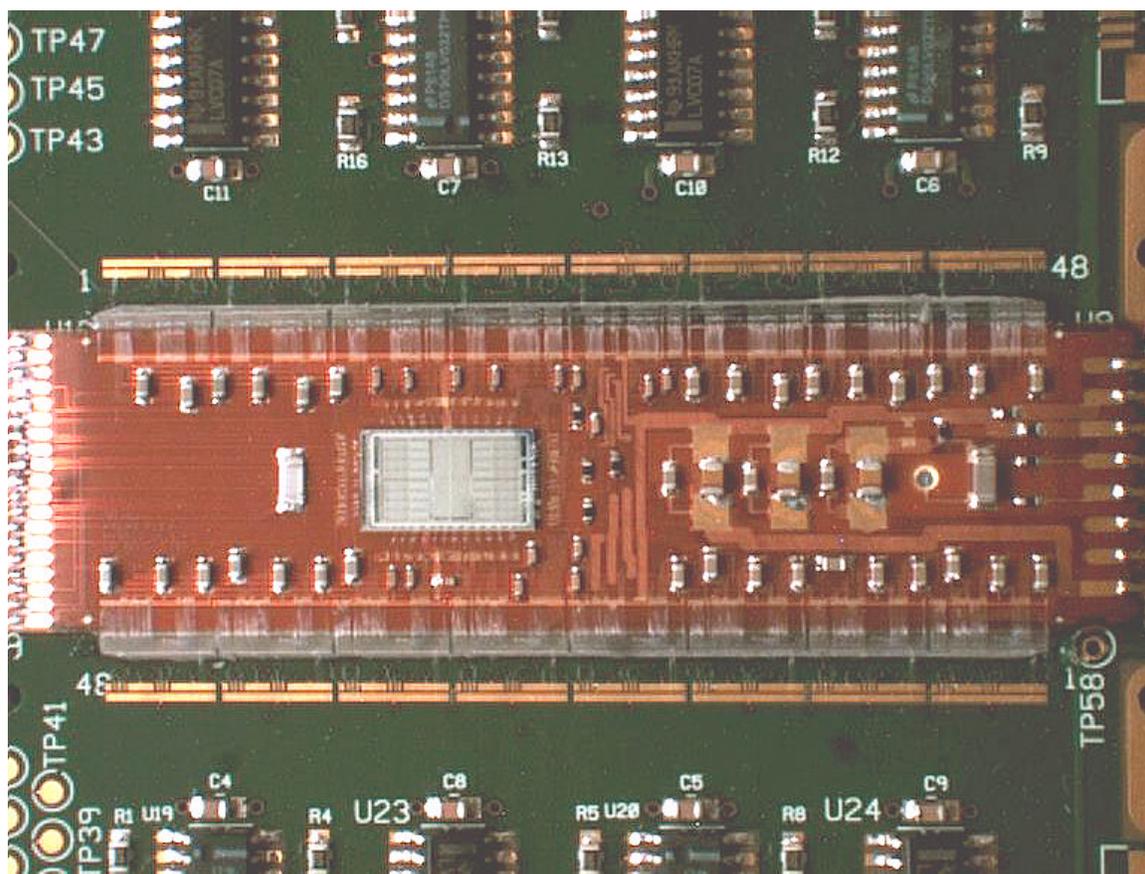
Chips have all control and output pads on one side, so that they can be butted together to form a 2 x 8 chip array

Chips are mounted on sensor, which also serves as an interconnect substrate.

A kapton flex hybrid is mounted on the sensor and connected with wire-bonds.

The flex hybrid includes bypass capacitors, the output driver and connections to the readout bus.

Test module mounted on PC board for test



Low-power comparators tend to have large threshold dispersion across IC.

Thresholds also change with radiation damage.

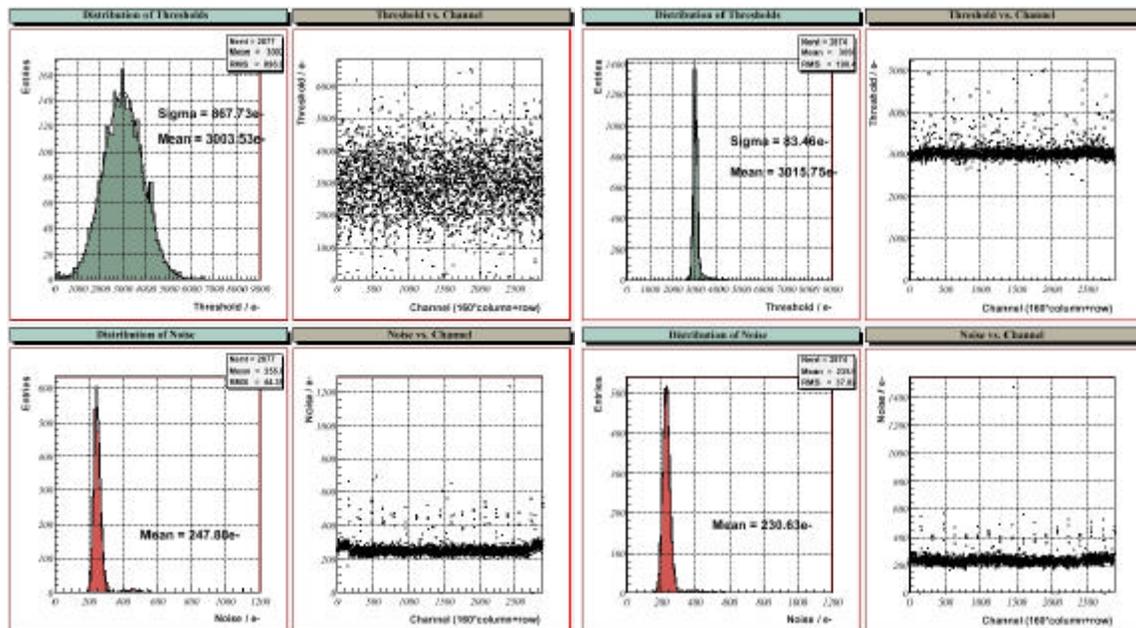
Use main DAC for threshold setting and trim DACs on each pixel to correct for individual threshold variations.

Thresholds are trimmed pixel by pixel to maintain uniformity after radiation damage (software, automated).

Noise and threshold across IC

Before Trimming

After Trimming



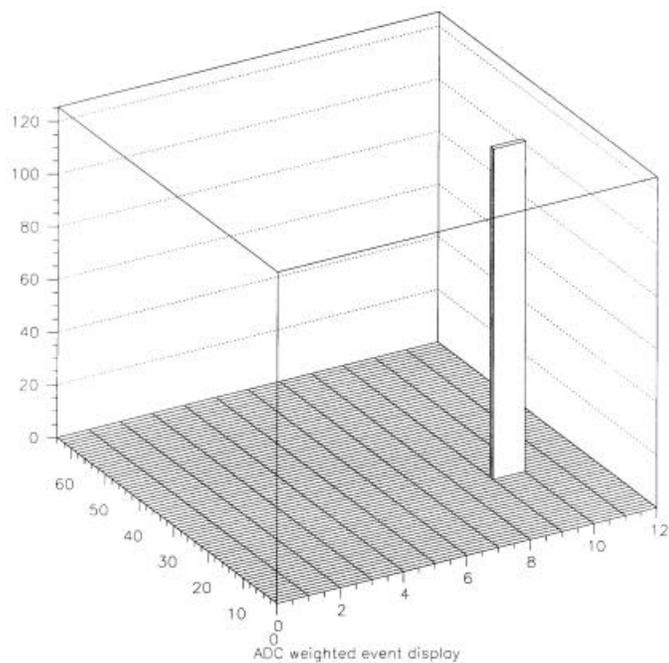
After trimming

Threshold dispersion: 85 e rms

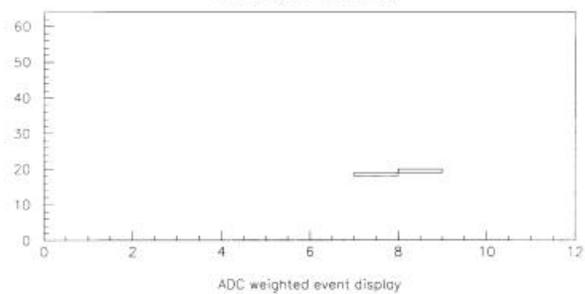
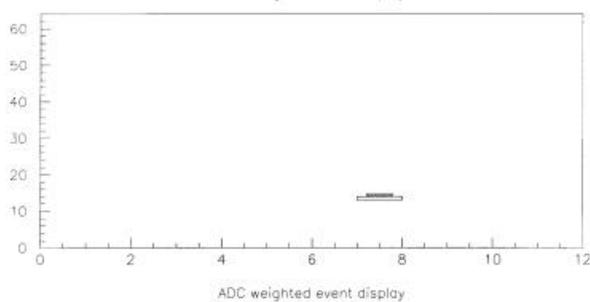
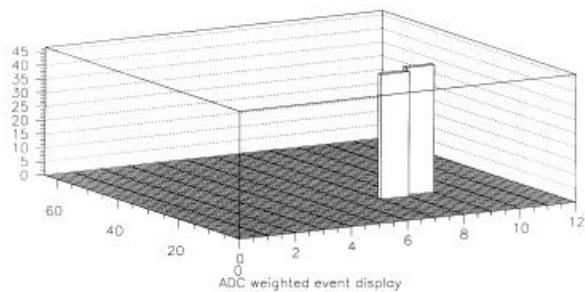
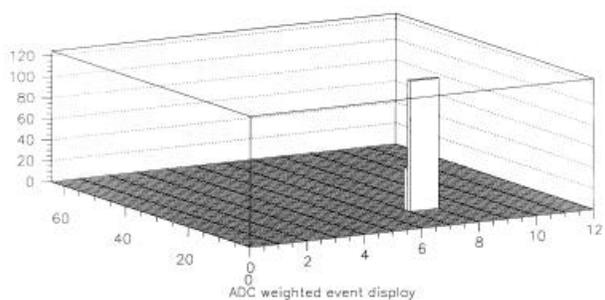
Noise: 230 e rms

Test Beam Results

Track through single pixel



Charge sharing



Advantages of pixels at LHC

2D segmentation

P Pattern recognition at small radii

Low capacitance

P high S/N

P allows degradation of both detector signal and electronic noise due to radiation damage

small detector elements

P detector bias current per element still small after radiation damage

Drawback:

Engineering complexity order of magnitude greater than previous chips

Questions

What is the ultimate limit of radiation resistance?

detectors

oxygenation extends Si detector lifetime

limits of Si?

other materials? diamond, SiC?

cryogenic operation?

electronics

CMOS beyond 100 Mrad?

0.25 mm CMOS demonstrated to >70 Mrad

cryogenic operation?