Development of a Tracker Concept

Tracking detector for the LHC

Builds on work begun in 1983 for the SSC

LHC: Colliding proton beams
7 TeV on 7 TeV (14 TeV center of mass)

Luminosity: 10^{34} cm^{-2}s^{-1}

Bunch crossing frequency: 40 MHz

Interactions per bunch crossing: 23

Charged particles per unit of rapidity: 150

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

where $r_\perp$ = distance from beam axis

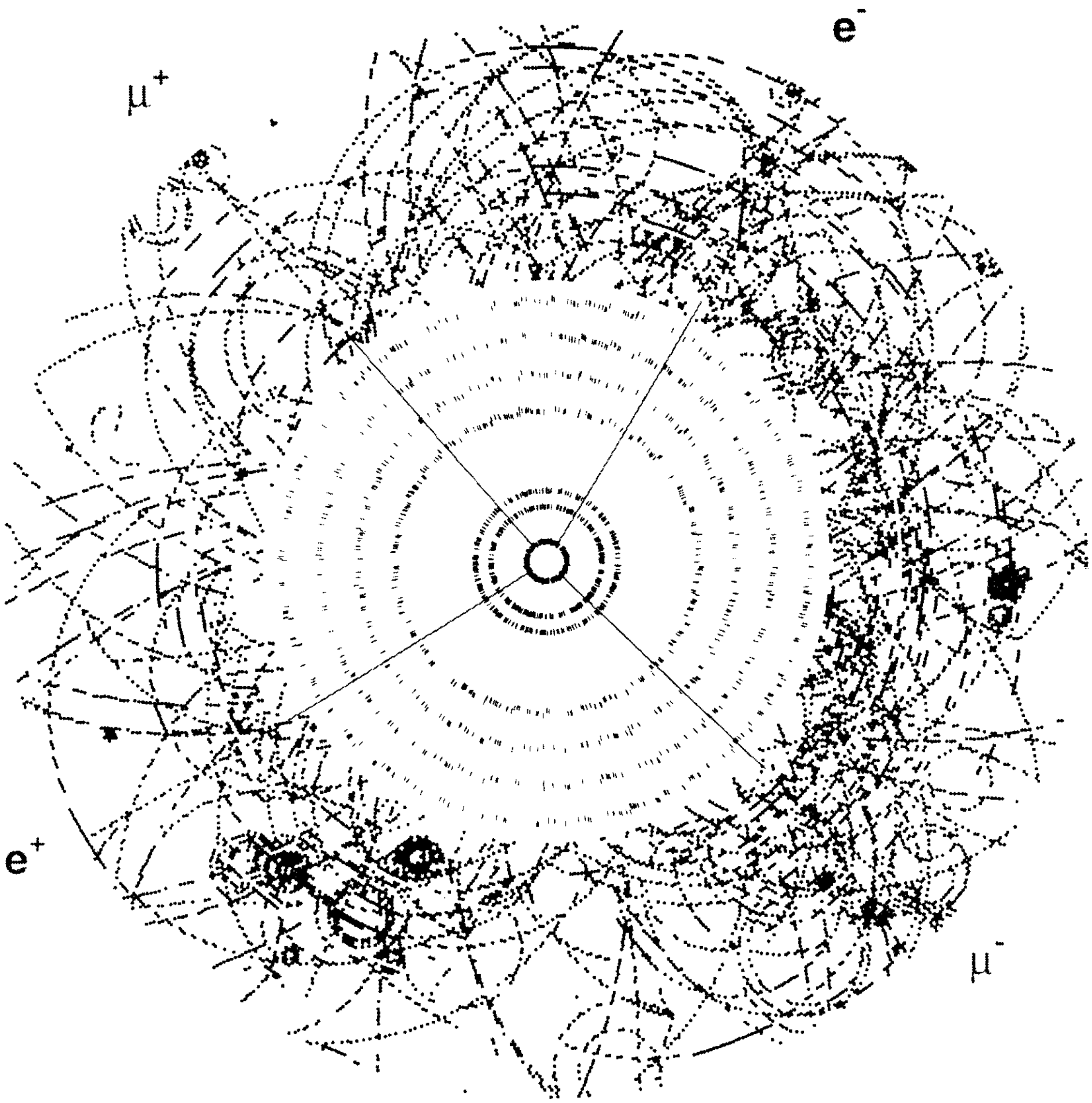
If the detector subtends ±2.5 units of rapidity,
the total hit rate in the detector is $3 \cdot 10^{10}$ s^{-1}

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”

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



Azimuthal projection (along beam axis)

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. $5 \cdot 10^{13}$ cm^{-2}
r ~ 30 cm	typ. $2 \cdot 10^{13}$ 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.

Impact parameter resolution

$$\sigma_b^2 \approx \left(\frac{\sigma_1 r_2}{r_2 - r_1}\right)^2 + \left(\frac{\sigma_2 r_1}{r_2 - r_1}\right)^2 = \left(\frac{\sigma_1}{1 - r_1/r_2}\right)^2 + \left(\frac{\sigma_2}{r_2/r_1 - 1}\right)^2$$

$\Rightarrow$ a) the ratio of outer to inner radius should be large

b) the resolution of the inner layer σ_1 sets a lower bound on the overall resolution

c) the acceptable resolution of the outer layer scales with r_2/r_1.

If the layers have equal resolution $\sigma_1 = \sigma_2 = \sigma$

$$\left(\frac{\sigma_b}{\sigma}\right)^2 \approx \left(\frac{1}{1 - r_1/r_2}\right)^2 + \left(\frac{1}{r_2/r_1 - 1}\right)^2$$

The geometrical impact parameter resolution is determined by the ratio of the outer to inner radius.

The obtainable impact parameter resolution decreases rapidly from

σ_b/σ = 7.8 at r_2/r_1=1.2 to
σ_b/σ = 2.2 at r_2/r_1= 2 and
σ_b/σ < 1.3 at r_2/r_1 > 5.

For σ = 10 μm and $r_2/r_1 \approx 2$: $\sigma_b \approx$ 20 μm.

Similar conclusions apply for the momentum resolution.

The inner radius is limited by the beam pipe, typically r = 5 cm.

At the high luminosity of the LHC radiation damage is a serious concern, which tends to drive the inner layer to greater radii.

Amount of material and its distribution is critical:

Small angle scattering

$$\Theta_{rms} = \frac{0.0136\,[GeV/c]}{p_\perp} \sqrt{\frac{x}{X_0}} \left[1 + 0.038 \cdot \ln\left(\frac{x}{X_0} \right) \right]$$

Assume a Be beam pipe of x= 1 mm thickness and R= 5 cm radius.

The radiation length of Be is X_0= 35.3 cm, so that $x/X_0 = 2.8 \cdot 10^{-3}$ and at $p_\perp$= 1 GeV/c the scattering angle Θ_{rms}= 0.56 mrad.

This corresponds to $\sigma_b = R\Theta_{rms}$= 28 μm, which exceeds the impact parameter resolution.

Scattering originating at small radii is more serious, so it is important to limit material especially at small radii.

For comparison: 300 μm of Si $\rightarrow$ 0.3% X_0

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 $5 \cdot 10^{-2}$ cm^2 is about 10^5 s^{-1}, corresponding to an average time between hits of 10 μs.

  ⇒ longer shaping time allowable

  ⇒ 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

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

With careful design, power requirements don't increase.

⇒ 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 ⇒ collection times <25 ns

Radiation damage is a critical problem in semiconductor detectors:

a) detector leakage current

$$I_R = I_{R0} + \alpha \Phi A d$$

$\Rightarrow$ shot noise

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

$\Rightarrow$ 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

$\Rightarrow$ thin detector

$\Rightarrow$ allow for operation below full depletion

$\Rightarrow$ less signal

Requires lower noise to maintain minimum S/N

$\Rightarrow$ decrease area of detector element (capacitance)

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

plasma-assisted polymerization in avalanche region

$\Rightarrow$ 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.

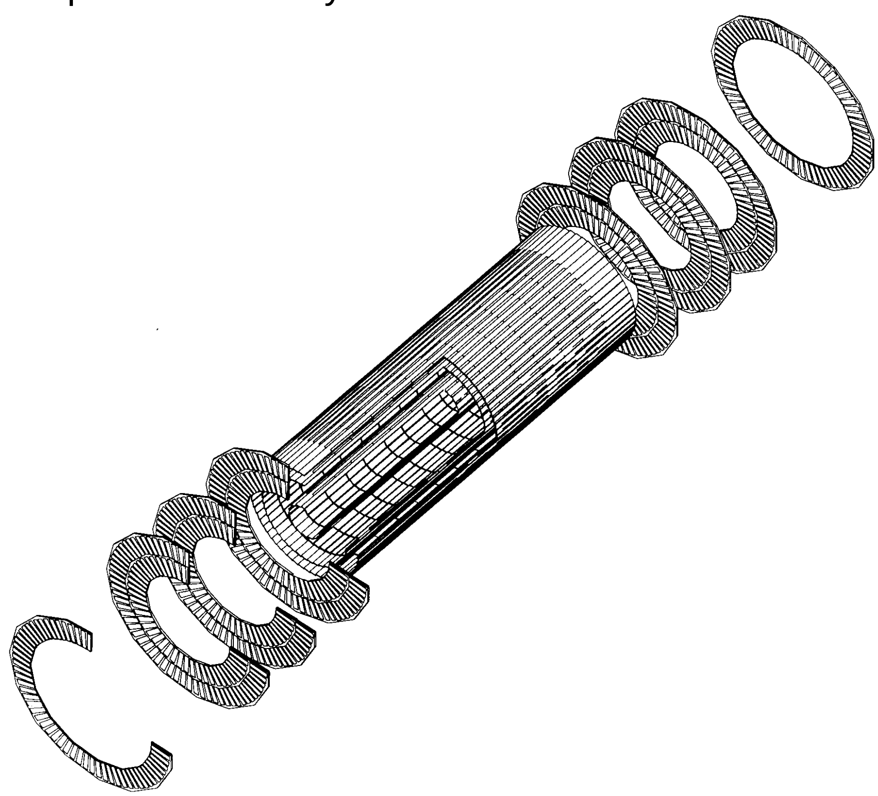
Arrangement of ATLAS Tracker

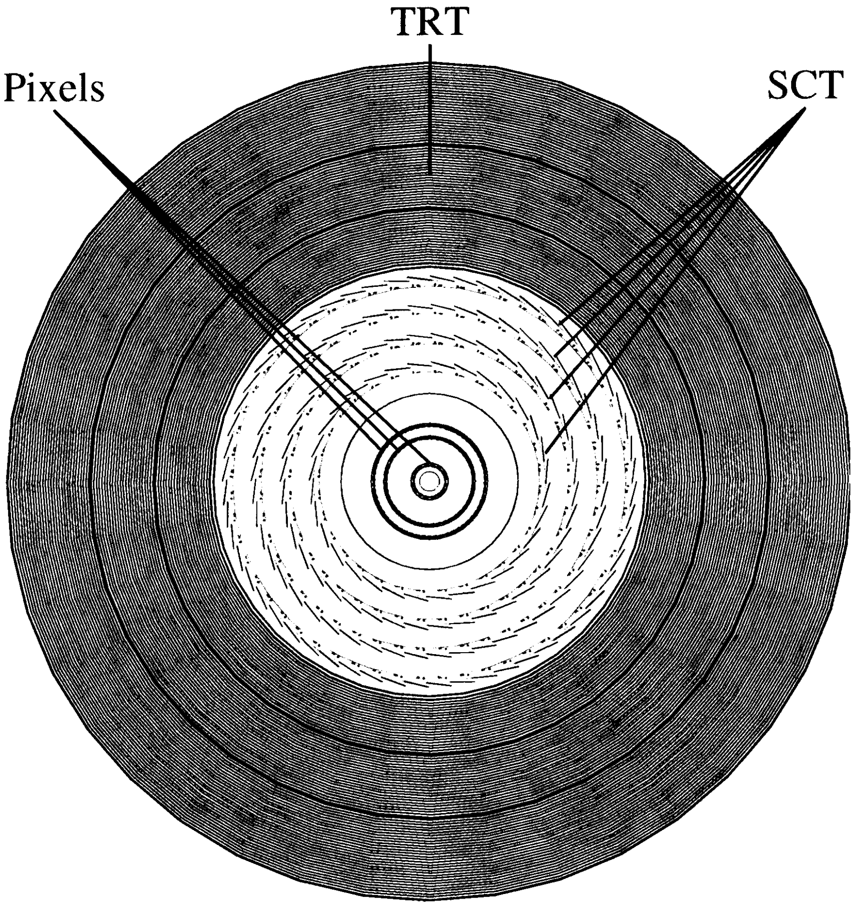
Coverage provided by

a) barrel in central region

b) disks in forward regions

Example: Pixel Subsystem





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

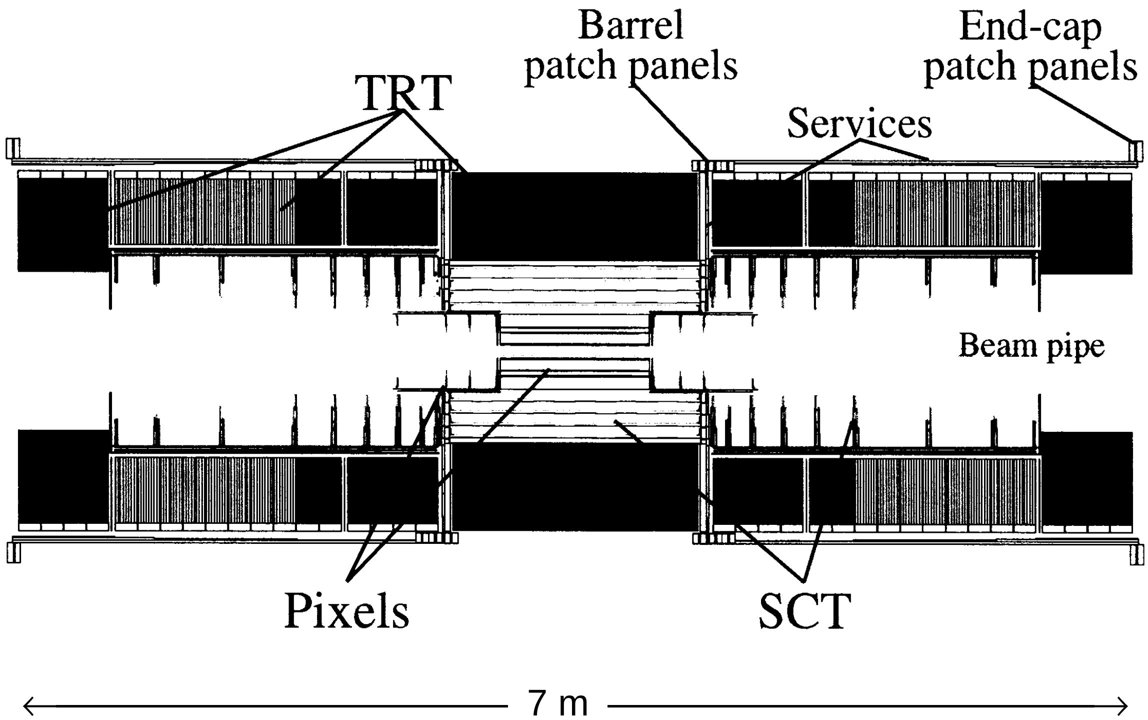
- high event rate (2D non-projective structure)
- radiation damage

  small capacitance ~ 100 fF $\Rightarrow$ low noise $Q_n \approx$ 100 el

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

Pixels and strips provide primary pattern recognition capability

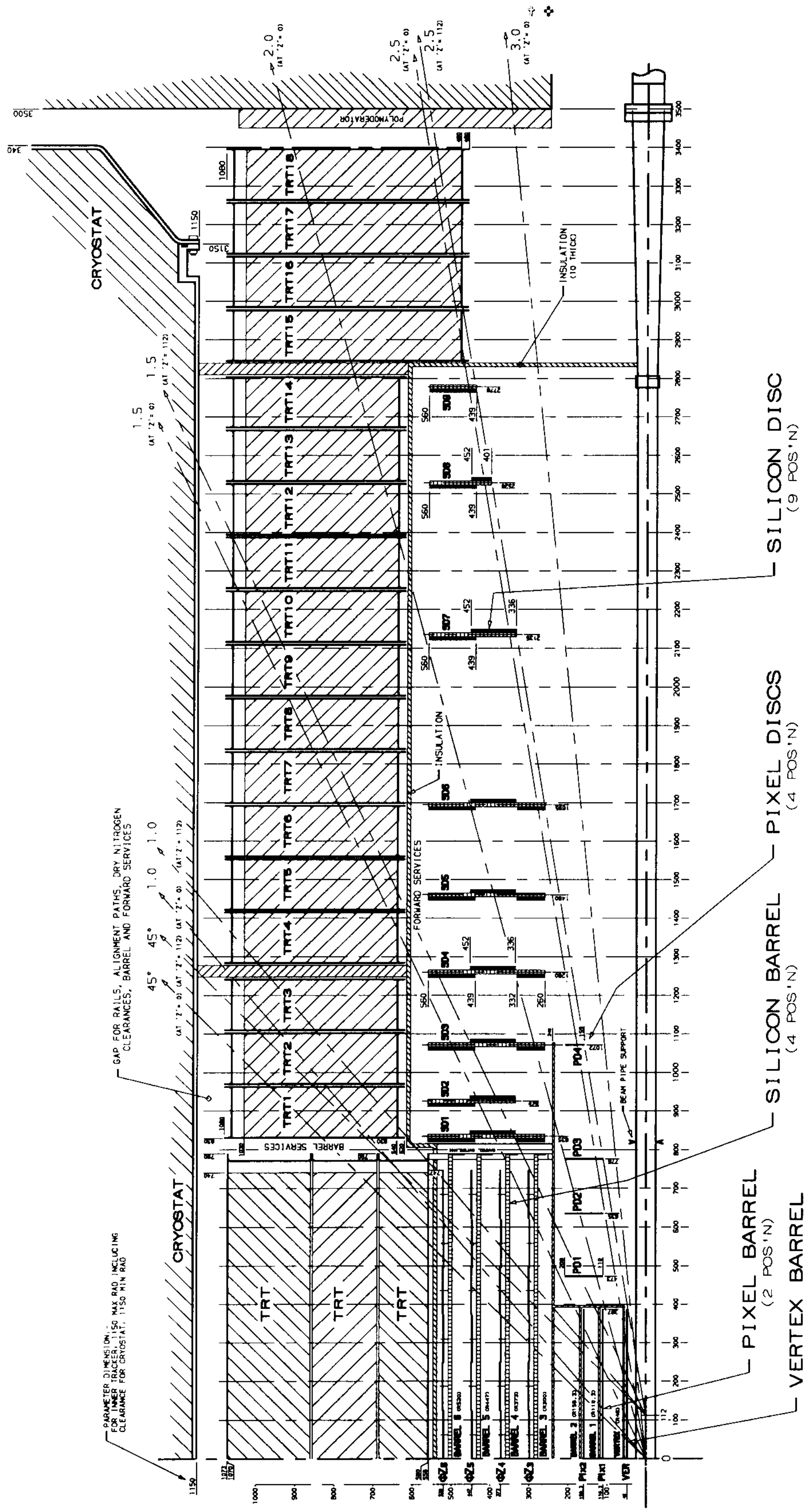
Straw drift chambers at outer radius (56 – 107 cm)
~70 layers yield 40 space points at large R and augment pattern recognition by continuous tracking (least expensive solution)



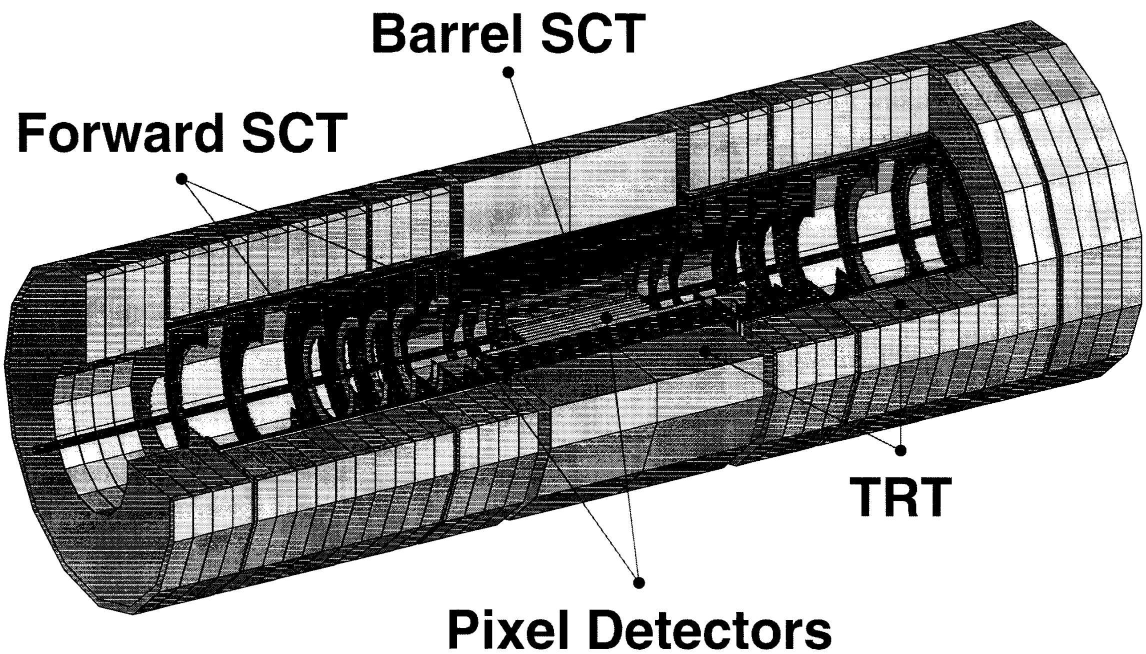
Strip modules use back-to-back single-sided detectors with small-angle stereo (40 mr) to provide z-resolution with negligible “ghosting”.

Resolution provided by 3 detector types in barrel

	$R\phi$	z
Pixels	12 µm	66 µm
Strips	16 µm	580 µm
Straws	170 µm	—


SILICON DISC
(9 POS'N)
PIXEL DISCS
(4 POS'N)
SILICON BARREL
(4 POS'N)
PIXEL BARREL
(2 POS'N)
VERTEX BARREL
CRYOSTAT
CRYOSTAT
INSULATION
FORWARD SERVICES
BARREL SERVICES
BEAM PIPE SUPPORT
POLYMODERATOR
TRT
TRT
TRT

Isometric View of Barrel Region



Segmentation ⇒ 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 µm x 300 µm:

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

Occupancy for strip electrodes with 80 µm 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.

⇒ 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

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)

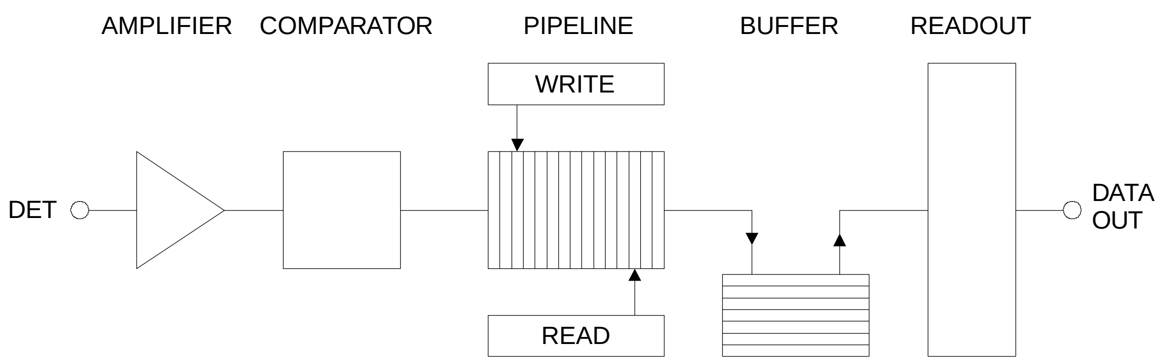
Goal is to obtain adequate position resolution, rather than the best possible

$\Rightarrow$ Binary Readout

detect only presence of hits

identify beam crossing

Architecture of ATLAS strip readout



Unlike existing colliders …

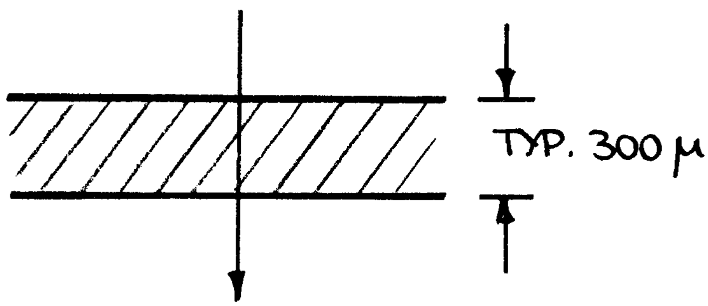
Crossing frequency >> readout rate

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

Required Signal-to-Noise Ratio

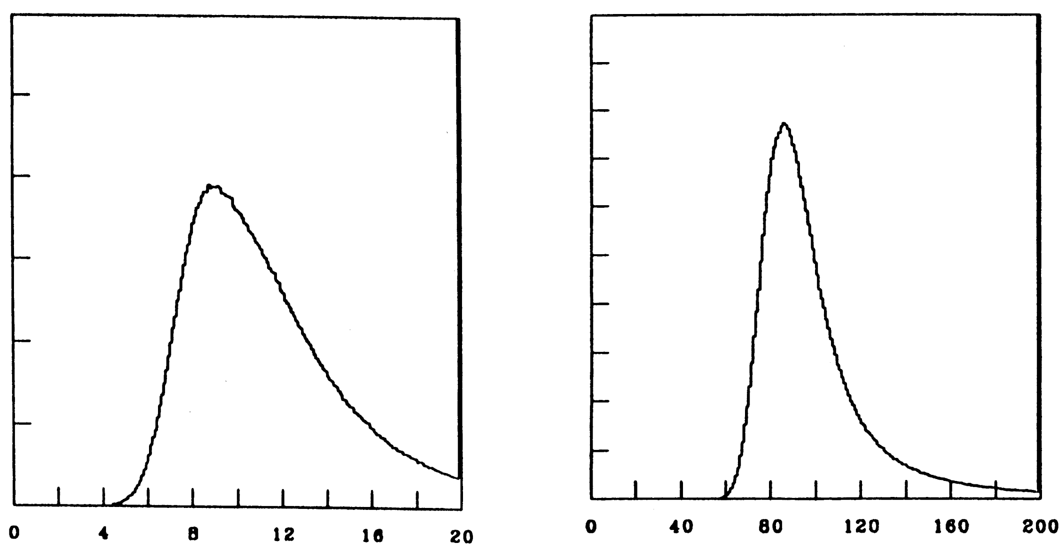
Acceptable noise level established by signal level and noise occupancy

1. Signal Level



For minimum ionizing particles: Q_s= 22000 el (3.5 fC)

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

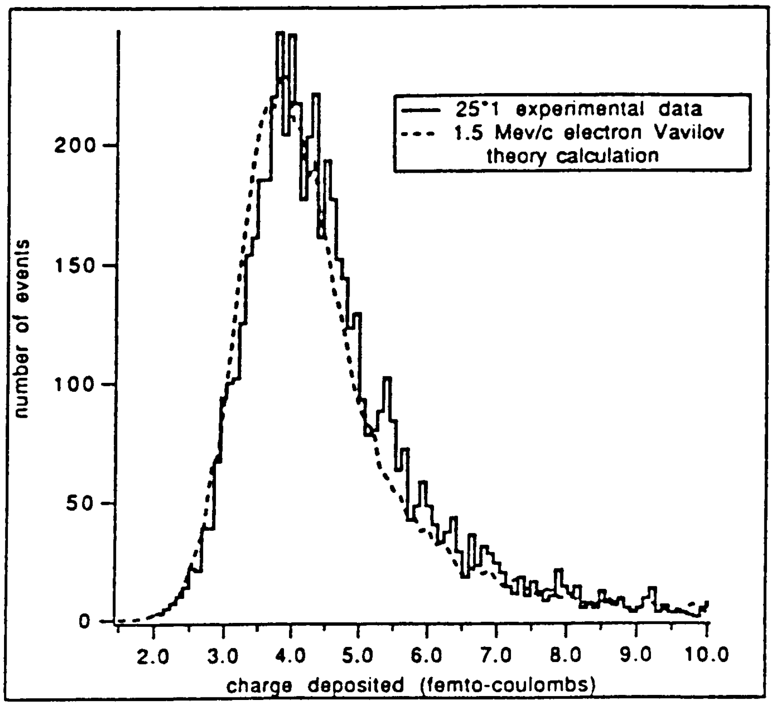


Si : 40 µm thick

Si : 300 µm thick

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 previously, 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

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

In the strip system the average hit occupancy is about 5 x 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

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

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

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

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

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

ATLAS requires $Q_n \leq 1500 \; el$.

What type of front-end transistor will provide this noise level at minimum power, bipolar transistor or MOSFET?

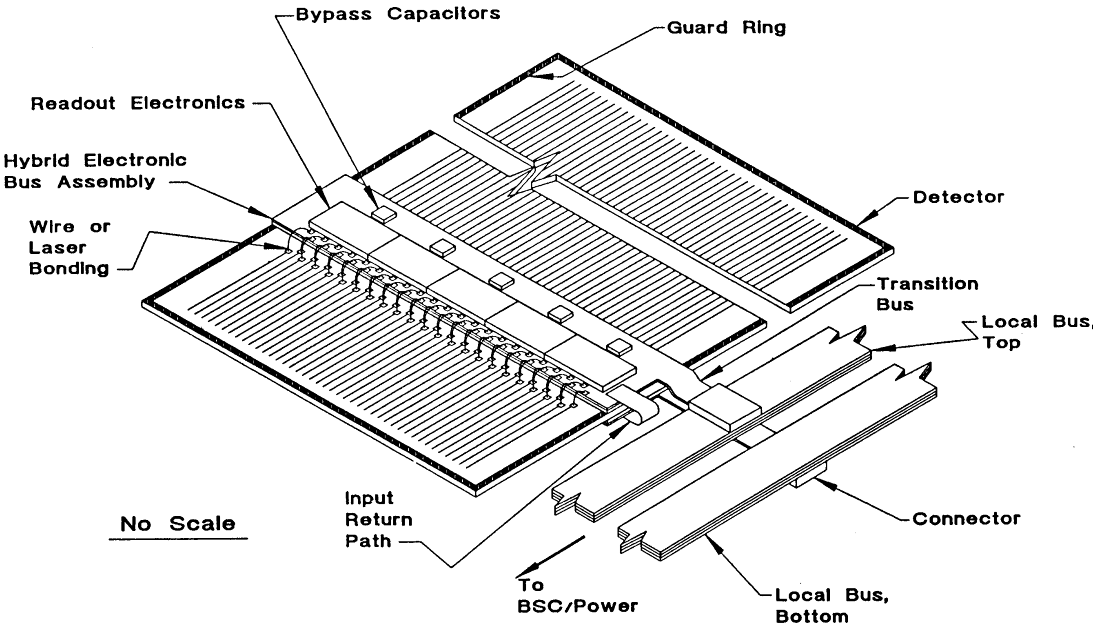
Applying the scaling rules outlined previously yields the following tables (actual noise levels will be ~20% higher):

Total Power of CMOS Front-Ends					
I(det) ≈ 10^{-7} A/cm					
Q_n [el]	Power [mW] vs. Strip Length				
	6cm	8cm	12cm	15cm	18cm
1050	2.0	4.0			
1100	1.7	3.3			
1200	1.3	2.6	7.8		
1300	1.1	1.9	5.2	12.0	
1400	1.0	1.5	4.0	7.4	17.2

Total Power of BJT Front-Ends								
$\Phi = 10^{14}$ cm^{-2}								
I(det) ≈ 10^{-7} A/cm; B=100								
Q_n [el]	Preamplifier Current [μA] vs. Strip Length				Power per Channel [mW] vs. Strip Length			
	6cm	12cm	15cm	18cm	6cm	12cm	15cm	18cm
1100	20	122			0.61	0.96		
1200	16	75	181		0.59	0.80	1.17	
1300	13	56	101		0.58	0.73	0.89	
1400	11	45	76	126	0.57	0.69	0.80	0.98
1500	10	37	61	95	0.57	0.66	0.75	0.87
1600	8	31	50	76	0.56	0.64	0.71	0.80
I(det) ≈ 10^{-7} A/cm; B=30								
Q_n [el]	Preamplifier Current [μA] vs. Strip Length				Power per Channel [mW] vs. Strip Length			
	6cm	12cm	15cm	18cm	6cm	12cm	15cm	18cm
1100	24				0.62			
1200	18				0.60			
1300	14				0.58			
1400	12	58			0.58	0.74		
1500	10	43	95		0.57	0.69	0.87	
1600	8.3	34	61		0.56	0.65	0.75	
1700	7.3	29	48	82	0.56	0.64	0.70	0.82

BJT front-ends with a strip length of 12 cm were chosen.

Module Configuration



Two 6 x 6 cm^2 detectors are butted edge-to-edge and connected by wire bonds to form a 6 x 12 cm^2 detector.

Two of these assemblies are glued back-to-back to form a double-sided detector with 40 mr small-angle stereo.

The strips are on an 80 μm pitch, so each side has 768 channels.

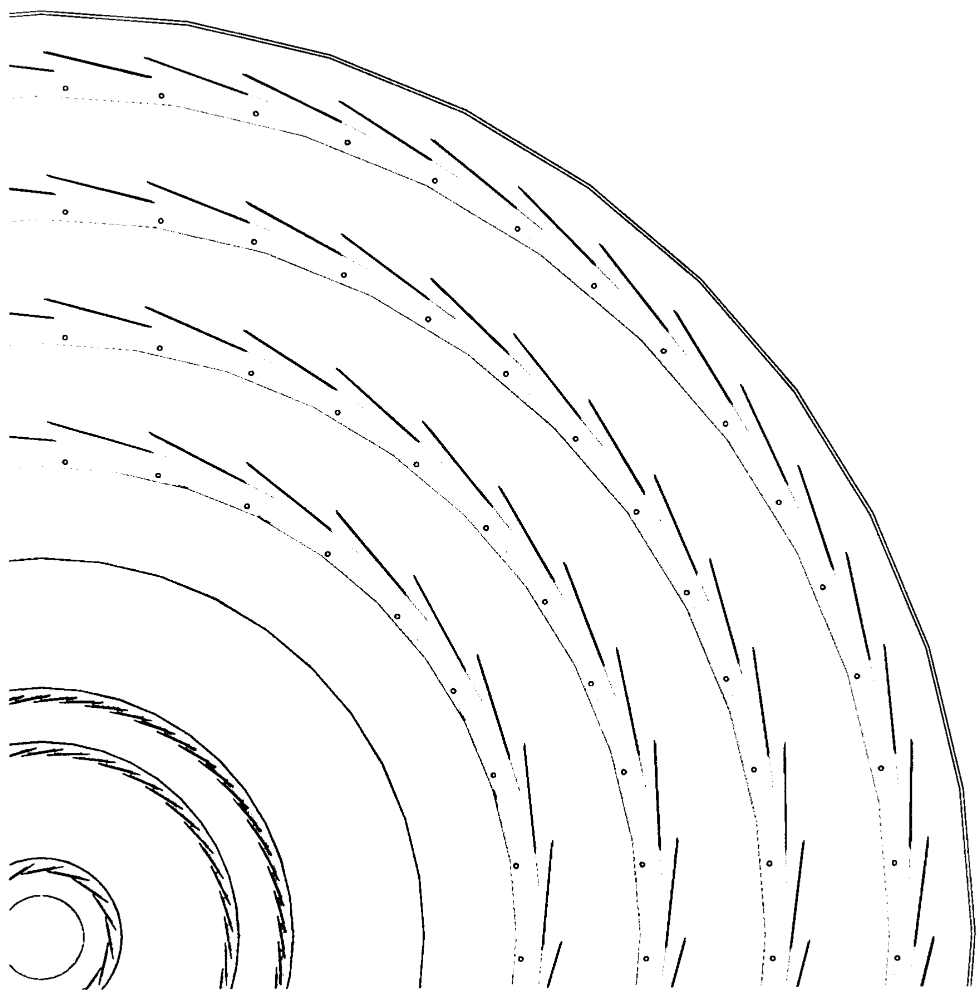
Integrated circuits with 128 ch each are mounted on a ceramic hybrid.

The hybrid is mounted on the detector, to facilitate mounting modules end-to-end in a row.

The amplifiers are connected to the middle of the detectors to reduce the noise contribution from the resistance of the strip electrodes.

Power and signal connections are made through low-mass Kapton cables.

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



Some Experimental Results using the CAFE Chip

CAFE Noise Before and After Irradiation

Measured on full-size modules (12 cm strips)

ATT7 and ATT8 use ATLAS baseline detector configuration:

n-strip on *n*-bulk, AC coupled (fab. by Hamamatsu)

ATT7 detector uniformly irradiated to 10^{14} cm^{-2} (MIP equiv)
CAFEs irradiated to 10^{14} cm^{-2} (MIP equiv)

ATT8 CAFEs from run 2
non-irradiated reference module

Noise measured on complete modules (ATT7 at about -10 °C)

measurement site	ATT7 chip 0	ATT7 chip 1	ATT8 chip 0	ATT8 chip1
LBNL, 28-Jun-96	1440 el	1380 el	1375 el	1435 el
H8 beam line, 15-Jul-96	1470 el	1380 el	1350 el	1410 el
H8 beam line, 7-Aug-96	1400 el	1375 el	1400 el	1375 el

Electronic calibration (~ 10% absolute accuracy)

CAFE Timing Performance

1. Chips from run 1 measured on test boards

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

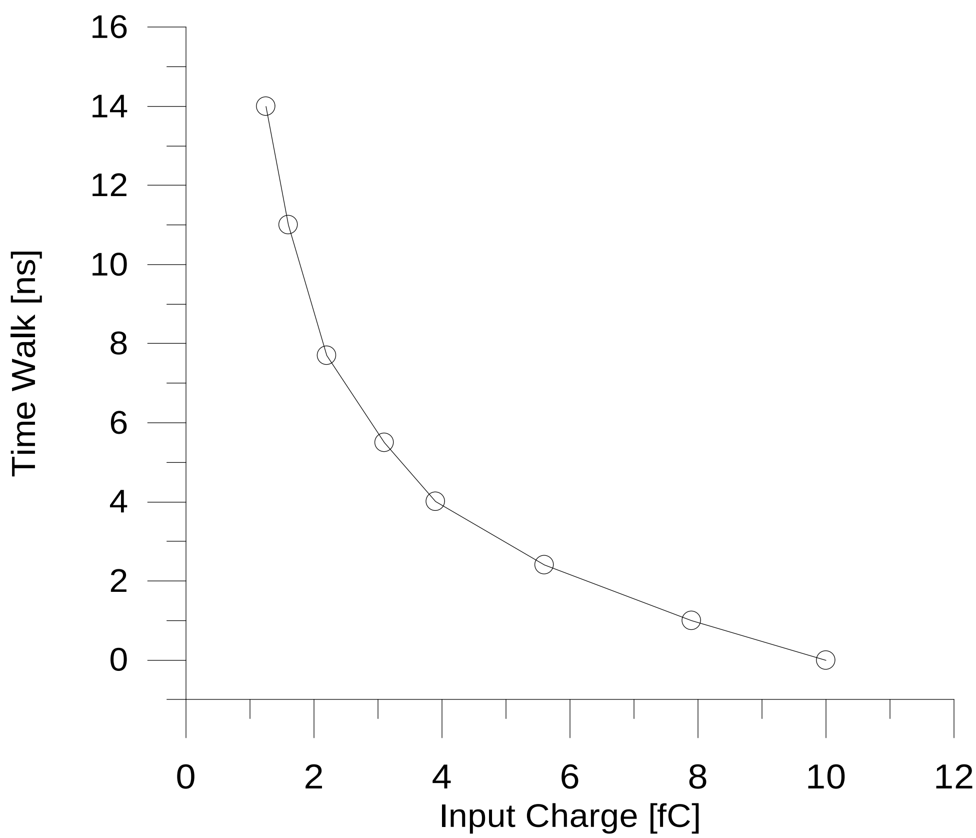
Time Walk 16 ns (1.25 - 10 fC) at 1 fC threshold
1.25 - 4 fC: 12 ns
4 fC - 10 fC: 4 ns

Jitter at 1.25 fC ≈ 4 ns FWHM

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

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

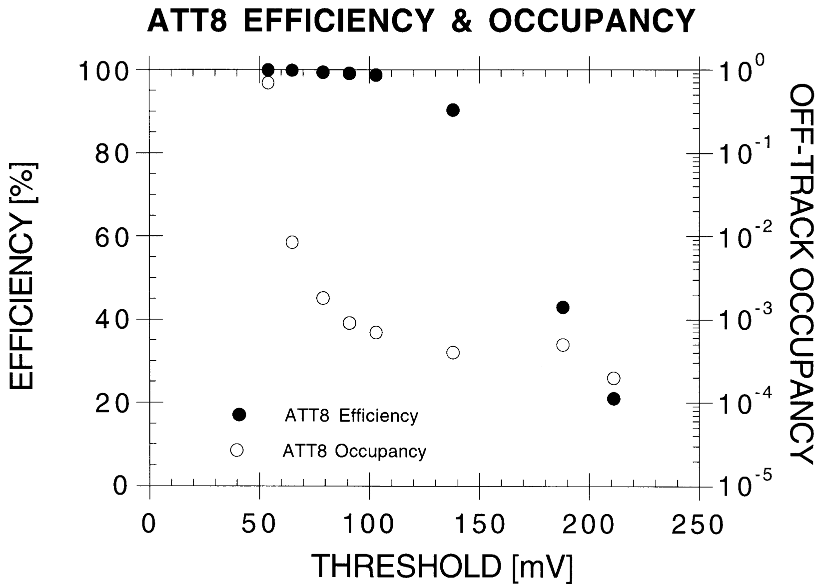
C_{load}= 15 pF, 1 fC threshold, jitter as above



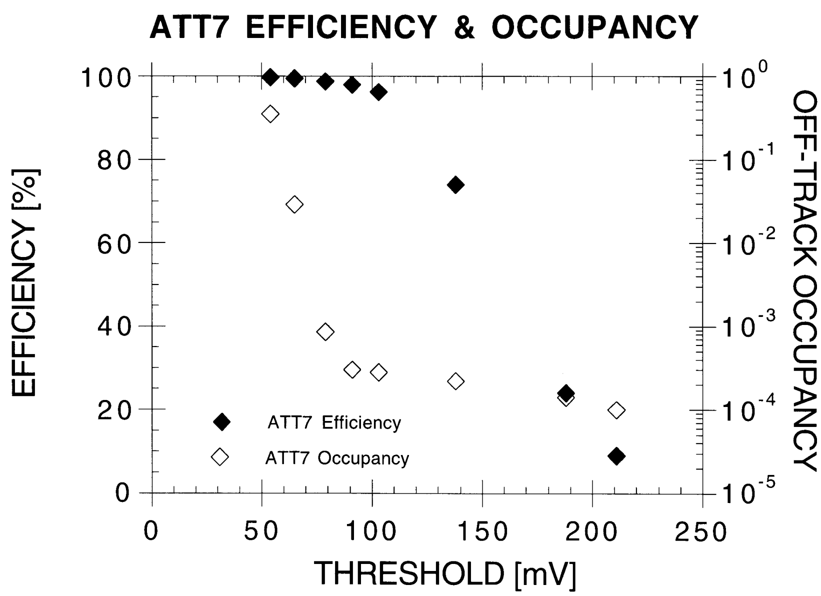
Test Beam Data

Tracking Efficiency vs. Occupancy for Full-Length Modules

non-irradiated module



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



Tracking Efficiency and Pulse Height vs. Detector Bias (irradiated, ATT7, and non-irradiated, ATT8)