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2003-12-16

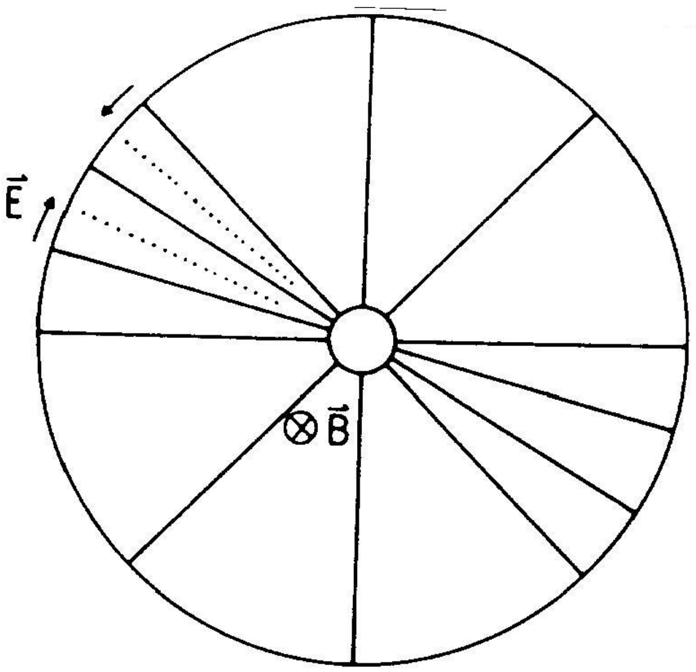
1.2.4. (Inner) tracking and vertexing

As we will see, mainly three types of tracking detectors are used:

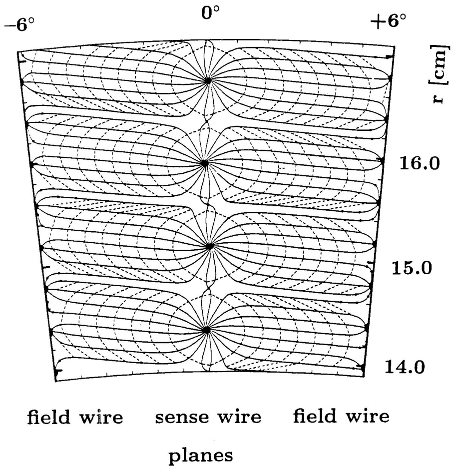
- drift chambers
- silicon strip and silicon pixel detectors
- scintillating fibres

Before we will discuss the different detectors in detail, some general comments on these devices:

Drift chambers inside solenoid magnets often look like this 'jet chamber':



The dots indicate long anode wires ($> 1\,\mathrm{m}$) parallel to the beam line, the thick straight lines are the cathodes. In addition there are field shaping wires, not shown. The drift lines are shown here:

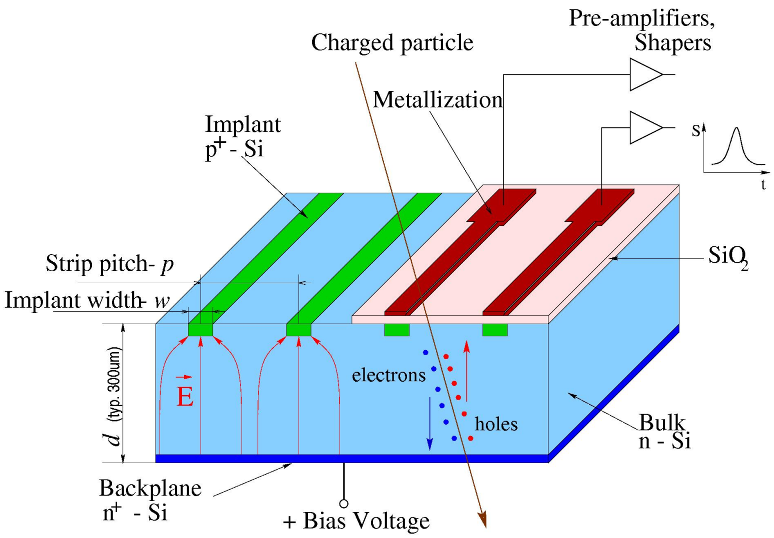


The number of anode wires fired by one particle from the interaction region varies between $30 \ldots 300$. For each wire the drift time (relative to a fast external signal, for example generated by the accelerator for each bunch crossing) for the electrons to reach the amplification region is measured. This allows a precision of $50 - 200\,\mu\mathrm{m}$ per wire, resulting in a sagitta resolution of few $10\,\mu\mathrm{m}$. If in addition to the drift time (TDC) also the pulse height is measured (ADC), a good dE/dx measurement can be performed, helping in identifying the particle (see below).

(Dis-)advantages:

- \+ standard technology
- \+ contains only a few percent of a radiation length of material (avoids showering)
- \- slow: drift distance / drift speed $\sim 50\,\mathrm{mm}\ /\ 50\,\mathrm{mm}/\mu\mathrm{s} \sim 1\,\mu\mathrm{s}$
- \- pattern recognition difficult (if many tracks), occupancy high
- \- strong B field influences driftlines (‘Lorentz angle’ large)

Silicon strip detectors are semiconductors:

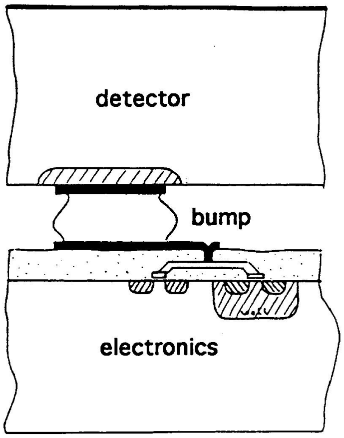


The material is typically $300\,\mu\mathrm{m}$ thick, the strips $10 - 50\,\mu\mathrm{m}$ apart and a couple of cm long. The voltage across the diode (strip versus backplane) is chosen such that there are no free charges inside the detector (as long as there is no particle traversing), the device is fully depleted. A minimum ionizing particle generates about 30000 electrons and holes. Typically 4-10 layers are used to measure a track.

(Dis-)advantages:

- \+ high spatial resolution $\sim 10\mu\mathrm{m}$ (combining charge from neighboring strips)
- \- expensive
- \- detector contains up to one radiation length of material (⟶ showering)
- \+ fast: charge collection $\sim 20\,\mathrm{ns}$
- \- limited radiation hardness ($\longrightarrow T < -10^0$ C)

Silicon pixel detectors have a typical pixel size of only $200\mu\mathrm{m} \cdot 20\,\mu\mathrm{m}$; each pixel has its own readout electronics:

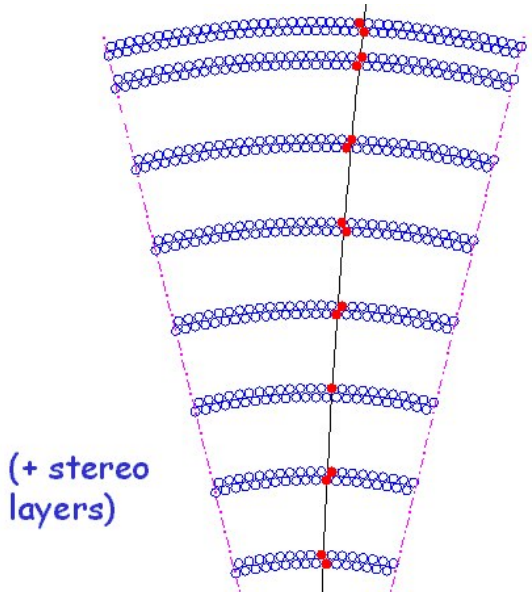


Pixel detectors are used as 'vertex detectors' close to the beam pipe.

(Dis-)advantages:

- \+ 3 D track reconstruction
- \+ high spatial resolution
- \- many channels ⟶ expensive
- \+ many channels ⟶ low occupancy
- \+ fast: charge collection $\sim 20\,\mathrm{ns}$
- \- limited radiation hardness

Scintillating fibres allow a fast measurement in the $x - y$ plane:

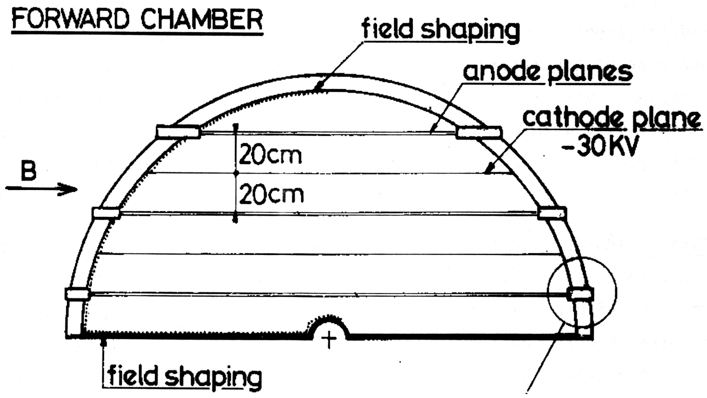


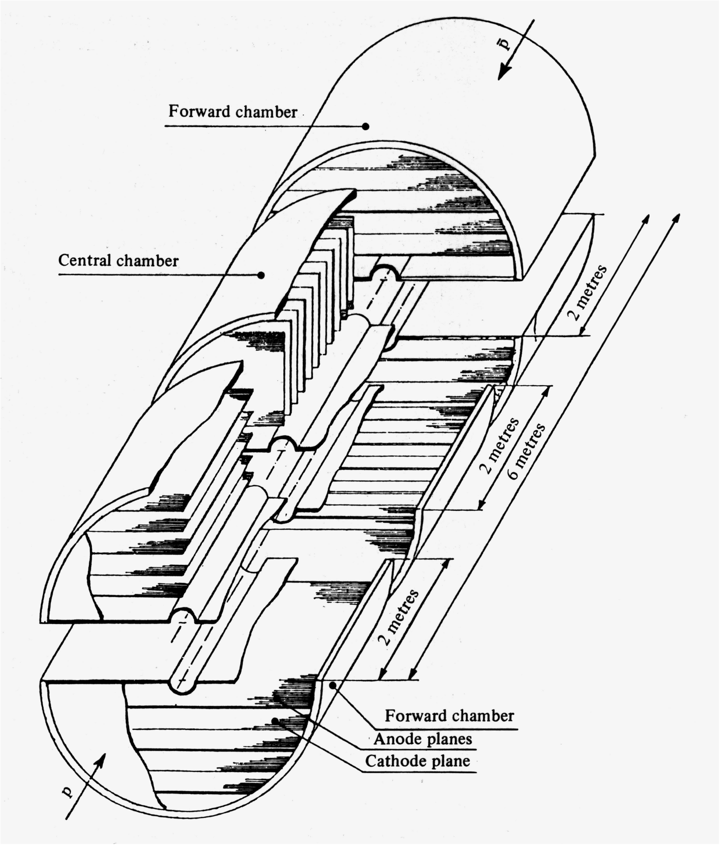
The fibres are typically $1\,\mathrm{mm}$ tick and $1\,\mathrm{m}$ long; they are strung parallel to the beam axis. The scintillating light can be measured with photomultipliers.

(Dis-)advantages:

+ fast, decay time = few ns
- z-coordinate (along beam axis) difficult to measure
- pattern recognition difficult (if many tracks), occupancy high
- light yield low ($\sim$ 10 photons per track !)

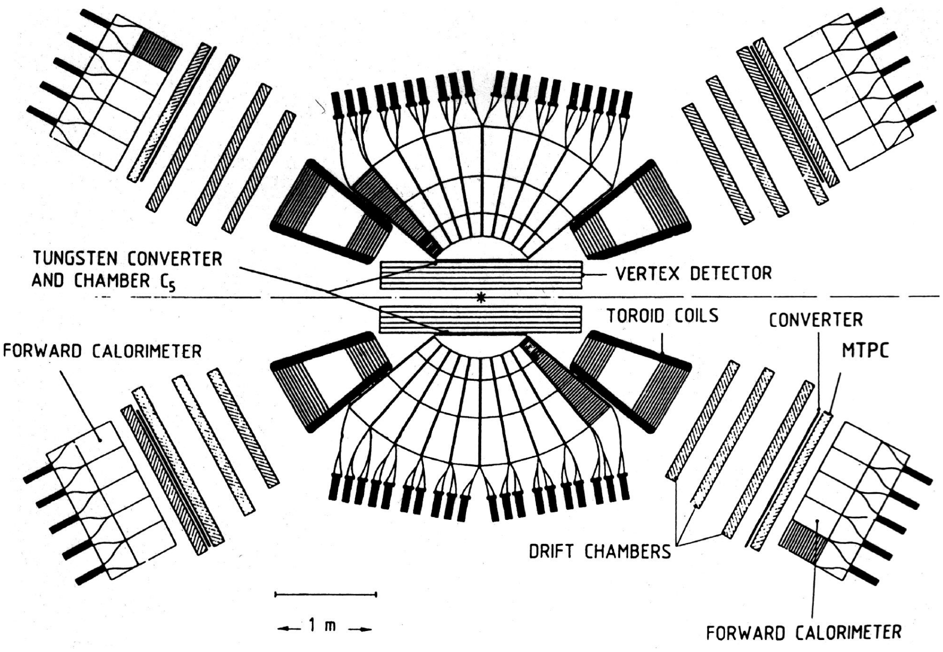
The large central detector ($r = 1.3\,\mathrm{m}$) of the **UA1** experiment was made of planar drift chambers, oriented such that the particles from the interaction point fly approximately parallel to those planes. Every second plane is a cathode plane; in the forward region:



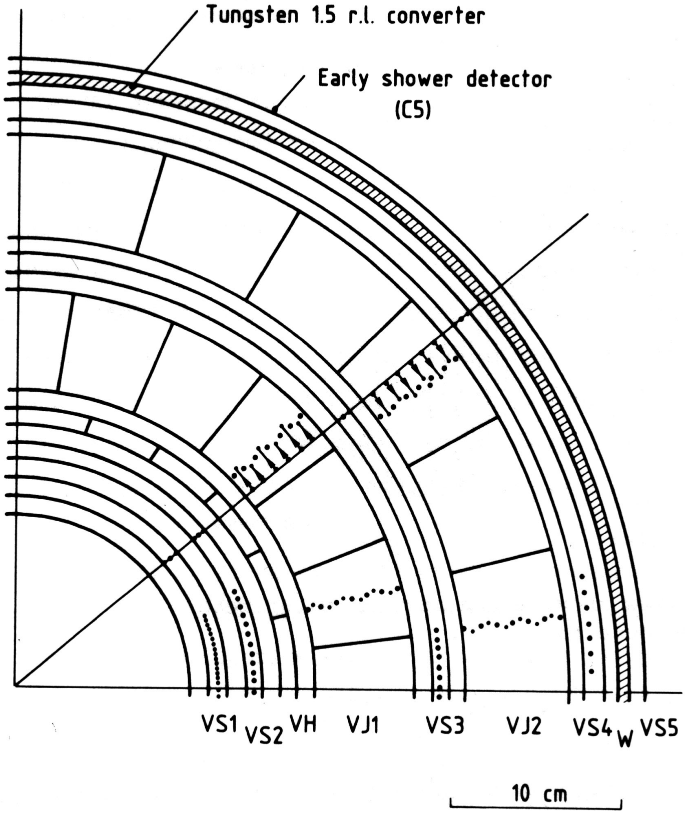


The magnetic dipole field causes up- and forward-going tracks to be bent in a direction perpendicular to the wire planes - thus the momentum can be measured easily. The electrons created by ionisation have to drift up to $\mathbf{20\,cm}$. Each anode wire plane contains about 200 (350) wires in the central (forward) region, $\mathbf{5\,mm}$ apart, measuring the track with an accuracy of $\boldsymbol{\sigma = 250\,\mu\mathrm{m}}$ per wire. The pulse height is measured, too. The coordinate along the wires (up to $\mathbf{2.2\,m}$ long) is determined from the ratio of the pulse heights measured at the two ends with a precision of $\mathbf{1\%}$ of the wire length. The sum of the pulse heights is proportional to $\boldsymbol{dE/dx}$.

The **UA2 apparatus** looked like this (at the time of W/Z discovery):



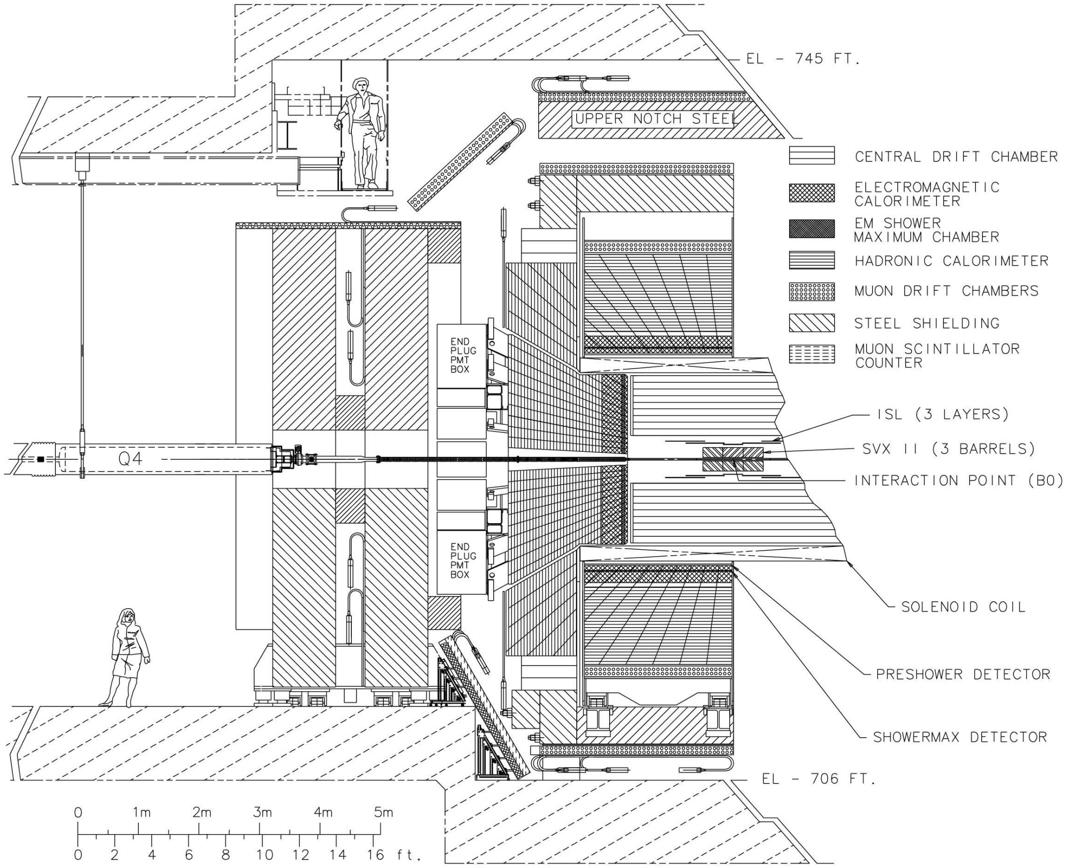
This was one of the first detectors calling its inner tracker a 'vertex detector', a cylindrical chamber:



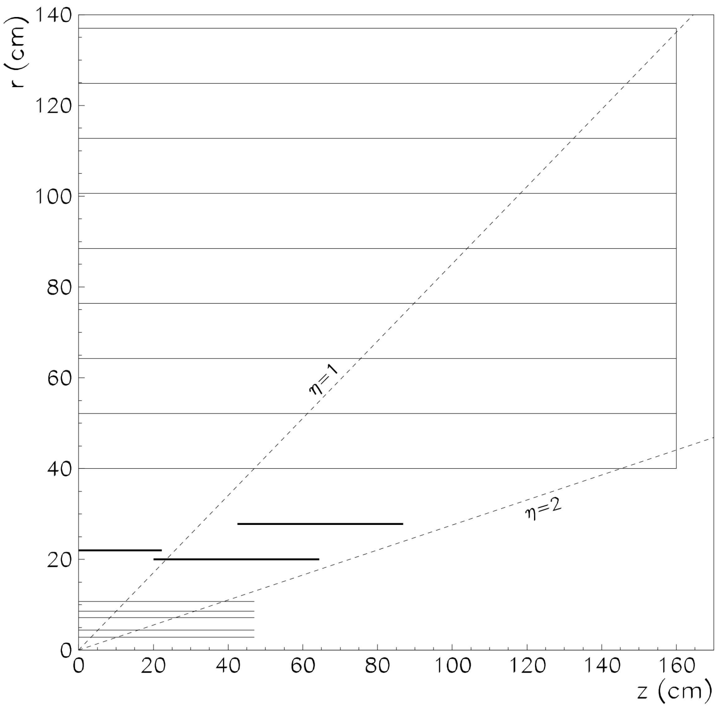
They consisted of drift chambers of 'jet' type (VJ1,VJ2) with a resolution of $300\,\mu\mathrm{m}$ per wire, proportional chambers with cathode strip readout (allows to measure z!) and a layer of scintillators (VH). Charge division was (also) used to determine the z coordinate. Along the beam axis the vertex could be localized with a precision of $1.5\,\mathrm{mm}$; measurements of decay lengths (lifetimes) of short-lived particles were not possible.

The z vertex coordinate must be known to determine particle momenta, which was possible only in the forward (backward) regions, equipped with a toroidal field. The main goal at that time was to verify that the W bosons are polarized (positive electrons from W decays fly preferrentially in the direction of the proton beam). After traversing the B field, the tracks were measured with several layers of drift- and proportional chambers. A momentum resolution of $0.5\% \cdot p/\mathrm{GeV}$ was reached. Later the toroids and chambers were removed, in favor of a good endcap calorimeter.

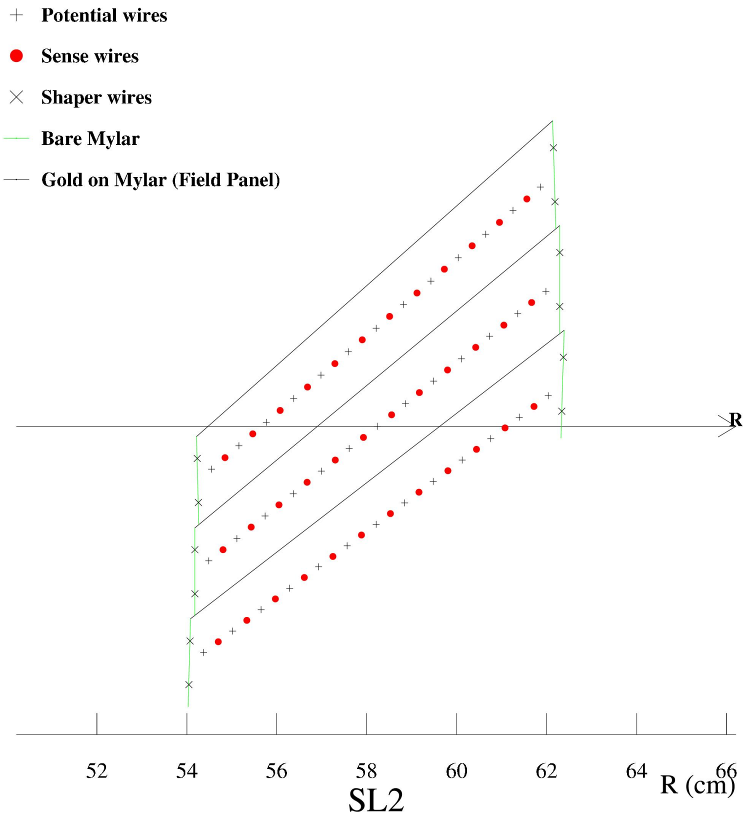
CDF got a new central tracker (shorter drift times!) and a new silicon vertex detector for the run II data period:

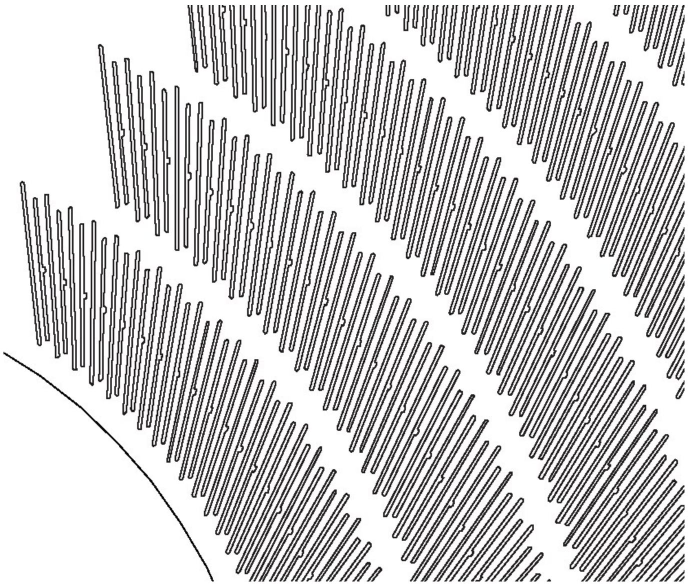


The tracker consists of three parts:

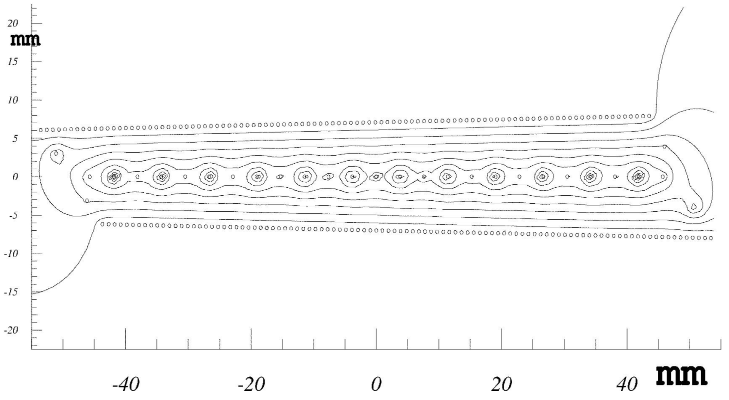


The ‘central outer tracker’ (COT) is a $3\,\mathrm{m}$ long drift chamber with short drift distances of less than $1\,\mathrm{cm}$ and a ‘fast’ gas (Ar Et CF_4, $\sim 100\,\mathrm{mm}/\mu\mathrm{s}$), so that the maximum drift time is below $132\,\mathrm{ns}$ as (originally) required for run IIb. The chamber radius is large, approximately $1.4\,\mathrm{m}$, allowing for a good momentum resolution ($B^2!$). The 60000 wires (half of them sense wires) are strung this way:





Advantage of this layout: tracks from vertex cross ‘suppercells’ under a large angle, thus avoiding left-right ambiguities. The electric field lines are shown here:

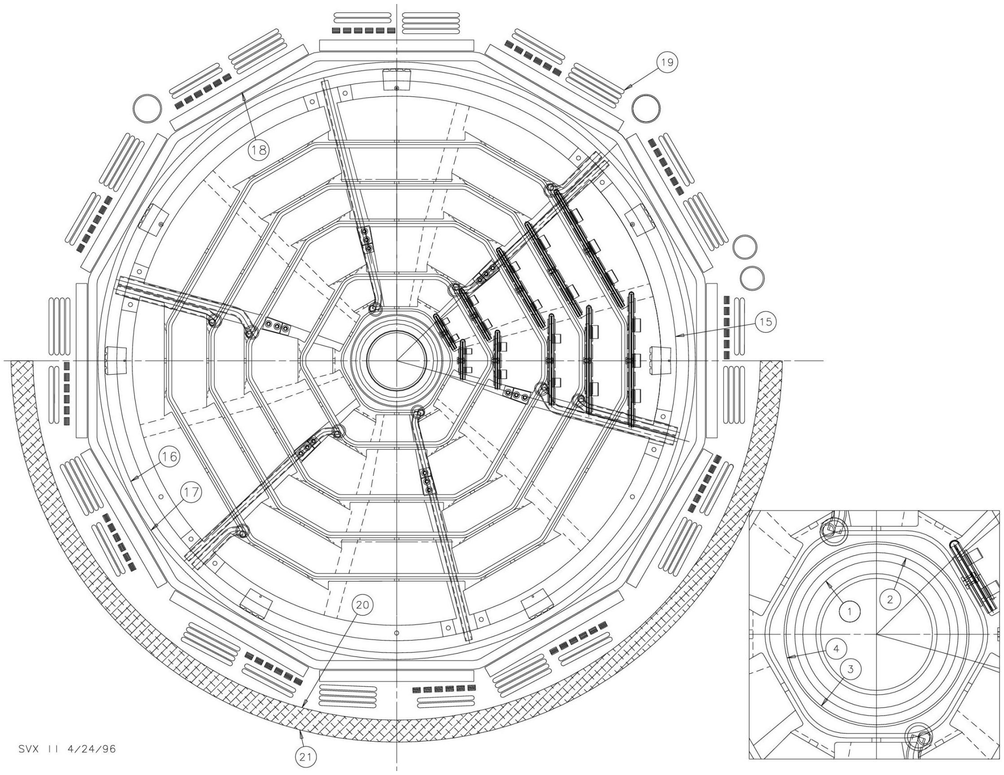


Note that the ‘lines’ of field wires are realized by gold plated mylar foils, thus simplifying the design. The position resolution is around $180\ \mu\mathrm{m}$ per signal wire.

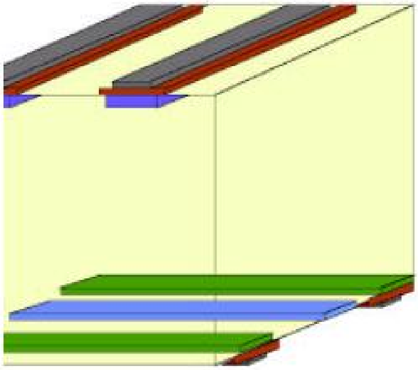
The elctronics allows apart from the arrival time measurement also a determination of pulse heights; for a total of 96 layers this gives a decent dE/dx measurement.

In between the COT and inner silicon detector another silicon device (with a moderate resolution), the ISL (Intermediate Silicon Layers) was inserted; it provides a tracking point allowing to match the COT and inner silicon tracks.

The CDF silicon detector has five layers



In total 5 double sided layers are ‘seen’ by a traversing particle:



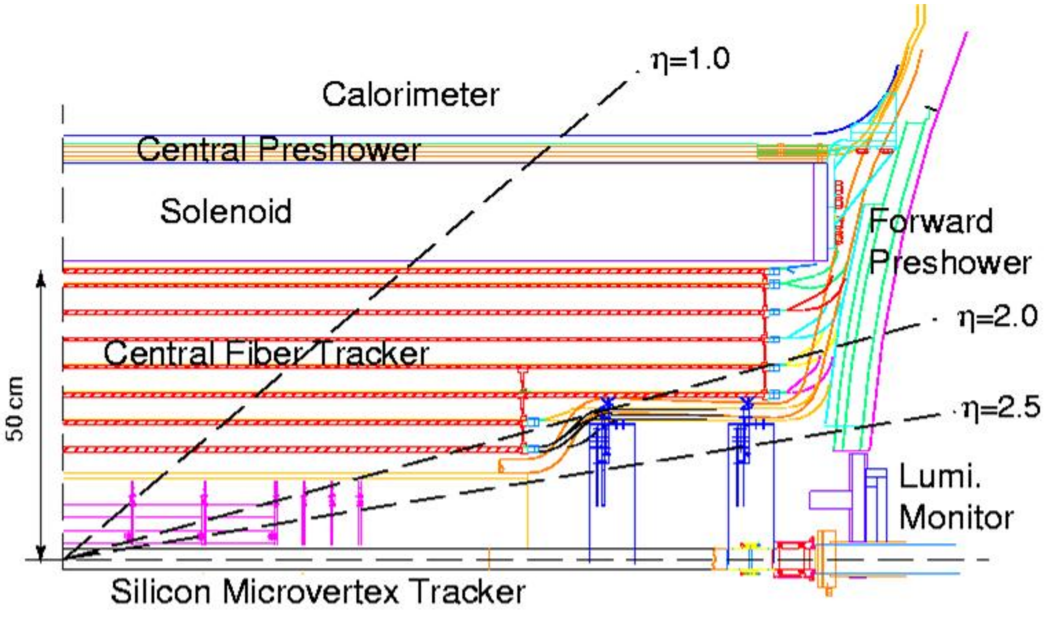
Only barrel modules with Si strips parallel to the beam axis[1] and strips measuring in the $x - y$ plane are used, there are no 'endcaps' (cf D0!). The layers are positioned at radii between $\mathbf{2.5\,cm}$ and $\mathbf{11\,cm}$. In addition a 'layer 00' Si detector is mounted directly on the beam pipe, at a radius of $\approx \mathbf{1.5\,cm}$, where it has to stand $\mathbf{10\,kGy/fb}$. To increase the lifetime these strips are operated at $\mathbf{0^0\,C}$.

Using all inner tracking devices together, a momentum resolution of

$$\frac{\Delta p_T}{p_T} = 0.001 \cdot p_T/\mathrm{GeV} \tag{1}$$

can be reached.

D0 has no drift chamber, due to the limited space inside the solenoid coil (determined by the calorimeter size. . .):



The 'barrel' shaped silicon modules are complemented by disk like modules, some in the end regions, others close to the vertex. Other parameters are similar to those of the CDF Si tracker. A barrel 'ladder' is about $\mathbf{12\,cm}$ long and looks like this:

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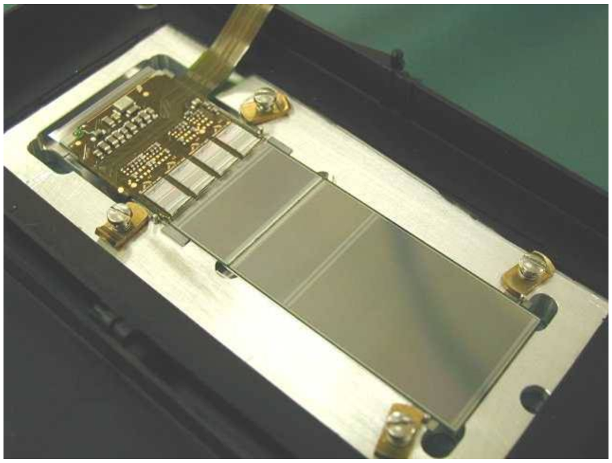
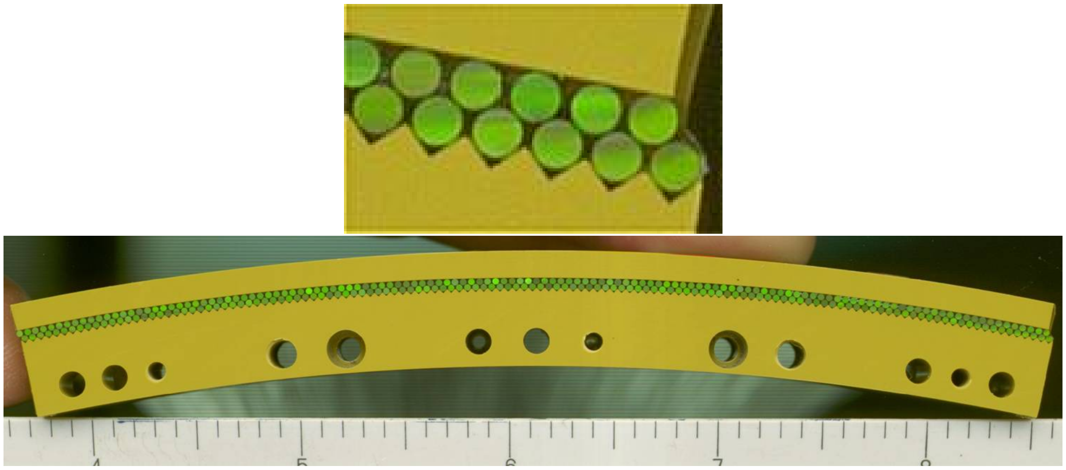
[1] $\pm\mathbf{1.2^o}$ stereo angle

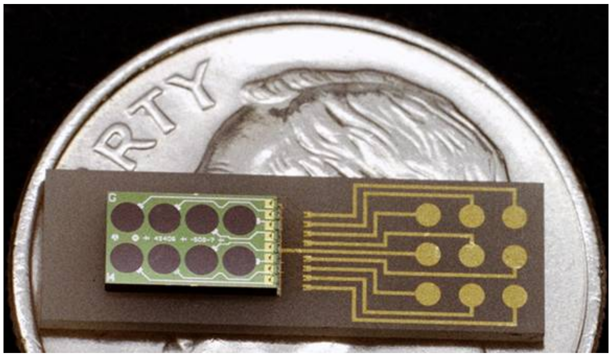


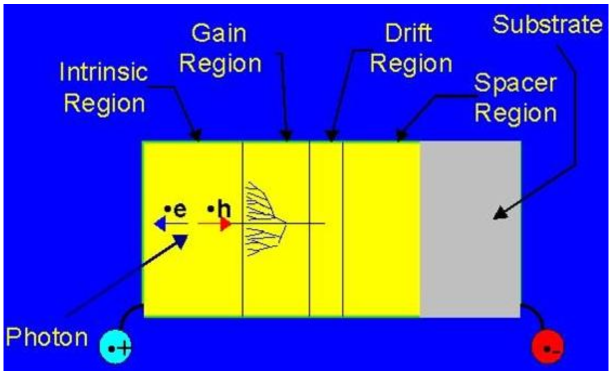
Both single sided and double sided modules are used.

Unique is the scintillating fibre tracker with ‘VLPC’ readout surrounding the silicon tracker:



The fibres are $2.5\,\mathrm{m}$ long and $0.835\,\mathrm{mm}$ thick; a minimal ionising particle produces results in about 10 photons arriving via clear fibres at the photon detectors, the ‘Visible Light Photon Counters’. These are semiconductor detectors operating at a temperature of $T \approx 9\,\mathrm{K}$, reaching a quantum efficiency of 75%:

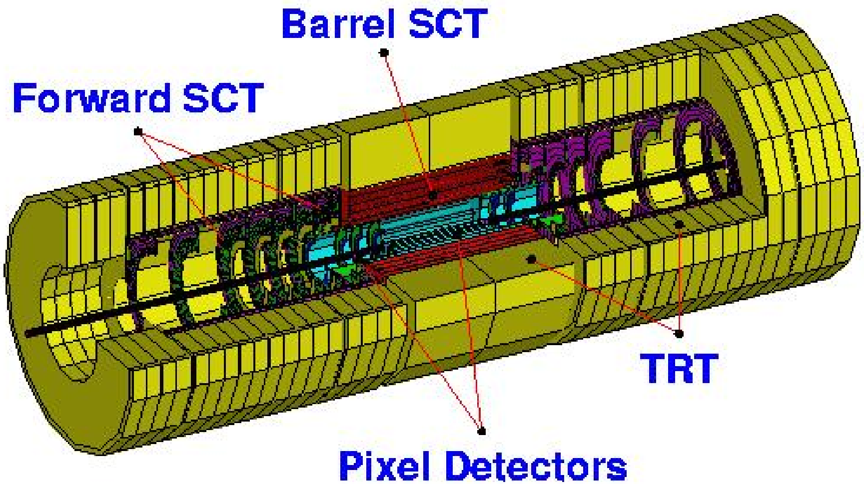




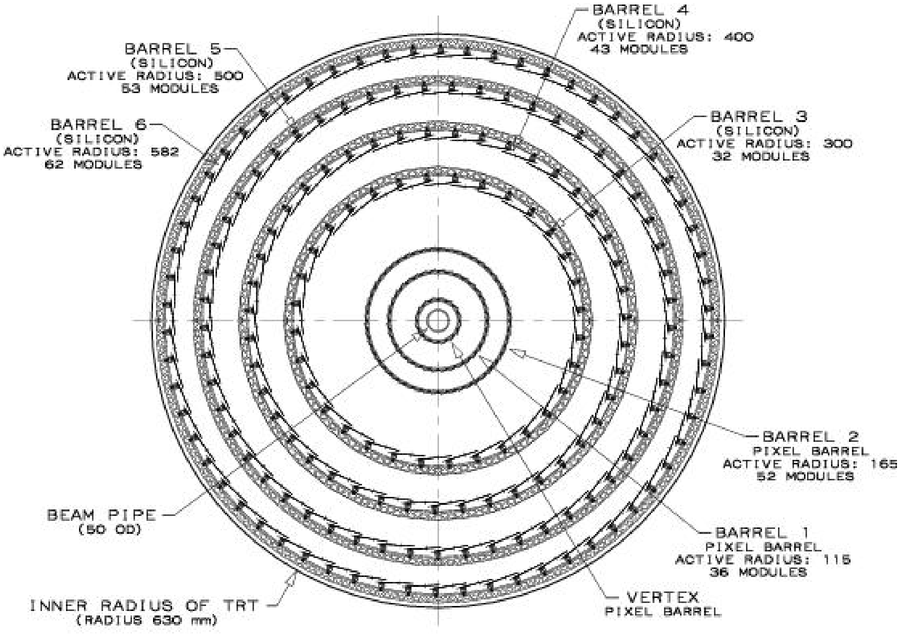
Due to the limited tracker radius, the p_T resolution is not quite as good as for CDF:

$$\frac{\Delta p_T}{p_T} = 0.002 \cdot p_T/\mathrm{GeV} \tag{2}$$

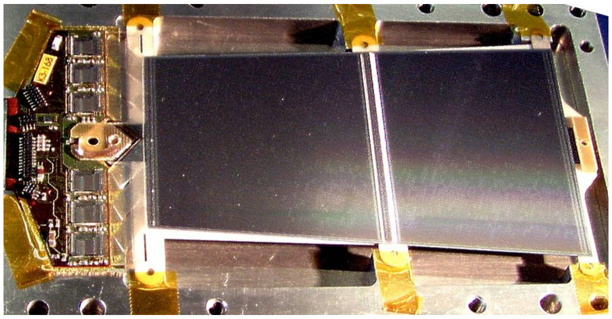
ATLAS uses a combination of silicon trackers and gas detectors to measure tracks:



Here two types of silicon devices are used, pixels and strips:



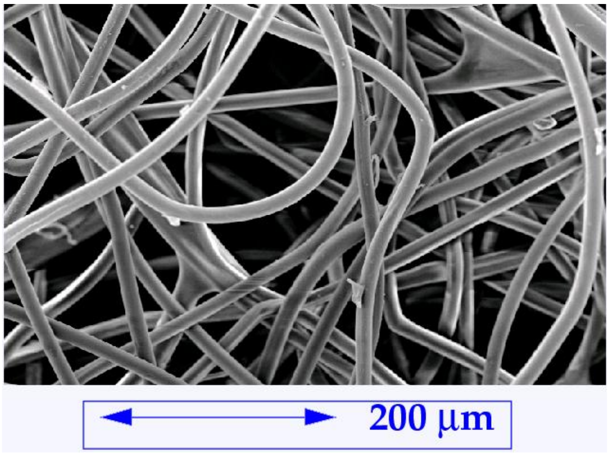
The silicon strip detector is similar to the one used in CDF. Double sided modules are used in both the barrel and endcap regions:



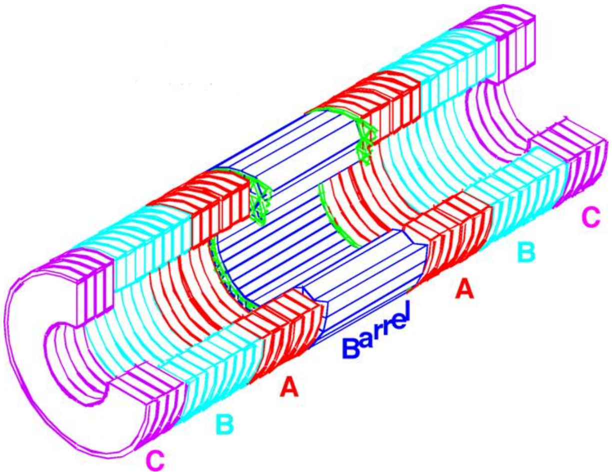
In total an area of $61\,\mathrm{m}^2$ is covered, the resolution is typically $15\,\mu\mathrm{m}$. A particle at $\eta \approx 0$ traverses four layers. The temperature will be kept at $-10^0\,\mathrm{C}$.

The pixel detector covers the innermost region; the inner of the three barrels is located at a distance of $5\,\mathrm{cm}$ from the beam line. There are in total 80 million pixels with a size of $50\mu\mathrm{m} \cdot 300\mu\mathrm{m}$.

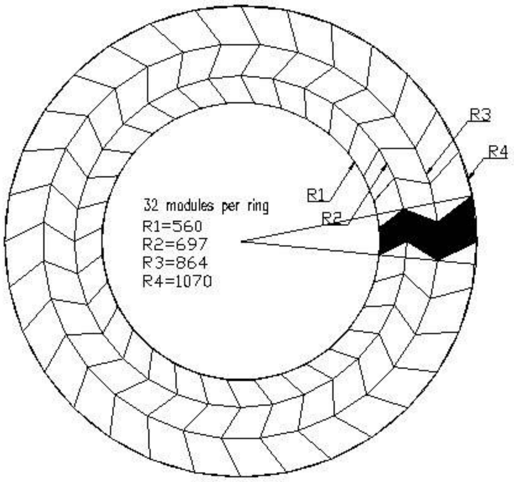
The outer part of the inner tracker, made out of barrel and endcap disks, consists of straw tubes together with a 'radiator' material with a huge effective surface, thus yielding a measurable amount of transition radiation:

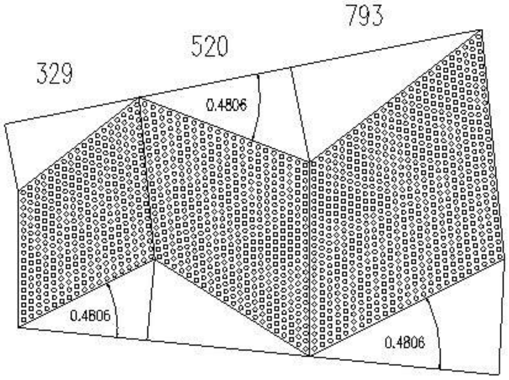


This 'Transition radiation Tracker' (TRT) encloses the silicon tracker; in the central region the tubes are oriented along the beam axis, in the forward regions they run radially:

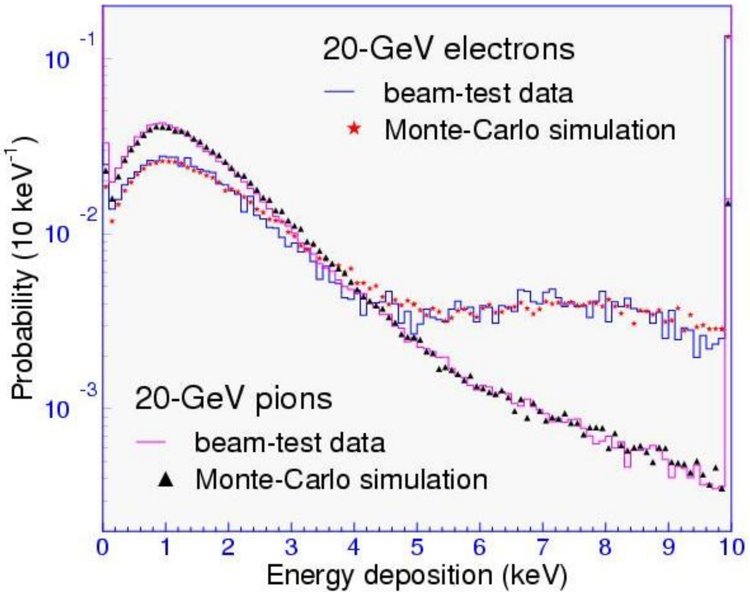


The tubes are $39 - 144\,\mathrm{cm}$ long and have a diameter of less than $1\,\mathrm{cm}$. The straw walls are made out of different (conducting) synthetic materials, with a total thickness of only $70\mu\mathrm{m}$. Due to the small diameter the drift time is short, around $40\,\mathrm{ns}$. The position resolution will be around $150\,\mu\mathrm{m}$. A particle produced at the collision point will traverse at least 36 straws. The loosely packed radiator material is inserted in between the tubes:



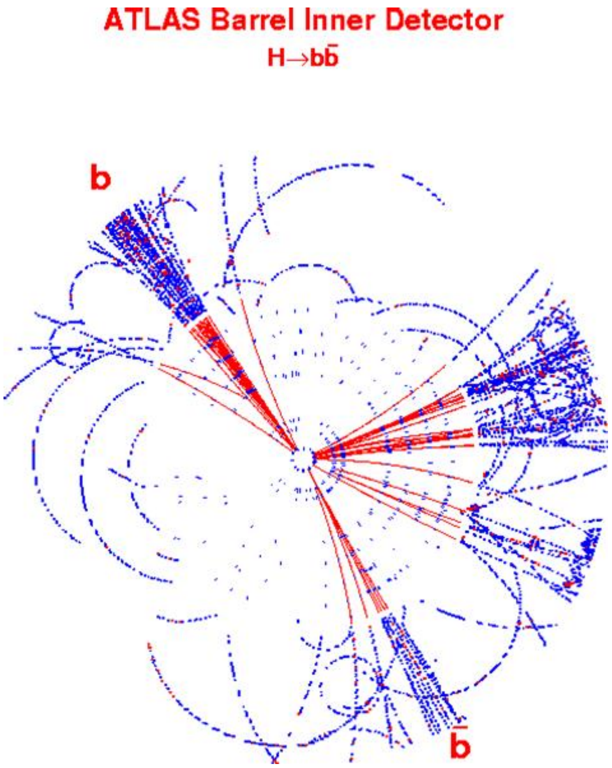


Transition radiation occurs at the surfaces; the probability is proportional to $\alpha \approx 1/137$, thus small. The (average) amount of light is proportional to γ of the charged particle flying through. Therefore a measurable effect can be expected only for electrons. Most TR photons will be able to traverse the polyethylene radiator and also the straw walls. Inside the tubes the photons are absorbed in the gas: 70% Xe (Z = 54), 20% CF_4, 10% CO_2. The corresponding energy deposits of about $5\,\mathrm{keV}$ adds to the charged particle's energy loss of about $2\mathrm{keV}$ per tube. Thus electrons can be identified:



In spite of the radiator material the construction is very 'light', at $\eta = 0$ the whole TRT detector represents only 15% of a radiation length.

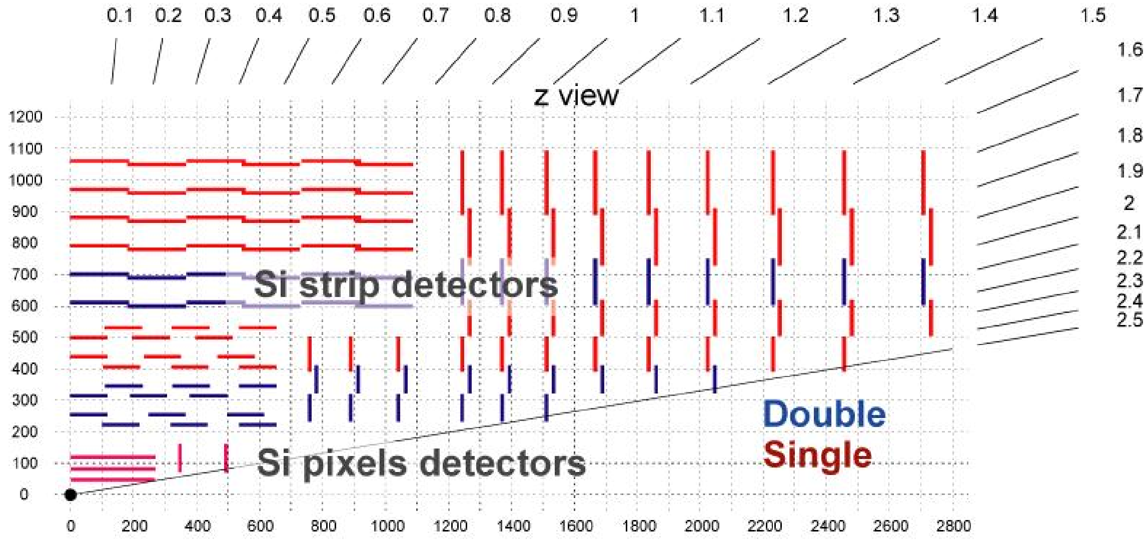
A simulated ATLAS event (inner tracker only) looks like this:



One can clearly see the different spatial resolutions achieved in the silicon and TRT parts.

CMS has an only-silicon inner tracker; the strip detector will have a total surface of $\mathbf{220\,m^2}$ = world record.

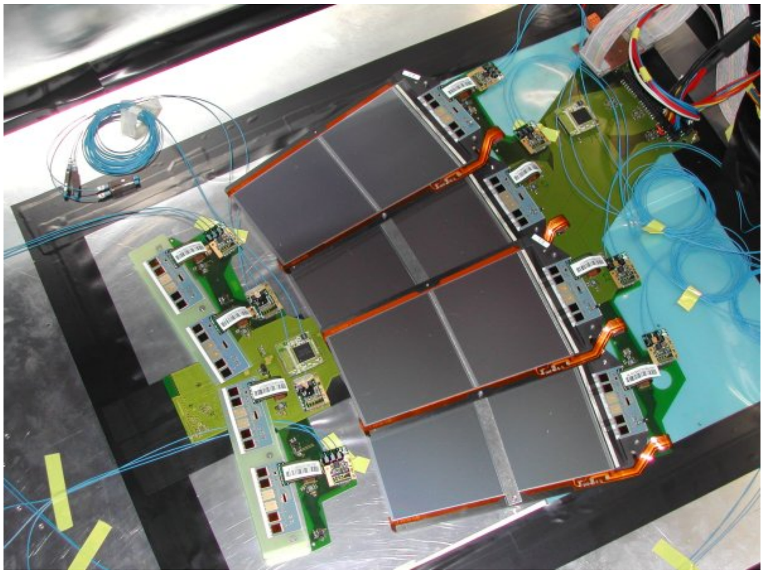
In the barrel region it is made out of 2 pixel layers and 10 strip layers.



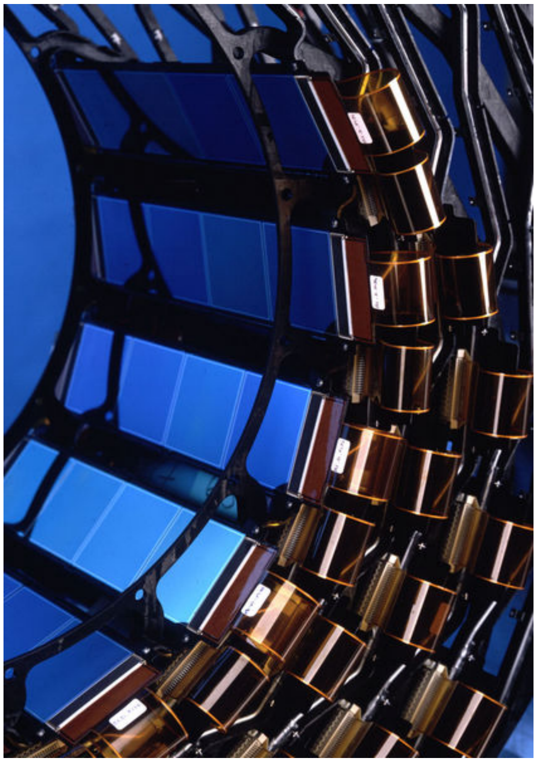
The layout of the CMS inner tracker

The total length amounts to more than $\mathbf{5\,m}$, the radius exceeds $\mathbf{1\,m}$.

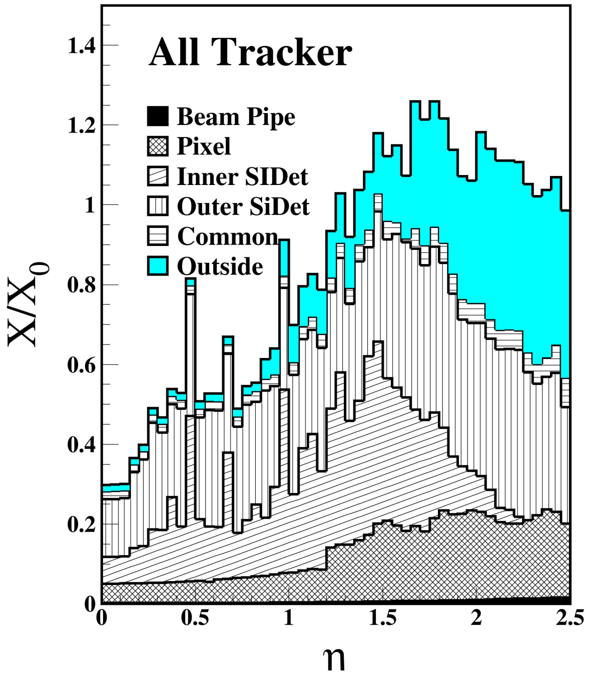
A silicon strip 'petal' in the endcap region:



Result of a test assembly:



A problem is the material thickness (represented by the beam pipe, tracking detectors, infrastructure) in front of the calorimeter:



This can lead to showering inside the silicon tracker. The situation is even worse for ATLAS, reaching $2\,X_0$ at $\eta = 0$.

Let's now take the CMS silicon strip tracker as an example to estimate the momentum resolution from the position resolution and the magnetic field strength.

A track at $\eta = 0$ traverses 10 silicon strip layers in between $r = 20\,\mathrm{cm}$ and $r = 100\,\mathrm{cm}$ with a resolution in the $r - \phi$ plane of $15\,\mu\mathrm{m}$ each. The magnetic field strength is $B = 4\,\mathrm{T}$. Thus, approximating the 10 layers by the 4 detector model discussed in chapter 1.2.1, using a resolution of $\Delta y = 15\,\mu\mathrm{m}/\sqrt{2.5} = 9\,\mu\mathrm{m}$:

$$c_{det} = 0.026 \cdot \frac{9\,\mu\mathrm{m/mm}}{(0.8\,\mathrm{m})^2/\mathrm{m}^2\ (4\,\mathrm{T})/\mathrm{T}} \approx 1.0 \cdot 10^{-4} \tag{3}$$

We can also estimate the multiple scattering effect, reading the value $L = 0.3X_0$ from the figure shown above:

$$c_{MS} = \frac{0.052}{0.8\,\mathrm{m/m}\ 4\,\mathrm{T/T}} \sqrt{0.3} \approx 1.0 \cdot 10^{-2} \tag{4}$$

Thus, a $100\,\mathrm{GeV}$ track will be measured with a precision of

$$\frac{\Delta p}{p} = 10^{-4} \cdot \frac{p}{\mathrm{GeV}} \oplus 1\% = 1\% \oplus 1\% = 1.4\,\% \tag{5}$$

This number is in good agreement with the outcome of CMS MC studies. The inclusion of the silicon pixels will improve this figure slightly.

Comparison of trackers:

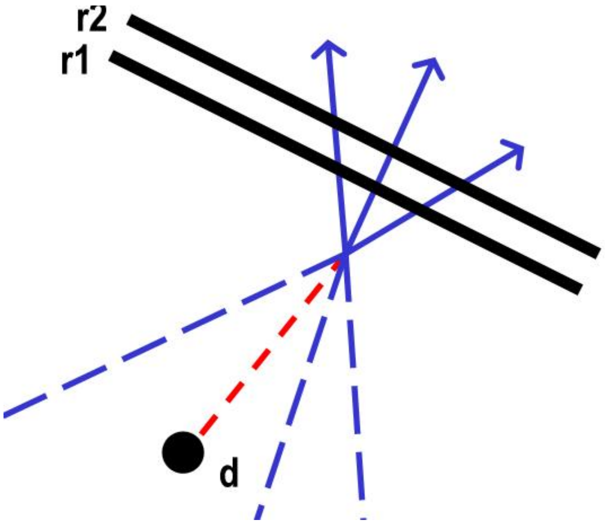
detector	type	pos. resol. $(R\,\phi)\,/\mu\,\mathrm{m}$	mom.-resol. $(\eta = 0, 100\,\mathrm{GeV})$	channels
UA1	drift	250	30%	6100
UA2	drift/prop	300	50%	?
CDF	silicon strip	7-11		700000
CDF	drift	180	10% total	30000
D0	silicon	10		800000
D0	fibres	100 (doublet)	20% total	80000
ATLAS	pixel	14		$1.4 \cdot 10^8$
ATLAS	silicon strip	15		$3 \cdot 10^6$
ATLAS	straw	150	4% total	400000
CMS	pixel	10		$5 \cdot 10^7$
CMS	silicon strip	15	1.6% total	10^7

Important is also the impact parameter resolution. For ATLAS it can be parametrized by

$$\delta d = 12\,\mu\mathrm{m} \oplus \frac{88\,\mu\mathrm{m}}{p_T/\mathrm{GeV}\,\sqrt{\sin\theta}} \tag{6}$$

in the $R - \Phi$ projection. The second term is due to multiple scattering.

To understand the impact parameter measurement, we study the following simple (CMS inspired) model, making use of two pixel layers:



We assume a particle originated at the origin, and the measured impact parameter d in the $r - \phi$ plane is due to the position uncertainty of $\delta_1 = \delta_2 \equiv \delta = 10\,\mu\mathrm{m}$ in both of the 2 CMS pixel layers, located at radii $r_1 = 4\,\mathrm{cm}, r_2 = 7\,\mathrm{cm}$ at low luminosity running[2]:

$$\delta d^{det} \equiv d = \frac{r_1}{r_2 - r_1}\,\delta_2 \oplus \frac{r_2}{r_2 - r_1}\,\delta_1 = 25\,\mu\mathrm{m} \tag{7}$$

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[2] Later, at higher luminosity and radiation dose, there will be two layers, at 7 and $11\,\mathrm{cm}$.

The smaller r_1 (for fixed $r_2 - r_1$), the better the resolution[3]. Taking into account also the silicon strips, the resolution improves to about $15\,\mu\mathrm{m}$. The multiple scattering contribution can be estimated by calculating the scattering angle in the beam pipe (CMS: beryllium) and the inner detector layer, assuming zero distance between beam pipe and first pixel layer:

$$\delta d^{MS} = r_1 \cdot \theta_{MS} = r_1 \cdot \frac{0.0136\,\mathrm{GeV}}{p_T}\sqrt{\frac{L}{X_0}} \tag{8}$$

First we estimate which contribution is dominant:
a) Assuming a thickness of $L = 1\,\mathrm{mm}$, and inserting $X_0(Be) = 35\,\mathrm{cm}$ we get

$$\delta d^{MS,pipe} \sim \frac{30\,\mu\mathrm{m}}{p_T/\mathrm{GeV}} \tag{9}$$

b) A single pixel layer is more than 2% of a radiation lengths thick, thus

$$\delta d^{MS,pixel} \sim \frac{80\,\mu\mathrm{m}}{p_T/\mathrm{GeV}} \tag{10}$$

Thus, the latter effect is most important!

Combining all measurements (incl. silicon strips) the CMS impact parameter resolution is pedicted (MC) to reach:

$$\delta d = 15\,\mu\mathrm{m} \oplus \frac{90\,\mu\mathrm{m}}{p_T/\mathrm{GeV}\,\sqrt{\sin\theta}} \tag{11}$$

Thus our estimate on the multiple scattering term was good, but the silicon strip tracker must not be neglected.

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[3] for fixed r_1 an increase of r_2 is beneficial!